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TECHNICAL APPENDIX

# A Simplified Model of US Crude Export Restrictions

The study "Navigating the U.S. Oil Export Debate" (Bordoff and Houser, 2015) published by Columbia University's Center on Global Energy Policy in collaboration with the Rhodium Group, assesses the economic, energy market, environmental, security, and geopolitical implications of modifying or removing current restrictions on crude oil exports from the United States. This appendix describes the simplified oil market model used to inform the authors' view of the impact of crude export restrictions on US oil production, global crude and refined product prices, and global oil consumption.

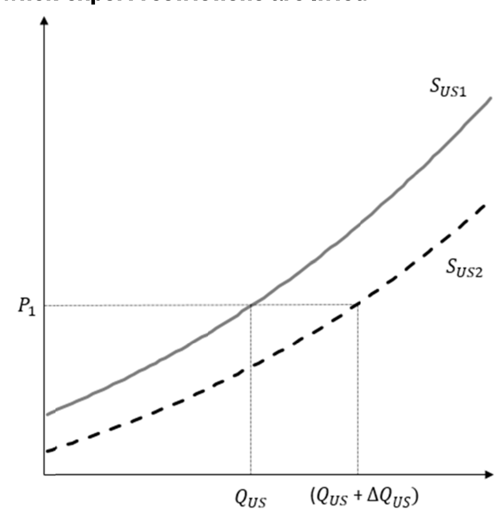
## THEORETICAL FRAMEWORK

As explained in Bordoff and Houser (2015), if recent US crude production growth continues, the ability of existing domestic refineries to process LTO will be exhausted, requiring new refinery investment or suboptimal utilization of current refinery capacity. To cover the cost of new investment or reduced efficiency of existing stock, refiners will likely require a discount from domestic LTO producers relative to the prevailing international price for similar quality crudes. All else equal, a decline in domestic crude oil prices will result in a decline in US production (or in the rate of production growth). This is depicted in Figure A1 by supply curve $S_{US1}$.

Allowing domestic LTO producers to market their product abroad would reduce or eliminate this discount by providing domestic producers with access to a much larger refinery market. All else equal, this would increase domestic crude production relative to a scenario in which export restrictions are kept in place. This is depicted in Figure A1 by supply curve $S_{US2}$. Assuming for the moment that the global oil price ($P_1$) remains the same, the removal of a domestic price discount shifts the US crude supply curve from $Q_{US}$ to $(Q_{US} + \Delta Q_{US})$.

The magnitude of additional US supply, i.e. $\Delta Q_{US}$, will depend both on the magnitude of the domestic price discount and the price elasticity of domestic crude supply.

**Figure A1: US supply curve shifts outwards when export restrictions are lifted**




### Global supply and demand curves

To assess the net global oil market impact of a shift in US crude oil supply, we combine the US supply curve with a supply curve for OPEC and the Rest of the World (ROW) to create a single global supply curve $S_{G1}$ (Figure A2).[1] So at global price $P_1$, reference global supply with the US export ban in place is:

[1] For simplicity, the model assumes a single supply elasticity for each region across time and price. In reality, there is likely meaningful variation in the price elasticity of both US and non-US supply at different price levels and in different time periods. We address this by tailoring the price

