A Leaky Future for Natural Gas: Assessing its Substitution for Oil in the Transportation Sector through 2020 and the Effect on Greenhouse Gas Emissions

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ABSTRACT

Recent and expected natural gas discoveries in the United States combined with the ability to locate and access them with new technologies is predicted to lead to a large increase in natural gas supply, and as a result natural gas consumption. This research focused on its substitution for oil in the transportation sector. Econometric analysis was used to estimate the effect of different variables, including consumption, reserve size, number of fuel pumps, and retail pump prices on natural gas consumed as vehicle fuel, as well as the relative substitution of natural gas for oil in the transportation sector under no carbon policy and a carbon tax. By estimating the level of natural gas used as vehicle fuel through 2020, I found that the market share of natural gas consumed in the transportation sector increased from 0.29% to 2.72% between 1997-2020 under no carbon policy, and from 0.29% to 2.76% under a carbon tax. Under no carbon policy, total CO_2 emissions from the transportation sector decreased by 50% from 1997-2020, and under a hypothetical carbon tax implemented beginning in 2012, decreased by 52% from 1997-2020. Different methane (CH_4) leakage scenarios were introduced (0, 5, and 10%), and it was determined that under a leakage level of 5%, the change in CO_2 equivalent emissions from 1997-2020 under no carbon policy was 50%, and under a carbon tax approximately 50% as well. With a leakage of 10%, the change in CO_2 equivalent emissions from 1997-2020 under no carbon policy was 50%, and under a carbon tax approximately 48%. Thus, if leakage rates are not known within a 5% range, a carbon tax promoting natural gas substitution will lead to greater total greenhouse gas emissions from the transportation sector than no carbon policy.

KEYWORDS

methane leakage, carbon tax, carbon dioxide, energy substitution, energy policy

INTRODUCTION

Energy production and consumption have been dynamic parts of the global economy for centuries, and their importance is reflected by people's dependence on them. Key economic factors and policy formation affect resource discovery and extraction, especially with fossil fuel-derived energy. Harold Hotelling (1931) provides the most commonly used framework for theorizing resource discovery and extraction, postulating that if reserve sizes are known and no new discoveries take place, resource prices rise at the rate of interest, which maximizes the value of the resource stock. Energy infrastructure also affects long run prices, and thus competitiveness of a fuel in a given energy sector (e.g. transportation, electricity, heating, etc.) (Hartley et al. 2012). While energy products can be harnessed for different purposes due to differences in physical state (solid, liquid, or gas), ability to be transported, and pollution standards, they often compete with one another for similar uses. Examples of different energy uses include coal for electricity generation, oil as a transportation fuel, and natural gas for residential heating. Availability of different products and relative demand for each leads to cycles of substitution between these products (Chakravorty et al. 1997). One such cycle is occurring presently with natural gas, which is substituting for coal in electricity generation and oil in transportation in the U.S., and is expected to continue to do so over the next 5-10 years due to production increases and newly accessible reserves (Pirog and Ratner 2012). With this substitution comes a great deal of uncertainty about potential economic and environmental outcomes.

Advances in hydraulic fracturing, commonly known as fracking, have increased the ability to exploit once inaccessible and recently discovered natural gas reserves (Considine et al. 2009). A significant number of these newly accessible production sites are located within the continental United States, including large areas of the Marcellus Shale on the east coast (Kargbo et al. 2010), Barnett Shale in Texas (Montgomery et al. 2005), and Monterey Shale in California (Park et al. 2013). Natural gas is attractive considering its supposed cleanliness as a fuel, and with climate change a primary global concern its increased production provides both economic and environmental benefits. Carbon dioxide (CO_2) emissions of natural gas are about half those of coal (Logan et al. 2012) and about 60% of those generated by oil (Hekkert et al. 2005). However, there is great concern about methane (CH_4) emissions associated with natural gas production due to leakages along the entire natural gas supply chain (Alvarez et al. 2012). Methane has a radiative forcing capacity (heat trapping effect) that is 20-30 times greater than that of CO_2 over a 100-year time horizon, and the EPA estimates the percentage of gross production of natural gas lost to leakage to be 1.65% (EPA 2013). However, there have been conflicting studies on the actual level of methane leakage from natural gas production. Allen et al. (2013) estimate leakage to be 0.42% of gross natural gas production, Karion et al. (2013) find leakage levels to range between 6.2% and 11.7%, and Miller et al. (2013) estimate levels that are approximately 5 times greater than EPA estimates. Given different potential leakage levels, increased natural gas use may generate greater total greenhouse gas emissions than is the case under its current level of use.

Carbon pricing policies being considered in the U.S. designed to limit or monetize carbon emissions only apply to CO_2 emissions, not CH_4 emissions. Carbon taxes, producer reduction subsidies, or cap and trade mandates may give natural gas a competitive price advantage over oil or coal, given that it produces fewer CO_2 emissions per unit of energy content (Metcalf 2009). The Weitzman model suggests that with inelastic demand for a resource, which is the case for oil and natural gas, a carbon tax is superior to a quantity control mandate in reaching efficient production levels given pollution externalities (Weitzman 1974). There are also studies that show the early effectiveness of a carbon emissions trading scheme in the European Union, and many are working on estimating the impacts of introducing such schemes in other developed countries (Ellerman and Buchner 2007). These policies may promote natural gas substitution into different energy sectors despite the fact that CH_4 leakages may make it “dirtier” overall. Although natural gas can be used for several different energy purposes (e.g. electricity generation, residential heating, etc.), this paper focuses on its substitution into the transportation sector because natural gas can be used as a “travel” fuel. With the transportation sector nearly fully dependent on petroleum, and about 70% of all petroleum in the U.S. used for transportation purposes (Knittel 2012), natural gas substitution into this sector has enormous implications. Yet there is little understanding of how carbon pricing policies and other economic and physical factors of natural gas and petroleum (e.g. prices, production, reserve sizes, infrastructure levels, etc.) may impact natural gas substitution into the transportation sector, and whether its substitution will actually lead to a future reduction in total GHG emissions generated by transportation under different leakage scenarios.

In this paper I address the following research question: How will recent discoveries of shale gas in the United States affect the substitution of natural gas into the transportation sector with and without a hypothetical carbon tax? Specifically, will estimated substitution levels of natural gas with and without a carbon tax lead to increased or decreased total potency of greenhouse gas emissions generated by the transportation sector, given three different leakage scenarios (0, 5, and 10 percent)? To answer these questions, I collected data on several key economic and physical variables affecting natural gas and petroleum, including production levels, prices, relative levels of infrastructure in place, emission strengths of CO_2 and CH_4, and leakage estimates. I then built an econometric model for estimating the effect of different parameters on the level of substitution of natural gas into the transportation sector.

METHODS

Data Collection and Preparation

I accessed the Energy Information Administration (EIA) Database to collect data on different variables associated with natural gas production, prices, reserve sizes, and infrastructure and oil production, prices, and infrastructure over time. From the EIA database I obtained data from 1997-2011, including the following natural gas annualized variables: **(1)** U.S. natural gas vehicle fuel consumption (MMcf); **(2)** U.S. natural gas total consumption in millions of cubic feet (MMcf); **(3)** U.S. dry natural gas proved reserves (MMcf); **(4)** number of U.S. natural gas fuel pumps; and **(5)** U.S. natural gas residential price (dollars per Mcf).[1] I also obtained oil variables from the EIA from 1997-2012, which included: **(1)** U.S. total gasoline retail sales by refiners (thousand gallons per day)[2]; **(2)** real motor gasoline price (dollars per gallon); and **(3)** number of U.S. petroleum fuel pumps. Other important data collected were the estimated long run own price elasticities of demand for oil and natural gas over this time period, which I estimate to be -0.7 based on estimates found in the literature (Brons et al. 2008; Hughes, Knittel, and Sperling 2006; Krichene 2002; Davis 2013). I also found the CO_2 coefficients for natural gas (53.1 tonnes/MMcf)

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[1] Data was converted to $/gallon equivalent to compare with oil. The residential price is the point at which an individual, residential consumer receives gas from a distributing gas utility company (a fuel company).

[2] This data as well as the natural gas consumption data (total consumption and consumption in vehicle fuel) was converted to units of gallons of gasoline per year equivalent.

and oil (.0089 tonnes/gallon) from the EIA, and used them to calculate the total CO_2 emissions from natural gas and gasoline consumption.

To prepare the data for regression, I converted the data to appropriate units and verified some of the data collected to obtain the most accurate analysis possible. First, I created an Excel sheet with the aforementioned variables of interest to use in the regressions. I then made sure all variables with the same units had the same order of magnitude (i.e. one is not in thousands while another is). I also converted production variables into gallons of gasoline per year equivalent to achieve unit uniformity. Finally, I used regression over time with the data from 1997-2012 in Excel to extrapolate the general trend over time for each independent variable of interest through 2020 (i.e. generated estimated data for 2013-2020). If the independent variable being regressed had a linear time trend, I simply used the slope of the line to determine the annual value in each of the future years through 2020. If the independent variable being regressed had a quadratic time trend, I used the equation of the function generated by Excel to estimate the annual value of the variable in each of the future years through 2020.

Analysis

With the data now verified and modified appropriately, I used STATA Version 13 to run a time series regression of each independent variable on the dependent variable "U.S. natural gas vehicle fuel consumption (gallons of oil per year equivalent)" for data ranging from 1997-2011. The regression model took the following form:

$$NG\_Vfuelcons_t = \beta_0 + \beta_1 NG\_Totcons_t + \beta_2 NG\_Reserves_t + \beta_3 NG\_Stations_t + \beta_4 NG\_Price_t + \beta_5 Oil\_Totcons_t + \beta_6 Oil\_Price_t + \beta_7 Oil\_Stations_t + u_t$$

The meanings of each of these variables are below (Table 1).

Table 1. Model variables and meanings

Variable	Meaning
$NG\_Vfuelcons_t$	Annual U.S. natural gas vehicle fuel consumption (MMcf) at time *t*
$NG\_Totcons_t$	Annual U.S. natural gas total consumption (MMcf) at time *t*
$NG\_Reserves_t$	U.S. dry natural gas proved reserves (MMcf) at time *t*
$NG\_Stations_t$	Number of U.S. natural gas fuel pumps at time *t*
NG_Price_t	U.S. real natural gas residential price (dollars per Mcf) at time *t*
$Oil\_Totcons_t$	Annual U.S. total gasoline retail sales by refiners (MMcf) at time *t*
Oil_Price_t	U.S. real motor gasoline price (dollars per gallon) at time *t*
$Oil\_Stations_t$	Number of U.S. gasoline fueling stations at time *t*
u_t	Error term at time *t*

I used the regression results to identify t-statistics, p-values, and confidence intervals for the marginal effect of each independent variable on the predicted value of the dependent variable, holding constant the other independent variables not being considered. With the estimated beta coefficients for each variable, I estimated the consumption of natural gas as vehicle fuel from 2012-2020 (using the extrapolated data on the independent variables). This was done by substituting into the regression equation the extrapolated data of the independent variables from each year. I then calculated total CO_2 emissions generated by the transportation sector in each year using the new data for the dependent variable generated from the regression as well as the gasoline consumption data, which was independently extrapolated through 2020. I made an assumption that the transportation sector is made up of only oil and the marginal input of natural gas, and did not include electricity, solar, biofuel, or other fuels other than oil and natural gas as transportation fuels.

Using the same steps in forming the regression explaining the effect of each of the independent variables on natural gas consumed as vehicle fuel under no policy, I engaged in statistical analysis using a carbon tax. I simulated a carbon tax of $12/ton of CO_2 emitted, which is the peer-reviewed mean value found by the Climate Change 2007 Working Group II: Impacts, Adaptation, and Vulnerability (Parry 2007). I then converted this into a dollar amount per gallon of gasoline using the number of tonnes of carbon emitted per gallon of gasoline as well as a dollar amount per 1,000 cubic feet of natural gas using the number of tonnes of carbon emitted per 1,000 cubic feet, and implemented this tax each year from 1997-2011. I used -0.7 as an estimated price elasticity of demand for oil and natural gas to calculate the resulting decreases in quantities consumed for each fuel because of a carbon tax (Davis 2013). I ran a regression with the new data under the carbon policy to see how this changed natural gas consumed as vehicle fuel into the future.

In order to determine the effect of emissions generated into the future, I used a difference-in-difference method to compare the difference in emissions in the transportation sector from 1997-2020 with no policy intervention versus a carbon tax. This difference was calculated using the percentage change in CO_2 emissions generated by the transportation sector as a whole (which in my case is made up of only oil and natural gas, for simplicity) under no tax and under the carbon tax from 1997-2020. Using different leakage levels (0, 5, and 10%) on the amount of natural gas consumed as vehicle fuel, and computing the total strength of emissions from natural gas consumed as vehicle fuel based on these leakage levels, I compared total emissions with no policy and with the policy.

RESULTS

Data Collection and Preparation: No Carbon Tax

I accessed data from the EIA and organized it into a Microsoft Excel spreadsheet. I converted all EIA data quantity categories to gallons of gasoline equivalent (GGE) and all price categories to dollars per GGE to achieve uniformity across fuels, and I converted the gasoline retail sales by refiners to gallons per year.

