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The Producer Surplus Associated with Gasoline Fuel Use in the United States¹

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Abstract

Estimating the producer surplus – the revenue above the average long-run cost – is an important part of social cost-benefit analyses of changes in petroleum use. This paper estimates the producer surplus associated with changes in gasoline fuel use in the United States, and then applies the estimates of producer surplus to two kinds of social cost-benefit analyses related to petroleum use: (1) estimating the wealth transfer from consumers to producers as a result of policies that affect oil use and oil imports to the US, and (2) comparing the actual average cost of gasoline with the average cost of environmentally superior alternatives to gasoline, such as hydrogen. Our results show that a 50% reduction in gasoline use in the US in 2004 would have saved the US \$72 billion in producer surplus payments to foreign oil producers. Applying our estimates to the comparison of the social lifetime cost of hydrogen vehicles versus gasoline vehicles, we find that inconsistently counting producer surplus from a US national perspective while counting climate change damages from a global perspective can overstate the present value lifetime costs of gasoline vehicles by \$2,200 to \$9,800 per vehicle.

JEL codes: Q41, Q43

Keywords: oil, marginal costs, producer surplus, gasoline, wealth transfer, drilling costs, exploratory wells, development wells

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1. Introduction

Estimating the producer surplus – the revenue above the long-run average cost – is an important part of social cost-benefit analyses of changes in petroleum use. This paper estimates the producer surplus associated with changes in gasoline fuel use in the United States, and then applies the estimates of producer surplus to two kinds of social cost-benefit analyses related to petroleum use: (1) estimating the wealth transfer from consumers to producers as a result of policies that affect oil use and oil importing in the US, and (2) comparing the actual average cost of gasoline (where the average cost is the observed price minus the estimated fraction of price that is producer surplus) with the average cost of environmentally superior alternatives to gasoline, such as hydrogen.

The first use of estimates of producer surplus in social cost-benefit analyses is to estimate wealth transfers as a result of policies affecting US oil use. Estimates of the producer surplus for gasoline can be used to better understand wealth transfers from oil consumers to oil producers, as part of an analysis of the total costs and benefits to the US of policies related to oil use and oil imports. The total producer surplus change is a measure of the wealth transfer from consumers to producers. We designate the producer surplus change as ΔPS_t , where t stands for “transfer”. To estimate the transfer of wealth associated with oil use, we estimate the change in total producer surplus associated with different levels of reduction of oil supply. This change in total producer surplus has two parts: one due to the change in consumption, and the other due to the change in price. We estimate both of these formally.

The second use of estimates of producer surplus in social cost-benefit analyses is to estimate the average cost of gasoline in cost-benefit analyses of transportation fuel policies. Owing in part to the environmental, economic and security concerns related to oil consumption and to concerns about the economic impact of high oil prices, there is considerable interest in understanding the social costs and benefits of policies that reduce gasoline use, especially policies that promote non-petroleum alternative transportation fuels. Estimates of the producer surplus fraction for gasoline can be used to estimate the average cost of gasoline in social cost-benefit comparisons of various transportation fuels, as well as in social cost-benefit analyses of other policies that reduces petroleum consumption, such as fuel economy improvements,

carbon taxes, or the substitution of alternative fuels. We designate the producer surplus fraction of revenues as PSf_{ac} , where ac stands for “average cost”.

Since cost-benefit analyses are concerned with real resource costs, the relevant measure of resource cost is the average cost, not price. However, while we can observe price, we cannot observe average cost directly, and if we have reason to believe that there is a large difference between observed price and average cost – for example, because oil-rich countries appear to accumulate great wealth, suggesting that their (price-times-quantity) revenue far exceeds their (average) cost – then it is important to estimate average cost explicitly rather than use price as a proxy for average cost.

Consider the case of comparing the costs and benefits of transportation fuels. Under the assumption that all transportation fuel options (including petroleum) offer the same non-cost vehicle amenities (performance, cargo capacity, etc.), and therefore have the same social benefits, these alternatives can be compared strictly on the basis of social cost. The social lifetime cost includes the cost of vehicles, the cost of fuel, and external costs such as air pollution damages, climate change impacts, noise, and oil security. Fuel (or resource) cost estimates can be made for non-petroleum fuels using engineering-economic models, but this is problematic for gasoline, because such detailed but generalizable engineering cost data are difficult to obtain. Instead, to estimate the average cost of gasoline, in a social cost-benefit comparison of gasoline with alternative non-petroleum fuels, we first estimate the producer surplus fraction of total price-times-quantity payments for different levels of reduction in the supply of gasoline, and then calculate gasoline average cost as the price minus the producer surplus fraction of price.

For both of these cost-benefit analysis examples, we estimate the producer surplus for US petroleum refiners, the producer surplus for US oil producers, the producer surplus for the Organization of Petroleum Exporting Countries (OPEC), and the producer surplus for producers in the rest of the world (ROW). We do this for current and future oil supply.

We pursue the following research questions. First, how can we use existing data to estimate gasoline cost curves? Second, what is the historical production cost for gasoline? Third, what is the producer surplus fraction for gasoline, historically and projected into the future? Fourth, what is the total producer surplus change, in the US, and abroad, associated with

petroleum use reduction? And finally, what does this imply about the future competitiveness of alternative fuels compared to gasoline and about their wealth transfers?

According to our results, both kinds of producer surplus estimates depend on the size of the reduction in oil use and the year and region for which oil cost curves are estimated. We estimate that if demand for gasoline in the US in 2004 had contracted by 10% (50%), then the change in producer surplus in the US refinery and US oil industry would have been \$15.2 (\$31.63) billion, or \$4.84 (\$1.86) per gallon of gasoline, and the producer surplus fraction of revenues would have been 31.89% (49.03%). The change in producer surplus for gasoline made from imported oil would have been greater – \$5.48/gallon for a 10% contraction and \$2.28/gal for a 50% contraction – because foreign producers have much lower average production cost. In fact, a 50% reduction in gasoline use in the US in 2004 would have saved the US \$72 billion in producer surplus payments to foreign oil producers. Applying our estimates to the comparison of the social lifetime cost of hydrogen vehicles versus gasoline vehicles, we find that inconsistently counting producer surplus from a US national perspective while counting climate change damages from a global perspective can overstate the present value lifetime costs of gasoline vehicles by \$2,200 to \$9,800 per vehicle.

We organize the paper as follows: Section 2 presents a detailed discussion of the producer surplus concept. Section 3 reviews the previous literature. Section 4 describes the general method of analysis, and summarizes the detailed analysis, including data and methods used for constructing oil and gasoline cost curves, that are detailed in Appendix C. Section 5 analyzes the results, and Section 6 illustrates the use of estimates of producer surplus in an analysis of the changes in transfer of wealth from the US to foreign oil producers as a result of US oil conservation policies and in an analysis of the social cost of gasoline versus hydrogen. Section 7 concludes the paper.

2. Producer Surplus

The total revenue a producer receives from selling a good in the market is the market price of the good times the quantity of the good sold. The total revenue comprises two parts: producer surplus and total cost. Producer surplus is the area above the producer's marginal cost

curve and below the price, and which measures the revenue, above and beyond cost, that a producer receives for selling a good in the market. The shaded area in Figure 1 indicates the producer surplus in an imperfectly competitive market for some firm with marginal cost MC_0 below market price P_0 . We use an imperfectly competitive market in our illustration here because this better characterizes the world oil market, but, as we discuss below, producer surplus exists in perfectly competitive markets as well. The second part of the total revenue is the cost to the producers of producing the good, or the area under the long-run marginal cost curve, and represents the resource cost of producing the good.

Note that for any price, cost curve, and quantity, as in Figure 1, there is an average cost line that gives the same producer surplus and total cost. When we refer to average cost in this paper, we mean the average cost that gives the same producer surplus and total cost as does the actual cost curve. Note also that we speak interchangeably of subtracting producer surplus from price-times-quantity revenues and subtracting from price the fraction of price that is producer surplus, because the fraction of price that is the producer surplus is equal to the ratio of producer surplus over price-times-quantity revenues. Note also that because the world oil market is not perfectly competitive, the supply curve is not necessarily the same as the long-run marginal cost curve.

The producer surplus is a wealth transfer from consumers to producers within the society, not an economic cost. When alternative fuels are compared using a social cost-benefit analysis, the comparison should be based on their long-run marginal cost curve, or average cost, and producer surplus should be viewed as a social transfer instead of a cost and therefore should not “count” as a social cost.

To clarify the importance of comparing alternatives on the basis of economic cost (and hence of subtracting producer surplus from revenues), we use the following example. Table 1 presents a case with two fuel types I and II produced by two different firms A and B, respectively. Suppose markets for both fuels are perfectly competitive in long-run equilibrium with no market failures or any externalities, and they provide the user identical benefits. The only difference is in the production cost, which is \$20/MBTU for Firm A and \$40/MBTU for Firm B. The difference is that firm A is endowed with large reserves of fuel I that can be recovered easily with little effort; specifically, the labor requirement by firm A is only half of

that by firm B for the same production level. It is clear that society prefers fuel I because it has lower social resource cost for the same level of benefits. However, for our cost-benefit analysis to reflect this, we either must estimate the long-run marginal cost curve (or average cost) directly (from the “bottom up,” based on the amount and cost of individual inputs), or else subtract the producer surplus from the price-times-quantity revenues.

In imperfectly competitive markets such as the oil market, the concentration of low-cost resources in a handful of countries and the oligopolistic nature of the market enable the producers to affect prices by controlling output. Oil suppliers produce less oil than they would under perfect competition and as a result the oil market price can exceed marginal cost. As a consequence producers can have a rate of return greater than the normal rate of return.

In contrast, in a perfectly competitive market the competition in the industry would drive the market to a long-run equilibrium in which price would equal marginal cost. Thus each firm would earn the normal rate of return and zero economic profit. However, even in perfect competition owners of low-cost oil resources still would receive producer surplus as economic rent.

The following is an example to illustrate these economic concepts.² Suppose an oil producer owns a parcel of an oil field. The total revenue from selling oil from the field is \$75M, in an imperfect market, and the only input is capital (no labor). The producer could earn \$30M if she invests the capital into the next best business; hence, the capital cost – which in this case is the total economic cost – is \$30M. The producer surplus is the total revenue less the economic cost: $\$75\text{M} - \$30\text{M} = \$45\text{M}$.

Now, assume the revenue would be \$65M if the market were perfect. Thus the economic rent associated with the land is $\$65\text{M} - \$30\text{M} = \$35\text{M}$. The economic profit is $\$75\text{M} - \$65\text{M} = \$10\text{M}$ (the difference between the actual revenue and the revenue that would be were the market perfect).

It is important to note that in a competitive market economic profit is zero in the long-run equilibrium but producer surplus generally is not zero. Producer surplus comprises economic profit and economic rent (see Figure A1 of Appendix A), and in a competitive market

² For a definition of some terms related to producer surplus, see Table A1 and Figure A1, both in Appendix A.

there is only normal profit, not economic profit, but generally there is economic rent. The amount of economic rent is determined by the relationship between average cost and the competitive market price; the lower the average cost relative to the competitive price, the greater the economic rent and the greater the producer surplus. The average cost will be relatively low if many producers are endowed with low-cost resources and hence have low economic cost, and if a handful of “marginal” producers have high long-run marginal costs and determine the relatively high competitive market price. This is precisely the situation in the oil industry, where there is a large difference between the low cost of producing oil from a giant field in Saudi Arabia and the high cost of producing low quality oil from deepwater wells. On top of this large economic rent, oil producers also enjoy economic profit, because the oil market is not competitive, and this adds to oil industry producer surplus.

It also is useful to examine economic rent more closely, to understand why it is a transfer between consumers and producers, or between producers, and not a net economic cost to society. The abundant and cheap petroleum resources (oil rights) for those countries originally endowed with the low-cost oil are valuable and other entities would be willing to pay for them. In a competitive market with competitive bidding, the maximum amount that other entities would be willing to pay for these rights to low-cost oil is the difference between the market price and the average economic production cost (including normal profit). The firms buying these oil rights would count this maximum payment as a cost. However, this cost is just a transfer payment to the original owners of the low-cost oil, for whom the payment is economic rent above their actual economic cost. Thus, economic rent, even when accounted as a “cost” by firms paying for the oil rights, is just a transfer payment, and not a real economic (resource) cost the way drilling costs are.

From a global perspective, producer surplus is a transfer from consumers to producers, and the location of the consumers and producers does not matter. However, if one conducts a social cost-benefit analysis for a particular country (e.g., the US), then one does not count the welfare of consumers or producers outside of that country. In this case, a producer surplus transfer from domestic consumers to foreign producers is in fact a real wealth loss for the country in question, because the welfare of foreign producers is not counted in a country-specific analysis and as a result the loss to consumers is not balanced by a gain to producers.

Estimating the producer surplus is therefore an important part of social cost-benefit analyses of changes in petroleum use. This paper estimates the producer surplus associated with changes in gasoline fuel use in the United States, and then applies the estimates of producer surplus in two kinds of social cost-benefit analyses related to petroleum use: (1) estimating the wealth transfer from consumers to producers as a result of policies that affect oil use and oil importing in the US, and (2) comparing the actual average cost of gasoline (where the average cost is the observed price minus the estimated fraction of price that is producer surplus) with the average cost of environmentally superior alternatives to gasoline, such as hydrogen.

3. Literature Review

In this section, we review studies that are relevant to our general method of analysis, including studies of oil production cost, factors that affect oil supply cost according to theory, oil supply projection, and the estimation of producer surplus generally.

Biedermann (1961) estimates a cost function for crude oil production based on empirical data, considering three major factors that affect the cost of getting crude oil from the reservoir to the top of well: drilling costs, well operating costs and the cost of physical waste and depletion. The US average drilling cost per well and average depth per well in 1953 are fitted with a quadratic function. Linear cost-output relationships within certain limits are assumed for well operating costs for both short-run and long-run considerations. Depletion and waste costs are modeled as a function of production rate, exploitation rate, expected oil price, reservoir (or oil field) lifetime and interest rate. A hypothetical relationship is assumed between exploitation rate and production rate, which is only valid for a given production mechanism under certain geological conditions of a reservoir.

Cleveland (1991) argues that two opposing forces -- technical change and resource depletion -- determine the long-run average cost of oil discovery and production. A U-shaped cost path hypothesis is empirically tested with the lower 48 US data from 1936 to 1988 on the quantity and dollar cost of oil added to reserves and oil extracted.

Chakravorty et al. (1997) estimate the extraction cost for energy resources as a

nonlinear function of cumulative extraction and analyze the effects of technological change in cost reductions for the backstop technology for resource extraction.

Stock effects and technological progress are further examined by Lin and Wagner (2007), who extend the Hotelling model (Hotelling, 1931) of optimal resource extraction and find that in order for market prices to be constant and consistent with the empirical observation that the growth rates of market prices have remained zero over a long period of time, the ratio of technological progress to the stock effect must exactly offset the exogenous growth in demand.

Aguilera (2014) reviews several methods for assessing current and long-term production costs of petroleum. For the cumulative availability curve showing total costs and total future volume, the shape is determined by geological factors and the curvature by demographics. Changes in technology and input costs cause the curve to shift over time. The author emphasizes that projections of long-term petroleum production cost should account for the cost-reducing effects of improved technology versus the cost-increasing effects of depletion. The study suggests that “producers are capable of developing the technologies needed to offset the cost rises.”

Shell’s scenario analysis for possible oil and gas futures (Bentham, 2014) stresses that political and societal choices are also important besides resources and technology to achieve a balance of positive features in the future. In a study on petroleum resources of the Middle East and North Africa, Khatib (2014) further confirms the complexity for oil and natural gas prospects due to region-specific factors.

