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Renewable Fuel and the Global Rebound Effect

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Abstract

Evaluations of renewable fuel standards typically compute the reduction in global greenhouse gas emissions based on the amount of fossil fuel "displaced." However they universally fail to provide any explanation of how displaced fuel stops the production of fossil fuel. In spite of this, they assume that every gallon displaced does, in fact, stop exactly one gallon of production.

In its 2010 analysis of the national Renewable Fuel Standard Program (RFS2), the Environmental Protection Agency (EPA) explains that this is not the case, but it continues to rely on this assumption nonetheless. In fact, to the extent displacement does stop production, it must do so by reducing the world oil price. But reducing this price will increase the demand for fossil fuel just as it decreases supply. This increase in demand is the global rebound effect, and it partly cancels the climate benefits of producing renewable fuels.

The main difficulty with estimating this effect lies in estimating OPEC's response to a decline in the price of oil. To make use of a broad spectrum of expert opinion on this question, the sensitivity of the world oil price to a change in supply is estimated from the results of several well-respected models. The estimated sensitivities are then combined with the EPA's estimated world demand elasticity of oil. The resulting estimates of the global rebound effect range from 29 percent to 70 percent, with the estimate based on EPA's values coming in at 32 percent. This value implies that a traditional estimate that ethanol will reduce GHG emissions by 22 percent should be corrected to indicate an increase of 10 percent in GHG emissions.

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1 Introduction

"The displacement of gasoline and diesel with renewable fuels has a wide range of environmental and economic impacts." So begins the EPA's Regulatory Impact Analysis (RIA) of the Renewable Fuel Standard Program (RFS2). But when fuel is "displaced," what happens to it? Whether the displaced fuel causes more fuel to be burned in Chinese car engines or causes Iran to pump less oil from the ground matters a great deal. On this crucial question, the EPA is almost silent. In the next 1100 pages of its RIA, no methodology for determining the destination of the displaced fuel is ever discussed.

Instead, the EPA's calculations simply assume that no gasoline or diesel will be displaced to other vehicles throughout the world or to any consumer or industrial use whatsoever. But the EPA understands this assumption is incorrect and explains why in the concluding paragraph of Section 2.7 of the RIA, the section in which the environmental impact of "displacement" is discussed.

> Increased renewable fuel use domestically is expected to also have the effect of lowering the world crude oil price and therefore **increase international demand for petroleum-based fuels and increase GHG [greenhouse gas] emissions**. … This increase in demand outside of the U.S. due to price changes would **partially negate the decrease in GHG emissions domestically** from reduced petroleum fuel demand due to biofuels. This impact of biofuels use on crude oil imports and world crude oil price is included [only] in our Energy Security Analysis discussed in Chapter 5 [emphasis added]. (US EPA 2010, the second page numbered 427, pdf page 512)

As the EPA explains, the increase in the international demand for petroleum-based fuels means that some of the displaced gasoline and diesel will find its way indirectly into the fuel tanks and engines of international consumers demanding more fuel at a lower world price.

While the EPA should be commended for acknowledging that this price effect is omitted from its calculations, it must be noted that it failed to make any estimate of the consequences of this omission or to argue that the resulting error is small. The omitted effect is the global rebound effect (GRE), and this report shows how to estimate it and how to use it to estimate the magnitude of errors in the EPA's conclusions.

An estimate of the value of the GRE based on EPA values taken from the RIA puts the value of the global rebound effect at 32 percent. If this is correct, then, when corn ethanol saves 22 percent of the greenhouse gas (GHG) emissions from a displaced gallon of gasoline, 32 percent of the displaced gasoline goes to "increased international demand for petroleum-based fuels." This increases GHG emissions by 32 percent of the lifecycle emissions attributable to the displaced gallon of gasoline. The net result is that for gasoline displaced by this ethanol, global GHG emissions increase approximately 10 percent instead of decreasing by EPA's reported 22 percent.

The inclusion of the indirect effect is not only logically necessary but is required of the EPA by the Energy Independence and Security Act of 2007, which created the RFS2. As the EPA notes, "Congress states that: The term

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'lifecycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (*including* direct emissions and *significant indirect emissions* such as significant emissions from land use changes) [emphasis added]." Rebound emissions are "significant indirect emissions."

1.1 Estimating the Global Rebound Effect

This report estimates the global rebound effect not just from values in the RFS2 RIA and its background information, but also from values given in reports from other government, quasi-government and private research institutions. The other reports utilized in this study are from the U.S. Department of Energy (1998 and 2008), Wharton Economic Forecasting Associates (1998), the Electric Power Research Institute (1998) and the International Energy Agency (2005 and 2007). The Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change reports even larger effects on the world price of oil.

The values of the global rebound effect calculated from information in these reports are 29%, 29%, 32%, 33%, 36%, 45%, and 70%. The final value, which might appear to be an outlier, is based on the International Energy Agency's 2007 analysis of a "High Growth Scenario," which means, in effect, a high oil-demand scenario. This is the only one of the reports that seriously attempts to estimate the impact of the demand for oil in a future with oil prices nearly as high as US EIA is now forecasting. (The EPA report does assume high prices, but it uses out-of-date market data to form its estimates.) If the IEA analysis is right, the impact of renewable fuels in reducing dangerously high oil demand could cause a surprisingly large reduction in the world price of oil and consequently a surprisingly large global rebound effect.

While the magnitude of the global rebound effect is uncertain, and there is some chance it could be considerably smaller than the estimate based on EPA's values, there is also some chance that it will be much greater. But, given the available information, it is unreasonable to conclude that the effect is likely to be smaller than the estimate implied by EPA's own values.

1.2 How the Global Rebound Effect Works

Displacement of fossil fuel by renewable fuel is only the first step in reducing GHG emissions. To succeed, displacement of fossil fuel from vehicles in the U.S. must prevent the pumping of oil, mostly in foreign countries, and especially in countries that belong to OPEC. In spite of the fact that the displacement effect provides the primary environmental benefit reported in the RIA, EPA provides no explanation of how it works and no estimate of how strongly it will affect supply. It simply assumes without comment that displacement will affect only supply and not demand. That is, the EPA's analysis tacitly assumes that every barrel of oil displaced from local consumption will cause some mix of global oil producers to reduce their total output by exactly one barrel.

Of course, to some unknown extent, local displacement will reduce global oil production. This effect works through the decrease in the world oil price noted by the EPA, as quoted above. This means that the supply-reduction effect works through exactly the same price channel as the demand-increase effect which the EPA implicitly sets to zero in its calculations.

The extent to which the price of oil affects producers is measured by "supply elasticity," and the effect on consumers is measured by the "demand elasticity." Both tend to be low in the short-run and high in the long run. These elasticities are taken into account by the Oil Supply Metrics Model, which calculated the oil price reduction reported in the RIA. When David Greene and Paul Leiby (2005) presented this model to US DOE, they listed the short-run supply and demand elasticities as 0.06 and 0.10 respectively, and the long-run supply and demand elasticities as 0.6 and 0.7 respectively.[1] Note that in both cases demand is more elastic than supply. If this were the whole story, slightly more displaced oil would end up being consumed than would end up reducing production by suppliers. In other words, the global rebound effect would be greater than 50 percent.