Additionally, I calculated the annual CO_2 emissions from “Natural gas used as vehicle fuel,” “Total natural gas consumption,” and “Total gasoline consumption” using the CO_2 fuel coefficients of natural gas and oil. For natural gas, the CO_2 production coefficient was 53.1 tonnes CO_2/MMcf. So the CO_2 emissions for a given category and year were calculated in Equation 1 as follows:

$$\text{□□}_2\ \text{□□□□□□□□□} = 53.1 * (\text{□□□□□□□ □□□ □□□□□□□□ □□ □□□□}) \qquad (1)$$

Where the “natural gas category” represents either natural gas used as vehicle fuel or natural gas consumption. For gasoline, the CO_2 production coefficient was .0089 tonnes CO_2/gallon. So the CO_2 emissions for a given category and year are calculated as follows:

$$\text{□□}_2\ \text{□□□□□□□□□} = .0089 * (\text{□□□□□□□□ □□□□□□□□□□□ □□ □□□□□□□}) \qquad (2)$$

I then extrapolated trends for each of the independent variables in my regression model, which again is as follows:

$$NG\_Vfuelcons_t = \beta_0 + \beta_1 NG\_Totcons_t + \beta_2 NG\_Reserves_t + \beta_3 NG\_Stations_t + \beta_4 NG\_Price_t + \beta_5 Oil\_Totcons_t + \beta_6 Oil\_Price_t + \beta_7 Oil\_Stations_t + u_t \qquad (3)$$

An example of one of the extrapolations can be seen below (Figures 1a and 1b). I used these extrapolations to determine values for each of my independent variable categories for the years 2012-2020. The remaining independent variable extrapolations are found in Appendix A.

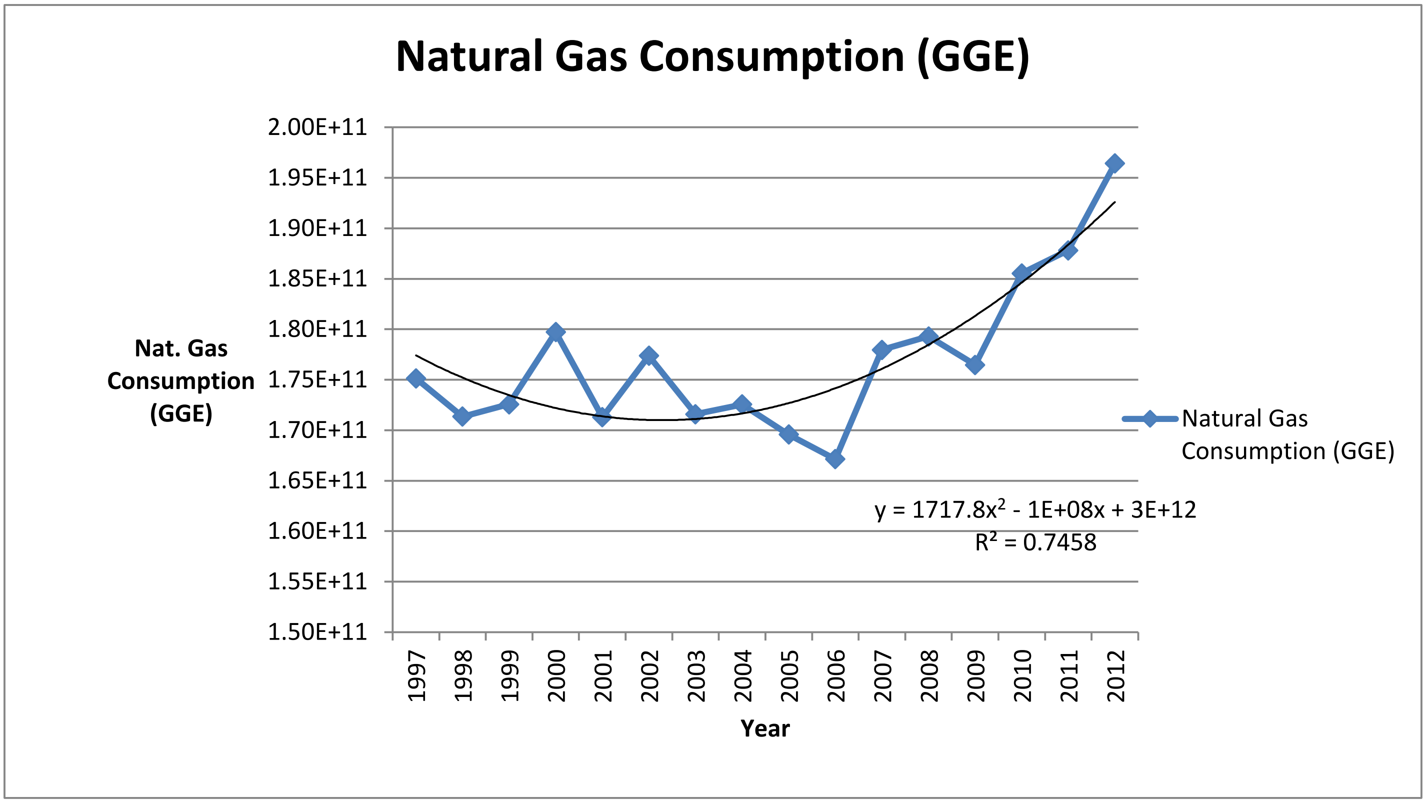

Figure 1a: Total natural gas consumption in GGE in the U.S. from 1997-2012 and the associated quadratic trend.

Natural gas consumption has been increasing at an exponential rate since around 2006 (Figure 1a).

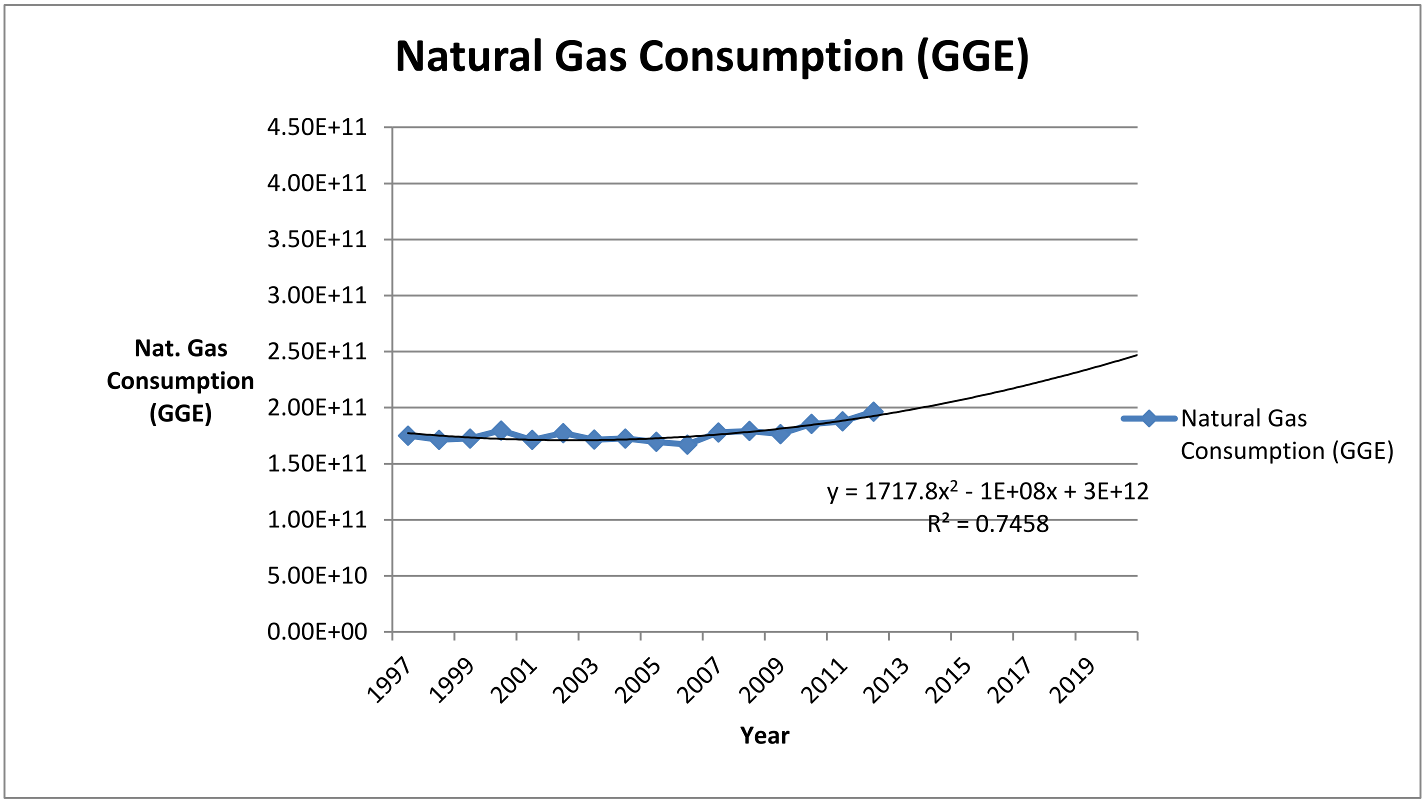

Figure 1b: Total natural gas consumption in GGE in the U.S. from 1997-2020 using extrapolated quadratic trend.

Figure 1b extrapolates the trend from Figure 1a through 2020, and confirms the rapid increase of total natural gas consumption in the U.S.

Analysis: No Carbon Tax

I used the collected EIA data from 1997-2011 to run a regression in STATA Version 13 using Equation (3), and found all of the independent variables to be statistically significant at least at the 10% level except for natural gas price and size of natural gas reserves (Table 2).

Table 2. Results from estimation under no carbon policy

	NG_Vfuelcons
NG_Totcons	-0.00161^{*}
	(-2.90)
NG_stations	-64987.4^{*}
	(-3.42)
NG_reserves	0.0000273
	(1.33)
NG_price	-1934942.4
	(-0.80)
Oil_totcons	-0.00534^{+}
	(-2.32)
Oil_price	16349775.8^{*}
	(2.40)
Oil_stations	-2402.2^{***}
	(-5.68)
Constant	953656729.1^{***}
	(5.75)
Observations	15

t statistics in parentheses
$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The values above represent the β coefficients for each of the independent variables. Because the natural gas reserves variable and the natural gas price variable are insignificant at the 10% significance level, I reran the estimation, which is found below (Table 3).

Table 3. Results from estimation under no carbon policy with significant parameters

	NG_Vfuelcons
NG_Totcons	-0.00120*
	(-2.77)
NG_stations	-60364.4**
	(-3.75)
Oil_totcons	-0.00827***
	(-8.82)
Oil_stations	-2602.3***
	(-7.33)
Oil_price	12688185.6*
	(2.94)
Constant	1.00796e+09***
	(9.15)
Observations	15

t statistics in parentheses
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Using the extrapolated data, I plugged in values for each of the significant independent variables, and calculated "Natural gas consumed as vehicle fuel (MMcf)" from 2012-2020 using these significant coefficients and the regression equation. The table of "Natural gas consumed as vehicle fuel" from 1997-2020 and the resulting CO_2 emissions in each year is shown below (Table 4). Because of increased natural gas used as vehicle fuel, estimated CO_2 emissions from its consumption in the transportation sector are increasing and continue to do so through 2020.

Table 4: Natural gas consumed as vehicle fuel from 1997-2020 and resulting CO_2 emissions (no carbon policy)

Year	Natural Gas Vehicle Fuel Consumption (GGE)	Resulting Carbon Dioxide Emissions (tonnes)
1997	64146586.6	442216.8
1998	71949239.3	496007.1
1999	89518687.4	617128.2
2000	98222535.0	677131.2
2001	111963830.7	771861.6
2002	115152674.0	793845.0
2003	140732742.9	970190.1
2004	158009495.3	1089293.4
2005	176264467.7	1215140.4
2006	182850122.3	1260540.9
2007	189905630.6	1309180.5
2008	200126874.6	1379644.2
2009	209986100.2	1447612.2
2010	220785033.3	1522058.4
2011	248383162.4	1712315.7
2012	253721008.8	1749114.0
2013	258069537.0	1779092.1
2014	265808579.4	1832443.9
2015	273114567.2	1882810.2
2016	279987500.2	1930191.2
2017	286427378.4	1974586.7
2018	292434201.9	2015996.9
2019	298007970.7	2054421.6
2020	303148684.7	2089860.9

Data Collection and Preparation: Carbon Tax

The data modification and unit conversions for the carbon tax scenario were identical to the no carbon policy scenario, except that I modified them using the implementation of a carbon tax and the price elasticity of demand. Using the carbon content of both natural gas and gasoline and a carbon tax of \$12/ton CO_2, I calculated a \$0.66 tax/Mcf of natural gas and a \$0.11 tax/gallon of gasoline.