Forecasts of future oil production involve great uncertainties. Jakobsson et al. (2014) indicate that bottom-up models would help to identify areas of uncertainties and new research questions though modeling challenges exist.

EIA uses its NEMS model (EIA, 2010, 2010a, 2010b) to project the world oil price and crude-like liquids supply with regional detail by simulating the interaction between US and global petroleum markets. Uniform supply and demand functions with constant elasticity are employed to model the market equilibrium with assumptions on economic growth and expectations of future US and world crude-like liquids production and consumption. Within NEMS, the Oil and Gas Supply Module (OGSM) projects US crude oil and national gas

production based on forecasted profitability to explore and develop wells for each region and fuel type. For crude oil, drilling and equipping costs per well are modeled as a polynomial function of well depth. The NEMS model makes various assumptions to model each of the many components of cost separately, including cost of chemical handling plant, lifting costs, secondary workover, etc. It also models the number of patterns drilled each year, which requires additional assumptions. In contrast, the model presented in our paper is more parsimonious and requires fewer assumptions than does the NEMS method.

To estimate the producer surplus fraction of payments for gasoline fuel, Delucchi (2004) characterizes the long-run marginal cost curve with a nonlinear function developed by Leiby (1993) for US oil producers, OPEC, and the rest of the world. From Leiby's estimates for three parameters (lower oil price limit, upper bound on supplies, and curve shape) for US oil producers, producer surplus is about 40% of price-times-quantity revenues. For the downstream producers (refiners and marketers), Delucchi assumes that 20% to 30% of pre-tax retail cost of gasoline fuel and diesel fuel is producer surplus.³ Leiby used the data from EIA 1993 AEO to construct oil cost curves.

These previous studies indicate that oil supply cost is determined by many factors, including well drilling, well operation, reserve depletion and technological change. Generally, oil cost increases nonlinearly with oil output, and technological change and reserves are two important factors that affect the average cost of oil supply in the long run. This paper attempts to model the US oil cost as an exponential function of oil output, considering exploration, development, production and other related costs. Recent data from the JAS and EIA are used to characterize each cost component in detail. Based on prior theoretical studies and EIA's projections, we also estimate the future oil cost in the US.

4. Methods

In order to estimate the producer surplus associated with transportation fuels, we must first estimate the cost curves for petroleum fuels. With the estimated cost curves, we can estimate the average cost as a fraction of price (the complement of PS_{fac}). We estimate the

³ Delucchi also uses these estimates in the Advanced Vehicle Cost and Energy Use Model [9].

average cost *fraction*, rather than the absolute average cost, because the average cost fraction presumably varies much less over time than does the absolute average cost.

This analysis begins with a construction of the US oil cost curve based on the most recent data publicly available from American Petroleum Institute (API). We then derive the gasoline cost curve assuming that oil and gasoline costs have the same correlation as their prices, and use this to estimate the producer surplus for gasoline. Three energy projection scenarios from the Energy Information Administration (EIA) Annual Energy outlook (AEO) 2009 are also examined to project future oil and gasoline cost curves for the producer surplus calculations.

4.1. US Oil Cost Curve

The current US oil cost curve includes exploration, development, production and other related costs. We use the current detailed cost data to model the relationship between total oil marginal cost in dollars per barrel (including exploration, development, production, and other related costs) and oil output in barrels. Formally, the overall equation is as follows:

$$MC_{oil} = MEC + MDC + OED + MPC \quad (1)$$

$$MEC = f_E(Q), \quad MDC = f_D(Q), \quad OED = C_{OED}, \quad \text{and} \quad MPC = f_P(Q)$$

where:

MC_{oil} = marginal cost of oil (2005 \$/bbl)

MEC = marginal exploration cost of oil (2005 \$/bbl) including costs of drilling and equipping wells for exploratory wells

MDC = marginal development cost of oil (2005 \$/bbl) including costs of drilling and equipping wells for development wells

OED = other exploration and development –related marginal cost (2005 \$/bbl)

MPC = marginal production cost of oil (2005 \$/bbl) including operation, administration and other expenses

f_E, f_D, C_{OED} and f_P are marginal cost function formulae to be estimated by fitting functions to actual data, or else by scaling fitted functions, or by assuming costs are

independent of oil output (and therefore are constant), where subscripts E, D, OED and P refer to exploration, development, other exploration and development, and production, respectively. C_{OED} is a constant.

Q = oil output in million barrels per day

According to the API data in 1989, the most recent year where disaggregated costs data are available, the estimated cost of drilling and equipping exploratory oil and gas wells was about 35% of total exploration cost, and the estimated cost of drilling and equipping development was about 60% of total development cost (API, 1989).

The cost of drilling wells is determined mainly by the well depth, diameter, casing design, and location-specific characteristics. However, a large number of factors and events impact drilling performance, and it is complex and challenging to quantify well costs (Kaiser, 2007). Fortunately, the API's Joint Association Survey (JAS) is an authoritative source for drilling costs. The JAS employs a statistical model to estimate drilling cost using survey data. Tabulated data of average costs for drilling wells in the US from the JAS on drilling costs for the period 1976 to 2004 show a general trend that drilling costs increase non-linearly with depth intervals (API, 2004; Augustine et al., 2006). We use the most recent JAS data, which are for the year 2004, to construct an oil cost function for the year 2004.⁴

From the JAS and EIA data (EIA, 2009b) we can estimate the average production per well, and knowing the number of exploratory or development wells we can estimate the oil production in barrels. Based on historical data from API, we apply econometric modeling to derive functions for the relationships between oil production levels and oil exploration costs or oil development costs. To construct the marginal production cost curve (for the oil production stage), we assume it has an exponential shape, and then calibrate the parameters in the exponential function calibrated to fit data in years 2003 and 2004. Other exploration or development-related average costs are assumed to be independent of oil production level. The sum of all these costs generates the oil marginal cost curve for 2004.

⁴ Note, however, that other sources suggest that oil supply costs have increased appreciably since 2004. According to the IEA World Energy Outlook 2009 (IEA, 2009), the worldwide upstream oil and gas capital expenditures significantly increased between 2004 and 2008, from about \$220 billion in 2004 to around \$480 billion in 2008. The escalating expenditures on oil exploration and developments suggest that oil cost became much higher beyond 2004. However, since we are unable to obtain international data beyond 2004, we focus on the period 1976 to 2004.

For future oil marginal cost curves, we develop a regression model to find the trend in the average cost over time and then shift the 2004 curve based on the projected average cost. Our analysis adopts the EIA AEO 2009 (EIA, 2009a) updated reference, high economic growth, low economic growth, high price and low price cases for the future oil supply, oil and gasoline prices, and reserves projected through 2030 in the US. These projections are based on results from the EIA's National Energy Modeling System (NEMS).

To estimate the gasoline cost curve, we assume that the relationship between gasoline costs (which we do not know) and oil costs (which we estimate) is the same as the relationship between gasoline prices and oil prices (both of which we know). We also estimate the oil cost curves for OPEC and ROW with data from World Bank as compared with the US case.

As explained in detail in Appendix C, we estimate each marginal cost component separately as a function of oil output based on data available from American Petroleum Institute (API, 2004) and EIA (EIA, 2008a). The sum of all the costs incurred to oil supply yields the total oil cost curve shown in Figure 2. Table 2 summarizes the data source and method to estimate each cost component. The final function form for the marginal cost function for oil we use is given by:

$$MC_{oil}(Q_{oil}) = \exp(a_1 + b_1 \cdot Q_{oil}) + \exp(a_2 + b_2 \cdot Q_{oil}) + C_{OED} + c \cdot \exp(d \cdot Q_{oil}) \quad (2)$$

Total US oil production (Q_0) including lease condensate in 2004 was 5.419 MMBD and the oil price P_0 was \$38/bbl (crude oil domestic first purchase price) (EIA, 2009b). According to our estimated oil cost curve $MC(Q)$, the corresponding marginal cost of oil MC_{oil} was \$28.85/bbl, with a standard error of \$24.23/bbl, and ranges from a lower bound of \$28.31/bbl to an upper bound of \$29.49/bbl. This divergence between price and marginal cost is due most likely to world oil market not being perfectly competitive (on account of occasional oligopolistic behavior), although it is possible that we have omitted some costs. Our estimated average oil cost, as calculated by the integral of the marginal cost curve from 0 to 5.419 MMBD divided by the oil production, is \$11.29/bbl.

The US oil producer surplus fraction (PSf) of total prices-times-quantity payments in 2004 is given by:

$$PSf = 1 - \frac{\int_0^{Q_0} MC(Q) dQ}{P_0 * Q_0} \quad (3)$$

where $MC(Q)$ is the marginal cost of oil for the US in 2004. Results show that the US oil producer surplus fraction (PSf) of total prices-times-quantity payments in 2004 is about 70%, with a standard error of 13%, and ranges from a lower bound of 68.03% to an upper bound of 71.84%.

4.2. US Gasoline Cost Curve

We estimate the marginal wholesale cost of producing gasoline from US crude oil, compare that with the price of gasoline, and estimate the associated total producer surplus, for the refining industry and the oil industry.

As derived and estimated in Appendix C, the marginal cost for gasoline MC_g is given by:

$$MC_g = a \cdot MCf_{g,r} + b \cdot [\exp(a_1 + b_1 \cdot Q_o) + \exp(a_2 + b_2 \cdot Q_o) + C_{OED} + c \cdot \exp(d \cdot Q_o)] , \quad (4)$$

where $MCf_{g,r}$ is the marginal cost fraction of the price constant for gasoline refining. The parameter a is a constant in \$/gg (year 2005 \$) and is what the EIA (2009b) calls the “refiner margin” for motor gasoline, and b is the ratio of the contribution of the crude oil price to wholesale gasoline price, in \$/gg, to the price of crude oil produced, in \$/bcp. Our results show that MC_g ranges from a lower bound of \$1.00/gal to an upper bound of \$1.03/gal, and has a standard error of \$0.61/gal.

As derived and estimated in Appendix C, the producer surplus PS_g for gasoline is given by:

$$PS_g = a \cdot (1 - MCf_{g,r}) + b \cdot PS_o . \quad (5)$$

We find that PS_g ranges from a lower bound of \$0.72/gal to an upper bound of \$0.75/gal, and has a standard error of \$0.13/gal.

The producer surplus associated with domestic gasoline fuel made from domestic crude oil is the area bounded by price line and marginal cost curve from output level zero to the estimated 122 mmgd gasoline output in 2004 from domestic oil.

The calculated producer surplus is about 56.7% of total price-times-quantity payments, which includes both domestic oil production and refinery industries. This producer surplus fraction is lower than that oil producer surplus fraction (70% from Figure 2), which follows from our assumption about the producer-surplus fraction for refining ($1-MCF_{g,r}$, Equation (5)).

We may break the producer surplus into two components: one related to the steepness of the cost curve (the area PS2, about 58%), and the other related to the price being higher than it should be (the area PS1, about 42%) due to the scaling up of oil price/MC gap (our assumption to derive gasoline cost). PS1 is the rectangle area below the gasoline price and above the marginal cost \$1.01/gal) at Q_g , and PS2 is the area below the marginal cost \$1.01/gal) and above the marginal cost curve. Using the terms defined in Table A1 of Appendix A, PS1 is economic profit, and PS2 is economic rent. If our estimate of the cost curve is accurate, then the petroleum-refining industry is not competitive, and receives economic profit (PS1 in Figure 3). However, it is possible we have under-estimated costs and that there is no economic profit (PS1=0).

The area under the gasoline cost supply (total gasoline cost) is about \$69.96 million per day while the area under the oil cost curve in Figure 2 (total oil cost) is about \$61.17 million per day (about 53.4% is for gasoline). To estimate the producer surplus in the refining industry only, we assume that the revenue to the refining industry is the revenue difference between gasoline and oil, and the cost to the refining industry is the cost difference between gasoline and oil. We calculate the producer surplus fraction in the refining industry is about 28%, much lower than that in the oil industry.

4.3. Producer surplus as a function of the change in gasoline consumption

In the previous section we estimated the total producer surplus for gasoline that could have been produced from domestic crude oil in 2004. In this section we estimate producer surplus as a function of the size of the change in gasoline consumption. We estimate the total producer surplus change for the change in consumption (we designate this ΔPS_t , where t stands for “transfer”), and producer surplus as a fraction of the change in price-times-quantity payments (we designate this PS_{fac} , where ac stands for “average cost”). ΔPS_t is calculated with the following equation:

$$\Delta PS_t = [(P_g^0 \cdot Q_g^0) - \int_0^{Q_g^0} MC(Q_g) dQ_g] - [(P_g^* \cdot Q_g^*) - \int_0^{Q_g^*} MC(Q_g) dQ_g] , \quad (6)$$

where P_g^0 = the before-change gasoline price, P_g^* = the after-change gasoline price, Q_g^0 = the before-change gasoline quantity, Q_g^* = the after-change gasoline quantity at the new equilibrium (shown in Figure 4), and $MC(Q_g)$ = marginal cost function of gasoline MC_g . We break the total producer surplus change (ΔPS_t) into two pieces: one (we call this component $\Delta PS_{t,c}$, which is the triangular area ABC) is due to the equilibrium consumption change and the second component (called $\Delta PS_{t,i}$, which is the rectangular area BCP^0P^*) is due to the change in price (“inframarginal” consumption), shown in Figure 4.

We assume that the US oil market is competitive. Given this, Figure 4 (D = demand) illustrates two supply-demand equilibrium cases before and after oil demand contracts, where MC (cost curve S) has the same shape as we estimate for 2004 (Figure 2), but vertically shifts up so that the curve passes through the point (P_0, Q_0) , and intersects the original demand curve D at A . When oil demand declines from Q_0 to Q' , the new demand curve D' will pass through point N (P_0, Q'), but with the same demand elasticity as the initial demand curve D .

The new demand curve D' intersects the cost curve S at B , corresponding to a new, lower price P^* (and, incidentally, to a quantity Q^* greater than Q' , on account of the lower price spurring additional consumption). As explained in detail in Appendix C, we calculate the total producer surplus reduction ΔPS_t , and its components $\Delta PS_{t,c}$ and $\Delta PS_{t,i}$.

The other kind of producer surplus (PS_{ac}) is based on the initial change in consumption due to the change in the demand curve, is expressed as a fraction of $P \cdot \Delta Q$, and is given by:

$$PSf_{ac} = \frac{\Delta PS}{P_g^0 \cdot \Delta Q_g} = \frac{[P_g^0 Q_g^0 - \int_0^{Q_g^0} MC(Q_g) dQ_g] - [P_g^0 Q_g' - \int_0^{Q_g'} MC(Q_g) dQ_g]}{P_g^0 \cdot (Q_g^0 - Q_g')} . \quad (7)$$

As the change in consumption increases, the producer surplus fraction increases because we move down the marginal cost curve. The total producer surplus change from the changes in consumption and price (Equation (6)) will also increase as the consumption reduction increases.

In Section 5 we discuss the results of our analysis of producer surplus as a function of change in gasoline supply. Note we are estimating the impact of changes in total gasoline supply,

as given for example in Table 5.11 of EIA (2009b). (Total gasoline supply is not the same as the amount of gasoline that would have been produced from all domestic crude oil supply.)

4.4. Estimating producer surplus for OPEC and the rest of the world

As explained in detail in Appendix C, we estimate the following marginal cost functions for OPEC and the rest of the world (ROW):

$$MC_{OPEC} = c_{OPEC} \exp(d_{OPEC} Q_{OPEC}) \quad (8)$$

$$MC_{ROW} = c_{ROW} \exp(d_{ROW} Q_{OPEC}), \quad (9)$$

where Q is in billion barrels and MC is in constant 2005 US dollars per barrel.