Such a rebound effect could easily reverse the environmental benefits of many renewable fuels. But there is one more piece to the story. Supply elasticity estimates usually do not include OPEC's reaction to the world price of oil. It may be that OPEC cuts production more than other producers in response to a price decrease. Unfortunately OPEC's behavior is not well understood, which is why this report relies on many different expert judgments in order to estimate the global rebound effect.

[1] http://www1.eere.energy.gov/ba/pba/docs/oil_security_metrics_model.ppt. See slide 36.

1.3 Two Fallacies

Two arguments frequently lead to a fallacious rejection of the rebound effect. These need to be taken seriously simply because they arise so often.

1.3.1 Fallacy 1: Small Bites Don't Add Up

The first fallacy holds that renewable fuel production is just too small to affect the world oil market, so it cannot increase international oil demand. This is wrong on two counts. First, if small displacements of fossil fuel had no impact on the world oil market, they would affect neither supply nor demand and the displaced fuel would simply increase the global inventory of liquid fuel. By 2022, inventory would be increasing by over 500 million barrels a year. But changes in inventory that are 100 times smaller are big enough to make the news because they do change the price of oil, as illustrated by the following excerpts from a 2009 news report: "Oil tops $72 on inventory drop. … Crude for October delivery rose 2.23%, or $1.58. … The Energy Information Administration said crude stocks dropped 4.7 million barrels in the week ended Sept. 11 [2009]."[2]

In spite of this, owners of particular ethanol plants may argue that their particular effect is negligible. There are two correct responses to this argument. First of all, as the cited news story shows, the argument is simply incorrect. Even one typical ethanol plant will produce, over its lifetime, more than the 4.7 million barrels that caused $1.58 change in the world price of oil. And, since that change affects essentially the entire world's supply of oil, it has an enormous impact.

The second response is that even the smallest ethanol plant is like one airplane passenger. Each passenger on a plane may be right in claiming that the plane would have flown without them. They can then conclude they caused no fuel use. With this logic we can prove that almost no passengers cause any fuel to be used. Nonetheless we know that if they all stayed home, no planes would fly. On average, they do cause fuel to be used—we just can't tell which passengers cause a whole flight to be added, and which cause no change. The only reasonable way to deal with this uncertainty is to assign each passenger an average effect, which is just how carbon footprints are calculated. So for both reasons—because even small ethanol producers do have an impact, and because average impacts should be used in any case—there is no justification for claiming renewable fuel sources are too small to matter. They all matter proportionally.

1.3.2 Fallacy 2: The Rebound Effect Takes 10 or 20 Years

The global rebound effects estimated in this paper are long-run effects. This means they take 10 or 20 years to fully materialize. But that view is misleading. The long-run effect does take that long to develop, but the short and medium run effects will likely be quite similar, and perhaps stronger. To see this, one must look at the market's price response, as well as at demand elasticity. The *long-run* price response estimated by EPA is $1.06 per barrel. But the *short-run* price-response is five or ten times greater. In fact, between July 2008 and December 2008, demand dropped 3% and price dropped by $100/bbl. So even though short-run demand elasticity is very low, short-run price response is very high. This means that the global rebound effect may have its full long-run strength right from the start.

Another approach to this is to compare supply and demand elasticities. Those reported above (Green and Leiby 2005) show short-run demand exceeding short-run supply by a greater proportion than it does in the long-run. This indicates that the short-run rebound effect is stronger than the long-run rebound effect. However, this does not take into account OPEC and the speed of its reaction. But for small gradual changes that reaction may well be slow. So nothing in this report should be taken to indicate that the short-run rebound effect is any weaker than the long-run rebound effect.

2 Calculating Estimated Values for the Global Rebound Effect

OPEC's response plays a significant role in determining the global rebound effect (GRE). So do global supply and demand elasticities. All three, and especially OPEC's response, are difficult to estimate, and there is a range of expert opinion regarding these estimates. Consequently, this study does not attempt to estimate the GRE directly

[2] http://money.cnn.com/2009/09/16/markets/oil/index.htm

from estimated elasticities and behavioral parameters. Instead it uses model outputs, and in one case model inputs, to construct estimates of the GRE that are consistent with those models. By doing so, it makes use of the broad range of expert judgments that are embodied in those models.

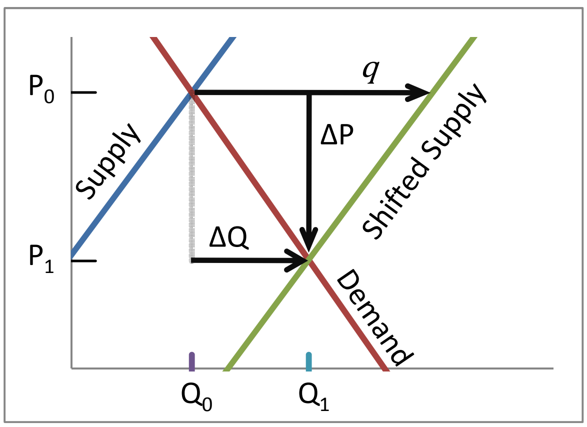
This section describes two methods for making use of model inputs and outputs, then the use of demand elasticities is discussed, and finally the main results of this study are presented. In the following two sections, the values used in this section's summary table are documented in detail. Note that in all cases long-run values are used because short-run values change too quickly to compare across models, and because long-run values are ultimately more important.

The first method for using model data applies to reports that concern a stated shift in the supply or demand curve. The second method applies to reports that do not state the size of that shift but instead give the change in demand that results from a combination of such a shift *and* the global rebound effect.

2.1 Estimation Method #1

This method applies when the initial demand or supply shift is known. Consequently it applies to the US EIA (2008) and US EPA (2010) reports. For example, the increase in the supply of renewable fuels is given in the RFS2 RIA. Similarly, the EIA analysis gives the change in production of Alaskan oil. These exogenous changes in supply lead to a change in the world price of oil. In both cases there is a supply increase, so in both cases the world price of oil is reduced.

Figure 1. Estimation Method #1



Estimation Method #1 uses "price sensitivity," s, when the shift in a supply or demand curve is known. $GRE = e \cdot s$; e = demand elasticity.

Figure 1 show the supply-curve shift, q, that drives the price reduction in models where Method 1 is applicable. The arrow labeled ΔQ shows the increase in demand due to the global rebound effect. This is the increase in demand caused by the drop in the world price of oil from P0 to P1. The strength of the rebound effect, GRE, is the ratio of ΔQ to q. In Method 1 the formula for this ratio is $GRE = e \cdot s$, where s is the price sensitivity and e is the elasticity of demand. This formula is explained and derived in Appendix A.