To determine the resulting change in quantity because of the increased price, I first calculated the percentage change in price for both the natural gas and gasoline price data under a no carbon policy and then under a carbon tax. I incorporated these percentage changes in price and used the price elasticity of demand estimate, -0.7, to find the percentage decrease in quantity for each of the quantity-related variables that are applicable (e.g. "Natural gas consumed as vehicle fuel," "Total natural gas consumption," and "Total gasoline sales by refiners"). We denote the price elasticity of demand by $\varepsilon_D = -0.7$, and calculate the percentage change in quantity the three relevant quantity-related variables using the following equation:

$$\varepsilon_D = \frac{\left({q_{tax} - q_{no\ tax}}/{q_{no\ tax}}\right)}{\left({p_{tax} - p_{no\ tax}}/{p_{no\ tax}}\right)} = \frac{\%\Delta(q)}{\%\Delta(p)} = -0.7 \tag{4}$$

With this percentage decrease in quantity for the natural gas and gasoline, I calculated the hypothetical quantities under the carbon tax using a simple percentage change equation:

$$□_{□□□} - □_{□□\ □□□}/□_{□□\ □□□} = \%\Delta(□)$$

Solving for q_{tax} since $q_{no\ tax}$ was known from the original dataset and $\%\Delta(q)$ was just calculated. With these new quantity and price estimates from 1997-2012, I used the same extrapolation technique as under the no carbon policy scenario, but with the hypothetical data instead.

Analysis: Carbon Tax

The regression analysis for the carbon tax scenario was identical to the no carbon policy scenario, except I used the carbon tax-adjusted EIA data from 1997-2011 to run the regression. As was the case with the results displayed in Table 2, all of the independent variables were statistically significant at least at the 10% level under a \$12/ton CO_2 tax except for natural gas reserves and natural gas prices (Table 5).

Table 5. Results from estimation under a carbon tax

	NG_Vfuelcons
NG_Totcons	-0.00147*
	(-2.49)
NG_stations	-59228.7*
	(-3.03)
NG_reserves	0.0000244
	(1.14)
NG_price	761889.6
	(0.34)
Oil_totcons	-0.00552^{+}
	(-2.21)
Oil_price	14620970.4^{+}
	(2.18)
Oil_stations	-2362.4**
	(-5.24)
Constant	877056612.7**
	(5.13)
Observations	15

t statistics in parentheses
$^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The values above represent the β coefficients for each of the independent variables. Because the natural gas reserves variable and the natural gas price variable are insignificant at the 10% significance level, I reran the estimation, which is contained below (Table 6).

Table 6. Results from estimation under a carbon tax with significant parameters

	NG_Vfuelcons
NG_Totcons	-0.00139*
	(-2.77)
NG_stations	-66833.1**
	(-4.43)
Oil_totcons	-0.00794***
	(-8.61)
Oil_price	17138446.6**
	(3.78)
Oil_stations	-2640.9***
	(-6.95)
Constant	1.01073e+09***
	(8.12)
Observations	15

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Using the extrapolated data, I plugged in values for each of the significant independent variables, and calculated "Natural gas consumed as vehicle fuel (MMcf)" from 2012-2020 under the tax using these significant coefficients and the regression equation. The table of "Natural gas consumed as vehicle fuel" with the tax from 1997-2020 and the resulting CO_2 emissions in each year is shown below (Table 7). As is the case with Table 4, estimated CO_2 emissions from natural gas consumption in the transportation sector are increasing and continue to do so through 2020. However, because of the tax these emissions are lower in quantity in each year than with no carbon policy.

Table 7. Natural gas consumed as vehicle fuel from 1997-2020 and resulting CO_2 emissions (carbon tax)

Year	Natural Gas Vehicle Fuel Consumption (GGE)	Resulting Carbon Dioxide Emissions (tonnes)
1997	62453040.4	430541.8
1998	69702811.5	480520.6
1999	86937741.6	599335.6
2000	95980580.6	661675.5
2001	109221329.2	752955.2
2002	112113925.6	772896.3
2003	137455900.3	947600.0
2004	154830044.8	1067374.8
2005	173275727.3	1194536.5
2006	180028835.0	1241091.4
2007	187138437.0	1290103.9
2008	197518440.1	1361662.0
2009	206204425.6	1421541.9
2010	217371507.3	1498526.1
2011	245258966.3	1690778.0
2012	250554025.3	1727281.3
2013	255960193.0	1764550.6
2014	263740682.7	1818188.1
2015	271107603.0	1868974.5
2016	278061673.4	1916914.8
2017	284603516.0	1962013.3
2018	290733671.3	2004273.7
2019	296452611.3	2043699.2
2020	301760750.0	2080292.7

Comparative Analysis of No Carbon Policy and a Carbon Tax with Leakage Considerations

The market share of natural gas in the transportation sector was estimated to increase from 0.29% to 2.72% from 1997-2020 under no carbon policy and from 0.29% to 2.76% under a carbon tax. Under no carbon policy, total CO_2 emissions from the transportation sector decreased by 50% from 1997-2020, and under a hypothetical carbon tax implemented beginning in 2012, decreased by 52% from 1997-2020. The magnitude of CO_2 emissions (that is, without considering methane leakages) in 2020 under a hypothetical carbon tax is 2 million tonnes lower than under no carbon policy. I compared the total CO_2 emissions from the transportation sector in 2020 between the no carbon policy and carbon tax scenarios, and determined the relative contributions from natural gas and gasoline (Table 8).

Table 8. Relative contribution of natural gas and gasoline to transportation sector CO_2 emissions

	No Carbon Policy		Carbon Tax	
Year	% of Transportation Sector CO2 emissions from NG	% of Transportation Sector CO2 emissions from Gasoline	% of Transportation Sector CO2 emissions from NG	% of Transportation Sector CO2 emissions from Gasoline
1997	0.2	99.8	0.2	99.8
1998	0.2	99.8	0.2	99.8
1999	0.3	99.7	0.3	99.7
2000	0.3	99.7	0.3	99.7
2001	0.4	99.6	0.4	99.6
2002	0.4	99.6	0.4	99.6
2003	0.5	99.5	0.5	99.5
2004	0.6	99.4	0.6	99.4
2005	0.6	99.4	0.6	99.4
2006	0.6	99.4	0.6	99.4
2007	0.7	99.3	0.7	99.3
2008	0.8	99.2	0.8	99.2
2009	0.9	99.1	0.9	99.1
2010	1.0	99.0	1.0	99.0
2011	1.3	98.7	1.3	98.7
2012	1.8	98.2	1.8	98.2
2013	1.8	98.2	1.8	98.2
2014	1.9	98.1	1.9	98.1
2015	1.9	98.1	1.9	98.1
2016	2.0	98.0	2.0	98.0
2017	2.0	98.0	2.0	98.0
2018	2.0	98.0	2.1	97.9
2019	2.1	97.9	2.1	97.9
2020	2.1	97.9	2.2	97.8

In 2020, natural gas has a slightly higher share of total transportation sector CO_2 emissions under a carbon tax, estimated to be 2.2%, compared to 2.1% under no carbon tax.

The methane leakage from natural gas production was addressed under three different hypothetical scenarios: 0%, 5%, and 10% of total emissions. I multiplied the CO_2 emissions generated in each year by .05 and .1 for the 5% and 10% leakage levels, respectively, and multiplied these emissions by 27 in order to account for the increased radiative forcing capacity of methane. I've included the additional emissions generated by natural gas in the transportation sector under each of these leakage scenarios below, and measured the new share of transportation emissions generated by natural gas under no carbon policy and a carbon tax (Tables 9a and 9b).

Table 9a. Relative contribution of natural gas, with leakages, and gasoline to transportation sector CO_2 emissions under no carbon policy

Year	% of Transportation Sector CO2 emissions from NG (0% Leakage)	% of Transportation Sector CO2 emissions from Gasoline	% of Transportation Sector CO2 emissions from NG (5% Leakage)	% of Transportation Sector CO2 emissions from Gasoline	% of Transportation Sector CO2 emissions from NG (10% Leakage)	% of Transportation Sector CO2 emissions from Gasoline
1997	0.2	99.8	0.5	99.5	0.8	99.2
1998	0.2	99.8	0.6	99.4	0.9	99.1
1999	0.3	99.7	0.7	99.3	1.1	98.9
2000	0.3	99.7	0.8	99.2	1.3	98.7
2001	0.4	99.6	0.9	99.1	1.4	98.6
2002	0.4	99.6	0.9	99.1	1.4	98.6
2003	0.5	99.5	1.1	98.9	1.7	98.3
2004	0.6	99.4	1.3	98.7	2.1	97.9
2005	0.6	99.4	1.5	98.5	2.3	97.7
2006	0.6	99.4	1.5	98.5	2.3	97.7
2007	0.7	99.3	1.6	98.4	2.5	97.5
2008	0.8	99.2	1.8	98.2	2.8	97.2
2009	0.9	99.1	2.1	97.9	3.2	96.8
2010	1.0	99.0	2.4	97.6	3.7	96.3
2011	1.3	98.7	3.1	96.9	4.8	95.2
2012	1.8	98.2	4.1	95.9	6.3	93.7
2013	1.8	98.2	4.1	95.9	6.4	93.6
2014	1.9	98.1	4.3	95.7	6.6	93.4
2015	1.9	98.1	4.4	95.6	6.7	93.3
2016	2.0	98.0	4.5	95.5	6.9	93.1
2017	2.0	98.0	4.6	95.4	7.0	93.0
2018	2.0	98.0	4.7	95.3	7.2	92.8
2019	2.1	97.9	4.8	95.2	7.3	92.7
2020	2.1	97.9	4.8	95.2	7.4	92.6

Table 9b. Relative contribution of natural gas, with leakages, and gasoline to transportation sector CO_2 emissions under a carbon tax

It is clear that under a carbon tax, the relative share of emissions from natural gas, including leakages, is higher than under no carbon policy in 2020. With a leakage level of 5%, the change CO_2 equivalent emissions from 1997-2020 under no carbon policy is 50%, and under a carbon tax is approximately 50% as well. With a leakage of 10%, the change CO_2 equivalent emissions from 1997-2020 under no carbon policy is 50%, and under a carbon tax is approximately 48%. This suggests that higher levels of leakage make a carbon tax more dangerous to emissions reductions because it promotes natural gas simply based on its lower CO_2 emissions per unit of energy compared to gasoline, and does not account for leakages.

Year	% of Transportation Sector CO2 emissions from NG (0% Leakage)	% of Transportation Sector CO2 emissions from Gasoline	% of Transportation Sector CO2 emissions from NG (5% Leakage)	% of Transportation Sector CO2 emissions from Gasoline	% of Transportation Sector CO2 emissions from NG (10% Leakage)	% of Transportation Sector CO2 emissions from Gasoline
1997	0.2	99.8	0.5	99.5	0.8	99.2
1998	0.2	99.8	0.6	99.4	0.9	99.1
1999	0.3	99.7	0.7	99.3	1.1	98.9
2000	0.3	99.7	0.8	99.2	1.3	98.7
2001	0.4	99.6	0.9	99.1	1.4	98.6
2002	0.4	99.6	0.9	99.1	1.4	98.6
2003	0.5	99.5	1.1	98.9	1.7	98.3
2004	0.6	99.4	1.3	98.7	2.1	97.9
2005	0.6	99.4	1.5	98.5	2.3	97.7
2006	0.6	99.4	1.5	98.5	2.4	97.6
2007	0.7	99.3	1.6	98.4	2.5	97.5
2008	0.8	99.2	1.8	98.2	2.8	97.2
2009	0.9	99.1	2.1	97.9	3.2	96.8
2010	1.0	99.0	2.4	97.6	3.8	96.2
2011	1.3	98.7	3.1	96.9	4.8	95.2
2012	1.8	98.2	4.1	95.9	6.3	93.7
2013	1.8	98.2	4.2	95.8	6.5	93.5
2014	1.9	98.1	4.3	95.7	6.6	93.4
2015	1.9	98.1	4.4	95.6	6.8	93.2
2016	2.0	98.0	4.5	95.5	7.0	93.0
2017	2.0	98.0	4.6	95.4	7.1	92.9
2018	2.0	98.0	4.7	95.3	7.3	92.7
2019	2.1	97.9	4.8	95.2	7.4	92.6
2020	2.1	97.9	4.9	95.1	7.5	92.5

There are 6 total scenarios involving natural gas substitution for oil in the transportation sector. There are three different leakage levels and two different policy scenarios (no carbon policy and a carbon tax), making 6 scenarios total. The change in emissions over time from natural gas use in the transportation sector is indicated below (Figure 2).