The oil marginal cost curves for OPEC and ROW in 2004 are shown in Figure 5. Compared to the US oil cost curve in Figure 2, OPEC has a much lower marginal cost and the cost increase with output level is very little, i.e. the marginal oil cost of OPEC is quite inelastic with respect to its output. According to the World Bank data, OPEC oil output in 2004 was about 25.3 MMBD with average cost of \$2.9/bbl and ROW oil output in 2004 was about 37.4 MMBD with average cost of \$9.3/bbl. In contrast, our estimate for the corresponding marginal cost is \$2.84/bbl for OPEC and \$9.36/bbl for ROW. Given the world oil price at \$38/bbl in 2004, OPEC earns a large amount of producer surplus. To shed some light on the foreign producer surplus, we provide some rough calculations of producer surplus from OPEC and ROW in 2004 as compared to the US results.

Given the 2004 oil price P^0 (\$38/bbl), the oil producer surplus fraction of total price-times-quantity payments is about 92.5% for OPEC and about 75.5% for ROW as shown in Figure 6 (shaded areas). This amounts to \$35/bbl for OPEC and \$29/bbl for ROW. By contrast, the US oil producer surplus fraction in 2004 is about 70% (Figure 2) and \$27/bbl. Comparing magnitudes, the total OPEC producer surplus associated with total OPEC production in 2004 (25.3 MMBD) is \$325 billion, which is more than six times the total US producer surplus associated with total US oil production (5.419 MMBD), about \$53 billion. In 2004, OPEC oil production is more than 4 times US oil production. According to the recent data from EIA FRS (EIA, 2008a), total cost (acquisition, exploration, development and production) incurred for petroleum operations increased sharply from 2004 to 2008 for the US and foreign producers.

Particularly, the 2008 petroleum expenditure in the Middle East is about 3.2 times the 2004 one in real dollars, and oil price rose from \$38/bbl to \$86.69/bbl in 2005 dollars. We can make some rudimentary projections of producer surplus fraction for 2008, which we project to be about 92%.

With our estimated producer surplus to the US refinery only from Section 4.2, we can estimate the total gasoline producer surplus fraction with imported oil from OPEC or ROW. Table 3 summarizes all the producer surplus fractions in 2004 for oil industry in the US, OPEC and ROW, for US refinery industry, and for the total gasoline cost given three different combinations (US oil + US refining, OPEC oil + US refining, and ROW oil + US refining). We assume actual total oil inputs and gasoline outputs in 2004, but with different sources for the oil input. For the US, the total gasoline producer surplus fraction for imported oil would be higher than that for domestic oil. Results show that MC_{OPEC} ranges from a lower bound of \$2.83/bbl to an upper bound of \$2.86/bbl, and that MC_{ROW} ranges from a lower bound of \$9.37/bbl to an upper bound of \$9.80/bbl. We report the upper bound and lower bound values for all the OPEC and ROW producer surplus statistics in Table 3.

How much would producer surplus decrease with a 10% contraction of world oil demand? We first calculate the percentage change in world quantity resulting from an assumed percentage change in world demand, and then assume that the calculated percentage change in world quantity applied to OPEC, ROW, and US. To answer the question, we should first estimate the world oil price P^* after the oil demand change, which depends on our view of the world oil market. If we assume it is a competitive world market, then P^* equals marginal cost (MC^*) where the MC^* at Q^* (quantity after the change) is determined by the “world” long-run marginal cost function. If we assume that OPEC simply maintains price, then P^* equals P^0 . Any assumptions between MC^* and P^0 are possible. We derive the “world” oil cost curve including the US shown in Figure 7 with the World Bank data using the same method as the OPEC and ROW oil cost curves in this section. Our derived hypothetical “world” marginal cost, which depicts world short-run cost curve in 2004, is given by:

$$MC_{world} = 7123 * \exp(0.000034 * Q_{world}). \quad (10)$$

The “world” oil marginal cost is about \$7.13/bbl, much lower than world oil price P^0 . If the

“world” oil cost curve is believable to some extent, then we can conclude that the world oil market is not perfectly competitive, most likely due to OPEC behavior. To formally model OPEC behavior is beyond the scope of this paper, and will be addressed in the future research. As the 2004 “world” oil MC curve is almost flat, we assume that oil demand contraction would result in the same percentage change in world quantity.

Tables 4a-c presents the result of two different kinds of producer surplus change for 10%, 20% and 50% oil-demand contractions under three scenarios of OPEC pricing behavior, in order to examine the sensitivity to P^* and therefore to assumptions about OPEC market power. The range of cases (scenarios) we examine spans perfect competition to full OPEC market power. For Case 1, $P^*=MC^*$ (this is not likely according to the World Bank data); for Case 2, P^* = the mean of P^0 and MC^* we call this P1); for Case 3, $P^*=P^0$, the same price as before the demand contraction (assuming in this case that OPEC’s strategy is to maintain oil price).

Under Case 1 (Table 4a), for a 10% contraction in demand for oil, the total producer surplus reduction ΔPS_t (289.5 billion\$) for OPEC expressed as \$/bbl ($\Delta PS_t/\Delta Q$) is \$312.8/bbl where $\Delta PS_{t,c}$ per barrel is \$34.9, and $\Delta PS_{t,i}$ per barrel is \$277.8. OPEC’s producer surplus fraction $PS_{f,ac}$ for the 10% demand contraction is 91.9%. As the oil demand contraction increases, the total producer surplus reduction will increase and $\Delta PS_{t,c}$ per barrel will increase slightly, but $\Delta PS_{t,i}$ per barrel will decline. For ROW and US, P^* is lower than their marginal cost and they would not produce crude oil.

As shown in Table 4b, for Case 2, $\Delta PS_{t,c}$ per barrel increases slightly while $\Delta PS_{t,i}$ decreases sharply with increasing contraction of oil demand for both OPEC and US. However, for ROW, $\Delta PS_{t,c}$ per barrel declines as oil-demand contraction increases due to decreasing marginal cost curve. The \$/bbl change in $\Delta PS_{t,i}$, the “inframarginal” producer surplus, is proportional to the change in price: the greater the change in price, the greater the \$/bbl reduction in producer surplus on the inframarginal consumption.

If there is no change in price, then $\Delta PS_{t,i}$ is zero (Case 3 of Table 4c). There will be no change in price if, after the initial contraction of demand, OPEC reduces its output so that the amount of high-cost supply forced into the market raises the price back to the original, pre-contraction level. Whether OPEC would actually do this in the face of a demand contraction depends on the details of its short-run and long-run objective functions.

OPEC’s short-run strategy is to maximize producer surplus by finding the optimal output that maximizes their revenue, when the benefit from the higher price no longer more than compensates for the reduced sales. OPEC’S long-run strategy is more complicated as they do not want to maintain high prices for so long that consuming countries begin to take long-run oil conservation measures. Both of these strategies are difficult to model, even for OPEC itself, and as a result we offer only scenarios, rather than predictions.

For Cases 2 and 3, OPEC has more producer surplus reduction per barrel than ROW which in turn has more producer surplus reduction than does the US. Therefore, oil consumption contraction would have more impact on foreign producers than on US producers.

4.5. Future Oil and Gasoline Marginal Cost

As explained in detail in Appendix C, we estimate the future oil marginal cost curve and then the future gasoline marginal cost for the US based on historical data and our estimated 2004 US oil marginal cost curve. In general, the cost of oil in the US in the future can be influenced by geopolitics, technological progress, oil output, world oil price, remaining reserves, investors’ strategy, alternative energy options, and other factors. Here we model the future annual total cost (TC) in billion dollars of petroleum from both oil and gas wells (the API and the EIA FRS do not provide cost data for oil wells and gas wells separately) as a function of time (t), oil price (P_{oil}), oil output (Q_{oil}), gas output (Q_{gas}) and remaining reserves (Rev) of oil and gas:

$$TC = f(t, P_{oil}, Q_{oil}, Q_{gas}, Rev). \quad (11)$$

Our estimated US future oil marginal cost curves for the four EIA oil-price cases (all except HP) are shown in Figure 8, as compared with the 2004 curve (Figure 5). As shown in Figure 8, the estimated future curve for the low-price case (LP) is not reasonable, and the other three curves are almost the same (about \$30/bbl more than the 2004 value). Therefore we analyze the reference case only in this paper.

Figure 9 shows the estimated future gasoline cost curve in the US. Using the same conversion factor (the ratio of actual motor-gasoline produced by refineries to crude oil input to refineries in 2004) as in Section 4.2, we estimate the future gasoline production (132.80 million gallons per day) that refineries would produce if they used all and only domestic crude

oil.

As estimated in Appendix C, our results for the marginal costs for OPEC and ROW beyond 2004 are as follows:

$$MC_{OPEC,t} = 0.396 * \ln(t) * \exp(-1.6 * 10^{-4} * Q_{OPEC,t}) \quad (12)$$

$$MC_{ROW,t} = 1.28 * \ln(t) * \exp(1.76 * 10^{-5} * Q_{ROW,t}). \quad (13)$$

5. Results

5.1. Producer surplus as a function of change in total gasoline supply in the US in 2004

We calculate the percentage change in total gasoline supply⁵ associated with the assumed percentage contraction of demand, then assume that this percentage change in quantity applies to supply from US, OPEC and ROW. Then we calculate the producer surplus changes for gasoline made in US from US crude oil, OPEC crude oil and ROW crude oil respectively.

For 10%, 20%, 50% and 100% contractions of demand for motor gasoline in the US in 2004, the calculated percentage changes in total gasoline supply are 7.06%, 14.36%, 38.21% and 100%, respectively. According to EIA Annual Energy Review (EIA, 2009b) and Transportation Energy Data Book (EIA, 2011), the total gasoline supply in 2004 was 9.105 MMBD, 65% crude oil was imported, and among total imports, OPEC share was 43.4%. Given this, then 3.18 MMBD gasoline supply was from US oil, 2.57 MMBD from OPEC oil, and 3.35 MMBD from ROW oil.

Table 5 presents the producer surplus changes (ΔPS_t in \$ billion including $\Delta PS_{t,c}$ and $\Delta PS_{t,i}$, and PS_{fac}) for 10%, 20%, 50%, and 100% contractions of demand for motor gasoline in the US. Because $\Delta PS_{t,c}$ is the producer surplus associated with the foregone gasoline use, it always increases with increasing percentage reductions in gasoline use. The $\Delta PS_{t,c}$ in terms of \$/gal is constant for gasoline made in US from OPEC and ROW crude oil due to the little curvature of OPEC and ROW oil cost curves (Equations (8) and (9)). However, $\Delta PS_{t,i}$, the producer surplus associated with the inframarginal supply, increases with larger reductions in gasoline use only when the supply curve is steeper than 45 degrees, because in this case, loosely

⁵ The total gasoline supply elasticity is set as 0.25 and demand elasticity is -0.11 as used in NEMS (EIA, 2010b).

speaking, the increase in producer surplus due to the price change is greater than the decrease in producer surplus due to the quantity reduction.

For the US, as the gasoline demand contraction increases the producer surplus fraction PSf_{ac} increases and hence the average cost as a fraction of price decreases. For OPEC and ROW, PSf_{ac} is much higher than in the US and remains stable as a function of demand reduction, which means that in OPEC and ROW average costs are much lower than in the US and basically constant.

As shown in Table 5, the producer surplus associated with all gasoline use in the US in 2004 (i.e., the producers surplus for a 100% reduction in gasoline use) was \$33.57 billion in the US, \$36.98 billion for OPEC and \$47.74 billion for the ROW. The total wealth transfer from US consumers to foreign producers thus was \$84.72 billion (OPEC plus ROW). The wealth transfer from US consumers to foreign producers is much larger than the transfer from consumers to domestic producers because foreign producers have much lower average costs and hence earn much higher producer surplus.

5.2. Producer surplus as a function of change in total gasoline supply in the US over the period 2005-2030

With the future gasoline cost curve from Section 4.2, which includes both oil recovery and refining for the period 2005 to 2030, we can calculate the producer surplus as the area below the gasoline price (\$2.75/gal, the average gasoline price from 2005 to 2030) and above the marginal cost curve integrated from 0 to 132.80 million gallons per day. The resulting producer surplus fraction with respect to price-times-quantity payments is 40.5%, much lower than the 2004 level. This is to be expected, because we simply have shifted the cost curve up without changing its shape, which means that the cost portion of price-times-quantity payments – the area under the long-run marginal cost curve – will be larger in the future than it was in 2004.

To estimate the producer surplus for OPEC and ROW beyond 2004, we use the estimates for the marginal costs for OPEC and ROW beyond 2004 from Equations (12) and (13). In this analysis, we choose the year 2025 to estimate producer surplus for OPEC and ROW with world crude oil price, oil import share, US domestic oil supply, total gasoline supply

in the US, and US gasoline price in 2025 from EIA AEO 2014 reference case. For future oil production for OPEC and ROW, OPEC and DOE/EIA have different projections as shown in Table 6. To simplify our analysis, we use the mean value of these estimates. Table 7 presents our estimates of total producer surplus change for gasoline made in the US from OPEC and ROW crude oil for 10%, 20%, 50%, and 100% of contractions of demand for motor gasoline in the US.

6. Discussion

Our estimates of producer surplus confirm that the average cost of gasoline in the US is much less than the price paid by consumers. This result has important implications for estimates of wealth transfers from oil consumers to oil producers as part of an analysis of the total costs and benefits to the US of policies related to oil use and oil imports, and for analyses involving the social cost of gasoline (e.g., comparisons of the social cost of gasoline vehicles versus the social cost of hydrogen vehicles).

6.1, Producer surplus in estimates of wealth transfers as a result of policies affecting US oil use

As a result of much lower average oil cost of OPEC and ROW than that of the US, the producer surplus fraction PS_{fac} was quite high (more than 75%) for gasoline made in the US from imported oil in 2004 and it did not change much with gasoline use contraction. Our estimate for 2025 shows that the producer surplus associated with the US gasoline use is larger for both OPEC and ROW than that in 2004 primarily due to high oil price projected in 2025. Policies that reduce the US oil use would greatly reduce the wealth transfer from the US to the foreigners.

6.2, Producer surplus in comparisons of the social cost of transportation fuels

To illustrate the importance of treating producer surplus properly in cost-benefit analysis of transportation fuels, we summarize and update the results of a previous analysis (Sun et al., 2010) of the social lifetime cost of hydrogen fuel cell vehicles compared with conventional gasoline vehicles. The social lifetime cost includes the vehicle retail cost, fuel

cost, operating and maintenance costs, externality costs of oil use, noise damage costs, air pollution damage costs, climate change damage costs, and adjustments for non-cost social transfers including taxes and fees and producer surplus associated with fuels and vehicles. We estimate the social lifetime cost from two perspectives: (1) a global perspective, which counts all climate change damages everywhere in the world but ignores all producer-surplus wealth changes as non-cost transfers between global producers and consumers, and (2) a US perspective, which counts climate change damages only in the US but does count as a cost to US consumers wealth transfers of producer surplus to foreign countries.

Table 8 shows the results of the analysis. In addition to showing the internally consistent US and global perspectives, Table 8 also shows two common, incorrect perspectives: a hybrid estimate of the SLC, in which climate change damages from the global perspective are added to producer surplus losses from the US perspective, and a perspective that counts all producer surplus as a cost; i.e., uses pre-tax price times quantity as the fuel cost.

The results of Table 8 show that analyses (e.g., Goedecke et al., 2007, Ogden et al., 2004) that incorrectly use price-times-quantity payments and hence incorrectly include producer surplus in an estimate of the social cost of gasoline will overestimate the present value lifetime social cost of gasoline vehicles by \$2,280 to \$9860.

According to our results in Table 8, the social lifetime cost of gasoline vehicles is \$70,534 from a US perspective and \$67,454 from a global perspective, both of which are slightly higher than the social lifetime cost of hydrogen fuel cell vehicles, which is \$65,377.

