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Did the shale gas boom reduce US CO_2 emissions?

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Abstract: The shale gas boom in the US is widely seen as responsible for reducing US CO_2 emissions through substitution of gas for coal in power generation. The story is more complex because increased gas use in other sectors may not be displacing carbon-intensive fuels, but rather reducing incentives to adopt more efficient processes and less carbon-intensive products. In this paper we consider the emissions implications for the U.S. under a counterfactual modeling of the 2011 US economy without the shale gas boom. We apply a general equilibrium model of the 2011 US economy, estimating the supply responses of coal-fired and gas-fired generations based on U.S. state-level data. We find that under the counterfactual, the higher gas price has a dampening effect on economic activities and consequently lowers non-power sectors' emissions. As many have observed, absent a full economy-wide model, power sector emissions increase because of gas-to-coal switch as a result of higher gas prices. However, we find across a wide range of model settings that if gas prices would have remained at 2007 levels in 2011, economy-wide emissions would have been lower. Only a model setting that allowed very little reduction in electricity demand, reflecting a short-run demand response, generated an increase in economy-wide emissions. In other words, the shale gas boom likely led to higher emissions except possibly in the very short run, and in all cases in the long run if the low gas prices persist.

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1. Introduction

The development of hydraulic fracturing combined with horizontal drilling in recent years has made it possible to economically extract shale gas reserves in the U.S. that were otherwise not technically recoverable. Due to this technology advancement, shale gas output expanded more than 12-fold (EIA, 2018a). During the same period, the percent of natural gas withdrawals from shale in the U.S. rose from less than 9% to around 55% (EIA, 2017a). Although the conventional natural gas production continued to decline, the surge in shale gas production has contributed to a nearly 40% increase in the overall US natural gas production over the past decade, from 19266 billion cubic feet (BCF) in 2007 to 26592 BCF in 2016, which was about 97% of domestic natural gas consumption in that year (EIA, 2017a; 2017b). In terms of the shale gas output share (out of the U.S. total), the five leading states in 2016 are Pennsylvania (29.7%), Texas (29.5%), Ohio (8.1%), West Virginia (7.5%), and Louisiana (6.5%). Together they accounted for 81.3% of the U.S. total shale gas production in that year (**Table 1**).

The shale gas boom in the U.S. has transformed not only its energy sector but also its power sector. From 2007 to 2016, the average price of natural gas used by the power sector in the U.S. dropped by 64.7%. During that period, natural gas used by the power sector increased by 47.1%, accompanied by a 53.7% increase in output from gas-fired generation (EIA, 2017c). Changes in coal prices may have also contributed to the shift to gas generation. Between 2007 and 2011, coal prices rose from $2.03/MBtu to $2.58/MBtu before falling back to $2.12/MBtu in 2016. The increase in price through 2011 was likely associated with continued rise in world prices for coal over that time (EIA, 2011; EIA, 2017c).

Cheap gas made coal-fired generation less economic, with both the power sector coal consumption and coal-fired generation levels in 2016 decreasing by almost 40% compared with their 2007 levels.[1] In 2016, the coal-fired generation output was lower than the output from the gas-fired generation for the first time since 1950 (EIA, 2017c; EIA, 2017d). Other contributors to the coal-to-gas switch in the power

1 The US power sector coal consumption level reduced from 21.95 EJ in 2007 to 13.71 EJ in 2016, and during the same period the US coal-fired generation fell from 2016.46 TWh to 1239.15 TWh (EIA, 2017c; EIA, 2017d).

Table 1. Shale gas output by state from 2007 to 2016.

Unit: Billion Cubic Feet	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
The U.S. Total	1293	2116	3106	5331	7991	10368	11413	13441	15207	17023
Arkansas	94	279	527	794	940	1027	1026	1038	923	733
California					101	90	89	3	2	6
Colorado	0	0	1	1	3	9	18	236	325	164
Kansas						1	3	1	1	0
Kentucky	2	2	5	4	4	4	4	2	1	0
Louisiana	1	23	293	1232	2084	2204	1510	1191	1153	1111
Michigan	148	122	132	120	106	108	101	96	65	84
Mississippi						2	5	2	3	2
Montana	12	13	7	13	13	16	19	42	39	19
New Mexico	2	0	2	6	9	13	16	28	46	497
North Dakota	3	3	25	64	95	203	268	426	545	582
Ohio	0	0	0	0	0	14	101	441	959	1386
Oklahoma	40	168	249	403	476	637	698	869	993	1082
Pennsylvania	1	1	65	396	1068	2036	3076	4009	4597	5049
Texas	988	1503	1789	2218	2900	3649	3876	4156	4353	5029
Virginia						3	3	3	3	4
West Virginia	0	0	11	80	192	345	498	869	1163	1270
Wyoming	0	0	0	0	0	7	102	29	36	5
Eastern States	2	2								

Source: EIA (2018b). States with only zero outputs or missing data during 2007 and 2016 are not shown.

sector include the Mercury and Air Toxics Standard of 2011. The announcement of the Clean Power Plan (CPP) in 2015 may have contributed to decisions to retire older coal, even though it was not, and now appears never will be, implemented.

This study aims at answering the following question: what could be the emissions and economic implications on the US economy if there were no shale gas boom, leaving gas more expensive? It is useful to briefly analyze the chain of effects if the gas price had not fallen: first, there would be less gas generation and more electricity output from coal, nuclear, wind, and solar. However, given the non-dispatchable nature of wind and solar, regulatory complexities or political obstacles in expanding nuclear power, and the fact that the tiny share of oil-fired generation is essentially served as a peak load option due to its higher operating costs,[2] the reduced gas-fired generation most likely will be replaced by coal-fired power especially within a short time frame when generation is largely limited by available capacity. This alone would lead to more power sector CO_2 emissions. However, electricity prices would have been higher, reducing electricity use and production, which would lead to an offsetting reduction in emissions. Higher electricity prices would lead to substitution away from electricity and toward other fuels (gas, oil, etc.) throughout the economy, tending to increase emissions from non-power sectors (other industries and residential sector). However, under our counterfactual, gas prices are higher throughout the economy, so substitution between electricity and gas could go either way, but other fuels (coal and oil) would be favored, tending to increase emissions. Lastly, higher overall energy prices would induce the adoption of more energy efficient technologies and conservation measures throughout the economy, leading to lower overall energy use (fuels and electricity) and lower emissions. As a result of the complex interactions throughout the economy, to answer the question of whether the shale gas boom reduced or increased emissions requires an empirical assessment of the magnitude of each of the separate substitution effects outlined above.

2 In the U.S., oil-fired generation accounts for only 3% of the capacity and less than 1% of total electricity generation in 2016. See EIA (2017e).

Given the potentially critical role of coal- and gas-fired generation, we first estimate gas and coal generation supply response as described in Section 2. Section 3 presents an economy-wide model for the U.S. economy for 2011, including trade linkages to the rest of the world and our strategy for incorporating the supply elasticity estimates into the model. Section 4 analyzes the counterfactual simulation results where the pre-shale-gas-boom gas prices of 2007 are imposed on the U.S. economy in 2011. Section 5 offers concluding remarks for the study.

2. Estimation

To parameterize the supply response of coal-fired and gas-fired generations with respect to a higher electricity price prompted by an increased gas price when there is no shale gas boom, we use the state-level panel data for the U.S. for estimation purposes. Precisely, the levels of generation, average electricity prices, and capacity are from EIA (2018b; 2018c; 2018d). We take fuel prices from the State Energy Data System (SEDS) database (EIA, 2017f), and the Gross State Product (GSP) for each state from BEA (2018), as summarized in **Table 2**.

With the aforementioned data, we conduct a regression analysis based on data that include observations from 1997 to 2015. In particular, in estimating the supply elasticity of coal-fired generation, we have 867 observations coming from an unbalanced panel with 46 states and 15 to 19 years of data. For the case of estimating the supply elasticity of gas-fired generation, the unbalanced panel is composed of 46 states, 14 to 19 years of data, and 866 observations.

A classical issue of estimating the supply or demand response is that both the equilibrium levels of electricity price and quantity are endogenously determined, which suggests that if one regresses the observed generation level on the electricity price directly, there will be an endogeneity issue since the price will be correlated with the error term. To overcome this, our strategy is to formulate the simultaneous equation system (e.g., Goldberger (1991)[3]), and then use the two-stage least square (2SLS) approach to estimate coefficients of the system. Taking the estimation for the

3 See Chapters 32 and 33 in Goldberger (1991) for details about the identification and estimation of the simultaneous equation model.

Table 2. Data for estimating the supply elasticity of coal-fired power.

Data type	State	Year	Source
Generation level	All	1990–2016	EIA (2018c)
Electricity price	All	1990–2016	SEDS/EIA (2018d)
Capacity	All	1990–2016	EIA (2018e)
Energy price	All	1970–2015	EIA (2017f)
State-level GDP	All	1997–2016	BEA (2018)

supply elasticity of coal-fired generation as an example, the system includes the following two equations:

$$Demand: \quad (1)$$
$$\ln GCOAL_{it} = \beta_{1,i} + \beta_{2,t} + \beta_3 \ln PELEC_{it} + \beta_4 \ln PCOAL_{it} + \beta_5 \ln CCOAL_{it} + u_{2,it}$$

$$Supply: \quad (2)$$
$$\ln GCOAL_{it} = \alpha_{1,i} + \alpha_{2,t} + \alpha_3 \ln PELEC_{it} + \alpha_4 \ln GSP_{it} + u_{1,it}$$

In the equations above, $GCOAL_{it}$ is the equilibrium level of total annual coal-fired electricity output of state i in year t, $PELEC_{it}$, GSP_{it}, $PCOAL_{it}$, and $CCOAL_{it}$ are the state-level average electricity price, gross state product, the average coal price for the power sector, the coal-fired power capacity in year t, respectively. We also control for the state fixed effect ($\alpha_{1,i}$ for Equation (1) and $\beta_{1,i}$ for Equation (2)) and the time fixed effect ($\alpha_{2,t}$ for Equation (1) and $\beta_{2,t}$ for Equation (2)) of each equation in the system. The error terms are represented by $u_{1,it}$ and $u_{2,it}$ for Equations (1) and (2), respectively. What we are interested in is to get an estimate for β_3, the supply elasticity for coal-fired generation.