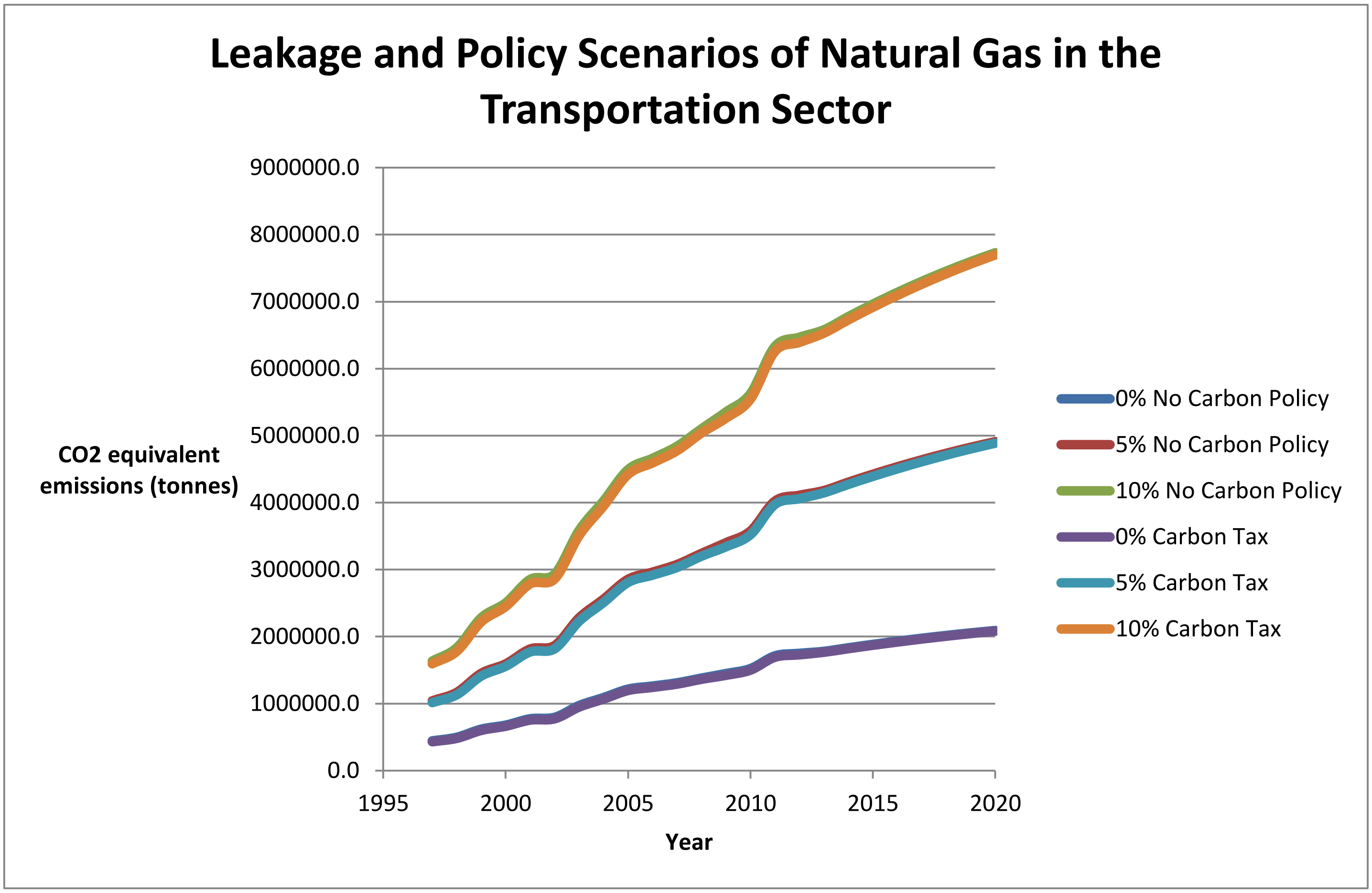

Figure 2: Six leakage (0, 5, and 10%) and policy (no carbon policy and carbon tax) scenarios and the effect on emissions

While the emissions from the transportation sector as a whole have been decreasing over the 1997-2020 time period due to decreasing consumption of oil, increased natural gas use combined with leakages is contributing to a steep, upward sloping trend in CO_2 emissions equivalent from natural gas used in the transportation sector (Figure 2). While the difference in emissions between no carbon policy and a carbon tax is relatively small (although it does increase with higher leakage levels), Figure 2 shows that as natural gas is further substituted into the transportation sector, the level of leakage becomes increasingly important in determining the "cleanliness" of natural gas compared to gasoline.

I have also distinguished the relative magnitudes of the "leakage effect" versus the "carbon tax effect." The leakage effect is the increase in emissions from the transportation sector due to a 5% increase in leakage from natural gas production. The carbon tax effect is the reduction in emissions from the transportation sector due to the implementation of a carbon tax. Looking at the six different scenarios, the overall CO_2 equivalent emissions generated by the transportation sector in 2020 (from natural gas use, gasoline use, and leakages) are 102.2 million tonnes under a carbon tax and 10% leakage. However, this level of emissions exceeds that of the scenario of 5% leakage and no carbon tax, which generates 101.5 million tonnes of CO_2 equivalent emissions. Similarly, the overall CO_2 equivalent emissions generated by the transportation sector in 2020 (from natural gas use, gasoline use, and leakages) are 99.4 million tonnes under a carbon tax and 5% leakage. However, this level of emissions exceeds that of the scenario of 0% leakage and no carbon tax, which generates 98.7 million tonnes of CO_2 equivalent emissions. This analysis suggests that a 5% increase in leakage generates more CO_2 equivalent emissions than is reduced by implementing a carbon tax.

DISCUSSION

The model I use predicts that the market share for natural gas in the transportation sector will remain relatively low (below 5%) in 2020 under both no carbon policy and a carbon tax. While a carbon tax led to a higher market share of natural gas in the transportation sector in 2020 than no carbon policy (2.76% versus 2.72%), the difference was smaller than anticipated. However, the results revealed an interesting relationship between a carbon policy and leakage levels. Under no carbon policy, total CO_2 emissions from the transportation sector decreased by 50% from 1997-2020, and under a hypothetical carbon tax implemented beginning in 2012, they decreased by 52% from 1997-2020, which represents a reduction in 2 million tonnes of CO_2 in 2020 under a carbon tax. However, as scenarios with greater leakage were introduced (from 0% to 5% to 10%), it was determined that a carbon tax caused less CO_2 equivalent emissions reduction than no carbon policy. Thus, leakage levels have a more significant effect than a carbon tax in determining the ultimate effect of natural gas on emissions and the environment, and comparison of the analyzed scenarios provided critical insight into the desirability of specific policies regarding emission regulation from the transportation sector. Because leakages ended up having a greater effect on emissions than the implementation of a carbon policy, I emphasize alternative approaches and policies to address natural gas use in the transportation sector. Many of the complexities associated with different policies and expansion of my formulated model are left for future research.

Analysis of the Different Scenarios

The optimal scenario for reducing emissions in the transportation sector is under a carbon tax and 0% leakage. Because a carbon tax leads to a greater reduction in the use of more carbon-intensive fuels, without considering leakages, emissions under a carbon tax will be less than under no carbon policy (Pearce 1991). Davis and Kilian (2011) estimate the reduction in gasoline consumption in the U.S. to be 1.5% with a 10 cents/gallon carbon tax, which is similar to my findings of 1.4% under a carbon tax of 11 cents/gallon. However, because a carbon tax that does not account for methane leakages promotes cleaner carbon based fuels, for example natural gas, there may be scenarios in which its increased share in the transportation sector relative to gasoline causes greater total emissions due to the extreme potency of methane leakages.

As is pointed out in my Results section, I estimated the effect of an increase in leakage by 5% versus an implementation of a carbon tax on the increase and decrease in total emissions from the transportation sector, respectively, and was able to determine the magnitude of a "leakage effect" and "carbon tax effect." Under a carbon tax and 10% leakage, the overall CO_2 equivalent emissions generated by the transportation sector in 2020 (from natural gas use, gasoline use, and leakages) are 102.2 million tonnes. However, this level of emissions exceeds that of the scenario of 5% leakage and no carbon tax, which generates 101.5 million tonnes of CO_2 equivalent emissions. Similarly, the overall CO_2 equivalent emissions generated by the transportation sector in 2020 (from natural gas use, gasoline use, and leakages) are 99.4 million tonnes under a carbon tax and 5% leakage. However, this level of emissions exceeds that of the scenario of 0% leakage and no carbon tax, which generates 98.7 million tonnes of CO_2 equivalent emissions. This analysis suggests that a 5% increase in leakage generates more CO_2 equivalent emissions than is reduced by implementing a carbon tax.

Continuing this analysis, I mentioned previously that under no carbon policy, overall transportation sector emissions fell by 50% from 1997-2020, and by 52% under a carbon tax over this same period. With a leakage level of 5%, the change CO_2 equivalent emissions from 1997-2020 under no carbon policy was 50%, and under a carbon tax was approximately 50% as well. With a leakage of 10%, the change CO_2 equivalent emissions from 1997-2020 under no carbon policy was 50%, and under a carbon tax was approximately 48%. The 10% leakage scenario is especially compelling, and points out a very important phenomenon: because a carbon tax promotes natural gas due to the fact that it generates fewer CO_2 emissions per unit of energy burned than gasoline, with a high enough level of methane leakage a carbon tax actually increases overall CO_2 equivalent transportation sector emissions compared to no carbon policy because of the potency of methane leakage from natural gas use.

While I expected that the market share of natural gas in the transportation sector would not exceed 5% by 2020, it was surprising to find that the difference in market share between no carbon policy and a carbon tax was not greater. Several economic factors may explain this. First, natural gas infrastructure is minimal compared to that of gasoline. In 2011 the U.S. had 910 natural gas pump stations compared to 157,393 gasoline stations. Individuals place great importance on fuel pump accessibility, and if there are no natural gas fueling stations in reasonable proximity, it would be very inconvenient to own a natural gas vehicle (Yeh 2007). Additionally, natural gas prices in gallons of gasoline equivalent terms are extremely low compared to prices of gasoline; between 1997-2020 the average price of natural gas in gallons of gasoline equivalent terms is $1.22 compared to $3.10 for a gallon of gasoline. Thus, any policy, including a carbon tax, that increases the price of gasoline by relatively more than natural gas based on carbon content will likely have relatively little influence on a consumer’s decision to switch from a gasoline vehicle to a natural gas vehicle considering that they had not already done so under this large fuel price difference. Combining convenience of fuel pump accessibility and low natural gas prices, it is clear that there is a shadow price (an implicit price not observed in the actual price) for natural gas that is causing consumers to continue using gasoline instead of switching to natural gas. People implicitly value fuel pump location, the types of cars they are able to purchase (i.e. there are many fewer natural gas vehicle models than gasoline vehicle models), tank storage capacity (natural gas vehicles can not hold nearly the capacity that gasoline vehicles hold), and certainty about low prices for natural gas in the future (Deutch 2011).

Although natural gas is expected to have a relatively low market share in the transportation sector by 2020, the impact of leakages is quite substantial, and can be the difference in whether policy decisions, like a carbon tax, are successful in actually reducing emissions. It is possible that if second generation biofuel continues to remain costly and a CO_2 emissions tax is introduced to the U.S. transportation sector, natural gas could see an increase in market share, increasing the importance of these decisions. Awareness of methane leakages is a crucial part of this study, and if they cannot be controlled or new infrastructure is not introduced to limit them, natural gas may not be considered as a viable, "transition fuel" alternative to other fossil fuels (Weinhold 2012).

Policy Approaches

The introduction of a tax has been shown to be the optimal policy in addressing pollution externalities from natural gas and oil given that there is inelastic demand for these resources (Weitzman 1974). However, there are several alternative and complementary approaches that can achieve a more optimal emissions reduction when considering leakages. Mandates like the Renewable Fuels Standard (RFS) that determine a minimum amount of renewable and/or clean fuel that needs to be used by the transportation sector have proven to be effective in driving substitution (Rajagopal and Zilberman 2011). Policies promoting research and development of new technologies can also incentivize oil companies to invest in more natural gas fuel pumps and retail infrastructure and car companies to invest in more efficient natural gas vehicles (Shittu and Baker 2010).

There is a growing movement to introduce a carbon fee alternative to a carbon tax, which assigns different prices to different types of emissions based on their relative potencies as greenhouse gases (Murray, Mazurek, and Profeta 2011). If leakages can be measured accurately, this type of alternative will allow policy makers to assign a higher price to methane emissions from natural gas wells, thereby holding natural gas producers accountable for these more potent GHG emissions. Based on the results I've obtained using my estimation, under leakage scenarios greater than 5%, a carbon fee alternative policy may make natural gas more costly than oil because of the harsher penalty placed on methane emissions. However, quantitative analysis of the effect of a carbon fee alternative and how it may affect the exact cost comparison of natural gas to oil is beyond the scope of this study.

Limitations and Future Directions

Assessing the substitution of natural gas for oil in the transportation sector through 2020 required a robust econometric model and a great deal of data, yet, while this project was able to meet both of these requirements, there is still room to modify the model and incorporate additional data. Time was an important limiting factor in this analysis, and given the quantitative nature of this study, it was more valuable to focus on sending a clear message about natural gas leakages than it was to quantitatively address several different policy situations. Additionally, there are no concrete estimates on the aggregate level of leakage in the U.S., and thus I selected a large range (0% to 10%) to work with in my analysis. I was also limited by the fact that I could only use data from 1997-2011, as the data for my dependent variable, "Natural gas used as vehicle fuel" was only available as far back as 1997 (EIA 2011). My econometric model was very basic, and did not include interaction terms, additional parameters, non-linear trends in the variables, and did not address possible endogeneity among the variables. These complexities were not addressed for purposes of time and clarity, yet they may be considered in future research.