7. Conclusion

Estimating the producer surplus is an important part of social cost-benefit analyses of changes in petroleum use. This paper estimates the producer surplus associated with changes in gasoline fuel use in the United States, and then applies the estimates of producer surplus to two kinds of social cost-benefit analyses related to petroleum use: (1) estimating the wealth transfer from consumers to producers as a result of policies that affect oil use and oil importing in the US, and (2) comparing the actual average cost of gasoline (where the average cost is the observed price minus the estimated fraction of price that is producer surplus) with the average cost of environmentally superior alternatives to gasoline, such as hydrogen.

According to our results, both kinds of producer surplus estimates depend on the size of the reduction in oil use and the year and region for which oil cost curves are estimated. We estimate that if demand for gasoline in the US in 2004 had contracted by 10% (50%), then the change in producer surplus in the US refinery and US oil industry would have been \$15.2 (\$31.63) billion, or \$4.84 (\$1.86) per gallon of gasoline, and the producer surplus fraction of revenues would have been 31.89% (49.03%). The change in producer surplus for gasoline made from imported oil would have been greater – \$5.48/gallon for a 10% contraction and \$2.28/gal for a 50% contraction – because foreign producers have much lower average production cost. In fact, a 50% reduction in gasoline use in the US in 2004 would have saved the US \$94 billion in producer surplus payments to foreign oil producers. Applying our estimates to the comparison of the social lifetime cost of hydrogen vehicles versus gasoline vehicles, we find that inconsistently counting producer surplus from a US national perspective while counting climate change damages from a global perspective can overstate the present value lifetime costs of gasoline vehicles by \$2,200 to \$9,800 per vehicle.

Because there is a large cost difference between low-cost and high-cost oil producers, and because OPEC manipulates output to control prices, many oil producers, but especially those in OPEC, enjoy very large economic rent and economic profit, which together compose producer surplus. In 2004, US drivers paid \$278 billion for gasoline, of which \$92 billion was taxes, \$58 billion was actual economic cost, and \$128 billion – the largest portion – was producer surplus. From a global perspective, this producer surplus was just a transfer from consumers to producers. However, from the perspective of the US, the producer surplus paid to foreign oil producers -- \$84.7 billion in 2004 -- was a real cost. In future years, the producer surplus would be even larger, for example, \$122.5 billion in 2025 based on our analysis.

However, in cost-benefit analyses, one may treat producer surplus as a cost only if one takes a limited domestic perspective and ignores the welfare of foreign producers. And if one does take a domestic perspective regarding producer surplus, one must take a domestic perspective regarding *all* components of the social cost, including climate change damages. A reduction in gasoline use has greater producer surplus benefits but lower climate change damage benefits in a domestic as compared to a global perspective. For example, EIA AEO 2013 reference case projects that motor gasoline consumption in the US in 2025 is 13.86

quadrillion Btu. A 50% reduction in gasoline use in the US in 2025 would save the US \$168 billion in producer surplus lost to foreign countries, assuming 50% is from foreign oil and US \$2.6 billion in climate change damages for LDV⁶ only in the US, every year. However, from a global perspective, the 50% reduction in gasoline use in the US would save nothing in terms of producer surplus (which from a global perspective is just a transfer from consumers to producers) but would save US \$20 billion per year in climate change damages to the world.

An inconsistent treatment of producer surplus and climate change damages thus can result in an error of hundreds of billions of dollars in cost-benefit analyses. The producer surplus estimates developed in this study can be used to avoid these errors.

⁶ The US LDV vehicle miles traveled in 2025 is 3,089 billion under EIA AEO2013 reference case.

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Figure 1. Producer Surplus in an imperfect market

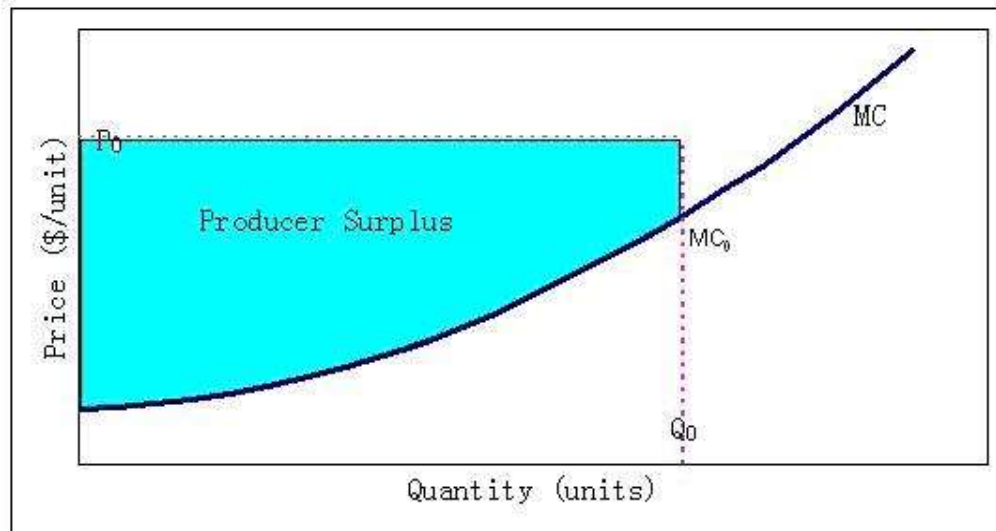


Table 1. Two-fuel case

	Firm A	Firm B
Fuel type	I	II
Selling price	\$50/BTU	\$50/BTU
Value to consumer	\$55/BTU	\$55/BTU
Marginal cost of production	\$20/BTU	\$40/BTU
Producer surplus	\$30/BTU	\$10/BTU

Figure 2. US oil cost curve in 2004

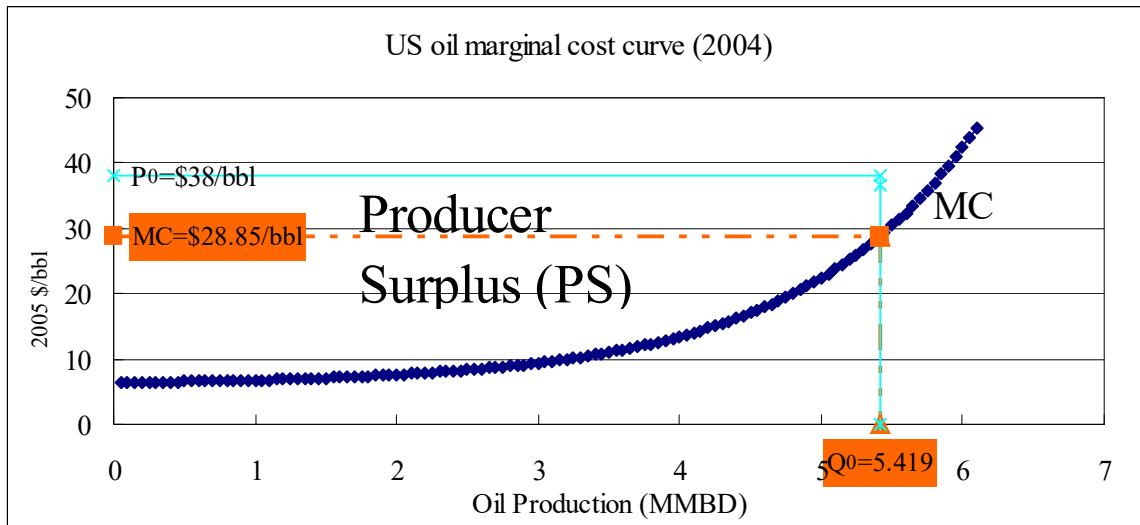


Table 2. Summary of each cost component in 2004 oil marginal cost function

Cost component	Data source	Model/Method
Exploration (MEC)	JAS/API (API, 2004) for oil wells	$MEC = \exp(a_1 + b_1 Q)$
Development (MDC)	JAS/API (API, 2004) for oil wells	$MDC = \exp(a_2 + b_2 Q)$
Other costs (OED)	FRS/EIA (EIA, 2008a) for oil and gas wells for 2003-2004	Compare historical data 1977-1982 from FRS (EIA, 2008a) and API (API, 1989), scale FRS cost with the ratio API/FRS, and assume average OED is independent of oil output
Production (MPC)	FRS/EIA (EIA, 2008a) for oil and gas wells for 2003-2004	Scale FRS cost with the ratio API/FRS; Assume MPC is an exponential function of output $MPC = c \cdot \exp(d \cdot Q)$, justified by US Economic Census on oil and gas operations.

Figure 3. Marginal Cost of producing gasoline from US crude oil in 2004

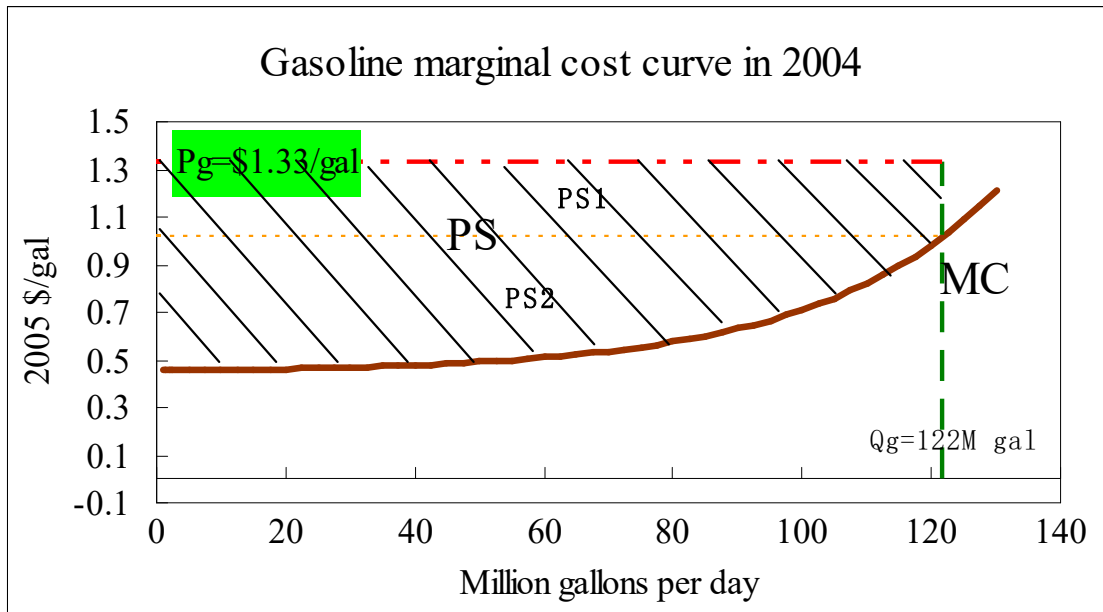


Figure 4. US oil market in 2004 ($P^0=\$38/\text{bbl}$ and $Q^0=5.419\text{MMBD}$)

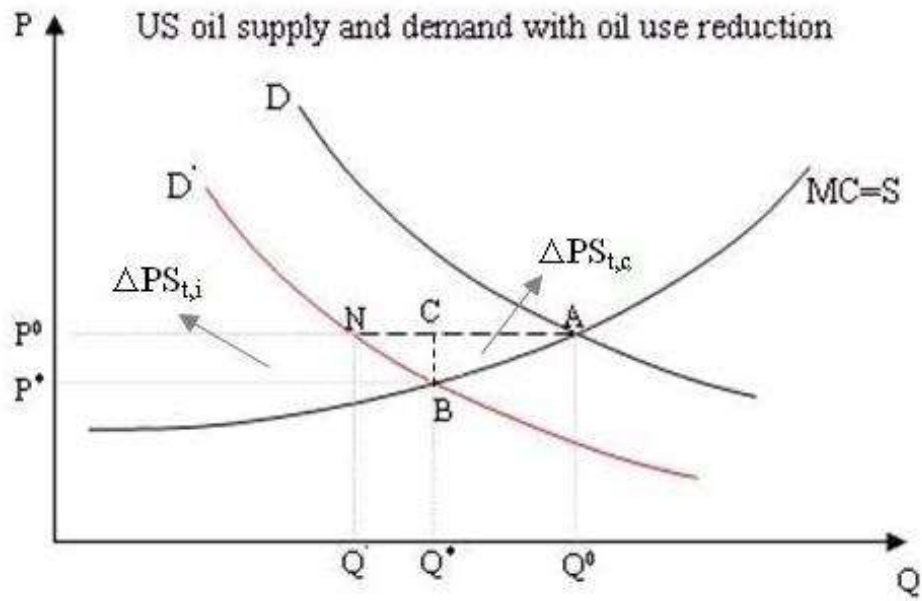


Figure 5. Oil supply cost curves for OPEC and ROW

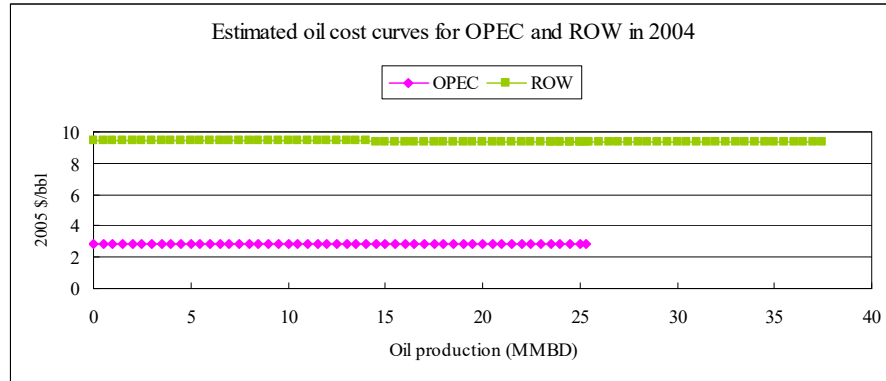


Figure 6. Oil producer surplus calculation for OPEC and ROW

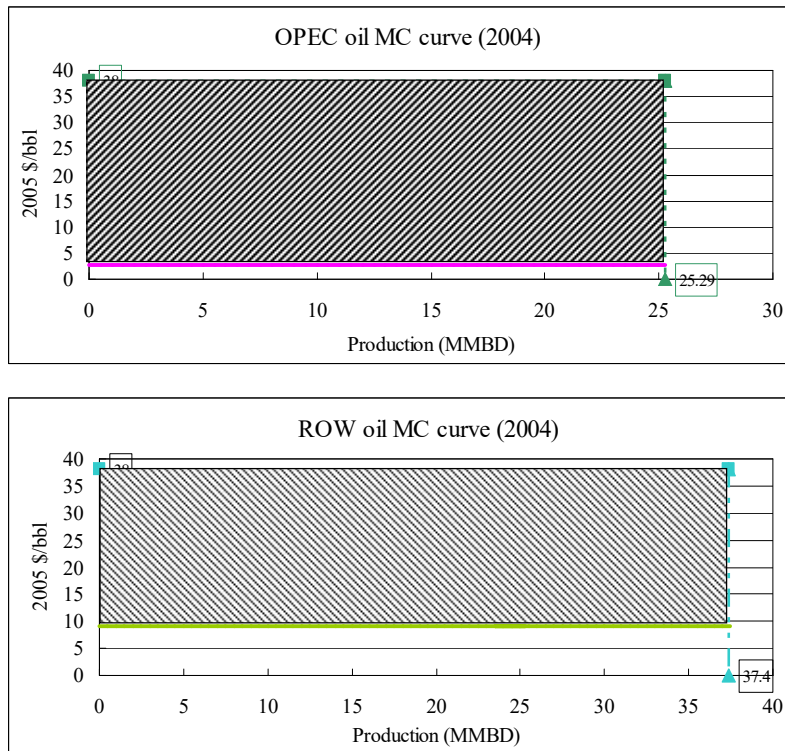


Table 3. Summary of all the producer surplus fractions in 2004, for total production

Oil industry	US	70.3%	\$27/bbl
		[68.03%, 71.84%]	[\$25.85, \$27.30]
	OPEC	92.5%	\$35/bbl
		[92.47%, 92.54%]	[\$35.14, \$35.17]
	ROW	75.5%	\$29/bbl
		[74.08%, 75.41%]	[\$28.15, \$28.65]
US refinery	US	27.9%	\$0.12/gal (\$5/bbl)
		[27.67%, 28.04%]	[\$0.118, \$0.119]
Total gasoline in US (oil + refinery)	US oil + US refinery	56.7%	\$0.75/gal (\$32/bbl)
		[53.93%, 56.64%]	[\$0.717, \$0.753]
	OPEC oil + US refinery	71.8%	\$0.96/gal (\$40/bbl)
		[71.75%, 71.91%]	[\$0.954, \$0.956]
	ROW oil + US refinery	60.5%	\$0.80/gal (\$34/bbl)
		[59.24%, 60.26%]	[\$0.788, \$0.801]

Note: Upper and lower bound values are reported in square brackets.