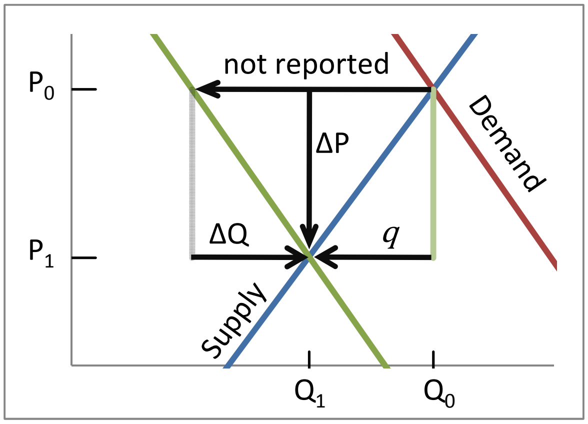
The rebound quantity, ΔQ, is the amount of the initial supply increase that is displaced to consumers instead of being displaced back to suppliers who then reduce their production. This is the amount by which the RFS2 RIA over-counts the fossil-fuel reduction that reduces GHG emissions.

2.2 Estimation Method #2

This method applies when there is an initial unreported demand-curve shift, but the resulting change in demand is given. The second method is applied to the remaining five reports. In the IEA's (2005) low-demand scenario, for example, the demand reduction is the result of policy. But the direct results of that policy, e.g. reduced gasoline usage by smaller cars, are not given. Only the net result of those changes *and* the world oil price reduction is reported.

That net reduction is shown as q in Figure 2. The initial shift in the demand curve is shown as "not reported." This time, the strength of the rebound effect, GRE, is the ratio of q to "not reported." In Method 2, the formula for this ratio is $GRE = e \cdot f/(1+e \cdot f)$, where f is the inverse (i.e. reciprocal) supply elasticity and e is the elasticity of demand. As with price sensitivity, the inverse supply elasticity is determined from q and ΔP. This GRE formula is also explained and derived in Appendix A.

Figure 2. Estimation Method #2



Estimation Method #2 uses inverse supply elasticity, f, when the net change in demand is known. $GRE = e \cdot f/(1+e \cdot f)$.

In the cases where Method 2 is applied, the demand curve shifts, but the amount of the shift is not reported. However the net changes in price and quantity are reported and since the supply curve is not shifted, these changes reflect the global supply curve for liquid fuel. Consequently the reported changes allow the calculation of the elasticity of supply.

2.3 Global Demand Elasticity

The rebound effect can be viewed as a two-step process—the price falls and that causes demand to increase. So, along with the price sensitivities just discussed, an estimate of global demand elasticity will be needed. As discussed below, demand elasticities from a peer-reviewed background report for the RFS2 RIA will be used. But in one case, there is a difficulty with using these values with the price sensitivity.

In the case of the US EPA values used to estimate GRE, the price sensitivity and demand elasticity are from the same source so there is no possibility of an inappropriate match. But in the case of the US EIA report on Alaskan oil, the higher price sensitivity is at least a weak indication that the report is based on a lower than typical demand elasticity. Because of this weak indication, and to be cautious, the EPA's "Low" values for demand elasticity will be used. But, having gone to the lower limit on elasticity, the resulting estimate of GRE should be considered an underestimate as indicated in the right column of Table 1.

Estimates of GRE that utilize Method #2 need no such correction, because this method uses the (inverse) supply elasticity and, unlike price sensitivity, that is unrelated to demand elasticity. So for the first five reports listed in Table 1, the "Mid" value of EPA's demand elasticity is used (Leiby 2008, Table A4).

2.4 Principal Results Concerning the Global Rebound Effect

Table 1 summarizes the principle findings of this study. The first column lists the seven reports that were found from which a price sensitivity or supply elasticity could be computed. The next two columns list the value of whichever could be inferred from the report. The fourth column gives the "Mid" value for global demand elasticity as derived from Leiby's (2008) report to EPA for the RFS2 RIA, or in one case the "Low" value. The column labeled GRE gives the value of the global rebound effect as estimated from the previous four columns.

Table 1. Estimates and under-estimates of the Global Rebound Effect

	Price Sensitivity (s)	Inverse Supply Elasticity (f)	Demand elasticity (e)	Estimation Method	GRE	Under Estimate?
US EIA Kyoto 1998	---	3.09	26.6%	#2	**45%**	
WEFA Kyoto 1998	---	2.11	26.6%	#2	**36%**	
EPRI Kyoto 1998	---	1.87	26.6%	#2	**33%**	
IEA 2005 (low demand)	---	1.50	26.6%	#2	**29%**	
IEA 2007 (high demand)	---	8.92	26.6%	#2	**70%**	
US EIA 2008	1.62	---	18.1%	#1	**29%**	Likely
US EPA's RFS2 RIA 2010	1.19	---	26.6%	#1	**32%**	

For Method #1, $GRE = e \cdot s$, and for Method #2, use $GRE = e \cdot f / (1 + e \cdot f)$. WEFA is the Wharton Economic Forecasting Associates, EPRI is the Electric Power Research Institute, IEA is the International Energy Agency. Price sensitivity or inverse supply elasticity is computed from the report listed at the left. Demand elasticity is taken from Leiby (2008, Table A4). The "Low" demand elasticity from Leiby (2008, Table A4) is used for US EIA 2008 to avoid an upward bias to GRE.

Note that the values in the GRE column do not cluster near zero and hence do not support the approach to estimating GHG emissions pursued by the RFS2 RIA. Also note that the value of GRE implied by EPA's own report appears quite reasonable, though perhaps a little low. In spite of this, using its own value would have made a dramatic difference for corn ethanol and corn ethanol suppliers. And it would have made a significant difference for all renewable fuels.

The uncertainty in GRE is likely even greater than it appears to be, given the variation in the values listed. This is suggested by the one outlier (IEA 2007), which also happens to be the value that may be the most relevant going forward. The IEA estimated that in a world where increased economic growth caused an increase in demand of 3.2%, the world oil price would jump by 40%. This is the only estimate that specifically applies to a world with high oil prices. The EPA's estimate takes its supply and demand elasticities from academic studies completed between 1975 and 2003 (Leiby 2008, Table A1), and reaches conclusions that are proportionally similar to conclusions from prior years. The EPA-based estimate of GRE shows no sign of any jump in oil price sensitivity that the IEA deems likely to occur in a tight future oil market.

In spite of the uncertainty in GRE estimates, the evidence presented here clearly indicates that the 32 percent value derived from the EPA's own investigation should not be dismissed as an over estimate. It appears from the values in Table 1 that there is at least an even chance (50% or more) that the true value of GRE is even greater. A GRE of this magnitude would likely mean that most production of corn ethanol in the United States was increasing the global emissions of greenhouse gases (US EPA 2010, Figure 2.6-1).

3 The Sensitivity of the World Oil Price

The first step in the rebound process is the reduction in the world price of oil. But because OPEC influences the price of oil, estimating this effect is particularly difficult. This section relies on the expert judgments of petroleum market behavior—including OPEC behavior—as embedded in major models used to analyze energy and climate policies. Some of these models have been used and tested for years. Their designers have had to confront the questions of global supply and demand for oil and of OPEC's behavior and have had to answer these questions explicitly.