With the expansion of the model and access to more data, this same analysis can be used to extrapolate natural gas substitution further into the future. And with the addition of additional parameters, this model could more accurately estimate the extrapolated values of natural gas used as vehicle fuel through 2020 and beyond. Some of these parameters might include other measures of infrastructure for natural gas and oil, including number of pipelines, refining centers, and drilling wells (in the case of natural gas). Also, because the export of liquefied natural gas from the U.S. to other countries has a great deal of potential, it may be useful to include a count variable (i.e. a variable that takes a value of 0, 1, 2, etc. depending on what each value represents) depicting whether or not the U.S. and/or importing countries have trade restrictions on natural gas in place, if the importing countries have trade restrictions in place on natural gas, or both (Levi 2012). The model may also be expanded to engage in analysis that estimates the increased substitution of natural gas for coal considering different policy measures, and, in turn, estimating this effect on the reduction in GHG emissions from electricity used to fuel electric vehicles in the transportation sector. Increased certainty about leakages and ability to monitor methane emissions will also help refine my analysis of different scenarios.

Broader Implications

With such large projected increases in natural gas availability in the U.S. over the next decade or more, the importance of domestic energy security, environmental concerns, and cheap energy will determine its future in the U.S. and possibly globally (EIA 2011). The U.S. federal government has been considering implementing a national carbon policy for some time now, and the chances of doing so will only continue to increase. At the sate level, California has already implemented a cap and trade program. With a national carbon policy on the horizon, there is increasing awareness of the destructiveness of methane leakage emissions for our atmosphere (Weinhold 2012). However, despite leakages, natural gas can act as a much cleaner alternative to coal for producing electricity, and is already substituting for it in large amounts (Hayhoe et al. 2002). With increased diffusion of electric vehicles, natural gas may indirectly fuel a greater percentage of transportation through electricity production (Peterson, Whitacre, and Apt 2011). On the other hand, as this study has shown, natural gas substitution for oil will depend heavily on the types of carbon policies introduced, especially if they address methane emissions. And, as mentioned earlier, foreign demand may also drive exports from the U.S. to countries with increasing natural gas demand, like China, in the form of liquefied natural gas. (Lin, Zhang, and Gu 2010)

Assuming the introduction of a carbon fee alternative, the movement to push natural gas to substitute for oil in the transportation sector will rely heavily on technological improvements to control leakages (Wang and Huang 2000). If energy companies foresee a carbon fee alternative, investment in new transportation infrastructure to promote natural gas may be a poor choice if leakages cannot be effectively addressed. Climate change is a growing global concern, and if technological improvements cannot be made to control leakage, companies will likely continue to invest in electric vehicles or second generation biofuels for use in the transportation sector. Increased certainty about leakage levels and monitoring and enforcement of policies to control them will spell the future for natural gas as a viable energy source for the United States as it moves towards cleaner and more sustainable energy.

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Kurt Spreyer, my thesis advisor, was essential to the construction and motivation behind my thesis. Our meetings were always extremely productive and his insight and questions helped me develop and refine the ideas I have presented here. Patina Mendez’s guidance as a lecturer was critical in my idea development as well. David Zilberman, my faculty mentor, was critical in helping me overcome obstacles and clarify my ideas and provided continuous inspiration. Gal Hochman of Rutgers University was also a fantastic advisor in helping me develop and work through my ideas. My work group, the GHGEs, was always supportive and their feedback was always very helpful. My friends have provided constant support and conversations with them have helped me to refine my ideas and think about them more critically. My parents and grandparents have been supportive throughout my four years at Cal and my undergraduate education would not have been possible without them.

REFERENCES

Allen, D. T., V. M. Torres, J. Thomas, D. W. Sullivan, M. Harrison, A. Hendler, S. C. Herndon et al. 2013. Measurements of methane emissions at natural gas production sites in the United States. Proceedings of the National Academy of Sciences 110:17768-17773.

Alvarez, R. A., S. W. Pacala, J. J. Winebrake, W. L. Chameides, and S. P. Hamburg. 2012. Greater focus needed on methane leakage from natural gas infrastructure. Proceedings of the National Academy of Sciences 109:6435-6440.

Brons, M., P. Nijkamp, E. Pels, and P. Rietveld. 2008. A meta-analysis of the price elasticity of gasoline demand: A SUR approach. Energy Economics 30.

Chakravorty, U., J. Roumasset, and K. Tse. 1997. Endogenous substitution among energy resources and global warming. Journal of Political Economy 105:1201-1234.

Considine, T., R. Watson, R. Entler, and J. Sparks. 2009. An emerging giant: Prospects and economic impacts of developing the Marcellus shale natural gas play. The Pennsylvania State University, Dept. of Energy and Mineral Engineering 39.

Davis, L. 2013. The economic cost of global fuel subsidies. Energy Institute at Haas Working Paper Series.

Davis, L. W., and L. Kilian. 2011. Estimating the effect of a gasoline tax on carbon emissions. Journal of Applied Econometrics 26:1187-1214.

Deutch, J. 2011. Good news about gas-the natural gas revolution and its consequences. Foreign Affairs 90:82-93.

Energy Information Administration (EIA), US. 2011. International energy outlook 2011. US Energy Information Administration.

Ellerman, A. D., and B. K. Buchner. 2007. The European Union emissions trading scheme: Origins, allocation, and early results." Review of Environmental Economics and Policy 1:66–87.

Hartley, P. R., K. B. Medlock III, and J. E. Rosthal. 2012. The relationship of natural gas to oil prices. The Energy Journal 29:47-66.

Hayhoe, K., H. S. Kheshgi, A. K. Jain, and D. J. Wuebbles. 2002. Substitution of natural gas for coal: climatic effects of utility sector emissions. Climatic Change 54:107-139.

Hekkert, M. P., F. Hendriks, A. Faaij, and M. L. Neelis. 2005. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. Energy Policy 33:579-594.

Hotelling, H. 1931. The economics of exhaustible resources. The Journal of Political Economy 39:137-175.

Hughes, J. E., C. R. Knittel, and D. Sperling. 2006. Evidence of a shift in the short-run price elasticity of gasoline demand. Working paper no. w12530. National Bureau of Economic Research.

Kargbo, D. M., R.G. Wilhelm, and D.J. Campbell. 2010. Natural gas plays in the Marcellus shale: Challenges and potential opportunities. Environmental Science & Technology 44:5679-5684.

Karion, A., C. Sweeney, G. Pétron, G. Frost, R. M. Hardesty, J. Kofler, B. R. Miller et al. 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophysical Research Letters 40:4393-4397.

Knittel, C. R. 2012. Reducing petroleum consumption from transportation. National Bureau of Economic Research.

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

Levi, M. A. 2012. A Strategy for US Natural Gas Exports. Hamilton Project, Brookings Institution.

Lin, W., N. Zhang, and A. Gu. 2010. LNG (liquefied natural gas): a necessary part in China's future energy infrastructure." Energy 35:4383-4391.

Logan, J., G. Heath, J. Macknick, E. Paranhos, W. Boyd, and K. Carlson. 2012. Natural gas and the transformation of the US energy sector: Electricity. National Renewable Energy Laboratory (NREL), Golden, CO.

Metcalf, G. E. 2009. Market-based policy options to control US greenhouse gas emissions. Journal of Economic Perspectives 23:5–27.

Miller, S. M., S. C. Wofsy, A. M. Michalak, E. A. Kort, A. E. Andrews, S. C. Biraud, E. J. Dlugokencky et al. 2013. Anthropogenic emissions of methane in the United States. Proceedings of the National Academy of Sciences 110:20018-20022.

Montgomery, S. L., D. M. Jarvie, K. A. Bowker, and R. M. Pollastro. 2005. Mississippian Barnett Shale, Fort Worth Basin, North-central Texas: Gas-shale play with multi–trillion cubic foot potential.” AAPG Bulletin 89:155–175.

Murray, B. C., J. V. Mazurek, and T. H. Profeta. 2011. Examination of the carbon fee alternative for the state of California. Nicholas Institute, Duke University Working Paper.

Park, J., P. Gordon, and F. Aminzadeh. 2013. Macroeconomic impacts of developing the Monterey Shale using advanced-extraction technology. The Monterey Shale & California’s Economic Future 25.

Parry, Martin L., ed. 2007. *Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Vol. 4. Cambridge University Press.

Pearce, D. 1991. The role of carbon taxes in adjusting to global warming. The economic journal 938-948.

Peterson, S. B., J. F. Whitacre, and J. Apt. 2011. Net air emissions from electric vehicles: The effect of carbon price and charging strategies. Environmental science & technology 45:1792-1797.

Pirog, R., and M. Ratner. 2012. Natural gas in the US economy: Opportunities for growth. Congressional Research Service: A Report Prepared for Members and Committees of Congress.

Rajagopal, D., G. Hochman, and D. Zilberman. 2011. Multicriteria comparison of fuel policies: Renewable fuel standards, clean fuel standards, and fuel GHG tax. UC Center for Energy and Environmental Economics.

Shittu, E., and E. Baker. 2010. Optimal energy R&D portfolio investments in response to a carbon tax. Engineering Management, IEEE Transactions 57:547-559.

US Environmental Protection Agency (EPA). 2013. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2011. Environmental Protection Agency, Washington, DC. EPA 430-R-13-001.

Wang, M., and H. Huang. 2000. A full fuel-cycle analysis of energy and emissions impacts of transportation fuels produced from natural gas. No. ANL/ESD--40. Argonne National Lab., Illinois, United States.

Weinhold, B. 2012. The future of fracking: new rules target air emissions for cleaner natural gas production. Environmental health perspectives 120:a272.

Weitzman, M. L. 1974. Prices vs. quantities. The review of economic studies 41:477-491.

Yeh, S. 2007. An empirical analysis on the adoption of alternative fuel vehicles: the case of natural gas vehicles. Energy Policy 35:5865-5875.

APPENDIX A: Independent Variable Trends and Extrapolations through 2020

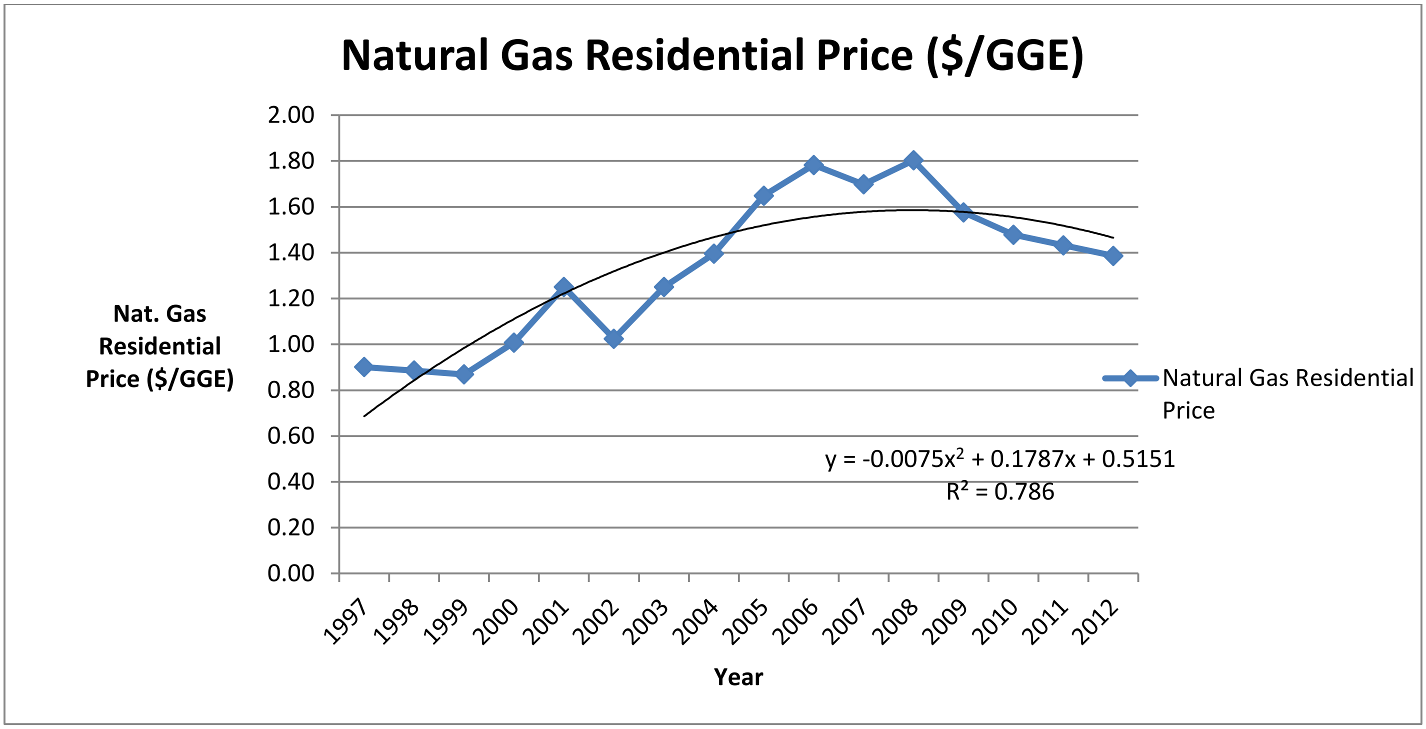

Figure A1: Natural gas residential price in the U.S. from 1997-2012 and the associated quadratic trend.