Figure 7. “World” oil cost curve

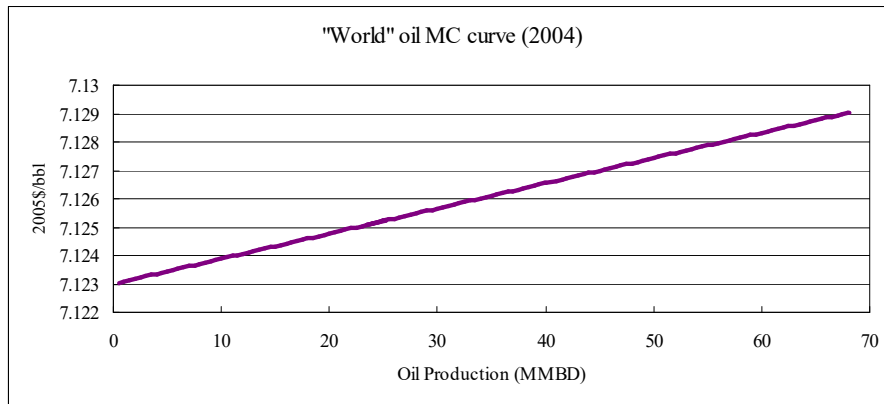


Table 4a. Oil producer surplus changes after 10%, 20% and 50% contractions of world oil demand under price-response Case 1.

		Case 1 (P*=MC*)			
Contraction of world oil demand	Quantity reduction apportioned to:	ΔPS_t (\$/bbl)		ΔPS_t (\$ billion)	PS _{fac}
		$\Delta PS_{t,c}$	$\Delta PS_{t,i}$		
10%		P*=\$7.13/bbl			
	OPEC	35.16 [35.14, 35.17]	277.84	-289.7 [289.68, 289.70]	92.5% [92.48%, 92.54%]
	ROW	-	-	-	
	US	-	-	-	
20%		P*=\$7.13/bbl			
	OPEC	35.16 [35.14, 35.17]	123.48	-293.7 [293.63, 293.68]	92.5% [92.48%, 92.54%]
	ROW	-	-	-	
	US	-	-	-	
50%		P*=\$7.13/bbl			
	OPEC	35.16 [35.14, 35.17]	30.87	-305.6 [305.49, 305.60]	92.5% [92.47%, 92.54%]
	ROW	-	-	-	
	US	-	-	-	

Note: Upper and lower bound values are reported in square brackets.

Table 4b. Oil producer surplus changes after 10%, 20% and 50% contractions of world oil demand under price-response Case 2.

		Case 2 (P*= $\text{mean}(P^0, MC^*)$)			
Contraction of world oil demand	Quantity reduction apportioned to:	ΔPS_t (\$/bbl)		ΔPS_t (\$ billion)	PS _{fac}
		$\Delta PS_{t,e}$	$\Delta PS_{t,i}$		
10%		P*=\$22.57/bbl			
	OPEC	35.16 [35.14, 35.17]	138.87	-161.1 [161.06, 161.08]	92.5% [92.48%, 92.54%]
	ROW	28.62 [28.21, 28.63]	138.87	-229.5 [228.92, 229.49]	75.3% [74.24%, 75.34%]
	US	13.44 [12.78, 13.98]	138.87	-30.21 [30.08, 30.32]	35.4% [33.63%, 36.80%]
20%		P*=\$22.57/bbl			
	OPEC	35.16 [35.14, 35.17]	61.72	-179.3 [179.30, 179.35]	92.5% [92.48%, 92.54%]
	ROW	28.6 [28.21, 28.63]	61.72	-247.6 [246.43, 247.58]	75.3% [74.24%, 75.34%]
	US	16.69 [16.01, 17.24]	61.72	-31.1 [30.83, 31.32]	43.9% [42.12%, 45.36%]
50%		P*=\$22.57/bbl			
	OPEC	35.16 [35.14, 35.17]	15.43	-234.1 [234.03, 234.15]	92.5% [92.47%, 92.54%]
	ROW	28.61 [28.19, 28.64]	15.43	-301.7 [298.81, 301.90]	75.3% [74.18%, 75.37%]
	US	22.60 [21.85, 23.16]	15.43	-37.7 [36.97, 38.27]	59.5% [57.50%, 60.96%]

Note: Upper and lower bound values are reported in square brackets.

Table 4c. Oil producer surplus changes after 10%, 20% and 50% contractions of world oil demand under three price-response Case 3.

		Case 3 (P*=\$38/bbl)			
Contraction of world oil demand	Quantity reduction apportioned to:	ΔPS_i (\$/bbl)		ΔPS_i (\$ billion)	PS _{fac}
		$\Delta PS_{i,c}$	$\Delta PS_{i,i}$		
10%		P*=\$38/bbl			
	OPEC	35.16 [35.14, 35.17]	0	-32.5 [32.52, 32.55]	92.5% [92.48%, 92.54%]
	ROW	28.62 [28.21, 28.63]	0	-39.2 [38.65, 39.22]	75.3% [74.24%, 75.34%]
	US	13.44 [12.78, 13.98]	0	-2.67 [2.53, 2.77]	35.4% [33.63%, 36.80%]
20%		P*=\$38/bbl			
	OPEC	35.16 [35.14, 35.17]	0	-65.1 [65.05, 65.10]	92.5% [92.48%, 92.54%]
	ROW	28.62 [28.21, 28.63]	0	-78.4 [77.30, 78.45]	75.3% [74.24%, 75.34%]
	US	16.69 [16.01, 17.24]	0	-6.62 [6.35, 6.84]	43.9% [42.12%, 45.36%]
50%		P*=\$38/bbl			
	OPEC	35.16 [35.14, 35.17]	0	-162.7 [162.62, 162.74]	92.5% [92.47%, 92.54%]
	ROW	28.61 [28.19, 28.64]	0	-196.01 [193.11, 196.20]	75.3% [74.18%, 75.37%]
	US	22.60 [21.85, 23.16]	0	-22.41 [21.67, 22.97]	59.5% [57.50%, 60.96%]

Note: Upper and lower bound values are reported in square brackets.

Figure 8. Current and Predicted future oil marginal cost curves

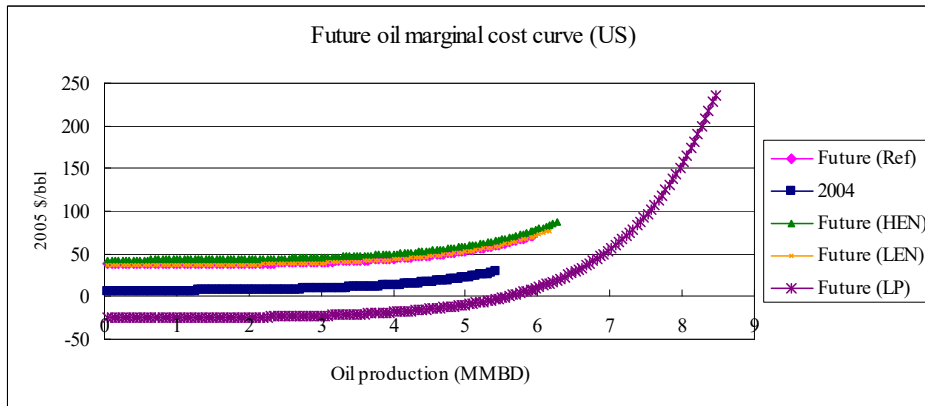


Figure 9. Estimated gasoline marginal cost curve

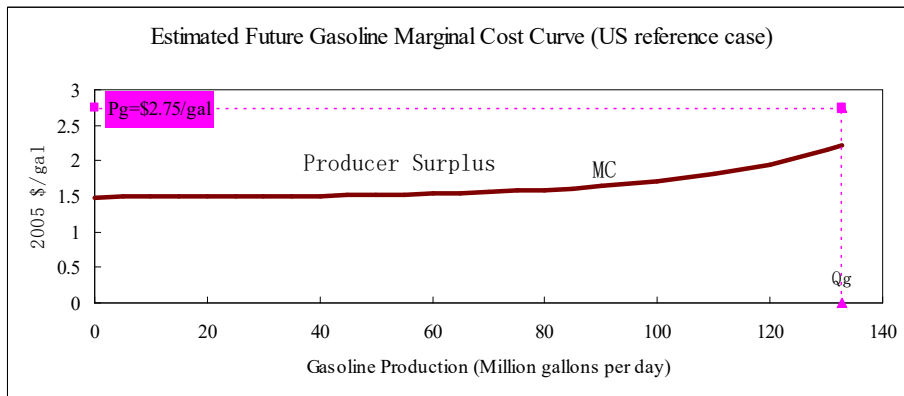


Table 5. The US producer surplus changes for 10%, 20%, 50%, and 100% contractions in demand for motor gasoline in the US in 2004.

A. Gasoline made in US from US crude oil

	Contraction of demand for gasoline by:			
	10%	20%	50%	100%
$\Delta PS_{t,c}$				
\$ billion	1.24	2.95	10.32	33.57
\$/gal	0.40	0.46	0.61	0.75
$\Delta PS_{t,i}$				
\$ billion	13.95	22.09	21.31	0
\$/gal	4.45	3.46	1.25	0
ΔPS_t				
\$ billion	15.20	25.04	31.63	33.57
\$/gal	4.84	3.92	1.86	0.75
PSf_{ac}	31.89%	37.97%	49.03%	56.73%

B. Gasoline made in US from OPEC crude oil

	Contraction of demand for gasoline by:			
	10%	20%	50%	100%
$\Delta PS_{t,c}$				
\$ billion	2.61	5.31	14.13	36.98
\$/gal	1.03	1.03	1.03	1.03
$\Delta PS_{t,i}$				
\$ billion	11.25	17.81	17.19	0
\$/gal	4.45	3.46	1.25	0
ΔPS_t				
\$ billion	13.86	23.12	31.32	36.98
\$/gal	5.48	4.49	2.28	1.03
PSf_{ac}	77.52%	77.52%	77.52%	77.52%

C. Gasoline made in US from ROW crude oil

	Contraction of demand for gasoline by:			
	10%	20%	50%	100%
$\Delta PS_{t,c}$				
\$ billion	3.37	6.85	18.24	47.74
\$/gal	1.02	1.02	1.02	1.02
$\Delta PS_{t,i}$				
\$ billion	14.67	23.23	22.41	0
\$/gal	4.45	3.46	1.25	0
ΔPS_t				
\$ billion	18.04	30.08	40.65	47.74
\$/gal	5.47	4.48	2.27	1.02
PSf_{ac}	76.73%	76.73%	76.72%	76.72%

D. Gasoline made in US (all: sum of A, B, and C)

	Contraction of demand for gasoline by:			
	10%	20%	50%	100%
$\Delta PS_{t,c}$				
\$ billion	7.22	15.11	42.69	118.29
\$/gal	0.80	0.83	0.88	0.93
$\Delta PS_{t,I}$				
\$ billion	39.88	63.13	60.91	0
\$/gal	4.45	3.46	1.25	0
ΔPS_t				
\$ billion	47.10	78.24	103.60	118.29
\$/gal	5.25	4.29	2.13	0.93
PSf_{ac}	61.26%	63.39%	67.26%	69.95%

Table 6. Projections for 2025 oil supply from OPEC and DOE/EIA (million barrels per day)

OPEC	54.3 (incl. NGLs)	41 (incl. NGLs, about 79% is crude oil)	57 (incl. NGLs)	46 (high price)	61 (reference)	71 (low price)
Non-OPEC	58.9	60.1	56.4			
Source	Barkindo, 2006	OPEC, 2012	Qabazard, 2006	EIA 2003	EIA 2003	EIA 2003

Note: the percentage 79% (OPEC, 2012) was used to estimate crude oil production from the other two sources (Barkindo, 2006, Qabazard, 2006).

Table 7. The foreign producer surplus changes for 10%, 20%, 50%, and 100% contractions in demand for motor gasoline in the US in 2025

A. Gasoline made in US from OPEC crude oil

	Contraction of demand for gasoline by:			
	10%	20%	50%	100%
ΔPS_t (\$billion)	\$20	\$34.90	\$48.82	\$53.26
PS_{fac}	77.33%	77.33%	77.33%	77.33%

B. Gasoline made in US from ROW crude oil

	Contraction of demand for gasoline by:			
	10%	20%	50%	100%
ΔPS_t (\$billion)	\$30.23	\$52.74	\$73.71	\$80.23
PS_{fac}	77.01%	77.01%	77.01%	77.01%

Table 8. Social lifetime cost of hydrogen fuel cell versus gasoline vehicles in 2025 (Present value of cost streams over life of vehicle; 2005 USD)

	Gasoline			Hydrogen	
	Correct: US losses	Correct: global losses	Incorrect: hybrid US/global	Incorrect: all producer surplus is a cost	(US)
Fuel cost excluding taxes	\$4,906	\$4,906	\$4,906	\$4,906	\$6,102
Fuel taxes	\$1,763	\$1,763	\$1,763	\$1,763	\$1,904
Fuel producer surplus	\$4,704	0	\$4,704	\$7,087	\$132
Climate change damages	\$333	\$2,613	\$2,613	\$2,613	\$213
Other external costs	\$13,090	\$12,434	\$13,090	\$12,434	\$4,603
All other costs	\$45,739	\$45,739	\$45,739	\$48,507	\$52,423
Total	\$70,534	\$67,454	\$72,815	\$77,310	\$65,377

Notes: All values except producer surplus are from Ref. (Sun et al., 2010), using high estimates of external costs. Producer surplus estimates here are equal to fuel cost without producer surplus adjustment multiplied by the ratio of producer surplus without producer surplus adjustment to fuel cost, where this ratio is from the analysis here (0.405 for the US producers and 0.77 for foreign producers). The treatment of producer surplus for hydrogen fuel is discussed in Appendix B.