In matrix form, the system can be written as:

$$Y'\gamma = X'\theta + u' \quad (3)$$

where

$$Y' = [\ln GCOAL_{it} \quad \ln PELEC_{it}] \quad (4)$$

$$X' = [1 \quad 1 \quad lnGSP_{it} \quad \ln PCOAL_{it} \quad \ln PGAS_{it} \quad \ln CCOAL_{it} \quad \ln CGAS_{it}] \quad (5)$$

$$\gamma = \begin{bmatrix} 1 & 1 \\ -\alpha_3 & -\beta_3 \end{bmatrix} \quad (6)$$

$$\theta' = \begin{bmatrix} \alpha_{1i} & \alpha_{2t} & \alpha_4 & 0 & 0 & 0 & 0 \\ \beta_{1i} & \beta_{2t} & 0 & \beta_4 & 0 & \beta_5 & 0 \end{bmatrix} \quad (7)$$

$$u' = [u_{1t} \quad u_{2t}] \quad (8)$$

It is worth noting that without changing the structural form of the system, we include two additional explanatory variables $PGAS_{it}$ (the state-level average gas price for the power sector of in year t) and $CGAS_{it}$ (the gas-fired power capacity in year t), as shown in Equation (5). This is done by adding the two-by-one zero matrices presented in column 5 and column 7 in Equation (7). While the two explanatory variables ($PGAS_{it}$ and $CGAS_{it}$) are not included in the structural form of the system, after we solve for a reduced-form expression of Y, they are in the reduced-form estimation.

Solving Equation (3) for Y, we have:

$$Y' = X'\pi + v \quad (9)$$

where

$$\pi_{7\times2} = \theta\gamma^{-1} \quad (10)$$

$$v_{7\times2} = u'\gamma^{-1} \quad (11)$$

In the first stage of estimation, the coefficients of the reduced-form equations are estimated. In particular, only the reduced-form equation where the log of electricity price is the dependent variable needs to be considered since the purpose is to get the predicted values for the log of electricity prices. In the second stage, coefficients of Equation (2) are estimated by replacing the observed electricity prices with their predicted counterparts obtained in the first-stage regression to resolve the endogeneity issue. Note that to avoid multicollinearity, $PGAS_{it}$ and $CGAS_{it}$ are not included in the structural form equations, but they are added in the reduced-form equations since the aim in the first-stage regression is to get the predicted values of electricity prices. The estimate for the supply elasticity of coal-fired generation is 2.52 (p-value < 0.001). Details of the results for the first- and second-stage regressions are shown in **Table 3a** and **Table 3b**. Following the same approach, we also estimate the gas-fired generation's supply elasticity, which is 1.23 with a p-value < 0.01 (**Table 3c** and **Table 3d**). Both estimates will be used to parameterize the economy-wide model in the following section. The estimations are done by the statistical computing software R.

3. Economy-wide Model

Our economy-wide model is a static computable general equilibrium (CGE) model, which uses the newly available GTAP 9-Power database (Peters, 2016) with power sector details and the base year of 2011 as the main source of economic and energy flow data. The model has three types of agents in the U.S. and in the rest of the world: household, producers, and government. The household provides primary factors (labor, capital, and natural resources) to producers, receives income in return, and allocates income to consumption and savings to maximize its utility. Producers convert primary factors and intermediate inputs into goods and services, then sell them domestically or abroad to other producers, households, or governments to maximize their respective profits. The government, which is treated as a passive entity as in Paltsev *et al.* (2005), collects taxes from household and producers to finance government consumption and transfers. As in many CGE models, in our benchmark setting, each input (except the fixed factors that will be discussed later) can move freely among sectors to pursue the highest return until the opportunity for arbitrage disappears.

Table 3. (a) First-stage estimation results for coal-fired generation. (b) Second-stage estimation results for coal-fired generation. (c) First-stage estimation results for gas-fired generation. (d) Second-stage estimation results for gas-fired generation.

Dependent variable: ln(PELEC)		Estimate	Std. Error	t-value	Pr(>|t|)	
Table 3A	**ln(PCOAL)**	0.3430	0.0614	5.5852	0.0000	***
	ln(PGAS)	0.0198	0.0396	0.5009	0.6166	
	ln(CCOAL)	-0.1465	0.0604	-2.4269	0.0155	*
	ln(CGAS)	-0.0208	0.0131	-1.5891	0.1124	
	ln(GSP)	0.0583	0.0976	0.5974	0.5504	
	Number of observations	867				
	Total Sum of Squares	5.1829				
	Residual Sum of Squares	4.9550				
	R-Square	0.0440				
	Adj. R-Squared	-0.0375				
	F-statistic	7.3399	on 5 and 798 DF, p-value: 9.7299e-07			

Dependent variable: ln(GCOAL)		Estimate	Std. Error	t-value	Pr(>|t|)	
Table 3B	**ln(PELEC_HAT)**	2.52338	0.6879	3.6682	0.00026	***
	ln(PCOAL)	-1.02348	0.2400	-4.2647	2.24E-05	***
	ln(CCOAL)	1.68854	0.1190	14.1958	< 2.20E-16	***
	Number of observations	867				
	Total Sum of Squares	10.9290				
	Residual Sum of Squares	7.5883				
	R-Square	0.3057				
	Adj. R-Squared	0.2484				
	F-statistic	117.4020	on 3 and 800 DF, p-value: < 2.22e-16			

Dependent variable: ln(PELEC)		Estimate	Std. Error	t-value	Pr(>|t|)	
Table 3C	**ln(PCOAL)**	0.3423	0.0615	5.5701	3.48E-08	***
	ln(PGAS)	0.0200	0.0396	0.5051	0.6137	
	ln(CCOAL)	-0.1466	0.0604	-2.4280	0.0154	*
	ln(CGAS)	-0.0212	0.0131	-1.6190	0.1059	
	ln(GDP)	0.0575	0.0977	0.5887	0.5562	
	Number of observations	866				
	Total Sum of Squares	5.1807				
	Residual Sum of Squares	4.9531				
	R-Squared	0.0439				
	Adj. R-Squared	-0.0376				
	F-statistic	7.3244	on 5 and 797 DF, p-value: 1.0072e-06			

Dependent variable: ln(GGAS)		Estimate	Std. Error	t-value	Pr(>|t|)	
Table 3D	**ln(PELEC_HAT)**	1.229752	0.466322	2.6371	0.008524	**
	ln(PGAS)	-0.4584	0.109205	-4.1976	3.00E-05	***
	ln(CGAS)	0.840421	0.036012	23.3376	<2.20E-16	***
	Number of Observations	866				
	Total Sum of Squares	64.1760				
	Residual Sum of Squares	37.4490				
	R-Squared	0.4165				
	Adj. R-Squared	0.3683				
	F-statistic	190.0840	on 3 and 799 DF, p-value: < 2.22e-16			

Significance level: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

Activities of different agents and their interactions can be described by: 1) zero-profit conditions; 2) market-clearing conditions; and 3) income-balance conditions. For the household and producer, the associated economic activities are utility and output, respectively. Let us denote the activity level, the associated marginal cost and marginal benefit (i.e., marginal revenue or marginal utility) of pursuing that activity by Q, MC, and MB, respectively. A typical zero-profit condition expressed in the format of mixed complementary problems (MCP) (Mathiesen, 1985; Rutherford, 1995; Ferris and Peng, 1997) can be written as:

$$MC - MB \geq 0; Q \geq 0 ; [MC - MB] \cdot Q = 0 \quad (12)$$

For instance, when a zero-profit condition is applied on a production activity, if the equilibrium output $Q > 0$, $MC = MB$ must hold, and if $MC > MB$ in equilibrium, Q will be zero because it is not economic to engage in the production activity. Note that $MC < MB$ is not an equilibrium state since in that case Q will increase until $MC = MB$. Other activities such as investment, imports, exports, and commodity aggregation have their own zero-profit conditions. To illustrate a market-clearing condition, let us denote the equilibrium price, the quantity supply and quantity demand by P, S, and D, respectively. A typical market-clearing condition in MCP format is:

$$S - D \geq 0; P \geq 0 ; [S - D] \cdot P = 0 \quad (13)$$

The market-clearing condition states that for each market, if the equilibrium price $P > 0$, then $S = D$ will hold. If in equilibrium $S > D$, $P = 0$. Likewise, $S < D$ is not an equilibrium since in that case, P will continue to increase until the market is cleared ($S = D$). The income-balance condition specifies the income of household I that supports its spending levels E (including savings). A typical income-balance condition in MCP format can be written as:

$$E - I \geq 0; E \geq 0 ; [E - I] \cdot E = 0 \quad (14)$$

In CGE models, the expenditure E is equal to income I, hence equation (14) can be re-written as $E = I$. In our model, the price index for the aggregate consumption of the U.S. is chosen as the numeraire of the model, so all other prices are measured relative to it.

To characterize production technology and consumer preferences, our model uses Constant Elasticity of Substitution (CES) functions and the special cases of it, including Leontief (elasticity of substitution of zero) and Cobb-Douglas (elasticity of substitution of one) functions. In the model, each commodity can be imported and domestically produced, and they are aggregated together as an Armington good (Armington, 1969). Appendix A provides an example of a CES function applied to represent a production activity. The model is written and solved using the modeling languages of GAMS and MPSGE (Rutherford, 1999), and most of the settings including the nesting structures of CES functions and substitution elasticities between inputs are borrowed from Chen *et al.* (2016). Interested readers may refer to that study for details.