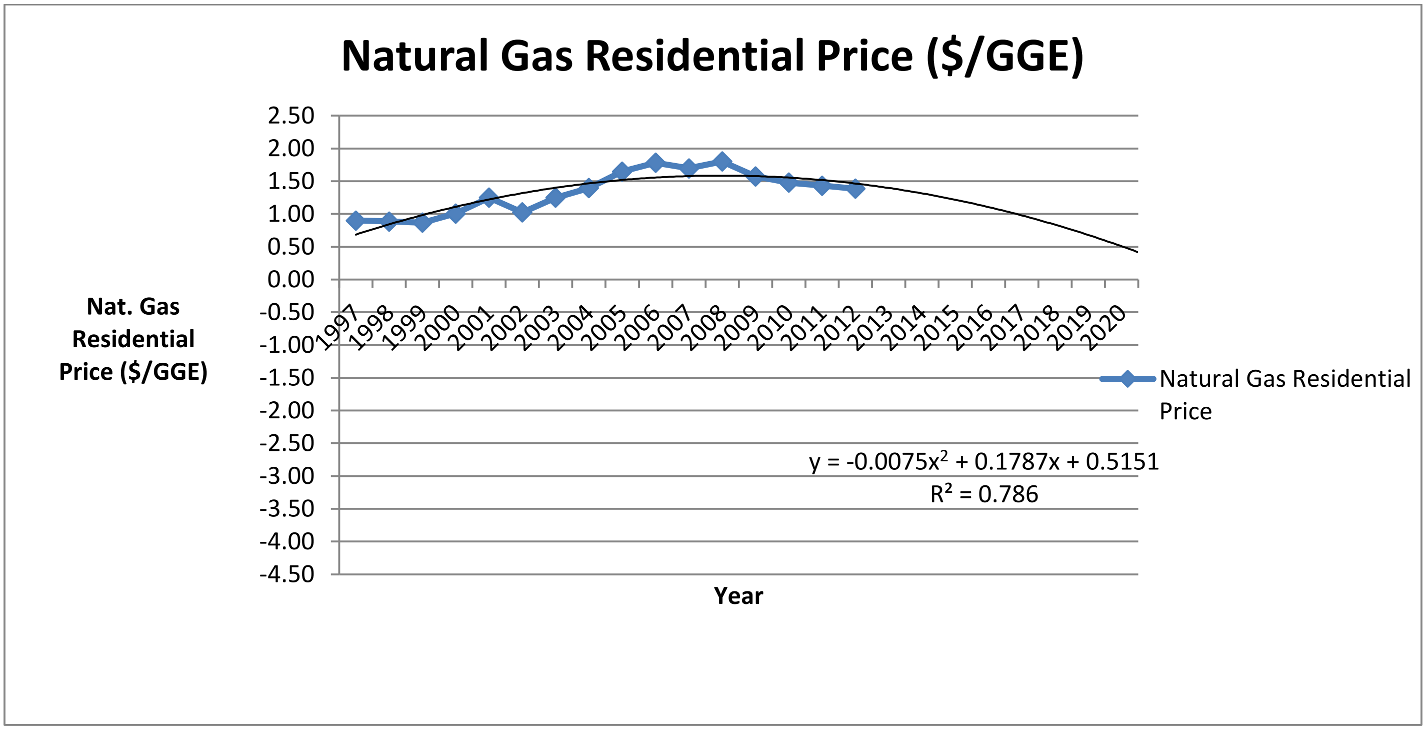

Figure A2: Natural gas residential price in the U.S. from 1997-2020 using extrapolated quadratic trend.

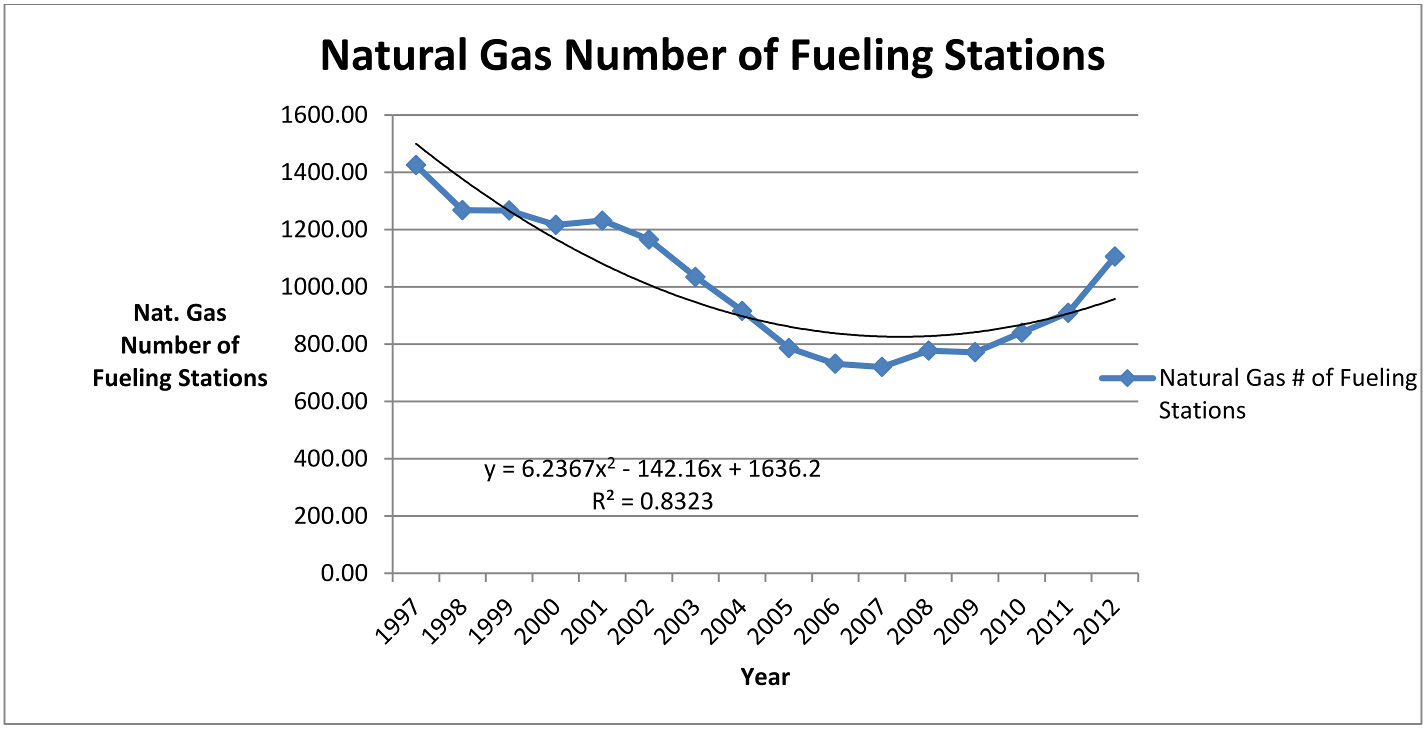

Figure A3: Total natural gas fueling stations in the U.S. from 1997-2012 and the associated quadratic trend.

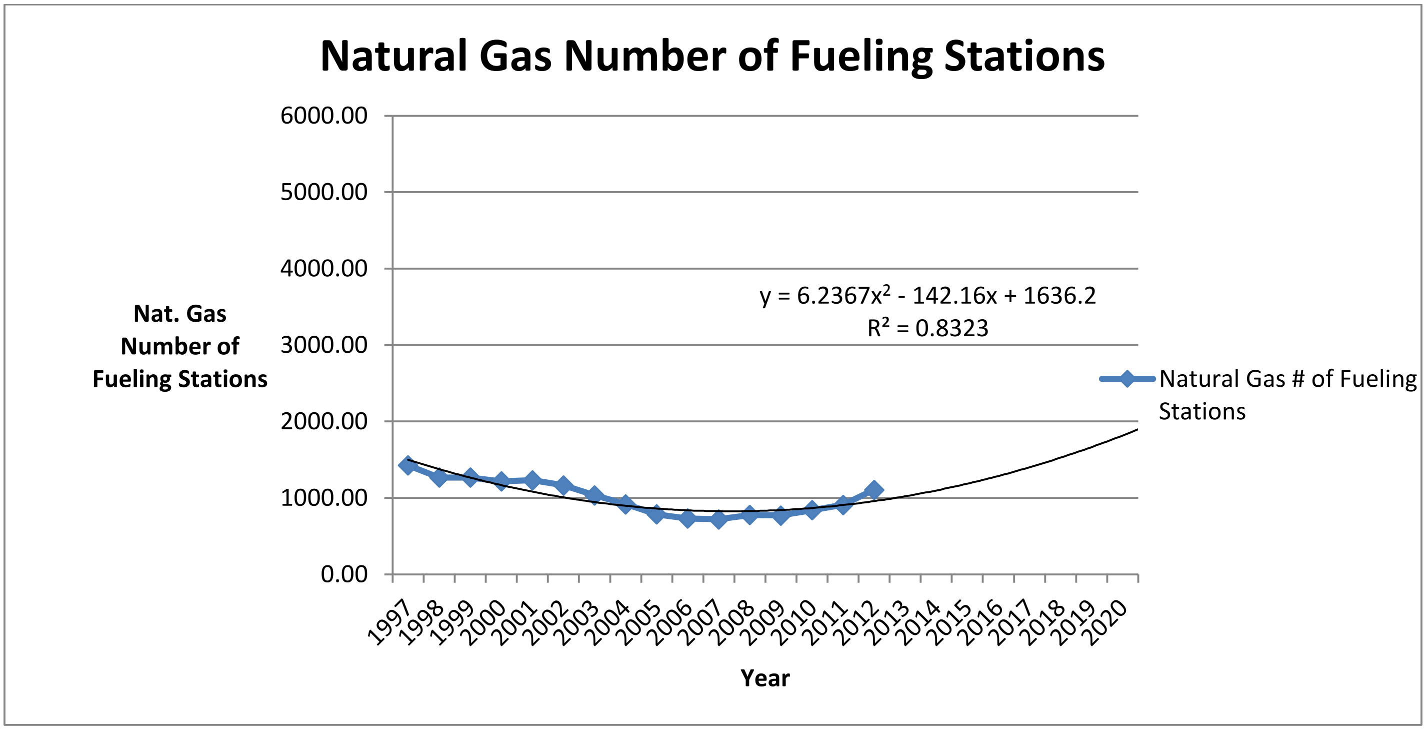

Figure A4: Total natural gas fueling stations in the U.S. from 1997-2020 using extrapolated quadratic trend.

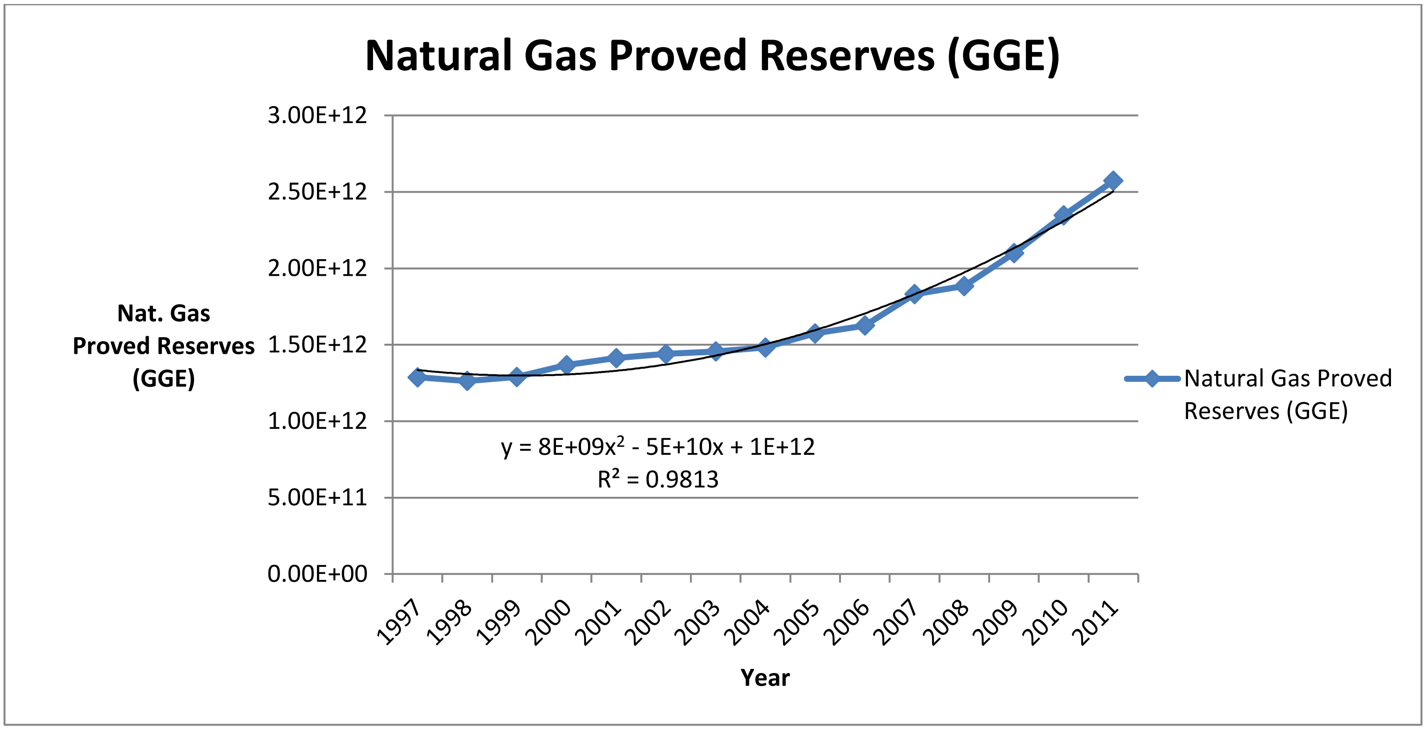

Figure A5: Total natural gas proved reserves in GGE in the U.S. from 1997-2012 and the associated quadratic trend.

