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Oil Supply Shocks, US Gross Domestic Product, and the Oil Security Premium

Appendix

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RESOURCES FOR THE FUTURE

Oil Supply Shocks, US Gross Domestic Product, and the Oil Security Premium: Appendix

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D. New Estimates of the Security Costs of US Oil Consumption

A. Oil Supply Shocks and the US Economy: An Estimated DSGE Model

Nathan S. Balke and Stephen P.A. Brown*

Abstract

We use a medium-sized dynamic stochastic general equilibrium (DSGE) model of the US economy to evaluate how US real GDP responds to oil price shocks that originate from shocks to the global oil supply. The core of the model is a standard macroeconomic DSGE model that includes nominal and real frictions. The model includes oil/energy as an input to production and consumption and captures multiple domestic sectors (consumption, final goods, intermediate goods, transportation services and oil/energy production). The model also represents general international trade and oil imports. The inclusion of a transportation services sector allows the model to capture the importance of petroleum products in the transportation sector, which accounts for close to two thirds of US consumption of refined products. It also allows an evaluation of the effect that fuel efficiency and alternative energy use in the transportation sector may have on sensitivity of the US economy to oil supply shocks. The model parameters are set through a combination of calibration and Bayesian estimation techniques, using quarterly data for 1991 through 2015. Baseline estimation of the model finds the elasticity of US real GDP with respect an oil price shock in the range of -0.007 and -0.010, which is at the lower end of estimates in the literature. These estimates are fairly robust to changes in the model's specification. Using the model to conduct counterfactual analysis, we show that reducing the share of US oil imports below recent historical averages can substantially reduce the real GDP/oil price elasticity.

A-1. Introduction

Since the early 1970s, economic research has focused on how the US economy has responded to world oil price shocks. As surveyed by Brown and Yücel (2002), Jones et al. (2004), and Kilian (2008c), the aggregate economic effects were interpreted as the consequences of unfavorable oil supply shocks—with the consequences being rising oil prices, slower real GDP growth (possibly recession), higher unemployment rates, and higher price levels. As oil prices have fluctuated throughout the 2000s, however, albeit with less volatility than previously, they seem to have yielded a much smaller response in US real GDP than expected.

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Some of the explanations for a weaker response have included increased global financial integration, greater flexibility of the US economy (including labor and financial markets), the reduced energy intensity of the US economy, increased experience with energy price shocks, better monetary policy, and smaller and less frequent shocks. Contributions include Huntington (2003), Stock and Watson (2003), Nakov and Pescatori (2007), Blanchard and Gali (2010), Edelstein and Kilian (2007), and Herrera and Pesavento (2009) and Kilian and Lewis (2011), who (except for Nakov and Pescatori) mostly treat oil price shocks as exogenous.

In contrast with these earlier efforts, a growing literature examines the implications of modeling oil price movements as endogenous and arising from both demand and supply shocks. The newer efforts include Kilian (2008 a,b; 2009; 2014), Balke et al. (2010), Baumeister and Hamilton (2015), and Baumeister and Kilian (2016). According to Kilian (2008b), Balke et al., and Baumeister and Hamilton, the differing sources of oil price shocks can explain some of the apparent changes in the relationship between oil price movements and aggregate economic activity. Nonetheless, the newer empirical literature, such as Kilian and Vigfusson (2011 a,b), Kilian (2014) and Baumeister and Hamilton and Baumeister and Kilian, continues to find that oil price shocks—even those specifically arising from exogenous supply shocks—have a much smaller effect on aggregate economic activity than is found in the earlier literature.

Dynamic stochastic general equilibrium (DSGE) modeling is an approach that allows for identification of the various sources of oil price shocks and at the same time can capture alternative explanations of why the economy has become less sensitive to oil price shocks. Although DSGE models are widely used to examine aggregate economic activity and macroeconomic policy, few empirical exercises involving DSGE models have been used to examine the effect of oil supply shocks on world oil prices and aggregate economic activity. Notable exceptions include Bodenstein et al. (2011) and Bodenstein and Guerrieri (2011) and Balke et al. (2010). Although these efforts identified various sources of oil price shocks, the efforts represented US oil consumption rather broadly, and none of these efforts allowed for the frictions that are now typically found in DSGE models.

In the present analysis, we expand inquiry by using a medium-sized DSGE model of the US economy that also represents the world oil market, US international trade and aggregate economic activity in the rest of the world (ROW). The model provides a mapping from structural shocks—such as those in technology, preferences and oil supply—to observables such as oil prices, oil production, and other measures of economic activity. We use a combination of calibration and Bayesian methods to determine the model's parameters and to assess the stochastic process generating the exogenous shocks. The latter allows us to identify exogenous oil supply shocks and to estimate their effects on world oil prices and US real GDP.

The core of the model is essentially a standard macroeconomic DSGE model that includes nominal frictions (price) and real frictions (real wage, capital and labor adjustment costs). To this model, we introduce oil/energy as an additional input to production (and consumption), multiple sectors (consumption, final goods, intermediate goods, transportation services, and oil/energy production). We introduce a specific transportation sector to the model to capture the importance of petroleum products in transportation and to reflect the role of fuel efficiency standards in petroleum demand. This allows us to evaluate the effect of fuel efficiency standards on the sensitivity of oil price shocks on economic activity. In addition, the domestic (US) economy interacts with the ROW through the world oil market and final goods market. This captures the effect that US consumption and production of oil has on the world oil market.

The model is used to examine how US real GDP responds to an oil price shock that originates in an exogenous oil supply shock originating in the ROW, which provides an elasticity of US GDP with respect to oil price shocks of -0.007 for the baseline case. Through the use of counterfactual exercises, the model also is used to examine how changes in the ratio of oil imports affects US oil consumption and the response of the US economy to world oil supply shocks.

The remainder of this section is organized as follows. Section A-2 describes the DSGE model of the US economy, the world oil market, US international trade and ROW economic activity. Section A-3 covers the estimation of the model and the posterior distribution of some the key parameters in the model. Section A-4 provides the key empirical results of the model through impulse response functions and historical decompositions. Section A-5 provides estimated elasticities of various model parameters and impulse responses. Section A-6 provides counterfactual analysis, and Section A-7 offers concluding remarks.

A-2. Model

Our model builds on the work of open economy models of oil such as Backus and Crucini (2000), Balke et al. (2010), Bodenstein et al. (2011), and Bodenstein and Guerrieri (2011). Where we differ is that we allow a specific role for transportation in the use of oil products and for oil intensity/efficiency to evolve endogenously. Unlike these other models, we do not model structurally the rest-of-the world as data limitations make estimating structural parameters in the rest-of-the-world difficult.

The main features of the model are as follows:

US economy

a. Largely neoclassical, dynamic macroeconomic model with real wage and nominal price rigidities, adjustment costs for capital and labor.

b. Multi-sector model with emphasis on oil's impact through transportation sector and through consumption.

c. Endogenous oil efficiency/intensity.

World oil market

a. Quasi-structural model of rest-of-world supply and demand for oil

b. Interacts with US oil supply and demand in world oil market to determine price of oil

Non-oil interaction of US with ROW

a. Reduced form model of trade in non-oil goods between US and ROW. Model allows for feedback from US and oil markets to rest-of-world. In the long-run, an increase in US oil imports must be met by an increase in net exports of the non-oil good to ROW, but that need not hold in the short-run.

A-2.1. Domestic (US) Household Sector

Household utility is given by:

$$\sum_{i=0}^{\infty} \beta^i u(c_t, l_t) \tag{A-1}$$

where in the benchmark model

$$u(c_t, l_t) = \frac{(c_t - x_c h_t)^{1-\sigma}}{1-\sigma} - \chi \frac{{l_t}^{1+\eta}}{1+\eta} \tag{A-2}$$

where h_t represents habits (external) that evolve according to $h_t = {c_{t-1}}^{1-\gamma_h} {h_{t-1}}^{\gamma_h}$. Consumption, c_t, is given by:

$$c_t = z_{c,t}\left(\psi_n {n_t}^{\rho_c} + (1-\psi_n) k{s_{c,t}}^{\rho_c}\right)^{1/\rho_c} \tag{A-3}$$

and

$$l_t = \left(1+\phi\left(\frac{l_{f,t}}{l_{f,t-1}}\right)\right)l_{f,t} + \left(1+\phi\left(\frac{l_{m,t}}{l_{m,t-1}}\right)\right)l_{m,t} + \left(1+\phi\left(\frac{l_{o,t}}{l_{o,t-1}}\right)\right)l_{o,t} \qquad \text{(A-4)}$$

Consumption depends on expenditures on nondurables, n_t , and the service flow from durables, $ks_{c,t}$. Households allocate labor to production of final goods, $l_{f,t}$, intermediate goods, $l_{m,t}$, and oil production, $l_{o,t}$. The $\phi\left(\frac{l_{f,t}}{l_{f,t-1}}\right)$ terms represent adjustment costs to households of reallocating their labor supply. We use the functional form:

$$\phi_l\left(\frac{l_{j,t}}{l_{j,t-1}}\right) = a_{jl}\frac{\left({}^{l_{j,t}}/_{l_{j,t-1}} - 1\right)^2}{2} \qquad \text{(A-5)}$$

We assume real wage frictions similar to those in Blanchard and Gali (2010). Here the real wage (in terms of the final good) before adding the adjustment costs of changing labor is given by

$$w_t = (w_{t-1})^{\alpha_w}\left(\lambda_{l,t}\right)^{1-\alpha_w} \qquad \text{(A-6)}$$

where

$$\lambda_{l,t} = \left(\frac{1}{\rho_w}\right)\lambda_{c,t}\left(\frac{-U_l(c_t,l_t)}{U_c(c_t,l_t)}\right) \qquad \text{(A-7)}$$

$\lambda_{c,t}$ is the real shadow price of the consumption good, $\left(\frac{-U_l(c_t,l_t)}{U_c(c_t,l_t)}\right)$ is the marginal rate of substitution between leisure and consumption, and $\left(\frac{1}{\rho_w}\right)$ is a markup greater than one.

The service flow from durables depends on the stock of durables, $k_{c,t}$, and energy usage, $o_{c,t}$:

$$ks_{c,t} = z_{ksc,t}\left(\psi_{co}(e_{c,t-1}o_{c,t})^{\rho_{ksc}} + (1-\psi_{co})k_{c,t-1}{}^{\rho_{ksc}}\right)^{1/\rho_{ksc}} \qquad \text{(A-8)}$$

The term $e_{c,t-1}$ represents the current period's energy intensity/efficiency in generating the flow of services from consumer durables. Note that the only margin with which to change capital services in the current period is by energy usage ($o_{c,t}$), as energy intensity/efficiency and the stock of durables are predetermined in the current period. In this application, we are thinking of energy consumption ($o_{c,t}$) as gasoline consumption by households and the durables as representing automobiles.

The stock of durables evolves according to a standard capital accumulation equation:

$$k_{c,t} = (1-\delta)k_{c,t-1} + z_{I,t}I_{c,t} \qquad \text{(A-9)}$$

where $I_{c,t}$ is purchases of new durables. The $z_{I,t}$ represents an investment technology shock which is common to durable/capital goods across the economy. Oil usage efficiency/intensity evolves according to:

$$e_{c,t} = v_{c,t} {x_{c,t}}^{\delta} {e_{c,t-1}}^{1-\delta} \tag{A-10}$$

where $x_{c,t}$ is most recent increment to efficiency (relative to $e_{c,t-1}$), $v_{c,t}$ is an exogenous efficiency "shock" and δ is the depreciation rate of durables.

Household budget constraint is given by:

$$\begin{aligned}\left(w_{f,t}l_{f,t} + w_{m,t}l_{m,t} + w_{o,t}l_{o,t}\right) + \pi_{f,t} + \pi_{m,t} + \pi_{ksm,t} + \pi_{o,t} - p_{f,t}n_t \\ - p_{f,t}\left(1 + \phi_I(I_{c,t}/k_{c,t-1})\right)\left(1 + \phi_e\left(x_{c,t}\right)\right) I_{c,t} - na_t = 0\end{aligned} \tag{A-11}$$

where $\pi_{f,t}$, $\pi_{m,t}$, $\pi_{ksm,t}$, and $\pi_{o,t}$ are profits from firms in the final goods sector, intermediate goods sector, intermediate capital services providers, and oil producers, respectively. na_t is the change in net assets of households with the ROW. We will not model this interaction with the ROW explicitly but with a reduced form relationship with feedback from US to ROW.

The term $\phi_I(I_{c,t}/k_{c,t-1})$ reflects adjustment costs of changing consumer durables. In the steady state, we assume these adjustment costs have the following properties: $\phi_I(\delta) = 0$, ${\phi_I}'(\delta) = 0$, and ${\phi_I}''(\delta) > 0$. The term $\phi_e(x_{c,t})$ captures the cost of changing efficiency from its steady state value. We normalize this cost function so that in the steady state this cost is zero. We assume that in the steady state: $\phi_e\left(x_{c,ss}\right) = 0, {\phi_e}'\left(x_{c,ss}\right) > 0$, and ${\phi_e}''\left(x_{c,ss}\right) = 0$. We interact the costs of increasing efficiency with those of investment to capture the notion that efficiency improvements are embodied in capital and that increasing efficiency increases investment costs. We use the following functional forms:

$$\phi_I(I_{c,t}/k_{c,t-1}) = a_{ck}\frac{\left({I_{c,t}}/{k_{c,t-1}} - \delta\right)^2}{2} \tag{A-12}$$

$$\phi_e\left(x_{c,t}\right) = a_{ec}(x_{c,t} - x_{c,ss}) + b_{ec}\frac{(x_{c,t} - x_{c,ss})^2}{2} \tag{A-13}$$

A-2.2. Final Goods Production

Final goods are used in consumption (nondurables) and in investment in the various types of capital and in consumer durables. Final goods producers take prices as given. Final goods producers take intermediate goods, $y_{m,t}$, and transportation services, $tr_{f,t}$ to produce the final good.

$$y_{f,t} = z_{f,t}\left(\psi_m y_{m,t}{}^{\rho_f} + (1-\psi_m) y_{tr,t}{}^{\rho_f}\right)^{1/\rho_f} \tag{A-14}$$

Intermediate input is a composite good of a continuum of differentiated goods given by:

$$y_{m,t} = \int_0^1 \left(y_{m,t}(z)^{\rho_m}\right)^{1/\rho_m} dz \tag{A-15}$$

Demand for the z-th intermediate good is given by:

$$y_{m,t}(z) = \left(\frac{p_{m,t}}{p_{m,t}(z)}\right)^{\frac{1}{1-\rho_m}} y_{m,t} \tag{A-16}$$

where $p_{m,t}(z)$ is the price of the zth variety and $p_{m,t}$ is a price index over varieties given by:

$$p_{m,t} = \int_0^1 \left(p_{m,t}(z)^{\frac{\rho_m}{\rho_m-1}}\right)^{(\rho_m-1)/\rho_m} dz \tag{A-17}$$

Transportation input is a function of labor and capital services in transport:

$$y_{tr,t} = z_{tr,t}\left(\psi_{tr,l} l_{tr,t}{}^{\rho_{tr}} + (1-\psi_{tr}) ks_{tr,t}{}^{\rho_{tr}}\right)^{1/\rho_{tr}} \tag{A-18}$$

In turn, capital services in transport is a function of capital and energy usage:

$$ks_{tr,t} = z_{kstr,t}\left(\psi_{o,tr}(e_{tr,t-1} o_{ftr,t})^{\rho_{kstr}} + \left(1-\psi_{o,tr}\right) k_{tr,t-1}{}^{\rho_{kstr}}\right)^{1/\rho_{kstr}} \tag{A-19}$$

Again, we are thinking of energy usage as primarily gasoline and the capital as equipment used in transportation (trucks, trains, aircraft and associated infrastructure).

Final goods producers maximize the present value of profits:

$$\begin{aligned}\sum_{i=0}^{\infty} M_{t,t+i}\big(&p_{f,t} y_{f,t} - w_{tr} l_{tr,t} - p_{m,t} y_{m,t} \\ &- p_{f,t}\left(1+\phi_I(I_{tr,t}/k_{tr,t-1})\right)\left(1+\phi_e(x_{tr,t})\right) I_{tr,t}\big)\end{aligned} \tag{A-20}$$

Again, the cost of investment depends on $\phi_I(I_{tr,t}/k_{tr,t-1})$ and$\phi_e(x_{tr,t})$ which have similar properties to the function described above for consumption. Capital in transportation services evolves according to:

$$k_{tr,t} = (1-\delta) k_{tr,t-1} + z_{tr,t} I_{tr,t} \tag{A-21}$$

while efficiency/intensity evolves according to:

$$e_{tr,t} = v_{tr,t} {x_{tr,t}}^{\delta} {e_{tr,t-1}}^{1-\delta} \tag{A-22}$$

where $x_{tr,t}$ is most recent increment to efficiency (relative to $e_{tr,t-1}$).

A-2.3. Intermediate Input Production

Intermediate goods producers use labor and capital services to produce a differentiated good. The production technology is given by:

$$y_{m,t}(z) = z_{m,t} l_{m,t}(z)^{\psi_{m,l}} ks_{m,t}(z)^{1-\psi_{m,l}} \tag{A-23}$$

where $z_{m,t}$ is a common productivity factor. Intermediate good producers face a monopolistically competitive market structure. Since intermediate goods producers are price setters, they face a demand for their product given by.

$$y_{m,t}(z) = \left(\frac{p_{m,t}}{p_{m,t}(z)}\right)^{\frac{1}{1-\rho_m}} y_{m,t} \tag{A-24}$$

Intermediate goods producers maximize the present value of profits:

$$\sum_{i=0}^{\infty} M_{t,t+i} \Big(p_{m,t+i}(z) y_{m,t+i}(z) - w_{m,t+i} l_{m,t+i}(z) - r_{m,t+i} ks_{m,t+i}(z) - p_{f,t+i} \phi_p \big(\frac{p_{m,t+i}(z)}{p_{m,t+i-1}(z)}\big) y_{m,t+i}(z)\Big) \tag{A-25}$$

where $r_{m,t}$ is the rental rate for capital services used by intermediate goods producer z ($ks_{m,t}(z)$). We assume that producers face Rotemberg-type adjustment costs to changing prices which are given by $\phi_p\left(\frac{p_{m,t}(z)}{p_{m,t-1}(z)}\right) = a_c \frac{\left(\frac{p_{m,t}(z)}{p_{m,t-1}(z)\pi_{m,t-1}^{\iota_\pi}} - 1\right)^2}{2}$, where ι_π is an indexing parameter. One can rewrite the intermediate goods producer's problem as

$$\sum_{i=0}^{\infty} M_{t,t+i} \Big(\big(p_{m,t+i}(z) - \lambda_{m,t+i} - p_{f,t+i} \phi_p \big(\frac{p_{m,t+i}(z)}{p_{m,t+i-1}(z)}\big)\big) y_{m,t+i}(z)\Big) \tag{A-26}$$

$\lambda_{m,t}$ is marginal cost of production and is the same across intermediate goods producers:

$$\lambda_{m,t} = z_{m,t}^{-1} \left(\frac{w_{m,t}}{\psi_{m,l}}\right)^{\psi_{m,l}} \left(\frac{r_{m,t}}{1-\psi_{m,l}}\right)^{1-\psi_{m,l}} \tag{A-27}$$

Intermediate goods producers choose $p_{m,t}(z)$ to maximize the present value of profits.

A-2.4. Capital Goods Suppliers to Intermediate Good Production

There are suppliers of capital services to intermediate goods producers. The suppliers of capital services to intermediate goods producers choose energy and capital to maximize the present value of profits:

$$\sum_{i=0}^{\infty} M_{t,t+i}\big(r_{m,t}ks_{m,t} - p_{o,t}o_{m,t} - p_{f,t}\big(1+\phi_I(I_{m,t}/k_{m,t-1})\big)\big(1+\phi_e(x_{m,t})\big)I_{m,t}\big) \tag{A-28}$$

Capital services in intermediate goods is given by:

$$ks_{m,t} = z_{ksm,t}\big(\psi_{m,o}(e_{m,t-1}o_{m,t})^{\rho_{ksm}} + \big(1-\psi_{m,o}\big)k_{m,t-1}{}^{\rho_{ksm}}\big)^{1/\rho_{ksm}} \tag{A-29}$$

Along with

$$k_{m,t} = (1-\delta)k_{m,t-1} + z_{I,t}I_{m,t} \tag{A-30}$$

and

$$e_{m,t} = v_{m,t}x_{m,t}{}^{\delta}e_{m,t-1}{}^{1-\delta} \tag{A-31}$$

A-2.5. Domestic Oil Production

Domestic oil production depends on labor and capital. We abstract from depletion; depletion would be reflected in the depreciation in the capital of energy production sector. Domestic oil producers maximize:

$$\sum_{i=0}^{\infty} M_{t,t+i}\big(p_{ot}y_{o,t} - w_t l_{o,t} - p_{f,t}\big(1+\phi_I(I_{o,t}/k_{o,t-1})\big)I_{o,t}\big) \tag{A-32}$$

Oil production depends on labor and capital services

$$y_{o,t} = z_{o,t}\big(\psi_{o,l}(l_{o,t})^{\rho_o} + \big(1-\psi_{o,l}\big)k_{o,t-1}{}^{\rho_o}\big)^{1/\rho_o} \tag{A-33}$$

with

$$k_{o,t} = (1-\delta)k_{o,t-1} + z_{I,t}I_{o,t} \tag{A-34}$$

A-2.6. Monetary Policy and Interest Rates:

We assume that the US monetary policy follows Taylor-like rule:

$$R_t = R_{ss}\left(\left(\frac{\pi_{f,t}}{\pi_{f,ss}}\right)^{\gamma_\pi}\left(\frac{y_{f,t}}{y_{f,ss}}\right)^{\gamma_y}\right)^{1-\gamma_R}\left(\frac{R_{t-1}}{R_{ss}}\right)^{\gamma_R}\varepsilon_{R,t} \tag{A-35}$$

$\pi_{f,t}$ is the gross inflation rate in the final good price, and "ss" denotes long-run or steady-state values of the variables.

We also allow for "risk" or preference shocks. The standard Euler equation for the "risk free" rate is:

$$ {}_tE\left[(R_t/\pi_{f,t+1})\beta\frac{u_c(c_{t+1},l_{t+1})/\lambda_{c,t+1}}{u_c(C_t,l_t)/\lambda_{c,t}}\right] = 1 \tag{A-36} $$

where $\lambda_{c,t}$ is the price of consumption relative to the final goods price. For the discount factor for firm profits, we include an additional term:

$$ M_{t,t+1} = z_{risk,t}\beta\frac{u_c(c_{t+1},l_{t+1})/\lambda_{c,t+1}}{U_C(c_t,l_t)/\lambda_{c,t}} \tag{A-37} $$

When the model is log-linearized, $z_{risk,t}$ acts like an exogenous risk premium when discounting future profits. This in turn affects the optimal amount of investment in capital and energy efficiency/intensity. This "shock" is meant to capture financial frictions that are not explicitly modeled. In our framework, a positive risk shock is would result in a decline in the risk premium.

A-2.7. Market Clearing

The domestic (US) economy interacts with the ROW through trade in final goods, oil, and assets. For the final goods market,

$$ \begin{aligned} y_{f,t} - n_t - \left(1+\phi_I(I_{c,t}/k_{c,t-1})\right)\left(1+\phi_e\left(x_{c,t}\right)\right)I_{c,t} \\ - \left(1+\phi_I(I_{f,t}/k_{f,t-1})\right)\left(1+\phi_e\left(x_{f,t}\right)\right)I_{f,t} \\ - \left(1+\phi_I(I_{m,t}/k_{m,t-1})\right)\left(1+\phi_e\left(x_{m,t}\right)\right)I_{m,t} \\ - \left(1+\phi_I(I_{o,t}/k_{o,t-1})\right)I_{o,t} + p_{f,t}\phi_p(\tfrac{p_{m,t}}{p_{m,t-1}}))y_{m,t} - nx_{f,t} = 0 \end{aligned} \tag{A-38} $$

where $nx_{f,t}$is net exports of the final good to the ROW. For the oil market,

$$ y_{o,t} - o_{c,t} - o_{f,t} - o_{m,t} - o_{o,t} + row_{s,t} - row_{d,t} \tag{A-39} $$

where $row_{s,t}$ and $row_{d,t}$ are ROW oil supply and demand, respectively. The total trade balance is given by:

$$ nx_t = \frac{p_{o,t}}{p_{f,t}}\left(y_{o,t} - o_{c,t} - o_{f,t} - o_{m,t}\right) + nx_{f,t} \tag{A-40} $$

If goods and oil markets are in equilibrium, the trade balance is equal to the net change in household assets from the rest-of-the world ($nx_t = na_t$) and these are assumed to be zero in the steady state.

A-2.8. Rest of the World

Rather model the behavior of the ROW structurally, we model the ROW as reduced form equations. ROW oil supply is given by:

$$row_{s,t} = (row_{s,t-1})^{\theta_s}\left(\left(\frac{p_{o,t}}{p^*_{f,t}}\right)^{\eta_s} z_{row,t}\right)^{1-\theta_s} \tag{A-41}$$

where η_s is the long run price elasticity of supply, $\eta_s(1-\theta_s)$ is the short run elasticity of supply, and $z_{row,t}$ is a supply shock. $\left(\frac{p_{o,t}}{p^*_{f,t}}\right)^{\eta_s}$ is the real price of oil in terms of the foreign final good.

The parameter θ_s reflects the inertia in the response of output to both price and supply shocks.

ROW oil demand is given by:

$$row_{d,t} = (row_{d,t-1})^{\theta_d}\left(\left(\frac{p_{o,t}}{p^*_{f,t}}\right)^{\eta_d} y^{\eta_y}_{row,t} z^d_{row,t}\right)^{1-\theta_d} \tag{A-42}$$

where η_d is the long run price elasticity of supply, $\eta_d(1-\theta_d)$ is the short run elasticity of supply, $y_{row,t}$ is ROW economic activity, η_y is the long-run income elasticity of oil demand, and $z^d_{row,t}$ is an exogenous demand shock.

For the evolution of ROW economic activity ($y_{row,t}$), US net exports (nx_t), and the real exchange rate for the ROW ($\frac{p^*_{f,t}}{p_{f,t}}$), we specify a simple reduced form VARX(1) where the exogenous ("X") variables are current and lagged values of real oil prices and US production of final goods ($y_{f,t}$). The additional "X" variables represent the feedback to the rest-of-the-world from the world oil market and from the domestic US economy. We assume a recursive causal structure among $y_{row,t}$, nx_t, and ($\frac{p^*_{f,t}}{p_{f,t}}$) in that order. Thus, the ROW economic activity is given by:

$$\log\left(\frac{y_{row,t}}{y_{row,ss}}\right) = a_{row}(L)\log\left(\frac{y_{row,t-1}}{y_{row,ss}}\right) + b_{row}(L)\log\left(\frac{nx_{t-1}}{nx_{ss}}\right) + c_{row}(L)\log\left(\frac{p^*_{f,t-1}}{p_{f,t-1}}\right) + d_{row}(L)\log\left(\frac{p_{o,t}}{p_{f,t}}\right) + e_{row}(L)\log\left(\frac{y_{f,t}}{y_{f,ss}}\right) + \varepsilon_{row,t} \tag{A-43}$$

US net exports is given by:

$$\log\left(\frac{nx_t}{nx_{ss}}\right) = a_{nx}(L)\log\left(\frac{y_{row,t}}{y_{row,ss}}\right) + b_{nx}(L)\log\left(\frac{nx_{t-1}}{nx_{ss}}\right) + c_{nx}(L)\log\left(\frac{p^*_{f,t-1}}{p_{f,t-1}}\right) + d_{nx}(L)\log\left(\frac{p_{o,t}}{p_{f,t}}\right) + e_{nx}(L)\log\left(\frac{y_{f,t}}{y_{f,ss}}\right) + \varepsilon_{nx,t} \tag{A-44}$$

The real exchange rate for the ROW:

$$\log\left(\frac{p^*_{f,t}}{p_{f,t}}\right) = a_{rer}(L)\log\left(\frac{y_{row,t}}{y_{row,ss}}\right) + b_{rer}(L)\log\left(\frac{nx_t}{nx_{ss}}\right) + c_{rer}(L)\log\left(\frac{p^*_{f,t-1}}{p_{f,t-1}}\right) + d_{rer}(L)\log\left(\frac{p_{o,t}}{p_{f,t}}\right) + e_{rer}(L)\log\left(\frac{y_{f,t}}{y_{f,ss}}\right) + \varepsilon_{rer,t} \tag{A-45}$$

We assume the real exchange rate is one in the steady state.

A-2.9. Aside: Optimal Energy Usage and Efficiency

As energy enters in similar ways across the various sectors in the economy, we present for a general sector the conditions that describe the optimal use of energy and the choice of efficiency. Because energy usage and efficiency are tied to capital services and capital in the model, we also present the optimality conditions for investment and the stock of capital.

The first order condition for oil usage is given by:

$$p_{j,t}\frac{\partial y_{j,t}}{\partial ks_{j,t}}\frac{\partial ks_{j,t}}{\partial(e_{j,t-1}o_{j,t})}e_{j,t-1} - p_{o,t} = 0 \tag{A-46}$$

This equates the value of the marginal product of oil with the price of oil. The optimal level of efficiency ($e_{j,t}$) is given by

$$M_{t,t+1}\left[p_{j,t+1}\frac{\partial y_{j,t+1}}{\partial ks_{j,t+1}}\frac{\partial ks_{j,t+1}}{\partial(e_{j,t}o_{j,t+1})}o_{j,t+1} + (1-\delta)\frac{e_{j,t+1}}{e_{j,t}}\lambda^e_{j,t+1}\right] - \lambda^e_{j,t} = 0 \tag{A-47}$$

where $\lambda_{e,t}$ is the shadow price of efficiency. Note we can combine the FOCs for oil and efficiency to obtain

$$M_{t,t+1}\left[p_{o,t+1}o_{j,t+1} + (1-\delta)e_{j,t+1}\lambda^e_{j,t+1}\right] - e_{j,t}\lambda^e_{j,t} = 0 \tag{A-48}$$

If one recursively substitutes, one can write the total value of efficiency as:

$$e_{j,t}\lambda^e_{j,t} = \sum_{i=1}^{\infty}(1-\delta)^i M_{t,t+i}\, p_{o,t+i}o_{j,t+i} + \lim_{i\to\infty}(1-\delta)^i M_{t,t+i}e_{j,t+i}\lambda^e_{j,t+i} \tag{A-49}$$

This says that the total value of efficiency is the discounted expenditures on oil.

Investment in efficiency, $x_{j,t}$, trades off the value derived from increasing efficiency and higher capital investment costs:

$$-p_{f,t}\left(1+\phi_I(I_{j,t}/k_{j,t-1})\right)\phi_e{}'\left(x_{j,t}\right)I_{j,t} + \delta\lambda^e_{j,t}\frac{e_{j,t}}{x_{j,t}} = 0 \tag{A-50}$$

Note that in the steady state:

$$\lambda^e_j e_j = \frac{\beta p_o o_j}{1-\beta(1-\delta)} \tag{A-51}$$

The shadow price of efficiency in the steady state is:

$$\lambda^e_j = p_f\phi_e{}'\left(x_{j,ss}\right)k_{j,ss} \tag{A-52}$$

Combining the first order of conditions of capital (not shown) with those for efficiency implies that in the steady state the value of efficiency relative to physical capital:

$$\frac{\lambda^e_j e_j}{\lambda^k_j k_j} = \frac{s_{o,j}}{1-s_{o,j}} \tag{A-53}$$

where $s_{o,j}$ is the expenditure share of oil in the production of capital services.

Allowing efficiency to be a choice variable, dramatically changes the long-run elasticity of substitution of oil usage with respect to price changes. To see this, consider the short-run and long-run Allen Elasticities with respect to a permanent oil price change. Here we focus on capital services which we take to be a CES production function given by:

$$ks_{j,t} = z_{ksj,t}\left(\psi_{o,j}(e_{j,t-1}o_{j,t})^{\rho_{ksj}} + \left(1-\psi_{o,j}\right)k_{j,t-1}{}^{\rho_{ksj}}\right)^{1/\rho_{ksj}} \tag{A-54}$$

The short-run Allen elasticity of oil (keeping total capital services fixed) is essentially zero:

$$\frac{do_j}{dp_o}_{|dks=0,dk=0,de=0} = 0 \tag{A-55}$$

Because capital and efficiency are predetermined, there is no scope for substitution in the short-run. The long-run (across steady states) Allen elasticity of oil for the standard case when efficiency is constant is:

$$\frac{do_j}{dp_{o|dks=0,de=0}} = -\frac{\left(1 - s_{o,j}\right)}{(1 - \rho_{ksj})} \tag{A-56}$$

When efficiency can be chosen along with oil and capital, the long-run Allen Elasticity for oil (keeping capital services and price of final goods constant) is:

$$\frac{do_j}{dp_{o|dks=0}} = -\frac{\left(1 - s_{o.j}\right) - \frac{\rho_{ksj}}{1+\eta_{\varphi x}}}{\left(1 - \rho_{ksj}\right) - \frac{\rho_{ksj}}{1+\eta_{\varphi x}}} \tag{A-57}$$

where $\eta_{\varphi x} = \frac{\varphi''(x_{j,ss})x_{j,ss}}{\varphi'(x_{j,ss})}$ is elasticity of the marginal cost of increasing efficiency. Note that as long as $\rho_{ksj} < 0$, the long-run response of oil usage to price change is larger when efficiency can change over time. The difference between the case when efficiency is constant and when it is chosen gets larger the less oil and capital are substitutes (ρ_{ksj} becoming more negative) while this difference gets smaller the value of $\eta_{\varphi x}$. Figure A-1. displays the long-run Allen Elasticity for alternative values of $\eta_{\varphi x}$.

A-3. Estimation

Taking the first order conditions of household utility maximization and firms and the market clearing conditions, we (log) linearize the model around the deterministic steady state.[1] This yields a linear rational expectations model whose solution can be written in linear state-space form:

$$Y_t = H(\theta)S_t \tag{A-58}$$

$$S_t = F(\theta)S_{t-1} + v_t \tag{A-59}$$

where Y_t is a vector of endogenous control variables, S_t is a vector of (possibly unobserved) state variables, and v_t is a vector of exogenous structural shocks with $v_t \sim N(0, Q(\theta))$. The elements in the matrices $H(\theta)$, $F(\theta)$, and $Q(\theta)$ depend on the structural parameters in the model, denoted by θ. We use only a subset of the variables in our estimation. These are given by vector, Y_t^{obs}, so the observation equation in estimation is given b:

[1] We use a combination of Dynare subroutines and custom written Matlab code to solve and estimate the model.

$$Y_t^{obs} = H^{obs}(\theta)S_t \tag{A-60}$$

Given the data, the predictive likelihood for a given parameter vector and the data, $\mathbf{Y_T}$, is denoted by $L(\theta, \mathbf{Y_T})$ and can be obtained by the Kalman filter.

Given a prior distribution over the parameters, $p(\theta)$, the posterior distribution of the parameters satisfies

$$P(\theta|\mathbf{Y_T}) \propto L(\theta, \mathbf{Y_T})p(\theta) \tag{A-61}$$

We estimate the posterior distribution of the parameters by sampling from a random walk Metropolis-Hasting Monte Carlo Markov Chain (MH-MCMC).[2] We "tune" the chain by searching over the parameter space to maximize the "posterior probability". We use the first 600,000 draws of the chain to pick a scaling parameter and variance/covariance matrix for the Metropolis-Hastings draws over and then use the last 500,000 draws as our sample of realizations from the posterior distribution of the parameters. This sample of draws from the posterior distribution can be used estimate the posterior distribution of any function of the underlying parameters such as impulse responses and, in particular, the elasticity of real GDP with respect to oil price changes.

A-3.1. Shocks and Observables

In our benchmark model, we include twelve variables in our observation vector and twelve structural shocks. Our choice of shocks and observables was guided by our desire to estimate the output elasticity of US real GDP with respect to real oil price changes brought about by supply disruptions in the ROW. Furthermore, as we are interested in assessing change in energy usage in the transportation sector on this elasticity, we include observables and shocks pertaining to transportation. Table A-1 lists the variables included in the observation vector. The US macro variables include: log real GDP per capita, log total hours per capita, and the ex-post real interest rate (three-month Treasury bill minus the growth rate in the GDP deflator). Oil related US variables include: log of the share of gasoline consumption in nominal GDP, log of the share of investment in transportation equipment in nominal GDP, log of petroleum imports as

[2] We restrict the parameter space so that the Blanchard and Kahn (1980) condition for a unique, stable solution holds. In practice, this is done by rejecting parameter draws in which the BK condition fails to hold. This means that the posterior density is quite complicated with multiple modes, cliffs, and ridges. This in turn makes exploration of the parameter space quite challenging.

a share of GDP, and the log of US oil production. World oil market variables include: log real price of oil (deflated by the US GDP deflator) and the log ROW oil production. International trade variables include: world industrial production, real exchange rate for foreign goods (relative price of foreign final goods in terms of US final goods), and US net exports as a percent of nominal GDP.[3] We use quarterly data and our sample period starts in the first quarter of 1991 and runs through fourth quarter of 2015. We were reluctant to start our sample earlier given the structural changes that have occurred in the oil market. We judged this sample to be a good tradeoff between having sufficient sample size to estimate the parameters and having relatively few structural changes. As our focus was on more of the short-run consequences of oil price shocks and model solution was based on deviations from a steady state (or balanced growth path), variables with a substantial secular trend, US real GDP, US hours, US oil production, ROW oil production, and ROW economic activity, were detrended with deterministic, quadratic time trends; the other variables were demeaned.

To control for other sources of economic fluctuations other than oil supply shocks, we include a variety of US macro shocks (representing essentially different shocks to US oil demand), ROW shocks to oil supply and oil specific demand shocks, ROW economic activity and trade shocks, and, finally, sectoral shocks (TFP shocks to US goods and US oil production). The specific structural shocks we include are: TFP shock in the goods sector ($z_{m,t}$), shock to total consumption (or, equivalently, preference shock), monetary policy shock, risk shock, aggregate investment productivity shock, US oil production productivity shock, US price markup shock, ROW oil supply shock, ROW oil specific demand shock, and ROW reduced form shocks to world economic activity, ROW real exchange rate, and US net exports. While including more observables and shocks would have been desirable, we believe that the technical burden of estimating a larger model offset the benefit of increasing the size of the estimated model.

A-3.2. Prior Distribution of Parameters.

We can break the parameters in our model into roughly three groups: (1) calibrated parameters; (2) parameter over which we have informed priors; (3) parameters over which we have relatively uniformed priors. Table A-2 lists the calibrated preference and share parameters. The key share parameters that we set equal to their sample averages are: share of gasoline expenditures in consumption (this is a proxy for the share of oil consumption in total

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[3] Most of the data were obtained from St Louis Fed's Fred© database. The world industrial production series is from CPB Netherlands Bureau for Economic Policy Analysis and excludes construction activity.

consumption), share of automobile purchases in total consumption (proxy for share of capital in capital/transportation services used in consumption), the share of the transportation sector in aggregate gross output (we abstract from other inputs and approximate gross output as valued added plus transportation services). Similarly, we calculate labor share in gross output in transportation and oil extraction sectors. We also use the share of US oil imports in total US oil consumption and the share of US oil production in total world oil production to calibrate the relative sizes of the US and ROW oil supplies and demands. The shares of US oil consumption to nominal GDP and the ratio oil consumption in transportation services to total US oil consumption $\left(\frac{o_{c,t}+o_{tr,t}}{o_{c,t}+o_{tr,t}+o_{m,t}}\right)$ are used to set the share of oil in production of materials and the share in transportation.

For another group of parameters that are estimated, we have relatively informed priors. These are listed in Table A-3. For the macro parameters, we set prior modes to values common in the literature. For the ROW oil supply and demand elasticities, we set generalized beta distributions with a mode of 0.7 for the long-run and 0.15 for the short-run elasticities of supply and –0.7 for the long-run and –0.15 for the short-run elasticities of demand. The parameters governing the stochastic processes of the exogenous shocks as well as the ROW trade variables are relatively uninformed.

A-4. Empirical Results

A-4.1. Parameter Estimates

Table A-4, Panels A and B display the posterior distribution of some of the key parameters for the baseline model. Most of the "macro" parameters are well within the range implied by typical macro models. Some exceptions include the inverse of the intertemporal elasticity of substitution and the parameters governing the Taylor rule. The fact that we do not separate the ex-post real interest rate into a nominal interest rate and inflation observables and that nominal interest rates were constrained by the zero lower bound towards the end of our sample probably accounts for the somewhat low values on the inflation and output stabilization parameters in the Taylor rule.

Sectoral elasticities of substitution between nondurable and oil related consumption services as well as between intermediate goods and transportation in the production of final goods were estimated to be above one. Similarly, the elasticity of substitution between labor and capital services in the production of intermediate goods was estimated to be greater than one. On the other hand, the elasticity between labor and capital in oil production was estimated to be less than one. All the elasticities of substitution between oil and capital were estimated to be less than one, with elasticity of substitution between oil and capital in transportation particularly low (in the [0.01,0.10] range). If one weighted these oil/capital elasticities of substitutions by the steady shares in US oil consumption, the aggregate oil/capital elasticity of substitution is around 0.58.

The ROW oil supply and demand elasticities are presented at the bottom Table A-4, Panel A. The long-run price elasticity of oil supply and demand are roughly equal, with posterior median/mean of around 0.5 and –0.5, respectively. The short-run price elasticity of ROW oil demand is substantially (roughly a factor of five time) larger than that of ROW oil supply. Even after one year, the implied elasticity of ROW oil demand is substantially greater than that of ROW oil supply (–0.31 versus 0.09). This difference has implications for attributing the sources of short-run fluctuations in oil prices. Table A-4 Panel B reports the structural parameters associated with adjustment costs as well as parameters of the stochastic processes for the exogenous shocks. Most of the adjustment cost parameters suggest substantial slow adjustment in labor, capital, and oil intensity; the exceptions being labor and efficiency in the transportation sector and oil using consumer durables in consumption.

A-4.2. Model Fit

Figure A-2 displays the actual and one step ahead predicted values implied by model. The predicted value is from the Kalman filter and forms the basis for the likelihood function of the model ($Y_{t|t-1}^{obs} = H^{obs}(\theta)S_{t|t-1}$). From Figure A-2, one notes the predicted values from model track the observed variables pretty well (albeit typically with a lag). The exception is the ex post real interest rate. Here the predicted value from the model substantially misses the actual value.[4]

A-4.3. Impulse Response Analysis

To get a feel for the dynamics implied by the model, Figure A-3 displays the impulse responses of selected variable to a ROW oil supply shock. Here we consider a negative shock to ROW supply and scaled the impulses up so that real oil prices rise by 10% during the first year after the shock. We find that following a shock oil prices rise, peaking about two quarters after

[4] The failure of model to fit the ex post real interest rate may be related to the unusual parameter estimates for the Taylor rule discussed above and the zero lower bound on nominal interest rates.

the shock and then slowing return to its pre-shock level. US real GDP falls in response to the shock with the peak decline occurring around fourth quarter. US hours also fall in response to ROW oil supply shock but the 5th percentile and 95th percentile posterior interval includes zeros. Not surprisingly, ROW oil output falls in response to supply shock, but the response is "humped" shape given the inertia estimated in ROW supply. On the other hand, US oil supply rises in response to increases in oil prices brought about by the decline in ROW supply. This response peaks around seven quarters after the shock and is relatively small with an implied US oil supply elasticity in the first year after the shock of around 0.02. Finally, the value of US oil imports as percent of real GDP rises in response to the increase.

While space prevents presenting the IRFs for all eleven of the other shocks, Figures A-4–A-6 show the response to a ROW oil specific demand shock, US intermediate goods TFP shock and US risk shock. From Figure A-4 one observes that responses of oil prices, US real GDP, hours, oil production and oil imports are qualitatively similar to ROW oil supply shock; the exception is ROW oil production which rises in response to a positive ROW oil demand shock. This suggests that from the US point-of-view there is little difference between ROW oil supply shock and oil specific demand shock. With respect to the oil market, both US TFP and US risk shocks (see Figures A-5 and A-6) increase oil prices and increase ROW oil production. Their effects on US oil production differ in the TFP shock results in decline in US oil production while the risk shock raises US oil production. That a TFP shock in the intermediate goods sector lowers US oil production reflect the reallocation of labor and capital away from oil production and into goods.

A-4.4. Historical Decompositions

Figure A-7 displays the historical decomposition of real oil price fluctuations. Specifically, the figure displays the contributions of various groups of shocks to the forecast error implied by the model (based on the smoothed states) over a four-quarter horizon.[5] Given the relatively large number of shocks, we combine these into five groups: nontechnology shocks originating in the US (risk, interest rate rule, price markup, and consumption), non-oil technology shocks originating in the US (goods TFP and investment shocks), oil technology shock in US, ROW oil supply shock, ROW shocks (oil specific demand, ROW economic activity, real exchange rate, and net exports shocks).

[5] The implied forecasted error based on the smoothed states is $Y_{t+4}^{obs} - H^{obs}(\theta)F(\theta)^4 S_{t|T}$. $S_{t|T}$ is the estimated state vector at time t based on the full sample and is obtained from the Kalman smoother. This forecast error is decomposed into sources from the respective structural shocks.

From Figure A-7, one observes that a large fraction of oil price fluctuations over a one-year horizon appears to be driven by ROW oil demand shocks, either oil specific demand shocks or shocks that affect ROW oil demand through ROW economic activity. The run up in oil prices in the mid-2000s, the collapse and recovery in oil prices after 2009-10, and the recent decline in 2014-15 were all attributed largely to ROW demand shocks. Over our sample, ROW oil supply shocks do contribute to oil price fluctuations but not nearly to the extent that ROW demand shocks do. During the 2006-2015 period, ROW oil supply shock’s contribution to oil price movements was positive. According to the model, US shocks also contribute modestly to oil price fluctuations. US oil supply shocks show up as contributing to a decline in oil prices in the 2011-2014 period, but their contribution is relatively small.

Figures A-8 and A-9 display the historical decompositions for ROW oil production and US oil production, respectively. In contrast, to oil prices, oil production fluctuations over the course of a year tend to be driven primarily by oil supply shocks. For ROW oil production, the greater than expected oil production in the 1990s and the lower than expected production starting in 2006 were driven by oil supply shocks. For US oil production, the effects of the so-called “Shale Revolution” show up as large surprises in US oil production largely due US oil production (technology) shocks.

The finding that oil demand shocks appear to drive most of the real oil price fluctuations, while oil supply shocks drive oil output fluctuations, is consistent with our estimates of ROW oil demand and supply price elasticities presented in Table A-4.[6] The short-run ROW oil demand price elasticity was estimated to be in the -0.12 to -0.28 range while the short-run ROW oil supply price elasticity was estimated to be in the 0.01 to 0.04 range. Thus, demand shocks, everything else equal, result in larger price movements and smaller quantity movements than supply shocks.

Finally, Figure A-10 displays the historical decomposition for four quarter forecast error for US real GDP. Figure A-10 suggests that annual fluctuations in US real GDP over our sample were largely due to non-technology shocks originating in the US. The substantially lower than expected growth in 2000-2004 period and again in 2008-2010 periods were largely due to US non-technology shocks (particularly risk premium shocks). On the other hand, ROW oil supply shocks do not seem to have been a major contributor to US real GDP fluctuations over our sample. These results are consistent with Christiano et al. (2014) who find that risk premium

[6] Bodenstein and Guerrieri (2011) also find that oil price fluctuations were driven primarily by ROW oil efficiency shocks which would correspond to oil specific demand shock in our framework.

shocks were largely responsible for the decline in output during the 2007-2009 recession and that oil price fluctuations had relatively small effects on US GDP fluctuations. Note that US oil supply shocks provided a small positive contribution to US real GDP during the 2010-2014 period.

A-5. GDP/Oil Elasticities

As real GDP/Oil price elasticities play a prominent role in macroeconomic/energy policy discussions, Table A-6 displays GDP/Oil price elasticities for baseline model as well as for various other versions of the model. For the baseline model, the posterior mode, mean, and median values of the GDP/oil price elasticity all roughly equal to -0.007 and the 90 percent posterior interval [-0.012 -0.001]. These are on the low end of the elasticities estimated in the older empirical macroeconomics oil price literature (as documented by Jones et al. 2004, Leiby 2008 and Brown and Huntington 2013, 2015). More recently, however, estimated DSGE models such as Balke et al. (2010) and Bodenstein and Guerrieri (2011) or Kormilitsina (2015) who use a combination of calibration and estimation and get point estimates of the GDP elasticity of around -0.006, -0.012, and -0.006, respectively.

To test the sensitivity of the model to alternative modeling or estimation choices, we consider a model with preferences that eliminates the income effect for leisure (Greenwood, Hercowitz, and Huffman (1988)).[7] This makes it more likely that oil supply shock will have a larger effect on hours and, hence, GDP. We estimated this model using the same prior distribution for the parameters as in the baseline model. The estimated GDP/oil price elasticity is somewhat higher (mode, mean, and median are equal to -0.010, -0.009, and -0.009, respectively). We also considered the model in which we augment the vector shocks with a persistent ROW oil supply shock.[8] Estimates of the posterior mode of the GDP/oil price elasticity (due to transitory shocks) for this model is -0.010. We also estimated a version of the baseline model where we set the macro parameters equal to the modes of their prior distributions. In this case, mode of the GDP/oil elasticity is estimated to be substantially lower (-0.002) than the baseline case.

Because ROW oil specific demand shocks have similar effects on US economic performance as ROW oil supply shocks, we calculate the GDP/oil price elasticity for the case where the oil price increase is the result of ROW oil specific demand shocks. While the effect of

[7] The GHH utility function has the form $u(c_t, l_t) = \frac{(c_t - \chi \frac{{l_t}^{1+\eta}}{1+\eta} h_t)^{1-\sigma}}{1-\sigma}$.

[8] We set the autoregressive coefficient of this shock process to 0.99.

ROW oil specific demand shocks is qualitatively similar to ROW supply shocks, the GDP/oil price elasticities are a bit smaller than those implied by ROW oil supply shocks.

What accounts for the low GDP/oil price elasticities implied by the estimated DSGE models? To get a sense of the channels through which oil supply shocks affects economic activity in our model, consider a first order (log) linear approximation around the steady state for real GDP:

$$\hat{y}_t^{GDP} = \frac{1}{(1 - s_o + s_y^o)} (\hat{y}_t^f - s_o \hat{o}_t^y + s_y^o \hat{y}_t^o) \tag{A-62}$$

where $\hat{y}_t^{GDP}$ is deviations of log real GDP from the steady state, $\hat{y}_t^f$ is (log) output of final good or gross output, $\hat{o}_t^y$ is the (log) oil used in production of the final good, $\hat{y}_t^o$ is the (log) domestic production of oil, s_o is the share of oil in the production of final good, and s_y^o is the ratio of the value of domestic oil production to the value of the final good. Substituting for final goods, equation (62.) can be rewritten as:

$$\hat{y}_t^{GDP} = \frac{1}{\left(1 - s_o + s_y^o\right)} (s_l \hat{l}_t^y + s_k \hat{k}_{t-1}^y + s_o \hat{e}_{t-1}^y + s_y^o \hat{y}_t^o) \tag{A-63}$$

where $\hat{l}_t^y$, $\hat{k}_{t-1}^y$, and $\hat{e}_{t-1}^y$ represent (log) deviations of labor, capital, and oil efficiency used in the production of the final good from their steady state values, respectively, s_l is the share of labor in production of the final good, s_k is the share of capital in the final good. Note that oil usage and, hence oil prices, do not have a direct effect on real GDP; oil price movements only have an effect through labor, capital, oil efficiency/intensity, or on through domestic oil production.

Given that, in the short-run, capital and efficiency are fixed (or in the medium term are subject to substantial adjustment costs), an increase in oil prices can affect output only through their effect on labor input. Thus, the responsiveness real GDP to oil price increases depends largely on the responsiveness of labor input and the elasticity of domestic oil supply. An increase in oil prices and the resulting decline oil input usage might cause a decline in labor demand, but the negative income effect (given that the US is a net importer of oil) would lead to an increase in labor supply. These two conflicting effects tend to mute the response of labor quantities and, hence, real GDP. Real wage rigidities would tend to lead to larger labor quantity adjustment while adjustment costs in moving labor across sectors would tend to dampen labor response. For estimating the model over our sample period, the overall response of hours worked to supply shocks is relatively small (see the above impulse response functions), suggesting substantial flexibility in how agents respond to ROW oil supply shocks. As a result, the real GDP response implied by the estimated model is relatively modest.

Why is the GDP to oil price elasticity so low relative to the earlier, empirical literature? The general equilibrium approach taken by here implies that all prices respond—not just the price of oil—when there is an oil supply disruption. The price responses throughout the model generally lower the magnitude of quantity responses (for variables such as non-oil goods and of hours worked) than would be the case if prices and wages did not change. The larger price responses and lower quantity responses tend to reduce the elasticity of real GDP with respect to real oil price changes.

Despite the wage and price stickiness and of various types of adjustment costs, when taken to the data the model still finds substantially flexibility for economic agents to adjust to oil price changes. In addition, the older, purely empirical literature which was essentially a partial equilibrium or reduced form approach may not have correctly identified the effects of oil supply shocks (see Barsky and Kilian 2004). Furthermore, the reduced form empirical literature, such as Herrera and Pesavento (2009), Kilian (2009), Kilian and Murphy (2012) and Herrera (2016), has generally found a declining importance of oil price changes on economic activity over time. Indeed, Blanchard and Gali (2010) argued that a declining oil-to-GDP ratio, increased labor market flexibility, and better monetary policy have all contributed to declining importance of oil price changes in macroeconomic fluctuations.