Appendix

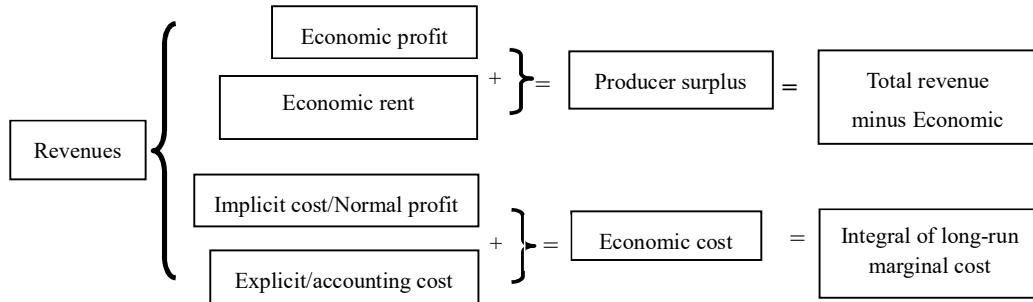
Appendix A. Terms and Concepts Relevant to Producer Surplus

Table A1. Glossary of terms relevant to the discussion of producer surplus

<p>Producer surplus: revenue received by producers from selling goods at the market price over and above the long-run average cost. It comprises economic profit and economic rent (Figure 2).</p>
<p>Economic profit: total revenue minus economic rent and economic cost. Economic profit is zero in long-run equilibrium in perfect competition. Hence, economic profit is the portion of producer surplus that arises in non-competitive markets, such as oligopolies.</p>
<p>Economic rent: extra payment for an input that firm is willing to pay over the minimum amount necessary to retain it in its current use (the opportunity cost of the input). Economic rent is the portion of producer surplus that is <i>not</i> due to non-competitive markets; in competitive markets in the long-run equilibrium, producer surplus = economic rent. Economic rent arises when some firms have exclusive access to low-cost factors of production, such as large, easy-to-exploit mineral reserves, technology protected by patents, or captive cheap labor.</p>
<p>Normal profit (implicit costs): The portion of revenue identified with implicit cost. Whereas in the long run in perfect competition economic profit is zero, normal profit is nonzero (Boyes and Melvin, 2008). Normal profit, based on a “normal” rate of return to investment, is not a component of producer surplus (Figure A1).</p>
<p>Explicit cost (also accounting cost): accounted cost that firms have to pay in the form of money; distinguished from “implicit” costs.</p>
<p>Economic cost (also resource cost, or opportunity cost, or long-run marginal cost): payment required to employ inputs for production; equal to implicit plus explicit costs. The long-run marginal cost curve represents economic cost.</p>
<p>Long-run average cost: the area under the long-run marginal cost curve for ΔQ, divided by ΔQ.</p>

Note: For a detailed discussion, see Nicholson (2004) and Pindyck and Rubinfeld (2004).

Figure A1. Connections between various economic concepts



Appendix B. Producer Surplus for Hydrogen Fuel

Estimates of the cost of hydrogen fuel are not derived from market prices (which for future hydrogen fuels do not exist), but rather are built from detailed engineering cost studies and hence are direct estimates of average economic cost. This means that in a comparison of the social cost of hydrogen vehicles with the social cost of gasoline vehicles, one does not need to subtract the producer surplus from the estimates of hydrogen cost. However, in a comparison of the private cost – the cost the consumer pays – one must estimate the *price* the consumer faces rather than the average cost. Because price projections are not available for hydrogen, one must estimate the price of hydrogen by *adding* the producer surplus to the aforementioned engineering estimates of the average cost of hydrogen. Table A1 summarizes the conceptual estimation of the social cost and the private cost of fuel for gasoline and hydrogen.

Table B1. Conceptual framework for the estimation of the social cost and the private cost of gasoline and hydrogen.

	Gasoline	Hydrogen
Private cost	Projections of gasoline price, e.g. from the EIA (2009a)	Estimated average cost plus estimated producer surplus
Social cost	Projected gasoline price minus estimated producer surplus	Engineering estimates of average economic cost, e.g. Lemus and Duarte (2010)

We have not analyzed the potential producer surplus on sales of hydrogen fuel. However, we believe the regional-market marginal cost curve for producing hydrogen is likely to be relatively flat, and that hence the price is likely to be close to the average cost. For example, imagine that we have a national program to produce hydrogen from wind or photovoltaic electrolysis of water. Suppose that half of the total hydrogen supply can be produced in windy or sunny areas at a relatively low cost, while the other half must be produced in less well-endowed areas at a relatively high cost. If there was a single national market, in which all producing regions were connected to all consuming regions by inexpensive transportation

modes, then there would be a single national price of hydrogen equal to the marginal cost of the high-cost producers plus transportation costs. In this case, the low-cost producers would enjoy considerable producer surplus. This would be analogous to the situation with oil today, in which oil can be transported anywhere in the world for a small fraction of the cost of marginal oil production. However, the transport of hydrogen is expensive, and varies considerably with distance (Yang and Ogden, 2007). Regions with high-cost primary energy sources (less solar or wind energy) will pay either for high-cost energy plus low-cost transport, or low-cost energy plus high-cost long-distance transport, whereas regions with low-cost primary energy sources will pay for low-cost energy plus low-cost, local transport. Thus, in a realistic hydrogen scenario there will be significant regional price heterogeneity, and in any one region, average cost will not be much less than marginal cost price. This is similar to the case for electricity today, where power costs vary considerably by region, and very long distance transport of power is rare.

Appendix C. Detailed Methodology

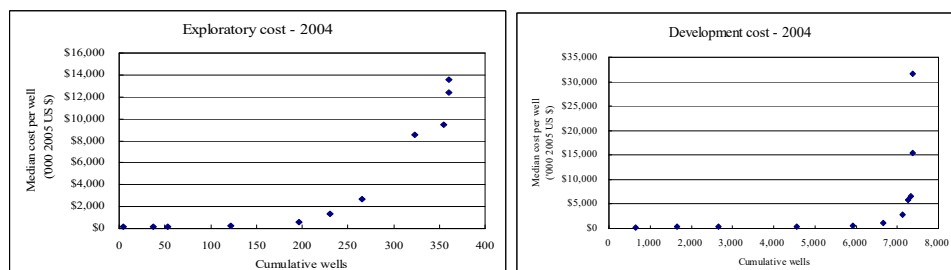
C.1. Current US oil cost curve

C.1.1. Marginal exploration cost (MEC) and marginal development cost (MDC)

We estimate the marginal exploration cost (MEC) and marginal development cost (MDC) with costs of drilling and equipping wells by depth intervals from the API/JAS. We employ an exponential function to characterize the marginal exploration cost and the marginal development cost.

It makes economic sense that the shallowest oil wells, which are the lowest cost, are explored and developed first, followed by less shallow ones, and lastly the deepest. The median cost per well, not affected by very high or low values, is chosen for our analysis because it is a better representation of the central tendency of the population than the average cost per well. We create a new variable “cumulative number of wells” for each well depth interval by adding up the number of wells with depth interval no more than its upper limit, rank the median cost from the lowest to the highest, and plot the cost per well in thousand dollars against cumulative wells shown in Figure C1. In this paper all prices and costs are adjusted to constant 2005 US dollars using a GDP deflator.

Figure C1. Median cost per well versus cumulative number of wells



The EIA Annual Energy Review (AER) 2009 contains information on crude oil production and crude oil well productivity for the years 1954-2009 (EIA, 2009b). Given the total production of 5,419 thousand barrels per day in 2004, we can calculate the average

production per exploratory or development well by dividing total production by total exploratory or development wells. For each well depth interval category (from the JAS data), the number of wells and median cost per well are converted into oil production in barrels and cost per barrel separately with the following two equations. The first equation determines the production per barrel in each depth interval:

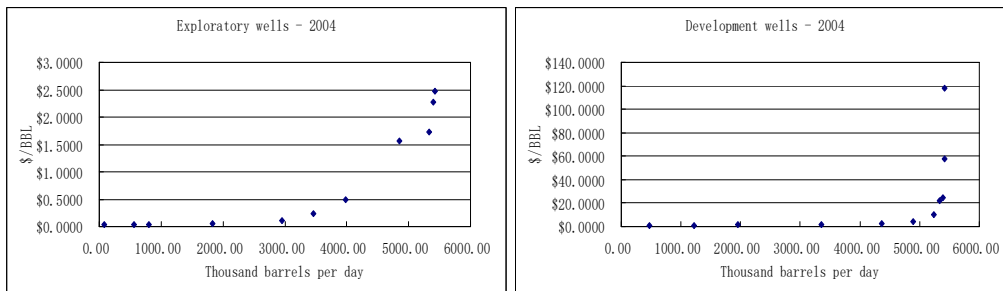
$$Q_i = W_i \times \frac{TP}{TW}, \quad (C1)$$

where Q_i is the oil production level in barrels for depth interval i , W_i is the number of exploratory or development wells for depth interval i (from the JAS data), TP is the total oil production (from the AER data), and TW is the total number of exploratory or development wells over all depth intervals (from the JAS data). The second equation determines the cost per barrel for each depth interval:

$$C_i = (W_i \times CW_i) / Q_i, \quad (C2)$$

where C_i and CW_i are cost per barrel and median cost per well for the i th depth interval. Figure C2 graphs the cost in dollar per barrel against cumulative production in barrels for exploratory and development wells.

Figure C2. Cost per barrel versus production levels



Using the above cost and production data points, we fit the data to three functional forms where y is the cost in \$/bbl and x is the production level in million barrels per day (MMBD). Regression results for the three functional forms are presented in Table 2. Of the

three, the exponential form (Specification #3 in Table C1) is chosen for both exploratory and development wells as it provides the best goodness of fit and the coefficients are statistically significant.⁷

Thus, we estimate marginal exploration cost (MEC) and marginal development cost (MDC) as a function of oil output (Q), as follows:

$$MEC = \exp(-4.0379 + 0.8579 * Q) \quad (C3)$$

$$MDC = \exp(-1.2995 + 0.7998 * Q) . \quad (C4)$$

⁷ We also tried the quadratic form used in NEMS. For exploration cost, a functional form $y=ax+bx^2$ fits the data is larger than that using the exponential form. For development cost, a quadratic function doesn't fit at all and no coefficient is statistically significant.

Table C1. Regression results with three assumed functional forms

		(1)	(2)	(3)
		$y = a + b x$	$\ln(y) = a + b \ln(x)$	$y = \exp(a + b x)$
Exploratory wells (MEC)	a	-0.4697 (0.3040)	-2.0698 *** (0.3936)	-4.0379 *** (0.2352)
	b	0.4098 *** (0.0820)	1.0730 ** (0.2717)	0.8579 *** (0.0634)
	R-squared	0.735	0.634	0.953
Development wells (MDC)	a	-16.1807 (23.803)	-0.1038 (0.6684)	-1.2995 (0.7239)
	b	9.7975 (5.5366)	1.6643 ** (0.4805)	0.7998 *** (0.1684)
	R-squared	0.258	0.571	0.715

Notes: Standard errors in parentheses. y is the cost in \$/bbl and x is the production level in million barrels per day (MMBD). Significance codes:

* 5% level, ** 1% level, and *** 0.1% level.

C.1.2. Other exploration and development (OED) costs

In addition to the costs of drilling and equipping wells, total exploration expenditures also include the costs of acquiring undeveloped acreage, land scouting, geological and geophysical activities, lease rental, direct overhead and general administration. Similarly, total development expenditures include the costs of lease equipment, acquiring producing acreage, improved recovery programs, direct overhead and general administration. The API provides survey data on oil and gas expenditures for exploration, development and production separately, but with no detailed breakdown for oil only that identifies the contribution of “other exploration and development” costs. Complete data for other exploration and development (OED) expenditures was available from API only for the period 1976-1982. Fortunately, the EIA Financial Reporting System (FRS) (EIA, 2008a) includes several schedules for review of the functional performance (financial data on energy supply) of the major US energy-producing companies in total from 1977 to 2007. Both oil and gas wells are included in the FRS schedules for petroleum operations. The comparison between API and FRS data for their overlapped period (1977-1982) shows that the total OED cost from FRS was about 25%-50% of that from API with the lowest percentage in 1979. A simple regression of API total OED cost (API_OED) on FRS total OED cost (FRS_OED) generates the results as follows:

$$API_OED = 2.67109 * FRS_OED . \quad (C5)$$

$$(0.21656)$$

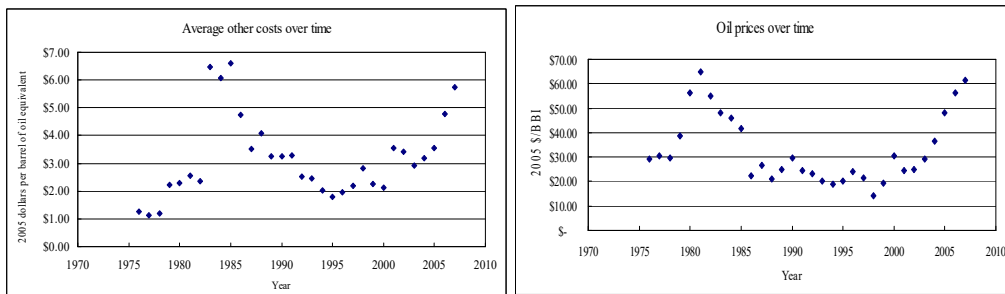
$$p\text{-value} = 0.00006$$

$$R\text{-Squared} = 0.9682$$

We employ this coefficient to scale up the FRS total OED costs to approximate API costs for the period for which we do not have actual API cost data, 1983 to 2007. Total OED costs including oil and gas wells are then divided by total oil and gas production levels (EIA, 2009b, EIA, 2008b) to obtain the average OED costs over time, which appear to have similar pattern with oil prices over time (Greene and Tishchishyna, 2009), as shown in Figure C3. The comparison, to some extent, justifies the method we use in Section 4.4 to project future oil costs. Next we make two assumptions: (1) oil and gas have the same average OED costs; and

(2) the average OED cost (\$/bbl) is independent of oil production. The second assumption is based on the calculated correlation coefficient (less than 0.1) between average OED cost and oil production over the period 1976 to 2007. With these assumptions, we can add the average OED cost in 2004 as a constant (C_{OED}) to the sum of exploratory and development drilling costs.

Figure C3. Average OED costs and oil prices over time



C.1.3. Marginal production cost (MPC)

To estimate the marginal production cost (MPC), we assume an exponential function and calibrate it with data from the EIA/FRS. Oil exploration and development are followed by oil production. However, we do not have current data on oil production costs. The production cost data available from API was for annual total oil and gas production from 1973 to 1991, involving direct operating expenditures, taxes, general and administration overhead and other indirect expenses. To find out what the oil production cost curve looks like after 1991, we investigate the detailed statistics on “support activities for oil and gas operations” in the mining sector from the US Economic Census (US Census Bureau, 1987-2007). These statistics are available every five years from the US Census Bureau. Five data sets for years 1987, 1992, 1997, 2002 and 2007 show that each cost category, including the payroll, cost of supplies, total shipments/receipts/services, total depreciation, total rents, and other expenses, increased non-linearly over time. Given that the annual US oil and gas production (in barrels of oil equivalent) changed very little (17-18 MMBD) during these years, we conclude that the marginal production costs also increased non-linearly with cumulative outputs.

To simplify modeling oil marginal production cost (*MPC*) change with oil production Q , we assume it has a similar shape to the above drilling cost shown in the following functional form, where c and d are parameters to be calibrated with 2003 and 2004 data:

$$MPC = c \cdot \exp(d \cdot Q). \quad (C6)$$

The most recent total production costs, available from both API and FRS, indicate that the FRS costs were about 70% of the API costs. We use this ratio to scale up the FRS total production costs in 2003 and 2004. Total production cost and oil and gas production in 2003 and cumulative production cost and production in 2003 and 2004 are the two data sets⁸ used to estimate the coefficients c ($= 2.9332$) and d ($= 0.006971$).

⁸ Here two equations are used for solving two unknowns (c and d).