There are several exceptions differentiating our study from Chen *et al.* (2016). First, Chen *et al.* uses an earlier version of the GTAP database that has an aggregated power sector and needs researchers to disaggregate the power sector on their own. The GTAP 9-Power database our study uses identifies all power sector technologies, including wind and solar, that are operated at a commercial scale in the base year. Power generation technologies and the corresponding notations we use are presented in **Table 4**.

Next, from the modeling perspective, in our study each fossil generation technology is treated as a perfect substitute to other dispatchable generations. To avoid the issue of getting a "bang-bang solution," for each dispatchable generation except for coal-fired and gas-fired generations, we assign part of the input as the fixed factor input for that technology so that we can calibrate the supply response based on Rutherford (2002), which demonstrates that for a given fixed factor input value share θ, a local approximation to a given technology's assumed or empirically observed supply elasticity γ can be achieved when the substitution elasticity between the fixed factor and other inputs is set to

$$\sigma = \gamma \cdot \theta / (1 - \theta) \quad (15)$$

The CES structure of this setting is presented in **Figure 1**. Due to the difficulty of expanding nuclear power discussed earlier, in the study we assume the supply elasticity for nuclear power (and therefore the fixed factor substitution elasticity) is zero, and this assumption also applies to oil-fired, hydro, and others to simplify the analysis. Non-dispatchable generation options (wind and solar) are aggregated together using a CES function with a substitu-

Table 4. Power generation technologies.

Technology	Notation
Coal-fired	cele
Gas-fired	gele
Oil-fired	oele
Nuclear	nele
Hydro	hele
Wind	wele
Solar	sele
Others	rele
Transmission and distribution	tele

tion elasticity of 2, and the aggregated output from wind and solar is then added to the sum of other outputs from dispatchable generations using a CES function with a substitution elasticity of 1, as in Chen *et al.* (2016), such that the expansion of non-dispatchable generations is dependent on the total output of dispatchable generation. Aggregation of outputs from different generation technologies uses a nested CES function.

Note that in the nested CES function, part of the gas-fired generation is considered as "indispensable" and is separated from the ordinary gas-fired generation because it is used as a peak load generation, or because for some states gas-fired generation might be favorable since it is not economic to use other types of generation due to, for example, high transportation costs for other fuels (to keep the term succinct, later on the gas-fired generation with this "favorable" condition will be included in the indispensable one) (**Figure 2**). For these cases, even with a higher gas price, the output from gas-fired generation that is indispensable cannot be significantly reduced. To represent this, the indispensable gas-fired output is combined with the sum of other dispatchable generations using a CES nest with a low substitution elasticity, which is set to 0.1.

Besides, while there could be gas-to-coal switch in the power sector when the gas price is higher, it is plausible that some gas-fired power plants will continue to be operated, at least in the short-run, as very likely not all inputs can be relocated to other sectors to pursue higher returns, and not all states can have an easy or cheap access to coal. Therefore, apart from the benchmark setting that assumes all inputs (except the fixed factor) are perfectly mobile, we also consider the case where part of the non-energy inputs to gas-fired generation are sector-specific and can withstand lower rates of return when the gas price is higher (Figure 2).

A caveat of setting up a CES function using Equation (15) to model the power generation is: as mentioned previously, it simply provides a local approximation for a given technology's supply response, i.e., the setting performs better in terms of matching the supply elasticity only when the shock (the increase in electricity price due to a higher gas cost) is small. This limitation is not a problem for those technologies that are assumed to have zero supply elasticities. However, for coal-fired and gas-fired generations where their non-zero supply elasticities may play crucial roles, this could be an issue under a larger shock. For instance, coal-fired generation might expand significantly under the counterfactual.

We develop a relatively complex production structure compared with those typical in GGE analysis to ensure that the system is flexible enough to capture supply elasticities for large changes in prices and to capture short- and long-run effects due to the existence of irreversible capital stock. The shale boom occurred in just a few years—our focus is the change in gas prices between 2007 and 2011—so we expect over that period a strong effect of irreversible capital stock, but we are also interested in the long run effect of changes. We refer to this structure as "global approximation" because it can approximate the supply response for large price changes. We consider two alternative frameworks that are commonly used in CGE modeling: the first, which is called "imperfect substitute," treats outputs from fossil generations as imperfect substitutes to each other, and aggregates them by a CES function with a substitution

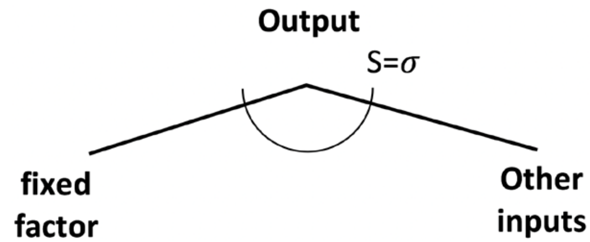

Figure 1. CES structure for modeling the supply response: Local approximation.

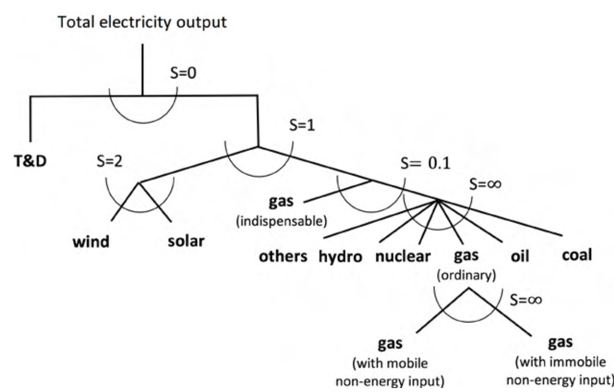

Figure 2. CES nesting structure for the power sector aggregation.

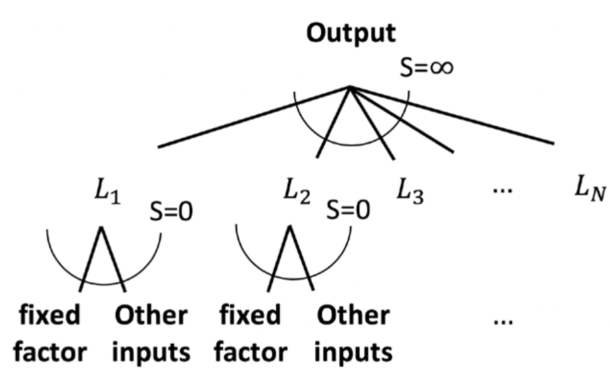

Figure 3. CES structure for modeling the supply response: Global approximation.

elasticity of 1.5, as in Chen *et al.* (2016); the second is the "local approximation" strategy presented in Rutherford (2002).

The "global approximation" approach is designed to ensure the CGE model can approximate supply responses of coal-fired and gas-fired generation that are consistent with our empirical estimations even under a larger shock. We revise the standard sectoral production structure used elsewhere in the model such that it includes N Leontief sub-nests $\{L_n|\ n = 1,2,\ldots,N\}$ with a rising marginal cost of production $\{C_n|\ n = 1,2,\ldots,N\}$, and each sub-nest produces the output that is a perfect substitute to other sub-nests (**Figure 3**). For the Leontief sub-nest L_n the costs of using the intermediate and primary inputs sum up to C_n, and there is a fixed factor input demand $F_n = F$ (F is a constant for all n) that may have a shadow price of zero when the fixed factor supply is not a binding constraint, i.e., $FS_n \geq F$. For $n = 1$, the marginal cost of production C_1 equals the base year price P_1, and $FS_n = F$, which means that any additional output beyond the base year level will incur a higher cost. Specifically, by controlling the levels of C_n and FS_n, the goal is to make the simulated output and price levels from the CGE model as consistent to the relationship described by the following equation as possible:

$$Q = A \cdot P^{\gamma} \tag{16}$$

In the equation above, Q is the output under the price level P and the supply elasticity γ, and A is a positive constant. The equation can be derived from the definition for the supply elasticity. For our application, we find the interval of $[C_1, 2C_1]$ is enough to cover the range of cost increase in our counterfactual, and therefore we set the marginal cost of production C_n to:

$$C_n = C_1 \cdot \left(1 + \frac{n-1}{N-1}\right) \tag{17}$$

On the other hand, the fixed factor demand F and supply FS_n are set to:

$$F = C_1 \tag{18}$$

$$FS_n = C_1^{1-\gamma} \cdot (C_n^{\gamma} - C_{n-1}^{\gamma}) \tag{19}$$

In Equation (19), the coefficient C_0 is assigned to a value of zero, since we want the base year fixed factor supply $FS_1 = C_1$, which equals the fixed factor demand, as discussed before. In short, the way C_n and FS_n are parameterized to ensure that the increases in marginal cost and output will trace the trajectory of Equation (16) closely and approximate the supply elasticity γ at a satisfactory level, as long as N is large enough. The strategy is similar to those used by Rausch and Zhang (2018) and Koopmans and Velde (2001). For the purpose of our application, we choose $N = 200$ as it is sufficient to provide a good approximation.

In the following section, sensitivity analyses will be conducted to explore the roles of gas generation's sector specificity and indispensability.

4. Counterfactual Simulation

To analyze the implications of a scenario without the shale gas boom, we run a counterfactual where the gas production cost in the U.S. is raised by 71% relative to the original cost in 2011 to 2007 level as reflected in the GTAP 9-Power database.

We begin by comparing simulated coal-fired power generation levels of various power sector modeling strategies. Besides our setting, which we call "global approximation," we also consider two alternative frameworks that are commonly used in CGE modeling: the first, which is called "imperfect substitute," treats outputs from fossil generations as imperfect substitutes to each other, and aggregate them by a CES function with a substitution elasticity of 1.5, as in Chen *et al.* (2016); the second is the "local approximation" strategy presented in Rutherford (2002) (see Section 3). For demonstration purposes, at this moment we use the standard parameterization without sector-specific or indispensable gas-fired generations for all three settings.