The following subsections examine reports based on these models, one per subsection, and use the reported values and descriptions to construct estimates of either price sensitivity or inverse supply elasticity. Price sensitivity is defined as follows:

s = (percent change in price) / (an initial policy-induced percentage change in supply)

The denominator of the price sensitivity definition does not take into account the effect of the price change on demand, and refers to a shift in a supply curve. Inverse supply elasticity is defined for an unreported demand-curve shift as:

f = (percent change in price) / (percent change in final demand for liquid fuel)

The two values, s and f, must be treated differently to find the global rebound effect and the two different formulas required are derived in Appendix A. The values of s and f that are documented in the following sections are listed here in Table 2 for convenience.

Table 2. Implied Responsiveness of World Oil Price to Changes in World Oil Demand or Supply

s or f	Report
f = 3.1	US EIA's report on the effect of the Kyoto Protocol, 1998.
f = 2.1	Wharton Economic Forecasting Associates' model of the Kyoto Protocol, 1998.
f = 1.9	Electric Power Research Institute's (EPRI) model of the Kyoto Protocol, 1998.
f = 1.5	International Energy Agency: *World Energy Outlook 2005* (low-demand scenario).
f = 8.9	International Energy Agency: *World Energy Outlook 2007* (high-demand scenario).
s = 1.6	US EIA's "Analysis of Crude Oil Production in the Arctic National Wildlife Refuge," 2008.
s = 1.2	US EPA's "Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis," 2010.

3.1 The US EIA's 1998 Report on the Effect of the Kyoto Protocol

In 1998 the Department of Energy's EIA studied the possible impact of compliance with the Kyoto Protocol by the United States and the so-called Annex I countries—basically the developed countries. It was assumed that carbon pricing in the United States would be used to drive reductions in the use of fossil fuels and hence in greenhouse gas emissions. It was also assumed that these reductions would be mirrored by the other Annex I countries. The reductions in the world oil price would cause increased demand throughout the world, which would partially offset these reductions. EIA reports the net U.S. effect of the carbon pricing and the reduced world oil price, because it is the net effect that must comply with the Kyoto Protocol. This means, q, in Figure 2, is what is reported, and Method 2 is the appropriate way to estimate the global rebound effect.

The US EIA's 1998 report on the impacts of the Kyoto Protocol estimated that it would reduce Annex-I oil use, which would in turn lower the world price of oil:

> Because of lower petroleum demand in the United States and in other developed countries that are committed to reducing emissions under the Kyoto Protocol, world oil prices are lower by between 4 and 16 percent in 2010, relative to the reference case price of $20.77 per barrel. (US EIA 1998, p. xix)

The range in estimated oil price reductions ("between 4 and 16 percent") is accounted for largely by the level of compliance with the Protocol and possibly by the quantity of carbon permits purchased in the international market. The report also confirms that the world oil price "has a strong impact on consumption … of oil in the United States." The "strong impact on consumption" is the global rebound effect.

> The world price of oil has a strong impact on consumption and production of oil in the United States. Conversely, U.S. demand for and production of oil affects the world price of oil. The feedback of U.S. oil markets on international markets is represented within the NEMS framework. (US EIA 1998, p.13)

In order to derive an appropriate value for world inverse supply elasticity, f, it is necessary to look at long run values. Since the effect begins in 2005 and the report covers through 2020, the 2020 values will be used. Also the impact of oil demand reduction by other developed countries must be taken into account. The report explains this as follows.

> For this analysis, it is assumed the other Annex I countries will reduce their consumption of oil in order to help meet their reduction targets. Each country is assumed to reduce its oil demand by the same percent that the United States reduces oil demand from the reference case level. (US EIA 1998 p. 13)

The US EIA report (1998) relies on EIA's 1998b International Energy Outlook, which estimates (Table A3) that in 2020 total industrialized oil consumption will be 55.3 Mb/d and that consumption by Eastern Europe and the former Soviet Union will be 10.1 Mb/d. Together these comprise the Annex I countries. Oil consumption in 2020 by the United States is estimated at 24.4 Mb/d. Any reduction in U.S. oil consumption due to the Protocol must then be multiplied by (55.3+10.1)/24.4 = 2.68 to find the reduction for Annex I countries.

Table ES3 (p. xxi) of the EIA report (1998) shows that the "Purchases of International Permits" falls from 363 to 160 to zero as emission fall from 24% above 1990 levels to 9% above and finally to 3% below. It seems almost certain that such purchases were also assumed to be zero at 7% below. This will be assumed and maximum compliance with the Protocol (emissions 7% below 1990 levels) will be utilized for estimation of the GRE. This assumption produces the smallest estimate of inverse supply elasticity of any compliance assumption, and hence the lowest estimate of GRE.

The 7% reduction level will be compared with the Reference Case, which is a 33% increase in emissions. Table B1 (p. 160–161) of the EIA report shows Consumption of Petroleum Products being reduced from the Reference Case (46.88 Quads/year) to the 7%-Below Case (41.67), which is an 11.1% reduction and corresponds to a 2.71 Mb/d reduction for the U.S. This in turn corresponds to a 7.27 Mb/d reduction for Annex I countries, based on the 2.68 Annex-I factor from above.

However, because of the decrease in the world price of oil, non-Annex I countries will have increased their consumption of oil. To be conservative, as discussed in Section 4, the EPA's low demand elasticity of 20% will be used (Leiby 2008, Table A4), along with the 15.3% price decrease documented below and the non-Annex I oil consumption of 50.6Mb/d (US EIA 1998b, Table A3). The increase in non-Annex I consumption is then 20% × 15.3% × 50.6, which equals a 1.54Mb/d increase in oil consumption. This gives a net decrease in the world's demand for oil of 7.27−1.54 = 5.72, or 4.9% of the world total of 116Mb/d.

The same Table B1 (US EIA 1998) lists the world price of oil in 2020 for the Reference Case ($21.69/bbl) and in the 7%-Below Case ($18.38/bbl). This amounts to a 15.3% reduction in the world price of oil, which allows the inverse supply elasticity to be calculated as follows.

World inverse supply elasticity, f = (% change in price)/(% change in demand) = 15.3%/4.9% = 3.09

3.2 Wharton Economic Forecasting Associates' Model of the Kyoto Protocol, 1998

The second estimate of oil supply elasticity comes from a report from Wharton Economic Forecasting Associates (WEFA 1998), "Global Warming: The High Cost of the Kyoto Protocol." At that time, WEFA was a leading econometrics and economic-forecasting firm founded by Nobel Prize economist Lawrence R. Klein, and was associated with the Wharton School of the University of Pennsylvania.

Page 22 of this report makes a remark concerning "other developed economies" that is parallel to the remark in the EIA analysis. "As demand for petroleum products declined here *and in other developed economies*, producer prices for crude oil would decline from baseline levels." (emphasis added) Although this is not explained in detail, it seems almost inevitable that the same proportional approach was used as is described by US EIA (1998). It would have required a huge additional effort to model the other developed countries individually and there is no further mention in the WEFA report of international modeling. Consequently the present estimate of f follows the same path as the above estimate of f for the EIA analysis.