A-6. Scenario Analysis

In the previous section, we used the historical data to set the values of key steady state relationships. In this section, we examine some counterfactual experiments that correspond to structural changes in the manner and the extent to which oil is used in the United States. Specifically, we consider two alternative counterfactual scenarios. In the first scenario, we consider the effect of a substantial decline in share of imported oil on total US oil consumption, while keeping the size of US oil production relative to the ROW the same. In this case, we set the share of imported oil in total US oil consumption to be 10 percent (down from 2/3). In the second scenario, we set the shares of oil expenditures in total consumption, the share of imported oil in total oil consumption, and the share of US oil production to be the same values at in the NEMS baseline scenario for the year 2030.[9] Scenario 2 differs from Scenario 1 primarily by changing the composition of oil consumption (relatively less oil used by households) and more

[9] In this scenario, the share of oil expenditures in consumption is equal to approximately 0.02 (down from 0.03), the share of oil imports in total US oil consumption was approximately 0.138 (down from 2/3), and the share of US oil production in world oil production was approximately 0.113 (up from 0.08)

domestic oil production (relative to the ROW). We re-estimate the benchmark model imposing the restriction that the parameter vector satisfy the conditions for a stationary, unique equilibrium for all three models: the baseline model, scenario 1, and scenario 2.

Table A-6 displays the implied GDP/real oil price elasticity for the benchmark as well as the two counterfactual scenarios. Comparing the benchmark results (line 1 of Table A-5 versus line 1 of Table A-6), it appears that imposing the restriction that the parameter vector results in unique, stationary solutions for all three models raises slightly (in absolute value) the estimated GDP/real oil price elasticity (line 1, Table A-6) above the case where the parameter vector was not restricted (line 1, Table A-5). Moving across scenarios, the counterfactual experiments imply a substantially reduced GDP/real oil price elasticity, roughly 40-60 percent lower than the estimated elasticity over our sample period. This suggests that existing trends in the oil market, lower US oil imports along with higher domestic production, will likely result in substantially less sensitivity of the US economy to oil prices due to ROW oil supply disruptions.

A-7. Conclusions

We use a medium-sized DSGE model of the US economy that includes representation of the world oil market, the international economy, and US trade to examine the effect of oil shocks on aggregate US economic activity. The model is based on quarterly data from 1991 through 2015. The model's parameters are established with a combination of calibrated parameters and Bayesian estimation. The estimated parameters include those over which we have informed priors and those which we have relatively uniformed priors. Using this approach, the most of the model's "macro" parameters are well within the range implied by typical macro models. Some exceptions include the inverse of the intertemporal elasticity of substitution and the parameters governing the Taylor rule.

As expected, the impulse response functions show normal price responses to changes in oil demand or supply. Increased US or ROW demand increases world oil prices. Increased US or ROW oil supply decreases world oil prices.

Consistent with previous research, US GDP is negatively affected by negative shocks in ROW oil production. Following a negative shock, ROW oil output show signs of correction, which suggests that rising prices stimulate a partial recovery in ROW production (possibly in areas of the world not affected by the disruption). US oil supply rises in response to increases in oil prices brought about by the decline in ROW supply. Finally, the value of US oil imports as percent of real GDP rises in response to the price increase.

Examining the effects of shocks to ROW oil demand, we find that the responses of oil prices, US real GDP, US hours worked, US oil production and US oil imports are qualitatively similar to ROW oil supply shock. The exception is ROW oil production which rises in response to a positive ROW oil demand shock. These findings suggest that from the US point-of-view, there is little difference between ROW oil supply shock and oil specific demand shock.

The historical decompositions obtained with the model show that ROW oil demand shocks—either oil specific demand shocks or shocks that affect ROW oil demand through ROW economic activity—account for most of the fluctuation in real world oil prices over the period from 1991 through 2015. ROW oil production is also an important source of the fluctuations in world oil prices. US oil production is a lesser source.

The annual fluctuations in US real GDP over our sample were largely due to non-technology shocks originating in the United States. The substantially lower than expected growth in 2000-2004 period and again in 2008-2010 periods were primarily due to US non-technology shocks (particularly risk premium shocks). In contrast, ROW oil supply shocks do not appear to have been a major contributor to US real GDP fluctuations over our sample period.

Taking into account the changes in oil prices and US GDP that result from a ROW oil supply shock, we find that the baseline model implies an elasticity of US real GDP with respect to oil prices of -0.007 to -0.010. These values are on the lower end of estimates in the earlier literature, but consistent with estimates in the newer literature. The estimate is fairly robust to changes in the model's specification.

On the other hand, we show that if the long-run share of oil imports in total oil consumption falls, the elasticity of GDP with respect to oil prices falls (in absolute value). In fact, exercises with the model suggest that a reduction of oil imports to 10 percent of oil consumption (down from the 67 percent average over our sample) will lower the real GDP/oil price elasticity by 40-60 percent.

A-8. References

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A-9. Figures and Tables

Figure A-1. Long-Run Allen Elasticities with Constant and Endogenous Efficiency

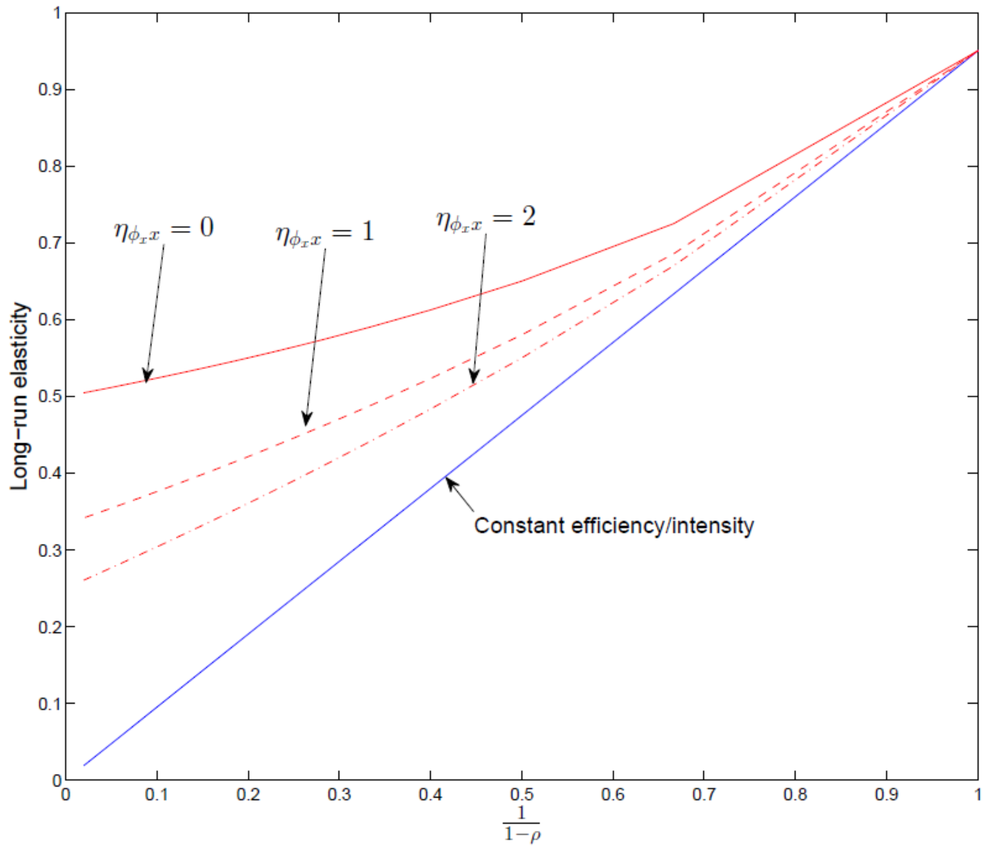


Figure A-2. Actual and One Step Ahead Predicted Value from Model

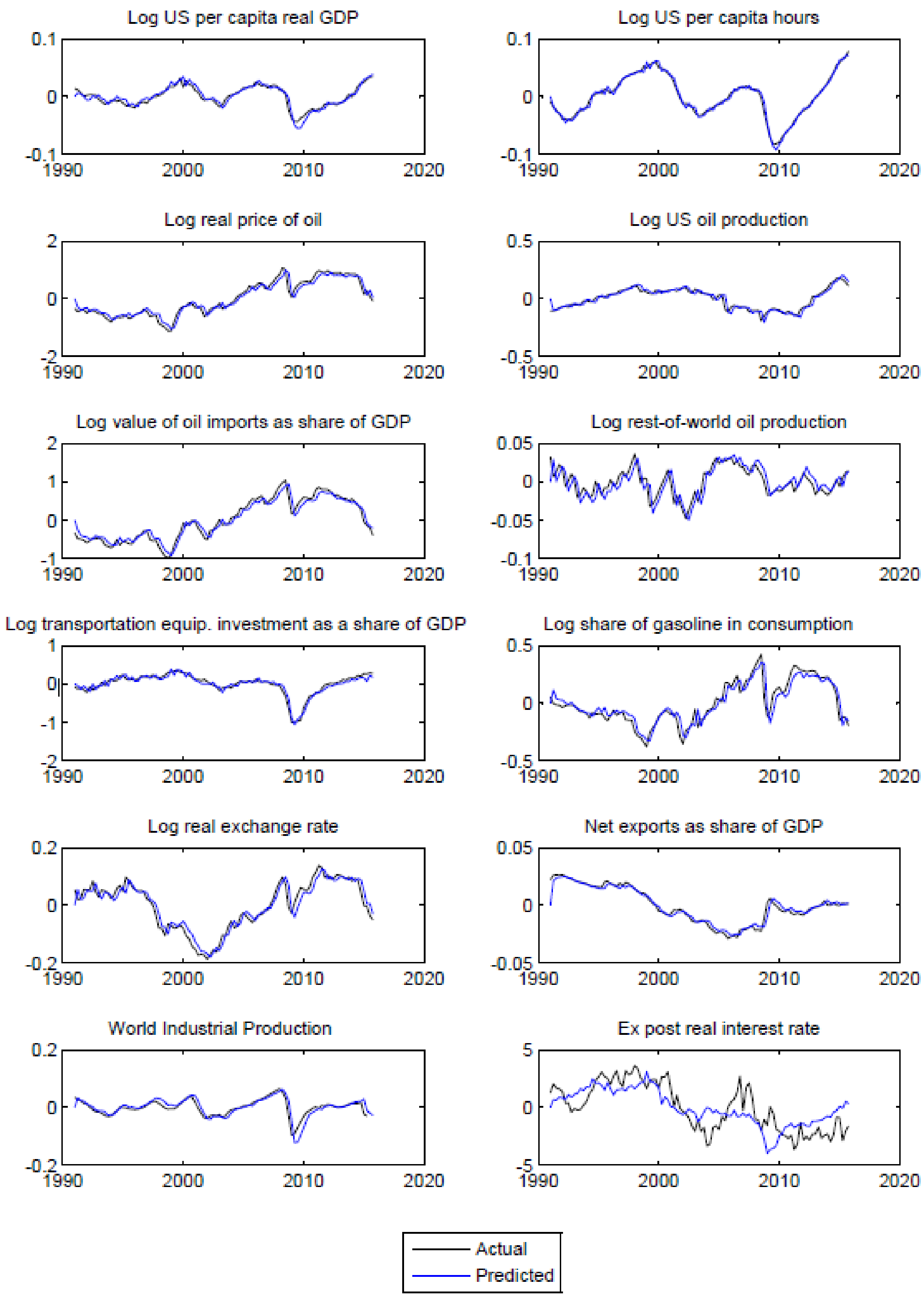


Figure A-3.

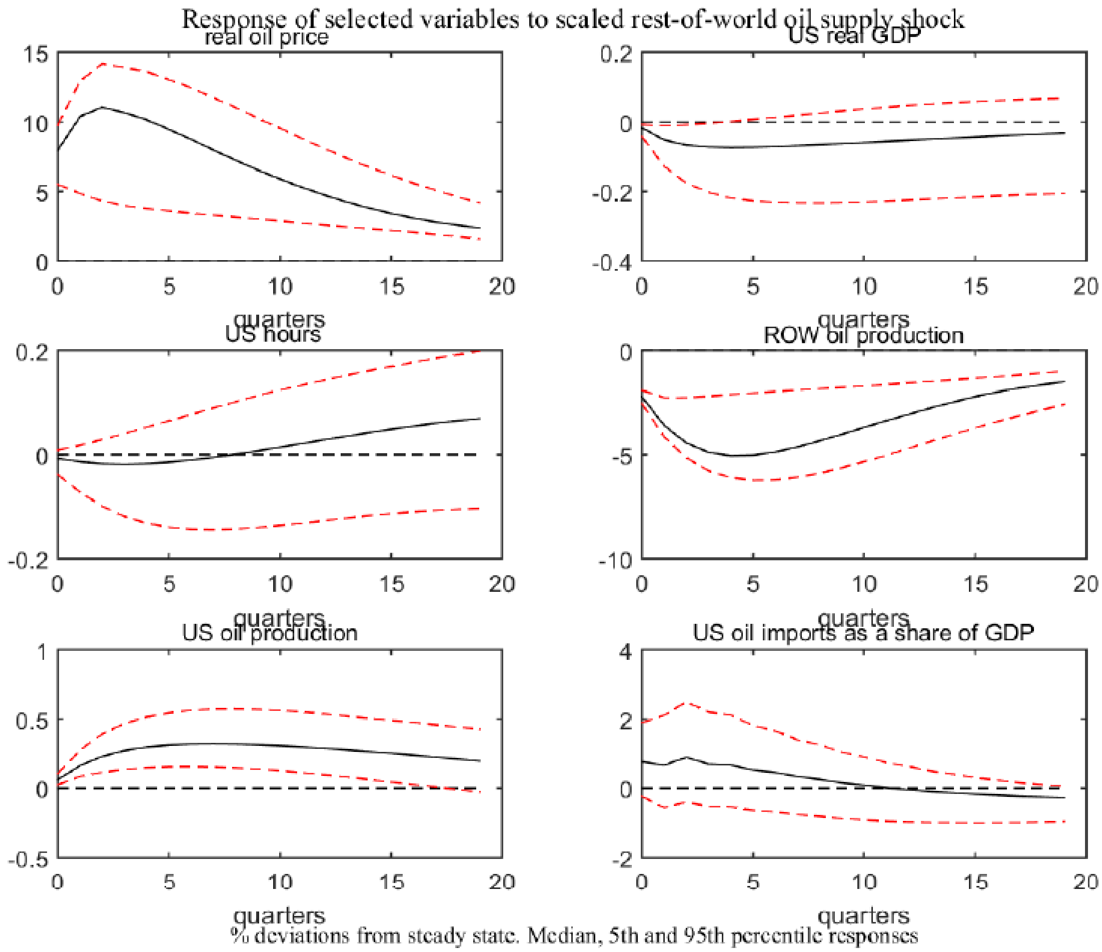

Response of selected variables to scaled rest-of-world oil supply shock
real oil price
US real GDP
US hours
ROW oil production
US oil production
US oil imports as a share of GDP
quarters
% deviations from steady state. Median, 5th and 95th percentile responses

Figure A-4.

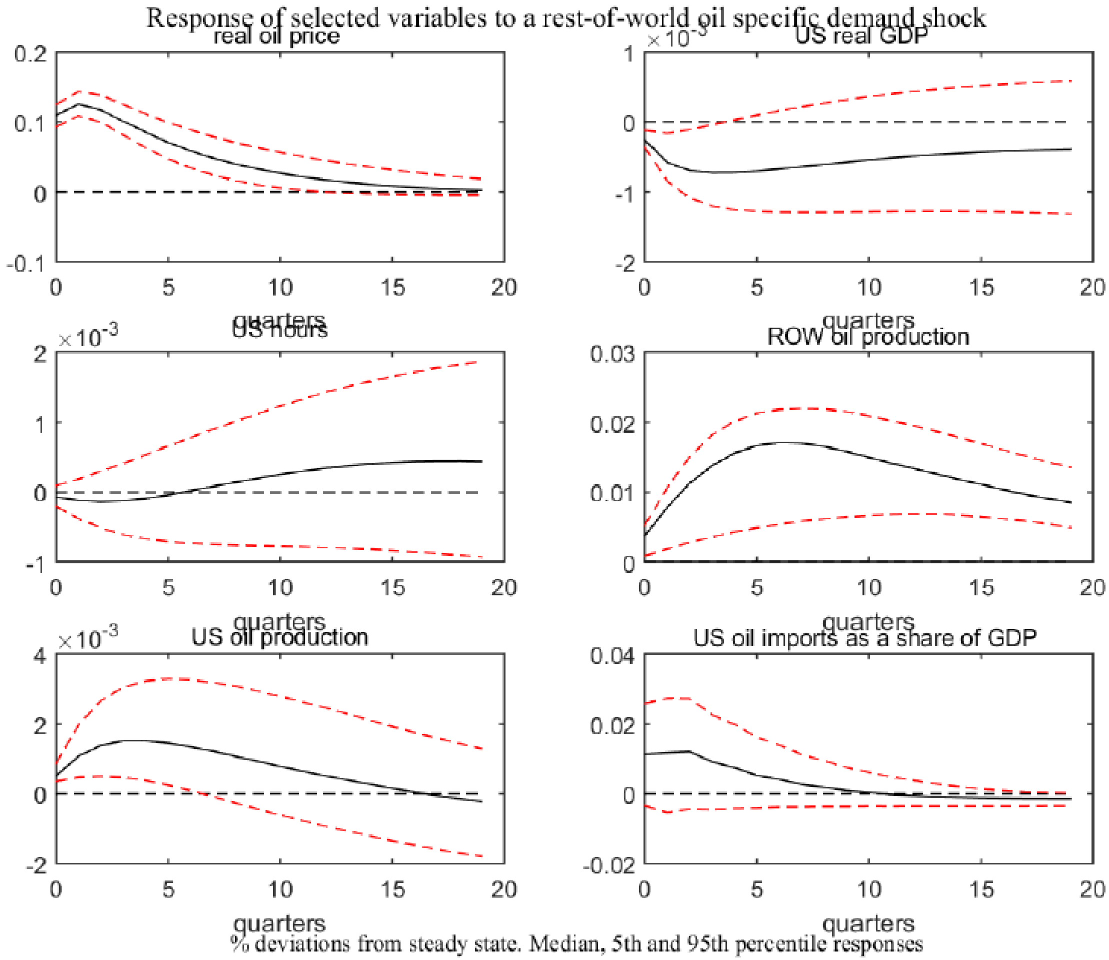
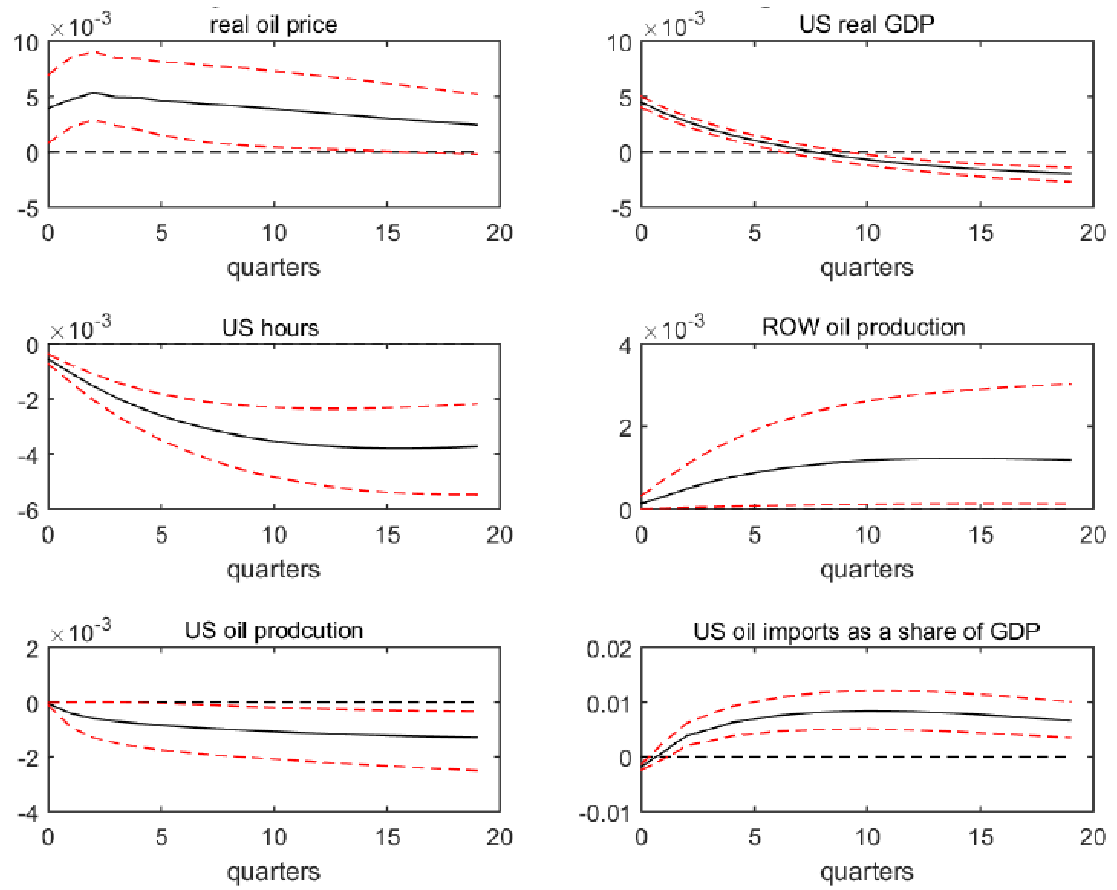
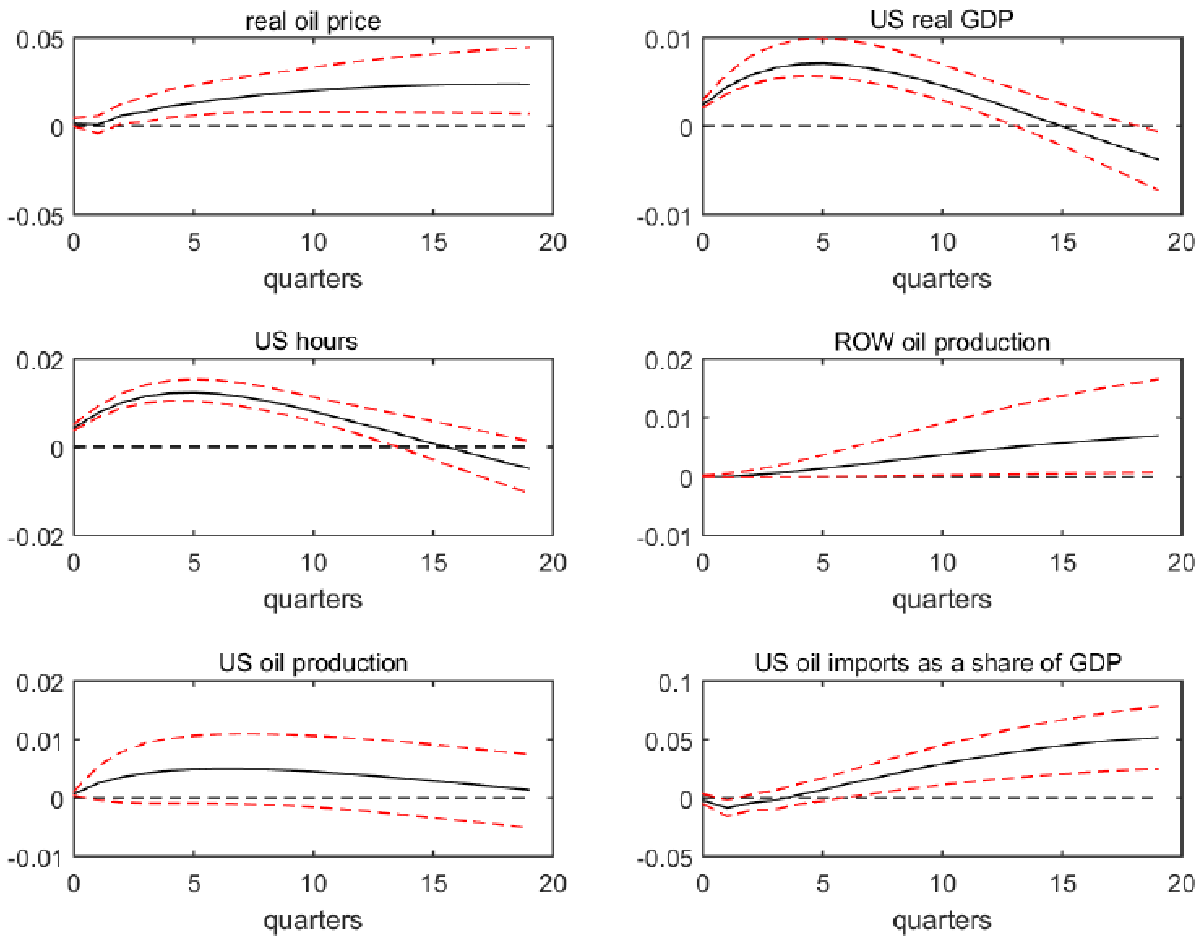

Response of selected variables to a rest-of-world oil specific demand shock
real oil price
US real GDP
×10^-3
US hours
×10^-3
ROW oil production
US oil production
×10^-3
US oil imports as a share of GDP
quarters
% deviations from steady state. Median, 5th and 95th percentile responses

Figure A-5. Response of Selected Variables to a US Intermediate Goods TFP Shock



% deviations from steady state. Median, 5th and 95th percentile responses

Figure A-6. Response of Selected Variables to a US Risk Shock



% deviations from steady state. Median, 5th and 95th percentile responses

Figure A-7. Decomposition of One Year Ahead Forecast Error for (Log) Real Oil Price

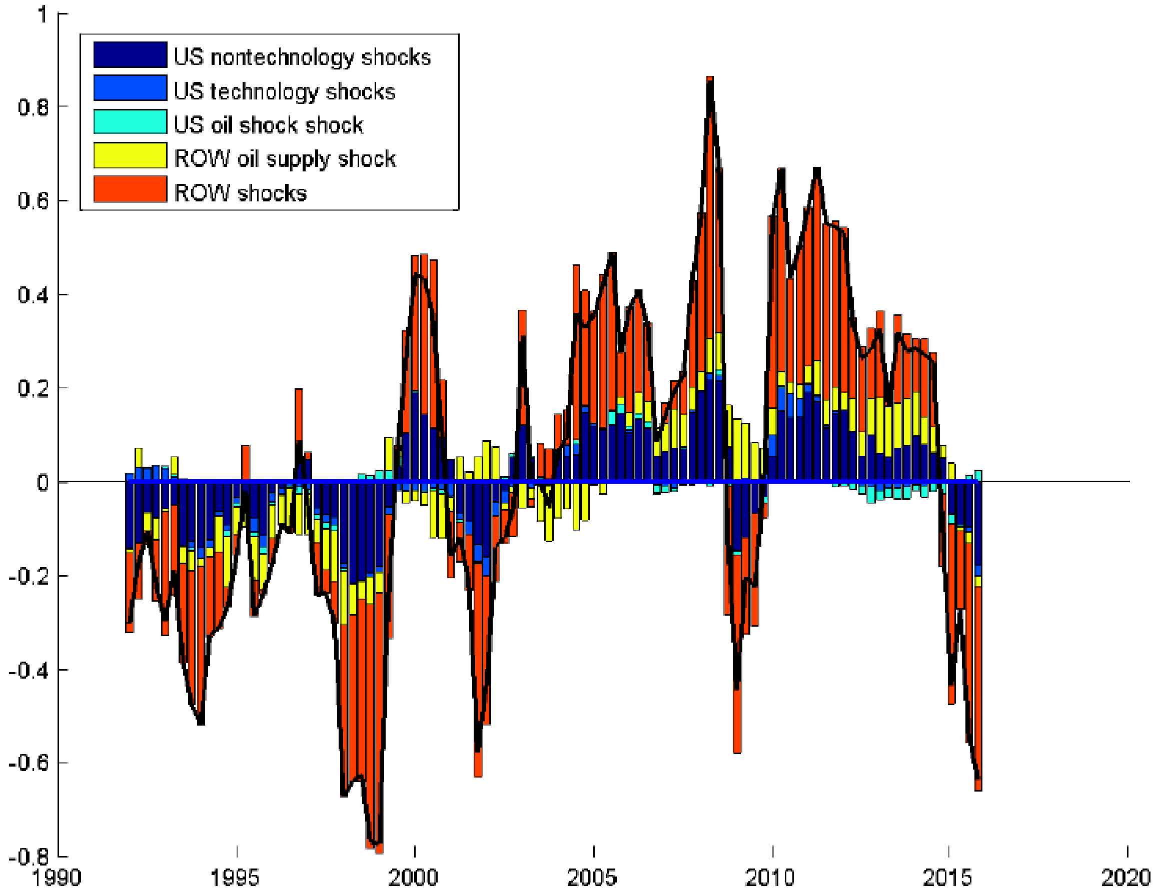


Figure A-8. Decomposition of One Year Ahead Forecast Error for Rest-of-World Oil Production

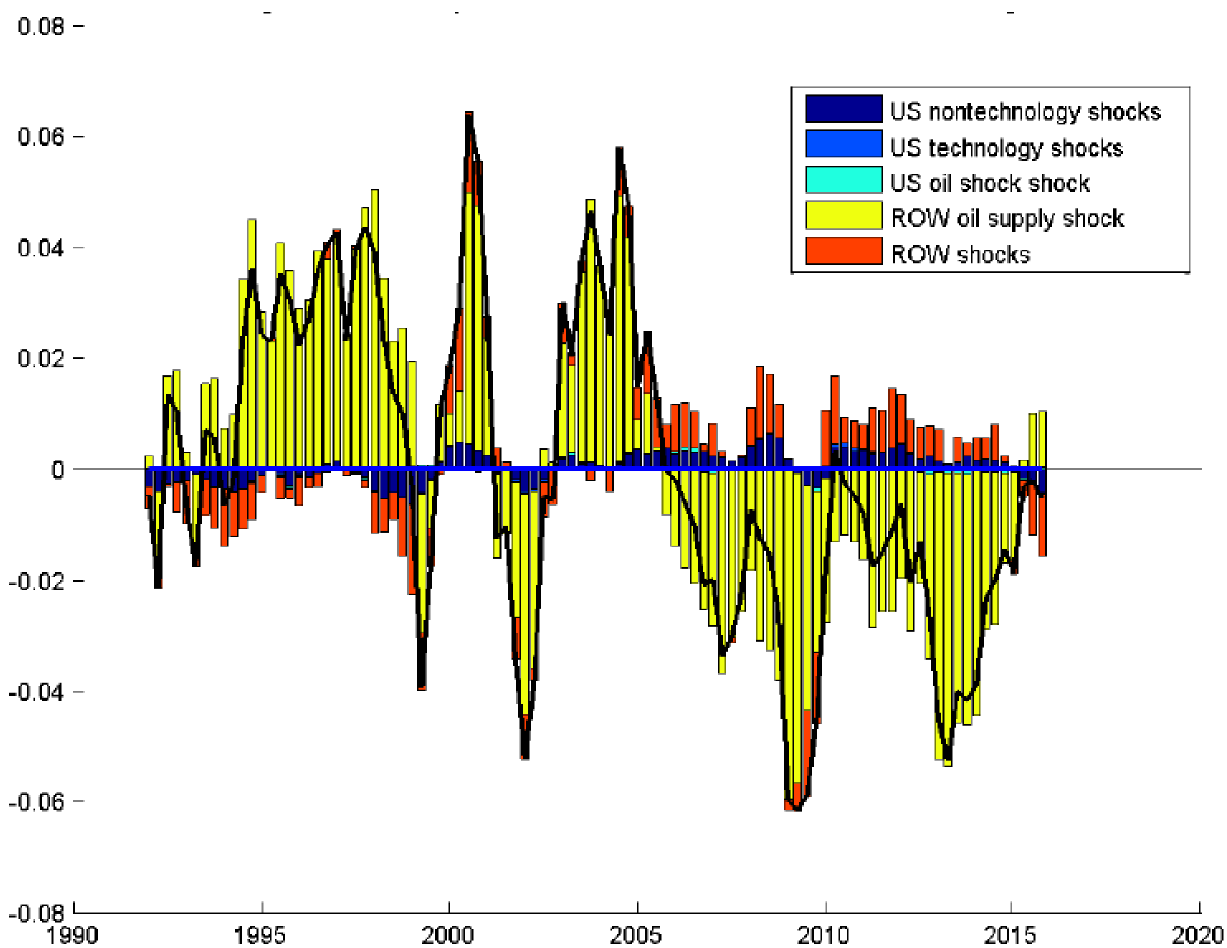


Figure A-9. Decomposition of One Year Ahead Forecast for US Oil Production

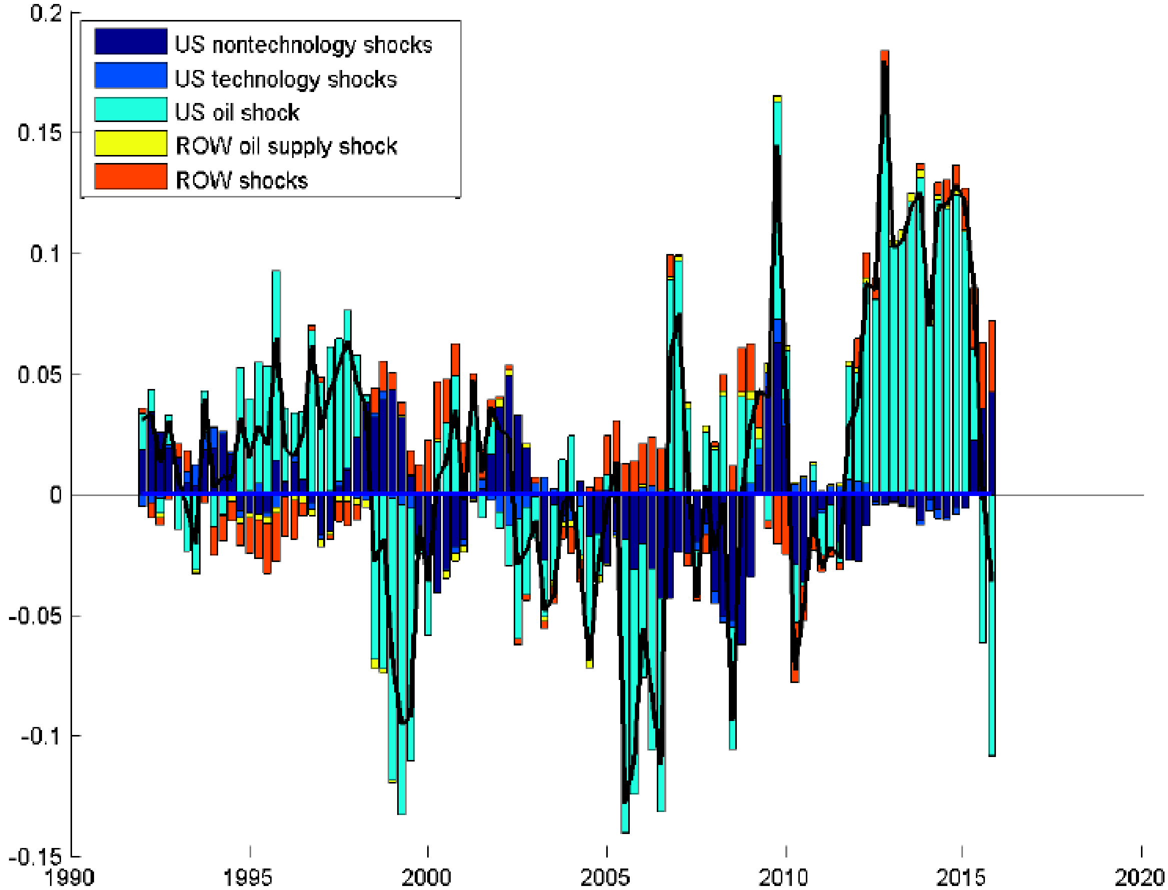


Figure A-10. Decomposition of One Year Ahead Forecast Error for (Log) US Real GDP

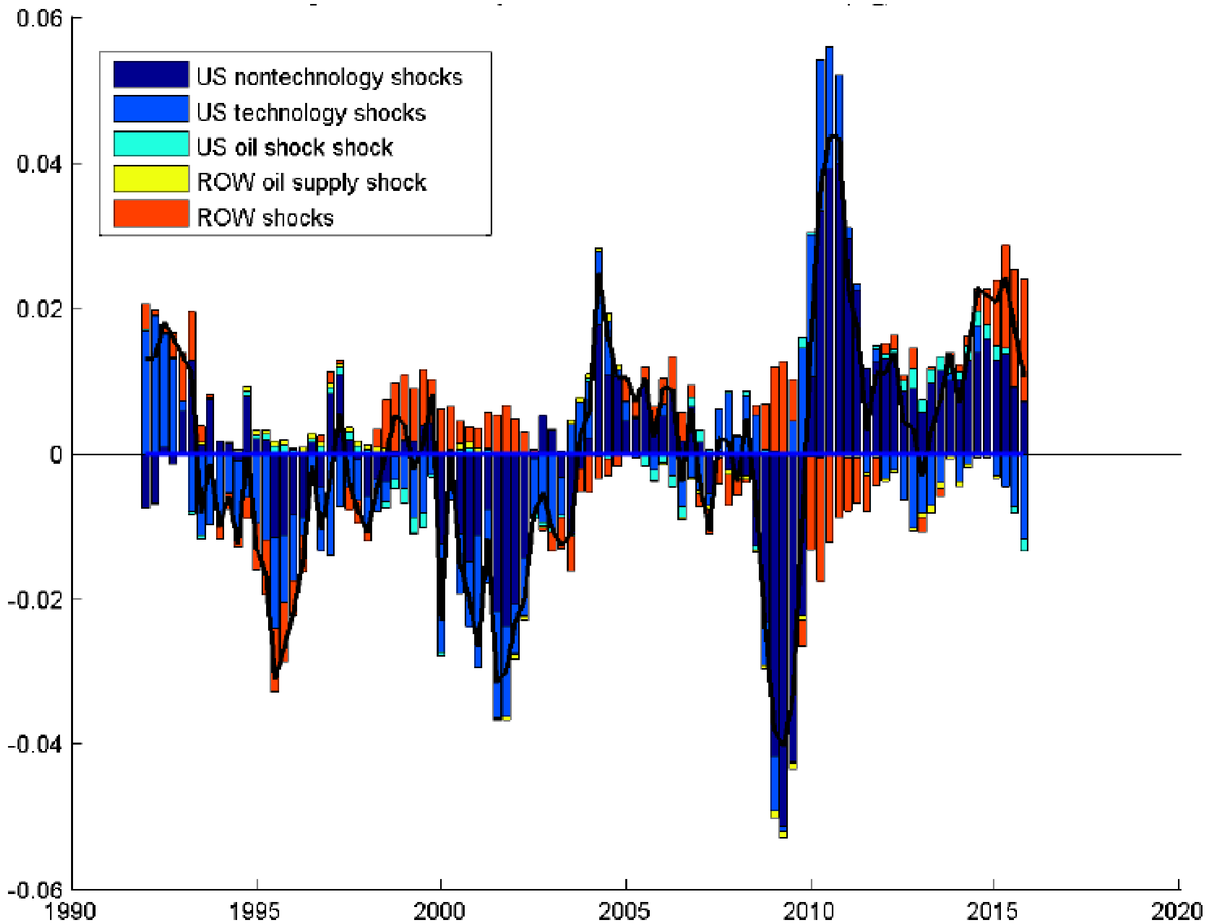


Table A-1. List of Observables and Structural Shocks

	Observable variable		Structural shock
1.	log(per capita US real GDP) (detrended)	1.	Productivity shock to goods, $z_{m,t}$
2.	log(per capita hours worked) (detrended)	2.	Productivity/preference shock to consumption, $z_{c,t}$
3.	Ex-post real interest rate	3.	US monetary policy shock
4.	log(US personal consumption expenditures on gasoline as a % of GDP)	4.	US risk shock: $R_t = R_t^{policy} z_{risk,t}$
5.	log(US transportation equipment investment expenditures as a % of GDP)	5.	Productivity shock to investment, $z_{I,t}$
6.	log(US oil production) (detrended)	6.	Productivity shock to domestic oil production, $z_{o,t}$
7.	log(US petroleum imports as % of GDP)	7.	US price mark-up shock
8.	log(real price of oil)	8.	ROW oil supply shock
9.	log(ROW oil production) (detrended)	9.	ROW oil specific demand shock
10.	log(world economic activity) (detrended)	10.	ROW shock to economic activity
11.	log(real exchange rate-trade weighted)	11.	ROW real exchange rate shock
12.	US net exports as a % of GDP	12.	ROW shock to US net exports

Table A-2. Calibrated Share Parameters

Parameters	value
discount factor in utility (β)	0.99
depreciation rate (δ)	0.025
US Consumption and labor shares:	value
share of gasoline in total consumption	0.03
share of motor vehicle expenditures in total consumption	0.045
share of labor in total hours	0.30
US Production shares	value
share of transport in aggregate gross output	0.03
share of labor in gross output of transport sector	0.50
share of energy input in transport gross output	0.25
share of labor in intermediate goods	0.60
share of petroleum products as inputs in intermediate goods	0.015
share of labor in value added of oil and gas extraction	0.15
US vs ROW shares	
share of oil imports in total US oil consumption	0.67
share of US oil production in total world production	0.08
Implied shares:	
share of transportation in total US oil consumption	0.67
share of oil expenditures in GDP	0.035

Table A-3. Prior Distribution of Key Parameters

parameter	Prior distribution	5^{th}	Mode	95^{th}
Macro parameters				
Inverse Frisch elasticity (η)	Gamma(2,0.5)	0.18	0.5	2.37
Inverse intermp. Elast. (σ)	Gamma(4,0.5)	0.98	2	4.58
Habits weight (χ_c)	Beta(.65,1.5,0,1)	0.19	.7	0.93
Habits persistence (γ_h)	Beta(.975,1.75,0,1)	0.04	.1	0.83
Inflation weight in Taylor rule (γ_π)	Beta(3,3,1.0,2.0)	1.19	1.5	1.81
Output weight in Taylor rule (γ_y)	Beta(5,3,0,1)	0.19	0.5	0.81
Taylor rule inertia (γ_R)	Beta(1.05,1.05,0,1)	0.06	0.5	0.94
Real wage persistence (γ_w)	Beta(.65,1.5,0,1)	0.19	0.7	0.93
Rothenberg price adjustment(α_p)	Gamma(3,50)	40.9	100	314.8
Rothenberg price indexation	Beta(.975,1.75,0,0.5)	0.02	0.05	0.41
Shock processes				
Autoregressive parameters	Beta(1.05,1.05,0,1)	0.06	0.5	0.94
Standard deviation	Gamma(0.067,1.3)	0.05	0.1	1.08
Sectoral parameters				
Elasticity of substitution $\left(\frac{1}{1-\rho_j}\right), j = c, f, tr, o$	Gamma(0.67,1.3)	0.47	1.0	2.47
Elasticity of substitution $\left(\frac{1}{1-\rho_j}\right), j = ksc, kstr, ksm$	Gamma(0.067,1.3)	0.05	0.1	1.08
Labor, capital, oil intensity adjustment costs	Gamma(1.5,100)	17.6	50	390.7
ROW parameters				
(-1)xROW long-run oil demand elasticity	Beta(2.2,4,0.4,1.5)	0.49	0.7	1.14
ROW long-run oil supply elasticity	Beta(2,2,4,0.4,1.5)	0.49	0.7	1.14
(-1)xROW short-run oil demand elasticity	Beta(1.2,4,0.4,1.5)	0.03	0.2	0.37
ROW short-run oil supply elasticity	Beta(1.2,4,0.4,1.5)	0.03	0.2	0.37

Table. A-4. Posterior Distributions of Key Parameters

Panel A

parameter	Mode	Median	Mean	5th	95th
Macro parameters					
Inverse Frisch elasticity (η)	0.42	0.68	0.70	0.29	1.22
Inverse intertemporal elast of substitution (σ)	12.03	11.79	11.92	9.78	14.57
Habits weight (χ_c)	0.26	0.23	0.23	0.14	0.30
Habits persistence (γ_h)	0.05	0.11	0.14	0.03	0.32
Inflation weight in Taylor rule (γ_π)	1.0025	1.0035	1.0035	1.0029	1.0042
Output weight in Taylor rule (γ_y)	0.008	0.016	0.016	0.007	0.030
Taylor rule inertia (γ_R)	0.004	0.004	0.004	0.002	0.007
Real wage persistence (γ_w)	0.53	0.46	0.46	0.29	0.58
Rothenberg price adjustment(α_p)	0.35	0.18	0.21	0.10	0.45
Rothenberg price indexation	0.03	0.09	0.09	0.03	0.19
Sectoral parameters					
Elasticity of substitution: nonoil and oil related durable services in consumption	1.52	1.55	1.64	1.13	2.08
Elasticity of substitution: transportation and goods in final goods	1.67	1.75	1.67	0.75	3.07
Elasticity of substitution: labor and capital services in transportation	1.15	1.57	1.62	0.99	2.49
Elasticity of substitution: labor and capital services in oil	1.35	0.61	0.70	0.41	1.27
Elasticity of substitution: oil and capital in consumption	0.54	0.55	0.55	0.49	0.63
Elasticity of substitution: oil and capital in transportation	0.03	0.03	0.04	0.01	0.10
Elasticity of substitution: oil and capital in goods	0.70	0.80	0.80	0.54	1.07
ROW parameters					
(-1)xROW long-run oil demand elasticity	0.45	0.50	0.53	0.42	0.61
ROW long-run oil supply elasticity	0.51	0.49	0.51	0.42	0.67
(-1)xROW short-run oil demand elasticity	0.28	0.18	0.19	0.12	0.28
ROW short-run oil supply elasticity	0.01	0.04	0.04	0.01	0.05
ROW long-run oil demand income elasticity	0.03	0.69	0.64	0.02	1.39

Table A-4. Posterior Distributions of Key Parameters

Panel B

parameter	Mode	Median	Mean	5th	95th
Adjustment cost parameters					
Labor: goods	401.8	302.3	322.5	185.1	514.7
Labor: transportation	2.40	2.33	2.94	1.12	6.31
Labor: oil	400.7	154.5	168.7	98.5	291.0
Capital: oil intensive consumer durables	0.07	0.05	0.08	0.01	0.26
Capital: goods	562.4	686.7	686.7	461.6	932.4
Capital: transportation	1299.1	1176.0	1195.1	1084.4	1370.6
Capital: oil	520.1	939.0	946.4	489.4	1434.8
Oil intensity/efficiency: oil intensive durables	11.9	22.6	30.9	10.9	68.3
Oil intensity/efficiency: transportation	0.04	0.01	0.01	0.00	0.04
Oil intensity/efficiency: goods	16.5	49.6	45.6	9.5	70.4
Autoregressive coefficient on exogenous shocks					
Intermediate goods TFP	0.90	0.91	0.91	0.86	0.94
Consumption	0.65	0.66	0.65	0.58	0.72
Investment technology	0.73	0.75	0.75	0.69	0.81
US oil technology	0.99	0.99	0.99	0.97	0.99
US markup shocks	0.90	0.91	0.91	0.88	0.93
US risk shocks	0.98	0.95	0.95	0.93	0.98
ROW oil supply shocks	0.18	0.78	0.64	0.12	0.86
ROW oil demand shocks	0.94	0.87	0.87	0.79	0.93
Standard deviations of exogenous shocks					
Intermediate goods TFP	0.0049	0.0049	0.0049	0.0044	0.0054
Consumption	0.068	0.076	0.077	0.059	0.096
Investment technology	0.058	0.079	0.078	0.057	0.095
US oil technology	0.027	0.028	0.028	0.023	0.031
US markup shocks	0.33	0.28	0.28	0.22	0.37
US risk shocks	0.016	0.021	0.021	0.013	0.028
ROW oil supply shocks	0.60	0.18	0.27	0.13	0.64
ROW oil demand shocks	0.088	0.12	0.12	0.078	0.16
US interest rate rule	0.0038	0.0038	0.0038	0.0034	0.0043
ROW economic activity	0.010	0.010	0.010	0.089	0.011
Real exchange rate	0.020	0.017	0.017	0.015	0.020
Net exports	0.096	0.094	0.095	0.082	0.110

Table A-5. Estimated GDP-Oil Price Elasticities due to Rest-of-World Oil Supply Shock

	Source: rest-of-world oil supply shock				
	Mode	Mean	Median	5th	95th
Baseline model	-0.007	-0.007	-0.007	-0.012	-0.001
No income effect in labor supply	-0.009	-0.009	-0.009	-0.013	-0.004
Baseline model with persistent ROW oil supply shocks	-0.010	-0.015	-0.013	-0.026	-0.009
Calibrated macro parameters	-0.002	-0.002	-0.002	-0.003	-0.001
	Source: rest-of-world oil demand shock				
Baseline model	-0.005	-0.005	-0.005	-0.008	-0.001
No income effect in labor supply	-0.006	-0.006	-0.006	-0.011	-0.000
Baseline model with persistent ROW oil supply shocks	0.001	-0.001	-0.001	-0.005	0.002
Calibrated macro parameters	-0.002	-0.002	-0.002	-0.002	-0.001

Table A-6. Alternative Estimation for Various Counterfactual Scenarios Using Baseline Model

	Mode	Mean	Median	5th	95th
Data	-0.010	-0.009	-0.009	-0.011	-0.007
Scenario 1-low import share	-0.004	-0.005	-0.005	-0.006	-0.002
Scenario 2-NEMS benchmark (2030) (low import share and high domestic oil production)	-0.004	-0.004	-0.004	-0.007	-0.002

B. The Role of Oil Supply Shocks on US Economic Activity: What Have We Learned?

Ana María Herrera*

Abstract

This section reviews recent research and explores the effect of oil supply disruptions on US GDP. We argue that differences in methodology due to identification assumptions and estimation techniques result in important dissimilarities in the response pattern of GDP. In particular, we find that specifications where the short-run elasticity of oil supply is assumed to be very close to zero result in a smaller and shorter-lived negative effect of oil supply disruptions on US GDP.

B-1. Introduction

The use of structural vector autoregressions (SVAR) to estimate the effect of oil supply and demand shocks on economic activity has become common in recent years. However, whereas there appears to be an agreement regarding the usefulness of this econometric tool, there is considerable disagreement concerning the size of the effect of oil supply shocks on real oil prices. Estimates of the effect of a one-unit oil supply shock on real oil prices vary from 1.43 to 3.73 with the peak occurring six to three months after the shock. This broad range of estimates reflects dissimilarities in methodology comprising differences in model specification, estimation, as well as identification assumptions.

Consider thus a researcher who is interested in estimating the effect of oil supply shocks on aggregate economic activity. How should one model the global market for crude oil? How would the modeling choice affect the impulse response estimates? To answer these questions, we start by estimating three alternative structural vector autoregressive models for the global crude oil market, which differ in the assumptions used to identify the source of the shocks and the estimation method. These models include Kilian (2009) SVAR, where identification is attained through short-run restrictions; Kilian and Murphy's (2012) specification that uses both impact and dynamic sign restrictions; and Baumeister and Hamilton's (2015) model, where more general beliefs regarding particular aspects of the model are used to form priors on some parameters of the SVAR. The two first specifications are estimated using a frequentist approach whereas the latter employs a Bayesian framework. An additional, though somewhat minor

*University of Kentucky. I am grateful to Christiane Baumeister, Martin Bodenstein, James Hamilton, David Montgomery, James Stock and participants at the Resources for the Future preliminary meeting on "New Approaches to Estimating the Macroeconomic Implications of Oil Price Shocks" for very helpful suggestions.

difference among these SVARs are the choice of proxy variable used to measure global economic activity and the sample period covered in the original study. Hence, they provide a good testing ground for examining how different SVAR estimation strategies affect the size of the estimated response of US GDP to oil supply shocks.

We start by re-estimating the three SVAR models for the global oil market using monthly data that spans the period between January 1973 and December 2015. We do so not only to use up-to-date information, but also to eliminate variation due to the use of different sample periods. We then extract the time series of structural oil supply innovations implied by each of the estimated models. Because our object of interest, US real GDP, is measured at a quarterly frequency we convert each of the monthly time series into a quarterly measure of oil supply disturbances. We then project the quarterly time series of supply shocks onto the log growth of US GDP and compute the impulse response functions.

Our estimates reveal significant differences in the size of the response of US GDP to oil supply disturbances and in the degree of persistence of an oil supply shock. First, specifications where the price elasticity of oil supply is assumed to be very close to zero (Kilian 2009, Kilian and Murphy 2012) result in an estimated peak response of GDP of about -0.45. In contrast, the peak response equals -1.13 when the model specification allows for supply elasticities further away from zero (Baumeister and Hamilton, 2015). Second, whereas the first group of models leads to a very short-lived impact on GDP—it becomes statistically insignificant three quarters after the shock—the latter suggests a long-lasting effect that becomes significant five quarters after the shock and remains negative in the medium-run.

We then investigate whether the effect of oil supply disruptions on economic activity has varied over time. Evidence from rolling regressions suggests a decline in the effect of oil supply disruptions, especially in the last decade. Alternatively, the reader might wonder whether dropping the earlier sample where large oil supply shocks prevailed would lead to variation in the estimated short-run elasticities of oil demand and supply and the estimated response of GDP. Indeed, dropping the pre-1984 sample leads to somewhat smaller estimates of the elasticity of demand and, thus, a larger increase in real oil prices. Yet an important caveat applies: dropping the earlier subsample might confound the effect of the Great Moderation and that of changes in the oil market.

This section is organized as follows. The next section describes the three SVAR models used to analyze the role of oil supply and demand shocks on real oil prices and economic activity. Section B-3 briefly describes the data sets. The following section discusses the effects of oil supply shocks on US real GDP. Section B-5 investigates whether the effect of oil supply shocks on the US economic activity has changed over time. The last section concludes.

B-2. SVAR Models for the World Crude Oil Market

Structural vector autoregressive models, SVAR hereafter, have been commonly used to estimate the effect of oil price shocks on economic activity. SVARs impose specific identification assumptions in order to recover economic shocks from observables and then study the effect of these shocks on the economy. An advantage of SVARs is that they allow the researcher to easily obtain estimates of the impact of a shock of interest without imposing many additional restrictive assumptions on the model. Nevertheless, the shocks recovered from an SVAR may differ greatly depending on the variables included in the model and the identification scheme. This section reviews three of the SVAR specifications used in the literature and employed to extract the oil supply shocks.