Under the counterfactual, the *global approximation*, *imperfect substitute,* and *local approximation* settings all demonstrate gas-to-coal switch in the power sector and higher producer prices for electricity. For the output of coal-fired power generation, the setting of imperfect substitute (denoted by "ImpSub") produces the lowest output—only 1.7% higher than the base year level. On the other hand, both the local approximation (denoted by "Local") and the global approximation (denoted by "Global") generate much higher level of outputs—25.0% and 28.2%, respectively (**Figure 4**). For the producer prices of coal-fired generation, the imperfect substitute setting also has the lowest response—only 0.4% increase compared with the base year level. The producer price under the local approximation setting is the highest (14.2% increase), while that under the global approximation setting increases by 11.2% (**Figure 5**).

Combining both price and output changes, one can derive the realized supply elasticity for coal-fired power based on the model response. Interestingly, the imperfect substitute setting results in the highest level of supply elasticity (4.82) due to the almost unchanged producer price under the counterfactual. Note that under this setting one cannot derive the substitution elasticity of aggregating the fossil generation based on the supply elasticity. Again, the substitution elasticity of 1.5 is drawn directly from Chen *et al.* (2016) and has no relationship with our em-

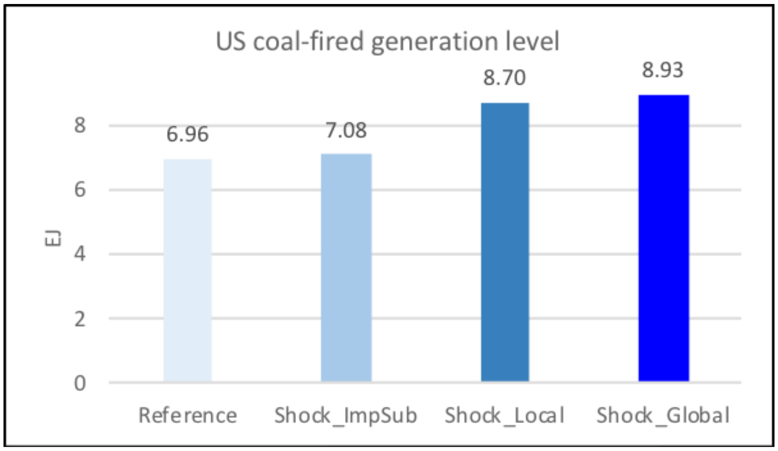

Figure 4. Coal-fired generation output levels under different settings.

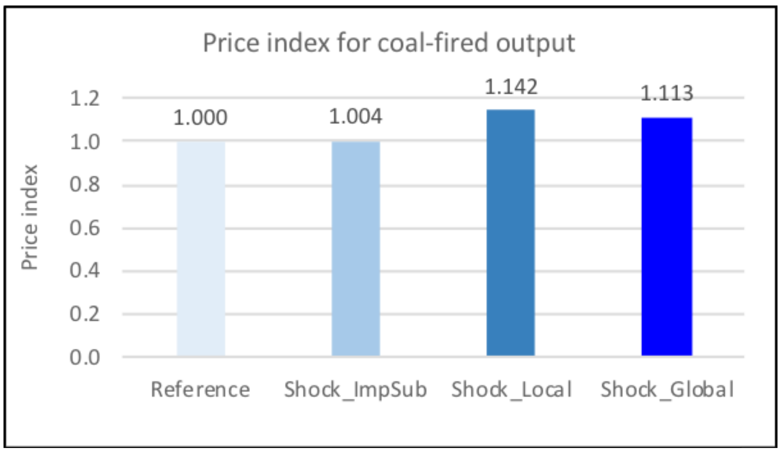

Figure 5. Coal-fired generation producer prices under different settings.

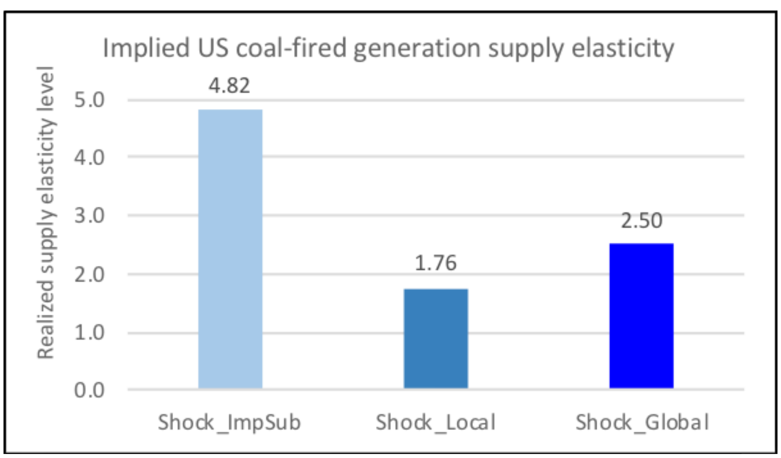

Figure 6. Implied Coal-fired generation supply elasticities under different settings.

pirical estimates. The implied supply elasticities based on the model responses are 1.76 and 2.50 under the settings of local and global approximation, respectively—the latter provides a much better approximation to the empirically estimated supply elasticity for the coal-fired generation (2.52) (**Figure 6**). While not shown here as it is not our focus, we check results under the local approximation setting, and as expected, when we impose a lower shock level in the counterfactual, the realized supply elasticity will be closer to our empirical estimate.

Given the superiority of the *global approximation* setting, we proceed to study the CO_2 emissions implication under different parameterizations for sector-specific and indispensable levels of gas-fired generation. Besides modeling the long-run response based on various substitution elasticities drawn from Chen *et al.* (2016), we also simulate the short-term response of the gas cost shock, where substitution possibilities between different inputs (e.g., electricity vs. non-electricity inputs) are more limited.

One approach to model this scenario is to set the relevant substitution elasticities to zero or to very small numbers. However, with the given high cost shock in our counterfactual, this approach often fails to find solutions. To overcome this, we focus on and control for the electricity demand. Specifically, under the considered shock, while the electricity demand in the long run tends to fall to a larger degree, we consider the case where in the short run, a certain level of electricity demand must be met. To achieve this, the representative consumer may need to pay an additional amount of money to the power sector. The additional payment is fairly allocated among various power generation technologies such that the payment itself does not change the relative cost of using each generation option.

We first present changes in power sector emissions relative to the baseline level under different time frames and without the presence of indispensable gas-fired generation. In the short run, electricity demand is unable to fall dramatically in response to higher electricity prices under the counterfactual, and on the supply side, it is harder to transform inputs of gas-fired generation for other usages, which suggests higher proportions of gas-fired generation inputs are sector-specific. In the long run, more substitution possibilities appear and allow further reduction in electricity demand, and gas-fired generation inputs become less sector-specific as more opportunities for converting inputs for other utilizations emerge. In **Figure 7**, any increase in emissions relative to the baseline level is represented by a percentage change in blue, and cells with darker colors are

Gas-fired output with sector-specific inputs	Long-run (LR) or short run response: 0.95 = electricity demand is 95% of pre-shock level									
	LR	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**SR: 0.99**
LR: 0%	0.9%	3.0%	4.8%	6.6%	8.4%	10.2%	12.0%	13.9%	15.8%	17.6%
10%	0.8%	2.4%	4.0%	5.7%	7.4%	9.0%	10.7%	12.5%	14.3%	16.1%
20%	0.7%	2.2%	3.8%	5.1%	6.6%	8.2%	9.8%	11.5%	13.1%	14.7%
30%	0.7%	2.2%	3.2%	4.6%	6.2%	7.6%	9.0%	10.6%	12.1%	13.7%
40%	0.7%	2.2%	3.1%	4.6%	5.5%	7.0%	8.6%	9.9%	11.3%	12.8%
50%	0.6%	2.2%	3.1%	4.1%	5.5%	6.7%	7.9%	9.5%	10.8%	12.1%
60%	0.6%	2.2%	3.1%	4.0%	5.5%	6.4%	7.9%	8.8%	10.3%	11.8%
70%	0.6%	2.2%	3.1%	4.0%	5.2%	6.4%	7.3%	8.8%	9.9%	11.2%
80%	0.5%	2.2%	3.1%	4.0%	4.8%	6.4%	7.3%	8.7%	9.7%	11.1%
SR: 90%	0.5%	2.2%	3.1%	4.0%	4.8%	6.4%	7.3%	8.1%	9.7%	10.5%

Figure 7. Changes in power sector emissions relative to the baseline level.

Gas-fired output with sector-specific inputs	Long-run (LR) or short run response: 0.95 = electricity demand is 95% of pre-shock level									
	LR	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**SR: 0.99**
LR: 0%	-4.1%	-3.2%	-2.5%	-1.8%	-1.1%	-0.3%	0.4%	1.2%	1.9%	2.7%
10%	-4.1%	-3.5%	-2.8%	-2.1%	-1.4%	-0.8%	-0.1%	0.6%	1.4%	2.1%
20%	-4.2%	-3.5%	-2.9%	-2.3%	-1.7%	-1.1%	-0.4%	0.3%	0.9%	1.6%
30%	-4.2%	-3.5%	-3.1%	-2.5%	-1.9%	-1.3%	-0.7%	-0.1%	0.6%	1.2%
40%	-4.2%	-3.5%	-3.2%	-2.5%	-2.1%	-1.5%	-0.9%	-0.3%	0.3%	0.9%
50%	-4.2%	-3.5%	-3.1%	-2.7%	-2.1%	-1.6%	-1.1%	-0.5%	0.1%	0.6%
60%	-4.2%	-3.5%	-3.1%	-2.8%	-2.1%	-1.8%	-1.1%	-0.7%	-0.1%	0.5%
70%	-4.2%	-3.5%	-3.1%	-2.8%	-2.3%	-1.8%	-1.3%	-0.7%	-0.3%	0.3%
80%	-4.2%	-3.5%	-3.1%	-2.8%	-2.4%	-1.7%	-1.4%	-0.8%	-0.4%	0.2%
SR: 90%	-4.2%	-3.5%	-3.1%	-2.8%	-2.4%	-1.7%	-1.4%	-1.0%	-0.3%	0.0%

Figure 8. Changes in economy-wide emissions relative to the baseline level.

regarded as less plausible from the time frame's perspective, since these areas can be regarded as combining the long-term demand response with the short-term supply response, or vice versa.