According to the Base Case table (WEFA 1998, p. 24), U.S. petroleum use was estimated to be 45,237 trillion Btu in 2020, and according to the Limiting Carbon table (p. 26), petroleum use would fall to 37,207 T Btu. That's a reduction of 17.8%. Using US EIA's IEO1998 as above, this corresponds to a reduction of 4.33 Mb/d in the United States and a reduction of 2.68 × 4.33 = 11.6 Mb/d for all Annex I countries.

Again this must be corrected for the increase in consumption in non-Annex I countries due to the world price decrease of 17.8% (see below). Using the same method as for the US EIA (1998) report, that increase is estimated to be 20% × 17.8% × 50.6, which equals a 1.80 Mb/d. This gives a net decrease in the world's demand for oil of 11.61−1.80 = 9.81, or 8.5% of the world total of 116Mb/d.

A similar table (p. 26-27) for energy prices lists Refiners Acquired Cost, and West Texas Intermediate Crude prices as dropping from $21.38/bbl and $23.41/bbl, by 17.8% each in 2020.

World inverse supply elasticity, f = (% change in price)/(% change in demand) = 17.8%/8.5% = 2.11

3.3 Electric Power Research Institute's Model of the Kyoto Protocol, 1998

The US EIA's 1998 Kyoto report summarizes the results of other publicly available estimates of the costs of achieving the Kyoto Protocol's carbon reduction targets in the United States for the period 2008 to 2020. Among these are estimates from the Electric Power Research Institute's (EPRI's) MERGE model (Manne and Richels 1997). MERGE was specifically developed for evaluating the regional and global effects of greenhouse gas reduction policies. The following analysis is based on the summary of those estimates provided in Chapter 7 of US EIA's 1998 report. A related report (Manne and Richels 1998, p. 3) contains a clear statement of the global rebound effect.

> Annex 1 emission reductions will result in lower oil demand, which in turn will lead to a decline in the international price of oil. As a result, non-Annex 1 countries may increase their oil imports and emit more than they would otherwise.

The MERGE model provides analysis of Annex I trading (US EIA 1998, p. 144). In fact, the model was run with and without Annex I trading and obtained the same outcome for world oil prices. So it will again be assumed that the model's estimates cover the reduction in oil consumption by all Annex I countries. In any case, this assumption results in a much lower estimate for inverse supply elasticity than the alternative assumption that only U.S. oil consumption was accounted for.

Tables C4 and C5 (US EIA 1998, p. 217) report the world oil price for the Reference Case in 2020 ($28.27/bbl) and for the 1990–7% Case ($24.74). The price reduction amounts to 12.5%.

Unfortunately, no figures for the corresponding reduction in U.S. oil consumption are given. However, the EIA report remarks that, "The declining carbon prices in the EPRI and EIA studies result from the projected increasing penetration of carbon-free or low-carbon generation technologies, coupled with greater selection of more efficient technologies that become economical with higher end-use fuel prices." (US EIA 1998, p. 142) In other words the two studies are quite similar in the success they attribute to the electricity sector. This indicates that they probably are similar in having a heavy reliance on coal-use reduction rather than on oil-use reduction as a means of reducing CO_2 emissions. The WEFA model is not listed as similar in this way and it estimates a much higher reduction in oil use than the US EIA analysis.

To fill this data gap cautiously, an average of the similar EIA model and the high-oil-reduction WEFA model will be used. In the 7%-Below Case of the EIA model, the reduction in oil consumption was calculated at 4.9%, and in the WEFA model it was calculated at 8.5%. The average is 6.7%, and this value will be used to compute the inverse supply elasticity.

World inverse supply elasticity, f = (% change in price)/(% change in demand) = 12.5%/6.7% = 1.87

3.4 International Energy Agency: World Energy Outlook 2005

The International Energy Agency's World Energy Outlook 2005 (IEA 2005) presents a "World Alternative Policy Scenario" that reduces the demand for oil and thereby reduces the world price of oil. It reports a global reduction in demand and a consequent reduction in the world price of oil. The reduction in demand includes the global rebound effect, so Method 2 is again appropriate.

The IEA report also remarks on the implications of price for demand, noting that long-term changes in price are particularly potent, and noting that falling oil prices have in the past resulted in improvements in energy intensity slowing "dramatically." Of course, this "slowing" means falling oil prices caused energy consumption to end up higher than it would have been.

> Persistently higher prices, which lead to a permanent shift in consumer and producer expectations of future price levels, have a particularly strong impact on fuel mix and

technological change. … The rate of improvement in energy intensity slowed dramatically after the crash in oil prices in 1986. (IEA 2005, p. 257)

The World Alternative Policy Scenario "analyses the impact of a range of policies and measures … which are aimed at addressing environmental and energy security concerns." In this scenario, "Demand for oil in the Alternative Policy Scenario rises to just under 5000 Mtoe in 2030, 580 Mtoe, or 10%, lower than in the Reference Scenario." (IEA 2005, p. 270) The result is that "The oil price averages $33 per barrel in the Alternative Policy Scenario. This is $6, or 15%, lower than in the Reference Scenario, because lower demand depresses prices." (IEA 2005, p. 275) Combining these two percentage changes gives the world inverse supply elasticity as viewed by the IEA in 2005.

World inverse supply elasticity, f = (% change in price)/(% change in demand) = 15% / 10% = 1.5

3.5 International Energy Agency: World Energy Outlook 2007

The IEA's *WEO 2007* report may be more relevant to future oil-market conditions. It considers (p. 47) a "High Growth Scenario" in which the "crude oil import price rises to $87 per barrel (in year-2006 dollars) in 2030 – 40% higher than in the Reference Scenario." This value is confirmed on pages 135 and 151, and the gap is confirmed in dollars, "the gap reaches $25 a barrel, or 40%, in 2030," on page 183.

But "40%" refers to an increase in price from a base of $62/bbl, and for the GRE, a decrease in price is of interest. So the percentage change should be computed as a price reduction of 29% from $87/bbl.

The next task is to identify the change in demand that drives the high growth scenario. Table 1.15: World Primary Energy Demand by Fuel in the High Growth Scenario (p. 109) shows oil demand at 5,771 Mtoe in 2030. The table also reports that this is 186 Mtoe, or 3%, higher than demand in the Reference Scenario. This is confirmed on page 74. Again, for GRE purposes, the decrease in demand from 5,771 to 5,585 gives the correct percentage, which is 3.22%. And this allows the calculation of the world inverse supply elasticity in this high-growth, high-demand scenario.

World inverse supply elasticity, f = (% change in price)/(% change in demand) = 29% / 3.22% = 8.92

The High Growth Scenario concerns an increase in demand caused by faster growth. But if such growth occurs, as it actually has, then the implications are clear for any program that reduces oil use. Reducing oil use counteracts the cause of the price increase and so counteracts the price increase itself—it reduces price relative to what it would have been. In other words, even though the IEA computed an upward price effect from increased demand, this necessarily tells us about the downward price effect that would be caused by reversing the demand increase, for example, with a renewable fuels standard.