B-2.1. Kilian (2009)

Kilian (2009) and Hamilton (2009a, b) were the first to underline the importance of separately identifying the effect of supply and demand driven shocks on the real price of oil. In the years preceding these studies it was common to estimate SVAR models where the extracted oil price shocks were a composite of demand and supply driven innovations. Yet, work by Kilian (2009) suggests that the thought experiment where oil prices are assumed to be exogenous to the

US economy needed to be reevaluated. In particular, his work indicates that unexpected oil price increases (or decreases) that are driven by structural supply and demand shocks may have very different effects on aggregate economic activity.

Kilian (2009) undertakes the task of separately identifying supply and demand driven shocks by specifying a model for the global oil market in the following manner. Let z_t represent a vector of observable monthly variables assumed to be governed by the following 24th-order vector autoregression

$$A_0 z_t = \alpha + \sum_{i=1}^{24} A_i z_{t-i} + \varepsilon_t \qquad \text{(B-1)}$$

where $z_t = [\Delta prod_t \quad rea_t \quad rpo_t]'$, $\Delta prod_t$ is the percentage change in global oil production, rea_t is an index of global economic activity, rpo_t is the real price of oil, ε_t is a vector of serially and mutually uncorrelated innovations, A_0 is a 3x3 matrix of contemporaneous coefficients and the A_i are 3x3 matrices of lagged coefficients.

Identification is obtained by assuming that A_0^{-1} has a recursive structure. In other words, crude oil supply does not respond contemporaneously (within a month) to innovations in the demand for oil. In addition, innovations in real oil prices that are driven by shocks to the oil market are assumed not to have a contemporaneous effect on global economic activity. These restrictions imply a structural model of the form

$$u_t = \begin{bmatrix} u_t^{\Delta prod} \\ u_t^{rea} \\ u_t^{rpo} \end{bmatrix}$$

$$= \begin{bmatrix} a^{11} & 0 & 0 \\ a^{21} & a^{22} & 0 \\ a^{31} & a^{32} & a^{33} \end{bmatrix} \begin{bmatrix} \varepsilon_t^{oil\ supply\ shock} \\ \varepsilon_t^{aggregate\ demand\ shock} \\ \varepsilon_t^{oil-market-specific\ demand\ shock} \end{bmatrix} = A_0^{-1}\varepsilon_t \tag{B-2}$$

Two modeling choices are key for Kilian's (2009) identification scheme. First, having the oil supply shock as the first shock in the Wold causal chain implies that oil production cannot adjust within a month (e.g., the supply curve for crude oil is vertical). Such an assumption is justified by the presence of adjustment costs in the conventional production of crude oil. Yet, some may argue that unconventional oil production, such as shale oil extraction, might react within a month to changes in oil prices. The question still remains whether the share of unconventional oil production in the world market is large enough to affect the world elasticity of supply. Second, economic activity is measured via an index of dry cargo freight rates. Kilian's objective in constructing such an index is not to come up with a new index of aggregate economic activity but to construct a measure of fluctuations in world demand, which in turn would affect oil prices.

Using data spanning the period between January 1973 and October 2006, Kilian (2009) finds that oil supply disruptions explain a small proportion of the variation in real oil prices relative to demand driven shocks. In contrast, aggregate demand shocks and, especially, oil-specific demand shocks explain most of the variation in real oil prices.

B-2.2. Kilian and Murphy (2012)

Kilian and Murphy (2012) use the tri-variate VAR setup in (1) to describe the global oil market. However, instead of imposing exclusion restrictions as in Kilian (2009), they attain identification via dynamic and impact sign restrictions. Because sign-identified VAR models are set identified, the authors propose to narrow down the set of admissible impulse response functions by imposing additional identifying restrictions. Their approach consists of following steps. First, they impose sign restrictions on the impact responses, which we reproduce in Table 1 from Kilian and Murphy (2012). Second, they reduce the number of admissible responses by imposing an upper bound of 0.0258 on the short-run oil supply elasticity. This restriction is motivated by the presence of adjustment costs, which would prevent crude oil production to respond to oil prices within the month. Finally, they also impose a bound on the response of real economic activity to the oil-market-specific demand shocks. That is, they classify as inadmissible models those that do not satisfy the restriction $-1.5 < a^{23} < 0$.

The findings of Kilian and Murphy (2012) resemble those of Kilian (2009) in that oil supply disruptions explain only a small fraction of the variation in the real price of crude oil. Among the admissible models, the peak effect of oil supply shocks on real oil prices is estimated to be somewhat larger than in Kilian (2009) but the effect is slightly shorter-lived.

B-2.3. Baumeister and Hamilton (2015)

Baumeister and Hamilton (2015) show that the algorithms commonly used by researchers in the estimation of impulse responses that are sign identified lead to nonuniform prior distributions for the structural parameters and the impulse response functions. Instead of imposing a bound on particular parameters of the SVAR, they develop an algorithm that summarizes the researcher's uncertainty regarding particular parameters of the structural VAR model using a prior distribution. Two additional advantages of their proposal are the ability to explicitly use prior information regarding the structural coefficients without imposing a bound that forces the researcher to discard all models that are an epsilon above the bound and the higher speed of the Bayesian algorithm relative to the slower estimation of SVARs identified via sign and bound restrictions.

Here we focus on Baumeister and Hamilton's (2015) four variable model, which takes into account that the world's stock of crude oil is measured with error. The dynamic structural model takes the following form:

$$\boldsymbol{A_t} = \boldsymbol{B x_{t-1}} + \boldsymbol{u_t}$$

where

$$\boldsymbol{y_t} = [q_t \quad y_t \quad p_t \quad \Delta i_t]', \boldsymbol{A} = \begin{bmatrix} 1 & 0 & -\alpha_{qp} & 0 \\ 0 & 1 & -\alpha_{yp} & 0 \\ 1 & -\beta_{qy} & -\beta_{qp} & -\chi^{-1} \\ -\psi_1 & -\psi_2 & -\psi_3 & 1 \end{bmatrix}, , \boldsymbol{u_t} = \begin{bmatrix} u_{1t}^* \\ u_{2t}^* \\ u_{3t}^* - \chi^{-1} e_t \\ \chi u_{4t}^* + e_t \end{bmatrix},$$

$$\Delta i_t = \chi \Delta i_t^* + e_t, \tag{B-3}$$

$\boldsymbol{x_{t-1}} = [\boldsymbol{y'_{t-1}} \quad \boldsymbol{y'_{t-2}} \quad \dots \quad \boldsymbol{y'_{t-m}} \quad 1]$, Δi_t represents a measure of the change in OECD crude-oil inventories as a percentage of the previous month's world oil production, χ<1, and et is a measurement error.

The researcher's information and/or beliefs about the contemporaneous coefficients are summarized in terms of a prior distribution on the elements of A, p[A]. Baumeister and Hamilton (2015) contend that there is no certainty regarding some of the zero or bound restrictions imposed by previous identification schemes. More specifically, the researcher has no certainty that the contemporaneous effect of oil supply shocks on real oil prices is equal to zero. Instead, one has reason to believe that the short-run price elasticity of oil supply is close to zero. Similarly, changes in world oil production may have a contemporaneous effect on economic activity that differs from zero, as oil production could respond quickly to changes in real oil prices. In other words, the short-run elasticity of oil supply is deemed to be small but there is no certainty that it equals zero. In addition, oil prices are considered to have a contemporaneous effect on global economic activity albeit the magnitude of the effect might be small. They also argue that it is not very natural to represent prior beliefs on the short-run price elasticity of oil supply, α_{pq}, as a bound that places zero weight on an elasticity that is say $\varepsilon = 0.001$ above 0.0258 but a positive weight on an elasticity that is $\varepsilon = 0.001$ below 0.0258. Instead they propose a prior that allows for a slowly declining weight.

Table 2 summarizes the priors for the main variables of interest (e.g., short-run price elasticity of supply, short-run price elasticity of demand). Baumeister and Hamilton (2015) find that oil supply shocks play a larger role in explaining fluctuations in real oil prices than either Kilian (2009) or Kilian and Murphy (2012).

B-3. Data

As mentioned before, alternative SVAR specifications differ not only in the identification assumptions but also in the variables included in the system. In Kilian (2009) and Kilian and Murphy (2012) the vector y_t includes the monthly rate of growth in world crude oil production, an index of real economic activity and the log of the real price of oil. Although the original data used by these studies is available from the data repository of the Journal of the European Economic Association, we reconstruct the series using the original sources. In order to consider up-to-date information, and to confine the divergence across models to differences in specification and identification, the data used in all SVARs covers the same sample period: January 1973 to December 2015.

As an index of real economic activity both Kilian (2009) and Kilian and Murphy (2012) use the cumulative average rate of increase in dry cargo ocean freight rates deflated by the US CPI and linearly detrended. This measure was proposed by Kilian (2009) and the updated version is available from his website at http://www-personal.umich.edu/-lkilian/reaupdate.txt. The log of real oil prices is measured as the log difference between the refiners acquisition cost (RAC) of imported crude oil and the US Consumer Price Index. The series is expressed as deviations from a linear trend. The nominal crude oil price is provided by the Energy Information Agency whereas the CPI is obtained from the St. Louis Fed FRED database. Data for the world oil production is also obtained from the Energy Information Agency and is measured in thousands of barrels per day.

As variables in y_t Baumeister and Hamilton (2015) also include the percent change in world oil production and, in the baseline model, the log difference between the nominal refiner acquisition cost of imported crude oil and the CPI. In an alternative specification, Baumeister and Hamilton (2015) investigate the effect of measuring the nominal price of oil by the spot price for West Texas Intermediate. Using this measure allows them to consider an earlier sample period starting in January 1958. The choice of oil price measure -Refiners Acquisition Cost, RAC, or West Texas Intermediate, WTI- does not appear to significantly affect the estimated short-run price elasticity of oil supply or the effect of oil price shocks on economic activity (see Baumeister and Hamilton, 2015). For this reason and to allow for a comparison across models based on the same oil price measure, we employ the imported refiners acquisition cost.

Baumeister and Hamilton's (2015)—hereafter BH—specification differs from the models described in the previous sections in that: (a) it includes a proxy for the change in global oil inventories and (b) global economic activity is measured as the log change in the industrial production index for the OECD and the six major non-member economies (Brazil, China, India, Indonesia, the Russian Federation and South Africa). Kilian and Murphy (2014) had previously noted the importance of including inventories in the SVAR specification in order to better extract the underlying structural shocks and to estimate the effect of these shocks on the behavior of real oil prices. In particular, demand for crude oil might increase for precautionary motives thus leading to inventory accumulation instead of heightened crude oil consumption. BH explicitly model the change in inventories as a variable that is measured with error.

Regarding the measure of global economic activity, an argument for using industrial production over the measure based on the shipping rates is that it constitutes a better proxy for world aggregate demand. Hence, if the researcher wants to use previous estimates of the income elasticity of oil demand to form a prior, industrial production might allow for a better comparison. Nevertheless, let us for a moment consider how the time series properties of both series differ by comparing the dry cargo shipping index, which is measured as deviations around a linear trend, and the linearly detrended log of the industrial production (IP) measure. Both series have a great deal of persistence with the autocorrelation for the shipping index being 0.965 and that of the IP being 0.982. Figure B-1 reveals that the series commove, the correlation equals 0.67, but do not exactly track each other. Thus, differences in the estimated responses might be partially due to dissimilarities in the aggregate economic activity measure. This is an issue that we will investigate in a later section.

B-4. Oil Supply Shocks and Aggregate Economic Activity

B-4.1. Alternative Measures of Oil Supply Shocks

The question of interest here is the effect of oil supply shocks on real GDP. The main hurdle in tackling this question is that data on real GDP is only available at the quarterly frequency. A possible way to proceed would be to build a SVAR model on quarterly data, yet identification schemes such as Kilian (2009) would be hard to justify using these lower frequency data. In particular, oil production is likely to react to innovations in oil prices or aggregate economic activity within a quarter thus invalidating the assumption that the oil supply curve is vertical. Hence, instead of estimating a SVAR on quarterly data, we follow Kilian (2009) in constructing alternative measures of the quarterly oil supply shocks by averaging the monthly structural innovations derived from the SVARs for each quarter.

Let $\hat{\varepsilon}^{i}_{stj}$ denote the estimated supply shock in month j of the t^{th} quarter implied by each of the $i = K$, *KM*, *BH* model specifications where *K* denotes Kilian (2009), *KM* stands for Kilian and Murphy (2012) and *BH* denotes Baumeister and Hamilton (2015). Then, for each of the specifications, we compute a quarterly measure of oil supply shocks

$$\hat{\xi}^{i}_{st} = \frac{1}{3}\sum_{j=1}^{3} \hat{\varepsilon}^{i}_{stj}\,, j = 1,2,3 \qquad \text{(B-4)}$$

Figure B-2 depicts these time series. For BH we plot the time series implied by the median of the posterior supply disturbances as well as the measure derived from the mean of the supply disturbances across draws. Four points regarding the structural oil supply shocks are apparent from Figure B-2. First, the time series implied by the K and KM specifications are very similar (the correlation equals 0.99). This indicates that the more complicated identification scheme of KM leads to very similar estimated shocks than the simpler Choleski decomposition used in K. Second, using the posterior median or the mean to derive the structural supply shocks makes little difference for the BH setup. Third, the supply shocks derived from the two earlier methods exhibit smaller variation than those derived from the latter. Indeed the standard deviations are 0.516 for $\hat{\xi}_{st}^{K}$, 0.513 for $\hat{\xi}_{st}^{KM}$, 1.043 and 1.065 for the median and mean of BH (see Table 3). Fourth, a reduction in the variance of oil supply disturbances is apparent in the late 1980s to early 1990s. Such reduction is evident in the figure regardless of the identification scheme and is confirmed when we test for a break in the variance using Quandt-Andrews unknown breakpoint test.[1] We are able to reject the null of no break at a 5 percent level for all measures using the MaxWald and ExpWald tests (see Table B-3). The MaxWald indicates a break in 1987:Q4 for $\hat{\xi}_{st}^{K}$ and $\hat{\xi}_{st}^{KM}$ and in 1990:Q4 for $\hat{\xi}_{st}^{BH}$.

Although there are noticeable differences between the oil supply shocks derived from the earlier models and BH there are also some similarities. In particular, there is evidence of supply disruptions in 1978:Q4 when Iran's production started falling and in 1980 when the Iran- Iraq War broke out. In addition, unexpected increases in oil supply are apparent before the collapse of OPEC in 1986 and during the shale oil expansion from 2014:Q3 to 2015:Q1.

B-4.2. The Effect of Oil Supply Shocks on US GDP

Under the identifying assumption that the constructed measure of oil supply shocks, $\hat{\xi}_{st}^{i}$, does not respond to changes in US GDP (Δy_t) within the quarter we may treat $\hat{\xi}_{st}^{i}$ as predetermined with respect to Δy_t. As Kilian (2009) notes the assumption that the series of quarterly shocks are predetermined with respect to US real GDP growth is not testable but a correlation between the innovations that is close to zero would suggest that unanticipated changes in crude oil supply are not associated with contemporaneous changes in real GDP

[1] We test for parameter constancy in the variance equation $var\left(\hat{\xi}_{st}^{i}\right) = \alpha_1 + \alpha_2 D_t + v_t$ where $D_t = \begin{Bmatrix} 1 \; if \; t < k \\ 0 \; if \; t \geq k \end{Bmatrix}$.

growth. Examination of the empirical correlation between the autoregressive residuals of GDP growth and the different measures of oil supply shocks are quite small,[2] thus leading credence to this assumption.

Hence, we estimate the effect of oil supply shocks on US GDP via OLS according to the following equation

$$\Delta y_t = \alpha_k + \sum_{j=0}^{12} \beta_j \hat{\xi}_{st-j}^{i} + v_t. \tag{B-5}$$

Impulse response coefficients at horizons h are given by the β_j*'s.*

Figure B-3 summarizes the response of the level of US real GDP to each of the supply shock measures described earlier. One and two-standard error bands have been computed using a Newey-West standard errors to deal with the presence of serial correlation in the error term.[3] The results summarized in Figure B-3 indicate that, regardless of the SVAR specification used to derive the measure of oil supply shocks, the response of real GDP to an unexpected decrease in world oil production is negative. Nevertheless, the figure illustrates how differences in the SVAR methodology lead to dissimilar conclusions regarding the importance of oil supply shocks and the dynamics of the GDP response. First, the peak the response of GDP to the supply shock measure is about twice as large when $\hat{\xi}_{st}^{BH}$ is used (-1.05 percent) instead of $\hat{\xi}_{st}^{K}$ (-0.46 percent) or $\hat{\xi}_{st}^{KM}$ (-0.44 percent).[4] Second, models that impose a very low price elasticity of oil supply (��and ��), and consequently a very large short-run elasticity of oil demand, suggest that unanticipated oil supply disruptions significantly lower real GDP on impact, yet the one-standard error band indicate the effect is statistically significant for less than a year. In contrast, in a set up where the price elasticity of oil supply is larger as in BH, the effect of oil supply disruptions on GDP is statistically insignificant on impact, but the one-standard error band suggest it becomes significant two quarters after the shock and remains so for the remainder of the forecast horizon.

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[2] The correlation between the autoregressive residuals for US GDP growth and $\hat{\xi}_{st}^{K}, \hat{\xi}_{st}^{KM}$ $\hat{\xi}_{st}^{BH}$ $median, \hat{\xi}_{st}^{BH}$ $mean$ are 0.0004, 0.00036, 000006, and 0.000002, respectively.

[3] The error bands depicted in the figure were computed using HAC standard errors with 24 lags. It is worth noting here that these error bands do not take into account the fact that the supply shock measure is itself an estimated series and thus may lead to the generated regressor problem.

[4] In comparing the results from the projection method with that of the monthly VAR one needs to keep in mind that the impulse here is a quarterly decrease in oil supply of 13 in average. Hence that would correspond to three time the impulse in the monthly SVAR specification.

B-4.3. SVAR Specifications and Implications for the Response of US GDP

How do these differences in the response of GDP growth relate to the underlying SVAR model of the world oil market? To answer this question let us take a look at the short-run elasticity of supply implied by the alternative SVARs. Table 4 summarizes the short-run elasticities of oil supply and demand for the alternative specifications. On the one hand, the short-run price elasticity of oil supply is significantly larger for BH (0.154) than for K or KM (0 and 0.023, respectively). On the other, the smaller the elasticity of supply, the larger the corresponding short-run price elasticity of oil demand. Note the short-run identification scheme of Kilian (2009), K, implies a demand elasticity of -4.1 for the 1973:M1-2015:M12 sample and the combination of sign and bound restrictions proposed by Kilian and Murphy (2012), KM, leads to an estimate of -1.49. Both of these number are significantly larger than the posterior median of -0.36 obtained using the specification proposed by Baumeister and Hamilton, 2015). Moreover, note that the estimates obtained from the first two specifications fall outside the 95 percent confidence set for BH and are considerably larger than estimates reported in the existing literature, which range between -0.02 and -0.25 (see Brown (2016) and references therein).

Having noted these important differences in the estimated elasticities of supply and demand, let us now examine how they translate into dissimilarities in the response of real oil prices to supply shocks. Figure B-4 plots the response of oil production and real oil prices to an unexpected decline of 1 percent in the world oil supply. As the figure illustrates the dynamic response of oil production is almost identical across specifications. In fact, the impulse response for K (red line) and KM (green line) fall almost on top of the posterior median (blue line) for BH and within the 95 percent confidence set for the latter. However, alternative identification schemes lead to very different real oil price responses. From impact to over 15 months after a supply disruption, the increase in the real price of oil is about twice as large for BH specification as for the alternative models. The combination of a slightly larger oil supply elasticity and smaller oil demand elasticity for KM than for K results in a slightly larger response of real oil prices. Yet, neither the response for K nor KM fall within the 95 percent confidence set for BH. All in all, using K specification, an unexpected one percent decline in world oil production is estimated to raise the real price of oil by 0.87 percent at the peak (six months after the shock). In contrast, among the admissible models in KM, the largest effect on real oil prices is 1.41 percent (5 months after shock) whereas the peak response for BH's posterior median is 3.28 percent (three quarters after the shock).

Large portion of the differences in the estimated response of US real GDP to oil sup- ply shocks may be traced to dissimilarities in the implied short-run elasticities and, thus, the response of real oil prices to supply shocks. Yet, recall that another difference between specifications is the proxy used for real economic activity. To inquire whether the muted response of real oil prices, and thus U.S real GDP, to oil supply shocks is explained by the use of the dry cargo shipping index, we replace it with the industrial production measure used in BH and re-estimate the SVAR specification in K. Figure B-5 reports the impulse response functions of oil production and real oil prices for the original K specification (red line) and the K-IP specification where we have used the world industrial production index as the measure of real economic activity. The figure also depicts the posterior median and 95 percent confidence sets for BH. Note that using this different measure of economic activity results in a somewhat larger response of real oil prices than the original K specification, yet it is still far smaller than the posterior median in BH. This pattern is consistent with a smaller estimate of the short-run elasticity of demand (-2.55) in K-IP relative to original K model. Nevertheless, using the industrial production index is not enough to bring down the demand elasticity to a magnitude in the ballpark of existing estimates (Brown, 2016).

As in the previous section, we extract the structural oil supply shocks, compute the quarterly measure of supply disruptions and then project it on the growth rate of US real GDP as in equation (B-5). Figure B-5 replicates Figure B-3 but replaces the response computed using KM with that of K-IP where we have replaced the dry cargo index with the world IP. Note that the key insights are unchanged. Kilian's (2009) specification with the world IP still produces a response of GDP that is smaller and shorter lived than that of BH. In addition, the difference between it and the original K specification is minimal.

B-5. Has the Effect of Oil Supply Shocks on US Real GDP Changed?

Work by Blanchard and Galí (2010), Edelstein and Kilian (2009), Herrera and Pesavento (2009) and Herrera and Karaki (2015) point to a muted effect of oil price shocks on aggregate economic activity since the Great Moderation. Such dampening also coincides with a decline in the volatility of crude oil prices and a reduction in the share of energy in personal consumption expenditures. Because the above mentioned studies do not separately identify the effect of oil supply and demand driven shocks we thus inquire here whether the response of US real GDP to oil supply shocks has changed.

B-5.1. Evidence Based on Recursive Regressions

We first evaluate time-variation in the relationship between oil supply shocks and US real GDP by sequentially estimating model (5) for each of the supply shock measures. That is, we take the supply disruption measures ($\hat{\xi}_{st}^{K}, \hat{\xi}_{st}^{KM}, \hat{\xi}_{st}^{BH}$) as given and evaluate whether the relation between supply driven shocks and US economic activity has changed over time. We estimate the IRFs to oil supply shocks starting with sample that covers the period between 1975:Q2 and 1990:Q1. Then, we add one observation and re-estimate the IRFs. We do this recursively until we reach the end of the sample; hence, the last estimation period corresponds to the full sample used in the previous section (1975:Q2-2015:Q4).

Figure B-7 summarizes the recursive estimates of the cumulative response of US real GDP to oil supply shocks. Three important insights are gained from the rolling estimates. First, regardless of the SVAR specification, a reduction in the impact of oil supply shocks on US real

GDP is apparent as the sample period used to estimate model (5) expands. This reduction is evident if we compare the cumulative response estimated with samples ending in the 1990s with estimates from the 2010s. Note how the areas in the darkest shade of blue, which represent greater declines in GDP, disappear over time. Second, this pattern whereby the effect of oil supply shocks declines in the 2010's is more pronounced for the K and KM measures of oil supply shocks than for BH. Interestingly for the latter a slow decline is apparent from 1990 until 1992, and then again around 2006. Lastly, the recursive estimates confirm our finding of a more persistent and larger effect of oil supply disruptions for BH.

In brief, recursive estimates of the impulse response functions are indicative of a decline in the effect of oil supply disruptions, especially in the last decade. Indeed, as Blanchard and Galí (2010) suggest the 2000s are different form the 1970s, a period where the Yom Kippur war in 1973 and the Iranian revolution of 1979 appear to have triggered important increases in the price of oil. Oil supply disruptions do not shock US real GDP nowadays as much as they did two decades ago. However, it is crucial to note that the magnitude of this decline is not independent of how the oil market is modeled. In fact, estimates obtained by using the oil supply shocks derived from *BH* exhibit less time-variation.

B-5.2. Evidence Based on the 1984:Q1-2015:Q4 Subsample

Given changes in the oil market, it has been suggested that estimates of the effect of oil price shocks should be obtained by dropping the 1970s. To investigate the effect of such proposal, in this section we re-estimate the SVARs on a subsample that excludes the period before the Great Moderation (January 1984 to December 2015) and then compute the implied monthly structural supply shocks. These supply disturbances are averaged as previously described to generate a quarterly measure of oil supply shocks. We focus on the two specifications that produce the largest discrepancies regarding the response of GDP in the full sample. These are the SVAR with zero short-run price elasticity of supply and a large elasticity of demand (K) and the SVAR with the largest supply elasticity and smallest demand elasticity (BH).

Figure B-8 plots the response of US real GDP to oil supply shocks for the 1984:Q1-2015:Q4 subsample. Note that the response of GDP is similar in magnitude across the two measures of oil supply disturbance. However, as it was the case for the full sample, the effect is shorter-lived for K than it is for BH. Namely, when using K the response is negative and statistically significant from impact up to a year after the shock, whereas for BH the one standard-error bands indicate the response is statistically significant up to three years after the shock.

The results summarized in the impulse response functions reveal more similarities between the SVAR specifications when the sample is restricted to the post-1983 period. Indeed, the one- standard error bands indicate that supply disturbances have a long-lasting negative effect on

US real GDP. Regardless of the specification the effect of a decline in world oil production exceeds 1 percent two years after the shock. As it is the case for the full sample, supply disruptions are estimated to increase the real price of oil in the 1984-2015 subsample. Using K the peak response of real oil prices occurs six months after the shock and equals 2.75 percent instead of 1.4 percent (see bottom panel of Table 4). This larger increase in the real oil price is explained by the smaller elasticity of oil demand (an estimated -1.45 relative to 1.09 in the full sample) for the same inelastic oil supply curve. As for BH, the estimated elasticity of supply decreases almost by half (from 0.15 to 0.08), the elasticity of demand falls slightly (from -0.36 to -0.31 for the latter) and the effect of oil supply shocks on the real oil price raises.(a peak of 5.2 percent three quarters after the shock).

Summarizing, dropping the pre-1984 sample results smaller differences in the estimated short-run elasticities of demand and supply across the two analyzed specifications. In particular, the elasticity of demand for K falls to less than half but is still large. Hence, the estimated response of real oil prices to oil supply disturbances are closer to each other in the subsample than the full sample. In particular, real oil prices appear to be more responsive to oil supply shocks for the K specification when dropping the pre-1984 subsample.

A word of caution is in needed here. While dropping the earlier subsample could be attractive to some on the premise that the later sample bears closer resemblance to the current oil market conditions, doing so might confound the effects of changes in the oil market with those of the Great Moderation.

B-6. Comparison with Demand Driven Shocks

To get a better grasp on the effect of oil supply and demand shocks on US real GDP we focus now on the BH specification and extract, in addition to the oil supply shocks, aggregate demand, consumption demand and inventory demand shocks. As in the previous sections we compute quarterly measures of these structural shocks by taking the average over the three months in each quarter and project them on the rate of growth of US real GDP.

Figure B-9 depicts the response of real GDP to unexpected increases in the real oil price driven by the demand shocks derived from BH specification. For ease of comparison the first panel replicates the response to the oil supply shock depicted in Figure B-2. In all cases the posterior median of the monthly shock is used to compute the quarterly shock measure. The figure illustrates important differences in how supply and demand driven shocks to the real oil price affect US real GDP, as well as differences in the response to the various demand shocks. Unanticipated increases in the real oil price due to heightened world economic activity causes US GDP to significantly raise on impact and up to a year after the shock. In contrast, the response of GDP to unanticipated increases in oil consumption is negative at all horizons, however the one-standard error bands imply the effect is statistically insignificant. Similarly, the response of US real GDP to oil price increases that result from greater inventory demand is statistically insignificant.

These results are largely consistent with Baumeister and Hamilton's (2015) findings regarding the role of oil demand and supply shocks on the world's industrial production. That is, unexpected oil price increases driven by supply disruptions have a recessionary effect on US and international economic activity. In contrast, positive aggregate demand shocks have an expansionary effect.

The reader may ask whether the dampening in the response of US real GDP to oil supply disturbances has also taken place for demand driven shocks. To answer that question, we estimate the impulse response functions to the demand shocks using the same rolling regression design employed for the supply disturbances. Figure B-10 summarizes the variation in the responses of US real GDP as we recursively increase the sample adding one observation starting with 1975:Q2-1990:Q1 as the estimation period and ending with the full sample. As is illustrated in the figure by the disappearance of the green and yellow shades, there is some dampening in the response of GDP to aggregate demand shocks in the 2000s. Nevertheless, the US economic activity becomes slightly more responsive to these shocks in the 2010s.

An alternative way to evaluate variation in the oil market parameters is to reduce the weight placed on data prior to 1984 while not dropping it out. Baumeister and Hamilton's (2015) setup renders itself to easily address the concern that pre-1984 data is less informative about the parameters of interest. Thus, we use as prior for the post-1983 subsample an inference that down weights the influence of the earlier subsample by a factor of μ=0.5. We then extract all the structural shocks, compute the quarterly structural shocks measures and project them on the rate of growth of US real GDP.

Figure B-11 plots the response of real GDP to the structural shock measure. Comparing this figure with Figure B-9 suggests that down weighting the earlier data results in only minor changes. In particular, the magnitude of the effect on real GDP are similar, the only noticeable differences are: (a) a less persistent effect of aggregate demand shocks and (b) a negative and significant, albeit small, effect of consumption demand shocks. On the other hand, the estimated effect of oil supply disruptions continues to be negative and persistent.

B-7. Conclusions

Estimates of the dynamic effect of oil supply disruptions on real oil prices differ greatly across studies. The root for these dissimilarities can be traced to differences in methodology, namely alternative identification schemes and estimation methods. This section reviewed recent SVAR models used to study the world oil market and evaluated the effect of the implied structural supply shocks on US real GDP.

We found that models that assume a smaller short-run price elasticity of oil supply and larger elasticity of demand imply a smaller and shorter-lived response of US economic activity to oil supply disruptions. For these models (Kilian 2009, Kilian and Murphy 2012) we found that the estimated peak response of GDP is around -0.45 percent. In contrast, the peak response is -1.1 percent when the model allows for larger supply elasticities (Baumeister and Hamilton, 2015). Furthermore, we showed that the first group of models result in a negative response of GDP to oil supply disruptions on impact but the effect becomes statistically insignificant three quarters after the shock. Instead, the latter specification suggests an insignificant effect on impact but a negative and significant effect in the medium-run.

We then investigated time variation in the response of GDP to oil supply disruptions.

Evidence from recursive regressions suggest that the impact of oil supply disturbances declined since the 2000s. However, this dampening is less marked for the SVAR specification that implies short-run demand elasticities that are within the bounds of the existing literature, BH. We further inquired into the effect of dropping the pre-1984 when estimating the SVAR models. Estimation results suggest that doing so could lead the researcher to estimate a larger response of oil supply disturbances on real GDP, especially when using short-run restrictions. Yet, such result might stem from commingling the effect of the Great Moderation and the changes in the oil market.

All in all, our results indicate that BH specification has two advantages when estimating the effect of oil supply disturbances on real GDP. First, estimates of the short-run elasticities of demand and supply seem to be between reasonable bounds as claimed by Baumeister and Hamilton (2015), regardless of whether one uses the whole sample period, drops the earlier years, or down weights the earlier years. Second, time variation appears to be less of an issue than for the two alternative specifications.

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B-9. Tables and Figures

Table B-1. Impact sign restrictions in Kilian and Murphy (2012)

	Oil supply shock	Aggregate demand shock	Oil-market-specific demand shock
Oil production	-	+	+
Real activity	-	+	-
Real price of	+	+	+

Table B-2. Priors for A Baumeister and Hamilton (2015)

	Distribution	Parameter values
Short-run price elasticity		
of oil supply, α_{qp}	Student $t\left(c_{qp}^{\alpha}, \sigma_{qp}^{\alpha}, \nu_{qp}^{\alpha}\right)$	$c_{qp}^{\alpha} = 0.1, \sigma_{qp}^{\alpha} = 0.2, \nu_{qp}^{\alpha} = 3$
Short-run price elasticity		
of oil demand, β_{qp}	Student $t\left(c_{qp}^{\beta}, \sigma_{qp}^{\beta}, \nu_{qp}^{\beta}\right)$	$c_{qp}^{\beta} = 0.1, \sigma_{qp}^{\beta} = 0.2, \nu_{qp}^{\beta} = 3$
Contemporaneous effect of		
oil prices on economic activity, α_{yp}	Student $t\left(c_{yp}^{\alpha}, \sigma_{yp}^{\alpha}, \nu_{yp}^{\alpha}\right)$	$c_{yp}^{\alpha} = 0.1, \sigma_{yp}^{\alpha} = 0.2, \nu_{yp}^{\alpha} = 3$
Fraction of world oil inventories		
held by OEDC countries, χ	Beta $\left(\alpha_{\chi}, \beta_{\chi}\right)$	$\alpha_{\chi} = 15, \beta_{\chi} = 10$

Table B-3. Properties of Quarterly Supply Shocks

	$\hat{\xi}_{st}^{K}$	$\hat{\xi}_{st}^{KM}$	$\hat{\xi}_{st}^{BH}$ median	$\hat{\xi}_{st}^{K}$ mean
Mean	0.003	0.003	-0.044	-0.043
Median	0.023	0.040	-0.042	-0.051
Maximum	1.743	1.706	3.333	3.400
Minimum	-1.675	-1.629	-3.441	-3.569
St. deviation	0.516	0.513	1.043	1.065
Skewness	-0.156	-0.181	0.142	0.142
Kurtosis	4.412	4.315	3.943	3.982
Normality test				
Jarque-Bera	14.205	12.643	6.586	7.099
p-value	0.001	0.002	0.37	0.029
Test of break of unknown time in the variance				
SupWald	37.003	35.752	10.560	9.153
p-value	0.000	0.000	0.020	0.039
Break date	1987:4	1987:4	1990:4	1990:4
ExpWald	15.055	14.453	2.554	2.025
p-value	0.000	0.000	0.027	0.051

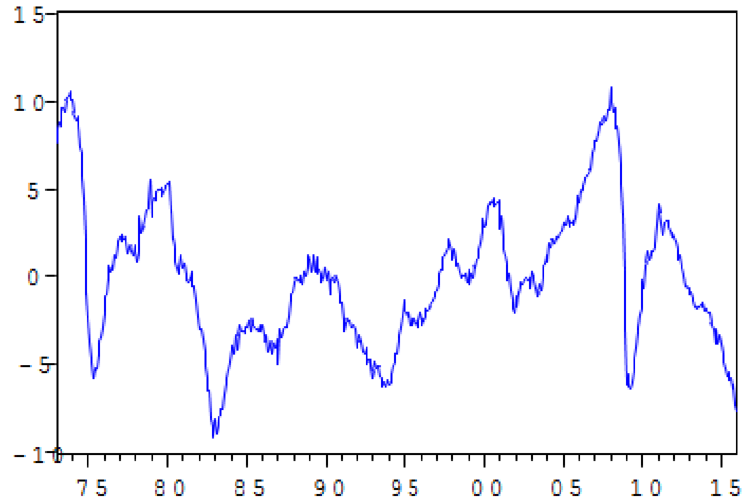
Table B-4. Estimated Short-Run Elasticities and Peak Real Oil Price Responses

Full Sample			
	K	*KM*	*BH*
Short-run elasticity of oil supply	0	0.023	0.153
			(0.062, 0.316)
Short-run elasticity of oil demand	-4.085	-1.489	-0.355
			(-0.772, -0.180)
Peak real oil price response to a 1% oil supply shock			
Percent change in real oil price	0.87%	1.41%	3.28%
			(2.22%, 4.05%)
Months after the shock	6	5	3
1984:Q1-2015:Q4			
	K		*BH*
Short-run elasticity of oil supply	0		0.080
			(0.031, 0.211)
Short-run elasticity of oil demand	-1.450		-0.221
			(-0.424, -0.096)
Peak real oil price response to a 1% oil supply shock			
Percent change in real oil price	2.75%		5.19%
			(3.665, 6.450)
Months after the shock	15		3
Full sample down weighting 1975:Q2-1983:Q4			
			BH
Short-run elasticity of oil supply			0.064
			(0.128, 0.302)
Short-run elasticity of oil demand			-0.309
			(-0.572, -0.151)
Peak real oil price response to a 1% oil supply shock			
Percent change in real oil price			3.75%
			(2.73%, 4.65%)
Months after the shock			3

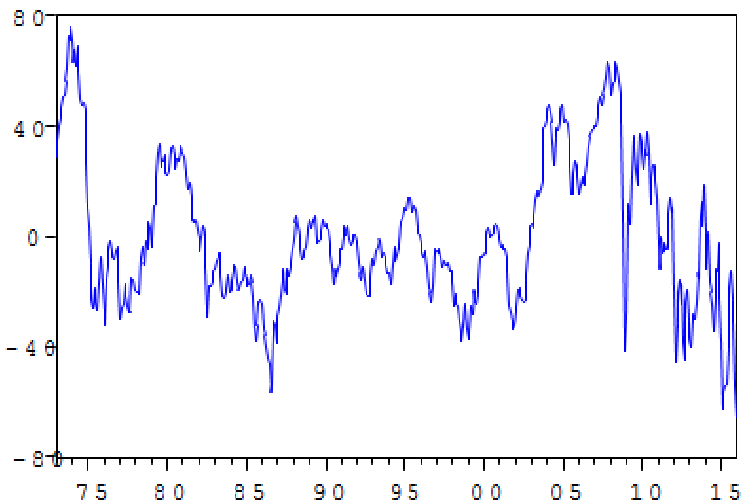
Note: This table reports point estimates for the *K* specification, estimates for the peak response in the *KM* specification and posterior median (in bold) and 95 percent confidence sets (in parenthesis) for the *BH* specification.

Figure B-1. Measures of Real Economic Activity

Industrial Production Index

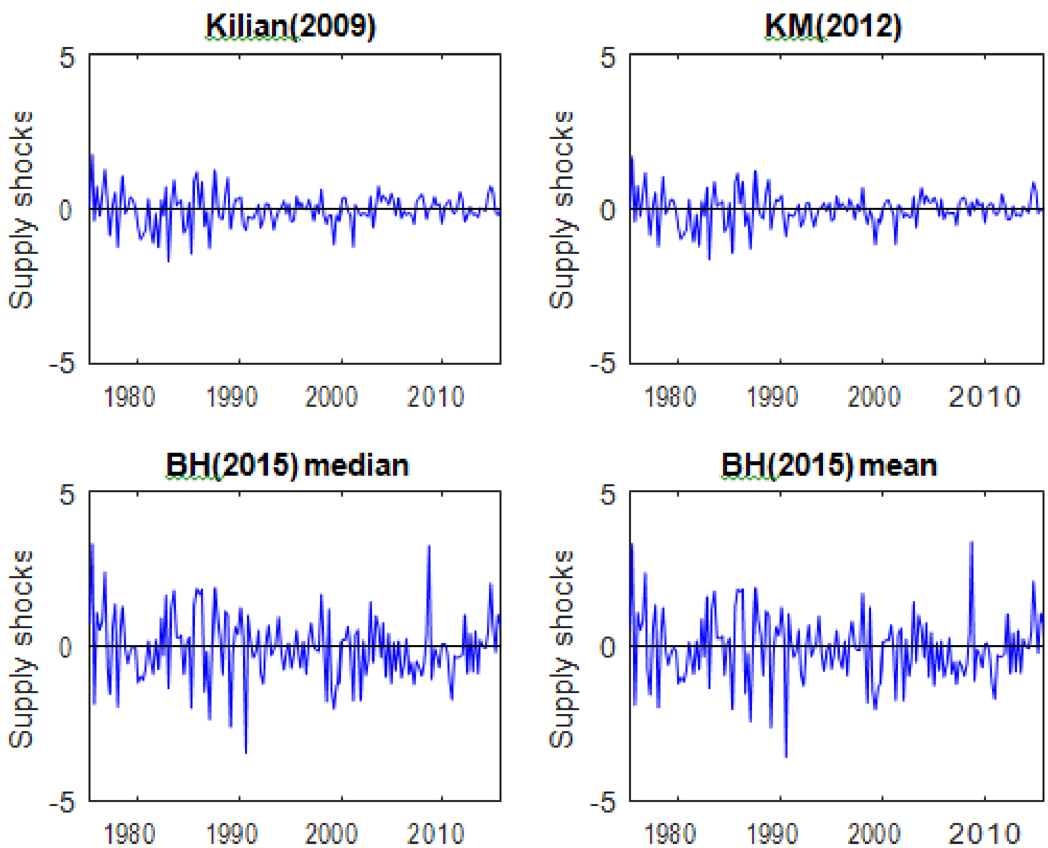


Dry Cargo Shipping Index



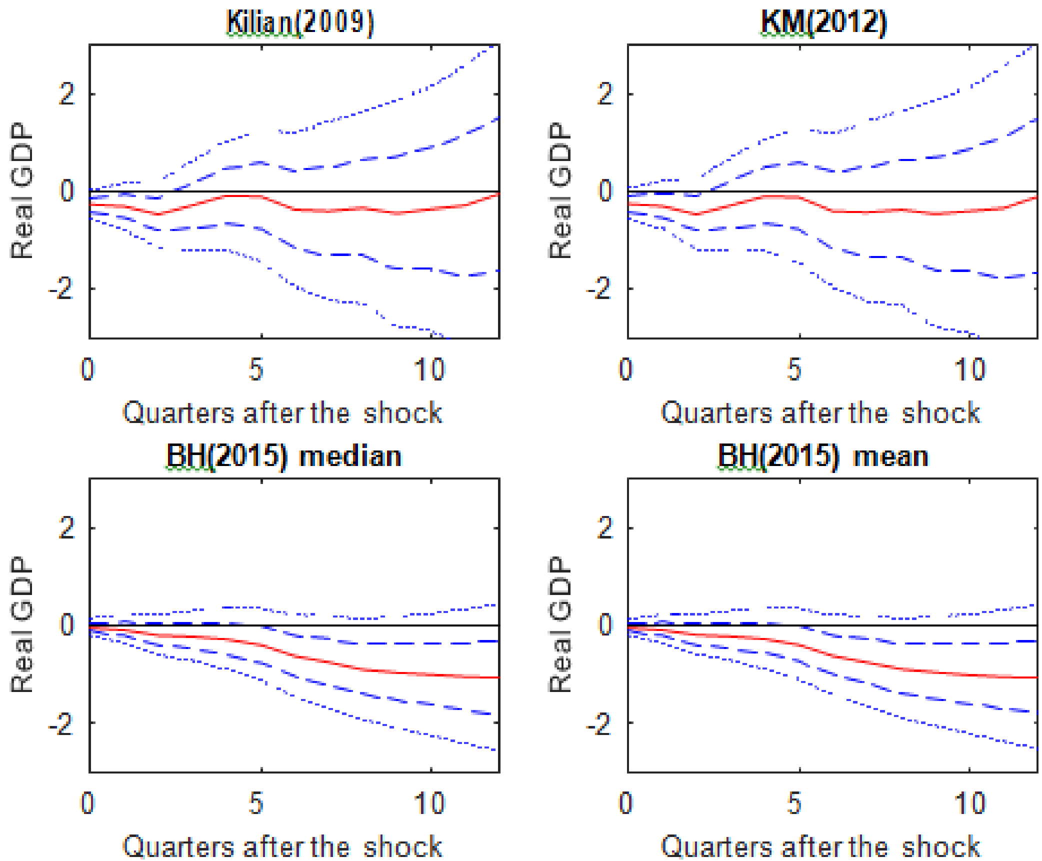
Note: The figure plots the linearly detrended logarithm of the dry cargo shipping index proposed by Kilian (2009) and of the industrial production index for the OECD and the six largest non-OECD economies.

Figure B-2. Quarterly Measures of Oil Supply Shocks



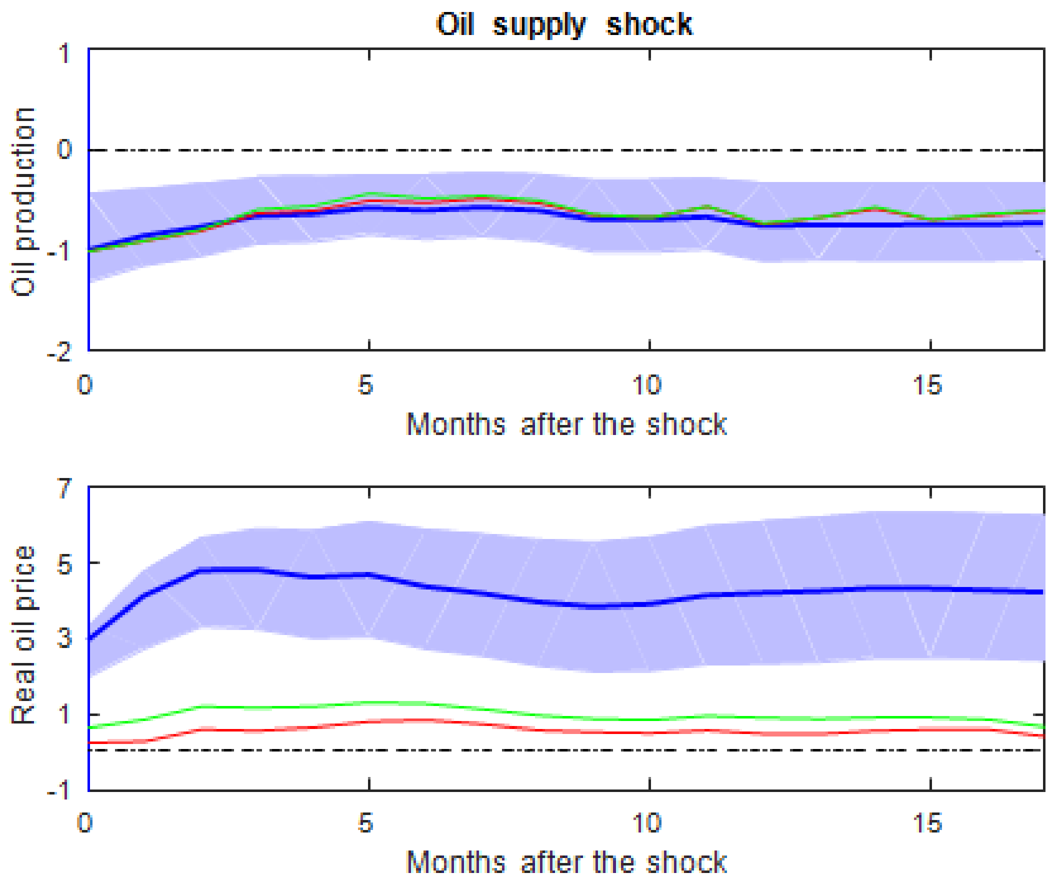
Note: The figure plots the structural supply shocks implied by Kilian (2009) specification, the admissible model with the largest response in Kilian and Murphy (2012) and the posterior median and mean for Baumeister and Hamilton's (2015) specification. The implied shocks are averaged to a quarterly frequency.

Figure B-3. GDP Response to Structural Oil Supply Shocks—Point Estimates with One and Two-Standard Error Bands



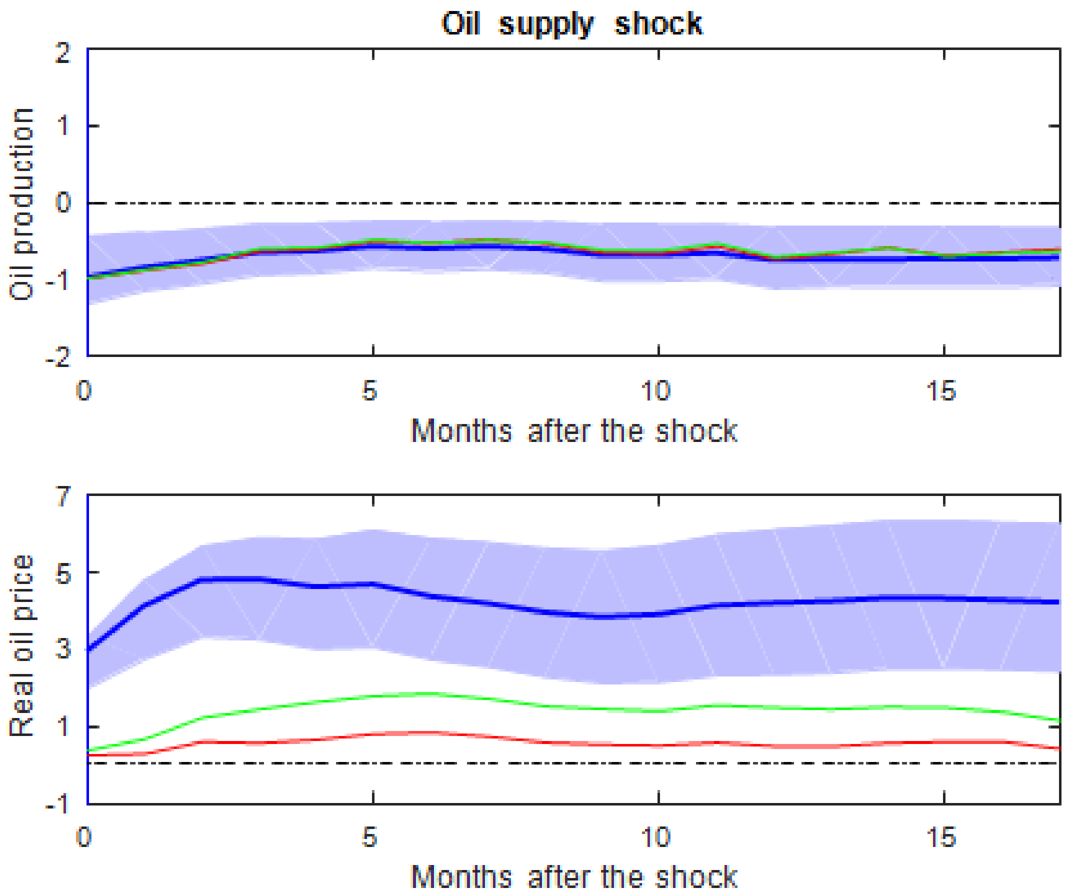
Note: The figure plots the cumulative responses estimated using the projection model (5) for each structural oil supply shock measure.

Figure B-4. Response to an Unexpected 13 Decline in World Oil Supply



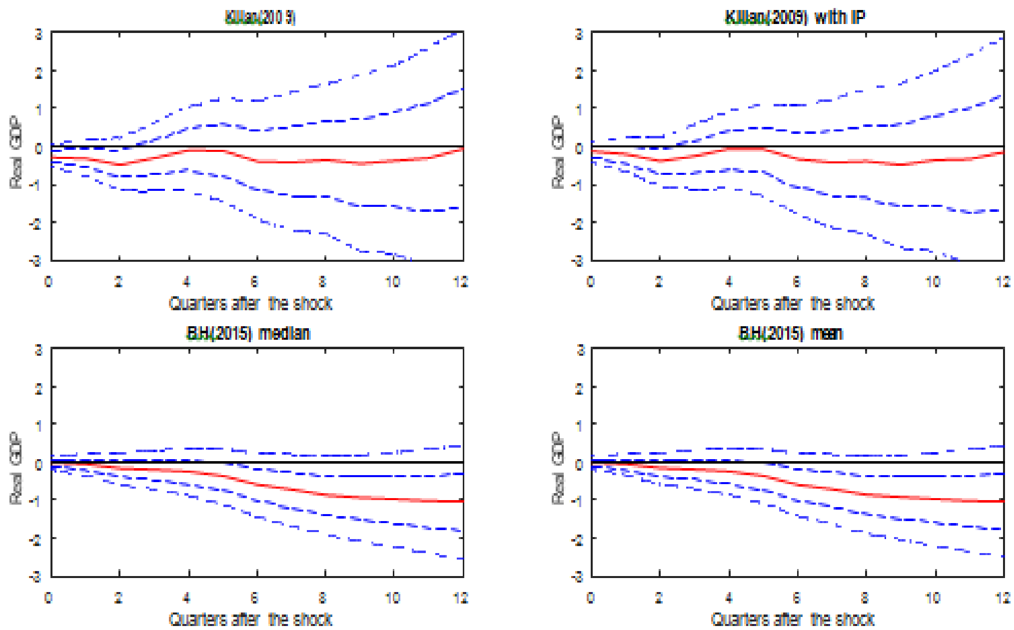
Note: The figure plots the impulse response functions to a 13 oil supply reduction for each of the SVAR specifications. The red line corresponds to Kilian (2009), the green line represents the peak response for Kilian and Murphy (2012) specification, the blue line corresponds to the posterior median for Baumeister and Hamilton (2015) while the blue area represents the corresponding 953 confidence set.

Figure B-5. Response to an Unexpected 13 Decline in World Oil Supply



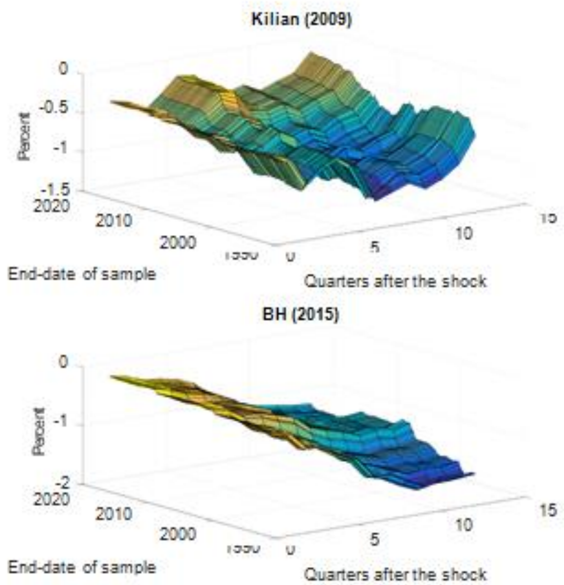
Note: The figure plots the impulse response functions to a 13 oil supply reduction for each of the SVAR specifications. The red line corresponds to Kilian (2009), the green line represents Kilian (2009) specification where the dry cargo index has been replaced with the industrial production index, and the blue line corresponds to the posterior median for Baumeister and Hamilton (2015) while the blue area represents the corresponding 953 confidence set.