We find that under the counterfactual, if in the short run the economy is less flexible in substituting other energy or non-energy inputs for electricity, the power sector emissions will be higher since more output from coal-fired generation is needed to compensate for the reduced output from gas-fired generation because of the higher gas price (Figure 7). Under the same short-run consideration, on the other hand, a higher proportion of inputs to gas-fired generation is sector-specific, and in that case the power sector emissions will be lower, since the sector specificity allows the gas-fired power to continue to operate even with lower rates of return for inputs, and therefore less output from coal-fired power is needed. Overall, we find that for the considered ranges of parameterization, the power sector emissions will be higher under the counterfactual.

Moving from power sector emissions, we examine in economy-wide emissions relative to the baseline level, which include the various additional effects of higher gas prices through the economy and higher electricity prices (**Figure 8**). Qualitatively, under different assumptions on electricity demand and gas-fired generation sector specificity, changes in emissions evolve in a pattern similar to the case for power sector emissions. However, we find that unless the short-run electricity demand remains higher and inputs to gas-fired generation are less sector specific, the economy-wide emissions could turn out to be lower than the baseline level, and in the long run, when the whole economy has more flexibility in substituting other inputs for electricity, even on the supply side the sector specificity level tends to decrease and more gas-to-coal switch may occur under the considered time frame, under the counterfactual, the emissions will decrease relative to the baseline level. The observation is due to the fact that a higher gas price under the counterfactual will also reduce the gas consumption of non-power sectors (**Figure 9**).

In addition, a shift from gas to coal in the power sector also slightly crowds out the coal use in non-power sectors (**Figure 10**). We do not find significant changes in refined oil consumption, although under the counterfactual, in general the sectoral consumption levels will decrease slightly due to the reduced economic activity (**Figure 11**). These results are also contingent upon the model's parameterization for the substitution possibilities of different inputs, which are mostly from Chen *et al.* (2016) except for those of the power sector, as discussed earlier. The nesting structures details and the relevant substitution elasticities of various activities are presented in Appendix B.

Our second set of sensitivity analysis explores changes in the power sector and economy-wide emissions with different assumptions on proportions of indispensable gas-fired generation and electricity demand. In this exercise, the proportion of sector-specific gas-fired generation is a constant, which is parameterized to 72% based on Meade *et al.* (2003), a Bureau of Economic Analysis (BEA) study.[4] With the existence of indispensable gas-fired gen-

4 In p. 61 of Meade *et al.* (2003), it provides investment details by the power sector. Among them, the following items are essentially sector-specific: fabricated metal products, engines and turbines, electrical transmission distribution and industrial apparatus, and total new structures. For the power sector, these items accounted for 72.4% of total new investment.

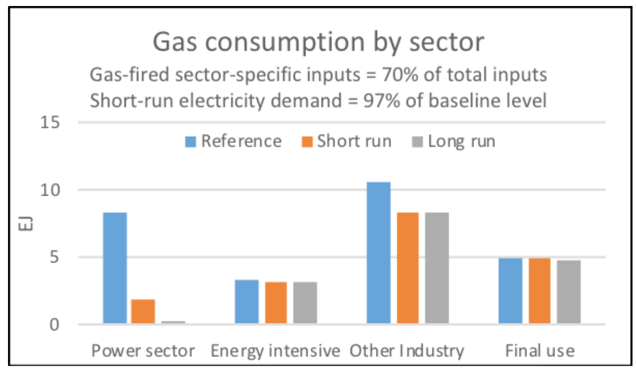

Figure 9. Gas consumption by sector.

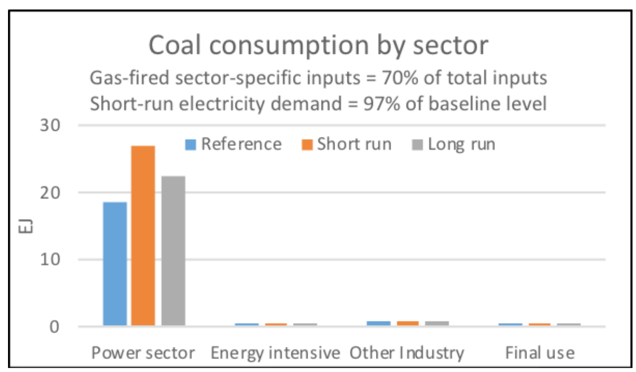

Figure 10. Coal consumption by sector.

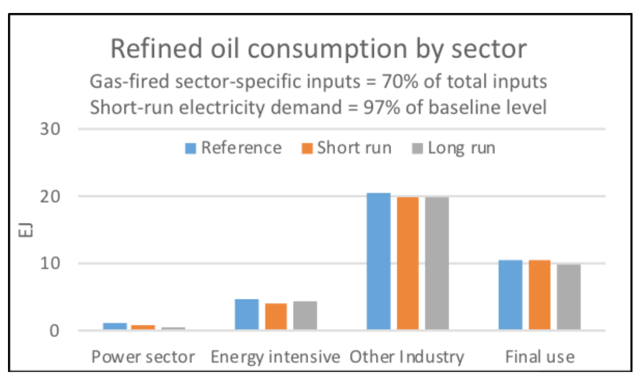

Figure 11. Refined oil consumption by sector.

eration, different from the previous case, CO_2 emissions from the power sector might be lower than the baseline level especially when the electricity demand is reduced, or when the proportion of indispensable gas-fired generation is higher, which tapers off the need for transitioning from gas to coal in the power sector (**Figure 12**).

Likewise, the economy-wide emissions are also less likely to exceed the baseline level with the existence of indispensable gas-fired generation under the counterfactual, since the gas-to-coal switch is dampened. In fact, unless the reduction in electricity demand under the counterfactual is minimal and the share of indispensable gas-fired generation is relatively low, the economy-wide emissions will be lower than the pre-shock level (**Figure 13**). This result reverses the conventional wisdom that the shale gas boom reduced emissions in the economy—quite the contrary, we find that except for a few cases where we assume almost no impact on electricity demand of higher prices and low shares of "indispensable gas," higher gas prices would have led to lower CO_2 emissions economy-wide. Or turned around, the shale gas boom likely led to higher emissions except possibly in the very short run with little electricity demand response, and in all cases in the long run. Our finding is comparable to McJeon *et al.* (2014), which conducts a model comparison work based on five multi-sectoral dynamics models and shows that increases in global supplies of unconventional natural gas may decrease or increase CO_2 emissions (from –2% to +11%), and most models report a small increase in climate forcing (from –0.3% to +7%).

Compared power sector emissions with economy-wide emissions, there are wide ranges of parameterizations that

Baseline indispensable gas-fired output share	Long-run (LR) or short run response: 0.95 = electricity demand is 95% of pre-shock level									
	LR	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**0.99**
0%	**0.6%**	**2.2%**	**3.1%**	**4.0%**	**5.1%**	**6.4%**	**7.2%**	**8.8%**	**9.8%**	**11.2%**
10%	**0.4%**	**1.0%**	**2.7%**	**4.0%**	**5.1%**	**6.4%**	**7.2%**	**8.8%**	**9.8%**	**11.2%**
20%	0.0%	-0.7%	**0.8%**	**2.5%**	**4.2%**	**5.8%**	**7.2%**	**8.8%**	**9.8%**	**11.2%**
30%	-0.5%	-2.5%	-1.0%	**0.6%**	**2.3%**	**4.0%**	**5.5%**	**7.2%**	**8.9%**	**10.6%**
40%	-1.0%	-4.0%	-2.5%	-1.0%	**0.6%**	**2.2%**	**3.7%**	**5.3%**	**6.9%**	**8.6%**
50%	-1.6%	-5.3%	-4.0%	-2.5%	-0.9%	**0.6%**	**2.0%**	**3.6%**	**5.2%**	**6.8%**
60%	-2.1%	-6.6%	-5.2%	-3.7%	-2.2%	-0.9%	**0.6%**	**2.2%**	**3.7%**	**5.3%**
70%	-2.6%	-7.5%	-6.2%	-4.9%	-3.4%	-2.0%	-0.5%	**1.0%**	**2.3%**	**3.8%**
80%	-3.1%	-8.3%	-7.0%	-5.6%	-4.4%	-3.0%	-1.5%	-0.1%	**1.4%**	**2.8%**
90%	-3.5%	-9.5%	-7.9%	-6.4%	-5.2%	-3.6%	-2.2%	-0.9%	**0.5%**	**1.9%**

Figure 12. Changes in power sector emissions relative to the baseline level.

Baseline indispensable gas-fired output share	Long-run (LR) or short run response: 0.95 = electricity demand is 95% of pre-shock level									
	LR	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**0.99**
0%	-4.2%	-3.5%	-3.1%	-2.8%	-2.3%	-1.7%	-1.4%	-0.7%	-0.3%	**0.3%**
10%	-4.2%	-4.0%	-3.3%	-2.8%	-2.3%	-1.7%	-1.4%	-0.7%	-0.3%	**0.3%**
20%	-4.3%	-4.6%	-4.0%	-3.3%	-2.6%	-2.0%	-1.4%	-0.7%	-0.3%	**0.3%**
30%	-4.5%	-5.3%	-4.7%	-4.0%	-3.3%	-2.6%	-2.0%	-1.3%	-0.6%	**0.0%**
40%	-4.6%	-5.8%	-5.2%	-4.6%	-4.0%	-3.3%	-2.7%	-2.0%	-1.4%	-0.7%
50%	-4.8%	-6.3%	-5.8%	-5.2%	-4.5%	-3.9%	-3.3%	-2.7%	-2.0%	-1.4%
60%	-4.9%	-6.8%	-6.2%	-5.6%	-5.0%	-4.4%	-3.8%	-3.2%	-2.6%	-1.9%
70%	-5.1%	-7.1%	-6.6%	-6.0%	-5.5%	-4.8%	-4.2%	-3.6%	-3.1%	-2.5%
80%	-5.3%	-7.5%	-6.9%	-6.3%	-5.8%	-5.2%	-4.6%	-4.0%	-3.4%	-2.8%
90%	-5.4%	-7.9%	-7.3%	-6.6%	-6.1%	-5.5%	-4.9%	-4.3%	-3.8%	-3.2%

Figure 13. Changes in economy-wide emissions relative to the baseline level.

have higher power sector emissions but with lower economy-wide emissions relative to the respective baseline emissions, which suggests that reductions of non-power sectors' emissions due to a higher gas price dominate the overall effect, and for the non-power sectors replacing gas by other types of fuel is harder as opposed to the gas-to-coal switch in the power sector.