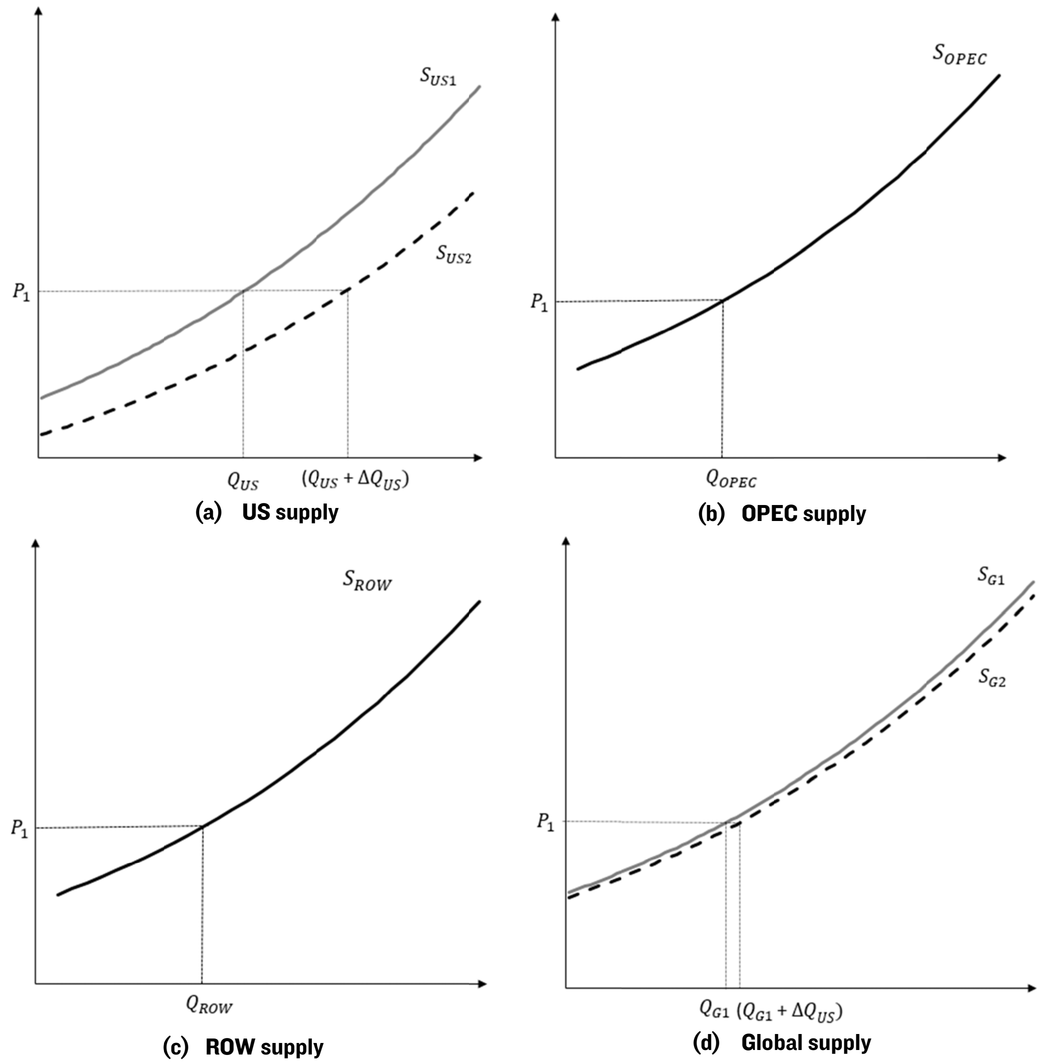
$$Q_{G1} = Q_{US} + Q_{OPEC} + Q_{ROW} \qquad \ldots (1)$$

where $Q_{OPEC}$ and $Q_{ROW}$ are supply available from OPEC and ROW regions respectively at price $P_1$ and are exogenously specified.

The price elasticity of global supply is the weighted average of $\epsilon_{SUS}$, $\epsilon_{SOPEC}$ and $\epsilon_{SROW}$, the supply elasticity of the US, OPEC, and ROW respectively, all of which are exogenously provided (see next section for the discussion on how we select the supply elasticity we use in the model).

$$\epsilon_{SG1} = \frac{(Q_{US} * \epsilon_{SUS} + Q_{OPEC} * \epsilon_{SOPEC} + Q_{ROW} * \epsilon_{SROW})}{(Q_{US} + Q_{OPEC} + Q_{ROW})} \qquad \ldots (2)$$

**Figure A2: Construction of global supply curve**




elasticity assumptions for a particular scenario to the specific time period and reference oil price level we wish to explore.

If the ban is lifted, a new global supply curve $S_{G2}$ is created by adding $\Delta Q_{US}$ to the reference quantity $Q_{G1}$ in Equation (1) and the supply elasticity $\epsilon_{SG2}$ is calculated by adjusting the supply elasticity in Equation (2), with the additional supply assumed to be completely inelastic.[2]

On the demand side, we divide the world into two regions – the United States and the Rest of the World (ROW). As on the supply side, regional demand curves are defined as reference demand at a given price and price elasticity is specified exogenously. Regional demand curves are summed to create a global demand curve.