Figure B-6. GDP Response to Structural Oil Supply Shocks—Point Estimates with One and Two-Standard Error Bands



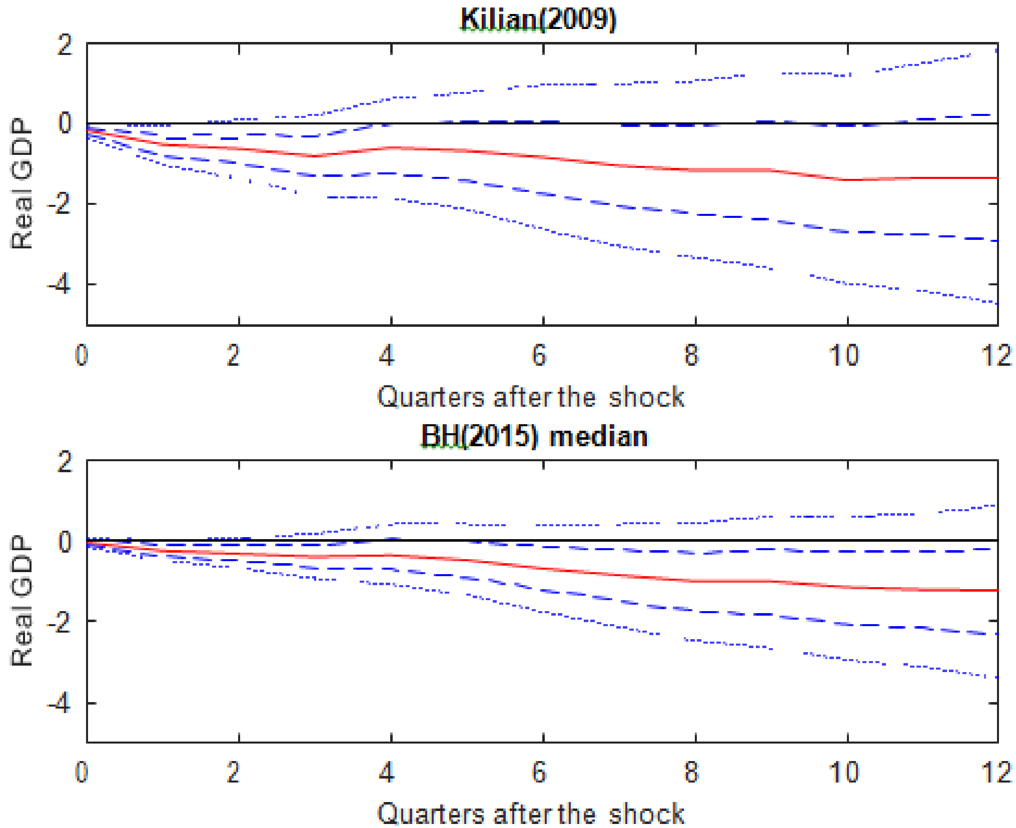
Note: The figure plots the cumulative responses estimated using the projection model (5) for each structural oil supply shock measure.

Figure B-7. Rolling Estimates of the Response of US Real GDP to Oil Supply Shocks



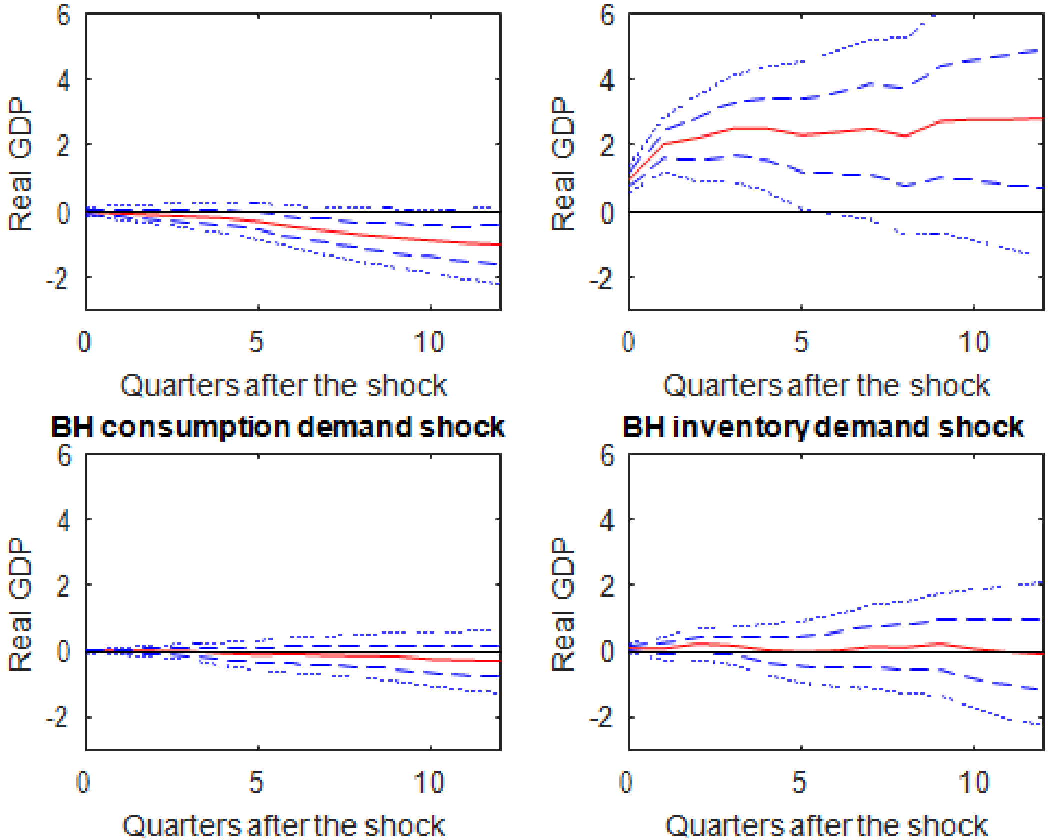
Note: The figure plots rolling estimates of the cumulative responses obtained using the projection model (5) for each of the structural oil supply shock measures.

Figure B-8. GDP Response to Structural Oil Supply Shocks (1984:Q1-2015:Q14) Point Estimates with One and Two-Standard Error Bands



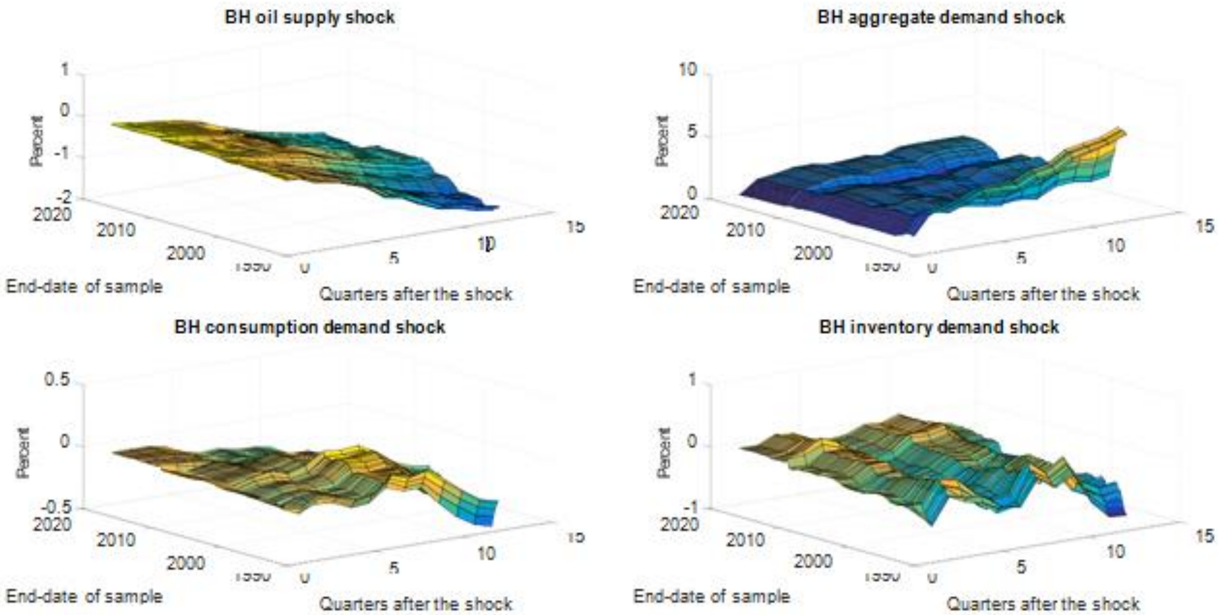
Note: The figure plots the cumulative response estimated for the *K* and *KM* structural supply shock measures using the projection model (5). Estimates are based in a subsample spanning the period between 1984:Q1-2015:Q4.

Figure B-9. GDP Response to Structural Shocks—Point Estimates with One and Two-Standard Error Bands



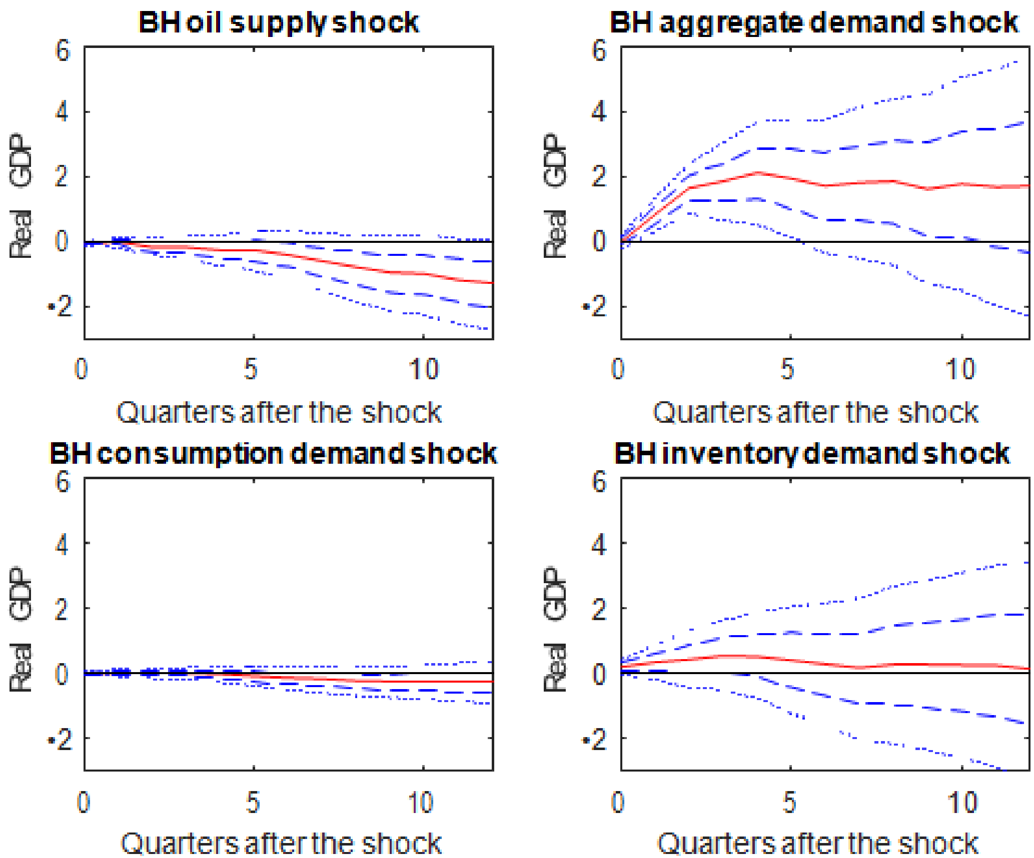
Note: The figure plots the cumulative response of US real GDP to the structural quarterly shock measures derived from *BH* estimated using the projection model (5). Estimates are based in a subsample spanning the period between 1984:Q1-2015:Q4.

Figure B-10. Rolling Estimates of the Response of US Real GDP to Structural Shocks



Note: The figure plots rolling estimates of the cumulative responses obtained using the projection model (5) for each of the structural shock measures derived from Baumeister and Hamilton's (2015) specification.

Figure B-11. GDP Response to Structural Shocks—Point Estimates with One and Two-Standard Error Bands



Note: The figure plots the cumulative response of US real GDP to the structural quarterly shock measures derived from BH estimated using the projection model (5). Estimates are based on the down weighting the data prior to 1984:Q1 in the oil market SVAR.

C. Oil Price Shocks and the US Economy: An Application of the National Energy Modeling System

Shashank Mohan*

C-1. Introduction

This chapter describes how the National Energy Modeling System (NEMS) was used to estimate GDP and the demand elasticity of oil prices. NEMS is developed and maintained by the Energy Information Administration (EIA) of the US Department of Energy (DOE). EIA primarily uses NEMS to produce the Annual Energy Outlook (AEO), an annual publication which presents long-term projections of energy supply, demand, and prices in the US.[1]

NEMS projects US energy production, consumption and prices on an annual basis, subject to assumptions including but not limited to macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies. It is modular in nature where each module of NEMS characterizes the future production, conversion, or consumption of energy in the US. It uses a version Gauss-Seidel algorithm, where the model starts with a base solution and then iterates through until it finds an equilibrium solution—a solution whose difference with the previous solution is less than a user-defined "tolerance" value.

The NEMS macroeconomic activity module (MAM) provides both the macroeconomic and financial projections used in the model as well as incorporates the macroeconomic impact of changes in the energy system. It is divided into three submodules: 1) US national economy, which provides national forecasts; 2) industrial, which translates national forecasts into industry-level projections; and 3) regional, which converts the results of above two submodules into census level forecasts. US national economy provides all the results used in this study. EIA uses

* Rhodium Group. The author thanks Christiane Baumeister, Martin Bodenstein, James Hamilton, David Montgomery, James Stock, and participants at the Resources for the Future preliminary meeting of "New Approaches to Estimating the Macroeconomic Implications of Oil Price Shocks." The views expressed are solely those of the author.

[1] The latest AEO, AEO 2016, presents the forecasts through 2040. For more information on AEO 2016 and earlier versions of AEOs, see here: http://www.eia.gov/outlooks/aeo/. NEMS source code is available to the public on request. The analysis presented here is performed using a version based off EIA's source code and maintained by Rhodium Group (RHG).

a version of IHS's Global Insight (GI) model of the US economy to fill in this submodule. The GI model is an econometric dynamic equilibrium growth model. It incorporates insights from Keynesian, neoclassical, monetarist, supply-side and rational expectations approaches. In addition, it includes the major properties of the long-term growth models presented by James Tobin, Robert Solow, Edmund Phelps and others. This structure guarantees that short-run cyclical developments will converge to a robust long-run equilibrium. It includes the impact of interest rates and wealth effects on spending, thereby recognizing the importance of credit conditions on the business cycle and on the long-run growth prospects for the economy.[2]

NEMS is a fairly established model for analyzing US energy policy choices and market developments, and utilizes a detailed representation of the US energy system for producing the forecasts. For example, to forecast onshore US oil production, NEMS assesses the technical and economic constraints at play level, sub-regions of basins. Moreover, EIA uses the best available resources to update market and policy data and the structure of the model on an annual basis. Similarly, the MAM is updated by IHS to account for both near-term conditions and long-term structural changes in the economy and financial markets. For these reasons, NEMS is a suitable model for the purposes of this exercise.

The rest of the chapter is organized as follows. Section 1 describes how an oil price shock affects oil consumption and GDP in NEMS. Section 2 outlines the details of how an oil price shock was modeled to derive GDP and demand elasticities. Results are reported in Section 3.

C-2. The Oil Price Shock Impact on Oil Consumption and GDP in NEMS

A sudden change in oil prices, i.e. an oil price shock, leads to a change in oil consumption in NEMS across all demand sectors - transportation, residential, commercial, industrial and electric power. A positive shock, i.e. an increase in oil prices, decreases oil consumption both in the year when the shock occurs[3] by reducing utilization of current capital stock, and in future years by diverting future capital stock towards more efficient equipment or fuel switching.[4] For example, in the case of passenger cars, a sudden increase in oil prices in

[2] For full documentation of the MAM and other modules of NEMS, please refer to documentation shared here http://www.eia.gov/outlooks/aeo/nems/documentation/index.cfm .

[3] NEMS forecasts the energy system on an annual basis.

[4] The electric power sector has perfect foresight in NEMS, so it is not possible to model a sudden oil price shock for the electric power sector. Oil consumption in that sector will change before the price shock. Since electric power accounts for less than 1 percent of oil consumption, this issue is ignored in our analysis.

2030, reduces total miles driven and hence oil demand in 2030 and forces consumers to buy more efficient cars or alternative-fuel cars which further reduces demand in and beyond 2030.

Like oil demand, an oil price shock affects GDP both during the shock year and in the future. During the shock year, higher oil prices increases consumer prices both directly by increasing liquid fuel prices (like gasoline) and indirectly by increasing prices for others final goods and services as higher prices for fuel used as an input is passed on to consumers. Higher consumer prices lead to lower real consumption, ceteris paribus.

On the investment side, higher oil prices lead to higher investment in oil exploration and development but crowds out investment in other sectors, as increased demand for investment in the oil industry leads to higher borrowing costs for other sectors. Furthermore, an increase in inflation leads to higher interest rates which further reduces housing demand, reducing investment in that sector.

Oil prices also affect US exports and imports in NEMS. Higher oil prices lead to a change in oil imports, import demand of non-oil goods and services, foreign demand of US goods and services, and the relative producer prices between US and foreign countries.[5] All these variables impact net US exports and hence US GDP.

The GDP impact in future years comes through the following channels:

1) *Changes in the energy system*: As discussed above, oil demand and oil supply (through increased investment in the oil & gas industry) changes persist into the future, even after the temporary price shock is gone. Those changes in oil demand and supply continue to impact GDP.

2) *Macroeconomic linkages*: In NEMS, consumer and business expectations are based on macroeconomic conditions in recent historical years. Additionally, the long-term interest rates modeled are partially dependent on recent historical inflation patterns. Therefore macroeconomic changes during the shock year continue to reverberate into the future.

[5] The details on how these variables change with the change in oil prices is described in detail in the Results section below.

C-3. Modeling an Oil Price Shock in NEMS

Since oil prices are modeled endogenously in NEMS, it is not possible to exogenously change the oil prices to mimic an oil price shock. So instead an oil price shock is modeled by simulating a global oil supply shock as described below.[6]

For each forecast year, the model starts with a base oil price determined by exogenous global oil supply and demand curves. Base prices[7] are then passed to various modules in NEMS to recalculate US oil demand and supply. The updated US oil demand and supply are then used to adjust the global demand and supply curves respectively to produce a new global oil price. This cycle continues until the model produces an equilibrium oil price.[8] To simulate an oil price shock in any given year, the initial exogenous oil supply curve is shifted upwards so that the base oil price reflects the desired increase in oil prices. This leads to a higher equilibrium oil price in that year due to the outward shift of the global supply curve, even though a higher base price leads to lower US oil demand and higher US supply. Figure C-1 shows the difference between the intended and actual shock in one of the scenarios (for scenario descriptions see below).

The oil price shock does not persist across years in NEMS, as the exogenous global supply and demand curves are defined for each forecast year. In the other two types of models employed in this study, DSGE and SVAR, oil price shocks persist by design. To produce comparable results, multiple one year shocks are modeled (Table C-1)[9], except for one scenario where the shock is applied for just one year.[10]

One drawback of modeling oil price shocks in NEMS is that it produces point estimates instead of a probability distribution. Any one set of results may be misleading because it may be sensitive to particular assumptions or parameters. To mitigate this issue, a range of elasticities

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[6] To derive GDP and oil demand elasticities by simulating an oil price shock, two NEMS runs are required—one with the base oil prices and the second with the oil price shock. Positive and negative shocks may behave unsymmetrically and hence will have different elasticities. So for a more complete analysis three NEMS runs would be required. Only positive price shocks were analyzed for this work.

[7] Although NEMS starts with one base oil price, Brent spot price, the different prices for various crude qualities are calculated based on that base price. These different crudes are then optimally mixed in the refinery modules to produce end-use liquid fuels like gasoline, diesel etc. It is the prices of these end-use fuel prices that determine oil consumption, while oil production is determined by prices of various crude qualities.

[8] This is in line with the Gauss-Seidel algorithm that NEMS employs to reach equilibrium quantities and prices.

[9] Source: DSGE model. See Appendix A.

[10] All shocks modeled in NEMS begin in 2030.

were produced by doing a sensitivity analysis[11]. The following parameters and assumptions were identified for the purpose of the sensitivity analysis[12].

1) **Federal Reserve Responsiveness:** By default, the Federal Reserve as modeled in NEMS, responds immediately to changes in inflation and unemployment**.** It can be argued that in reality, the Federal Reserve may perceive the oil price shock as temporary and hence will not change the federal funds rate based on changes in inflation due to that shock. Since interest rates impact both consumption and investment, varying the responsiveness of the federal funds rate to an oil price shock will change the impact on the US economy from that shock.
   NEMS value range: 0 to 1 (fractional value allowed), where 0 indicates a fixed federal funds fund rate and 1 indicates that the federal funds rate will be set according to the built-in response function. A fractional value indicates the weighting between the fixed and endogenously determined portion of the federal funds rate.
   Default value: 0.9
   Alternative value: 0.0 (constant federal funds rate)

2) **Foreign GDP elasticity with respect to oil prices:** In NEMS, the trade between the US and its trading partners is determined by the size of the GDPs, real exchange rates and the relative prices of goods. The foreign GDP elasticity with respect to oil prices determines the impact on foreign GDP. This will affect international trade which will in turn impact US GDP.
   NEMS value range: any real number
   Default value: -0.02
   Alternative value: -0.012[13]

3) **Base oil prices:** The impact on the US economy from an oil price shock will depend on the existing share of oil production and consumption in the economy. Oil prices determine both those shares and so will affect the impact on GDP.
   NEMS value range: EIA models low, reference and high oil prices.
   Default value: reference level oil prices.
   Alternative value: either low or high prices (Figure C-2).

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[11] Due to the complexity and time required to run NEMS, a Monte Carlo simulation was infeasible.

[12] Based on NEMS model structure and expert review.

[13] Based on literature review by Stephen P.A. Brown. See Appendix D.,

4) CAFE standards: CAFE standards determine the efficiency of new vehicles and hence determine oil consumption and how much the change in oil prices will impact oil consumption.
NEMS value range: CAFE standards for can be set for both light duty cars and trucks as well as heavy duty trucks from vehicles sold during the forecast years (2016-2040).
Default value: The base case includes the attribute-based CAFE standards for light-duty vehicles (LDVs) for Model Year (MY) 2011, the joint attribute-based CAFE and vehicle GHG emissions standards for MY 2012 through MY 2016 and for MY 2017 through MY 2025. For heavy-duty vehicles, the new standards which are fully phased in by MY 2018 are included.
Alternative value: CAFE standards are frozen both for light-duty and heavy-duty vehicles at 2017 levels.

Based on these parameters, the following matrix of scenarios was modeled in NEMS to estimate the range of demand and GDP elasticities:

C-4. Results

C-4.1. Impact on GDP

Figure C-3 presents the change in real GDP due to the oil price shock compared to the appropriate baseline GDP. As expected, initially, GDP falls because of the unexpected increase in oil price and by 2040 the net impact on GDP is near zero (except in the alternative high price scenario). However, during the middle years, somewhat counterintuitively, there is a net increase in GDP compared to the baseline. Though the magnitude and duration differs, this increase in GDP is observed in all scenarios.

This happens despite the fact that in those years, oil prices are still higher than the base as we model a persistent albeit declining oil shock (see Table C-1 above)[14]. Two features of the MAM, NEMS macro module, explain this result[15]:

1) *Impact on inflation and interest rates:* As described above, higher oil prices affect consumer prices both directly due to increased liquid fuel prices as well as indirectly, as increased costs for oil as an input is passed on to consumers in the prices of other goods and services.

[14] Except for ‘Reference—one year shock’ scenario.

[15] The data used to illustrate these features is from alternative reference case run. However the explanations are applicable to all the scenarios.

This shows up in the change in the Consumer price index (CPI) as shown in Figure C-4. The impact on the CPI declines roughly in line with the declining intensity of the oil price shock (see Table C-1).

However, the impact on inflation, measured as year-on-year change in CPI, is different. In the first year of the shock, the change in inflation is substantially higher compared to baseline, as expected. But from next year onwards, the change in inflation drops to near zero and remains around zero as the previous year's CPI already incorporates higher oil prices.

Long term interest rates in NEMS are dependent on a combination of current year's and previous years' values of inflation, CPI index and federal funds rate. Figure C-4 shows the change in long-term interest rates due to oil price shock in alternative reference scenario where federal funds rates do not change in response to the oil price shock. Despite fixed federal funds rate, long-term interest rates change in response to changes in CPI index and inflation. They are higher during the first few years and then are lower during the latter years, compared to what they are in the baseline. Similar behavior of long term interest rates can be observed across all scenarios.

Long-term interest rates impacts business investment and consumer purchase decisions especially of consumer durables and housing. Ceteris paribus, lower rates will stimulate investment and consumer purchases, and hence increase GDP. Higher interest rates will have a reverse impact (Figure C-5).

2) *Behavior of net exports:* A positive oil price shock reduces US imports through three channels. One, the increase in oil prices leads to lower US oil demand and higher oil production, which decreases the oil import bill. Two, lower consumption and investment leads to lower demand for imports. Three, In NEMS, non-oil imports are not only dependent on demand for imports, but relative producer prices of goods and services between the US and foreign countries. If US producer prices become lower than foreign producer prices, ceteris paribus, the US will import less than before. Foreign producer prices are modeled simplistically in NEMS and are dependent on oil prices. Under the default assumption, foreign producer prices rise more than the US producer prices, leading to a further reduction in US non-oil imports.

US exports in NEMS are modeled to be dependent on the size of foreign GDP and relative producer prices of goods and services between the US and foreign countries. Foreign GDP shrinks in response to oil price increase owing to negative GDP elasticity with respect to oil prices. As a result, demand for US exports decreases as a result of an oil price increase. On the other hand, as stated above, US producer prices rise less than the foreign producer prices, thus favoring US exports. The net effect of these two forces defines the changes in US exports. In the alternative reference scenario during the initial years, the fall in demand for US exports, due to a relatively large magnitude of oil price shocks, overwhelms the support from the advantageous relative prices. As a results, exports fall. However, as the intensity of the shock reduces during later years, US exports rise when relative price advantage is more than enough to compensate for the loss in demand (Figure C-6).

C-4.2. Impact on US Oil Demand and Supply

Unlike GDP, the impact of an oil price shock on oil demand and supply is straightforward and expected. Demand reduction, fuel-switching and purchase of more efficient equipment keeps oil demand lower than the baseline across all scenarios (Figure C-7). Among the scenarios where the shock persists, the impact is smallest in the alternative low price scenario. Low prices in the baseline reduces the size of the impact as the shock is modeled as a percent change from baseline prices. In the alternative low price scenario, a 10 percent shock to oil prices in 2030 results in about $5 per barrel (2015 dollars) increase in prices as opposed to about a $10 per barrel increase in the reference and alternative reference scenarios. This leads to lower incentives for fuel switching and the purchase of efficient equipment compared to other scenarios because of a smaller change in the relative prices of oil and other fuel choices. In addition, the incentives for demand reduction are also lower as oil expenditures are a smaller share of GDP (Figure C-8).

The reverse happens in the case of alternative high price scenario when oil prices are higher. However, the initial impact is lower than that in the reference scenarios. When oil prices are high, consumers are already using oil efficiently. Thus, a further increase in oil prices leads to little demand displacement in the first year of the shock. Nevertheless, the cumulative effect consumer choices, buying more efficient equipment and long term fuel switching, as well as further demand displacement due to continued oil price shocks adds up to provide big reductions in the future years.

On the supply side, an increase in oil prices stimulates both an increase in production from existing fields as well in new fields. The impact is highest in the alternative low price scenario. Many tight oil resources become economically viable with a small change in prices when oil prices are low. The impact is lowest in the alternative high price scenario. As the prices are already high in the baseline, most available drilling equipment are already employed to produce oil from economically viable resources. Therefore, a further increase in prices does little to stimulate further new investment in oil production. It pulls forwards some production while oil production falls during later years, keeping cumulative production during 2030-2040 largely the same.

C-4.3. GDP, Demand and Supply Elasticities

Table C-3 presents the GDP, oil demand and oil supply elasticities calculated for each of the scenarios[16]. GDP elasticity estimates fall within the range of old and new estimates from the literature, while short-run demand estimates fall in the range of old estimates. Except in case of the alternative high price scenario where short-run supply elasticity estimates are much higher than the current estimates available from the literature review. This difference is most likely because NEMS accounts for the latest tight oil resource discoveries which have made US supply much more elastic than historically determined estimates. As discussed above, in the alternative high price scenario, the scope of increasing supply in the short-run is close to zero.

C-5. Tables and Figures

Table C-1. Oil Price Shock by Year

2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
10.00%	9.08%	6.24%	4.06%	2.71%	1.94%	1.37%	0.93%	0.65%	0.47%	0.47%

Table C-2. Scenario Definition

Scenarios	***Oil shock***	***Oil prices***	***Federal Reserve responsiveness***	***Foreign GDP elasticity***	***CAFE standards***
Reference – one year shock	10% in 2030	Default	Default	Default	Default
Reference	According to Table C-1	Default	Default	Default	Default
Alternative reference	According to Table C-1	Default	Alternative	Alternative	Default
Alternative low price	According to Table C-1	Low oil prices	Alternative	Alternative	Alternative
Alternative high price	According to Table C-1	High oil prices	Alternative	Alternative	Default

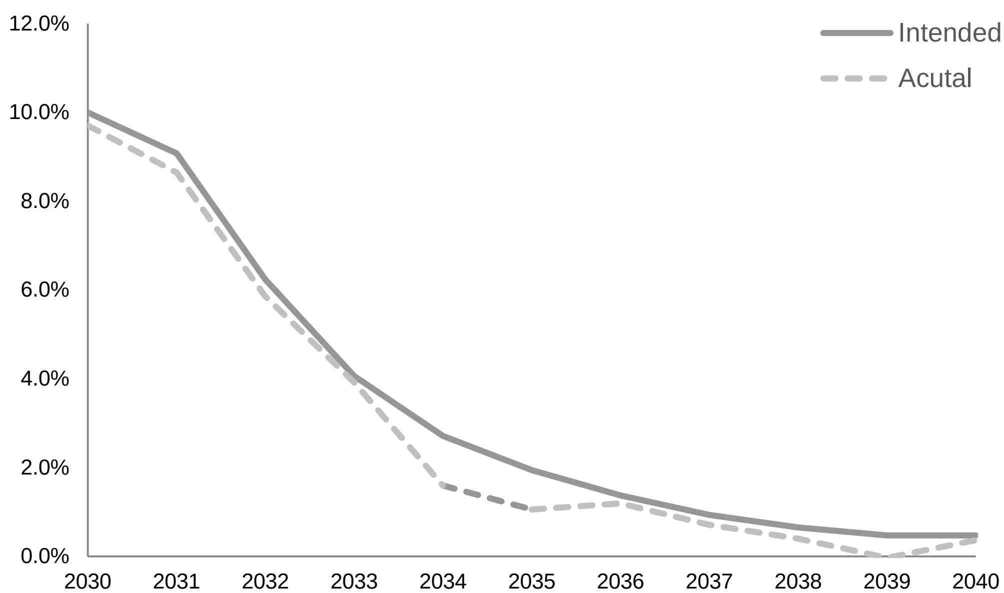
Note: All other assumptions and parameters are set to the AEO 2016 Reference case. A full set of assumptions in the model can be found here http://www.eia.gov/outlooks/aeo/assumptions/. Global short-term oil demand and supply elasticities are set to -0.25 across all the scenarios.

[16] Short-run demand elasticity is calculated by dividing the change in oil demand in 2030 by the change in oil price in 2030. A similar formula is used for calculating the short-run supply elasticity. GDP elasticity w.r.t. oil prices is calculated by dividing maximum change in GDP between 2030 and 2040 by maximum change in oil prices between 2030 and 2040.

Table C-3. GDP and Oil Demand Elasticities Derived from NEMS

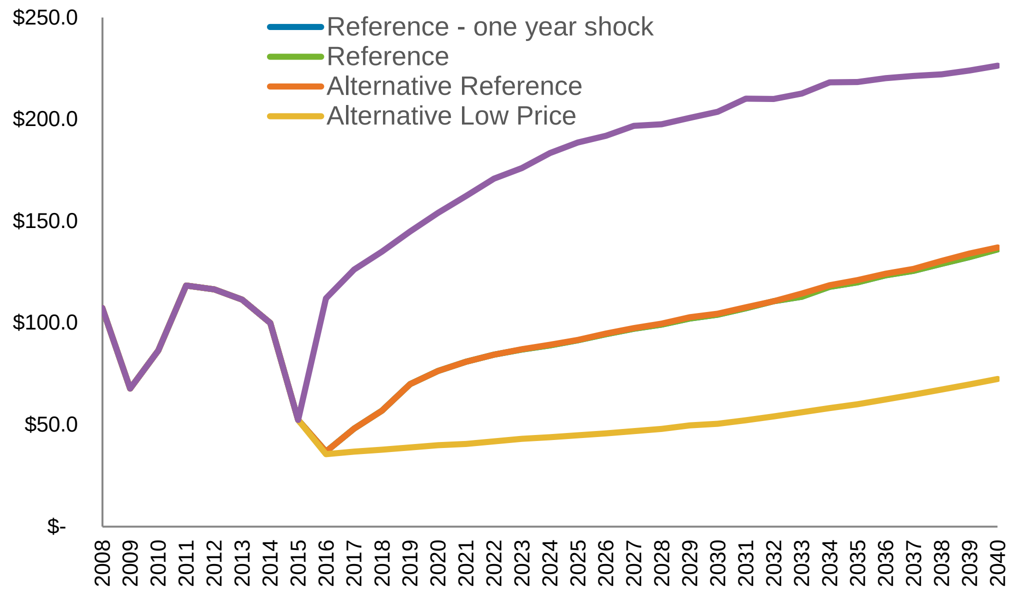
	GDP elasticity w.r.t. oil prices	***Short-run demand elasticity***	***Short-run supply elasticity***
Reference – one year shock	-0.0195	-0.0602	0.1570
Reference	-0.0255	-0.0676	0.1424
Alternative reference	-0.0189	-0.0470	0.1266
Alternative high price	-0.0231	-0.0441	**0.0042**
Alternative low price	-0.0128	-0.0330	0.1742
Literature review – old estimates	–0.012 to –0.078	–0.02 to –0.09	0.025 to 0.075
Literature review – new estimates	–0.012 to –0.029	–0.10 to –0.25	0.025 to 0.075

Figure C-1. Intended Versus Actual Oil Price Shock



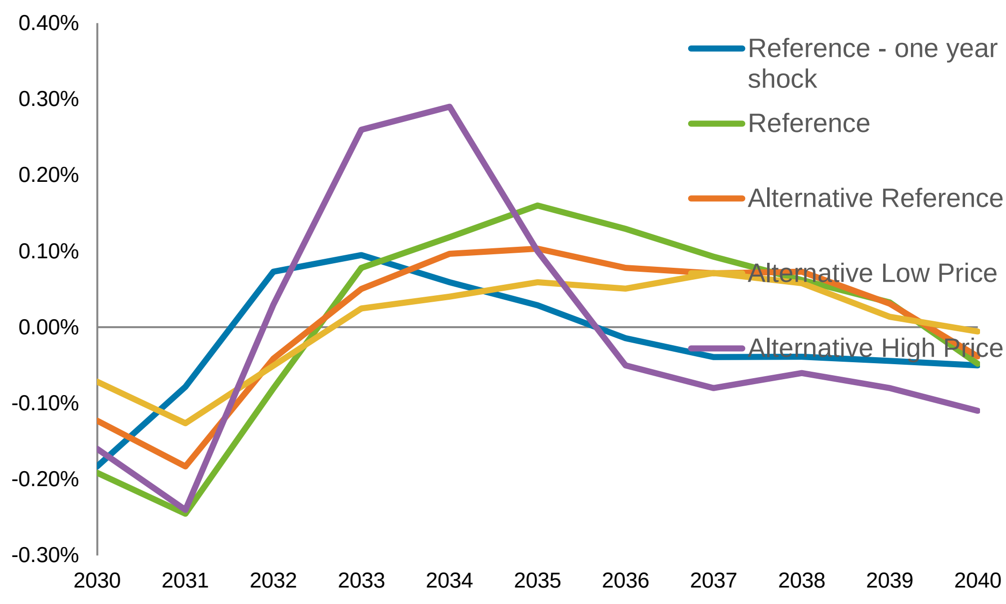
Note: Percent change from baseline Brent price; alternative reference scenario.
Source: RHG estimates

Figure C-2. Oil Prices Under Various Scenarios



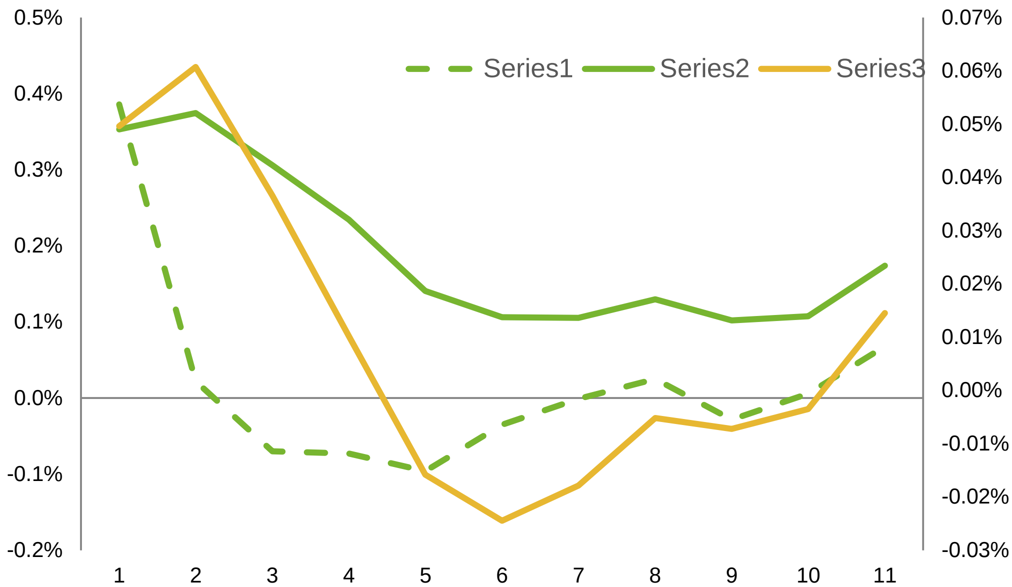
Note: 2015 dollar per barrel
Source: EIA, RHG estimates

Figure C-3. GDP Impact of Oil Price Shock



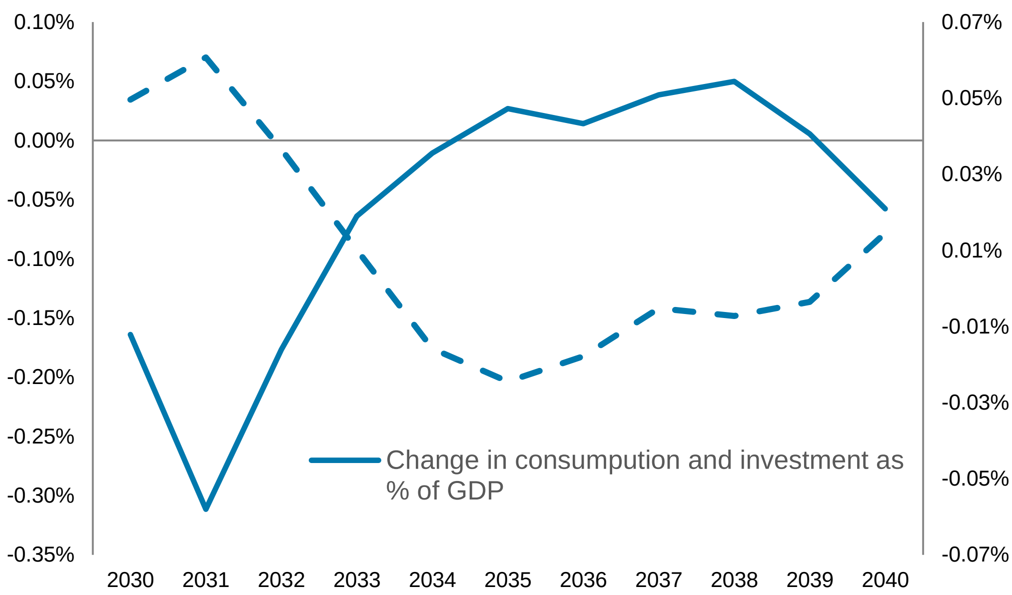
Note: Percent change from baseline GDP
Source: RHG estimates

Figure C-4. Change in CPI, Inflation and Interest Rates Due to the Oil Price Shock



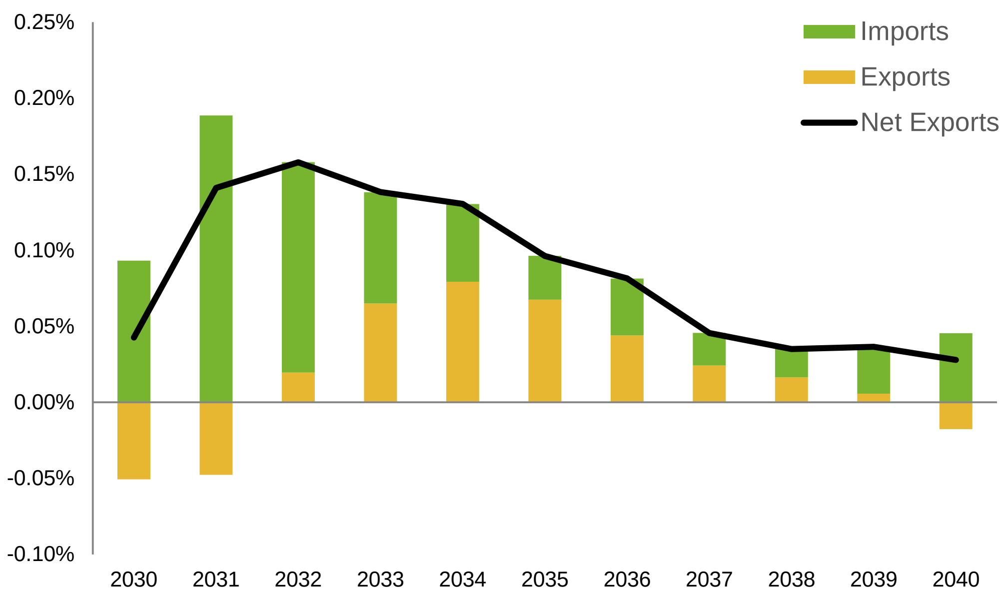
Note: Percent; alternative reference scenario
Source: RHG estimates

Figure C-5. Change in Consumption and Investment vis-à-vis Change in Interest Rates Due to Oil Price Shock



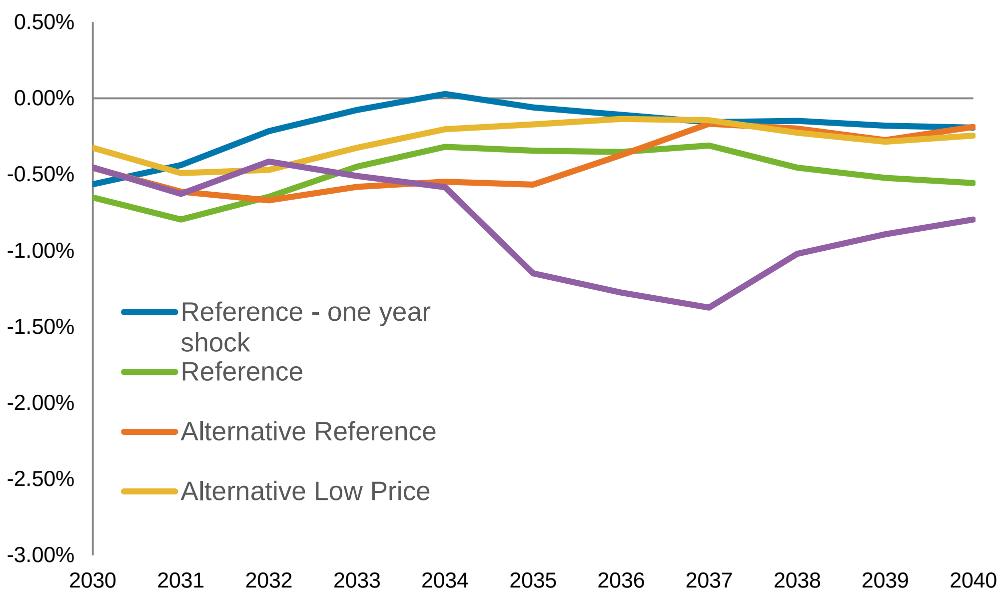
Note: Percent; alternative reference scenario
Source: RHG estimates

Figure C-6. Contribution of Exports and Imports to Change in GDP Due to Oil Price Shock*



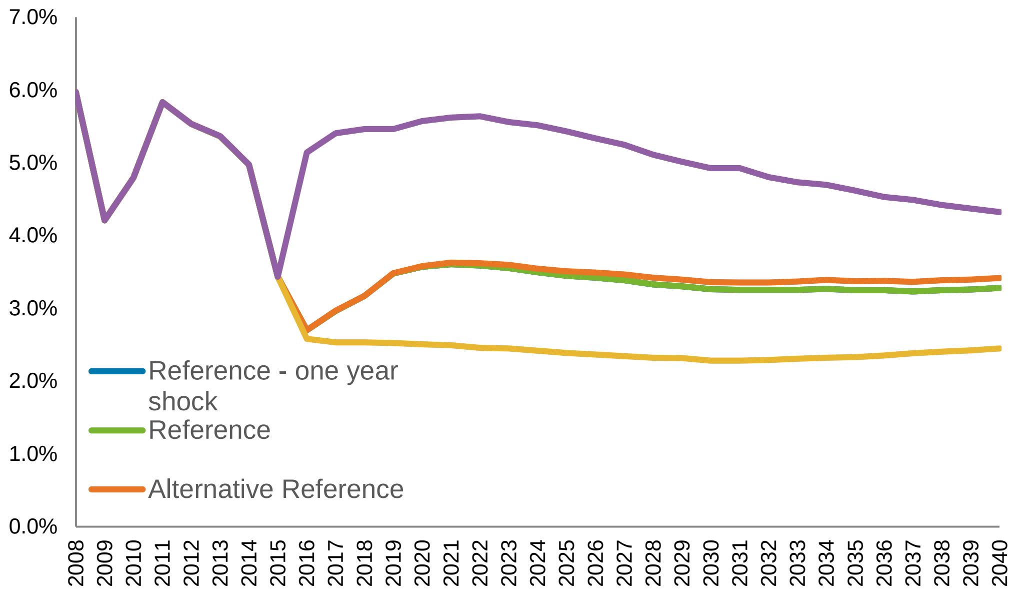
Note: Percent change from baseline GDP; alternative reference scenario
Source: RHG estimates; *Decline in imports contributes positively to GDP.

Figure C-7. Impact on US Oil Demand from an Oil Price Shock



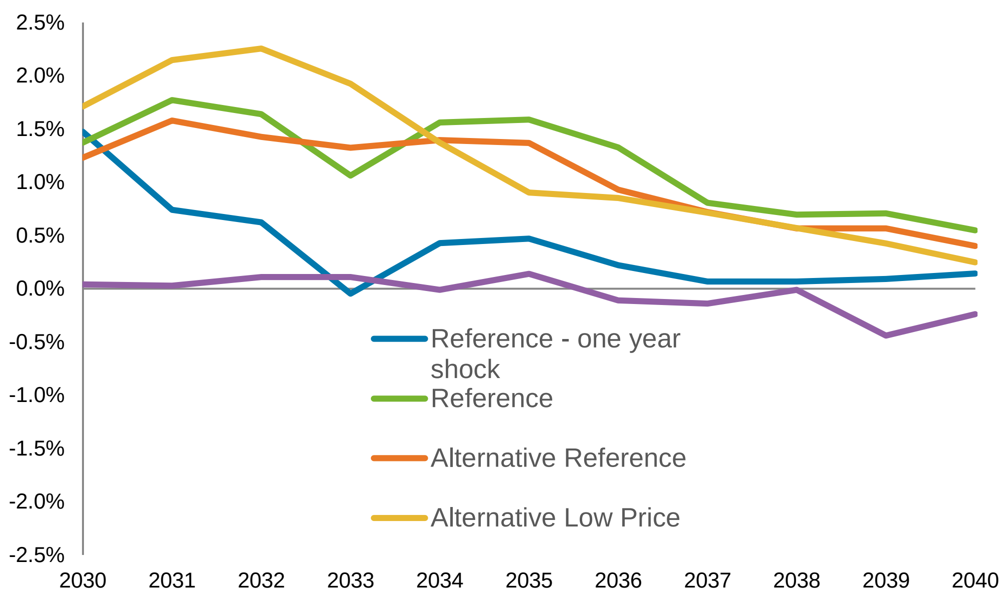
Note: Percent change from baseline
Source: RHG estimates

Figure C-8. Oil Expenditures as a Share of GDP



Note: Percent change from baseline
Source: RHG estimates

Figure C-9. Impact on US Oil Supply from an Oil Price Shock



Note: Percent change from baseline
Source: RHG estimates

D. New Estimates of the Security Costs of US Oil Consumption

Stephen P.A. Brown*

Abstract

In recent years, the United States has become much more self-reliant in producing oil, new estimates of the probabilities and sizes of world oil supply disruptions have become available, and a newer economics literature suggests that US GDP may be less sensitive to world oil price shocks and US oil demand may be more elastic. These developments suggest somewhat lower security costs may be associated with US oil consumption. Following the approach taken by Brown and Huntington (2013, 2015), this analysis provides estimates of the security premiums for US consumption of imported oil, US consumption of domestically produced oil, and the substitution of imported oil for domestically produced oil. Estimates of the expected security costs of US oil consumption are provided over the time horizon from 2015 through 2040, while taking into account projected world oil market conditions, the probabilities and sizes of world oil supply disruptions, the response of world oil prices to those supply disruptions, and the response of US real GDP to those oil price shocks. The estimated oil security premiums suggest that US oil security has become less of a policy concern, and the environmental costs of oil use are a relatively more important issue.

D-1. Introduction

Landsberg et al. (1979) introduced the idea that US dependence on imported oil will result in social costs that are greater than the market price paid for the oil. Dubbing the cost as the "import premium," they estimated the cost of consuming a barrel of imported oil over a barrel of domestically produced oil. The components of this traditional oil import premium include the macroeconomic risks associated with greater exposure to world oil supply disruptions, the effect of oil price shocks on transfers abroad, and a monopsony premium—the latter being the US opportunity to exercise market power in buying oil on the world market.

Since Landsberg et al., a number of others have estimated the oil import premium. These studies include the Energy Modeling Forum (1982), Bohi and Montgomery (1982a, 1982b),

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Broadman (1986), Bohi and Toman (1993), Parry and Darmstadter (2003), Toman (2003) and Leiby (2008). Some of the literature provided premiums at prevailing or projected world oil market conditions. Other literature has estimated optimal oil import premiums which allowed market conditions to change in response to implementing the premium as a tax.[1]

More recently the Council on Foreign Relations (2006) took a different approach and examined the political implications of US dependence on imported oil and identified six costs of US dependence on imported oil. The study offered no guidance about quantifying these costs, however.

In a departure from the previous economics literature, the National Research Council (2009) argues that the non-environmental externalities associated with US dependence on imported and domestic oil are extremely small or nonexistent. The council defines what is meant by externality and then proceeds to reject as externalities the macroeconomic risks associated with greater exposure to world oil supply disruptions, the effect of oil price shocks on transfers abroad, and the monopsony premium.

Brown and Huntington (2013) identify the components of the oil security premium as the change in the expected macroeconomic losses and the change in the expected transfers on the inframarginal barrels of imported oil associated with oil supply disruptions. Following conventions in the mainstream economics literature, they argue that the failure of the United States to exercise its market power in the world oil market does not represent a true economic externality. In addition, they see the expected transfers on the marginal barrel of imported oil occurring during a supply shock as something the purchaser can anticipate. They argue, however, that the change in the expected macroeconomic losses and the change in the transfers on the inframarginal barrels of imported oil are externalities because these expected losses will not be taken into account by those consuming the marginal barrel of oil. Brown and Huntington also estimate oil security premiums associated with US consumption of both domestic and imported oil. They find somewhat larger premiums for imported oil rather than domestic oil.

These oil security measures rely on prevailing or forecast market conditions and a set of parameters that are used to assess how the oil market responds to supply disruptions and how US real GDP responds to the resulting oil price shocks. Over the past few years, world oil market conditions have changed considerably (with the United States importing much less oil), new

[1] The optimal oil import premium would be lower than a premium estimated at prevailing market conditions because implementation of the tax reduces U.S. oil imports and the world oil price.

estimates of the probabilities of world oil supply disruptions have become available, and new estimates of the response of US real GDP to oil supply shocks and the short-run elasticity of oil demand have become available. These developments suggest that it is time to update the estimates of the external security costs of US oil consumption.

Following the approach taken by Brown and Huntington (2013, 2015), we provide updated estimates of the security premiums for US consumption of imported and domestic oil, as well as the substitution of imported oil for domestic oil. Some of the estimates rely on parameters derived from the economics literature and some are derived from a recent multi-model effort—the latter including a Structural Vector Autoregressive (SVAR) model, a Dynamic Stochastic General Equilibrium (DSGE) model and the energy-market simulation model NEMS. The advantage of using the parameter values from these three modeling efforts is that the sets of parameters are internally consistent for each model rather than being drawn separately from a range of studies.