In addition, we find that while a higher gas price under the counterfactual cuts the gas consumption by non-power sectors (**Figure 14**), it does not significantly increase the coal consumption outside the power sector (**Figure 15**). The sectoral refined oil consumptions decrease slightly due to reduced economic activities (**Figure 16**), similar to the case in our previous set of simulation (Figure 11).

Another crucial dimension we are interested in is the power generation mix under the counterfactual, when the gas price is beyond 70% higher than the baseline level. The base year (2011) data reveal that the total electricity output in the U.S. was about 16.1 EJ (4469.6 TWh), in which 43.27% and 24.42% were from coal-fired and gas-fired generations, respectively, with the rest coming from nuclear (18.98%), hydro (7.44%), wind (2.79%), solar (0.14%), oil (0.73%), and other (2.23%) (**Figure 17**).

We find that without considering the existence of indispensable gas-fired generation, the simulated gas-fired output tends to decrease significantly under the counterfactual. For instance, with the highest electricity demand (99% of the baseline level, i.e., 15.9 EJ) and the highest sector specificity level for gas-fired generation (90%) we consider (Figure 7 and Figure 8), the gas-fired output is at its maximum (1.2 EJ) among outputs under alternative settings, but the output is still a 70% reduction relative to the baseline level (3.9 EJ). On the other hand, the historical gas-fired output in 2007 (3.4 EJ) is only 13% lower than the 2011 output, according to the 2007 data in the GTAP 9-Power database.

The economic environments of 2007 and 2011 are different in many ways, and our goal is not to control for all the time-variant factors or relevant regulations and replicate the 2007 generation levels by implementing a counterfactual on a model with 2011 data. However, the observation still suggests that treating part of the gas-fired generation as indispensable might be necessary to better represent the reality.

Therefore, we present results for the generation mix with three different levels for the baseline output share of indispensable gas-fired generation: 10%, 50%, and 90%. The sector specificity level for gas-fired generation is set to 72% following Meade *et al.*, as mentioned before.

Under the counterfactual with a higher gas price, the simulated total gas-fired generation output will be between 1.08 EJ and 2.96 EJ under the short-run assumption that maintains 99% of the baseline electricity demand, depending

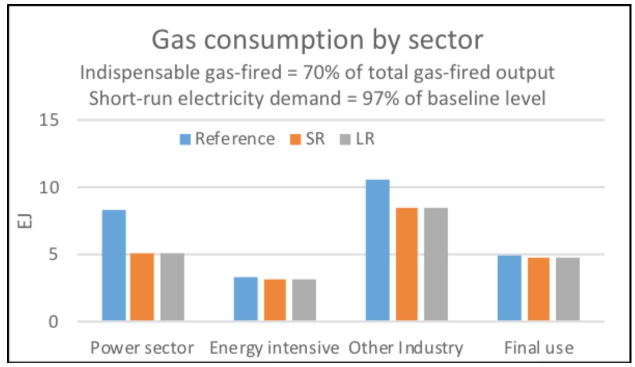

Figure 14. Gas consumption by sector.

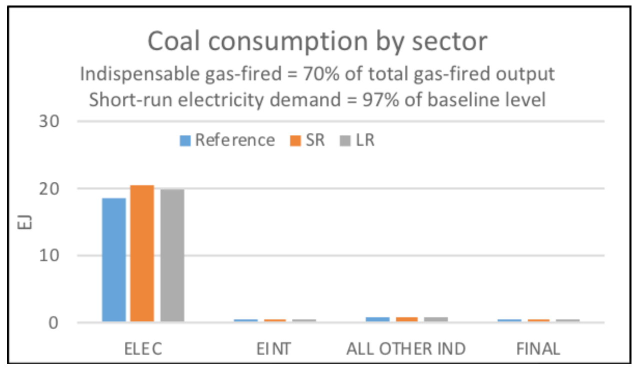

Figure 15. Coal consumption by sector.

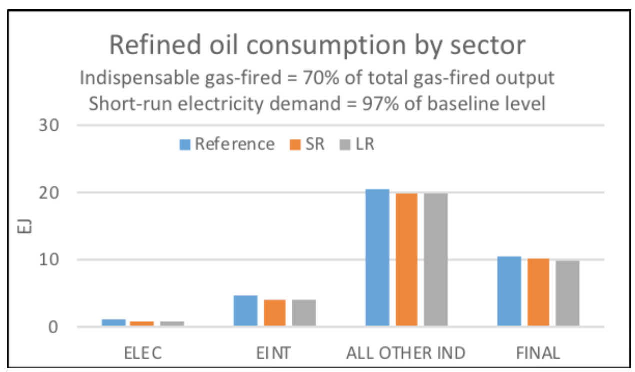

Figure 16. Refined oil consumption by sector.

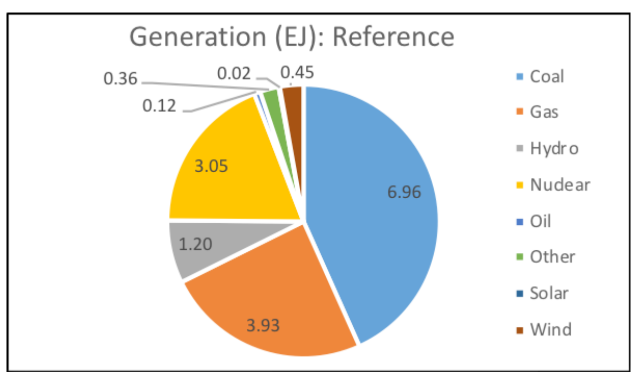

Figure 17. Generation mix: Reference/Baseline case.

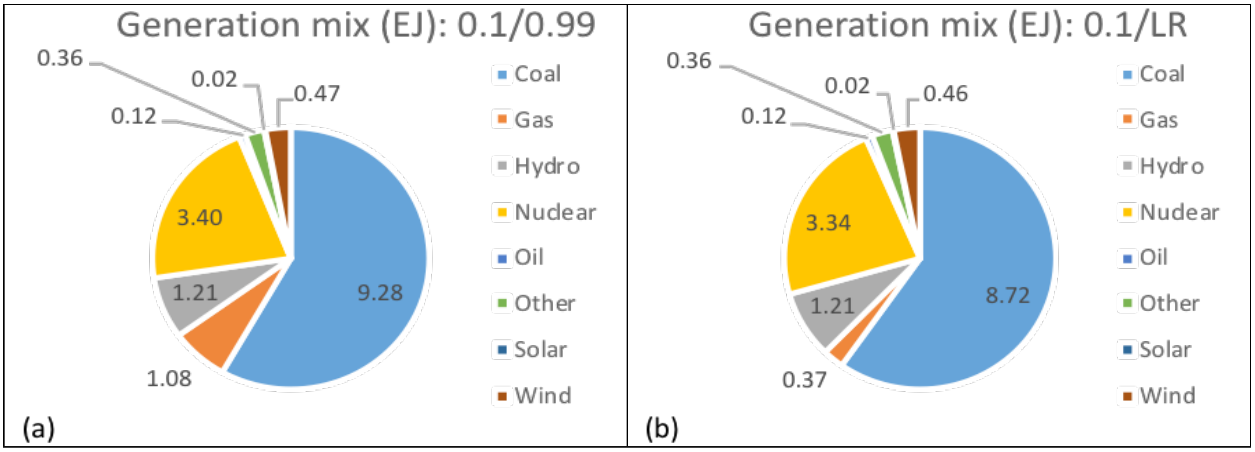

Figure 18. Generation mix: Counterfactual (baseline indispensable gas-fired output=10%).

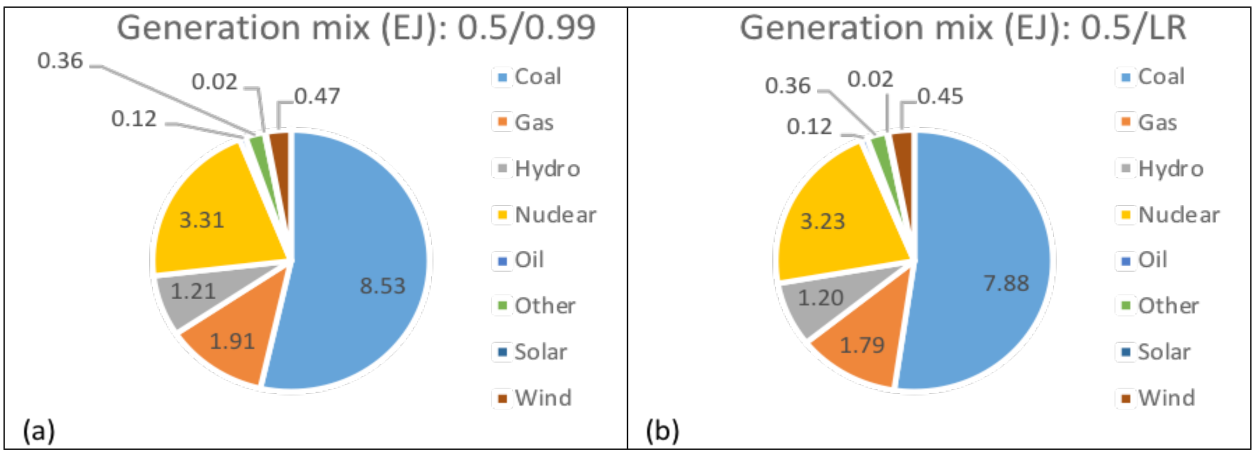

Figure 19. Generation mix: Counterfactual (baseline indispensable gas-fired output=50%).