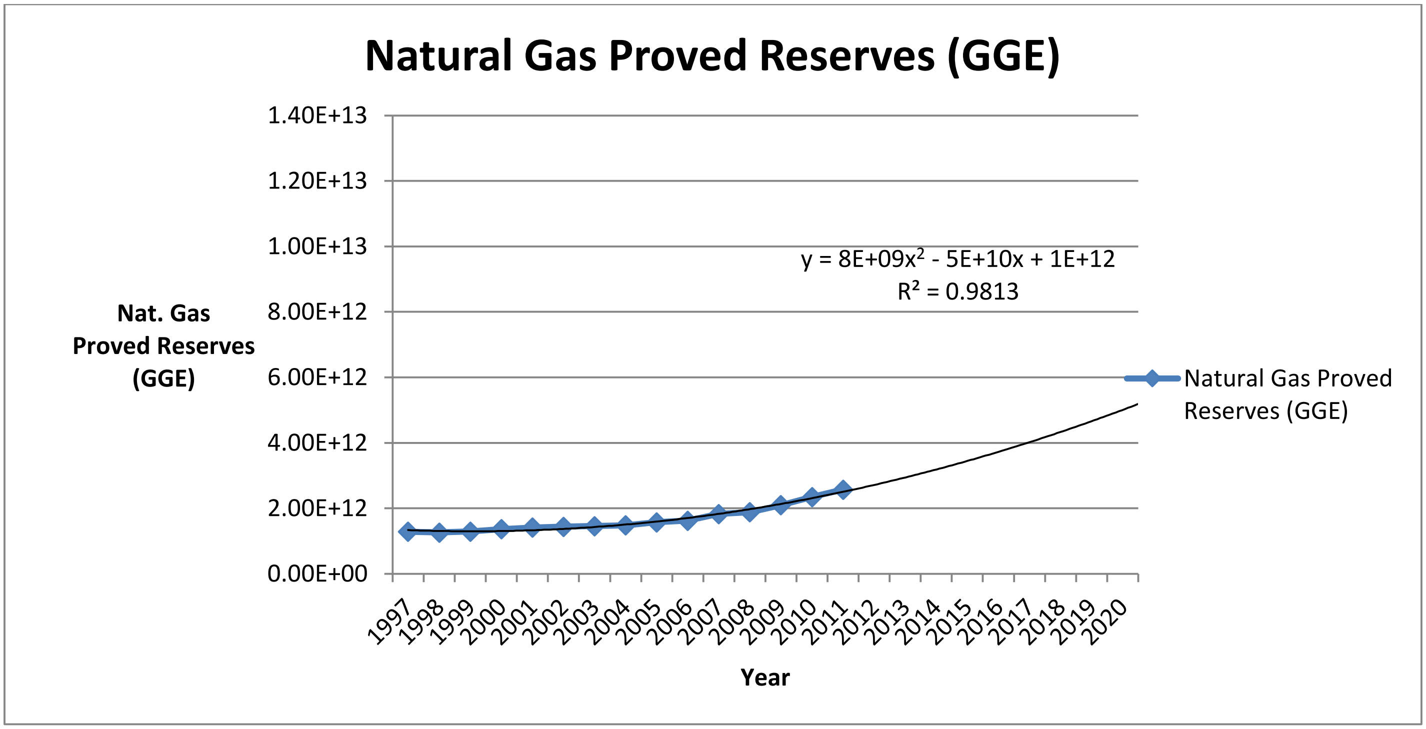

Figure A6: Total natural gas proved reserves in GGE in the U.S. from 1997-2020 using extrapolated quadratic trend.

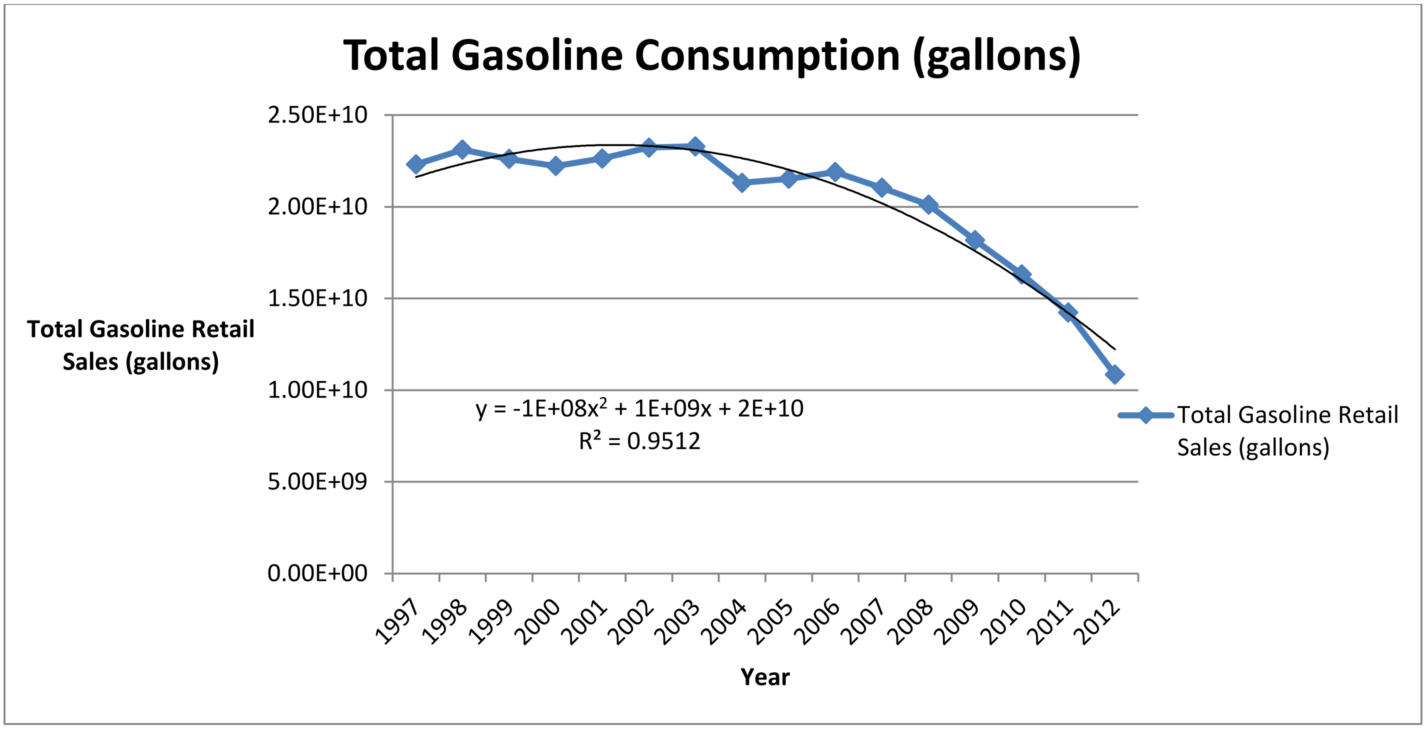

Figure A7: Total gasoline consumption in gallons in the U.S. from 1997-2012 and the associated quadratic trend.

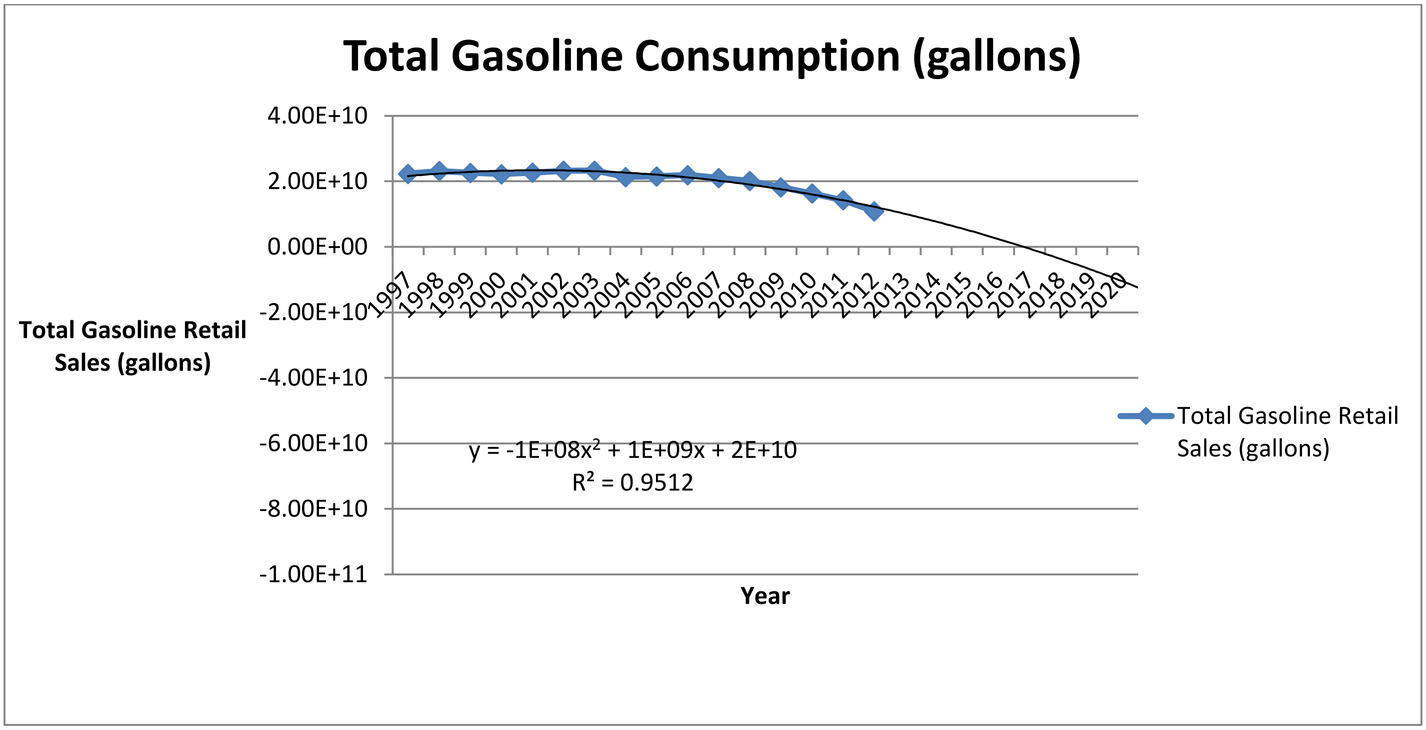

Figure A8: Total gasoline consumption in gallons in the U.S. from 1997-2020 using extrapolated quadratic trend.