The remainder of this section is organized as follows. Section D-2 presents a welfare-analytic approach which provides the theoretical basis for evaluating the economic costs of US oil consumption. Section D-3 presents seven sets of oil premiums to examine how changing world oil market conditions, changes in the estimated probabilities of disruptions, and differing estimates of the elasticities of oil demand and the response of US GDP to oil price shocks affect the security costs of US oil consumption. Section D-4 examines some policy implications, and Section D-5 offers concluding remarks.

D-2. The Economic Cost of US Oil Consumption

Previous economic research has suggested a number of possible costs associated with US oil consumption. These costs include the failure to exercise monopsony buying power over imported oil, the expected GDP losses associated with supply disruptions, the expected transfers associated with supply disruptions, and environmental degradation. Not all of these costs represent what economists consider market failures. The distinction is important because economists typically consider market failure as the only justification for a policy response, while policymakers often take a more expansive approach.

To assess the costs of US oil consumption, we develop a simple welfare-analytic model of US oil consumption similar to that of Brown and Huntington (2013, 2015). We first use the model to recap which of the different costs that are associated with US oil consumption ought to be considered market failures. We then use the model as a basis for estimating the security costs of US consumption of imported and domestic produced oil.

The economic welfare the United States obtains from its oil consumption, imports and production is the sum of US consumer and producer surpluses associated with oil less the environmental costs of oil use and the expected losses associated with the insecurity of imported or domestic oil, as follows:

$$W = \int_0^{Q_C} P_D(Q)\,\partial Q - TC_{US} - P_W Q_M - E(\Delta P_W)\cdot Q_M - E(\Delta Y) - X_C Q_C \qquad \text{(D-1)}$$

where W is the expected welfare associated with US oil consumption, production and imports; Q_C is the quantity of oil consumed in the United States; P_D is the value US consumers place on the marginal barrel of oil consumed at each quantity Q, which takes the value P_{US} at Q_C; TC_{US} is the total cost of US oil production, P_W is the world oil price; Q_M is the quantity of US oil imports; $E(\Delta P_W)\cdot Q_M$ is the expected transfers from the United States to the rest of the world as a result of the higher oil prices that result from world oil supply disruptions; $E(\Delta Y)$ is the expected value of the US GDP losses occurring as the result of world oil supply disruptions; and X_C is the value of the environmental externalities associated with US oil consumption.[2]

The approach taken in Equation (D-1) follows Brown and Huntington (2013) and treats oil as a fungible commodity that trades at a globally determined price. This fungibility means that the United States cannot alter the composition of world oil production by limiting its imports to stable countries (Nordhaus, 2009 and Brown and Huntington, 2013). Rather, US policy is limited to distinguishing between domestic and imported oil.

Oil's fungibility also means that reliance on domestic oil does not isolate the United States from world oil price shocks because world oil prices move together as shown in Figure D-1. Nonetheless, US policy can affect oil security through differentiating domestically produced oil from imported oil. Domestic oil production is politically stable, whereas historically unstable oil-producing countries are prominent among the marginal suppliers of imported oil, as found by Brown and Huntington (2016).[3] The increased production of stable supplies will lessen the price response to a supply shock, whereas the increased production of unstable supplies increases the size of supply shocks.

[2] The term *oil* is taken to include crude oil, refined products, and all liquid fuels that are close substitutes for refined products. The analysis is also simplified by the assumption that the environmental externalities associated with the consumption of either imported or domestic oil are the same.

[3] It should be noted that many oil producers outside the United States are also stable.

D-2.1. The Optimal Consumption of Imported Oil

For the consumption of imported oil, the optimality condition is:

$$P_{US} = P_W + \frac{\partial P_W}{\partial Q_M} Q_M + E(\Delta P_W) + \frac{\partial E(\Delta P_W)}{\partial Q_M} Q_M + \frac{\partial E(\Delta Y)}{\partial Q_M} + X_C \quad \text{(D-2)}$$

The optimal consumption of imported oil occurs when the value US consumers place on the last barrel of imported oil they consume is equal to the world oil price plus changes in the US terms of trade for oil that result from importing an additional barrel of oil, the change in the expected transfers from the United States to the rest of the world as a result of the higher oil prices that result from world oil supply disruptions that can be attributed to consuming an additional barrel of imported oil, the change in the expected GDP loss that results from a world oil supply shock that can be attributed to consuming an additional barrel of imported oil, and the environmental externalities associated with additional oil consumption.4 Other than environmental externalities, the components of Equation (D-2) are the basis for assessing security premiums for US consumption of imported oil.

D-2.2. The Optimal Consumption of Domestically Produced Oil

For the consumption of domestic oil, the optimality condition is:

$$P_{US} = MC_{US} + \frac{\partial E(\Delta P_W)}{\partial Q_D} Q_M + \frac{\partial E(\Delta Y)}{\partial Q_D} + X_C \quad \text{(D-3)}$$

The optimal consumption of domestic oil occurs when the value that US consumers place on the last barrel of domestic oil is equal to the marginal cost of producing that barrel of oil (MC_{US}), the change in the expected transfers from the United States to the rest of the world as a result of the higher world oil prices that result from world oil supply disruptions that can be attributed to consuming an additional barrel of domestic oil, the change in the expected GDP loss that results from a world oil supply shock that can be attributed to consuming an additional barrel of domestic oil, and the environmental externalities associated with additional oil consumption. Other than environmental externalities, the components of Equation (D-3) are the basis for assessing security premiums for US consumption of domestic oil.

[4] The analysis implies that the United States should set the domestic price of oil (P_{US}) above the world oil price (P_W).

D-2.3. The Externality Costs of US Oil Consumption

With a well-functioning market, oil consumers are expected to fully consider the private costs of their actions. In contrast, oil consumers are expected to ignore the costs that their consumption of oil may impose on others. Accordingly, deviations from the optimal US consumption of imported and domestic oil occur only to the extent that the costs identified in Equations (D-2) and (D-3) are regarded as externalities. As summarized in Table D-1, Subsections D-2.3.1 through D-2.3.4 evaluate whether the costs identified ought to be regarded as externalities and used in the evaluation of the security costs of US oil consumption.

D-2.3.1. Changes in the Terms of Trade for Imported Oil (Monopsony Premium)

Most previous analyses of the costs of US reliance on oil imports, starting with Landsberg et al. and continuing through Leiby (2008) and Greene (2011), have included as a cost of US dependence on imported oil the possibility for the United States to improve its terms of trade for imported oil during stable-market conditions, $\frac{\partial P_W}{\partial Q_M} Q_M$. Decreasing US oil imports would lower the price US consumers pay for all imported oil, but individual US consumers have no incentive to differentiate between domestic and imported oil when making their purchases. Consequently, US consumers create a pecuniary externality that depends on the size of US oil imports.

A US policy of limiting oil imports would improve the terms of trade for US oil imports. Although such action would benefit the United States by transferring income from abroad, the transfers would be a net wash for the world. Because the transfers associated with these improved terms of trade (sometimes known as the *monopsony premium*) are a net wash, the gains are not considered true externalities (Brown and Huntington, 2013). In addition, US actions to limit oil imports to capture such transfers would create economic inefficiencies in the global oil market by reducing world oil production. Although the US exercise of its monopsony buying power would be a countervailing force to the monopoly power exercised by OPEC, the US action to reduce imports and lower prices and the OPEC action to reduce production and increase prices have similar effects in reducing world oil production and consumption.

D-2.3.2. A Change in the Transfers Resulting from Oil Supply Disruptions

As is documented by the US Energy Information Administration (EIA 2017) and Huntington (2017), international oil supply disruptions have led to sharp oil price increases and

US economic losses.[5] These losses include transfers from US consumers to foreign oil producers. To the extent that international oil supply disruptions result in economic losses that are not taken into account by consumers in making their decisions about use, they are externalities that impose costs on others.

As shown in Equation (2) and explained by Brown and Huntington (2013), these transfers consist of two elements for imported oil. The purchaser of the marginal barrel faces an expected oil price shock, $E(\Delta P_W)$. In addition, the purchase of additional imported oil boosts non-US oil production and increases the size of expected oil supply disruption. The result is a bigger expected oil price shock for consumers of the inframarginal barrels of imported oil, with an increase of expected loss, $\frac{\partial E(\Delta P_W)}{\partial Q_M} Q_M$.

Brown and Huntington argue that the former element is not an externality because the purchaser of oil (or oil-using goods) ought to be able to understand that oil consumption is subject to oil price shocks.[6] On the other hand, the latter element should be considered an externality because individuals are not likely to take into account how their own oil purchases may affect the price shocks seen by others. When summed across total US oil imports, the latter effect can be fairly sizable.

As shown in Equation (3), the transfers consist of one element for US consumption of domestic oil, the change in the expected oil price shock for the inframarginal barrels of imported oil, $\frac{\partial E(\Delta P_W)}{\partial Q_D} Q_M$. As explained by Brown and Huntington (2013), increasing US domestic oil production increases the share of world oil production coming from stable sources.[7] Hence, increased domestic production dampens the expected price shock from oil supply disruptions, which decreases the expected transfers for the inframarginal barrels of imported oil. Because the benefits of smaller price shocks are conferred across all US oil consumers, an individual making a decision to buy oil (or oil-using goods) will not take these benefits into account, and an externality arises.

[5] As in Beccue and Huntington (2005 and 2016), EIA (2015) and Huntington (2017), oil supply disruptions refer to the geopolitical, military, and terrorist causes of foreign oil supply disruptions. They exclude the effects of natural supply disruptions brought about by such events as hurricanes or other severe weather conditions.

[6] In practice, consumers may not fully understand the probabilities of future oil supply disruptions and the accompanying price shocks, which could result in losses that are not fully considered in the decision process.

[7] Increased production in stable foreign countries, such as Canada, also increases the security of world oil supply.

D-2.3.3. Changes in the GDP Losses Resulting from Oil Supply Disruptions

As shown in Figure D-2, oil price shocks have preceded 10 of the 11 US recessions since World War II. Although the economics literature is divided on the exact size of the effect, these recessions underscore the idea that oil supply disruptions are likely to result in losses in US real GDP. In addition to the direct effects associated with reduced oil resources to use in production and consumption, economic research has variously attributed the losses to market power and search costs (John 1995), imperfect competition (Rotemberg and Woodford 1996), failures in monetary policy (Bohi 1989 and 1991, Bernanke et al. 1997, and Barsky and Kilian 2002 and 2004), the costs of reallocating resources (Mork 1989 and Davis and Haltiwanger 2001), the effects of uncertainty on investment (Hamilton 1996 and 2003, Ferderer 1996, and Balke et al. 2002), and coordination failures (Huntington 2003).

For whatever reason that oil supply disruptions have effects on US economic activity, the losses extend throughout the economy and are much greater than an individual might expect as part of an oil purchase. Consequently, consumers are unlikely to understand or consider how their own oil consumption affects the loss of economic activity resulting from world oil supply disruptions, which renders the expected losses in US real GDP as externalities.

Increased US oil consumption increases the economy's exposure to the losses in real GDP associated with oil supply disruptions, but the effects are different for imported and domestic oil. As described in Section D-2.3.2 above, increased US oil imports boost production of the unstable sources of world oil supply, strengthening the oil price shocks resulting from oil supply disruptions, and exacerbate the GDP loss, $\frac{\partial E(\Delta Y)}{\partial Q_M}$. In contrast, increased domestic oil production boosts the secure elements of world oil supply, dampens the oil price shocks from oil supply disruptions and lessens the GDP loss, $\frac{\partial E(\Delta Y)}{\partial Q_D}$. It follows that the expected GDP loss from an increase in the consumption of imported oil is greater than for an increase in the consumption of domestic oil.

D-2.3.4. Environmental Externalities

As has been examined in the economics literature, the consumption of either domestic or imported oil yields environmental costs that are externalities. Because the environmental externalities of oil use are not a security issue, a thorough examination of these externalities is beyond the scope of the present inquiry. As the basis for a comparison with the security costs, Section D-4 below provides a summary of the environmental costs of US oil consumption.

D-2.3.5. Foreign Policy Costs of US Oil Imports

The Council on Foreign Relations (2006) identifies six foreign policy costs that arise from US consumption of imported oil. These costs include 1) The adverse effect that significant disruptions in oil supply will have for political and economic conditions in the United States and other importing countries; 2) The fears that the current international system is unable to ensure secure oil supplies when oil is seemingly scarce and oil prices are high; 3) Political realignment from dependence on imported oil that limits US alliances and partnerships; 4) The flexibility that oil revenues give oil-exporting countries to adopt policies that are contrary to US interests and values; 5) An undermining of sound governance by the revenues from oil and gas exports in oil-exporting countries; and 6) An increased US military presence in the Middle East that results from the strategic interest associated with oil consumption. Brown and Huntington (2015) find these six costs are either implicitly incorporated in the welfare-theoretic analysis, are not externalities or cannot be quantified. To the extent these costs are externalities that cannot be quantified, the measured security costs of US reliance on imported oil will be understated.

D-2.3.6. The Cost of Government Policies to Enhance US Oil Security

As they have been conceived, the security estimates exclude the costs of government policies for mitigating the disruption costs. Such costs might include the foreign policy costs, defense spending or the strategic petroleum reserve. As Bohi and Toman (1993) and Brown and Huntington (2013) explain, such expenditures should not be considered a measure of the externality. Rather, the expenditures are a response to the externality.

D-2.4. Aggregate Measures of the Oil Premiums

Equations 2 and 3 provide the basis for six components of oil premiums, including the monopsony premium, the expected transfer on the marginal barrel of imported oil, the change in the expected GDP loss from an increase in the consumption of imported oil, the change in the expected GDP loss from an increase in the consumption of domestic oil, the change in the expected transfers on the inframarginal barrels of imported oil from an increase in the consumption of imported oil and the change in the expected transfers on the inframarginal barrels of imported oil from an increase in the consumption of domestic oil. As shown in Table D-2, these six components provide the basis for calculating four other components and six aggregate measures of the oil premiums. The six aggregate measures include oil-security premiums for the consumption of imported oil, for the consumption of domestic oil, and for the displacement of domestic oil with imported oil. They also include traditional oil premiums for the consumption of imported oil, for the consumption of domestic oil, and for the displacement of domestic oil with imported oil.

According to Leiby (2016), current US policy focuses on the Brown-Huntington oil security premium for US consumption of imported oil, which includes GDP losses and transfers on the inframarginal barrel of imported oil. This premium evaluates the external security costs associated with a marginal increase in the consumption of imported oil. The oil security premium for US consumption of domestic oil evaluates the external security cost associated with a marginal increase in the consumption of domestic oil. The oil security premium for imported vs. domestic oil evaluates the external security cost associated with the substitution of a barrel of imported oil for a barrel of domestic oil.

The traditional premiums also include the monopsony premium and the expected transfer on the marginal barrel of imported oil consumption.[8] Neither is an externality, but both might be taken into account on an informal basis by some policymakers who are evaluating the costs of US reliance on oil. The traditional oil premium for US consumption of imported oil evaluates the costs associated with a marginal increase in the consumption of imported oil. The traditional oil premium for US consumption of domestic oil evaluates the cost associated with a marginal increase in the consumption of domestic oil. The traditional oil premium for imported vs. domestic oil evaluates the cost associated with a marginal substitution of oil imports for domestic oil.

D-3. Quantifying the Costs of US Oil Consumption

Using computational methods based on the welfare-theoretic approach described in Section D-2 with actual world oil market conditions in 2014 and world oil market conditions projected by the US Energy Information Administration (EIA 2012, 2016), we estimate four components of the oil security premiums—the change in the expected GDP loss from the consumption of an additional barrel of imported oil, the change in the expected GDP loss from the consumption of an additional barrel of domestic oil, the change in transfers on the consumption of the inframarginal barrels of imported oil resulting from the consumption of an additional barrel of imported oil, and the change in transfers on the consumption of the inframarginal barrels of imported oil resulting from the consumption of an additional barrel of domestic oil.[9] With these four components, oil security premiums for the consumption of

[8] The traditional oil premiums are examined in Appendix A.

[9] Estimates of the monopsony premium and the expected transfers on the marginal barrel of imported oil are found in Appendix A.

imported oil, the consumption of domestic oil and the differential between imported and domestic oil are derived.

The four components of the oil security premiums are calculated with the computational methods developed by Brown and Huntington (2013, 2015) and described in Appendix B. For each year, the premiums are calculated taking into account world oil market conditions, the probability and sizes of disruptions, short-run demand and supply elasticities and the response of US real GDP to oil price shocks resulting from oil supply disruptions.

The analysis examines the implications of seven different sets of oil market conditions, probabilities and sizes of disruptions and demand and supply elasticities, and is divided into four parts. The first part examines how updated world oil market conditions and new estimates of the probabilities of disruptions, the short-run elasticity of demand and the elasticity of US real GDP with respect to oil price shocks affect the estimated oil security premiums. The second part examines the implications of using elasticities from three new macroeconomic modeling efforts including estimates from an SVAR model (Herrera 2016), a DSGE model (Balke and Brown 2016) and NEMS (Mohan 2016). The third and fourth parts examines how the premiums evolve from 2015 to 2040. The fifth part considers some issues in estimating the oil security premiums.

D-3.1. From Old to New Parameter Values

To update the Brown-Huntington (2015) estimates of the oil security premiums to those using the most current information requires three steps and yields three sets of oil security premiums. The first step is an update of the underlying evaluation scenario and of the sizes and probabilities of disruptions, but to use the estimates of the short-run elasticity of demand and the elasticity of GDP with respect to oil prices from the older literature. This update yields the security premiums identified as Benchmark-O. The second step is to use newer estimates of the short-run elasticity of demand and the elasticity of GDP with respect to oil price shocks to create the oil security premiums identified as Benchmark-N. The third step is to take an evolutionary approach by combining the older and newer estimates of the short-run elasticity of demand and of the elasticity of GDP with respect to oil price shocks to create the oil security premiums identified as Benchmark-E.

Taken together Benchmark-O and Benchmark-N yield good coverage of the estimated elasticities from the economics literature. Benchmark-O represents the older literature with higher oil security premiums that result from less elastic demand and with a greater response of US GDP to world oil price shocks. Benchmark-N represents the newer literature with lower oil security premiums that result from more elastic demand and a lesser response of US GDP to world oil price shocks.

Simply dividing the estimates of the elasticities into old and new and then computing the oil security premiums, however, downplays the uncertainty inherent in the estimated oil security premiums. It also ignores the possibility that both the older and newer literature offer insights into how world oil markets and the US economy might respond to future oil supply disruptions. In taking an evolutionary approach, Benchmark-E combines the insights from the older and newer literature and it allows for a range of estimates that better capture the uncertainty involved in calculating the oil security premiums.

D-3.1.1. World Oil Market Conditions

Brown and Huntington (2015) use the projected world oil market conditions in the 2012 AEO (EIA 2012), as the basis for their evaluation of the oil security premiums. Quantifying the difference on the oil security premiums between the oil market conditions that were projected in the 2012 AEO, today's market realities and the 2016 AEO provides insight into how changing oil market conditions affect the computation of these premiums. As shown in Table D-3, actual world oil market conditions in 2014 were substantially different than were projected as the 2013-14 average in the 2012 AEO. In 2014, world oil prices were somewhat lower, world oil consumption was higher, non-US oil consumption was higher, non-US oil production was lower, US oil consumption was slightly higher, US oil production was higher, US oil imports were considerably lower and US real GDP was higher.

D-3.1.2. Disruption Probabilities

The oil security premiums are calculated on the basis of the probabilities and sizes of the disruptions. Market outcomes are generated for each disruption size and the outcomes are weighted by the probabilities of each size of disruption (as explained in Appendix B).

Beccue and Huntington (2005, 2016) provide probabilities and sizes of expected world oil supply disruptions. Beccue and Huntington use a structured survey of experts to evaluate the likelihood of foreign oil supply disruptions over a ten-year period. Although severe weather and other natural phenomena could result in significant disruptions, their study focused on geopolitical, military, and terrorist causes of disruptions abroad. The expected disruptions are the net supply shock after all surplus capacity available to the market has been used.

The Beccue and Huntington probabilities are converted to the annual values shown in Table D-4.[10] The underlying world oil market conditions for Beccue and Huntington (2005) match the average 2013-14 world oil market conditions as projected in the *2012 AEO*, and the expected annual supply disruptions range from 0 to 17 million barrels per day (in 1 million barrel per day increments) against non-US production of 80 million barrel per day. The underlying world oil market conditions for Beccue and Huntington (2016) are the actual world oil market conditions that prevailed in 2014, and the expected annual supply disruptions range from 0 to 21 million barrels (in 1 million barrel per day increments) against non-US production of 78.78 million barrels per day. For other years, the size of these disruptions are scaled according to non-US oil production.

As shown in the table, the two sets of estimated disruption probabilities and sizes are somewhat different. The 2016 disruption estimates are based on smaller non-US production. The 2016 estimates also show smaller probabilities of small disruptions, but greater probabilities of medium and large disruptions. Overall, the probability of a disruption is lower.

D-3.1.3. Price, Income, and GDP Elasticities

Price and income elasticities and elasticities of GDP with respect to oil price shocks are used to compute the oil premiums. The older values shown in Table D-5 represent the Brown and Huntington (2013) interpretation of representative values from the literature. Their sources include the Atkins and Jazayeri (2004) and Dahl (2010) surveys of oil demand elasticities, the Hickman et al. review (1987) of participating models in an Energy Modeling Forum study, the Jones et al. (2004) survey of the elasticities of GDP with respect to oil price shocks, as well as Krichene (2002), Cooper (2003), Huntington (2005), Blanchard and Gali (2007), Leiby (2008), Hamilton (2009), Kilian (2009), Smith (2009), Balke et al. (2010), Kilian and Vigfusson (2011), and Kilian and Murphy (2014). The evolutionary values are obtained by combining the older estimates with the newer estimates.

The newer values of the elasticity of GDP with respect to oil price shocks are the author's interpretation of work by Kilian (2009), Herrera and Pesavento (2009), Balke et al., (2010), Blanchard and Gali (2010), Kilian and Vigfusson (2011), Kilian and Murphy (2014), Baumeister and Hamilton (2015), Herrera (2016) and Balke and Brown (2016). The evolutionary value of

[10] Beccue and Huntington (2005, 2016) provide a probability for each size disruption over a decade (φ_d), with $1 - \varphi_d$ representing the probability of no disruption. If the expected instability over the decade as equally distributed across each of the 10 years, the probability of a disruption in any given year (φ_a) is $\varphi_a = 1 - (1 - \varphi_d)^{1/10}$.

the short-run demand elasticity is a compromise between the older estimates and the newer estimates.

According to the newer research, demand is more elastic in the short-run, suggesting that oil users respond more flexibly to changes in oil prices than is indicated by the older literature. Similarly, the newer macroeconomic research shows the economy responds more flexibly to oil price shocks and there is less economic impact. The evolutionary estimates represent a compromise between the older estimates that show relatively little flexibility and the newer estimates that show considerably more flexibility.

D-3.1.3.1. A Closer Look at the Short-Run Demand Elasticities

The size of the oil price shock originating from a supply disruption depends critically on the short-run elasticities. More inelastic values of demand mean a greater price increase. An older literature, including surveys by Atkins and Jazayeri (2004) and Dahl (2010) and narratives by Hamilton (2009) and Smith (2009) finds that short-run oil demand is very inelastic, with Brown and Huntington (2013, 2015) using -0.055 in a range of -0.02 to -0.09. These older estimates of the short-run elasticities of demand show world oil consumption to be quite unresponsive prices, suggesting that there is relatively little flexibility in oil consumption.

More recent econometric studies of US crude oil and refined product demand, such as Davis and Kilian (2011), Kilian and Murphy (2014) and Coglianese et al. (2015), find that US oil demand is more elastic in the short run, with the author of the present work using a value of -0.175 in a range of -0.10 to -0.25 to represent the newer literature. Although these values are still fairly inelastic, they show considerably more flexibility on the part of oil consumers. With these more elastic values, the effect of any given oil supply disruption on world oil prices is considerably less than with the older elasticities.

Some of the recent econometric research uses cross-state data on tax changes to estimate gasoline demand, which yields a state-level response to changes in gasoline taxes. Such exercises are informative, but may not reflect how world oil consumption responds to rising oil prices. Cross-state data may yield estimates of demand that are more elastic than time-series estimates for the United States or the world. Using a simultaneous equation model of the world oil and natural gas markets, Krichene (2002) concludes, “The demand for crude oil has a low short run price elasticity: -0.05 in 1918-2004, -0.05 in 1918-73, and -0.003 in 1974-2004 … [and] crude oil demand is highly price-inelastic in the short run, as energy consumption is essentially determined by fixed capital.”

Hamilton (2009) and Smith (2009) also provide compelling narratives about the movements in oil prices using very low elasticities of world oil demand. Consider Hamilton's analysis of the 2004-2008 world oil market experience. Using the more elastic demand values would make it impossible to track the path of world oil consumption with the actual prices and world GDP that prevailed at the time.

In addition, consider the late-1973 oil supply disruption that resulted in a 1.4 percent decrease in world crude oil supplies from the 1973 to 1974. World oil prices rose by 115.5 percent, which implies an elasticity of demand of -0.012, and a more inelastic value if you consider the contraction in world economic activity. Overall, it is likely better to extend the range of demand elasticities used to estimate oil security premiums than to rely exclusively on the estimates from the newer literature. The evolutionary estimates of the short-run elasticity of demand combine the less elastic values of the older literature with the more elastic values of the newer literature, keeping the old mid-value of -0.055 in a range of -0.02 to -0.25.

D-3.1.3.2. The Response of US Real GDP to Oil Price Shocks

As shown in Table D-6, estimated elasticities of GDP with respect to oil price shocks (originating from an oil supply disruption) have a wide range of values, -0.012 to -0.12 as described by Jones et al. Leiby (2008) describes a narrower range of elasticity values at -0.01 to -0.08. Brown and Huntington (2013) use a mid-value of -0.044 in a slightly narrower range at -0.012 to -0.078, and Leiby uses a mid-value of -0.035 in a still narrower range of -0.01 to -0.054. The more recent empirical research—such as Kilian (2009), Herrera and Pesavento (2009), Balke et al., (2010), Blanchard and Gali (2010), Kilian and Vigfusson (2011), Kilian and Murphy (2014) and Baumeister and Hamilton (2015)—suggests a much weaker GDP response, with a mid-value of -0.018 in a range of -0.006 to -0.029.

The weaker response of GDP to oil price shocks may owe to improved monetary policy, the economy better adjusting to oil supply disruptions, improved modeling techniques, and/or the lack of major oil supply disruptions in the past decade. Huntington (2017) cautions that the world has not seen a major oil supply disruption since 2003, which raises the possibility that research that focuses on relatively recent data is likely to give considerable weight to an era in which the events of interest have not occurred. A meta-analysis by Oladosu et al. (2017) finds a mid-value of -0.0238 in a range of -0.0075 to -0.0402. Hence, it is likely premature to rely heavily on the least elastic values of GDP with respect to oil price shocks. An evolutionary approach of combining the older and newer estimates yields a mid-value of -0.028 in a range of -0.006 to -0.051, which may better represent the risks to economic activity.

D-3.1.4. Oil Security Premiums, from Brown-Huntington to the Newer Benchmarks

Using the methods, oil market conditions, the probability and sizes of disruptions and the elasticities described above, we develop four sets of oil premiums. These include a replication of Brown-Huntington (2015), Benchmark-O which uses updated world oil market conditions and probabilities and sizes of disruptions, Benchmark-N which uses the newer estimates of the short-run elasticity of demand and the response of GDP to oil price shocks, and Benchmark-E which uses the evolutionary estimates of the short-run elasticity of demand and the response of GDP to oil price shocks.

As shown in Table D-7, the GDP effects are greater for the consumption of imported oil than domestic oil (as described in section D-2.3.3 above). The difference arises because increased oil imports increase the size of the expected price shock because greater imports increase the size of potential disruptions in unstable regions of the world. In contrast, increased domestic oil production weakens the expected price response because greater US oil production increases the share of the oil market coming from stable supplies. Similarly, increased consumption of imported oil increases the transfers on the inframarginal purchases of imported oil, yielding a small expected cost. Increased consumption of domestic oil reduces the transfers on the inframarginal purchases of imported oil, yielding a small expected gain (shown as a negative loss in the table).

As shown in the table, the individual components of the oil premiums generally show smaller effects as we move from the Brown-Huntington assumptions to Benchmark-O. For Benchmark-O, a slightly larger GDP boosts the expected dollar value of the GDP loss. That effect is more than offset by increased US oil production and lower oil prices, which yield a smaller expected oil price shock than for the Brown-Huntington assumptions, resulting in smaller expected GDP losses and smaller expected transfers on inframarginal oil imports. The updated probabilities and sizes of disruptions also slightly reduce the estimates.

For Benchmark-N, the more elastic demand and weaker GDP responses combine to yield smaller expected GDP losses and expected transfers on inframarginal oil imports than are found with Benchmark-O. For Benchmark-E, the wider range of demand elasticities and evolutionary values of the GDP responses combine to yield expected GDP losses that are between those found for Benchmark-O and Benchmark-N. The expected transfers are somewhat greater for Benchmark-E than Benchmark-O because the less elastic GDP response leads to greater expected price shocks.

As shown in Table D-8, the aggregate oil security premiums that result from combining the individual components generally decrease from the Brown-Huntington assumptions to Benchmark-O to Benchmark-E and then Benchmark-N. The exception is the oil security premium for the consumption of domestic oil, which increases as we move from the Brown-Huntington assumptions to Benchmark-O. The increased aggregate results from combining a smaller expected GDP loss with a smaller expected gain in transfers on the inframarginal purchases of imported oil.

D-3.2. New Macro Modeling Efforts and US Oil Security Premiums

As part of a three-model effort, Herrera (2016), Balke and Brown (2016) and Mohan (2016), provide new estimates of the price elasticities of oil supply and demand and of the elasticity of US real GDP with respect to oil price shocks resulting from world oil supply disruptions. As shown in Table D-9, combining the three benchmark cases with the new modeling effort provides six sets of elasticities with which to examine the oil security premiums. The benchmark values represent different ranges of values from the economics literature, but each of the modeling efforts provides a set of elasticities that are internally consistent.

To obtain the elasticities identified in the table as SVAR-BH, Herrera uses the Baumeister and Hamilton (2015) approach to oil price decomposition in a structured vector autoregressive model to estimate the effects of oil supply disruptions on US macroeconomic activity. To provide the set of elasticities identified here as DSGE-S, Balke and Brown use a DSGE-S model that is based on standard preferences including a labor-leisure tradeoff.[11] The NEMS elasticities combine results from five different runs of NEMS that Mohan conducted under various assumptions about the size and duration of the oil supply disruptions, the baseline energy market conditions and the US monetary policy response.

As shown in the table, mid-values and upper and lower ranges are provided for the three benchmark cases. Median values and confidence bands at the 2.5th and 97.5th percentiles are provided for the SVAR and DSGE models. For NEMS, mean values and upper and lower ranges are used. In total, the effects of 15 sets of elasticities on estimated oil premiums are evaluated on an annual basis from 2015 to 2040 using the Beccue and Huntington (2016) estimates of the

[11] Balke and Brown also estimate a DSGE model with Greenwood, Hercowitz and Huffman preferences, which excludes a labor-leisure tradeoff. The model yields similar results to those found with standard preferences.

probabilities and sizes of disruptions and the reference projections of world oil market conditions from EIA's *2016 Annual Energy Outlook* (EIA 2016).[12]

Over this 25-year time period, world oil consumption is projected to increase from 93.90 million barrels per day to 122.44 million barrels per day. US oil consumption is projected to rise from 19.42 million barrels per day to 20.14 million barrels per day, with US oil production rising from 14.95 million barrels per day to 18.62 million barrels per day and US oil imports falling from 4.47 million barrels per day to 1.52 million barrels per day. Over the same time horizon, non-US oil consumption is projected to rise from 74.48 million barrels per day to 102.00 million barrels per day. The world oil price is projected to dip from $52.32 per barrel after 2015 before rising to $136.21 per barrel in 2040. US real GDP is projected to rise at about a 2.23 percent annual rate from $17.983 trillion in 2015 to $31.235 trillion in 2040.[13]

D-3.2.1. Comparing the Elasticities Across the Models

Given that the assumed oil market scenario and oil supply disruptions are the same across the five estimates of the oil security premiums, the elasticities take a central role in determining the differences in the oil security premiums across the various models. The more elastic are demand and supply, the smaller will be the price shocks arising from oil supply disruptions. The less responsive is real GDP with respect to oil price shocks, the smaller will be the GDP losses resulting from a given oil price shock. Lower values of the GDP elasticities also strengthen the overall price shock.

As shown in the table, the SVAR-BH, DSGE-S and NEMS modeling efforts yield short-run elasticities of demand that are in or beyond the more elastic range of Benchmark-N (which represents the newer literature). The three modeling efforts mostly yield elasticities of real GDP with respect to oil price shocks that are in the range of Benchmark-N. At the 97.5th percentile, SVAR-BH shows GDP to be fairly responsive to oil price shocks (within the context of the literature) at -0.0623, but that value is coupled with fairly elastic supply and demand at 0.3162 and -0.1797, respectively.

D-3.2.2. The Oil Security Premiums

As shown in Table D-10 and Figures D-3 and D-3a through D-3d, the SVAR-BH modeling effort yields estimates of the expected GDP losses that are generally consistent with

[12] As shown in the table, only the three benchmarks and NEMS provide a complete set of elasticities. For those cases where the elasticities are not provided, elasticities from the benchmark exercises are used as default values.

[13] All reported values are in 2015 dollars.

Benchmark-N and the lower range of Benchmark-E for both the consumption of imported and domestic oil. The high estimates from SVAR-BH are close to the high estimates for Benchmark-N and the mid estimates from Benchmark-E. The estimates from the DSGE-S and NEMS models are in or below the lower ranges of Benchmark-N. The low estimates from the three modeling efforts reflect both the more elastic values of short-run supply and demand and the less elastic response of US real GDP to oil price shocks found with the three modeling efforts.

Similar results are found for the expected transfers on the inframarginal barrels of imported oil. The expected transfers found for the three modeling efforts are generally consistent with Benchmark-N and the lower range of Benchmark-E. The low estimates depend mostly on the more elastic values of short-run supply and demand found with the three models. As shown in Figure D-4, these more elastic values yield relatively much lower expected oil price shocks than are found with the benchmark values.

As shown in Table D-11 and Figures D-5, D-5a and D-5b, summing up the individual components to yield aggregate oil security premiums yields very similar results. The oil security premiums for the SVAR-BH modeling effort is generally consistent with Benchmark-N and the lower range of Benchmark-E. For the aggregate oil security premiums for the consumption of imported oil, the consumption of domestic oil and imports vs. domestic oil, the high estimates from SVAR-BH are about the same as the mid estimates from Benchmark-E. The estimates for the DSGE-S and NEMS models are in or below the lower ranges of Benchmark-N.

D-3.3. Components of the Oil Security Premiums 2015–2040

As described above, four components are used to compute the oil security premiums. The two bigger components are the change in expected GDP losses that result from a marginal increase from a marginal increase in the consumption of imported or domestic oil. The two smaller components are the change in the expected transfers on the inframarginal consumption of imported oil that result from a marginal increase in the consumption of imported or domestic oil.

D-3.3.1. Change in the Expected GDP Loss from a Marginal Increase in the Consumption of Imported Oil

As shown in Figures D-6, D-6a and D-6b, the change in the expected GDP loss from a marginal increase in the consumption of imported oil increases from 2015 to 2040. The gains are largely driven by projected gains in US real GDP and non-US oil production. As shown in Figure D-6a, Benchmark-O finds the premium rising from a mid-value of $5.23 per barrel (in a range of $1.11 to $15.09) in 2015 to a mid-value of $8.74 per barrel (in a range of $1.85 to

$25.35) in 2040. Under Benchmark-E, the premium rises from a mid-value of $3.64 per barrel (in a range of $0.30 to $11.77) in 2015 to a mid-value of $6.09 per barrel (in a range of $0.50 to $19.76) in 2040. Under Benchmark-N, the premium rises from a mid-value of $1.23 per barrel (in a range of $0.58 to $3.40) in 2015 to a mid-value of $2.07 per barrel (in a range of $0.97 to $5.68) in 2040.

As shown in Figure D-6b, the premiums for the SVAR-BH, DSGE-S and NEMS modeling exercises also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, with the exception of the high estimates for SVAR-BH, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $0.85, $0.29 and $0.71 per barrel in respective ranges of $0.19 to $3.66, $0.21 to $0.41 and $0.46 to $0.96. For 2040, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $1.42, $0.49 and $1.19 per barrel in respective ranges of $0.32 to $6.12, $0.35 to $0.69 and $0.76 to $1.60.

D-3.3.2. Change in the Expected GDP Loss from a Marginal Increase in the Consumption of Domestic Oil

As shown in Figures D-7, D-7a and D-7b, the change in the expected GDP loss from a marginal increase in the consumption of domestic oil increases from 2015 to 2040. The gains are largely driven by projected gains in US real GDP and non-US oil production. As shown in Figure D-7a, Benchmark-O finds the premium rising from a mid-value of $3.95 per barrel (in a range of $0.83 to $11.51) in 2015 to a mid-value of $7.04 per barrel (in a range of $1.49 to $20.55) in 2040. Under Benchmark-E, the premium rises from a mid-value of $2.75 per barrel (in a range of $0.22 to $8.96) in 2015 to mid-value of $4.90 per barrel (in a range of $0.40 to $15.99) in 2040. Under Benchmark-N, the premium rises from a mid-value of $0.93 per barrel (in a range of $0.44 to $2.57) in 2015 to mid-value of $1.66 per barrel (in a range of $0.78 to $4.57) in 2040.

As shown in Figure D-7b, the premiums for the SVAR-BH, DSGE-S and NEMS models also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, with the exception of the high estimates for SVAR-BH, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $0.64, $0.22 and $0.53 per barrel in respective ranges of $0.14 to $2.76, $0.16 to $0.31 and $0.34 to $0.72. For 2040, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $1.14,

$0.39 and $0.95 per barrel in respective ranges of $0.25 to $4.93, $0.28 to $0.55 and $0.61 to $1.29.

D-3.3.3. Change in the Expected Transfers on the Consumption of Inframarginal Imports from a Marginal Increase in the Consumption of Imported Oil

As shown in Figures D-8, D-8a and D-8b, the change in the expected transfers on the consumption of inframarginal imports from a marginal increase in the consumption of imported oil decrease from 2015 to 2040. Rising oil prices play a role in the estimated value of the change in expected transfers on the consumption of inframarginal imports, but the value declines as US imports are reduced. It turns negative when US oil imports are reduced to the point where the larger oil supply disruptions would result in world oil prices rising to the point where the United States exports oil.

As shown in Figure D-8a, Benchmark-O finds the premium falling from a mid-value of $0.027 per barrel (in a range of $0.018 to $0.065) in 2015 to a mid-value of -$0.009 per barrel (in a range of -$0.004 to -$0.051) in 2040. Under Benchmark-E, the premium falls from a mid-value of -$0.031 per barrel (in a range of -$0.008 to -$0.097) in 2015 to a mid-value of -$0.011 per barrel (in a range of -$0.001 to -$0.089) in 2040. Under Benchmark-N, the premium falls from a mid-value of $0.012 per barrel (in a range of $0.008 to $0.025) in 2015 to a mid-value of -$0.002 per barrel (in a range of -$0.001 to -$0.009) in 2040.

As shown in Figure D-8b, the premiums for the SVAR-BH, DSGE-S and NEMS modeling exercises also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $0.004, $0.006 and $0.005 per barrel in respective ranges of $0.19 to $3.66, $0.21 to $0.41 and $0.46 to $0.96. For 2040, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are -$0.001, -$0.001 and -$0.001 per barrel in respective ranges of less than -$0.001 to -$0.002, -$0.001 to -$0.001 and -$0.001 to -$0.001.

D-3.3.4. Change in the Expected Transfers on the Consumption of Inframarginal Imports from a Marginal Increase in the Consumption of Domestic Oil

As shown in Figures D-9, D-9a and D-9b the change in the expected transfers on the consumption of inframarginal imports from a marginal increase in the consumption of domestic oil start negative and increase from 2015 to 2040. Rising oil prices play a role in the estimated value of the change in expected transfers on the consumption of inframarginal imports, but the value rises as US imports are reduced. It turns positive when US oil imports are reduced to the point where the larger oil supply disruptions result in world oil prices rising to the point where the United States exports oil.

As shown in Figure D-9a, Benchmark-O finds the premium rising from a mid-value of -$0.14 per barrel (in a range of -$0.10 to -$0.34) in 2015 to a mid-value of $0.05 per barrel (in a range of $0.02 to $0.28) in 2040. Under Benchmark-E, the premium rises from a mid-value of -$0.16 per barrel (in a range of -$0.04 to -$0.51) in 2015 to mid-value of $0.06 per barrel (in a range of $0.01 to $0.49) in 2040. Under Benchmark-N, the premium rises from a mid-value of -$0.06 per barrel (in a range of -$0.04 to -$0.13) in 2015 to mid-value of $0.01 per barrel (in a range of $0.01 to $0.05) in 2040.

As shown in Figure D-9b, the premiums for the SVAR-BH, DSGE-S and NEMS models also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR, DSGE and NEMS models are -$0.023, -$0.032 and -$0.028 per barrel in respective ranges of -$0.010 to -$0.051, -$0.025 to -$0.040 and -$0.028 to -$0.030. For 2040, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $0.003, $0.005 and $0.005 per barrel in respective ranges of $0.001 to $0.010, $0.004 to $0.007 and $0.004 to $0.005.

D-3.4. Oil Security Premiums 2015 to 2040

Estimates of the individual components are used to develop oil security premiums from 2015 to 2040. These premiums cover the external security costs of consumption of imported oil, the consumption of domestic oil and the substitution of imported oil for domestic oil. These premiums rise from 2015 to 2040, driven by projected gains in US real GDP, the world oil price and non-US production.

D-3.4.1. Oil Security Premiums for the Consumption of Imported Oil

As shown in Figures D-10, D-10a and D-10b, the oil security premium for US consumption of imported oil increases from 2015 to 2040. The gains are largely driven by expected GDP losses. The expected transfers on inframarginal consumption of imported oil are quite small. As shown in Figure D-10a, Benchmark-O finds the premium rising from a mid-value of $5.25 per barrel (in a range of $1.12 to $15.16) in 2015 to a mid-value of $8.73 per barrel (in a range of $1.85 to $25.30) in 2040. Under Benchmark-E, the premium rises from a mid-value of $3.67 per barrel (in a range of $0.30 to $11.87) in 2015 to a mid-value of $6.08 per barrel (in a range of $0.49 to $19.67) in 2040. Under Benchmark-N, the premium rises from a mid-value of

$1.25 per barrel (in a range of $0.59 to $3.42) in 2015 to a mid-value of $2.06 per barrel (in a range of $0.97 to $5.68) in 2040.

As shown in Figure D-10b, the premiums for the SVAR-BH, DSGE-S and NEMS modeling exercises also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, with the exception of the high estimates for SVAR-BH, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $0.85, $0.30 and $0.71 per barrel in respective ranges of $0.19 to $3.67, $0.21 to $0.42 and $0.46 to $0.96. For 2040, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $1.42, $0.48 and $1.18 per barrel in respective ranges of $0.32 to $6.12, $0.35 to $0.69 and $0.76 to $1.60.

D-3.4.2. Oil Security Premiums for the Consumption of Domestic Oil

As shown in Figures D-11, D-11a and D-11b, the oil security premium for US consumption of domestic oil also increases from 2015 to 2040. The gains are largely driven by expected GDP losses. The expected transfers on inframarginal consumption of imported oil are quite small. As shown in Figure D-11a, Benchmark-O finds the premium rising from a mid-value of $3.81 per barrel (in a range of $0.74 to $11.17) in 2015 to a mid-value of $7.09 per barrel (in a range of $1.51 to $20.84) in 2040. Under Benchmark-E, the premium rises from a mid-value of $2.59 per barrel (in a range of $0.18 to $8.45) in 2015 to a mid-value of $4.96 per barrel (in a range of $0.40 to $16.48) in 2040. Under Benchmark-N, the premium rises from a mid-value of $0.87 per barrel (in a range of $0.40 to $2.43) in 2015 to a mid-value of $1.67 per barrel (in a range of $0.79 to $4.62) in 2040.

As shown in Figure D-11b, the premiums for the SVAR-BH, DSGE-S and NEMS models also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, with the exception of the high estimates for SVAR-BH, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $0.62, $0.19 and $0.51 per barrel in respective ranges of $0.13 to $2.71, $0.13 to $0.27 and $0.32 to $0.69. For 2040, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $1.14, $0.40 and $0.96 per barrel in respective ranges of $0.25 to $4.94, $0.29 to $0.56 and $0.62 to $1.29.

D-3.4.3. Oil Security Premiums for Imported vs. Domestic Oil

As shown in Figures D-12, D-12a and D-12b, the oil security premium for the substitution of imported oil for domestic oil rises only moderately from 2015 to 2040. The gains in the oil security premium for consumption of imported are nearly offset by gains in the oil security premium for consumption of domestic oil. As shown in Figure D-12a, Benchmark-O finds the premium rising from a mid-value of $1.44 per barrel (in a range of $0.39 to $3.99) in 2015 to a mid-value of $1.64 per barrel (in a range of $0.33 to $4.46) in 2040. Under Benchmark-E, the premium rises from a mid-value of $1.08 per barrel (in a range of $0.12 to $3.67) in 2015 to a mid-value of $1.12 per barrel (in a range of $0.09 to $3.19) in 2040. Under Benchmark-O, the premium rises from a mid-value of $1.44 per barrel (in a range of $0.39 to $3.99) in 2015 to a mid-value of $1.64 per barrel (in a range of $0.33 to $3.19) in 2040. Under Benchmark-N, the premium rises from a mid-value of $0.38 per barrel (in a range of $0.19 to $0.99) in 2015 to a mid-value of $0.39 per barrel (in a range of $0.18 to $1.05) in 2040.

As shown in Figure D-12b, the premiums for the SVAR-BH, DSGE-S and NEMS models rise moderately from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, with the exception of the high estimates for SVAR-BH, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $0.24, $0.11 and $0.21 per barrel in respective ranges of $0.06 to $0.95, $0.08 to $0.15 and $0.15 to $0.27. For 2040, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $0.27, $0.09 and $0.23 per barrel in respective ranges of $0.06 to $1.18, $0.06 to $0.13 and $0.14 to $0.31.

D-3.5. Further Thoughts about Estimating the Oil Security Premiums

As demonstrated by the differences between Benchmark-O and Benchmark-N, elasticities from the newer economics literature suggest lower estimates of the oil security premiums. The estimated premiums for the SVAR-BH, DSGE-S and NEMS modeling exercises are generally consistent with the lower range of estimates from the newer literature. The lower estimates are the result of the newer literature finding that demand is considerably more elastic in the short run and the economy is considerably less vulnerable to the oil price shocks than was found in the newer literature. These newer estimates suggest considerably more flexibility in world oil markets and in the US economy’s ability to cope with the reduced availability of oil. As such, the lower estimates of the oil security premiums based on the newer literature leave unresolved how well such parameters represent how world oil markets and the US economy would respond to a sizable oil supply disruption.

Recognizing that there may be a bias toward accepting the findings of newer research over older, four issues need addressing: 1) Does the newer literature adequately capture how world oil markets and the US economy would respond to large oil supply disruptions? 2) Do reduced US oil imports weaken the response of US real GDP to oil supply disruptions? 3) Does a reduced US oil-to-GDP ratio affect the response of US real GDP to oil supply disruptions? 4) To fully assess the risks of US oil consumption, is it necessary to consider US exposure to foreign oil demand shocks?

D-3.5.1. The Lack of Big Oil Supply Disruptions in the Modern Era

Considering the differences between the current US economy and that of the 1970s, the effects of any oil supply disruptions are likely smaller than was estimated with data from the era in which the big oil supply shocks occurred. Oil consumption has likely become more flexible. The economy is better able to adjust to oil price shocks; consumers and businesses better know the effects of oil supply disruptions and monetary policy is better informed about how to respond to supply disruptions. Underscoring the effects of changes in the economy, Herrera (2016) uses rolling windows to find the elasticity of US real GDP with respect to oil prices declines from the 1990s to the 2010s.

Some of the older literature found that US GDP responded asymmetrically to world oil price shocks—with increased prices having a much bigger negative effect on economic activity than decreased prices having a positive effect on economic activity. Contributions include Mork (1989), Hamilton (1996, 2003), Davis and Haltiwanger (2001) and Balke et al. (2002). The asymmetric specification allowed US GDP to respond strongly to an oil supply disruption.

Since Kilian and Vigfusson (2011a, 2011b) specified a new set of tests for asymmetry and macroeconomic modelers began using newer data sets, however, no peer-reviewed articles have found an asymmetric relationship between oil prices and US GDP.[14] In the newer literature, which is specified with symmetry and relies on data sets that mostly exclude big disruptions, the elasticity of US real GDP with respect to oil price shocks has been much lower.

Huntington (2017) cautions, however, that the world has not seen a major oil supply disruption since 2003, which raises the concern that newer research, which relies on recent data,

[14] Herrera et al. (2015) find that some U.S. industries respond asymmetrically to oil price shocks, but they reject asymmetry in the aggregate.

may not capture the effects of major oil supply disruptions. Big oil supply disruptions may put more stress on economic relationships than the small oil supply disruptions we have seen in recent years, yielding stronger and asymmetric responses. Underscoring this perspective, Van Robays (2016) finds that global economic uncertainty increases the responsiveness of oil prices to oil supply disruptions. Consequently, large oil supply disruptions might generate more inelastic supply and demand responses and a stronger GDP response than would be suggested by models using recent data. The oil security premiums would be better represented by Benchmark-O.

Because we have not observed a modern economy with large oil supply disruptions, we have no reliable method to quantify the effects of these disruptions. Nonlinear models would allow the elasticities to vary with the size of disruptions but would not put any additional observations of large oil supply disruptions into a modern economy. Extending the data used for estimation farther back in time increases the possibility of structural change that is not well captured by the model. The result could be an average of old and new results or estimation problems and a poor fit.

If we consider a world in which the economy responds to small oil supply disruptions in a manner that is well captured by the newer literature and to big supply disruptions in a manner that is better captured by the older literature, we can consider an exercise in which the elasticities used to evaluate the security premiums evolve with the size of the disruptions. We could use elasticities from the newer literature for small oil supply disruptions and elasticities more similar to those found in the older literature for the big oil supply disruptions, with graduated intermediate elasticities to cover the transition from small disruptions to big disruptions. The resulting oil security premiums would lie somewhere between the estimates found with Benchmark-N and those found with Benchmark-O. If we consider the range of estimates that it provides, Benchmark-E might best reflect the uncertainty in what we know about the oil security premiums.

D-3.5.2. Reduced US Oil Imports

From 2005 to 2015, imports declined from 60 percent of US oil consumption to 24 percent. US reliance on oil imports is projected to decline further in the *2016 AEO* (EIA 2016). Because reduced US oil imports are the result of increased US oil production, we see an increase in the share of stable oil supplies in the world oil market, which cushions the price effects of a given disruption. The present analysis captures this effect.

What reduced reliance on oil imports do not do, however, is prevent a global oil price shock from reaching the United States. Because oil is a fungible commodity, the price shocks resulting from supply disruptions elsewhere in the world are transmitted to the US economy without regard to the quantity of oil that is imported. The present analysis incorporates this mechanism.

As the United States moves toward zero net oil imports, however, the losses in the sectors of the economy that are hurt by oil price shocks will be increasingly offset by the gains in the sectors of the economy that benefit from oil price shocks. Brown and Yücel (1995, 2013) have quantified these effects at the state level. Balke and Brown (2016) show that reducing the share of US oil imports below recent historical averages can substantially weaken the response of US real GDP to oil prices, and Peersman and Van Robays (2012) show that oil import dependence plays an important role in cross-country differences in the response to oil price shocks. Such effects are beyond the present analysis.

D-3.5.3. A Reduced Oil-to-GDP Ratio

From 1973 to 2015, the US oil-consumption-to-GDP ratio has declined by more than 60 percent. Examining eight OECD counties, Brown et al. (1996) found preliminary evidence that oil-importing countries with higher oil-to-GDP ratios faced more difficult trade-offs in inflation and GDP losses in response to oil price shocks than oil importing countries with lower oil-to-GDP ratios. Similarly, Bastianin et al. (2017) find that the effects of oil price shocks increase with energy dependence for Mediterranean countries in the European Union. Although such research suggests that a reduced oil-to-GDP ratio could weaken the response of the US economy to oil price shocks, the author is not aware of any peer-reviewed empirical research that shows such an effect for the United States.

D-3.5.4. Foreign Oil Demand Shocks

Oil security premiums rely on estimates of the price effects of world oil supply disruptions, but do not take into account probable foreign demand shocks. Identifying foreign oil demand shocks as an external security cost of oil consumption does not seem appropriate. Unless there is a Fukushima-like event that shifts Japanese electric power generation from nuclear power plants to those that are oil-fired, unexpected growth in global oil demand is not likely to yield sudden oil price movements because oil demand changes slowly. There also seems to be no reason to be more concerned about the effects of international business cycles affecting the US economy through variations in oil demand than any other channel through which business cycles are transmitted.

D-4. Evaluating Policy with the Oil Security Premiums

Ultimately, the purpose of estimating the security costs of US dependence on oil consumption is to provide guidance for energy policy. The differing assumptions made about the elasticities can lead to substantially different estimates of the costs of US dependence on oil. The range of estimates are consistent with relatively little intervention in US oil markets or considerably more intervention, although the newer estimates mostly suggest relatively little intervention.