C.1.4. Total oil cost curve

The standard error for the US oil producer fraction (PSf), as calculated by the Delta Method (DeGroot, 1986), is given by:

$$SE(PSf) = \left[(0.2352 * \frac{1}{P_0 Q_0} * \frac{1}{b_1} [\exp(a_1 + b_1 Q_0) - \exp(a_1)])^2 + (0.0634 * \frac{1}{P_0 Q_0} * \left\{ \frac{1}{b_1^2} [\exp(a_1 + b_1 Q_0) - \exp(a_1)] - \frac{1}{b_1} Q_0 \exp(a_1 + b_1 Q_0) \right\})^2 + (0.7239 * \frac{1}{P_0 Q_0} * \frac{1}{b_2} [\exp(a_2 + b_2 Q_0) - \exp(a_2)])^2 + \left(0.1684 * \frac{1}{P_0 Q_0} * \left\{ \frac{1}{b_2^2} [\exp(a_2 + b_2 Q_0) - \exp(a_2)] - \frac{1}{b_2} Q_0 \exp(a_2 + b_2 Q_0) \right\} \right)^2 \right]^{1/2} \quad (C7)$$

When evaluated at our parameter values, the standard error for the US oil producer fraction (PSf) is $SE(PSf) = 0.13$.

The standard error for the marginal cost of oil, as calculated by the Delta Method (DeGroot, 1986), is given by:

$$SE(MC_{oil}) = \left((0.2352 * \exp(a_1 + b_1 Q_{oil}))^2 + (0.0634 * Q_{oil} * \exp(a_1 + b_1 Q_{oil}))^2 + (0.7239 * \exp(a_2 + b_2 Q_{oil}))^2 + (0.1684 * Q_{oil} * \exp(a_2 + b_2 Q_{oil}))^2 \right)^{1/2} \quad (C8)$$

When evaluated at $Q_{oil}=5.419$ MMBD, the standard error for the marginal cost of oil is $SE(MC_{oil}) = 24.23$.

There is still uncertainty regarding the parameters c and d , which were calibrated using 2003 and 2004 data on Equation (C6). These parameters affect the marginal cost and producer surplus statistics above. To address this uncertainty, we use all combinations of 2 years between 2000 and 2004 to calibrate c and d . There are 5 years between 2000 and 2004, which makes a total of $5 \times 4 = 20$ combinations. For each of the combinations, we calculate c and d using the same GDP deflator (i.e., year 2005 \$). For each set of estimates of c and d , we calculate MC_{oil} and PSf . We then find the upper and lower bound values for MC_{oil} and PSf among all the estimates. Our results show that MC_{oil} ranges from a lower bound of \$32.31/bbl to an upper bound of \$29.49/bbl. We find that PSf ranges from a lower bound of 68.03% to an upper bound of 71.84%.

Ideally, we would estimate the oil cost curves for OPEC and ROW separately using a similar method. However, the API JAS data does not include detailed drilling cost data for other regions. Although the FRS data contains total oil costs for other foreign regions, including

Canada, OECD Europe, Africa, Middle East, FSU & East Europe, and other Western and Eastern Hemispheres, the cost data were incomplete for some regions and expenditures on oil wells and gas wells were not distinguishable. Furthermore, FRS covers major energy-producing companies only. We therefore treat OPEC and ROW differently, using data from the World Bank (Section C.3).

C.2. Current US gasoline cost curve

The objective in this section is to estimate the marginal wholesale cost of producing gasoline from US crude oil, compare that with the price of gasoline, and estimate the associated total producer surplus, for the refining industry and the oil industry. Because we already have estimated the marginal cost of producing crude oil in the US, and we know that the marginal cost of gasoline (MC_g) is related to the marginal cost of oil (MC_o), we will derive a simple linear relationship where the marginal cost of gasoline at the refinery gate is equal to the marginal cost of refining (in dollars per gallon of gasoline, or \$/gg) plus the marginal cost of the oil input to the refinery (expressed in \$/gg). This relationship will have the form:

$$MC_g = k_1 + k_2 MC_o, \quad (C9)$$

where MC_g is the marginal wholesale cost of gasoline at the refinery gate in \$/gg, k_1 is the constant marginal cost of refining in \$/gg (assumed to be independent of the cost and quantity of oil refined), MC_o is the marginal cost of oil in dollars per barrel of crude oil produced (\$/bcp) (Equation 7), and k_2 is a coefficient that converts the cost of oil production in \$/bcp to the contribution of oil cost to the marginal wholesale gasoline cost in \$/gg; hence, k_2 has units (\$/gg)/(\$/bcp). Note that we do not estimate the marginal cost of downstream gasoline marketing (gasoline transportation and gasoline retailing), because we believe that producer surplus in downstream marketing is relatively small, on account of the strong competition and similar cost structures among marketing firms.

To derive the expression for MC_g in Equation (C9), we first set up the following analogous linear relationship between the price of gasoline and the price of crude oil, which we can estimate on the basis of historical data (see Figure C4):

$$P_g = a + b \cdot P_o. \quad (C10)$$

P_g (\$/gg) is what the Energy Information Administration (EIA) calls the “refiner sales price to resellers.” Refiner sales prices to resellers are pre-tax wholesale prices for sales of motor gasoline to purchasers who are other than ultimate consumers (Table 5.22 of EIA, 2009b). These are thus wholesale prices at the refinery gate and presumably exclude downstream marketing price margins (transportation and retailing) as well as taxes.

P_o (\$/bcp) is the “crude oil domestic first purchase price” (Table 5.18 of EIA, 2009b), which according to the EIA’s glossary (EIA, 2009b) is “the price for domestic crude oil reported by the company that owns the crude oil the first time it is removed from the lease boundary.” The basis of this price thus appears to be the same as the basis of our estimates of the marginal cost of oil production (Equation 7).

a is a constant in \$/gg (year 2005 \$) and is what the EIA (2009b) calls the “refiner margin” for motor gasoline. The refiner margin is the difference between the price to resellers (P_g here) and what the EIA (2009b) calls the “crude oil refiner acquisition cost” expressed in \$/gg. The crude oil refiner acquisition cost expressed in this way is essentially the contribution of the oil price to the wholesale refinery-gate price of gasoline. We define the term $b \cdot P_o$ in Equation 9 so that it is this contribution of the oil price to the wholesale gasoline price (see explanation of b , next).⁹

b is a conversion coefficient: the ratio of the contribution of the crude oil price to wholesale gasoline price, in \$/gg, to the price of crude oil produced, in \$/bcp.

We estimate the parameters a and b in two ways. In the first method, we estimate a as the refiner margin reported by the EIA (Table 5.22 of EIA, 2009b), and estimate b by dividing the contribution of the crude oil price to wholesale gasoline price by P_o (Table 5.18 of EIA, 2009b). The contribution of crude oil price to wholesale gasoline price is calculated as the difference between P_g (Table 5.22 of EIA, 2009b) and the refiner margin for motor gasoline (Table 5.22 of EIA, 2009b).

⁹ The EIA also reports the actual refiner crude oil acquisition cost in \$/bbl, and presumably uses this to calculate the contribution of oil price to gasoline price, in \$/gg. The difference between the crude oil refiner acquisition cost in \$/bbl and the crude oil domestic first purchase price (P_o in Equation 8) is that the former includes some minor additional transportation and “other” fees, which typically are on the order of \$3/bbl (our estimate by comparing Table 5.18 with Table 5.21 in EIA, 2009b). However this difference is not relevant to our calculation because we use the coefficient b to convert P_o into the contribution of oil price to the wholesale gasoline price.

In the second method, we regress P_g on P_o (Table 5.18 of EIA, 2009b). The results of both methods are given in Table C2. All prices in are in constant 2005 US dollars. The two methods give similar estimates of a and b . The estimates of a (the refiner margin) differ by only 5-7%, and the estimates of b (the $\$/\text{gg}/\$/\text{bcp}$ coefficient) differ only by 2-3%. We will use the regression for the more recent period, 2000 to 2009; hence, $a = 0.368$ and $b = 0.0249$.

Figure C4. Crude oil domestic first purchase price and motor gasoline refiner sales prices to resellers

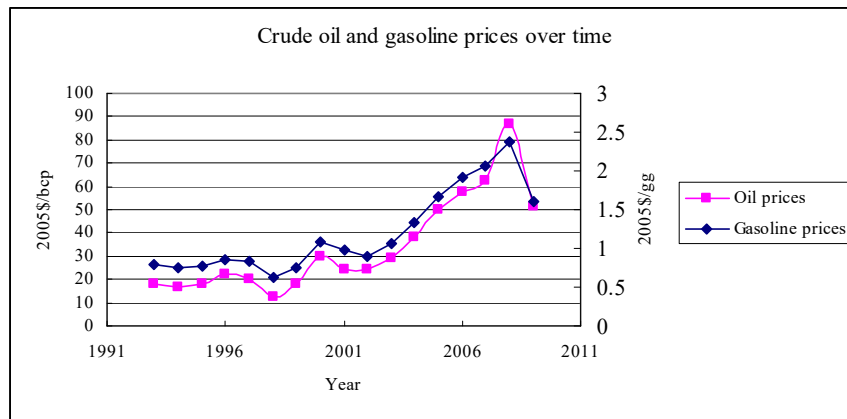


Table C2. Results of constant a and coefficient b

a	b	
a =Refiner margin	b =oil/gasoline ratio	
0.343	0.0250	Average 1993-2009
0.389	0.0244	Average 2000-2009
0.422	0.0239	Value in 2004
<i>Regress P_g on P_o (1993-2009 data)</i>		
0.320 ***	0.0257 ***	Unadjusted R-squared = 0.985
(0.0319)	(0.0008)	
<i>Regress P_g on P_o (2000-2009 data)</i>		
0.368 ***	0.0249 ***	Unadjusted R-squared = 0.975
(0.0699)	(0.0014)	

Notes: Standard errors in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

The next step is to derive an expression for marginal cost from Equation (C10). We know that the price is equal to the marginal cost plus producer surplus, so we can split all of the price terms of Equation (C10), including the constant a , into MC and producer surplus components:

$$\begin{aligned} P_g &= MC_g + PS_g = a \cdot MCf_{g,r} + a \cdot (1 - MCf_{g,r}) + b \cdot (MC_o + PS_o) \\ &= a \cdot MCf_{g,r} + a \cdot (1 - MCf_{g,r}) + b \cdot MC_o + b \cdot PS_o \end{aligned} \quad , \quad (C11)$$

where PS_g is producer surplus and $MCf_{g,r}$ is the marginal cost fraction of the price constant for gasoline refining. Next, we separate the MC and producer surplus terms:

$$MC_g = a \cdot MCf_{g,r} + b \cdot MC_o \quad (C12)$$

$$PS_g = a \cdot (1 - MCf_{g,r}) + b \cdot PS_o \quad (C13)$$

Note that Equation (C12) has the same form as Equation (C9). Next, we substitute the Equation (2) expression for MC_{oil} into the MC_o term of Equation (C12):

$$MC_g = a \cdot MCf_{g,r} + b \cdot [\exp(a_1 + b_1 \cdot Q_o) + \exp(a_2 + b_2 \cdot Q_o) + C_{OED} + c \cdot \exp(d \cdot Q_o)] \quad (C14)$$

The standard error for the marginal cost of gasoline, as calculated by the Delta Method (DeGroot, 1986), is given by:

$$\begin{aligned} SE(MC_g) &= [(0.0699 * 0.8)^2 + (0.0014 * MC_o)^2 + (0.2352 * b * \exp(a_1 + b_1 Q_o))^2 + \\ &(0.0634 * b * Q_o \exp(a_1 + b_1 Q_o))^2 + (0.7239 * b * \exp(a_2 + b_2 Q_o))^2 + (0.1684 * b * \\ &Q_o \exp(a_2 + b_2 Q_o))^2]^{1/2} \end{aligned} \quad (C15)$$

When evaluated at our parameter values, the standard error for the marginal cost of gasoline is $SE(MC_g) = 0.61$.

The standard error for the producer surplus PS_g , as calculated by the Delta Method (DeGroot, 1986), is given by:

$$\begin{aligned} SE(PS_g) &= [(0.0699 * 0.2)^2 + (0.0014 * P_o * PS_f)^2 + (0.2352 * \left(-\frac{b}{Q_o} * \frac{1}{b_1} [\exp(a_1 + b_1 Q_o) - \right. \\ &\left. \exp(a_1)]\right))^2 + \left(0.0634 * \frac{b}{Q_o} * \left\{\frac{1}{b_1^2} [\exp(a_1 + b_1 Q_o) - \exp(a_1)] - \frac{1}{b_1} Q_o \exp(a_1 + b_1 Q_o)\right\}\right)^2 + \\ &\left(0.7239 * \left(-\frac{b}{Q_o} * \frac{1}{b_2} [\exp(a_2 + b_2 Q_o) - \exp(a_2)]\right)\right)^2 + \left(0.1684 * \frac{b}{Q_o} * \left\{\frac{1}{b_2^2} [\exp(a_2 + b_2 Q_o) - \right. \right. \end{aligned}$$

$$\exp(a_2)] - \frac{1}{b_2} Q_0 \exp(a_2 + b_2 Q_0) \}}^2]^{1/2}. \quad (C16)$$

When evaluated at our parameter values, the standard error for the producer surplus PS_g is $SE(PS_g) = 0.13$.

There is still uncertainty regarding the parameters c and d , which were calibrated using 2003 and 2004 data on Equation (C6). These parameters affect the marginal cost and producer surplus statistics above. To address this uncertainty, we use all combinations of 2 years between 2000 and 2004 to calibrate c and d . There are 5 years between 2000 and 2004, which makes a total of $5 \times 4 = 20$ combinations. For each of the combinations, we calculate c and d . For each set of estimates of c and d , we calculate MC_g and PS_g . We then find the upper bound and lower bound values for MC_g and PS_g among all the estimates. We then find the upper and lower bounds for MC_g and PS_g among all the estimates. Our results show that MC_g ranges from a lower bound of \$1.00/gal to an upper bound of \$1.03/gal. We find that PS_g ranges from a lower bound of \$0.72/gal to an upper bound of \$0.75/gal.

Thus far we have estimated all of the terms except $MCF_{g,r}$, the marginal cost fraction of the refiner margin for gasoline. We assume $MCF_{g,r} = 0.80$ according to the average ratio of petroleum product net refining margin to petroleum product gross refining margin from 1988 to 2009 with data from EIA Financial Reporting System.

The next step is to find the price and quantity lines for gasoline production from domestic crude oil in our reference year of 2004. According to the EIA (2009b), in 2004 the refiner “sales price to resellers” for motor gasoline – the same price basis used for Equation (C10) and Figure C4 – was \$1.29/gallon in nominal dollars and \$1.33 in year 2005 dollars. Because our objective here is to estimate the marginal cost of producing gasoline from US crude oil, in US refineries, the relevant total quantity is the amount of gasoline that would have been produced had all domestically produced crude oil in 2004 been input to refineries, which is equal to $Q_{o,2004}$ (5.419 MMBD) multiplied by the ratio of actual motor-gasoline produced by refineries to crude oil input to refineries in 2004 (EIA, 2009b), resulting in 122 mmgd.

The producer surplus associated with domestic gasoline fuel made from domestic crude oil is the area bounded by price line and marginal cost curve from output level zero to the

estimated 122 mmgd gasoline output in 2004 from domestic oil.

C.3 Producer surplus as a function of the change in gasoline consumption

We break the total producer surplus change (ΔPS_t) into two pieces: one (we call this component $\Delta PS_{t,c}$, which is the triangular area ABC) is due to the equilibrium consumption change and the second component (called $\Delta PS_{t,i}$, which is the rectangular area BCP^0P^*) is due to the change in price (“inframarginal” consumption), shown in Figure 4 and estimated in the following equations:

$$\Delta PS_t = \Delta PS_{t,c} + \Delta PS_{t,i} \quad (C17)$$

$$\Delta PS_{t,c} = [(P_g^0 \cdot Q_g^0) - \int_0^{Q_g^0} MC(Q_g) dQ_g] - [(P_g^0 \cdot Q_g^*) - \int_0^{Q_g^*} MC(Q_g) dQ_g] \quad (C18)$$

$$\Delta PS_{t,i} = (P_g^0 - P_g^*) \cdot Q_g^* \quad (C19)$$

The only unknown is the after-change gasoline price P_g^* . To estimate this, we employ the oil demand function used in NEMS (EIA, 2010) as given by::

$$Q_d = \alpha \cdot P^{\varepsilon_d} \quad (C20)$$

where P is the price, Q_d is the demand quantity, $\varepsilon_d = -0.11$ is the demand elasticity from NEMS (EIA, 2010), and α is a constant to be determined by a point on the curve.