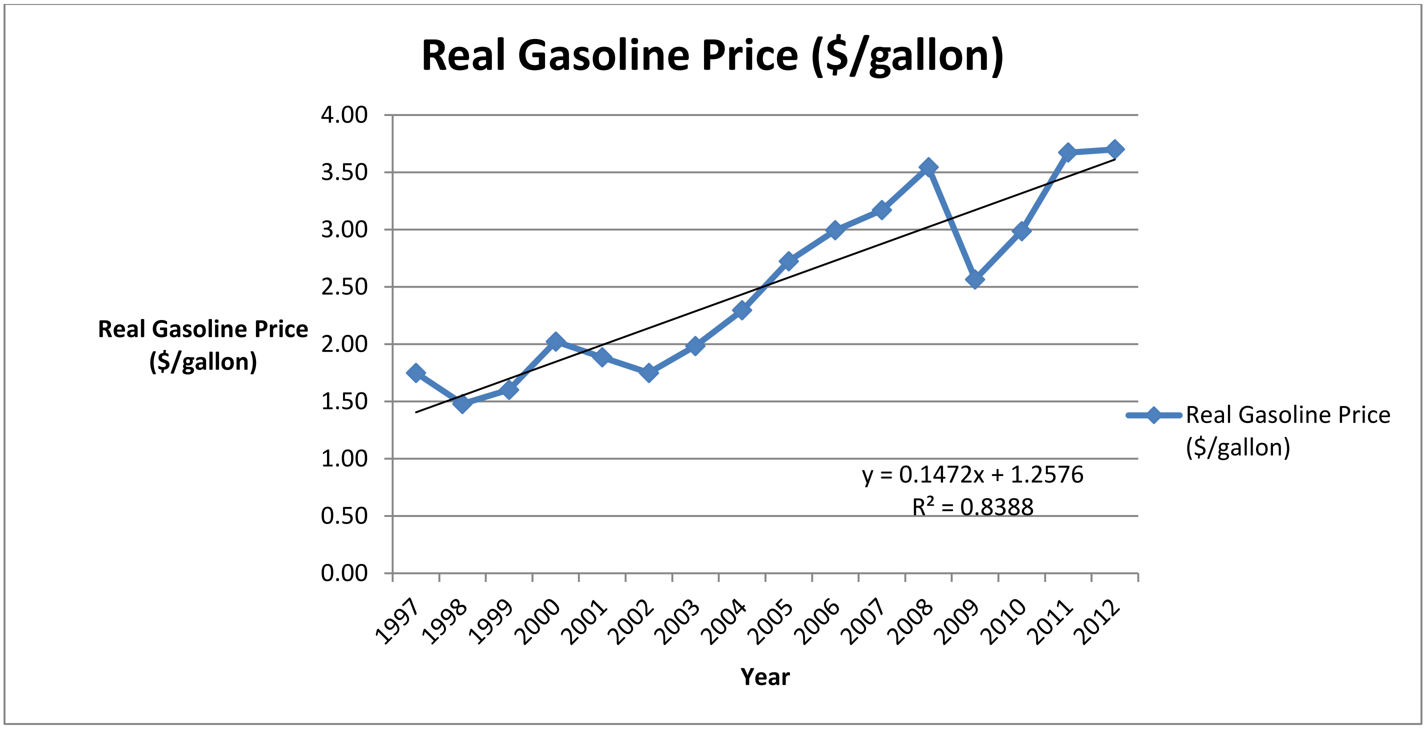

Figure A9: Gasoline price in the U.S. from 1997-2012 and the associated linear trend.

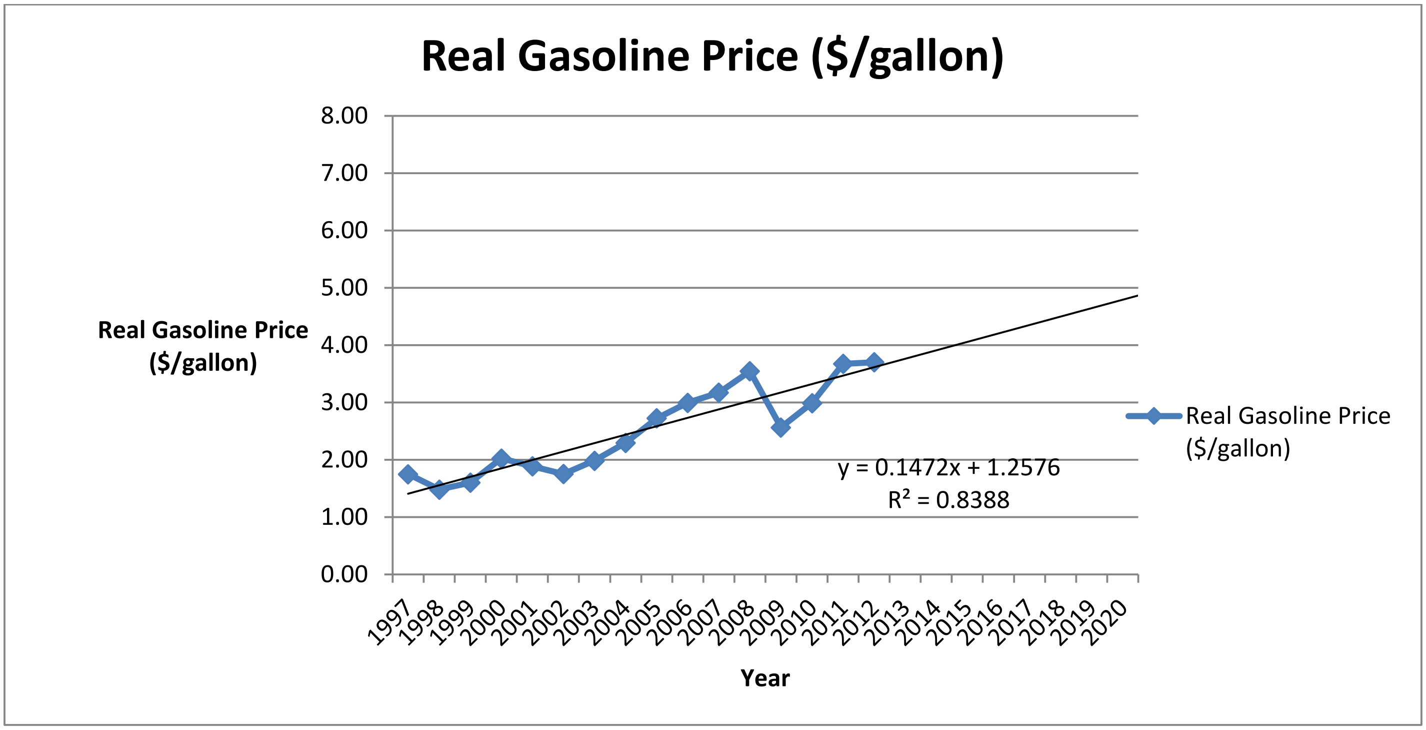

Figure A10: Gasoline price in the U.S. from 1997-2020 using extrapolated linear trend.

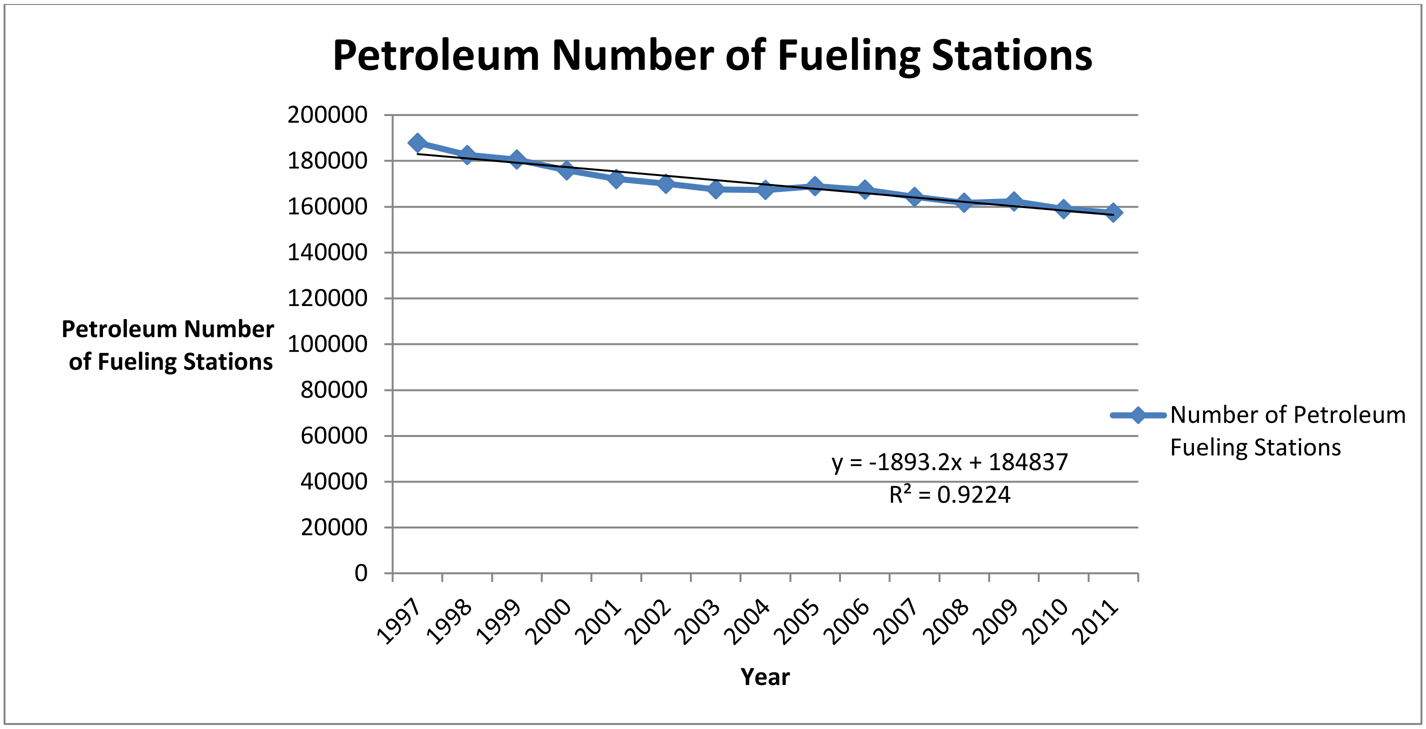

Figure A11: Total number of gasoline stations in the U.S. from 1997-2012 and the associated linear trend.

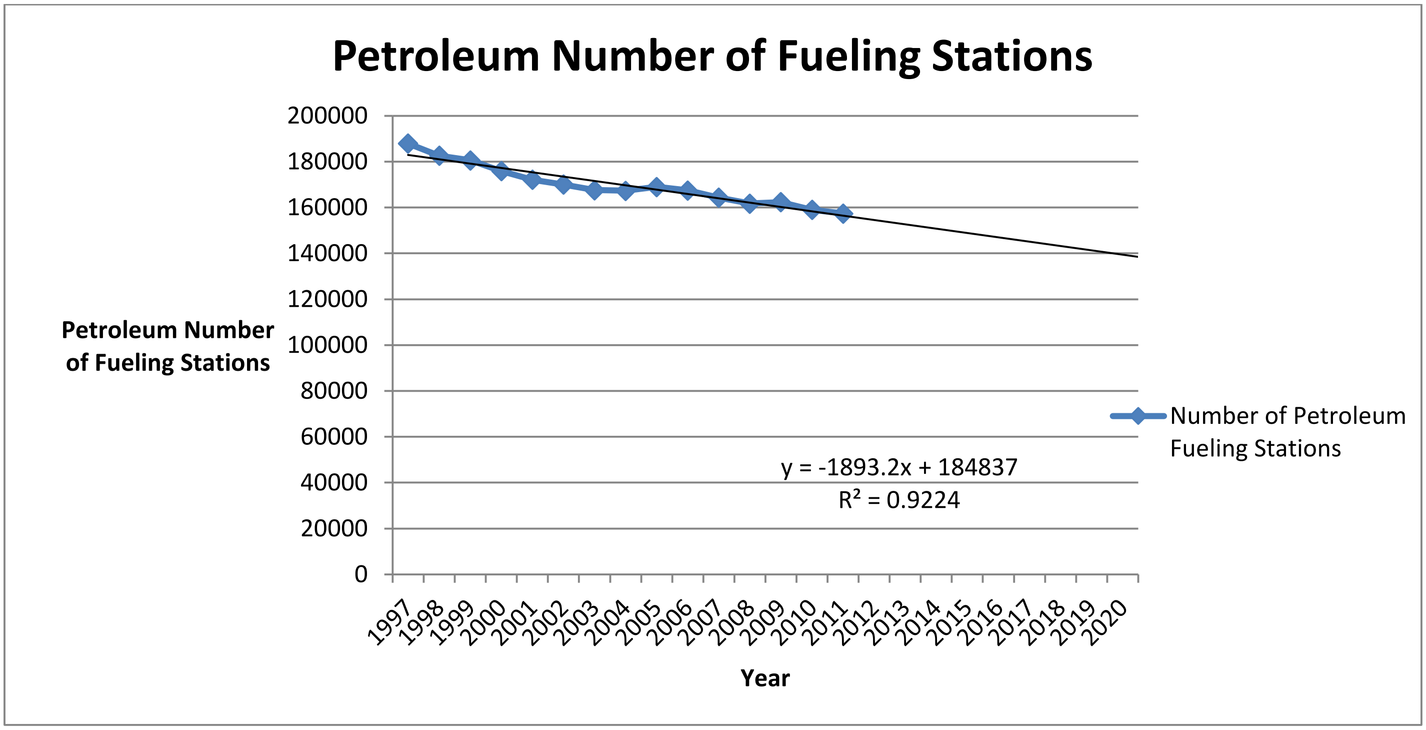

Figure A12: Total number of gasoline stations in the U.S. from 1997-2020 using extrapolated linear trend.