For Benchmark-O, the mid estimate of the oil security premium for US consumption of imported oil averages $6.92 per barrel from 2015 to 2040 (7.2 percent of the average world oil price over the same time period) in a range of $1.47 to $20.03 per barrel. For Benchmark-E, the mid estimate averages $4.83 per barrel from 2015 to 2040 (5.0 percent of the average world oil price over the same time period) in a range of $0.40 to $15.60 per barrel. For Benchmark-N, the mid estimate averages $1.64 per barrel from 2015 to 2040 (1.7 percent of the average world oil price over the same time period) in a range of $0.77 to $4.50 per barrel. The respective mean estimates for the SVAR-BH, DSGE-S and NEMS models are $1.12, $0.39 and $0.94 per barrel in respective ranges of $0.25 to $4.84, $0.28 to $0.54 and $0.60 to $1.27.

For Benchmark-O, the mid estimate of the oil security premium for US consumption of domestic oil averages $5.36 per barrel from 2015 to 2040 (5.6 percent of the average world oil price over the same time period) in a range of $1.10 to $15.73. For Benchmark-E, the mid estimate is $3.70 per barrel from 2015 to 2040 (3.9 percent of the average world oil price over the same time period) in a range of $0.29 to $12.21. For Benchmark-N, the mid estimate is $1.25 per barrel from 2015 to 2040 (1.3 percent of the average world oil price over the same time period) in a range of $0.58 to $3.46. The respective mean estimates for the SVAR-BH, DSGE-S and NEMS models are $0.86, $0.28 and $0.72 per barrel in respective ranges of $0.19 to $3.76, $0.20 to $0.40 and $0.46 to $0.97.

For Benchmark-O, the mid estimate of the oil security premium for the substitution of imported oil for domestic oil averages $1.56 per barrel from 2015 to 2040 (1.6 percent of the average world oil price over the same time period) in a range of $0.37 to $4.30. For Benchmark-E, the mid estimate is $1.13 per barrel from 2015 to 2040 (1.2 percent of the average world oil price over the same time period) in a range of $0.11 to $3.41. For Benchmark-N, the mid estimate is $0.39 per barrel from 2015 to 2040 (0.4 percent of the average world oil price over the same time period) in a range of $0.19 to $1.04. The respective mean estimates for the SVAR, DSGE and NEMS models are \$0.26, \$0.11 and \$0.22 per barrel in respective ranges of \$0.06 to \$1.08, \$0.08 to \$0.14 and \$0.15 to \$0.30.

No survey has yet provided a comprehensive review of the environmental costs of US oil use, but the National Research Council (2009) and Parry et al. 2014 provide fairly complete and recent assessments. Brown and Huntington (2015) combined estimates from a number of sources (such as Hall 1990, 2004; Fankhauser 1994; National Research Council 2009; Johnson and Hope 2012; US Interagency Working Group 2013; and Parry et al. 2014) to provide illustrative estimates of the environmental costs of US oil use. As shown in Table D-12, the resulting estimates include the social costs of local pollution and the CO_2 emissions that result from US oil consumption.[15]

The upper ranges of the oil security estimates from Benchmark-O and Benchmark-E put the costs of US reliance on imported oil or domestic oil close to the environmental costs of US oil use. In contrast, the mid and lower ranges of Benchmark-O and Benchmark-E and the estimates from Benchmark-N and the SVAR-BH, DSGE-S and NEMS models provide security cost estimates for US consumption of imported oil that are important but considerably lower than the environmental costs. Although the security costs of domestic oil consumption are lower, the mid estimates from Benchmark-O and Benchmark-E find that US consumption of domestic oil yields important security costs. Reliance on imported oil over domestic oil has a small security cost.

Taken together, the estimated costs of US oil dependence and the environmental costs of US oil consumption suggest the possibility of some tension in the development of US policy toward oil consumption, oil imports and domestic oil production. At one extreme, some policymakers and analysts will see US oil security as nearly an equally important issue to the environmental costs of oil use. At another extreme, some policymakers and analysts will think that US oil policy ought to focus on the environmental costs of oil use rather than the rather low security costs.

Although the policymakers and analysts may not focus on the elasticity assumptions that underlie the different estimates of the oil security premiums, the estimates depend greatly on these assumptions. Flexibility in world oil consumption, world oil production and in the US

[15] The estimated costs associated with CO_2 emissions are highly uncertain and are likely to be significantly revised by future studies. It also should be noted that a focus on the environmental costs of U.S. oil consumption abstracts from the possibility that the environmental effects associated with the production and transportation of imported and domestic oil may differ from each other.

economy's ability to cope with reduced oil supplies is critical to the low estimates of the oil security premiums. If the world oil market and the US economy are not as flexible as the newer elasticities indicate, the price shocks and economic losses will be greater. Larger oil supply disruptions, which are mostly outside the estimation range of the newer models, may put more stress on economic relationships than the small oil supply disruptions we have seen in recent years, yielding stronger responses.

D-5. Concluding Remarks

A fair amount of previous work addresses the non-environmental costs of US oil consumption with much of it taking the approach that these costs exceed the market price paid for the oil. The current work has taken the oil security approach (developed by Brown and Huntington, 2013) to estimate the non-environmental costs of US consumption of imported oil, US consumption of domestic oil and the substitution of imported oil for domestic oil from 2015 to 2040.

The oil security premiums for U.S consumption of imported and domestic oil includes only two components: the change in the expected GDP loss and the change in the expected transfers for the inframarginal barrels of imported oil that result from an oil supply disruption. Under this approach, the monopsony premium and the expected transfers on the marginal barrel of imported oil are excluded because they are not true externalities. The oil security premium for the substitution of imported oil for domestic oil is the difference between the premiums for the consumption of imported oil and the consumption of domestic oil.

A computational model based on a welfare-theoretic approach is used to evaluate six different sets of parameter values with the reference case projections for world oil market conditions in the *2016 AEO* (EIA 2016). Three sets of parameter values are taken from surveys of the economics literature. Benchmark-O represents the older literature in which oil demand is less elastic and GDP is more sensitive to oil price shocks; Benchmark-N represents the newer literature in which oil demand is more elastic and GDP is less sensitive to oil price shocks; and Benchmark-E takes an evolutionary approach by combining the old and new literature. The other three sets of parameters are from new macroeconomic modeling efforts to examine the relationship between oil supply shocks and US economic activity including an SVAR model, a DSGE model and runs of NEMS.

Changes in world oil market conditions from those expected a few years ago—such as increased US oil production—mean smaller expected oil price shocks, weaker expected effects of US GDP and smaller expected transfers on inframarginal oil imports, which contribute to somewhat smaller estimates of oil security premiums. The newer literature also suggests world oil demand is more elastic and that US real GDP is less responsive to oil price shocks than was previously thought, and these new elasticities contribute to considerably smaller oil security premiums. The elasticities and estimated premiums for SVAR, DSGE and NEMS modeling efforts are consistent with the lower range of values found with elasticities from the newer literature.

Although the SVAR, DSGE and NEMS modeling efforts yield results that are consistent with estimates that reflect Benchmark-N and the lower range of Benchmark-E, there is concern that these newer estimates better capture the market response and macroeconomic effects of the smaller oil supply disruptions that have occurred in recent years than the big oil supply disruptions that occurred in the 1970s and 1980s. The world oil market may have become more flexible and the US economy's flexibility in responding to oil price shocks likely has increased as people better understand and are better able to cope with oil supply disruptions and monetary policy is better informed about how to respond to supply disruptions. But, big oil supply disruptions are likely to put more stress on economic relationships than the small oil supply disruptions seen in recent years.

Nonetheless, only the highest estimates of the oil security premiums suggest that US oil security is nearly an equally important issue to the environmental costs of oil use. The mid estimates from the model that may best represent how the world oil market and the US economy will respond to world oil supply disruptions of various sizes (Benchmark-E) find US consumption of imported or domestic oil does yield important security costs, but those costs are much lower than the estimated environmental costs of oil use. Consistent with Brown and Huntington (2013), the substitution of domestic oil for imported oil only slightly improves US oil security. Oil conservation is more effective than increased domestic oil production at improving US oil security.

D-6. References

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D-7. Tables and Figures

Table D-1. Oil Security Premium Concepts

	Imports	Domestic
Monopsony Premium	Not a security issue Not an externality	Not applicable
Expected Price Shock for Purchaser of Marginal Imports	Not an externality	Not applicable
Change in Expected Transfers for Other Purchasers	An externality	An externality
Change in Expected GDP Losses	An externality	An externality
Environmental Externalities	Externalities, but not a security issue	Externalities, but not a security issue

Note: The traditional oil import premium is the sum of the differences between the premiums for imported and domestic oil.

Table D-2. Developing the Oil Premium Measures

	Imports	Domestic	Imports vs. Domestic
A. Monopsony Premium	computed as described in text	no value	A Imports minus A domestic
B. Expected Price Shock for Purchaser of Marginal Imports	computed as described in text	no value	B Imports minus B domestic
C. Change in Expected Transfers for Other Purchasers	computed as described in text	computed as described in text	C Imports minus C domestic
D. Change in Expected GDP Losses	computed as described in text	computed as described in text	D Imports minus D domestic
Oil Security Premiums C+D	C+D Imports	C+D Domestic	C+D Imports minus Domestic
Traditional Oil Premiums A+B+C+D	A+B+C+D Imports	A+B+C+D Domestic	A+B+C+D Imports minus Domestic

Table D-3. World Oil Market Conditions and US GDP

	Projections for 2013-14*	2014 Actual
World Oil Price (2015 US Dollars per barrel)	$116.62	$100.04
World Oil Consumption (million barrels per day)	90	92.79
Non-US Oil Consumption (million barrels per day)	69	73.63
Non-US Oil Production (million barrels per day)	80	78.78
US Oil Consumption (million barrels per day)	19	19.16
US Oil Production (million barrels per day)	10	14.01
US Oil Imports (million barrels per day)	9	5.15
US GDP (2015 US Dollars)	$16.954 trillion	$17.580 trillion

Sources: US Energy Information Administration; US Bureau of Economic Analysis; *EIA (2012) *2012 Annual Energy Outlook*; Author's calculations.

Table D-4. Sizes and Annual Probabilities of Disruptions

Disruption Size (million barrels per day)	Annual Probability 2005 Estimates	Annual Probability 2016 Estimates
0	0.843908554	0.899581023
1	0.030919163	0.003688530
2	0.032529155	0.012149011
3	0.045339487	0.015030933
4	0.002158576	0.016455510
5	0.007761138	0.009781145
6	0.010281493	0.008760577
7	0.010911735	0.010478909
8	0.007640165	0.008013227
9	0.001080596	0.004992078
10	0.001564854	0.002588981
11	0.001180577	0.003115885
12	0.001732513	0.002128716
13	0.000830936	0.000866718
14	0.000511190	0.000882371
15	0.000986074	0.000464093
16	0.000119553	0.000527113
17	0.000132331	0.000134663
18	–	0.000106642
19	–	0.000124019
20	–	0.000024215
21	–	0.000105641

Source: Adapted from Beccue and Huntington (2005 and 2016).
Note: 2005 estimates are based on non-US oil production of 80 million barrels per day. 2016 estimates are based on non-US oil production of 78.78 million barrels per day.

Table D-5. Price, Income and GDP Elasticities

Type	Older Values	Newer Values	Evolutionary Values
Short-Run Price Elasticity of Supply	0.05 0.025 to 0.075	0.05 0.025 to 0.075	0.05 0.025 to 0.075
Short-Run Price Elasticity of Demand	–0.055 –0.02 to –0.09	–0.0175 –0.1 to –0.25	–0.055 –0.02 to –0.25
Income Elasticity of Demand	0.70 0.55 to 0.75	0.70 0.55 to 0.75	0.70 0.55 to 0.75
Elasticity of US GDP with Respect to Oil Price Shocks	–0.044 –0.012 to –0.078	–0.018 –0.006 to –0.029	–0.028 –0.006 to –0.051
Long-Run Price Elasticity of Supply	0.4 0.35 to 0.45	0.4 0.35 to 0.45	0.4 0.35 to 0.45
Long-Run Price Elasticity of Demand	–0.4 –0.35 to –0.45	–0.4 –0.35 to –0.45	–0.4 –0.35 to –0.45

Source: Brown and Huntington (2013); Author's updates

Table D-6. Response of US Real GDP to Oil Price Shocks

Reference	Elasticity
Econometric Studies (Jones et al. 2004)	–0.012 to –0.12
Leiby (2008) Described Range	–0.01 to –0.08
Energy Modeling Forum (Hickman et al. 1987)	–0.02 to –0.075
US Department of Energy (Jones et al. 2004)	–0.025 to –0.055
Leiby (2008) Analysis Range	–0.035 –0.010 to –0.054
Brown and Huntington (2013) Analysis Range	–0.044 –0.012 to –0.078
Newer Estimates	–0.018 –0.006 to –0.029
Evolutionary Estimates	–0.028 –0.006 to –0.051

Sources: Brown and Huntington (2013); Author's updates

Table D-7. Components of the Oil Security Premiums, 2014 (2015 US Dollars per Barrel)

Model	Change in Expected GDP Loss		Change in Expected Transfers on Inframarginal Oil Imports	
	Marginal Consumption of Imported Oil	Marginal Consumption of Domestic Oil	Marginal Consumption of Imported Oil	Marginal Consumption of Domestic Oil
Brown-Huntington (2015)	$5.31 $1.12 to $15.42	$4.06 $0.86 to $11.85	$0.11 $0.07 to $0.28	–$0.89 –$0.60 to –$2.25
Benchmark-O	$5.21 $1.10 to $15.07	$3.96 $0.84 to $11.53	$0.06 $0.04 to $0.16	–$0.35 –$0.24 to –$0.89
Benchmark-N	$1.23 $0.58 to $3.39	$0.93 $0.44 to $2.57	$0.03 $0.02 to $0.06	–$0.15 –$0.10 to -0.33
Benchmark-E	$3.63 $0.30 to $11.75	$2.75 $0.22 to $8.97	$0.07 $0.02 to $0.24	–$0.41 –$0.10 to –$1.35

Sources: Model Estimates

Table D-8. Aggregate Oil Security Premiums, 2014 (2015 US Dollars per Barrel)

Model	Consumption of Imported Oil	Consumption of Domestic Oil	Imported vs. Domestic Oil
Brown-Huntington (2015)	$5.43 $1.20 to $15.70	$3.17 $0.26 to $9.60	$2.26 $0.94 to $6.10
Benchmark-O	$5.28 $1.15 to $15.22	$3.60 $0.60 to $10.63	$1.68 $0.55 to $4.59
Benchmark-N	$1.26 $0.60 to $3.45	$0.78 $0.34 to $2.24	$0.48 $0.26 to $1.21
Benchmark-E	$3.70 $0.31 to $11.99	$2.34 $0.12 to $7.62	$1.36 $0.19 to $4.37

Sources: Model Estimates

Table D-9. Price, Income and GDP Elasticities from the Individual Models

Model	Short-Run Price Elasticity of World Supply	Short-Run Price Elasticity of World Demand	US Income Elasticity of Demand	Elasticity of US GDP with Respect to Oil Price Shocks
Benchmark-O	0.05 0.025 to 0.075	–0.055 –0.02 to –0.09	0.7 0.55 to 0.075	–0.044 –0.012 to –0.078
Benchmark-N	0.05 0.025 to 0.075	–0.175 –0.01 to –0.25	0.7 0.55 to 0.075	–0.018 –0.006 to –0.029
Benchmark-E	0.05 0.025 to 0.075	–0.055 –0.02 to –0.25	0.7 0.55 to 0.075	–0.028 –0.006 to –0.051
SVAR-BH	0.1526 0.0618 to 0.3162	–0.3554 –0.1797 to –0.7722		–0.0274 –0.0127 to –0.0623
DSGE-S	0.0582 0.0494 to 0.0736	–0.3328 –0.2808 to –0.4228		–0.007 –0.0064 to –0.0084
NEMS	0.2313 0.2129 to 0.2386	–0.2094 –0.2052 to –0.2123	0.8	–0.0197 –0.0128 to –0.0255

Sources: Table 5; Herrera (2016); Balke and Brown (2016); Mohan (2016); Author's Calculations

Table D-10. Components of the Oil Security Premiums, 2015-40 Average (2015 US Dollars per Barrel)

Model	Change in Expected GDP Loss		Change in Expected Transfers on Inframarginal Oil Imports	
	Marginal Consumption of Imported Oil	Marginal Consumption of Domestic Oil	Marginal Consumption of Imported Oil	Marginal Consumption of Domestic Oil
Benchmark-O	$6.91 $1.46 to $20.01	$5.42 $1.14 to $15.81	$0.01 $0.01 to $0.02	–$0.07 –$0.05 to –$0.08
Benchmark-N	$1.63 $0.77 to $4.49	$1.28 $0.60 to $3.52	$0.01 $0.00 to $0.01	–$0.03 –0.02 to –0.06
Benchmark-E	$4.81 $0.39 to $15.60	$3.77 $0.31 to $12.30	$0.01 $0.00 to $0.02	–$0.07 –$0.02 to –$0.09
SVAR-BH	$1.12 $0.25 to $4.84	$0.88 $0.20 to $3.79	$0.00 $0.00 to $0.01	–$0.01 –$0.00 to –$0.03
DSGE-S	$0.38 $0.28 to $0.54	$0.30 $0.22 to $0.42	$0.00 $0.00 to $0.00	–$0.01 –$0.01 to –$0.02
NEMS	$0.94 $0.60 to $1.26	$0.73 $0.47 to $0.99	$0.00 $0.00 to $0.00	–$0.02 –$0.02 to –$0.02

Source: Model Estimates

Table D-11. Aggregate Oil Security Premiums, 2015-40 Average (2015 US Dollars per Barrel)

Model	Consumption of Imported Oil	Consumption of Domestic Oil	Imported vs. Domestic Oil
Benchmark-O	$6.92 $1.47 to $20.03	$5.36 $1.10 to $15.73	$1.56 $0.37 to $4.30
Benchmark-N	$1.64 $0.77 to $4.50	$1.25 $0.58 to $3.46	$0.39 $0.19 to $1.04
Benchmark-E	$4.83 $0.40 to $15.62	$3.70 $0.29 to $12.21	$1.13 $0.11 to $3.41
SVAR-BH	$1.12 $0.25 to $4.84	$0.86 $0.19 to $3.76	$0.26 $0.06 to $1.08
DSGE-S	$0.39 $0.28 to $0.54	$0.28 $0.20 to $0.40	$0.11 $0.08 to $0.14
NEMS	$0.94 $0.60 to $1.27	$0.72 $0.46 to $0.97	$0.22 $0.15 to $0.30

Source: Model Estimates

Table D-12. Environmental Costs of US Oil Use (2015 US Dollars per Barrel)

Source	Environmental Costs other than for CO_2 Emissions	Costs of CO_2 Emissions
Hall (1990, 2004)	\$20.22	\$2.61
Fankhauser (1994)	n.a.	\$4.60 \$1.49 to \$10.67
National Research Council (2009)	\$16.79	median \$5.23 mean \$15.68 \$0.52 to \$44.42
Johnson and Hope (2012)	n.a.	\$30.58 to \$63.03
US Interagency Working Group (2013)	n.a.	\$16.32
Parry, Heine, Lis and Li (2014)	\$12.11	\$16.46

Sources: Adapted from Brown and Huntington (2015).
Note: n.a. = not applicable

Figure D-1. World Oil Prices

Figure D-2. Oil Price Shocks Precede US Recessions

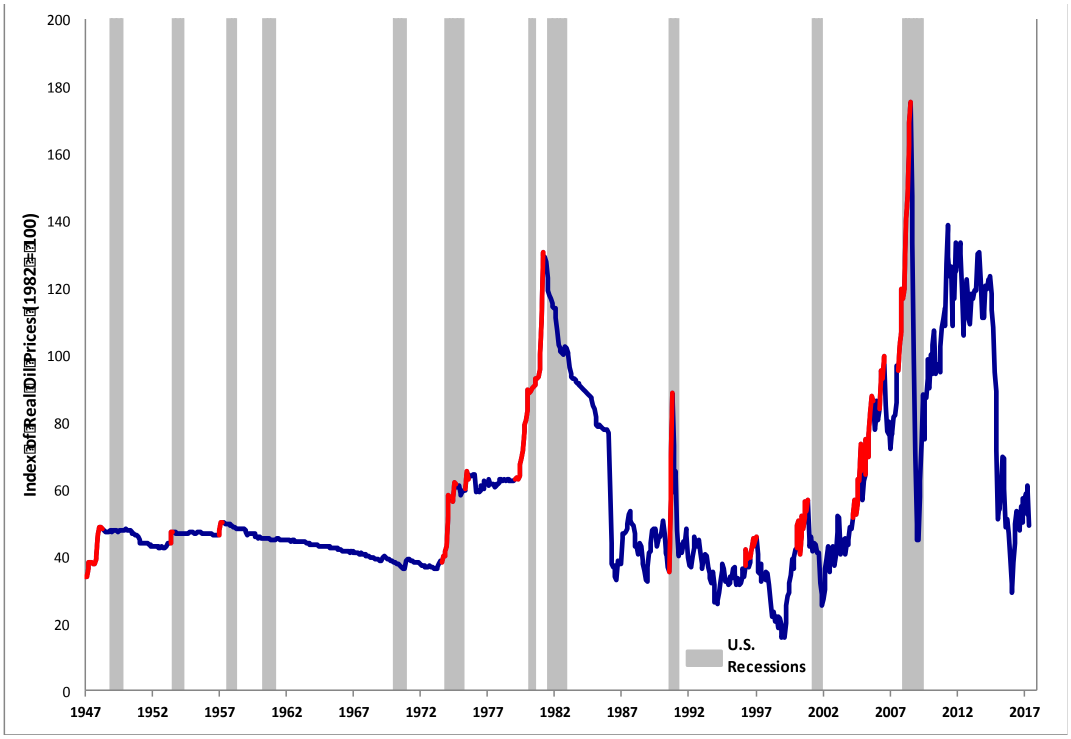


Figure D-3. Components of the Oil Security Premiums (2015-2040 Average)

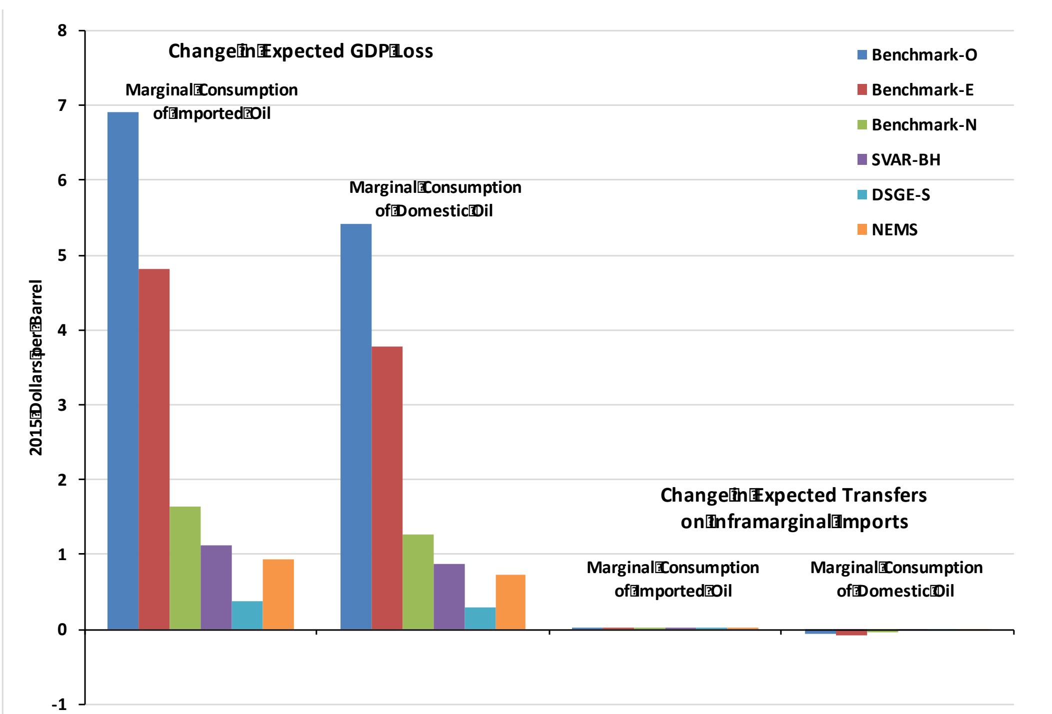


Figure D-3a. Change in Expected GDP Loss for Marginal Change in Imported Oil Consumption (2015-2040 Average)

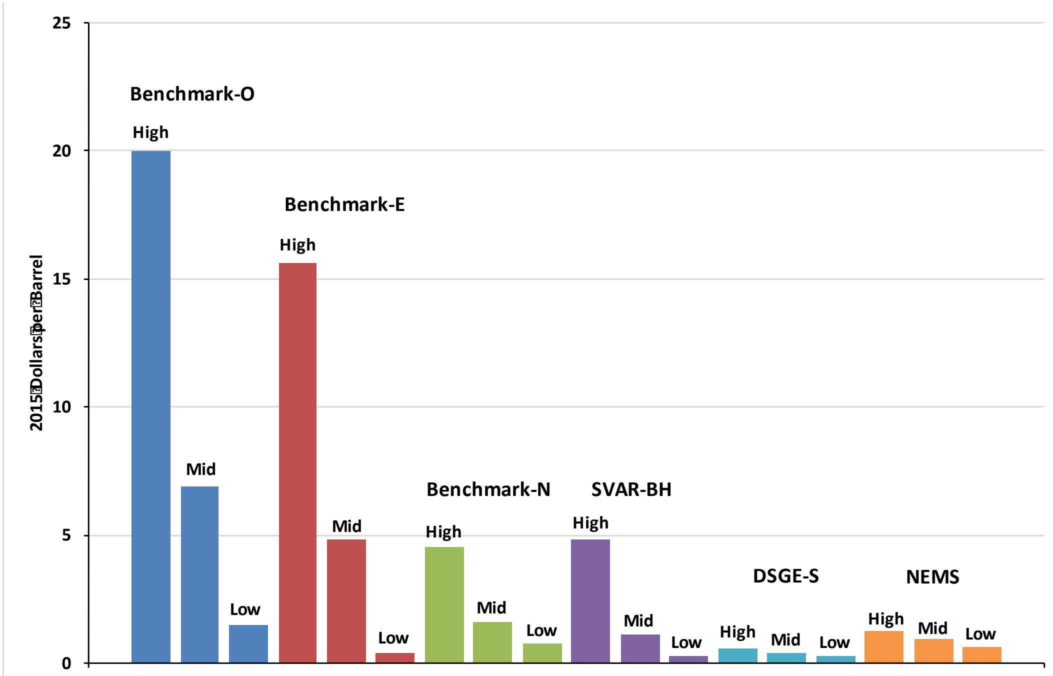


Figure D-3b. Change in Expected GDP Loss for Marginal Change in Domestic Oil Consumption (2015-2040 Average)

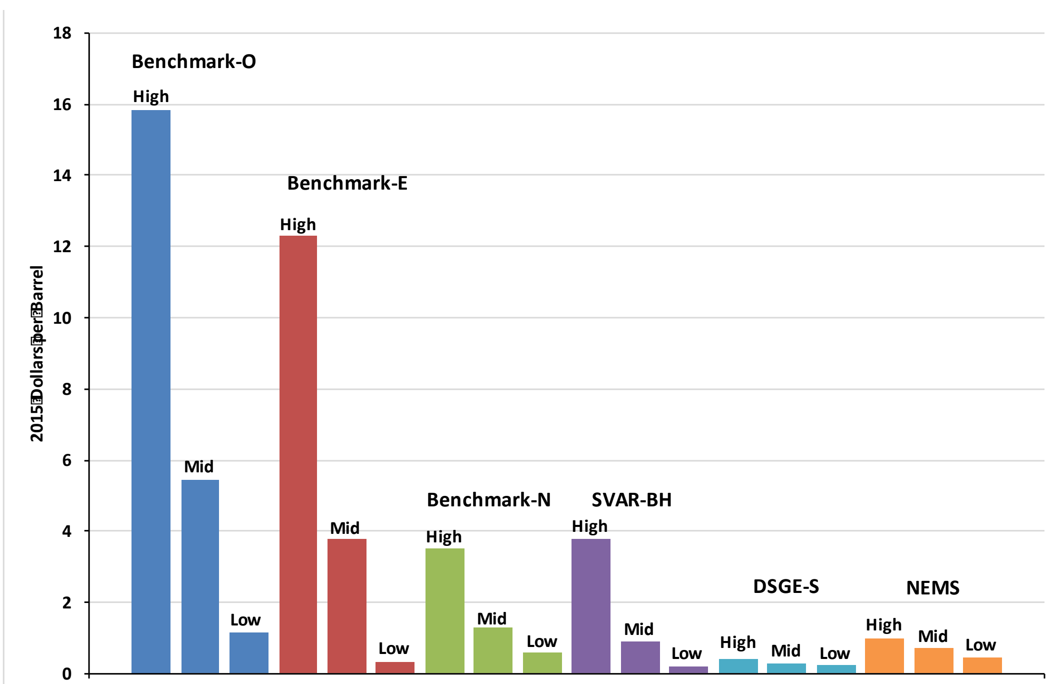


Figure D-3c. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Imported Oil Consumption (2015-2040 Average)

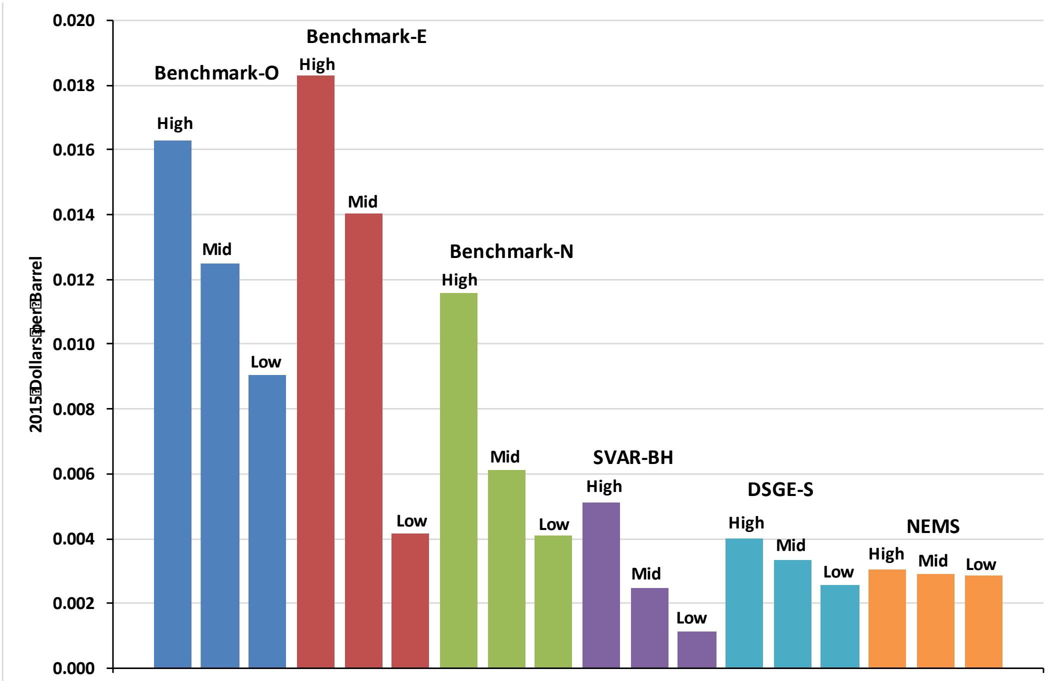


Figure D-3d. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Domestic Oil Consumption (2015-2040 Average)

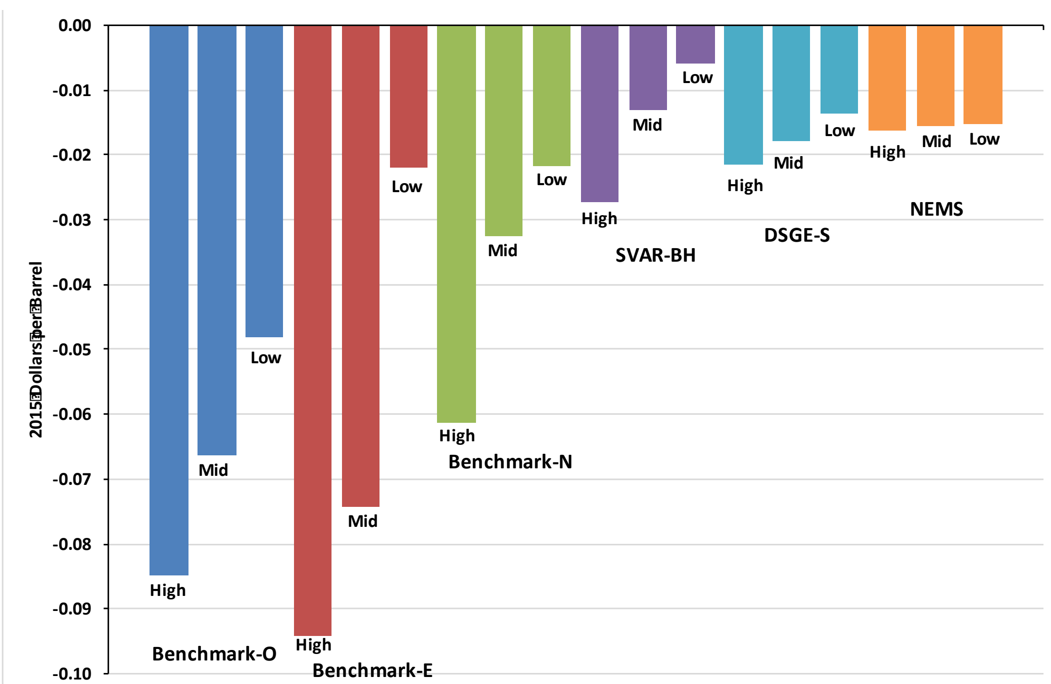


Figure D-4. Expected Oil Price Shock (2015-2040 Average)

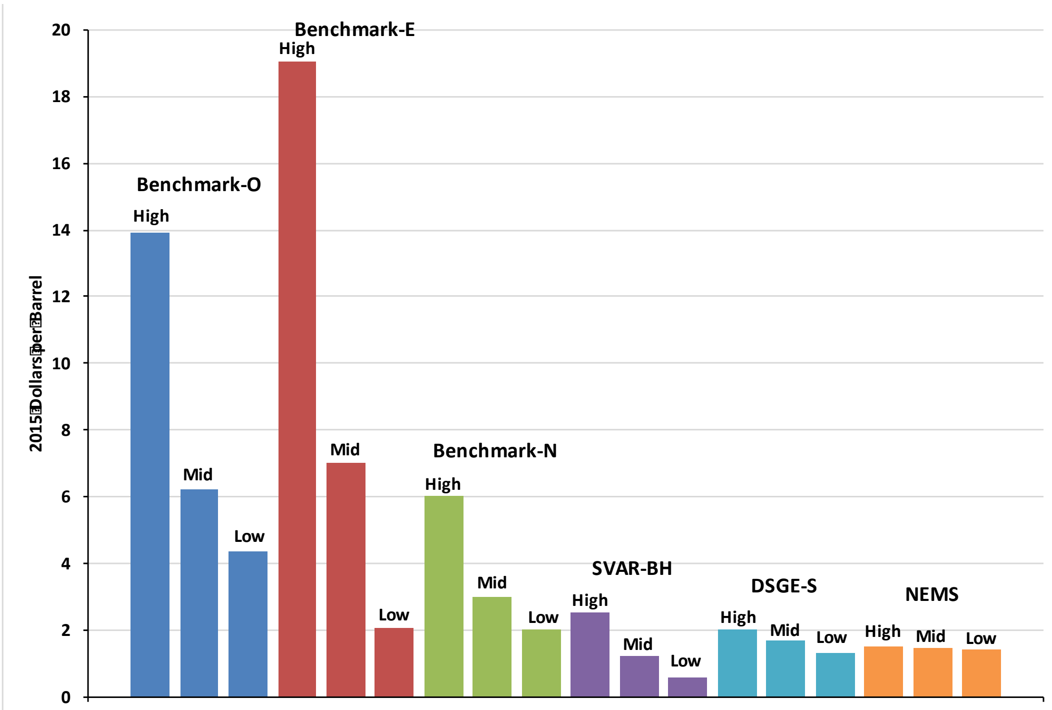


Figure D-5. Oil Security Premiums (2015-2040 Average)

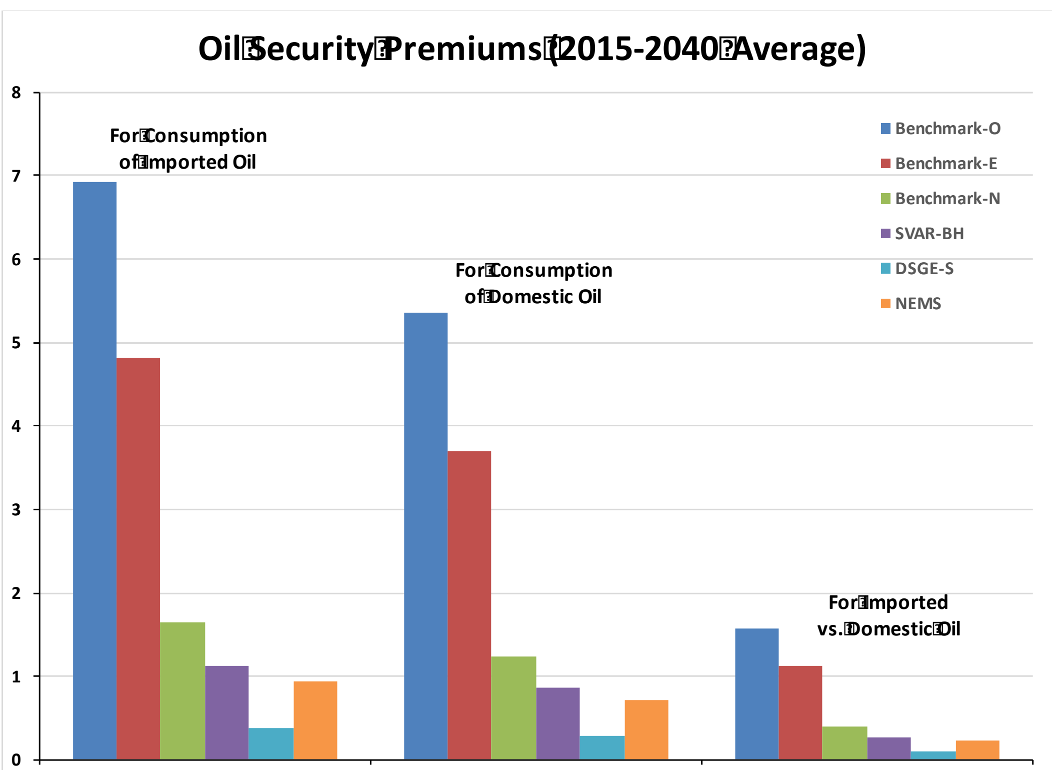


Figure D-5a. Oil Security Premiums for Marginal Change in Imported Oil Consumption (2015-2040 Average)

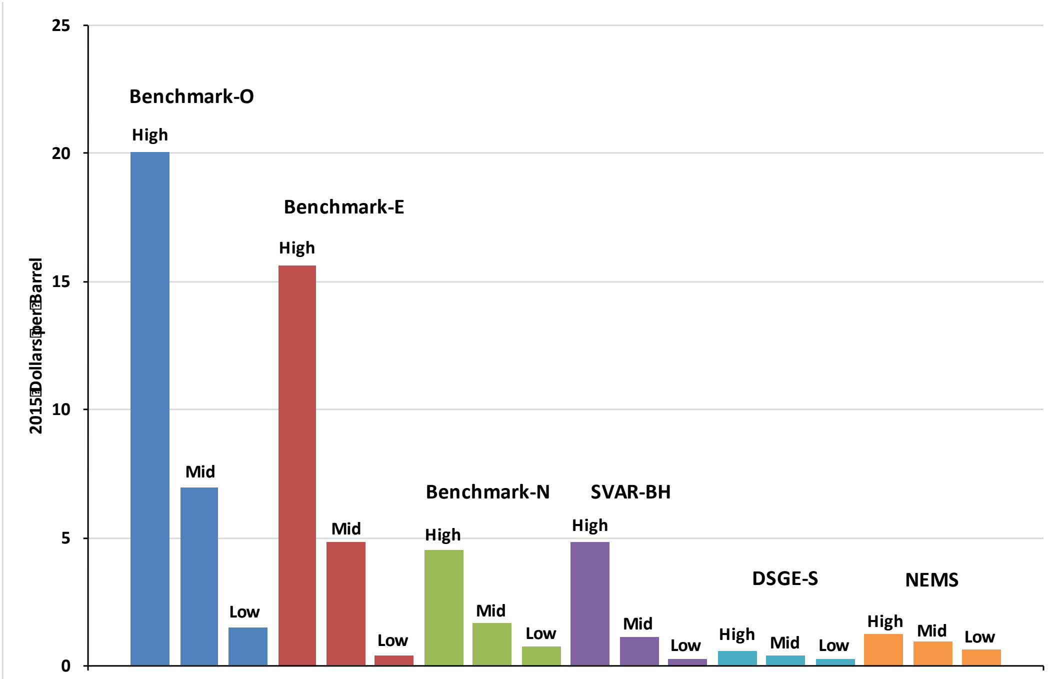


Figure D-5b. Oil Security Premiums for Marginal Change in Domestic Oil Consumption (2015-2040 Average)

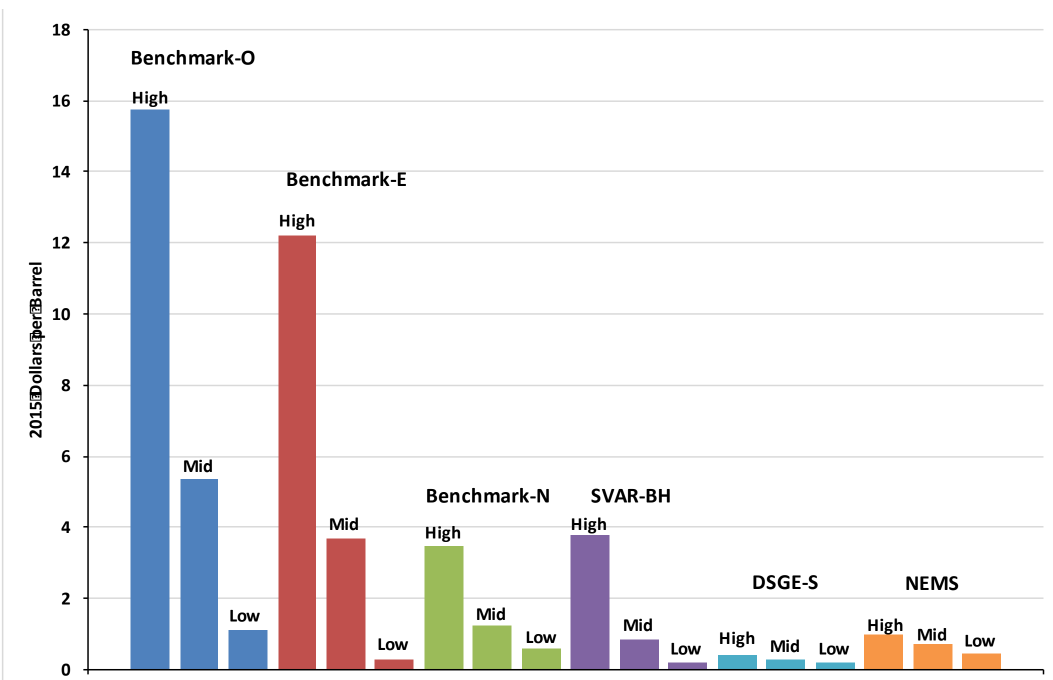


Figure D-5c. Oil Security Premiums for Imported vs. Domestic Oil (2015-2040 Average)

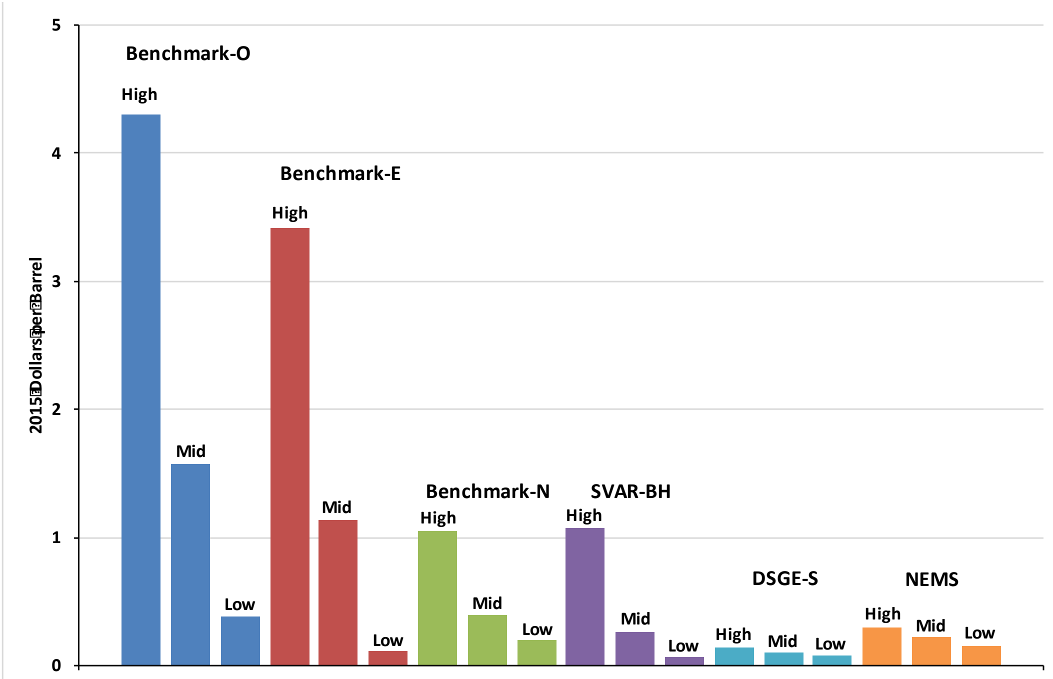


Figure D-6. Change in Expected GDP Loss for Marginal Change in Imported Oil Consumption

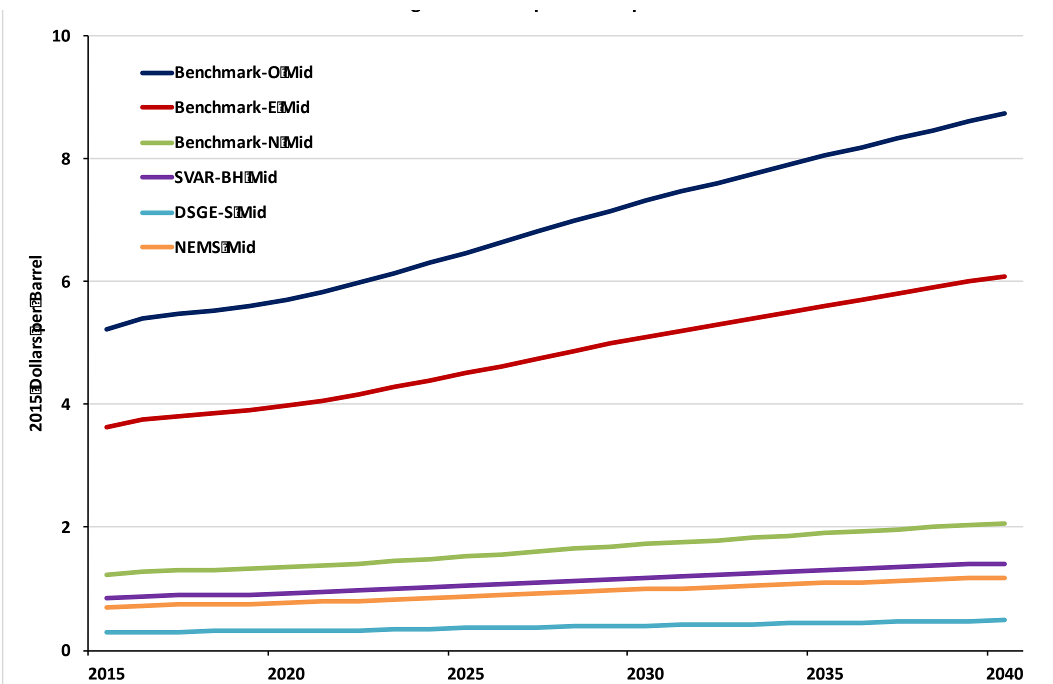


Figure D-6a. Change in Expected GDP Loss for Marginal Change in Imported Oil Consumption

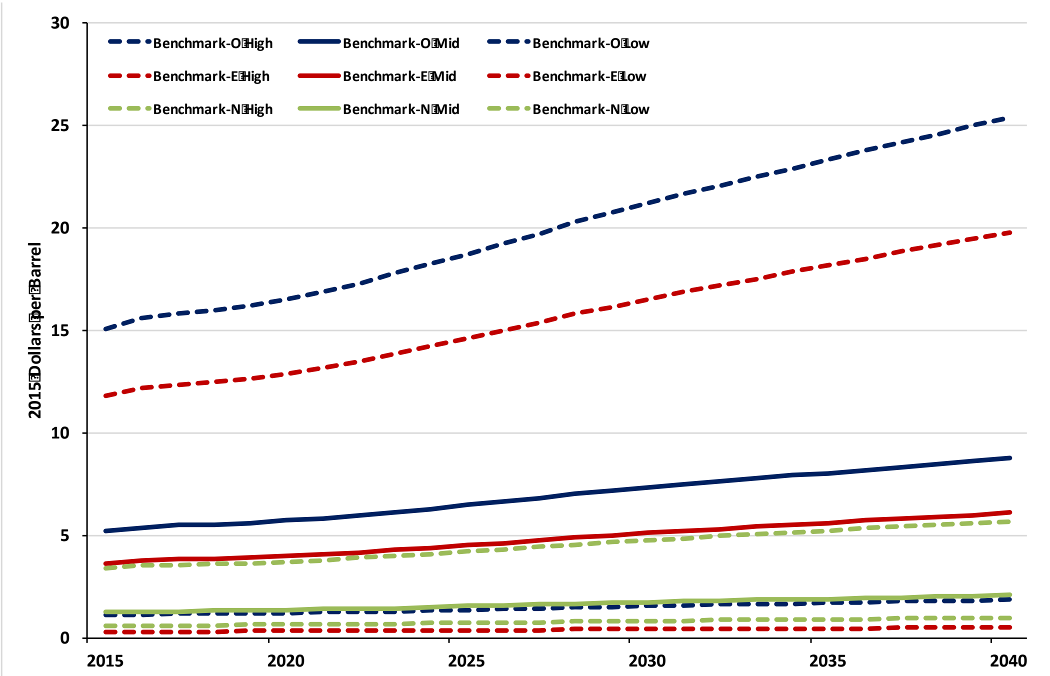


Figure D-6b. Change in Expected GDP Loss for Marginal Change in Imported Oil Consumption

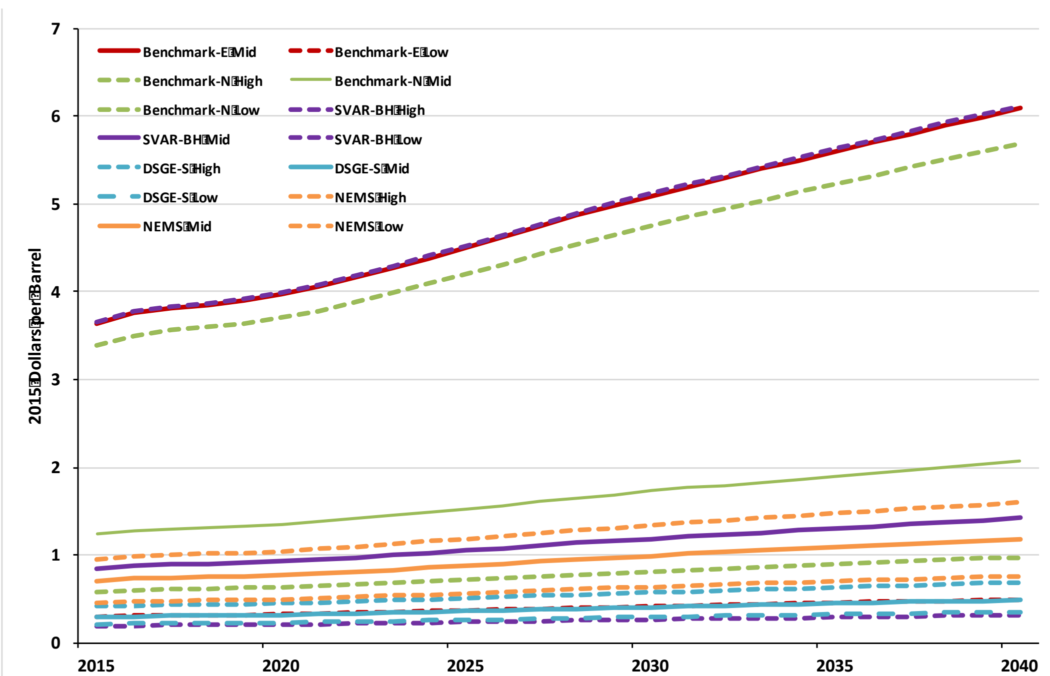


Figure D-7. Change in Expected GDP Loss for Marginal Change in Domestic Oil Consumption