We combine these supply and demand curves to assess the impact of a change in US supply on non-US supply, global price, and global demand (Figure A3).

For the changed global supply curve $S_{G2}$,

$$\epsilon_{SG2} = \log\left(\frac{Q_{G2}}{Q_{G1}+\Delta Q_{US}}\right) / \log\left(\frac{P_2}{P_1}\right) \quad \ldots (3)$$

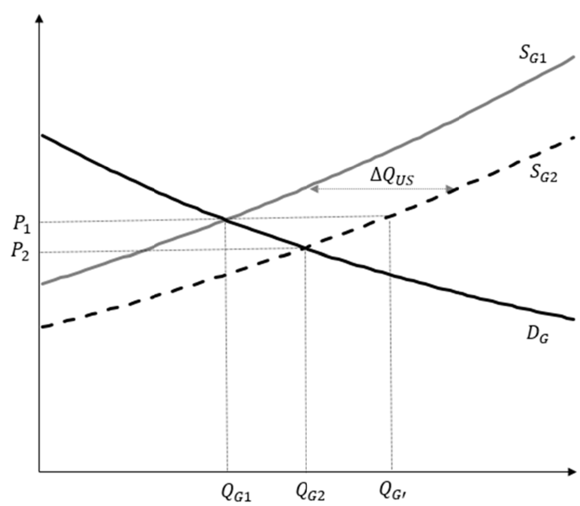
$$\epsilon_{DG} = \log\left(\frac{Q_{G2}}{Q_{G1}}\right) / \log\left(\frac{P_2}{P_1}\right) \quad \ldots (4)$$

where $\epsilon_{DG}$ is the price elasticity of global demand. Using (3) and (4) we solve for the new price $P_2$

$$P_2 = P_1 * \exp\left(\frac{\log\left(\frac{Q_{G1}+\Delta Q_{US}}{Q_{G1}}\right)}{\epsilon_{DG} - \epsilon_{SG2}}\right) \quad \ldots (5)$$

Substituting $P_2$ in either (3) or (4), we get the new equilibrium quantity $Q_{G2}$.

**Figure A3: Solving for new equilibrium price and quantity**




[2] To isolate the impact of a US supply shock, we assume that the increase in US supply resulting from a change in wellhead prices is unaffected by resulting changes in global oil prices.

## KEY VARIABLES

Using the framework described above, we assess the impact of lifting current crude oil export restrictions with a range of different assumptions for the following key variables.

***Refinery economics:*** Studies surveyed by Bordoff and Houser (2015) suggest current crude oil export restrictions could result in a domestic crude price discount of anywhere between $0 and $10 per barrel on average between 2015 and 2025, depending on the pace of US crude production growth, the ability of the US refining sector to absorb additional quantities of domestic light tight oil (LTO), and the cost of doing so. One scenario in one study (the "High Oil & Gas Resource" case in NERA, 2014) finds a $17 per barrel average discount with the assumption that almost no new domestic refinery investment occurs. We find this to be a highly unlikely outlier and exclude it from our analysis.

***US supply elasticity:*** Studies surveyed by Bordoff and Houser (2015) find an average price elasticity of US supply between 2015 and 2025 in the range of 0.4 to 2.1. All these elasticities are considerably higher than the estimates of long-term global oil supply elasticity found in the academic literature (Table A1), though robust econometric estimates are hard to come by. That is not surprising, as LTO production is often considered more price elastic than traditional sources of oil supply. We explored the elasticity of US tight oil supply in the Energy Information Administration's National Energy Modeling System (NEMS) by running the model over a range of price paths while holding the resource base constant. We found supply elasticities between 0.1 to 0.5, depending on the base price and year. We also explored the implicit price elasticity in the Rystad supply curve and found elasticities ranging from 0.1 to 1 between $100 a barrel and $60 a barrel, with the elasticity growing as base oil price declines. Based on this survey, we chose a likely US supply elasticity range of 0.1 to 1 for our analysis.