It should be noted that this "High Growth Scenario" does not refer to any extraordinary rate of growth. "Global demand for oil grows by 1.5% per year over the projection period – 0.1 percentage points faster than in the Reference Scenario" (p. 110). This means a renewable fuels standard could have an exceptionally strong impact on the price of oil if high growth continues in the future, as EIA oil-price projections indicate it likely will. DOE's Energy Information Agency is now predicting $130/bbl in 2030. This is higher than the prices in the IEA's high-growth scenario.

But what about OPEC? OPEC is the main reason some claim that the global rebound effect will be low or negligible. The idea is that OPEC will strenuously resist any price reductions. But consider how that argument is affected by the price of oil. The main reason Saudi Arabia occasionally argues for lower oil prices (the opposite of resisting reductions) is that the Saudis have understood that high prices cause unwanted counter-measures in the oil-consuming nations. These include mileage standards, gas taxes (in Europe), and renewable fuel standards.

But Saudi Arabia has only pushed for lower prices when prices were already quite high. This demonstrates the obvious. OPEC will resist price reductions far more strenuously in a low-price world than in a high price world. So consideration of OPEC tends to confirm the IEA's view that when oil prices are high, a change in demand will have a greater impact on price. This means that if the oil markets are expected to be tight and prices high in the future, the global rebound effect should be expected to be stronger than in the past—perhaps much stronger.

3.6 The US EIA's "Analysis of Crude Oil Production in ANWR," 2008.

This is the first case in which Method 1 is appropriate. In this case, production in ANWR is given but not the impact of this production on total supply and demand after the market adjusts. However, the long-run impact on the market price is reported. Production from ANWR shifts the supply curve as shown in Figure 1 and this produces the price reduction reported by the US EIA.

Table 2 (US EIA 2008) shows that, in the High Oil Resource Case, the low-sulfur light crude oil price would be $69.08 instead of $70.45, as it is in the Reference Case. This is a drop of 1.9 percent. Also, in the same table, U.S. crude production is shown rising from 5.6 to 6.9 Mb/d, and crude production from Alaska is shown as rising from 0.3 to 1.7 Mb/d. One increases by 1.3 and the other by 1.4, and the discrepancy is due to a rounding error, so a change of 1.35 Mb/d will be used.

US EIA's 2008 International Energy Outlook estimates 2030 world oil supply at 112.5 Mb/d, so a reduction of 1.35 Mb/d amounts to 1.2 percent. This allows the calculation of the oil price sensitivity.

World oil price sensitivity, s = (%price change)/(policy-induced % change in supply) = 1.9% / 1.2% = 1.62

3.7 The EPA's Regulatory Impact Analysis of RFS2, 2010

With regard to the oil market's reaction and the rebound effect, the EPA's Renewable Fuel Standard Program (RFS2) is essentially identical to the case of increased production from ANWR. So again, Method 1 is appropriate for the reasons stated above.

The EPA's Regulatory Impact Analysis of RFS2 provides another estimate of the impact of demand on world oil prices. Table 5.2.4-1., "Determinates of Monopsony Benefits of the RFS2 Renewable Fuel Volumes vs. AEO2007 Reference Case," lists the "Change in Price ($ per barrel [of Oil] in 2022)" as $1.06. This should be compared with the AEO2009 value for the price of oil in 2022, which the RIA lists as $116 per barrel (pages 137, 817, 827, etc.). This means $1.06 is a 0.91% decrease in the price of oil.

This must be compared with the increase in the supply of renewable fuels that causes the decrease in the price of oil. This increase is the difference for 2022 between "Table 1.2-1. AEO 2007 Reference Case Renewable Fuel Volumes" and "Table 1.2-3. Primary Control Case Projected Renewable Fuel Volumes." However, imported fuel should not be counted, as this fuel will mainly represent a shift in the location where the fuel is used, and that has little impact on a global analysis. The results are as follows:

Table 1.2-1: 12.29 billion gallons of ethanol and 0.63 billion gallons of biodiesel

Table 1.2-3: 19.92 billion gallons of ethanol and 8.34 billion gallons of biodiesel

Increase: 7.63 billion gallons of ethanol and 7.71 billion gallons of biodiesel

These values can be adjusted for their energy content using the following lower heating values (LHV):

1 gallon of ethanol = 77,012 Btu (from p. 255 of the RIA)

1 gallon of biodiesel = 118,000 Btu (from the GREET model)

1 gallon of oil = 129,670 Btu (from the GREET model)

The result is that the increase in biofuel is equivalent to 11.55 billion gallons per year of oil, which is 0.753 Mb/d. This should be compared with the world consumption of liquid fuels in 2022 interpolated from the 2020 and 2025 values in US EIA's International Energy Outlook, 2009. The interpolated value is 98 Mb/d. So the increase in supply is 0.77%. From this and the percentage decrease in the price of oil, the world oil price sensitivity can be computed.

World oil price sensitivity, s = (% price change)/(policy-induced % change in supply) = 0.91% / 0.77% = 1.19

3.8 The MIT Cap-and-Trade Study

The Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change published a study in 2007 of Cap-and-Trade proposals before Congress. It found that these proposals, when combined with weaker greenhouse gas initiatives in the rest of the world, would lower the world oil price by between 34 percent and 47 percent by 2050. Because the study does not report world oil use, the oil price sensitivity cannot be computed. However, it is worth noting the magnitudes of these two price effects. They are not negligible. (The percentage price reductions were calculated from Appendix C. The petroleum price index is 2.25 in 2050 in the Reference case (p. 66), 1.49 in the 287-bmt (weak-cap) scenario, and 1.20 in the 167-bmt (strong-cap) scenario.)

4 Global Demand Elasticity for Liquid Fuels

The $1.06 oil price decrease discussed above is documented in "Energy Security Impacts of Renewable Fuel Use Under RFS2 – Methodology" (Leiby 2010) (see footnote 301, p. 910 of the EPA's RIA). The Oil Security Metrics Model (OSMM) discussed in that report is further documented in "Estimating the Energy Security Benefits of Reduced U.S. Oil Imports: Final Report," (Leiby 2008) (see footnote 296, p. 910 of the EPA's RIA). This report was issued just after the completion of a peer review of the prior version of the report conducted on behalf of the EPA (US EPA, Coe, 2008). Leiby's 2008 report gives the demand elasticities used in the OSMM and apparently in the calculation of the $1.06 value.

These demand elasticities are apparently based on at least eight sources from the econometrics literature and reported in Table A1 (Leiby 2008, p. 51). Three demand elasticities are needed, one for the United States, one for OPEC and one for the rest of the world, because those are the regions used by the OSMM. Two of these, but not one for OPEC, are given in "Table A4: Range of Key Assumptions Used in Study." These two are shown in Table 2 along with an assumed zero elasticity for OPEC. The two listed elasticities are given in Low, Mid, and High versions.