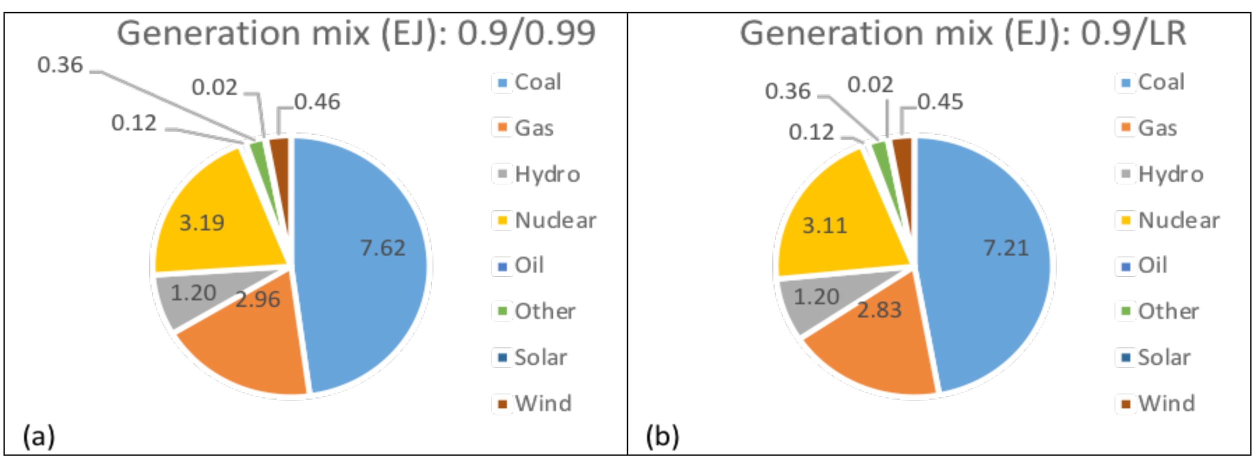

Figure 20. Generation mix: Counterfactual (baseline indispensable gas-fired output=90%).

on the pre-specified baseline indispensable output share for the gas-fired generation (**Figures 18a; 19a; 20a**). On the other hand, the output will be between 0.37 EJ and 2.83 EJ under the long-run assumption that allows more flexibility in adjusting the electricity demand (**Figures 18b; 19b; 20b**). The finding reveals that even we parameterize the baseline indispensable gas-fired generation share as high as 90%, under the counterfactual, the gas-fired output (2.83 EJ to 2.96 EJ, depending on the assumption on electricity demand and the time frame) is still lower than the historical number of 2007 (3.4 EJ).

One possible factor that could explain for the discrepancy is that the underlying input-output data for calibrating a typical CGE model is simply a snapshot of a changing economy. As a result, the model's input-output data may only represent a short-run equilibrium. For instance, with the 2011 gas price that is significantly lower than the 2007 level, the gas-fired generation would be expanding and consequently in the long run, the gas-fired output would be higher than that recorded in the GTAP 9-power database, and if the data that captures this long run equilibrium were observed and adopted for the CGE analysis, due to the larger gas-fired output in the baseline, the simulated gas-fired output with the counterfactual may be higher as well, compared with the simulated gas-fired output presented above. This would make the simulated output closer to the historical gas-fired generation level in 2007. In the welfare analysis below, we will present results taking into account both sector specificity and indispensability of gas-fired generation.

To analyze changes in welfare (total consumption) level under the counterfactual, as before, we consider the setting where the proportion of sector-specific gas-fired generation is set to 72%. Per the proportion of indispensable gas-fired generation, besides the 90% setting considered in the generation mix simulation, we also include the 50% and 10% cases for comparison purposes. For the demand assumption, in addition to the long-run setting, we present short-run settings with electricity demand maintaining at 99% and 95% of the baseline level, respectively.

We find if the economy is more flexible in substituting other energy or non-energy inputs for electricity, the negative impact on welfare could be lowered. For instance, under the long-run assumption where the representative consumer does not try to pay a higher electricity price to maintain a certain level of electricity supply, the negative impact on welfare will be smallest, which is between –0.43%and –0.37%, depending on the proportion of gas-fired generation that is indispensable (**Figure 21**).

On the other hand, under the same electricity demand assumption, if the proportion of indispensable gas-fired generation is higher, the negative welfare impact will be larger due to lack of flexibility in switching from the more expensive gas-fired generation to other alternative options, especially coal-fired generation, when the gas price is much higher. Specifically, the simulated negative welfare impact is between –0.44% and –0.37%, depending on the assumption for electricity demand. In short, under the counterfactual with a 71% increase gas price, the change in welfare level would be around –0.4%, while the proportion of the indispensable gas-fired generation and how the electricity demand would response due to a higher electricity price both have their own welfare implications.

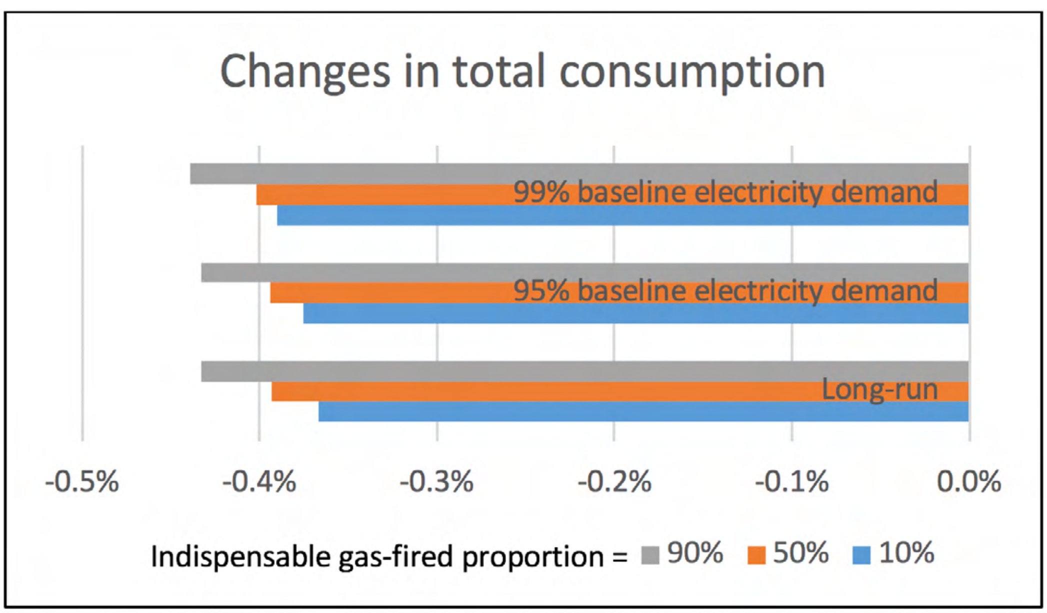

Figure 21. Changes in total consumption

5. Conclusions

The shale gas revolution has transformed the energy landscape of the U.S. economy. It is often regarded that with the cheap gas facilitating power sector's coal-to-gas transition, emissions from the power sector are reduced and that in turn results in the decrease of economy-wide CO_2 emissions during the past decade. Following the same rationale, it suggests that without the shale gas boom, the cheap gas will not be available, there would be no coal-to-gas transition in the power sector, and the economy-wide emissions would be higher. However, the changing economy over time in many different respects means that other factors such as the lower heating degree days and the declining energy intensity in recent years may have contributed to the final outcome as well.[5]

To explore the implications on the U.S. economy without the shale gas boom, we estimate the supply responses of coal-fired and gas-fired generations based on the U.S. state-level data and incorporate the estimates into an economy-wide model, which is constructed using the latest available global energy-economic database where the U.S. is explicitly identified. We use the model to study a counterfactual scenario that controls for all other factors but the production cost of gas, which is increased to represent an environment without the cheap gas. The strategy allows us to focus exclusively on the role of more expensive gas under the counterfactual.

The simulation results suggest that in the short run, while the higher sector specificity level of gas-fired generation tends to slow down the gas-to-coal transition, the inelastic electricity demand under the considered time frame is likely to increase the power sector emissions. However, the economy-wide emissions may increase or decrease, depending upon the non-power sectors' emissions responses.

We also demonstrate that in addition to how elastic the electricity demand is, the proportion of indispensable gas-fired generation will also determine whether or not emissions from the power sector and those of the whole economy would increase. If less gas-fired generation is regarded as indispensable and the electricity demand is highly inelastic as it may be in the short run, more gas-to-coal switch would be necessary especially when opportunities for expanding other generation options are limited, and a higher coal-fired output would be needed to meet the electricity demand. In this case, compared with the pre-shock level, emissions from the power sector or even the whole economy may be higher after the post-shock equilibrium is reached—an outcome that is accordant with conventional wisdom.

It is worth noting that a higher gas price would reduce emissions from the non-power sectors, as less substitution possibilities to replace gas by other energy or non-energy inputs are presented elsewhere. If the economy-wide emissions are increased, that would reflect the increase in power sector emissions outweighs the decrease in other sectors' emissions. At the same time, the results also reveal that a higher gas price might lower the economy-wide or even the power sector emissions compared with their respective baseline levels if more gas-fired generation is considered indispensable or if electricity demand is more elastic—an outcome that seems somewhat counter-intuitive at first glance. In fact, this simply reflects that with a higher gas price, if there is not much opportunity or necessity to switch from gas to coal within and beyond the power sectors, even if the power sector emissions still increase, reductions of other sectors' emissions due to dampened economic activities could ultimately reduce the economy-wide emissions. Following the same logic, the finding implies that other things being equal, if gas prices drop permanently due to reasons such as the shale gas boom, whether the economy-wide emissions would decrease depends not only on the power sector coal-to-gas switch but also on other sectors' response.