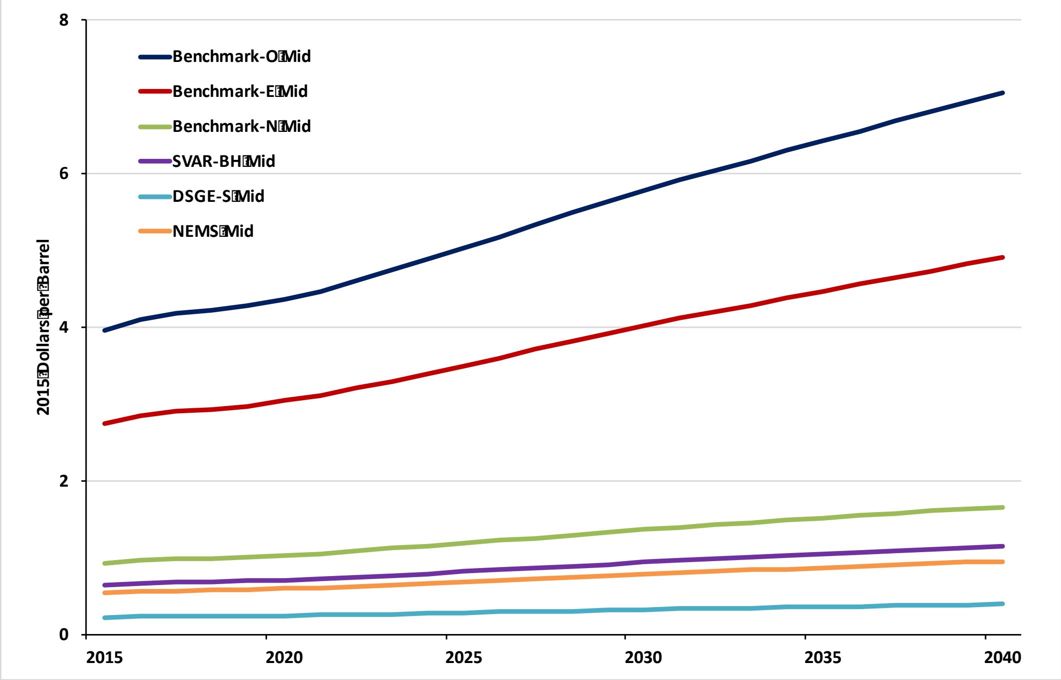


Figure D-7a. Change in Expected GDP Loss for Marginal Change in Domestic Oil Consumption

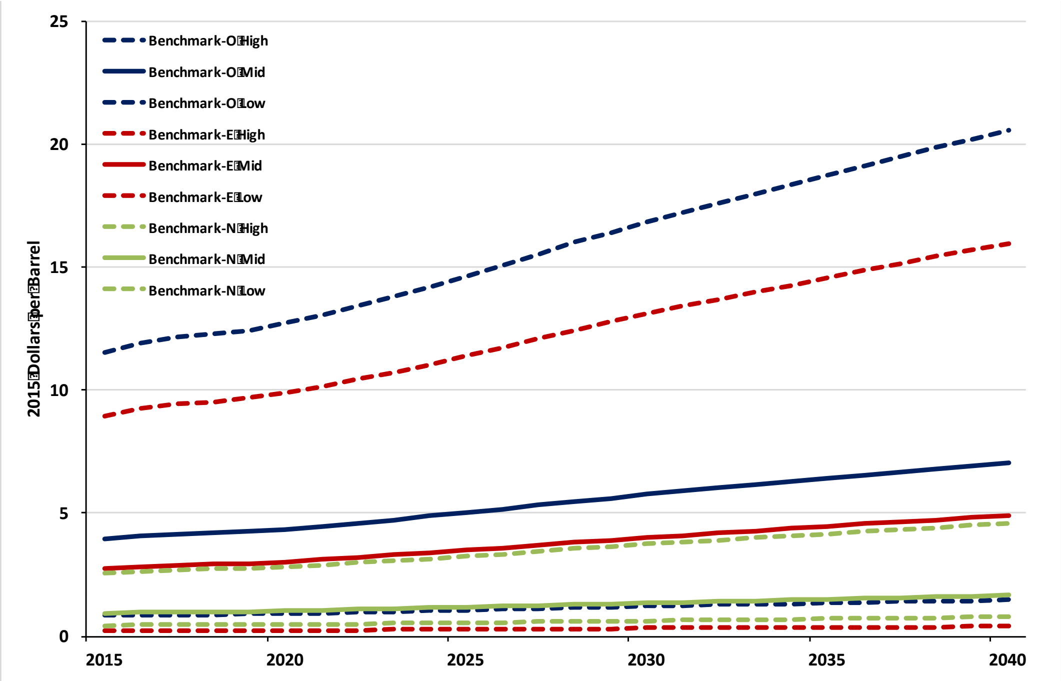


Figure D-7b. Change in Expected GDP Loss for Marginal Change in Domestic Oil Consumption

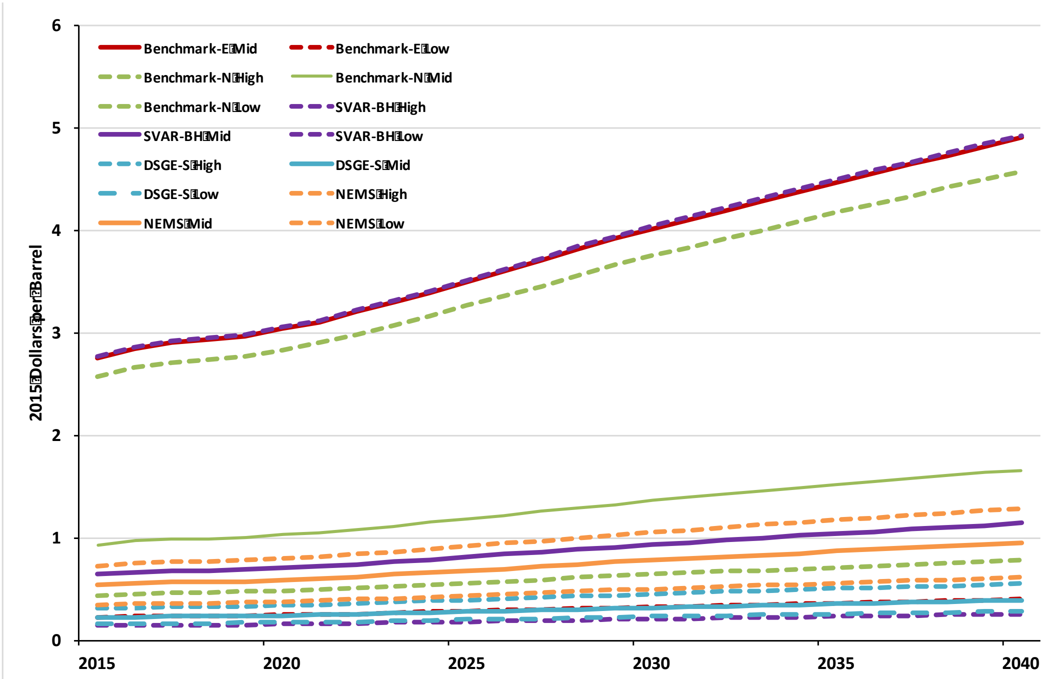


Figure D-8. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Imported Oil Consumption

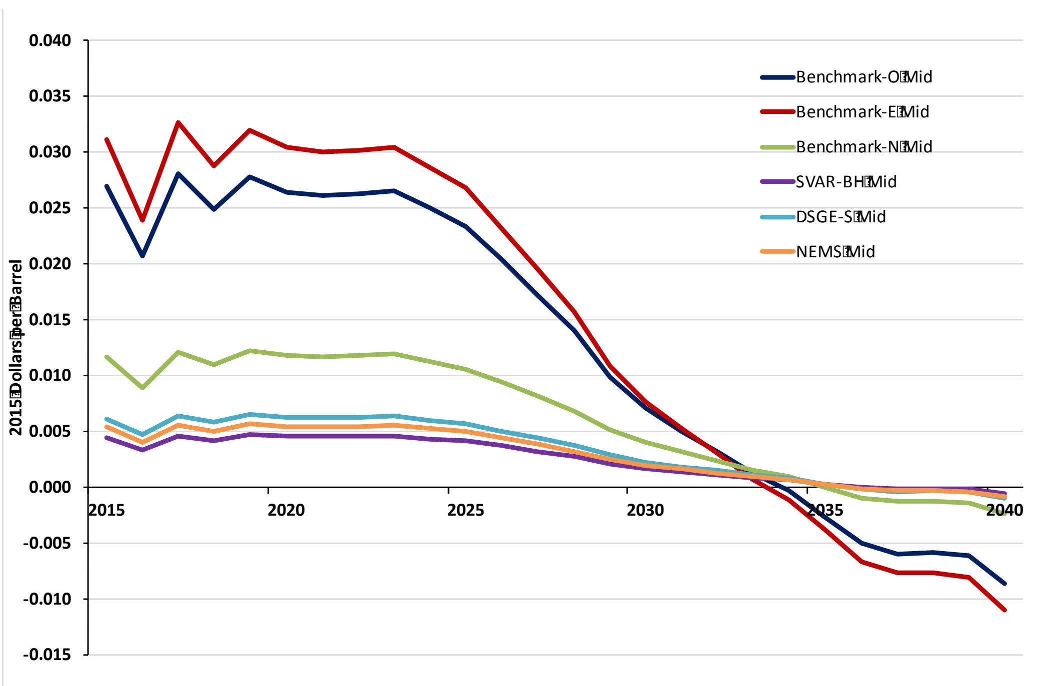


Figure D-8a. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Imported Oil Consumption

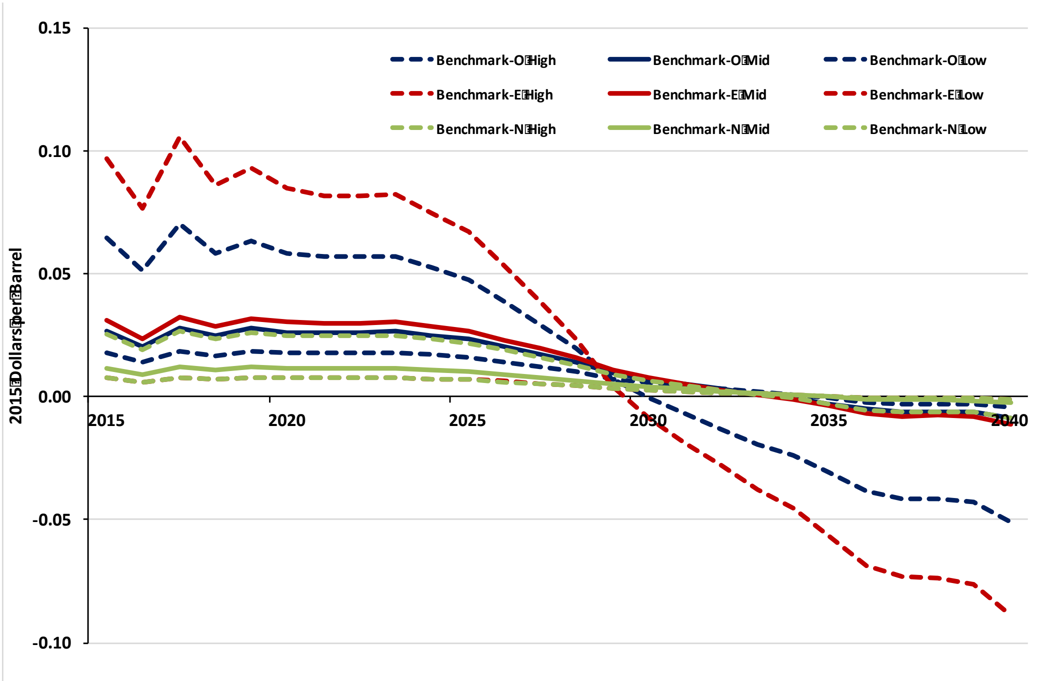


Figure D-8b. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Imported Oil Consumption

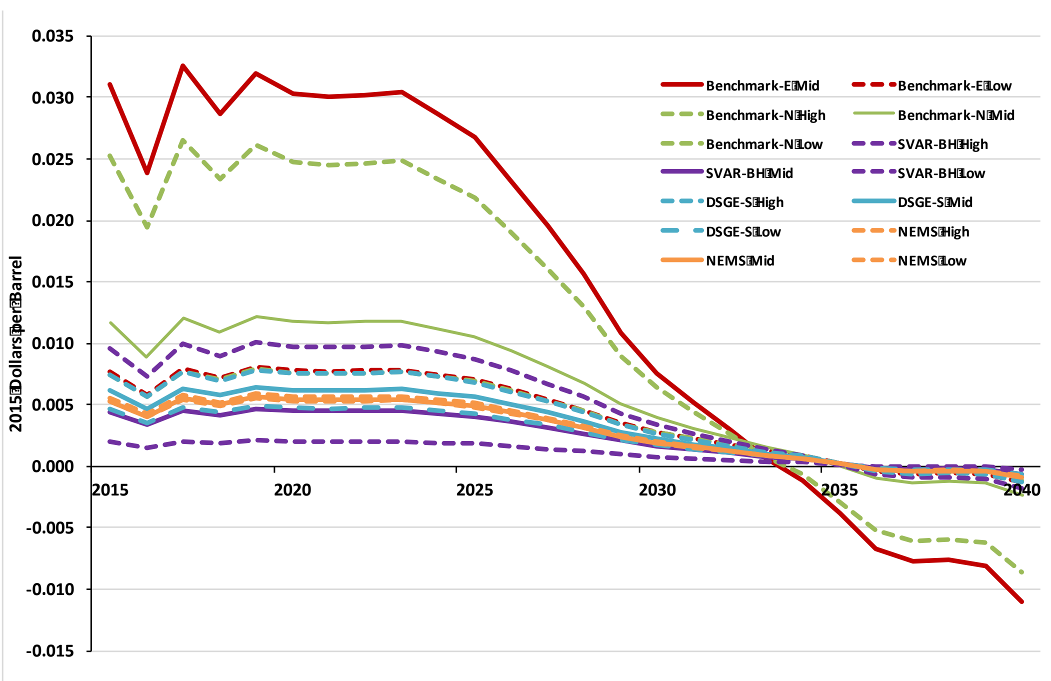


Figure D-9. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Domestic Oil Consumption

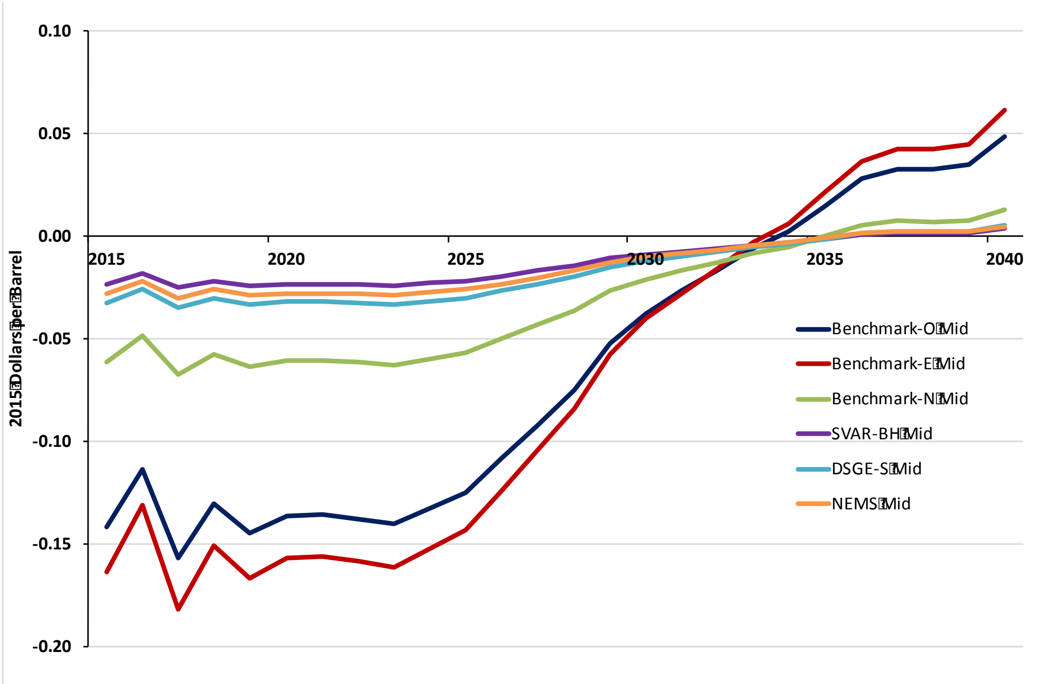


Figure D-9a. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Domestic Oil Consumption

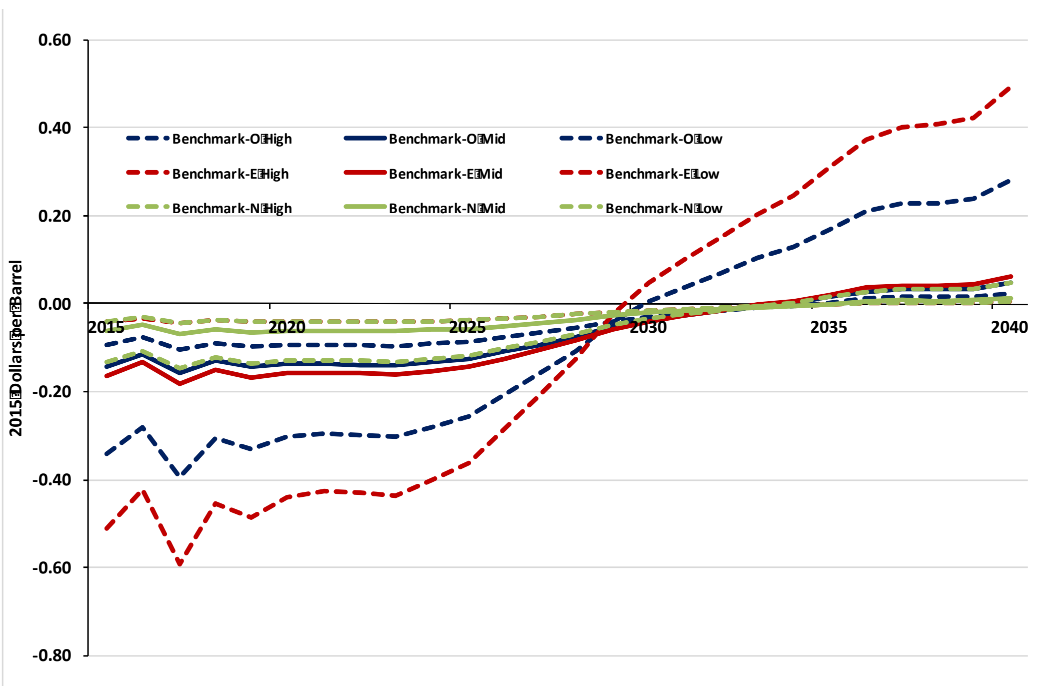


Figure D-9b. Change in Expected Transfers on Inframarginal Oil Imports for Marginal Change in Domestic Oil Consumption

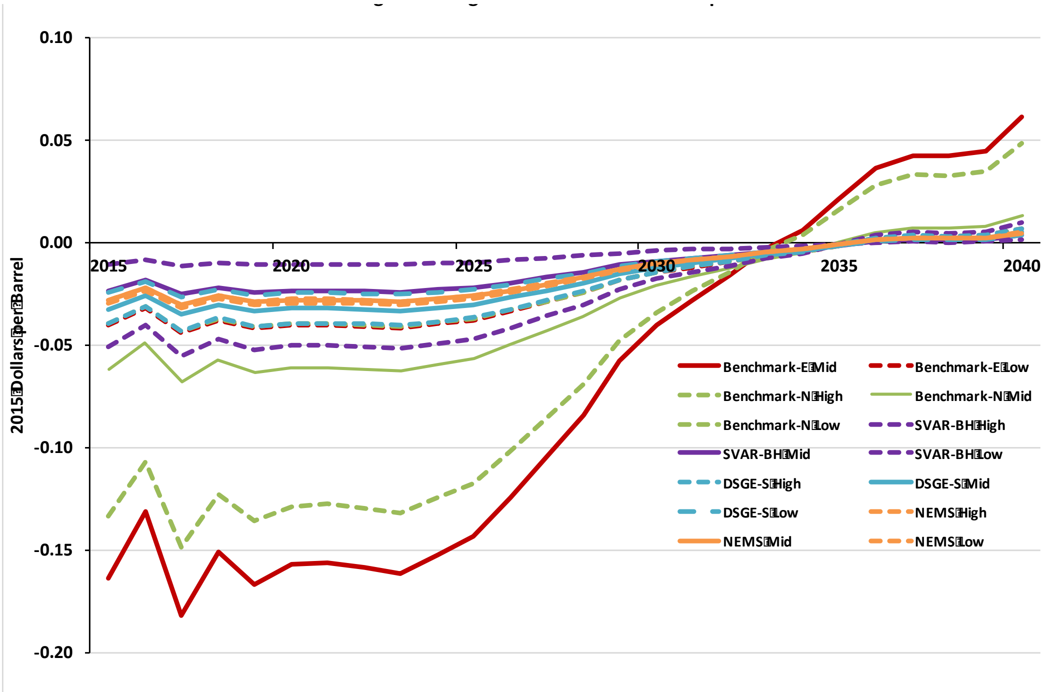


Figure D-10. Oil Security Premiums for Marginal Consumption of Imported Oil

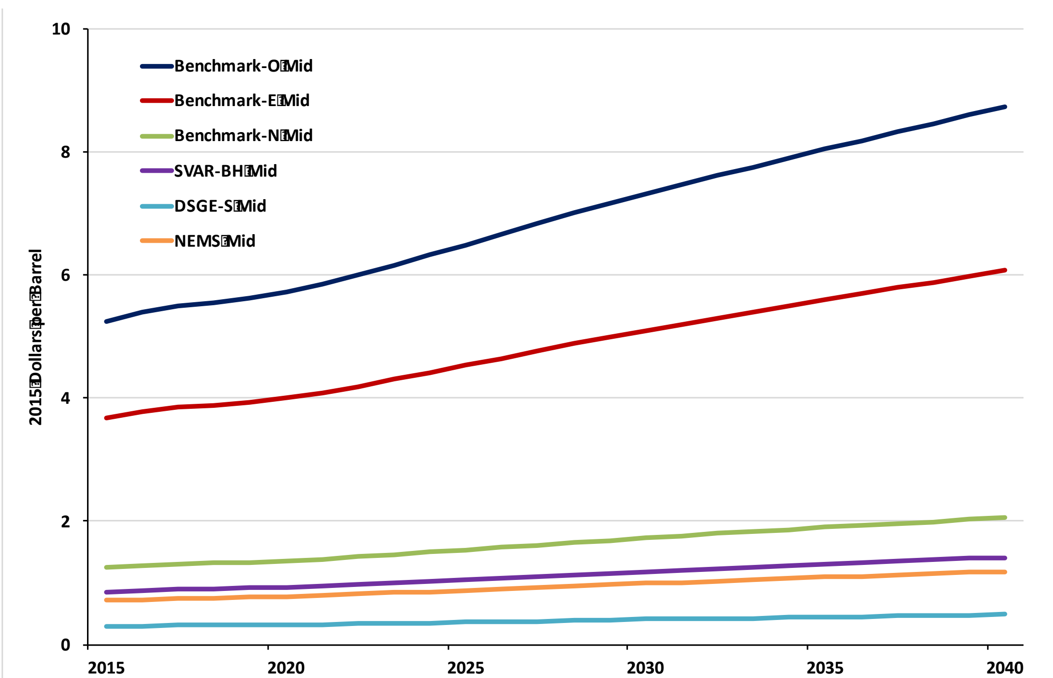


Figure D-10a. Oil Security Premiums for Marginal Consumption of Imported Oil

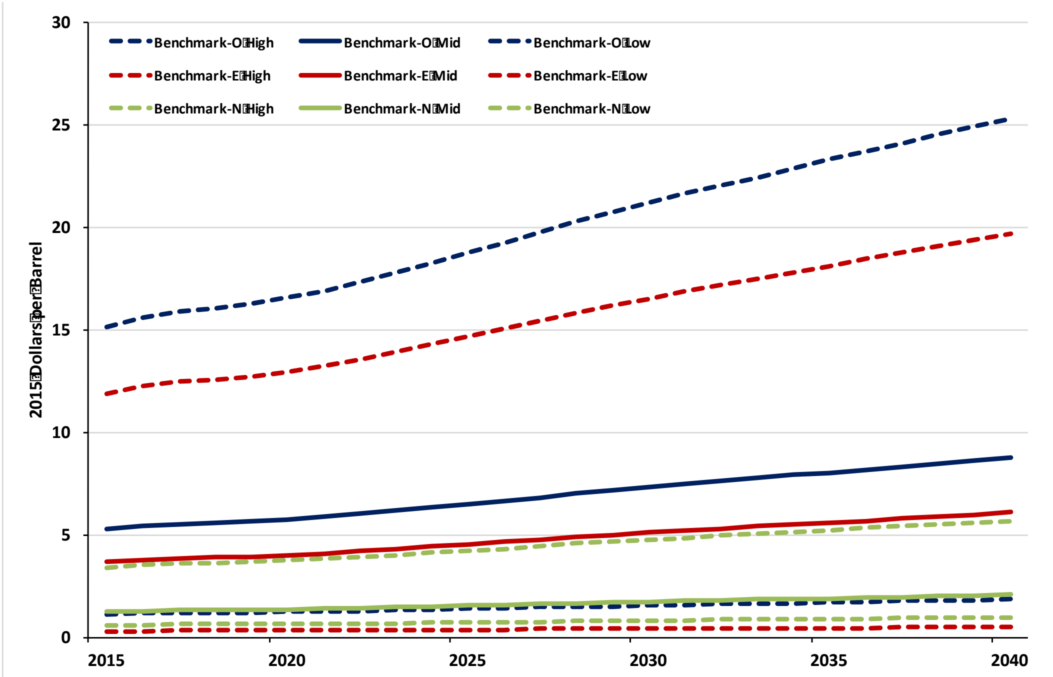


Figure D-10b. Oil Security Premiums for Marginal Consumption of Imported Oil

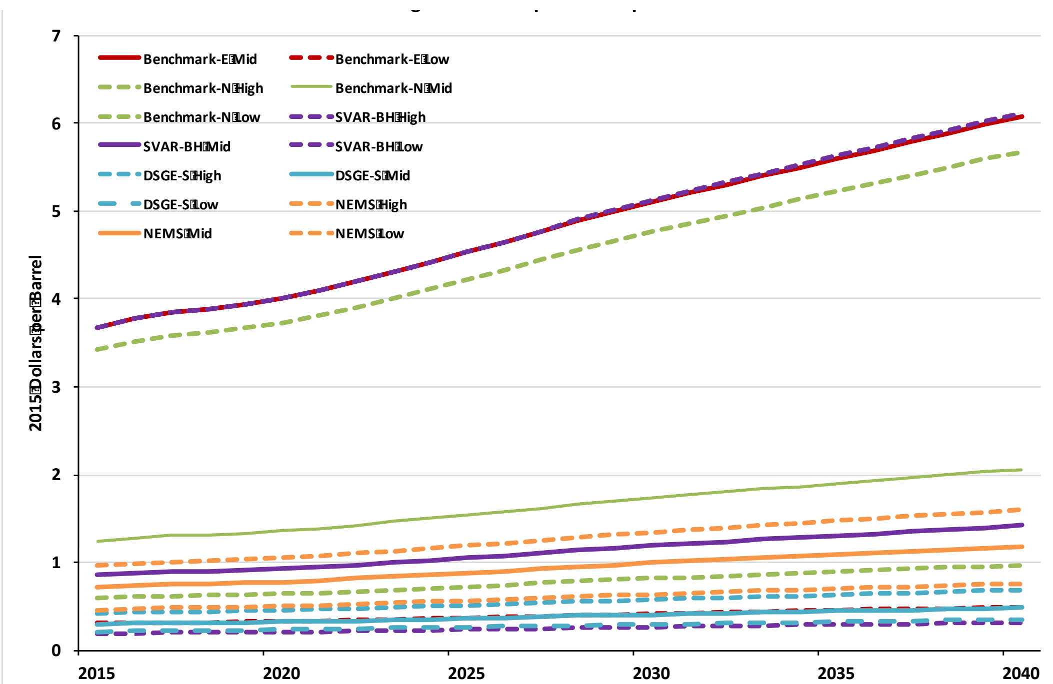


Figure D-11. Oil Security Premiums for Marginal Consumption of Domestic Oil

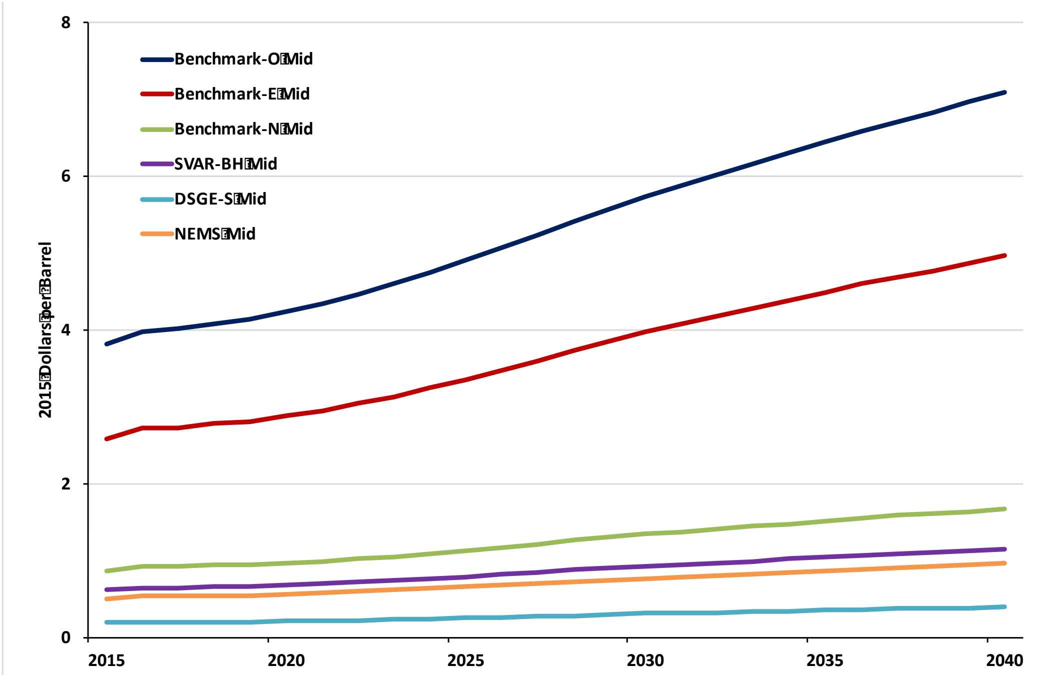


Figure D-11a. Oil Security Premiums for Marginal Consumption of Domestic Oil

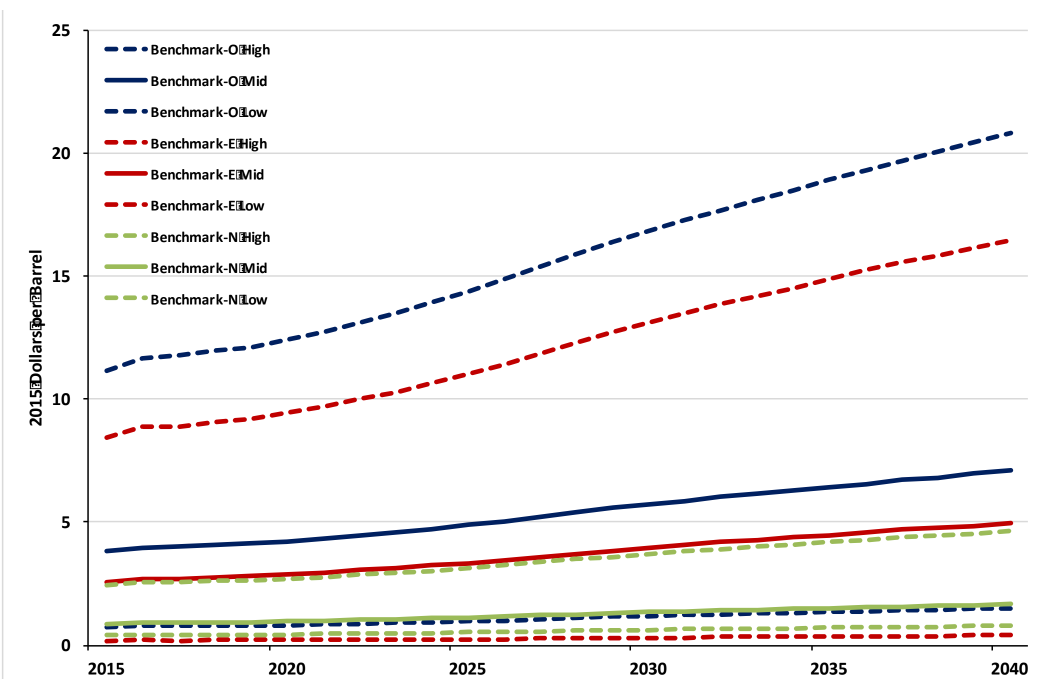


Figure D-11b. Oil Security Premiums for Marginal Consumption of Domestic Oil

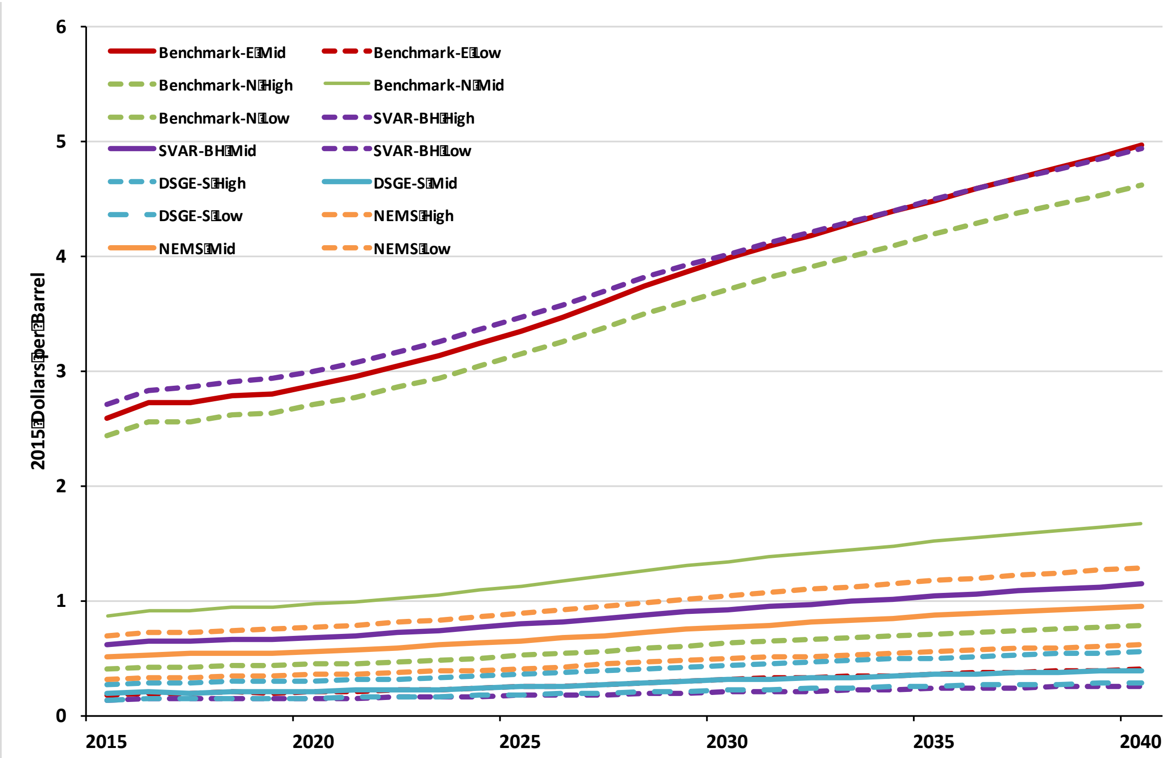


Figure D-12. Oil Security Premiums for Imported vs. Domestic Oil

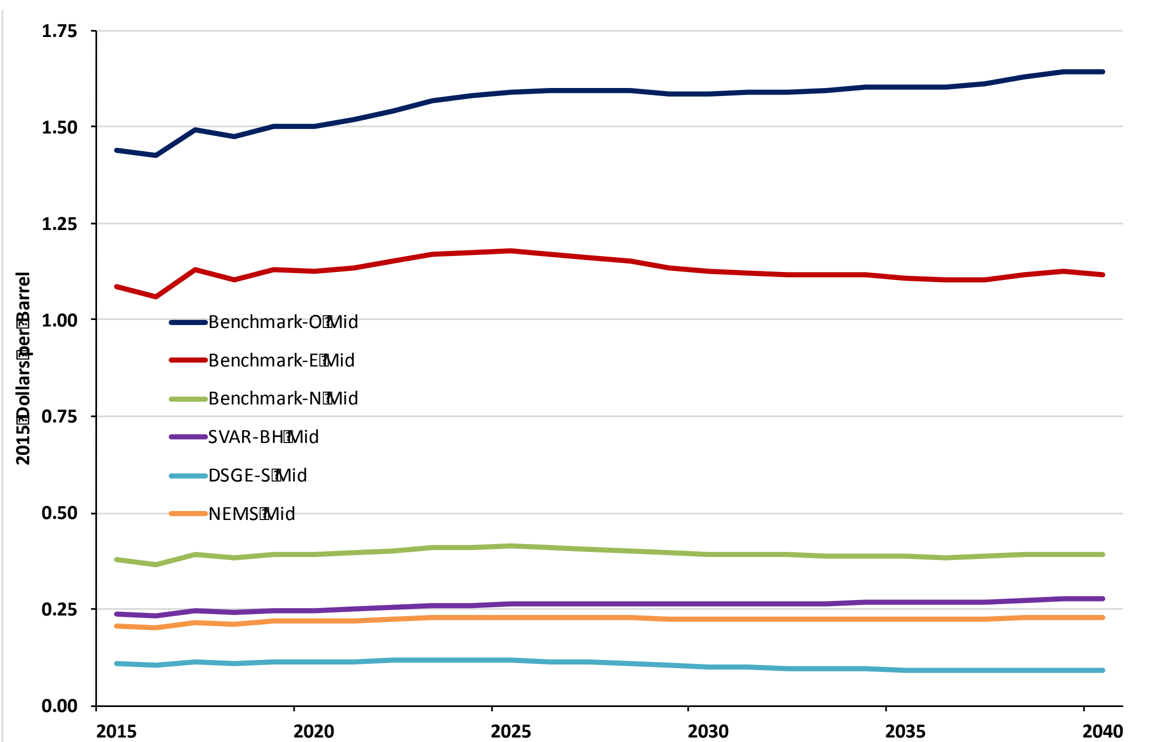


Figure D-12a. Oil Security Premiums for Imported vs. Domestic Oil

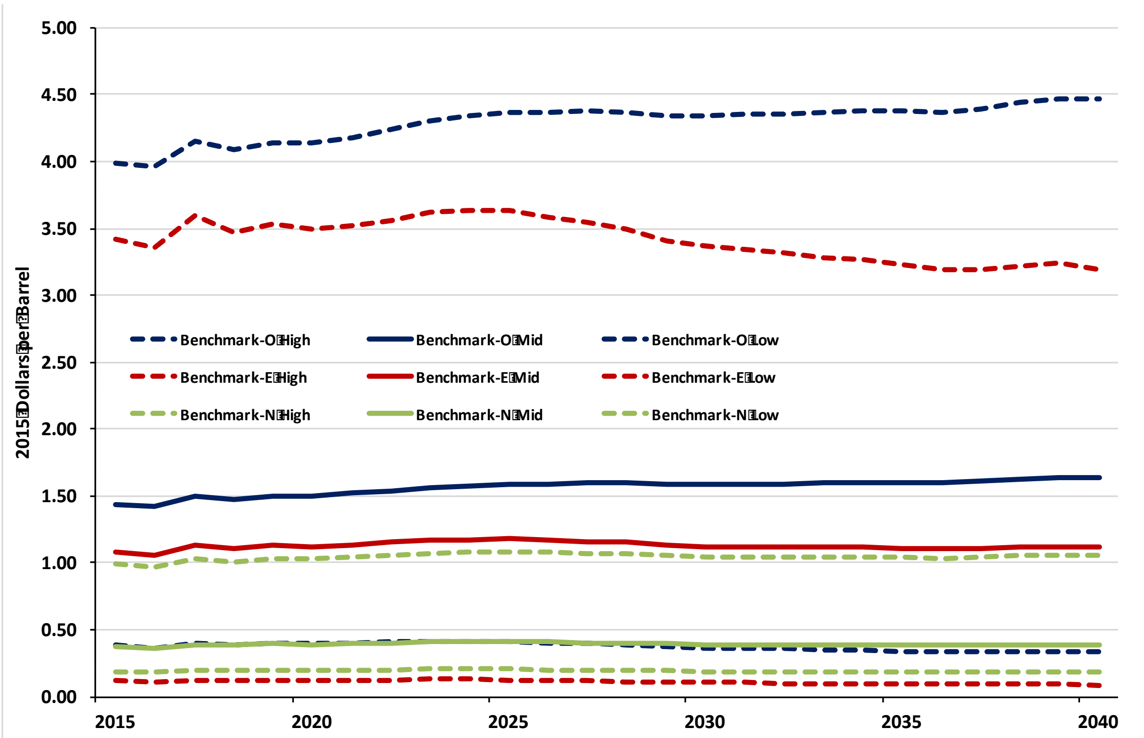
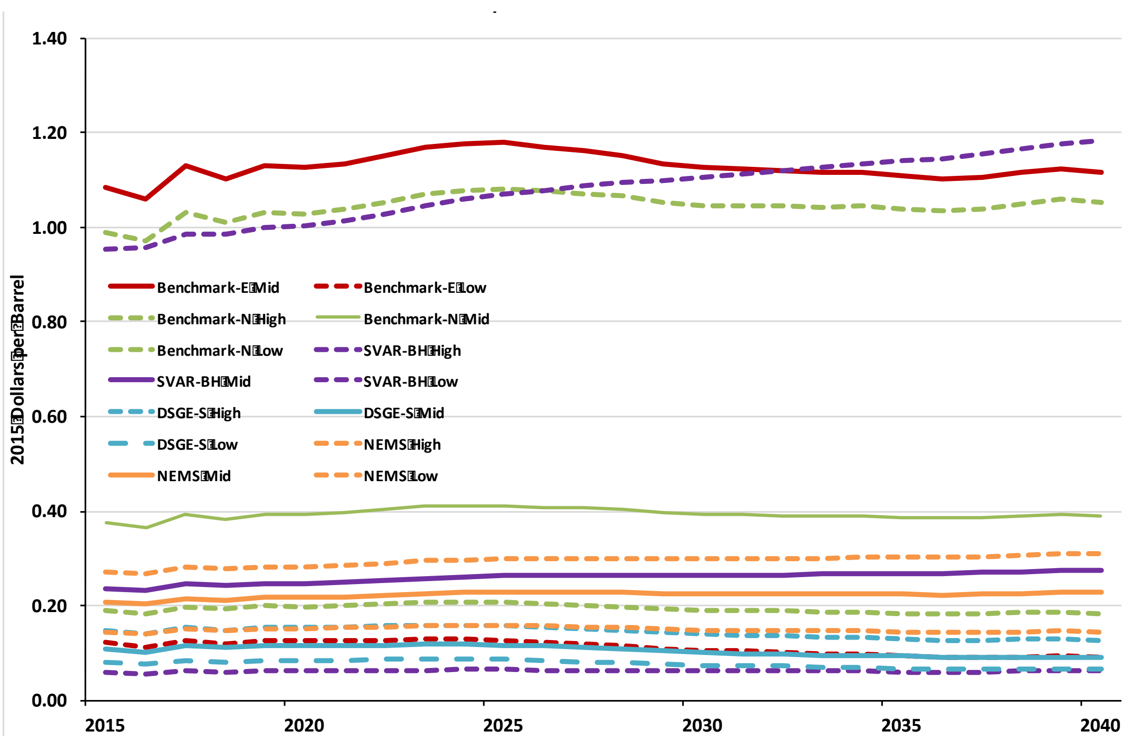


Figure D-12b. Oil Security Premiums for Imported vs. Domestic Oil



Supplemental Information (SI)-1. Traditional Oil Premiums

As explained in Section D-2 above, the traditional premium for U.S consumption of imported oil includes four components; the monopsony premium, the expected transfers on the marginal barrel of imported oil, the change in the expected transfers for the inframarginal barrels of imported oil, and the change in the GDP loss resulting from an oil price shock. The traditional premium for US consumption of domestic oil includes two components: the change in the expected transfers for the inframarginal barrels of imported oil and the change in the GDP loss resulting from an oil price shock. The traditional premium for the substitution of imported oil for domestic oil is the difference between the premiums for the consumption of imported and domestic oil.

Section D-3 above quantifies the expected GDP losses and the expected transfers for the inframarginal barrels of imported and domestic oil. This appendix uses computational methods based on the welfare-theoretic approach described in Section D-2 (and explained in Appendix B) with actual world oil market conditions in 2014 and world oil market conditions projected by the US Energy Information Administration (EIA 2012, 2016) to quantify the monopsony premium and the expected transfers on the marginal barrel of imported oil. It combines these two components with the expected GDP losses and transfers on inframarginal imports to quantify traditional oil premiums. It also examines briefly the implications of using the traditional premiums in thinking about US energy policy.

SI-1.1. Traditional Oil Premiums, from Brown-Huntington to the Newer Benchmarks

Using the methods, oil market conditions, the probability and sizes of disruptions and the elasticities described in Section D-3.1 above, we develop four sets of traditional oil premiums. These include a replication of Brown-Huntington (2015), Benchmark-O which uses updated world oil market conditions and probabilities and sizes of disruptions, Benchmark-N which uses the newer estimates of the short-run elasticity of demand and the response of GDP to oil price shocks, and Benchmark-E which uses the evolutionary estimates of the short-run elasticity of demand and the response of US real GDP to oil price shocks. The process of quantifying the traditional oil premiums includes developing the monopsony premium and the expected transfers on the marginal barrel of imported oil. These two components are combined with expected GDP losses and expected transfers on inframarginal barrels of imported oil to yield the traditional oil premiums.

SI-1.1.1. Additional Components of the Traditional Oil Premiums

As described in Section D-2.3.2 above, the consumer of the marginal barrel of oil faces an as shown in Table D1.1, the monopsony premium is greater for the Brown-Huntington assumptions than for Benchmark-O, Benchmark-N or Benchmark-E. The reduced values found in the Benchmark cases owe to substantially lower US oil imports in 2014 than EIA (2012) projected for 2013-14 average. The non-US long-run demand and supply elasticities are taken from Brown-Huntington (2015) and are the same for all four sets of calculations. The mid-value of the long-run demand elasticity is -0.40 in a range of -0.35 to -0.45, and the mid-value of the long-run supply elasticity is 0.40 in a range of 0.35 to 0.40.

As also is shown in the table, the expected transfer on the marginal barrel of imported oil is greater for the Brown-Huntington assumptions than either benchmark case. With the same elasticities, the differences between the two estimates primarily owes to US oil production accounting for a greater share of world oil production under Benchmark-O. As a result of greater demand elasticities, Benchmark-N shows smaller expected price shocks than Benchmark-O.

Benchmark-E shows a wider range with higher mid and upper estimates of the expected price shocks than Benchmark-O and a low that is nearly the same as the low for Benchmark-N. The higher estimates for the mid and upper range values depend on GDP being less responsive, which makes effective demand more inelastic and yields greater oil price shocks for the expected oil supply disruptions. The low estimate for Benchmark-E reflects the greater elasticity of short-run demand.

SI-1.1.2. The Traditional Premiums

As shown in Table D1.2, the traditional oil premium for the consumption of imported oil is greater under the Brown-Huntington assumptions than any of benchmark cases. The monopsony premium, the expected transfers on the marginal barrel of imported oil, the expected GDP losses and the expected transfers on the inframarginal barrels of imported oil all contribute to the differences. The table also shows that the values of the traditional premium for US consumption of imported oil are mostly greater for Benchmark-O, with a slightly higher upper value for Benchmark-E. Benchmark-N shows lower values than the other two benchmark cases.

As shown in the table, estimates of the traditional oil premium for US consumption of domestic oil are greater for Brown-Huntington than Benchmark-O which is greater than Benchmark-E and Benchmark-N. The estimates of the traditional premium for the substitution of imported oil for domestic oil are greater for Brown-Huntington than any of the Benchmark cases. Benchmark-E shows systematically higher values than Benchmark-O. The higher values for

Benchmark-E are the result of a greater difference between its traditional premium for imported and domestic oil, with that difference owing mostly to the expected transfers on the marginal barrel of imported oil.

SI-1.2. New Macro Modeling Efforts and Traditional Oil Premiums

As shown in Table D1.3, the SVAR-BH, DSGE-S and NEMS modeling efforts yield estimates of the monopsony premium that are similar to those found for the benchmark cases. Because SVAR-BH does not provide long-run elasticities for non-US demand and supply, the monopsony estimates for SVAR-BH are made with the same assumptions as those for the benchmark cases. The DSGE model finds the respective long-run elasticities of non-US demand and supply to be more elastic at -0.49 and 0.50 in respective ranges of -0.46 to -0.70 and 0.48 to 0.57. NEMS specifies long-run elasticities of non-US demand and supply at -0.25 and 0.25, respectively.

As shown in the table, Benchmark-E shows a wider range with higher mid and upper estimates of the expected price shocks than Benchmark-O and a low that is nearly the same as the low for Benchmark-N, which is consistent with the findings reported in Section D1.1 above. The low values found with Benchmark-N and the low values at the bottom of the Benchmark-E range owe to more elastic short-run demand. The expected transfers on the marginal barrel of imported oil found for the three modeling efforts are in the lower range of the values found for Benchmark-N. The lower estimates for these models depend mostly on the more elastic values of short-run supply and demand found with the three models.

As shown in Table D1.4, the average findings for the three benchmark cases over the 2015 to 2040 time period are similar to those found for 2014 world oil market conditions. The values of the traditional premium for US consumption of imported oil are mostly greater for Benchmark-O, with a slightly higher upper value for Benchmark-E. Benchmark-N shows lower values than the other two benchmark cases. Estimates of the traditional oil premium for US consumption of domestic oil are greater for Benchmark-O than Benchmark-E which are greater than for Benchmark-N. For the substitution of imported oil for domestic oil, however, Benchmark-E shows higher mid and upper values than Benchmark-O, while Benchmark-N shows the lowest values.

For all three of the modeling efforts, all three of the traditional oil premiums are concentrated in or below the lower ranges of Benchmark-E. The estimates for SVAR-BH shows similarities to Benchmark-N, but the estimates for DSGE-S are concentrated in or below the lower ranges of Benchmark-N. For NEMS, the upper estimates of traditional premiums for the consumption of imported oil and the substitution of imported oil for domestic oil are slightly above the mid-values of Benchmark-N.

SI-1.3. Additional Components of the Traditional Oil Premiums 2015–2040

As described above, six components are used to compute the traditional oil premiums. Four of the components—the change in the expected GDP losses from a marginal increase that result from a marginal increase in the consumption of imported oil or domestic oil and the change in expected transfers on inframarginal consumption of imported oil that result from a marginal increase in the consumption of imported or domestic oil—are described in section D-3.3 above. The two additional components are the monopsony premium and the expected transfers on the marginal barrel of imported oil.

SI-1.3.1. The Monopsony Premium

As shown in Figures D1.1, D1.1a and D1.1b, the monopsony premium generally decreases from 2015 to 2040. Forecasts of declining US oil imports more than offset the effects of the forecasted increase in oil prices. As shown in Figure D1.1a, the three benchmark cases find the monopsony premium falling from a mid-value of $3.81 per barrel (in a range of $3.39 to $4.35) in 2015 to a mid-value of $2.52 per barrel (in a range of $2.24 to $2.88) in 2040.

As shown in Figure D1.1b, the premiums for the SVAR-BH, DSGE-S and NEMS modeling exercises also fall from 2015 to 2040, with the SVAR-BH estimates the same as for the benchmark cases (by assumption), the DSGE-S estimates lower than for the benchmark cases, and the NEMS estimates greater than for benchmark cases. For 2015, the respective median or mean estimates for the SVAR-BH and DSGE-S models are $3.81 and $3.07 per barrel in respective ranges of $3.39 to $4.35 and $2.40 to $3.24. For 2040, the respective median or mean estimates for the SVAR-BH and DSGE-S models are $2.52 and $2.03 per barrel in respective ranges of $2.24 to $2.88 and $1.59 to $2.15. Estimates for the NEMS model decline from $6.09 per barrel in 2015 to $4.03 in 2040.

SI-1.3.2. Expected Transfers on the Marginal Barrel of Imported Oil

As shown in Figures D1.2, D1.2a and D1.2b, the expected price shock generally increases from 2015 to 2040. The gains are largely the result of forecasted gains in world oil prices. As shown in D1.2a, Benchmark-O finds the premium rising from a mid-value of $3.37 per barrel (in a range of $2.37 to $7.52) in 2015 to a mid-value of $8.89 per barrel (in a range of $6.24 to $20.04) in 2040. Under Benchmark-E, the premium rises from a mid-value of $3.81 per barrel (in a range of $1.12 to $10.30) in 2015 to a mid-value of $10.04 per barrel (in a range of $2.94 to $27.46) in 2040. Under Benchmark-N, the premium rises from a mid-value of $1.65 per barrel (in a range of $1.09 to $3.29) in 2015 to a mid-value of $4.33 per barrel (in a range of $2.88 to $8.69) in 2040.

As shown in Figure D1.2b, the premiums for the SVAR-BH, DSGE-S and NEMS modeling exercises also generally rise from 2015 to 2040, but they are concentrated in or below the lower ranges of Benchmark-E and Benchmark-N. For 2015, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $0.67, $0.92 and $0.79 per barrel in respective ranges of $0.31 to $1.38, $0.71 to $1.10 and $0.78 to $0.82. For 2040, the respective median or mean estimates for the SVAR-BH, DSGE-S and NEMS models are $1.75, $2.42 and $2.06 per barrel in respective ranges of $0.80 to $3.63, $1.30 to $2.03 and $2.03 to $2.16.

SI-1.4. Traditional Oil Premiums 2015–2040

Estimates of the individual components are used to develop traditional oil premiums from 2015 to 2040. These premiums cover the consumption of imported oil, the consumption of domestic oil and the substitution of imported oil for domestic oil. Most of the premiums rise from 2015 to 2040, with projected gains in US real GDP, the world oil price and non-US production more than offsetting the effects of decreased US oil imports. Some of the premiums fall, with the effects of decreased oil imports more than offsetting projected gains in US real GDP, the world oil price and non-US production.