***Non-US supply elasticity:*** For non-OPEC producers elsewhere in the world, we explored a supply elasticity range of 0.1 to 1.0 capturing both the range of available academic estimates of recent oil market experience (Table A1) and the range assumed for the US.

**Table A1: Long-term price elasticity of oil supply**

| | Period of analysis | Region | Elasticity |
|---|---|---|---|
| Ramcharran (2002) | 1973-1997 | OPEC | -0.17 |
| | 1973-1999 | non-OPEC | 0.10 |
| Krichene (2002) | 1918-1999 | World | 0.25 |
| | 1918-1973 | World | 1.10 |
| | 1973-1999 | World | 0.10 |
| Kirchene (2005) | 1918-2004 | World | 0.12-0.16 |
| | 1918-1973 | World | 0.44-0.46 |
| | 1974-2004 | World | 0.23-0.25 |
| Benes et al. (2012) | 1983-2003 | World | 0.05 |
| | 2003-2011 | World | 0.15 |

***OPEC supply elasticity:*** Given the uncertainty around potential OPEC response to an increase in US crude production due to modification of current export policy, we explore scenarios where OPEC producers a) maintain production, b) offset the increase in US production to prevent a decline in global prices, and c) behave as a non-OPEC producer with a supply elasticity ranging from 0.1 to 1.

***Demand elasticity***: For both US and non-US crude demand, we explore elasticities ranging from -0.072 to -0.3 based on recent academic estimates (Table A2).

**Table A2: Long term price elasticity of oil demand**

| | Period of analysis | Region | Product | Elasticity |
|---|---|---|---|---|
| Krichene (2002) | 1918-1999 | World | Crude oil | -0.05 |
| | 1918-1973 | World | Crude oil | -0.13 |
| | 1973-1999 | World | Crude oil | -0.01 |
| Cooper (2003) | 1971-2000 | 23 countries | Crude oil | -0.18 to -0.45 |
| Graham & Glaister (2004)* | Various | Various | Gasoline | -0.77** |
| Kirchene (2005) | 1918-2004 | World | Crude oil | -0.27 to -1.59 |
| | 1918-1973 | World | Crude oil | -0.32 to -2.73 |
| | 1974-2004 | World | Crude oil | -0.12 to -0.26 |
| Brons et al (2008)* | Various | Various | Gasoline | -0.84** |
| IMF (2011) | Unspecified | World | Crude oil | -0.072 |
| IMF (2012) | 1983-2011 | World | Crude oil | -0.08 |
| Lin & Prince (2013) | 1990-2012 | US | Gasoline | -0.24 to -0.29 |

*Based on literature review

**Mean estimate

## INPUT VARIABLES

For our simulations, we use the following oil market assumptions from the "High Oil & Gas Resource" case in the 2014 version of the EIA's Annual Energy Outlook and the EIA's 2014 International Energy Outlook. All are average annual values between 2015 and 2025.

| Global oil price (Brent, 2012 USD) |
|---|
| $93.14 per barrel |

| Global crude oil supply (million b/d) | |
|---|---|
| OPEC | 33.13 |
| US | 11.43 |
| Other non-OPEC | 37.21 |
| Total | 81.76 |

| Global crude oil demand (million b/d) | |
|---|---|
| US | 15.33 |
| ROW | 66.43 |
| Total | 81.76 |

Using the framework provided above, we analyze the impact on US crude production, non-US crude production, global crude prices, global crude demand, and US refined petroleum prices for a credible range of supply elasticities, demand elasticities, OPEC responses, and domestic crude price discounts export constraints.

| Variable | Low | High |
|---|---|---|
| Domestic crude discount | $0/barrel | $10/barrel |
| US supply elasticity | 0.1 | 1.0 |
| Non-US supply elasticity | 0.1 | 1.0 |
| OPEC response | Cuts production | Maintains production |
| Global demand elasticity | -0.072 | -0.3 |

In translating a given change in global oil prices into US refined product prices, we assume that a 1% change in the price of Brent crude results in a 0.9% change in the wholesale price of gasoline. We derive this relationship by performing a log-linear regression of the weekly average spot gasoline price at New York Harbor on the weekly average spot price of Brent crude, with an R2 of 94.9 and low standard error.

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