Table 3. Global Demand Elasticities for Liquid Fuels

	United State	Rest of World	OPEC	**Global Elasticity, e**
Oil consumption 2022	20.4Mb/d	68.4Mb/d	9.1Mb/d	
% of world oil consumption	21%	70%	9.3%	
Long-run demand elasticity (Low)	20%	20%	0%	**Low**
Contribution to world elasticity	4.2%	14.0%	0%	**18.1%**
Long-run demand elasticity (Mid)	27%	30%	0%	**Mid**
Contribution to world elasticity	5.6%	21.0%	0%	**26.6%**
Long-run demand elasticity (High)	30%	40%	0%	**High**
Contribution to world elasticity	6.3%	27.9%	0%	**40%**

Long-run demand elasticities are from Leiby (2008, Table A4).

The oil consumption figures in Table 3 are from US EIA's IEO2009, but the Middle East value has been converted to an OPEC value by multiplying it by 1.12. That factor was determined from US EIA's petroleum consumption data for 2008 (http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm).

The final (Mid) global demand elasticity value of 26.6% is found by summing the three contributions to its left. This value means that when the world price of oil increases 1%, the global consumption of oil decreases 0.266% in the long-run—about a decade.

Leiby (2008, p. 3) remarks that the elasticities in Table A4 reflect helpful comments from the peer review (EPA, Coe 2008) of the previous version of his paper and in particular reflect "Gately and Huntington 2002." Leiby goes on to say, "As a result, the net elasticity of import demand from non-U.S./non-OPEC regions approximately doubled from the value used in the 1997 study and the earlier draft of this study, in keeping with the recommendations of some reviewers."

This remark dovetails with a remark by one of the peer reviewers, Michael Toman, Lead Economist on Climate Change in the Development Research Group and Manager of the Energy and Environment Team. Toman gave the most extensive comments on elasticities (EPA, Coe 2008, p. 11) and suggested a "demand elasticity of at least –0.4” and noted that this would lead to an ROW (rest of the world, i.e. non-U.S./non-OPEC) import demand elasticity “over twice the elasticity apparently assumed in the study.”[3]

In other words, it seems clear that Leiby took Toman’s suggestion on demand elasticity to heart. However, Leiby’s “Mid” ROW demand elasticity is –0.3 and not –0.4 as suggested by Toman. However Leiby (2008, p. 45) considers seven “Alternate Cases,” two of which mention ROW demand elasticities. Case 3 has a Mid ROW demand elasticity of –0.3 as listed in Table A4 and used in the present study, but Case 4 has an ROW demand elasticity which seems to correspond to Toman’s suggestion. It has a triangular probability distribution extending from –0.3 to –0.7 with a mode (peak) at –0.4 and an average value of –0.467. Using this Toman-inspired value would have increased the estimate of GRE listed in Table 1, corresponding to the RFS2 RIA report, from 32% to 45%.

In conclusion, it seems that the long-run global demand elasticities used in the current study reflect EPA/Leiby values that have been well reviewed, reflect a broad range of academic opinion, and are, if anything, on the conservative side. Quite possibly this indicates that the GREs reported in Table 1 are somewhat downwardly biased.

5 Conclusion

The EPA has found that renewable fuels will reduce the world price of oil by about $1.06. This is not quite a 1 percent reduction, but it is caused by less than a 1 percent increase in the world’s supply of liquid fuel. So the price effect is fairly strong. In fact, as shown in Table 1, it is strong enough that a 1 percent increase in fuel reduces price by about 1.2%. That means the world will save more money on fossil fuel costs, thanks to the RFS2, than it spends buying the extra renewable fuel.

For example if fuel costs $100 per barrel and the world is using 100 Mb/d of fossil fuel (plausible values for 2022), then increasing production of renewable fuel by 1 Mb/d would reduce the price of 100 Mb/d of fossil fuel by about $1.20/bbl, saving the world’s consumers $120 million per day on fossil fuel. The renewable fuel, however, would only cost $100 million a day.

This much is a direct consequence of the $1.06 world-oil-price reduction reported by the EPA and the energy content of the extra renewable fuel produced under the RFS2. Given the size of the fossil-fuel cost savings it seems inevitable that significantly more fossil fuel will be consumed. It’s like having a sale, and the whole point of a sale is to induce consumers to buy more. Of course, many of the ways to use more gasoline—such as buying an SUV–take a while to have their effect. So the initial impact of the sale might appear to be rather limited. But this is likely not the case.

The $1.06 price drop is itself a long term effect and according to Leiby (2010, Figure 2) the short-run price effect is many times greater. In fact, recent experience indicates that a few percent excess supply due to reduced consumption can drop the price of oil by $100 in six months. So while consumers may be slow to take advantage of lower prices, the price effect should start quickly and make up for their slowness.

So the short-run rebound effect may be no less than the long-run rebound effect. Finding that long-run impact from the cost savings requires knowing how consumers respond to a change in price—that is, knowing their demand elasticity. The background documents for the EPA’s RIA show that the long-run global demand elasticity for fossil fuel is about 30%. This means that out of the $100 million a day saved worldwide in our current example, about $30 million a day will be spent buying more fuel—and almost all of that will be fossil in nature, just because most liquid fuel is fossil fuel. This $30 million a day spent on fossil fuel, and the resulting emissions, is very roughly what the EPA analysis will be missing by 2022.

This does not mean that total fossil fuel use will increase. The lower price of oil reduces supply while it increases demand. In fact the 32 percent value of the rebound effect found from EPA numbers means that, of the displaced fossil fuel, 68 percent will, in effect, be displaced back into the ground, and 32 percent will be displaced

[3] Note that, technically speaking, demand elasticities are negative, although they are often discussed as if they were positive as has been the case in the current study, including Tables 1 and 3.

into consumption. So there is a net reduction in fossil fuel use, but it is something like a 68 percent reduction and not a 100 percent reduction.

To see how standard estimates of emission reductions need to be adjusted, consider a type of renewable fuel with lifecycle GHG emissions of R from enough fuel to displace a barrel of fossil fuel. Next assume that using a barrel of fossil fuel has lifecycle emissions of F. The emission savings from using this renewable fuel is then calculated on a percentage basis as:

Nominal Lifecycle Emissions Savings $= NLES = (F - R) / F$

But this savings omits the emissions from the fossil fuel use caused by the global rebound effect. The rebound fuel use is GRE barrels of fossil fuel, and has emissions equal to $GRE \cdot F$. This must be added to the lifecycle emissions of the renewable fuel. So the total direct and indirect emissions from the renewable fuel is $R + GRE \cdot F$, and the actual savings is:

Actual Lifecycle Emissions Savings $= ALES = [F - (R + GRE \cdot F)] / F$

This simplifies to:

$$ALES = NLES - GRE$$

So, for example, if the fossil fuel has $F = 100$, and the renewable fuel has $R = 78$, then the nominal lifecycle savings is 22 percent. And if $GRE = 32\%$, then the actual lifecycle saving is $22\% - 32\%$, which is minus 10%, which is, of course, not a savings at all.