To explain why the simulated gas-fired output under the counterfactual is lower than the historical output of 2007, we point out that a potentially crucial factor is because the input-output data may only represent a short-run equilibrium. Following the same reason, since compared with the 2007 level, the gas price in 2011 is much lower, in the long run the economy might consume more gas as it prospers and consequently produce more emissions not reflected in the GTAP 9-Power database, which suggests that if this long-run equilibrium is captured in the database for the CGE analysis, due to the larger baseline emissions, the simulated economy-wide emissions with a higher gas production cost as a shock may be more likely to increase as well when compared with the historical 2011 emissions recorded in the GTAP 9-Power database—an outcome that seems to be more intuitive and coherent with conventional wisdom. Exploring ways of overcoming this potential data limitation could be a topic for future research.

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5 As mentioned in EIA (2016): "On a population-weighted national basis, the United States has about three times as many heating degree days as cooling degree days. For this reason, annual energy-related CO_2 fluctuations are more likely to resemble annual fluctuations in heating degree days."

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Appendix A: An example for a CES cost function

To provide an example of a CES function applied to represent a production activity, let us consider a technology that uses energy and non-energy inputs, and denote the rental prices of energy input Q_e and non-energy input Q_n by P_e and P_n, respectively. Following the calibrated share form for CES functions (Rutherford, 1998), the unit cost C for converting Q_e and Q_n into output Q can be formulated as:

$$C = \left[\alpha\left(\frac{P_e}{\bar{P}_e}\right)^{1-\sigma} + (1-\alpha)\left(\frac{P_n}{\bar{P}_n}\right)^{1-\sigma}\right]^{1/(1-\sigma)} \quad \text{(A01)}$$

where α is the cost share of energy, $\overline{P}_e$ and $\overline{P}_n$ are the base year (pre-shock) levels of P_e and P_n, respectively, and σ is the elasticity of substitution between the energy and non-energy inputs defined as:

$$\sigma = \left[\frac{d\left(\frac{Q_e}{Q_n}\right)}{\left(\frac{Q_e}{Q_n}\right)}\right] / \left[\frac{d\left(\frac{P_n}{P_e}\right)}{\left(\frac{P_n}{P_e}\right)}\right] \quad \text{(A02)}$$

Based on Section 3, if one denotes the equilibrium price of Q by P, which has a base year level of $\overline{P}$, the output of this technology is determined by the following MCP, which is simply the cost-benefit analysis for the production activity:

$$C \geq \frac{P}{\bar{P}};\ Q \geq 0;\ \left(C - \frac{P}{\bar{P}}\right) \cdot Q = 0 \quad \text{(A03)}$$

The production structure for a sector or the expenditure function for final consumption can be described by a diagram like that shown in **Figure A1**. In this case the diagram shows a cost function with two inputs, with prices P_e and P_n, that combine to produce a good with unit cost, C, and an elasticity of substitution between inputs, s.

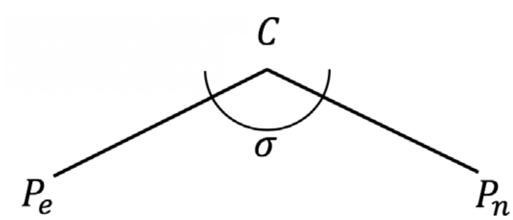

Figure A1. Nesting structure of the two-input CES cost function.

Appendix B: Structures and elasticities for CES cost/expenditure functions of non-power sectors

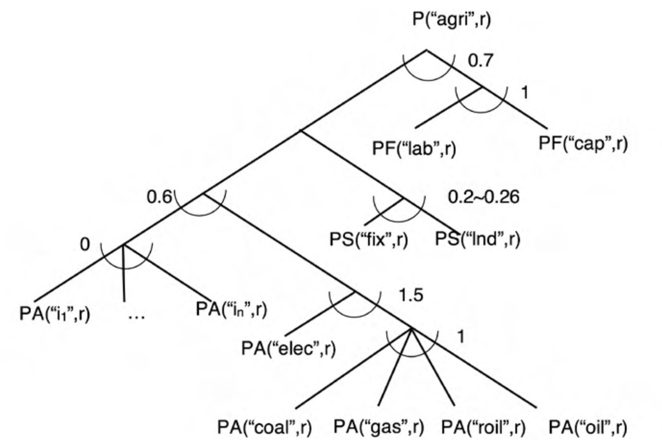

Figure B1. Crop, live, and forest sectors.

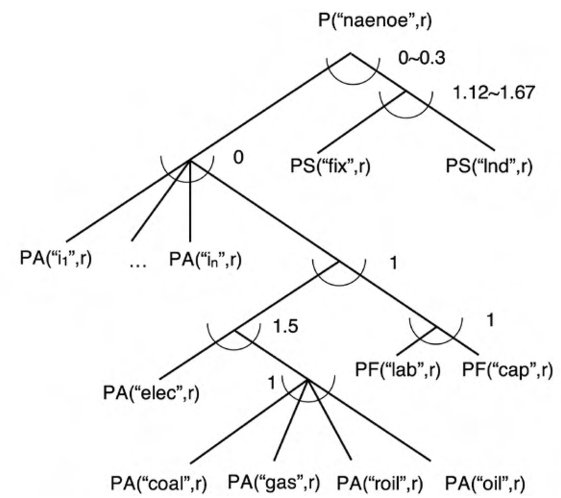

Figure B2. Dwelling, food, other, service, and transportation sectors.

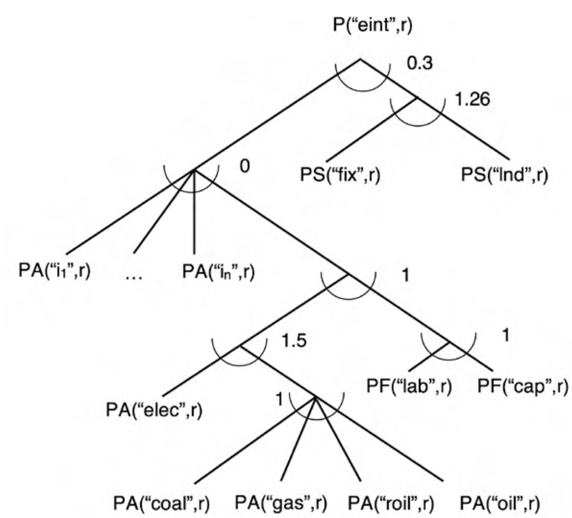

Figure B3. Energy-intensive sector.

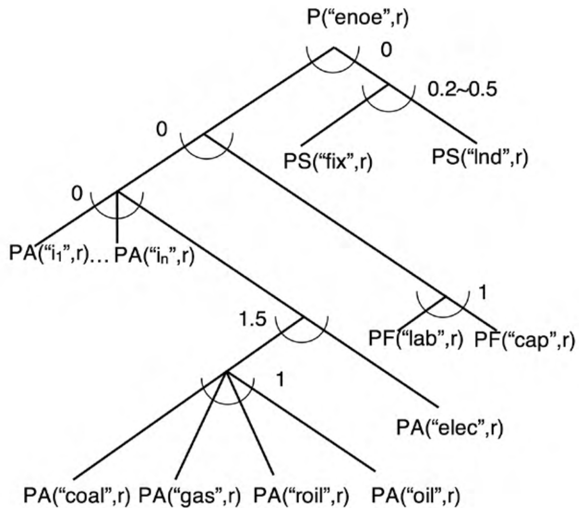

Figure B4. Oil, gas, refined oil and coal sectors.

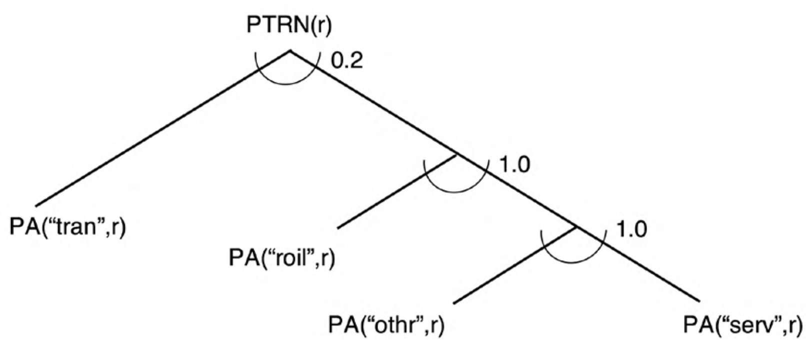

Figure B5. Household transportation.

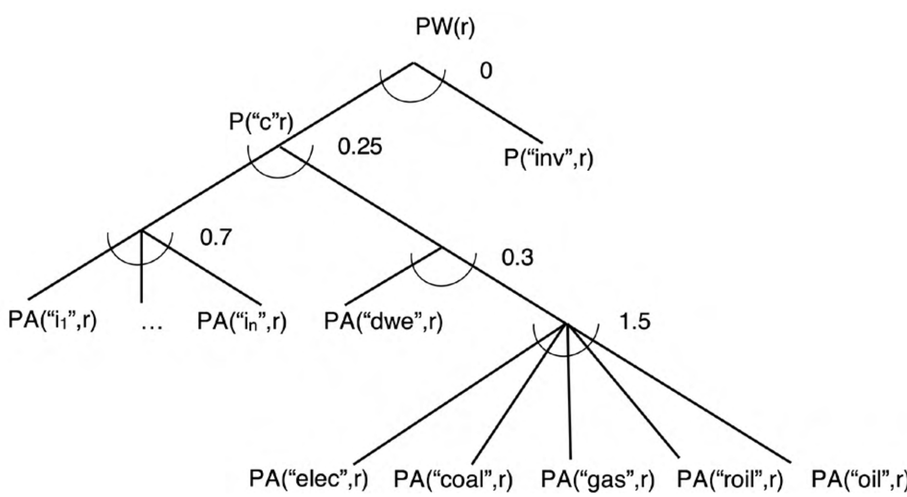

Figure B6. Household expenditure.

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