We assume that the US oil market is competitive. Given this, Figure 4 ($D =$ demand) illustrates two supply-demand equilibrium cases before and after oil demand contracts, where MC (cost curve S) has the same shape as we estimate for 2004 (Figure 2), but vertically shifts up so that the curve passes through the point (P_0, Q_0) , and intersects the original demand curve D at A . When oil demand declines from Q_0 to Q' , the new demand curve D' will pass through point $N (P_0, Q')$, but with the same demand elasticity as the initial demand curve D .

The new demand curve D' intersects the cost curve S at B , corresponding to a new, lower price P^* (and, incidentally, to a quantity Q^* greater than Q' , on account of the lower price spurring additional consumption). Based on Equations (2) and (C20), we estimate the after-change oil price P_o^* . Plugging into Equation (C10), we obtain the after-change gasoline price P_g^* . With Equations (C16), (C18), and (C19), we calculate the total producer surplus reduction

ΔPS_t , and its components $\Delta PS_{t,c}$ and $\Delta PS_{t,i}$.

C.4 Estimating producer surplus for OPEC and the rest of the world

To estimate producer surplus for OPEC and the rest of the world, we start with unpublished World Bank data on crude oil annual average world price and production in years 2003 and 2004 to develop oil supply cost curves for OPEC and ROW (the Rest of the World except the US). The World Bank data contains annual oil production, rent (total revenue minus total cost¹⁰, i.e. total producer surplus) and average world price for many countries from 1970 to 2004, including ten OPEC members (Iraq, Iran, Kuwait, Saudi Arabia, Venezuela, Qatar, Indonesia, United Arab Emirates, Algeria and Nigeria). We assume an exponential function form with two parameters similar to Equation (C4) for OPEC and ROW marginal cost curves. One country's total oil cost for each year is calculated with the world oil price times the country's oil output minus the country's oil rent.¹¹ The sum of total oil costs for the ten OPEC members gives the total OPEC oil cost and the sum of total oil costs for the rest of the countries (except the US) gives the total ROW oil cost.

We calibrate the parameters in Equations (8) and (9) for the oil marginal cost curves for OPEC and ROW using 2003 and 2004 data, and obtain $c_{OPEC} = 2.825$, $d_{OPEC} = 0.0008$, $c_{ROW} = 9.431$, and $d_{ROW} = 0.0004$. To obtain lower bound and upper bound values for the marginal cost and producer surplus statistics that are calculated from these parameters, we use all combinations of 2 years between 2000 and 2004 to calibrate these four parameters. There are 5 years between 2000 and 2004, which makes a total of $5 \times 4 = 20$ combinations. For each of the combinations, we calculate these four parameters. Results show that c_{OPEC} ranges from a lower bound of 2.821 to an upper bound of 2.873; that d_{OPEC} ranges from a lower bound of -0.0010 to an upper bound of 0.0009; c_{ROW} ranges from a lower bound of 9.088 to an upper bound of 10.101; that d_{ROW} ranges from a lower bound of -0.0040 to an upper bound of 0.0041.

¹⁰ Unfortunately, the World Bank data does not provide the definition of rent. We treat it as the difference between revenue (price times oil output) and total cost. As the World Bank data includes the US, we compare the calculated average oil cost (\$11.86/bbl) to our estimate (\$11.29/bbl) for 2004 and they are very close.

¹¹ Here the oil rent is defined as the product of oil output and the difference between oil price and average oil cost, same as the definition of total producer surplus. This is different from the economic rent discussed in Section 2.

To obtain lower bound and upper bound values for the marginal cost and producer surplus statistics that are calculated from these parameters, we use all combinations of 2 years between 2000 and 2004 to calibrate these four parameters. There are 5 years between 2000 and 2004, which makes a total of $5 \times 4 = 20$ combinations. For each of the combinations, we calculate these four parameters. For each set of estimates of these four parameters, we calculate MC_{OPEC} , MC_{ROW} , and all the producer surplus fraction statistics in Table 3. Results show that MC_{OPEC} ranges from a lower bound of \$2.83/bbl to an upper bound of \$2.86/bbl, and that MC_{ROW} ranges from a lower bound of \$9.37/bbl to an upper bound of \$9.80/bbl. We report the upper bound and lower bound values for all the OPEC and ROW producer surplus statistics in Table 3.

C.5. Future Oil and Gasoline Marginal Cost

C.5.1. Overview of the estimation method

In this section, we estimate the future oil marginal cost curve and then the future gasoline marginal cost for the US based on historical data and our estimated 2004 US oil marginal cost curve. In general, the cost of oil in the US in the future can be influenced by geopolitics, technological progress, oil output, world oil price, remaining reserves, investors' strategy, alternative energy options, and other factors. Here we model the future annual total cost (TC) in billion dollars of petroleum from both oil and gas wells (the API and the EIA FRS do not provide cost data for oil wells and gas wells separately) as a function of time (t), oil price (P_{oil}), oil output (Q_{oil}), gas output (Q_{gas}) and remaining reserves (Rev) of oil and gas, as given by Equation (11).

We fit the historical cost data from API and EIA FRS, and choose the best-fitting one among different functional forms for estimations. Assuming oil and gas production have the same average cost (in dollars per barrel), we then estimate the average oil cost in the future through 2030 by dividing the estimated total cost TC by total oil and gas production. To obtain the future oil marginal cost curve, we shift the 2004 US oil cost curve so that the curve produces the same average oil cost as we estimate. Finally, gasoline marginal cost curves are derived from oil cost curves using the method in Section C.2.

C.5.2. Detailed estimation method

The EIA AEO 2009 (EIA, 2009a) projects US oil and gas supply, demand, prices and end of year reserves through 2030 under five cases: reference, high price, low price, high economic growth and low economic growth. The lower 48 crude oil wellhead price in 2030 is projected to be \$45/bbl under low price case (oil output: 5.36 MMBD) and \$194/bbl under high price case (oil output: 8.47 MMBD).

The total cost incurred to extract and produce petroleum sources includes expenditures on acquisition, exploration, development and production. The historical total cost data from API and EIA FRS for the period from 1977 to 1991 indicates that the FRS total cost was about 70% of the API total cost. We extrapolate the API total cost by dividing the FRS total cost by 0.7 for the years 1991 to 2007. Thus we have total cost (TC) available over years 1977 to 2007. The time variable t is defined as the year minus 1975. For each case in EIA AEO 2009 (e.g., reference case, low-price case), a new variable “Price Difference” is generated by the annual oil price (EIA, 2009a, Greene and Tishchishyna, 2009) minus the average oil price over the years 1977-2030. The variable “Price Difference” is labeled as “ $Pdiff$ ” under the updated reference case, “ $PdHP$ ” under the high-price case, “ $PdLP$ ” under the low-price case, “ PdH ” under the high-economic growth case, and “ PdL ” under the low-economic growth case. Historical oil output and gas output are from EIA (EIA, 2008b) and projected ones are from EIA AEO 2009 (EIA, 2009a). Remaining oil and gas reserves (beginning-of-year) in 2007 are estimated by adding the 2007 oil and gas production to the 2007 end-of-year oil & gas reserves (billion barrels) (EIA, 2008b). For the period from 1977 to 2006, the beginning-of-year reserves are calculated backward.

We take the natural logarithm of the total cost TC as the dependent variable and try different combinations of the five variables (time, oil production, gas production, price difference and natural logarithm of reserves) as regressors. Regression results show that coefficients on oil production and price difference are statistically significant at 5% level and the coefficient on gas production is not statistically significant even at 25% level. Based on this, we may assume that changes in total cost over time are independent of changes in gas production (we assume that gas cost is included in the constant in the total cost function). In theory, TC should decrease with time (because technology improves over time), increase with

annual oil output (supply Q_{oil}), and increase with decreasing reserves (because remaining reserves are increasingly costly to access). We exclude results that are inconsistent with these theoretical expectations and finally choose oil output and price difference as two dependent variables for regression of total cost under the five cases shown in Table C3. The coefficients on oil output and price difference and the R-squared values are the same across the five cases; only the constants differ. Given this, it does not matter which case we use. For convenience we use the Reference oil price case.

Table C3. Regression of natural logarithm of total cost on oil output and price difference (using data from 1977 to 2007)

	Ln(tc)	Coefficient	Std Error
Reference (Ref)	Const	4.636 ***	0.197
	Q_{oil}	0.061 *	0.025
	Pdiff	0.028 ***	0.002
	R-squared = 0.861		
High-price (HP)	Const	5.351	0.225
	Q_{oil}	0.061	0.025
	PdHP	0.028	0.002
	R-squared = 0.861		
Low-price (LP)	Const	4.083 ***	0.184
	Q_{oil}	0.061 *	0.025
	PdLP	0.028 ***	0.002
	R-squared = 0.861		
High-Econ (HEN)	Const	4.749 ***	0.201
	Q_{oil}	0.061 *	0.025
	PdH	0.028 ***	0.002
	R-squared = 0.861		
Low-Econ (LEN)	Const	4.670 ***	0.198
	Q_{oil}	0.061 *	0.025
	PdL	0.028	0.002
	R-squared = 0.861		

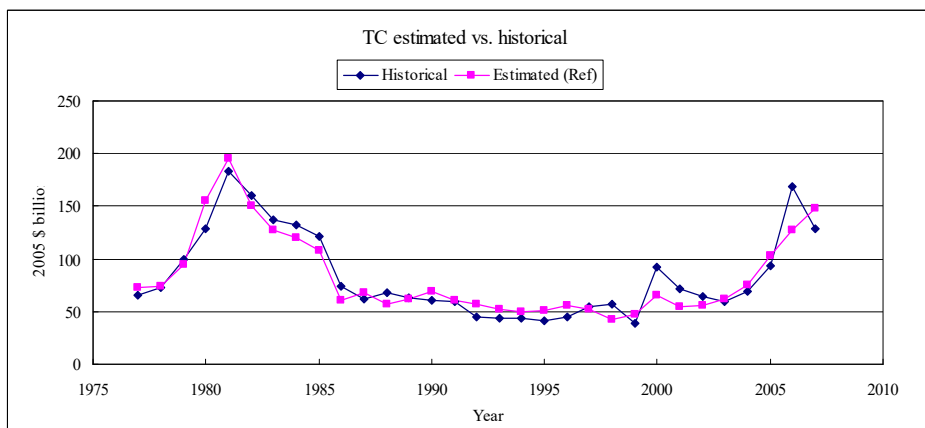
Notes: Standard errors in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

The functional form of total cost for the reference oil price case is given by:

$$TC = \exp(4.64 + 0.061 \cdot Q_{oil} + 0.028 \cdot Pdiff). \quad (C21)$$

Figure C5 shows the predicted (fitted) versus historical total cost against time for the reference case. The regression appears to reflect the general trend of total cost.

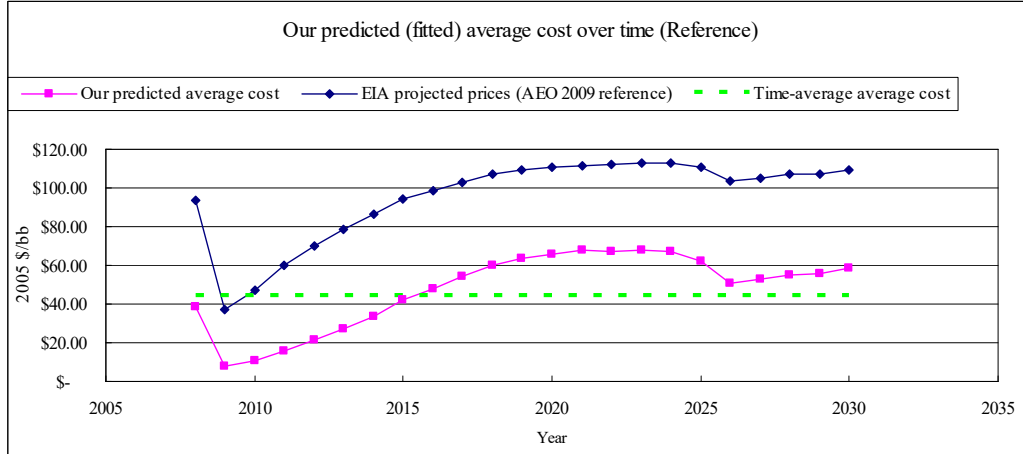
Figure C5. Estimated vs. actual total costs (\$/year)



To estimate the average cost beyond 2007, we assume that oil average cost is the same as gas average cost and divide predicted total annual cost beyond 2007 by total annual oil and gas output. We predict future total cost using Equation (C21) and the EIA’s Ref, LP, HEN, and LEN oil price projection cases. We do not use the EIA’s high oil price case (HP) because it entails increased production from onshore CO₂-enhanced oil recovery projects and offshore deepwater projects, and these sources have a cost structure different than that of the historical mix of sources upon which our regression is built. High oil price would also encourage unconventional oil development, which is beyond of the scope of our analysis. Moreover, our regression results for the high-price case are not realistic: the projected average oil cost beyond 2015 is over \$200/bbl, which is even higher than EIA projected price (AEO 2009 high price case).

The predicted future average cost, shown in Figure C6, closely follows the EIA’s AEO 2009 reference case projection of oil prices.

Figure C6. Our Projected oil average costs and EIA projected oil prices



To estimate the marginal cost curve for any future year, we vertically shift the 2004 oil marginal cost curve (Figure 2) such that the shifted curve generates the same average cost in that particular year, where the average cost is the integral of the oil cost curve from oil output zero to the EIA projected oil production, divided by the projected oil production. Formally:

$$MC_f = MC_{2004} + S \quad , \quad (C22)$$

where MC_f = future oil marginal cost, MC_{2004} = the 2004 oil marginal cost (equation 7) and where S = shifter (constant value) is given by:

$$S = \frac{AC_f \cdot Q_f - \int_0^{Q_f} MC_{2004} dQ}{Q_f} \quad . \quad (C23)$$

This method assumes that the US oil industry employs the current recovery technology in the future. To present a general trend of future oil marginal cost curve instead of a curve for each years, we take the average oil average cost (AC_f) for the period 2005-2030 as a proxy for estimating a single future oil marginal cost curve. The corresponding future oil production (Q_f) is just the time-average one (5.92 MMBD for the reference case).

In the final step, we use the method of Section C.2 to derive the gasoline marginal cost

curve from the oil marginal cost curve derived above. We regress gasoline price on oil price and a constant using the EIA projections from 2005 to 2030 for the reference case (EIA, 2009a). To derive the gasoline cost curves, we assume $MCF_{g,r} = 0.85$ because US refineries have shown decreasing net margins in recent years.

To estimate the producer surplus for OPEC and ROW beyond 2004, we simply repeat what we did for year 2004 in Section C.4 using the World Bank data for each year t from 1992 to 2003, assuming the same functional form as in Equation 7. Then we obtain time-dependent coefficients $c(t)$ and $d(t)$ for OPEC and ROW respectively. We regress each coefficient on time to estimate the trend, based on which we estimate future marginal cost for OPEC and ROW. Since the coefficients $d(t)$ for OPEC or ROW from 1992 to 2003 show little variation, we just take the average. Our results for the marginal costs for OPEC and ROW are presented in Equations (12) and (13).