6 Appendix A: Two Methods of Estimating the Global Rebound Effect

Three completely different types of scenarios produce the same global rebound effect: conservation, renewable fuels, and off-shore drilling. They are aligned because of a common linkage to the world oil market. All three reduce U.S. oil imports. Conservation can mean driving less or driving a more fuel efficient car. Either way less gasoline is used. Renewable fuels reduce gasoline use without the need for conservation. Finally, if the government opens new areas to offshore drilling, the resulting oil and gasoline will displace the gasoline that would have been used exactly in the same way that ethanol does.

This is not to say the three are equivalent. Conservation will reduce GHG emissions, renewable fuel may or may not, and offshore drilling will increase emissions. But in each case, the United States will import less oil. That will cause a glut of oil until the price falls enough to reduce supply and increase demand and bring the market back into balance. This will happen so quickly and smoothly that the supply-demand imbalance will not be noticed, but if it did not happen, oil inventories would build up without limit. Of course, the market will not let that happen. It will control the inventories by displacing the extra fuel either onto the supply side or the demand side.

Because all three scenarios work in the same way, they have the same impact. This is convenient because the same or very similar rebound formulas will work for all three scenarios. Unfortunately two different rebound formulas are needed, not because of different scenarios or differences in the economics of the market, but because different reports present different information. Some reports give the change in the initial supply (renewable fuel or offshore oil). These will be analyzed using Method 1. Others give the final change in demand after the rebound effect has taken its toll. These will be analyzed using Method 2.

6.1 Method 1: Using Price Sensitivity

Method 1 handles the case in which the amount of the supply-curve shift is known. This covers two of the reports discussed above, the US EPA's RIA (2010) which discusses a shift in supply caused by a regulated increase in renewable fuel, and the US EIA's analysis of an increase in supply caused by producing more Alaskan oil.

In such cases, the price reduction is affected by the slopes of both the supply curve and the demand curve. This is not a standard elasticity so it will be termed the price sensitivity, which will be defined as:

Price sensitivity = s = (% change in price) / (% shift in the supply curve)

In Figure A1, $s = (\Delta P / P_0) / (q / Q_0)$

Figure A1. GRE Estimation Method 1, Price Sensitivity

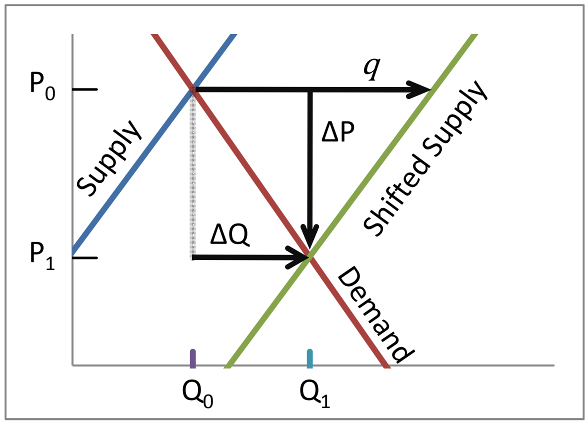


Figure A1 shows an increase of q in renewable fuel production, or equivalently an increase in oil production from a newly allowed offshore oil well. At first, the world oil market finds itself with excess supply and then the world price of oil falls by ΔP. As this happens, demand increases and supply decreases. The increase in demand is the global rebound effect (GRE), and the strength of this effect is defined as $GRE = \Delta Q / q$. This is the value we wish to find.

First, solve for q from the definition of s: $q = (\Delta P / P_0) / (s / Q_0) = (1/s)\, Q_0 \cdot (\Delta P / P_0)$

Next, define the price elasticity of demand, e. It is the percentage change in demand divided by the percentage change in price that is specified by the demand curve. Then solve that definition for ΔQ.

$e = (\Delta Q / Q_0) / (\Delta P / P_0)$, which implies $\Delta Q = e\, Q_0 \cdot (\Delta P / P_0)$.

Then find that $GRE = \Delta Q / q = e / (1/s) = e \cdot s$. So the strength of the global rebound effect is just the price sensitivity times the demand elasticity.

$$GRE = e \cdot s, \quad \text{where}$$

e = world petroleum demand elasticity, and

s = world oil price sensitivity

The value GRE can be used as follows. Suppose FF_0 is the initial level of fossil fuel use, and FF_1 is the final value. Then nominally, $FF_1 = FF_0 - q$. But actually, $FF_1 = FF_0 + \Delta Q - q = FF_0 - (q - \Delta Q)$. So the reduction in fossil fuel use is not q but $q - \Delta Q$. By the definition of GRE, this reduction can also be written as $(1 - GRE) \cdot q$.

6.2 Method 2: Using the Inverse Supply Elasticity

Method 2 handles the case in which the amount of the supply-curve shift is *not* known. In this case the actual change in demand, which includes the rebound effect, must be known and is shown as q in Figure A2. This covers the reports from the IEA and the reports that analyze the impact of the Kyoto Protocol.

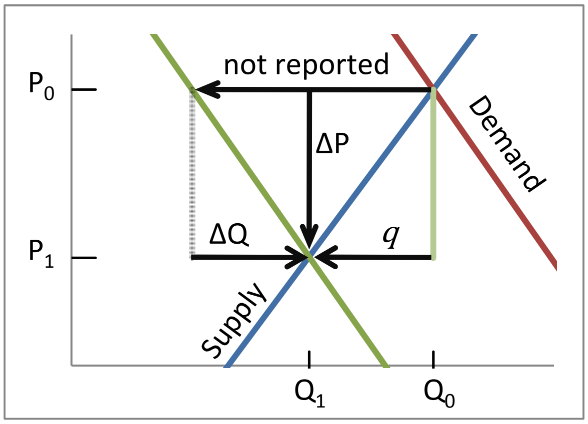
In such cases, the price reduction is determined only by q and the supply curve, as can be seen in Figure A2. The inverse supply elasticity, plays a role in this method that is similar to the role played by price sensitivity in Method 1.

Inverse price elasticity = f = (% change in price) / (% change in actual demand)

In Figure A2, $f = (\Delta P / P_0) / (q / Q_0)$

Note that the formula for f is the same as for s, but the meaning of q has changed.

Figure A2. Estimation Method #2



The increase in demand is the global rebound effect (GRE), and the strength of this effect is defined as:

$GRE = \Delta Q / \text{“not reported”} = \Delta Q/(q + \Delta Q)$. This is the value we wish to find.

First, solve for q from the definition of f: $q = (\Delta P / P_0) / (f / Q_0) = (1/f)\, Q_0 (\Delta P / P_0)$

Then, as before, solve for ΔQ, from the definition of the demand elasticity

$e = (\Delta Q / Q_0) / (\Delta P / P_0)$, which implies $\Delta Q = e\, Q_0 \cdot (\Delta P / P_0)$.

Then find that $GRE = \Delta Q/(q + \Delta Q) = e / (1/f + e) = e \cdot f / (1 + e \cdot f)$.

$GRE = e \cdot f / (1 + e \cdot f)$, where

e = world petroleum demand elasticity of oil, and

f = world inverse supply elasticity of oil

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