SI-1.4.1. Traditional Premiums for the Consumption of Imported Oil 2015–2040

As shown in Figures D1.3, D1.3a and D1.3b, the traditional oil premium for US consumption of imported oil increases from 2015 to 2040 for the benchmark cases and the SVAR-BH and DSGE-S models, while it generally decreases for the NEMS model. The difference between the estimates that are rising and the those that are falling mostly depends on the relative strength of the monopsony premium vs. the expected transfers on the marginal barrel of imported oil.

As shown in Figure D1.3a, Benchmark-O shows the premium rising from a mid-value of $12.44 per barrel (in a range of $6.88 to $27.03) in 2015 to a mid-value of $20.14 per barrel (in a range of $10.33 to $48.22) in 2040. Under Benchmark-E, the premium rises from a mid-value of $11.29 per barrel (in a range of $4.81 to $26.52) in 2015 to a mid-value of $18.64 per barrel (in a range of $5.67 to $50.01) in 2040. Although the high range for Benchmark-E starts below the high range for Benchmark-O, the former overtakes the latter by 2020 because bigger oil price shocks result from a less responsive GDP in Benchmark-E, and those effects gradually dominate some of the other processes at work. Under Benchmark-N, the premium rises from a mid-value of $6.70 (in a range of $5.07 to $11.06).

As shown in Figure D1.3b, the premiums for the SVAR, DSGE and NEMS models are in the range of Benchmark-N and concentrated in or below the lower range of Benchmark-E. The premiums for the SVAR and DSGE models increase from 2015 to 2040, while those for the NEMS model decline. For 2015, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $5.33, $4.29 and $7.59 per barrel in respective ranges of $3.88 to $9.40, $3.33 to $4.77 and $7.33 to $7.88. For 2040, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $5.69, $4.94 and $7.27 per barrel in respective ranges of $3.36 to $12.62, $3.81 to $5.74 and $6.83 to $7.79.

SI-1.4.2. Traditional Premiums for the Consumption of Domestic Oil 2015–2040

As shown in Figures D1.4, D1.4a and D1.4b, the traditional oil premium for US consumption of domestic oil increases from 2015 to 2040. The gains are largely driven by expected GDP losses. The expected transfers on inframarginal consumption of imported oil are quite small. As shown in Figure D1.4a, Benchmark-O finds the premium rising from a mid-value of $3.81 per barrel (in a range of $0.74 to $11.17) in 2015 to a mid-value of $7.09 per barrel (in a range of $1.51 to $20.84) in 2040. Under Benchmark-E, the premium rises from a mid-value of $2.59 per barrel (in a range of $0.18 to $8.45) in 2015 to a mid-value of $4.96 per barrel (in a range of $0.40 to $16.48) in 2040. Under Benchmark-N, the premium rises from a mid-value of $0.87 per barrel (in a range of $0.40 to $2.43) in 2015 to a mid-value of $1.67 per barrel (in a range of $0.79 to $4.62) in 2040.

As shown in Figure D1.4b, the premiums for the SVAR-BH, DSGE-S and NEMS models also rise from 2015 to 2040, but they are concentrated in or below the lower range of Benchmark-E. In fact, with the exception of the high estimates for SVAR-BH, the estimates for the three models are in or below the lower range of Benchmark-N. For 2015, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $0.62, $0.19 and $0.51 per barrel in respective ranges of $0.13 to $2.71, $0.13 to $0.27 and $0.32 to $0.69. For 2040, the respective median or mean estimates for the SVAR, DSGE and NEMS models are $1.14, $0.40 and $0.96 per barrel in respective ranges of $0.25 to $4.94, $0.29 to $0.56 and $0.62 to $1.29.

SI-1.4.3. Traditional Premiums for Imported vs. Domestic Oil 2015–2040

As shown in Figures D1.5, D1.5a and D1.5b, the premium for the substitution of imported oil for domestic oil (also known as the traditional oil import premium) increases from 2015 to 2040 for the benchmark cases and the DSGE-S models, while it generally decreases for the SVAR-BH and NEMS models. In comparison to the models that show rising premiums, the models that show decreases show weaker gains in the traditional premium for consumption of imported oil and stronger gains in the traditional premium for consumption of domestic oil.

As shown in Figure D1.5a, Benchmark-O finds the premium rising from a mid-value of $8.62 per barrel (in a range of $6.15 to $15.86) in 2015 to a mid-value of $13.05 per barrel (in a range of $1.51 to $20.84) in 2040. Under Benchmark-E, the premium rises from a mid-value of $8.70 per barrel (in a range of $4.63 to $18.07) in 2015 to a mid-value of $13.68 per barrel (in a range of $5.27 to $33.53) in 2040. The mid and upper values for Benchmark-E are higher than those for Benchmark-O because Benchmark-E finds higher expected transfers on the marginal barrel of oil. Under Benchmark-N, the premium rises from a mid-value of $5.83 per barrel (in a range of $4.67 to $8.62) in 2015 to a mid-value of $7.24 per barrel (in a range of $5.30 to $12.60).

As shown in Figure D1.5b, the premiums for the SVAR, DSGE and NEMS models are concentrated in or below the lower range of Benchmark-E, with the NEMS results and the upper range of the SVAR-BH results about the same as the mid-range for Benchmark-N. The premiums for the DSGE-S model increase from 2015 to 2040, while those for the SVAR-BH and NEMS models decline. For 2015, the respective mid-values for the SVAR-BH, DSGE-S and NEMS models are $4.71, $4.11 and $7.09 per barrel in respective ranges of $3.75 to $6.69, $3.19 to $4.50 and $7.01 to $7.19. For 2040, the respective mid-values for the SVAR-BH, DSGE-s and NEMS models are $4.55, $4.53 and $6.32 per barrel in respective ranges of $3.10 to $7.69, $3.52 to $5.18 and $6.21 to $6.50.

SI-1.5. Evaluating Policy with the Traditional Oil Premiums

Differences in the traditional oil premiums and the oil security premiums have significant effects on the estimated values. The upper ranges estimated under the traditional oil premium approach, pioneered by Landsberg et al. (1979), finds relatively high costs associated with US consumption of imported oil and the substitution of imported oil for domestic oil. Much lower costs are found for US consumption of domestic oil. The mid lower and lower ranges found with the narrower oil security measures developed by Brown and Huntington (2013) find only moderate costs associated with US consumption of imported and domestic oil. Much lower costs are found for the substitution of imported oil for domestic oil.

The differing estimates may represent philosophically different approaches to oil security policy. The narrower measures of oil security developed by Brown and Huntington (2013) and used for official US policy keep a sharper focus on how economists define externalities than do the more expansive measures used in the traditional oil premiums. Those who prescribe significant policy interventions to address US reliance on imported oil may be looking beyond standard economic thinking to broader measures of the costs of consuming imported oil that are captured by the traditional oil premiums.

Taken together, the oil security premiums, the traditional oil premiums and the environmental costs of US oil consumption show the possibility for considerable disagreement about the development of US policy toward oil consumption, oil imports and domestic oil production. Policymakers and analysts who favor the traditional oil premium estimates and rely on the upper range of estimates will see US oil security as equally or more important than the environmental costs of oil use. They will also see the cost of US consumption of imported oil as much greater than the use of domestic oil. Those policymakers and analysts who favor the narrower oil security premiums and use the lower ranges of estimates will find that US oil policy ought to focus on the environmental costs of oil use, and they will see little difference in the security costs of using imported or domestic oil.

SI-1.6. Tables and Figures

Table SI-1.1. Additional Components of the Oil Premiums, 2014 (2015 US Dollars per Barrel)

	Monopsony Premium	Expected Oil Price Shock (Transfer on the Marginal Barrel of Imported Oil)
Brown and Huntington (2015)	$17.38 $15.45 to $19.86	$7.56 $5.40 to $16.05
Benchmark-O	$8.45 $7.51 to $9.66	$6.55 $4.60 to $14.65
Benchmark-N	$8.45 $7.51 to $9.66	$3.15 $2.12 to $6.37
Benchmark-E	$8.45 $7.51 to $9.66	$7.39 $2.16 to $20.11

Source: Model Estimates

Table SI-1.2. Traditional Oil Security Premiums, 2014 (2015 US Dollars per Barrel)

Model	Consumption of Imported Oil	Consumption of Domestic Oil	Imported vs. Domestic Oil
Brown and Huntington (2015)	$30.36 $22.04 to $51.61	$3.17 $0.26 to $9.60	$27.19 $21.78 to $42.01
Benchmark-O	$20.28 $13.26 to $39.53	$3.60 $0.60 to $10.63	$16.68 $12.66 to $28.90
Benchmark-N	$12.90 $10.23 to $19.48	$0.78 $0.34 to $2.24	$12.12 $9.89 to $17.24
Benchmark-E	$19.55 $9.99 to $41.76	$2.34 $0.12 to $7.62	$17.21 $9.87 to $34.14

Source: Model Estimates

Table SI-1.3. Additional Components of the Oil Premiums, 2015–40 Average (2015 US Dollars per Barrel)

	Monopsony Premium	Expected Oil Price Shock (Transfer on the Marginal Barrel of Imported Oil)
Benchmark-O	$3.54 $3.15 to $4.05	$6.20 $4.36 to 13.90
Benchmark-N	$3.54 $3.15 to $4.05	$3.02 $2.01 to $6.04
Benchmark-E	$3.54 $3.15 to $4.05	$7.00 $2.05 to $16.57
SVAR-BH	$3.54 $3.15 to $4.05	$1.22 $0.56 to $2.53
DSGE-S	$2.86 $2.23 to $3.02	$1.69 $1.30 to $2.03
NEMS	$5.67	$1.44 $1.42 to $1.51

Source: Model Estimates

Table SI-1.4. Traditional Oil Security Premiums, 2015–40 Average (2015 US Dollars per Barrel)

Model	Consumption of Imported Oil	Consumption of Domestic Oil	Imported vs. Domestic Oil
Benchmark-O	$16.66 $8.98 to $37.98	$5.36 $1.10 to $15.73	$11.30 $7.88 to $22.25
Benchmark-N	$8.20 $5.93 to 14.60	$1.25 $0.58 to $3.46	$6.95 $5.35 to $11.14
Benchmark-E	$15.37 $5.60 to $38.22	$3.70 $0.29 to $13.79	$11.67 $5.31 to $24.43
SVAR-BH	$5.89 $3.96 to $11.42	$0.86 $0.19 to $3.76	$5.03 $3.77 to $7.66
DSGE-S	$4.94 $3.81 to $5.59	$0.28 $0.20 to $0.40	$4.66 $3.61 to $5.19
NEMS	$8.05 $7.70 to $8.45	$0.72 $0.46 to $0.97	$7.33 $7.24 to $7.48

Source: Model Estimates

Figure SI-1.1. Monopsony Premiums

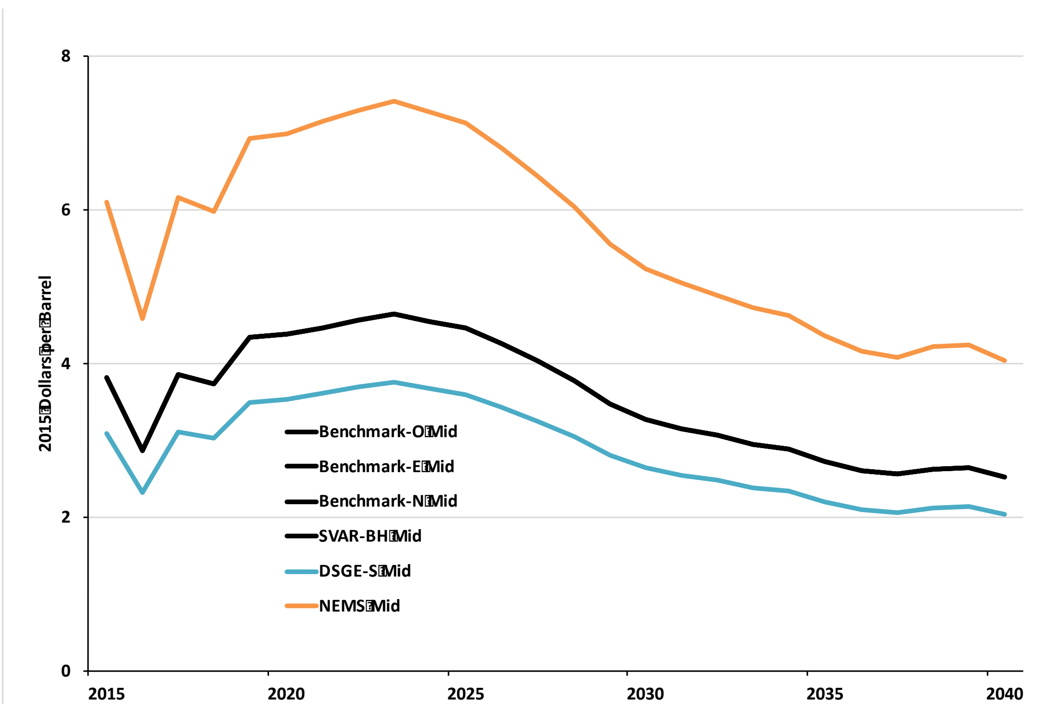


Figure SI-1.1a. Monopsony Premiums

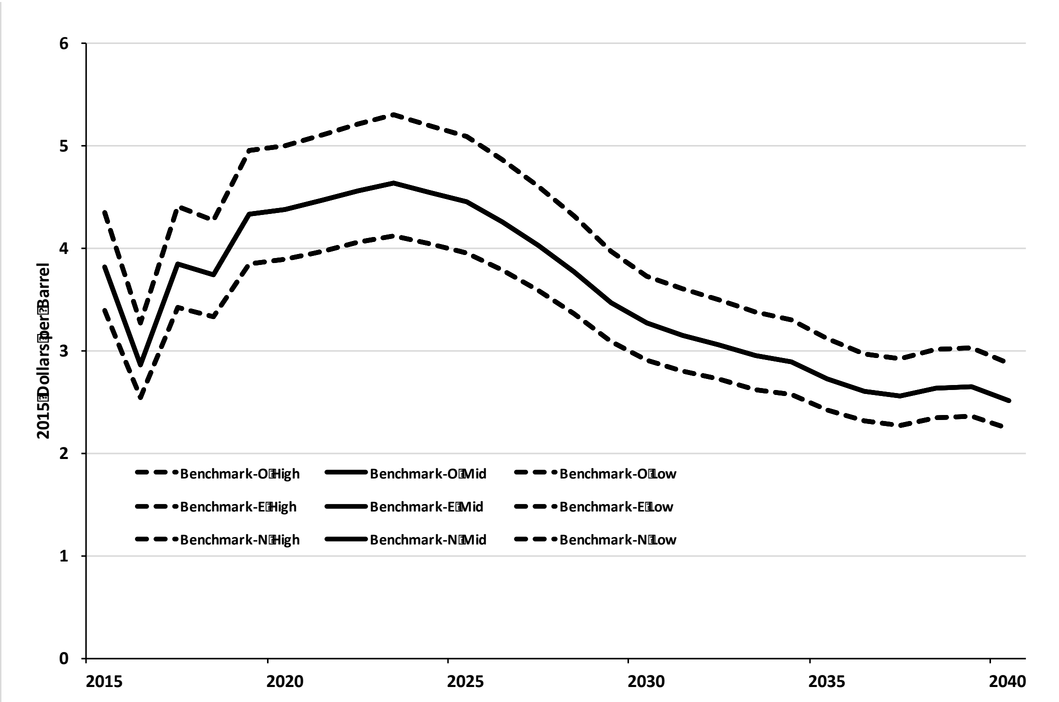


Figure SI-1.1b Monopsony Premiums

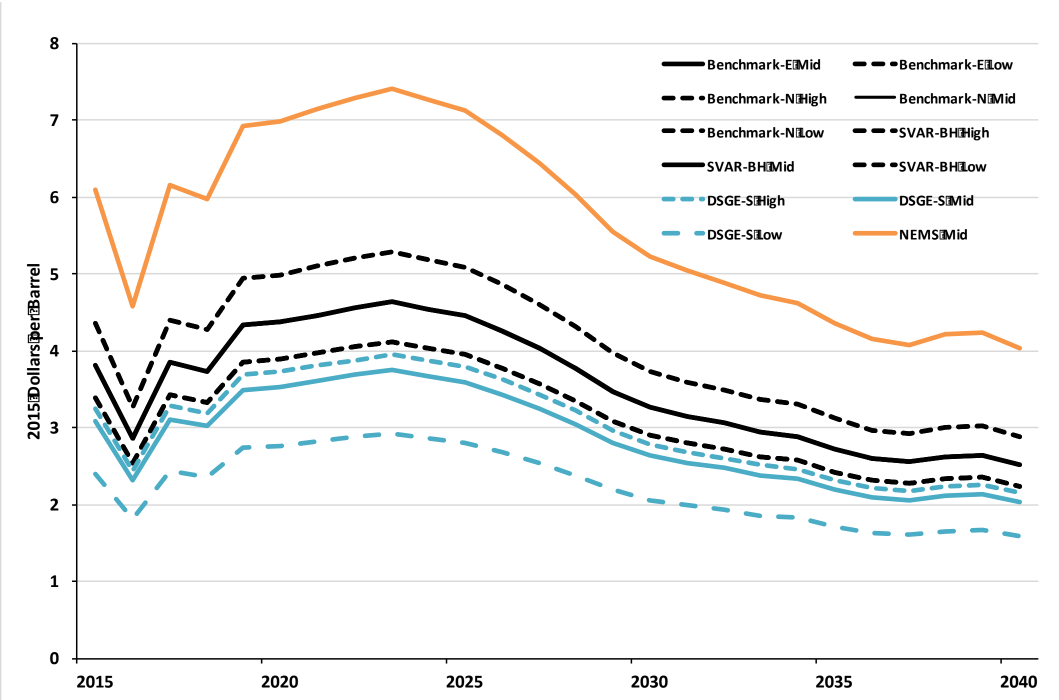


Figure SI-1.2. Expected Oil Price Shock (Expected Transfer on Marginal Barrel of Imported Oil)

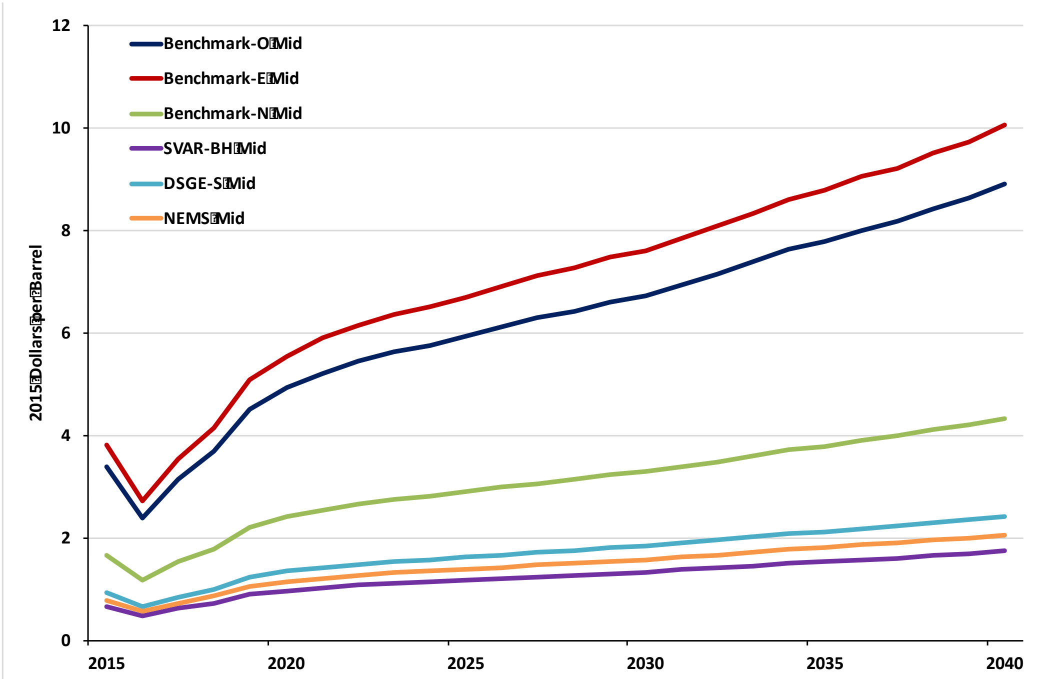


Figure SI-1.2a. Expected Oil Price Shock (Expected Transfer on Marginal Barrel of Imported Oil)

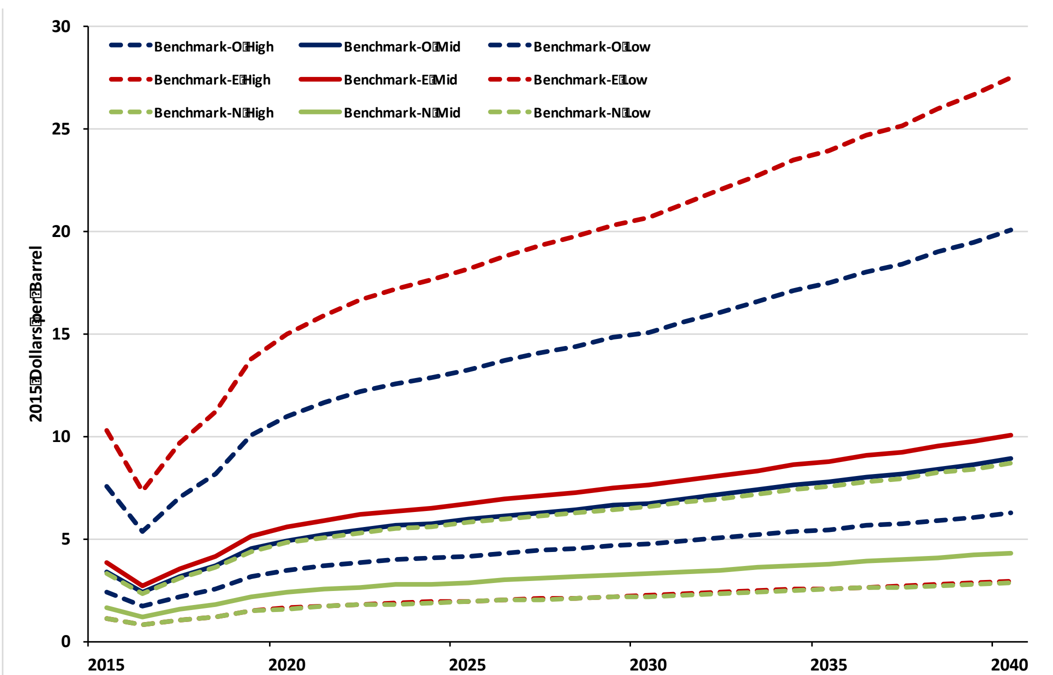


Figure SI-1.2b. Expected Oil Price Shock (Expected Transfer on Marginal Barrel of Imported Oil)

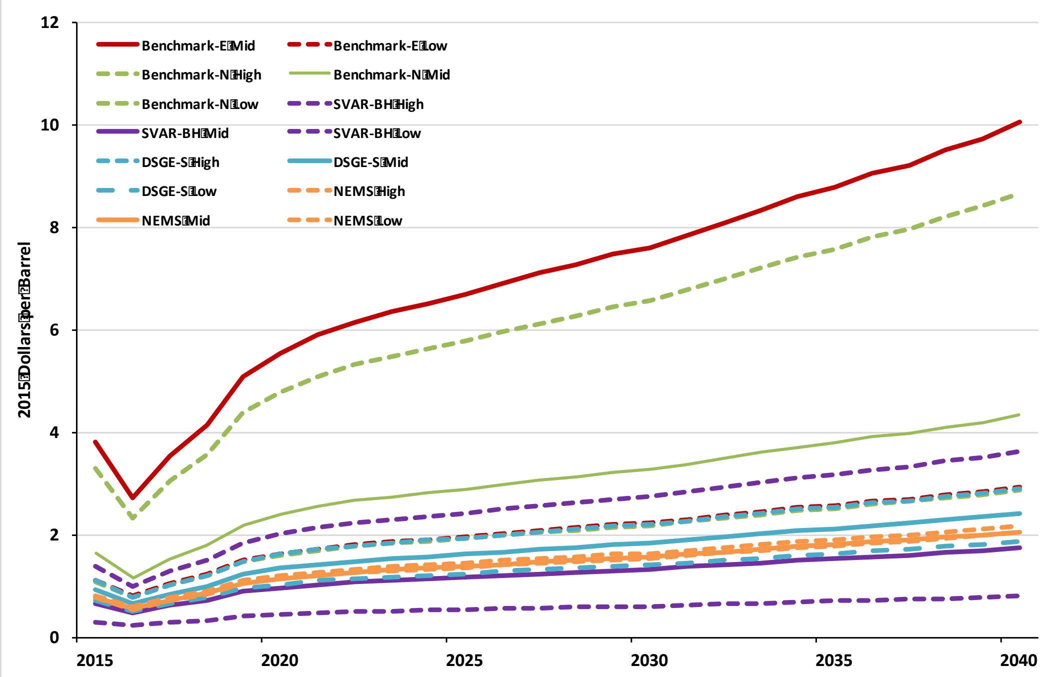


Figure SI-1.3. Traditional Oil Premiums for the Consumption of Imported Oil

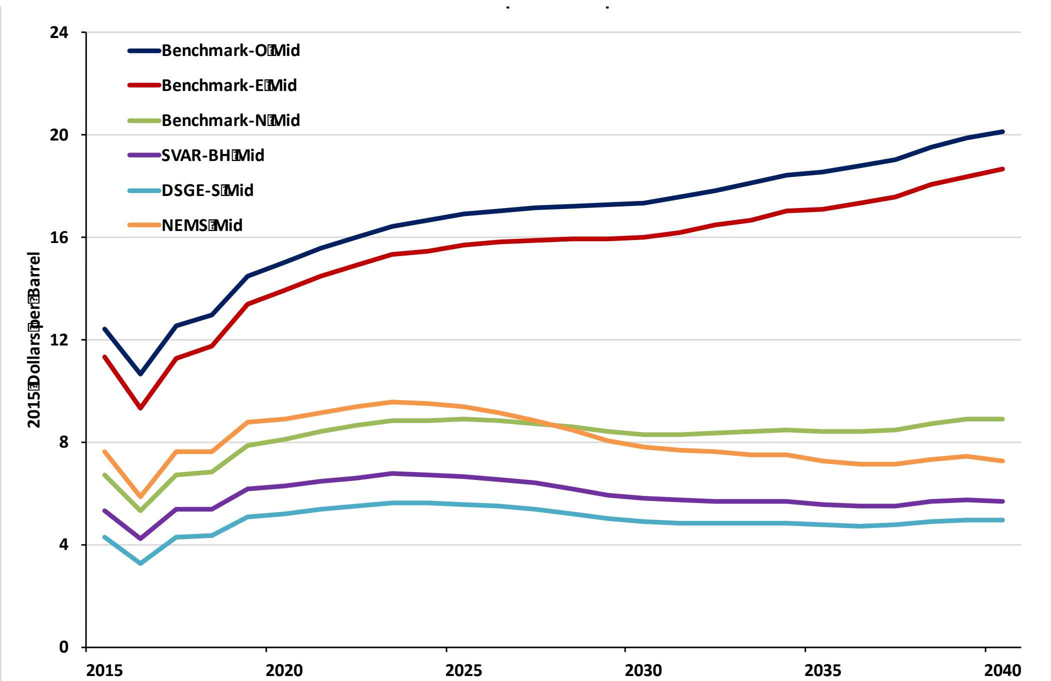


Figure SI-1.3a. Traditional Oil Premiums for the Consumption of Imported Oil

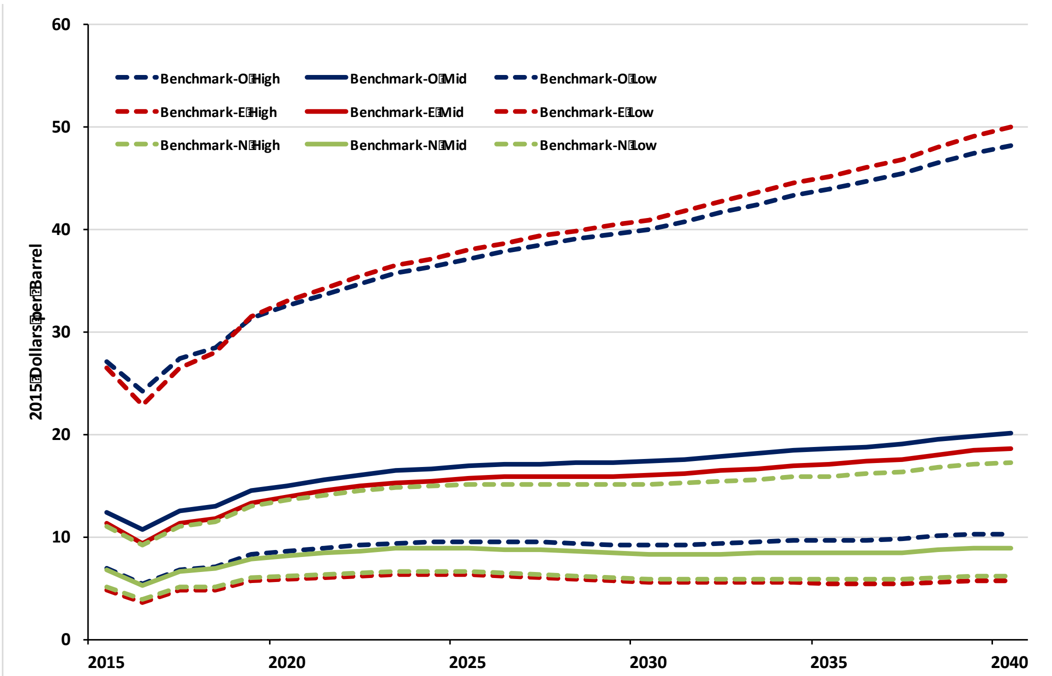


Figure SI-1.3b. Traditional Oil Premiums for the Consumption of Imported Oil

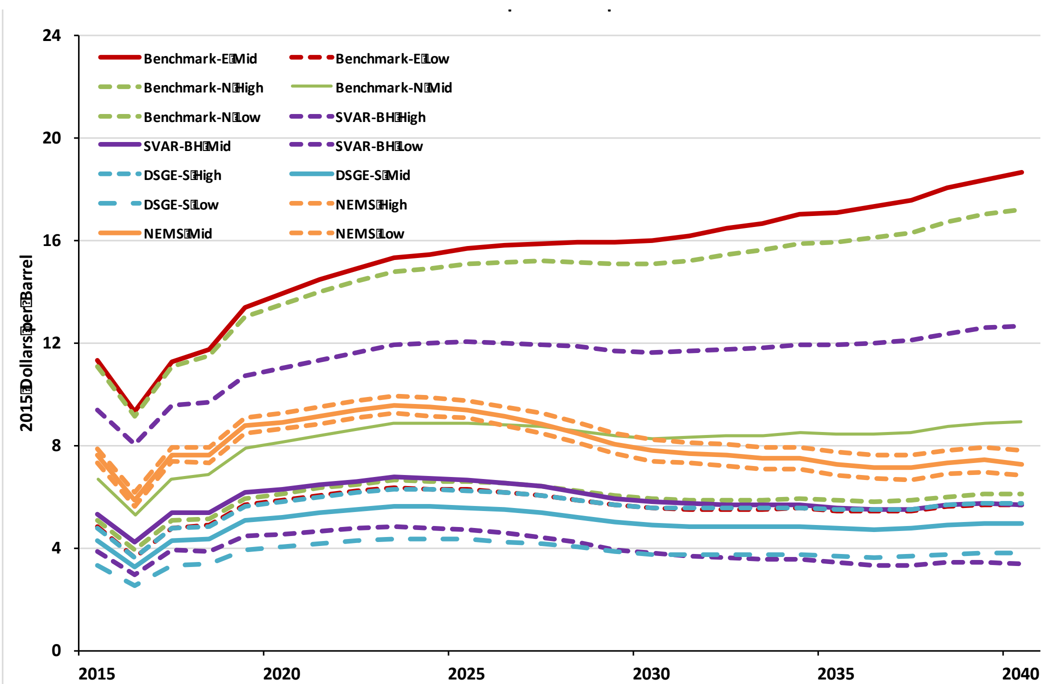


Figure SI-1.4. Traditional Oil Premiums for the Consumption of Domestic Oil

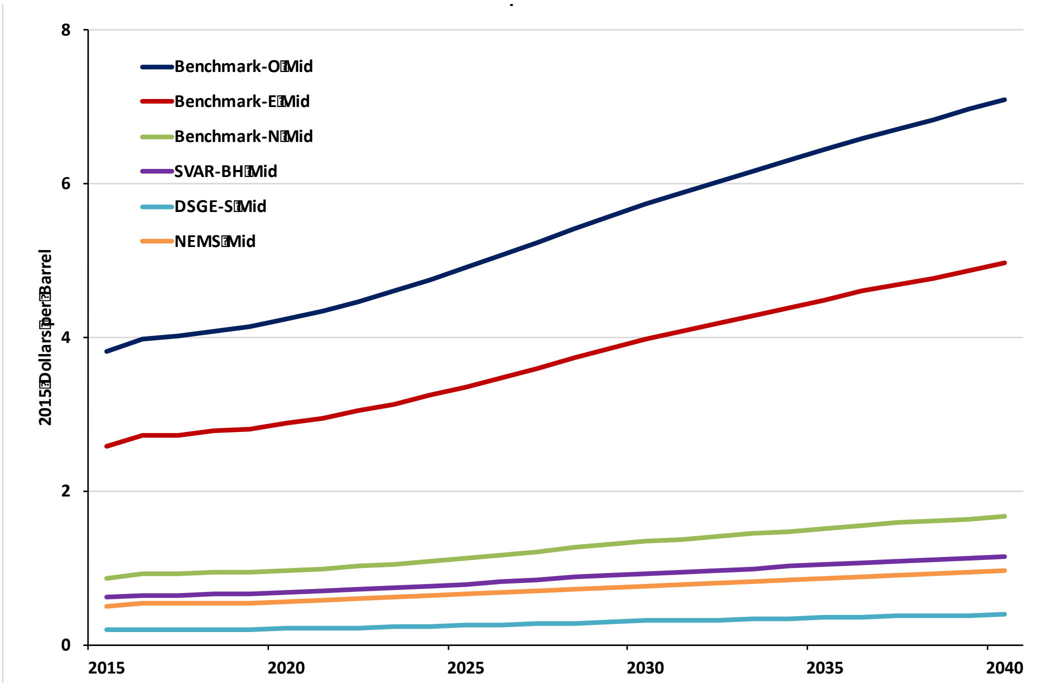


Figure SI-1.4a. Traditional Oil Premiums for the Consumption of Domestic Oil

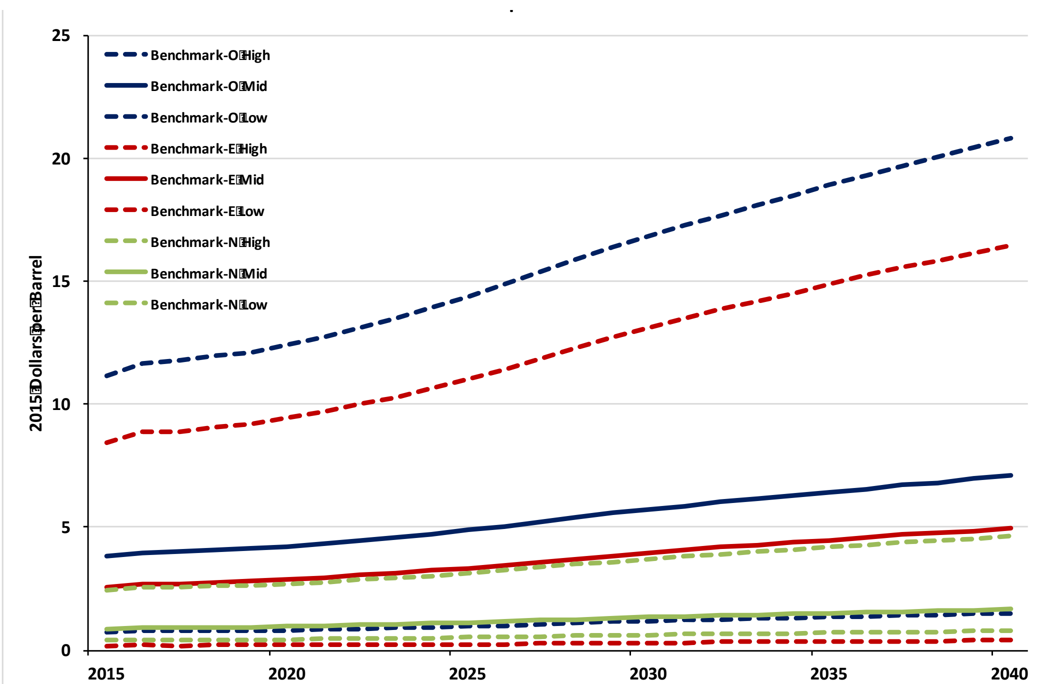


Figure SI-1.4b. Traditional Oil Premiums for the Consumption of Domestic Oil

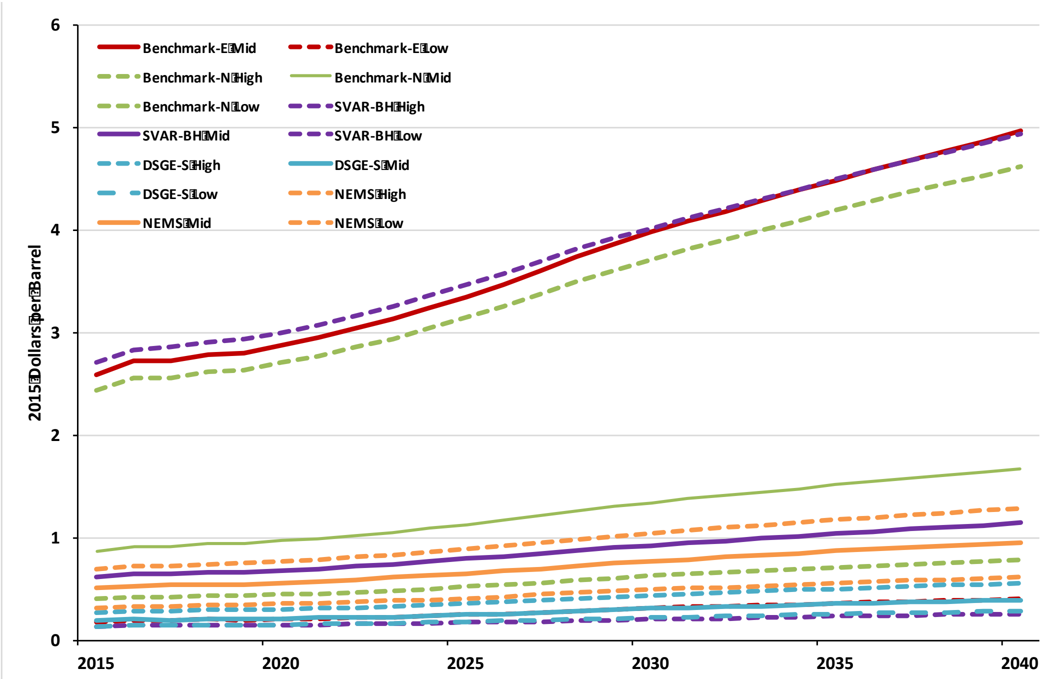


Figure SI-1.5. Traditional Oil Premiums for Imported vs. Domestic Oil

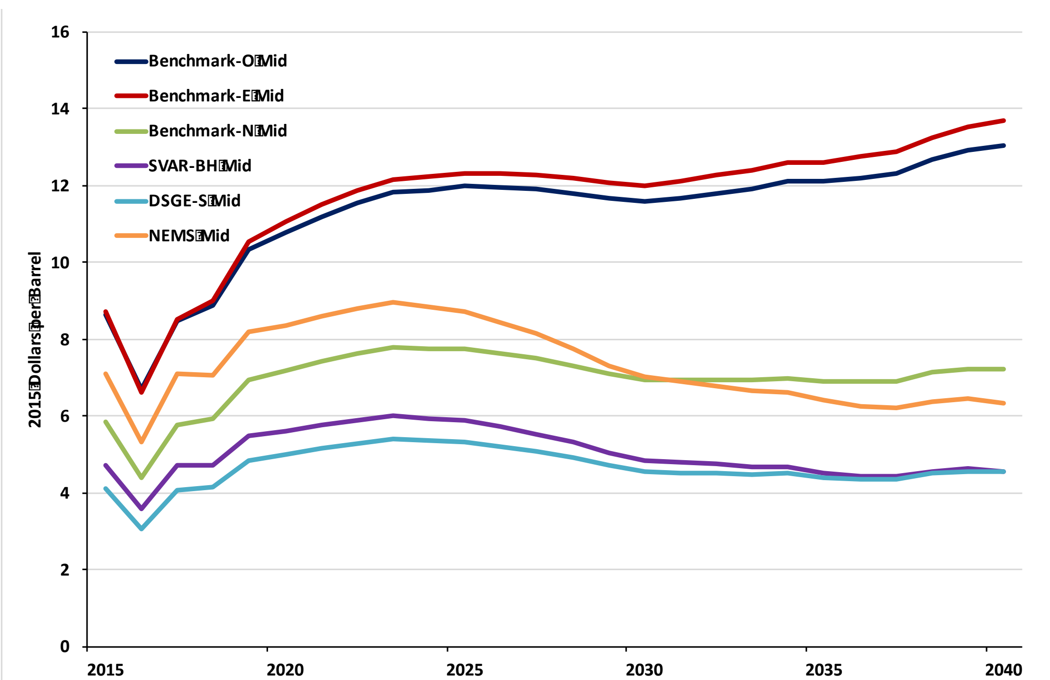


Figure SI-1.5a. Traditional Oil Premiums for Imported vs. Domestic Oil

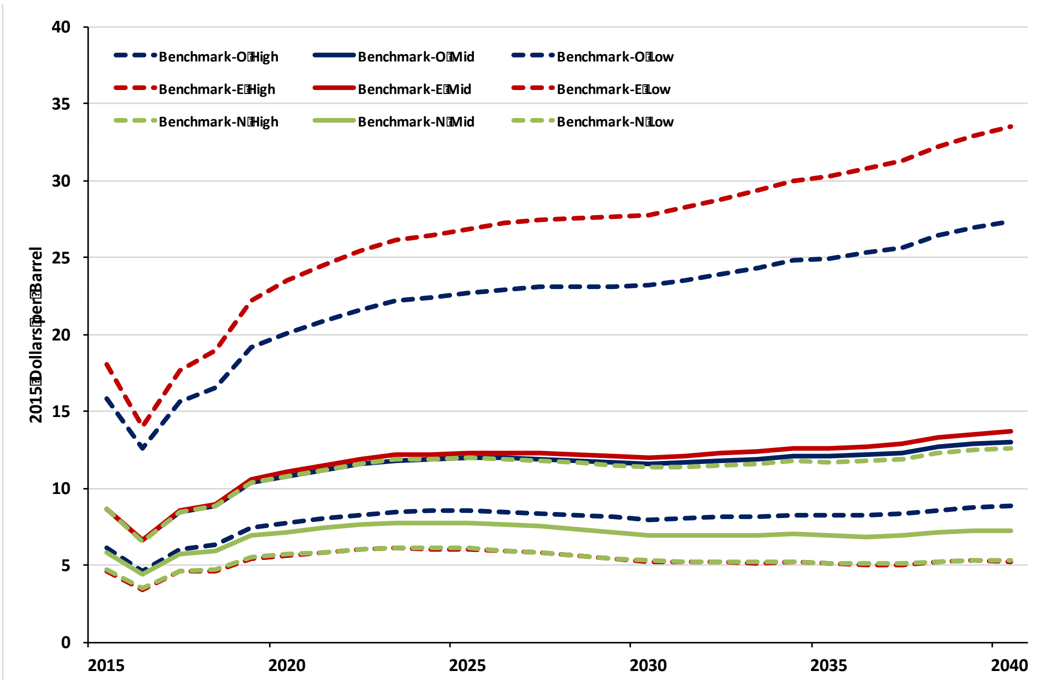
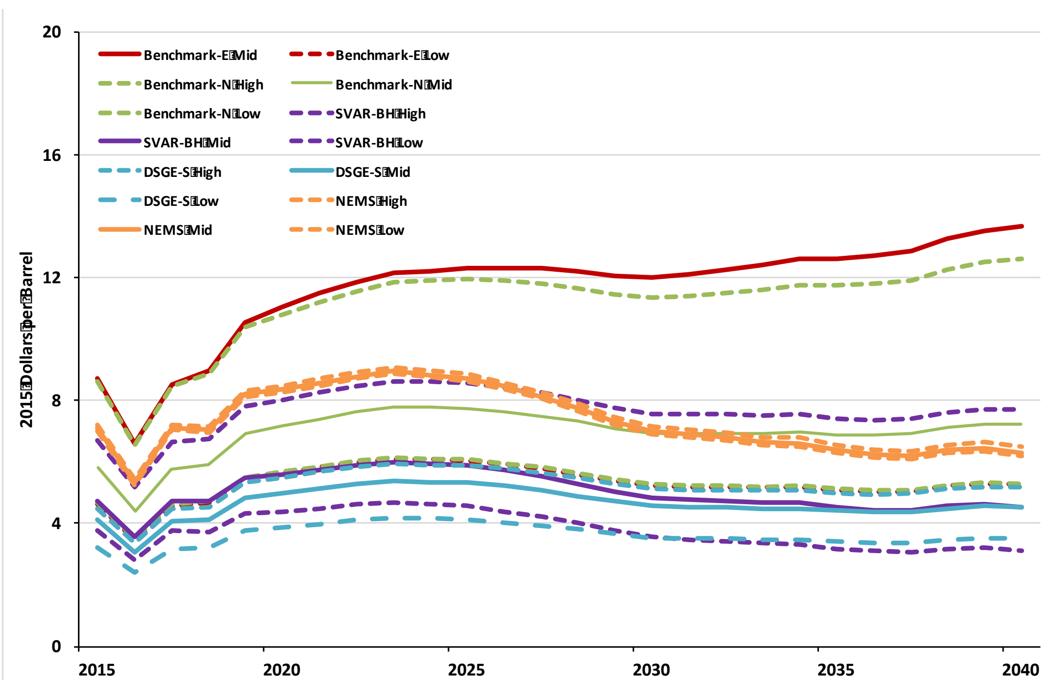


Figure SI-1.5b. Traditional Oil Premiums for Imported vs. Domestic Oil



Supplemental Information (SI)-2. Computing the Components of the Oil Security Premiums

Most broadly conceived, the oil premiums comprise six elements: 1) the monopsony premium, 2) the expected transfer on the marginal barrel of imported oil (which is equal to the expected price shock), 3) the change in the expected US GDP loss as the result of a marginal increase in US consumption of imported oil, 4) the change in the expected US GDP loss as the result of a marginal increase in US consumption of domestic oil, 5) the change in expected transfers on the inframarginal barrels of imported oil as a result of a marginal increase in US consumption of imported oil, and 6) the change in expected transfers on the inframarginal barrels of imported oil as a result of a marginal increase in US consumption of domestic oil. Brown and Huntington (2015) provide guidance in the calculation of all six components.

SI-2.1. The Monopsony Premium

As described in Section D-2.3.1 above, the monopsony premium for any given year is

$$MP = \frac{\partial P_W}{\partial Q_M} Q_M \qquad \text{(SI-2.1)}$$

where MP is the monopsony premium, P_W is the world price of oil and Q_M is the quantity of US oil imports.

Equation B.1 can be evaluated with market quantities and price and the long-term elasticities of non-US supply and demand as follows:

$$MP = \frac{P_W}{\eta_{SLR}\left(\frac{QS_{ROW}}{Q_M}\right) - \eta_{DLR}\left(\frac{QD_{ROW}}{Q_M}\right)} \qquad \text{(SI-2.2)}$$

where η_{SLR} is the long-run price elasticity of world oil supply, QS_{ROW} is the quantity of oil produced outside the United States, η_{DLR} is the long-run price elasticity of world oil demand and QD_{ROW} is the quantity of oil consumed outside the United States.

SI-2.2. Expected Transfers on the Marginal Barrel of Imported Oil

As described in Section D-2.3.2 above, the consumer of the marginal barrel of oil faces an expected oil price shock, $E(\Delta P_W)$, which is transferred to the oil producers. For the consumer of the marginal barrel of domestic oil, the transfer is a net wash for the United States. For the consumer of the marginal barrel of imported oil, the transfer goes to foreign producers. As described above, this transfer should not be considered an externality.

Evaluating the expected price increase for any given year involves summing over the products of the probabilities of individual disruptions and the oil price shocks that would result from those disruptions, as follows:

$$E(\Delta P_W) = \sum_{i=0}^{n} \varphi_i \cdot \Delta P_{Wi}(D_i) \qquad \text{(SI-2.3)}$$

where $E(\Delta P_W)$ is the expected price increase over *n+1* different sized oil-supply disruptions including zero disruption, φ_i is the probability of disruption D_i, $\Delta P_{Wi}(D_i)$ is the increase in price resulting from disruption D_i, and $\sum_{i=0}^{n} \varphi_i = 1$.

For each given oil supply disruption in a given year, the resulting price is

$$\Delta P_{Wi} = P_W((Q_W - D_i)/Q_W)^{1/\eta} - P_W \qquad \text{(SI-2.4)}$$

where ΔP_{Wi} is the change in price from disruption D_i, P_W is the world oil price before the supply disruption, Q_W is world oil consumption before the disruption and η is an encompassing short-run elasticity that takes into account world oil market conditions and a number of elasticities as follows:

$$\eta \equiv (\eta_{DUS} + \eta_{YUS}\eta_{GUS})\frac{QD_{US}}{Q_W} + (\eta_{DROW} + \eta_{YROW}\eta_{GROW})\frac{QD_{ROW}}{Q_W} - \eta_{SUS}\frac{QS_{US}}{Q_W} - \eta_{SROW}\frac{QS_{ROW}}{Q_W} \quad \text{(SI-2.5)}$$

where η_{DUS} is the short-run price elasticity of US oil demand, η_{YUS} is the US, income elasticity of oil demand, η_{GUS} is the elasticity of US real GDP with respect to oil prices, QD_{US} is the quantity of US oil consumption, η_{DROW} is the short-run price elasticity of ROW oil demand, η_{YROW} is the ROW income elasticity of oil demand, η_{GROW} is the elasticity of ROW real GDP with respect to oil prices, QD_{ROW} is the quantity of ROW oil consumption, η_{SUS} is the short-run price elasticity of US oil supply, QS_{US} is US oil production, η_{SROW} is the short-run price elasticity of ROW oil supply, and QS_{ROW} is ROW oil production.

SI-2.3. Change in Expected Transfers on Inframarginal Oil Imports

To evaluate the change in expected transfers on the inframarginal barrels of imported oil, the quantity of US oil imports is computed for each size disruption, D_i. World oil market conditions also are adjusted to a new equilibrium for a small increase in US oil consumption of either imported or domestic oil. A new set of disruption prices are calculated. The change in transfers on inframarginal imports is calculated for each size disruption and aggregated as follows:

$$\Delta E(\Delta P_W) \cdot Q_M = \sum_{i=0}^{n} \varphi_i \cdot Q_{Mi}(D_i) \cdot (\Delta P'_{Wi}(D_i) - \Delta P_{Wi}(D_i)) \qquad \text{(SI-2.6)}$$

where $\Delta E(\Delta P_W) \cdot Q_M$ is the change in expected transfers on inframarginal oil imports, $Q_{Mi}(D_i)$ is the quantity of US oil imports during disruption D_i, and $\Delta P_i'(D_i)$ is the increase in price resulting from disruption D_i with increased US consumption of imported or domestic oil.[16]

SI-2.4. Change in the Expected US Real GDP Losses

For a given oil supply disruption in a given year the resulting loss in US real GDP is

$$\Delta Y_i = Y_{US} \cdot \left(\frac{P_W + \Delta P_{Wi}(D_i)}{P_W}\right)^{\eta_{GUS}} - Y_{US} \qquad \text{(SI-2.7)}$$

where ΔY_i is real GDP loss from supply disruption D_i and Y_{US} is US real GDP before the supply disruption.

The expected US real GDP loss is the sum of the products of the probabilities of individual disruptions and the US real GDP losses that would result from those disruptions, as follows:

$$E(\Delta Y) = \sum_{i=0}^{n} \varphi_i \cdot \Delta Y_i(D_i) \qquad \text{(SI-2.8)}$$

To evaluate the change in expected real GDP losses for an increase in either imported or domestic oil, world oil market conditions are adjusted to a new equilibrium for a small increase in US oil consumption of either imported or domestic oil. A new set of disruption prices and expected real GDP losses are computed.[17] The difference between the two estimates is the change in the expected US GDP loss.

$$\Delta E(\Delta Y) = \sum_{i=0}^{n} \varphi_i \cdot \Delta Y_i'(D_i) - (\Delta Y_i(D_i) \qquad \text{(SI-2.9)}$$

where $\Delta E(\Delta Y)$ is the change in the expected US real GDP loss and $\Delta Y_i'(D_i)$ is the US real GDP loss from disruption D_i with increased US consumption of either imported or domestic oil.

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[16] As explained in Section D-2.3.2 above, the purchase of additional imported oil boosts non-U.S. oil production and increases the size of expected oil supply disruptions, which increases the expected oil price shock for consumers of the inframarginal barrels of imported oil. In contrast, the purchase of additional domestic oil dampens the expected price shock from oil supply disruptions, which decreases the expected transfers for the inframarginal barrels of imported oil.

[17] As explained in Section D-2.3.3 above, a greater value is obtained for an increase in the consumption of imported oil than for the consumption of domestic oil. This difference arises because the increase in domestic oil increases the share of world oil from stable producers while the increase in the consumption of imported oil increases the share of world oil from unstable producers.