Welfare Costs of Oil Shocks

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Abstract

This paper investigates the costs of oil shocks for the economy's welfare. Using a VECM, we empirically show that domestic US oil production shocks only have a weak and temporary impact on macroeconomic variables, while the effect of global oil price shocks is persistent and economically and statistically significant. We rationalize these findings within a calibrated two-sector model in which oil is an input factor for industrial production and also part of the household's consumption bundle. Based on the model, we show that oil shocks are associated with considerable welfare costs for oil-importing economies. Our framework enables several experiments regarding the welfare implications of a reduced oil share in production and consumption, the strategic petroleum reserve, and technological innovations such as fracking.

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1 Introduction

Oil prices are often indicative of the strength or sluggishness of the economy. This follows since oil is an important input in production but also serves as a major consumption good. Supply and demand shocks therefore play a key role in the fluctuations of oil prices, and consequently the economy's investment response to these shocks. In this paper, we quantify the welfare costs of different types of oil shocks for the economy. We find that oil shocks are associated with costs in the order of transitory business cycle shocks, which is remarkable given an oil share of the economy of about 3%.

We identify and quantify the effects of oil shocks on the US economy by considering a vector error correction model (VECM) with four variables: real consumption, industrial production, oil prices, and domestic oil production. While the former two variables capture business cycle fluctuations in the United States, the latter ones allow us to characterize the effect of two different types of oil shocks on the economy — oil supply shocks due to domestic production fluctuations, and oil price shocks that are caused by changes in supply and demand in the global oil market and affect the amount of oil imported to the US. Our estimation results show that domestic oil production shocks only have a weak and temporary impact on the economy, while the effect of oil price shocks is persistent and economically and statistically significant. In particular, a one standard deviation oil price shock depresses the macroeconomy's production output by more than 0.5% over a horizon of 4 years. We further show that imposing cointegration as part of the VECM system has important economic implications, as a simple unrestricted vector autoregression (VAR) model leads to qualitatively and quantitatively different results.

To analyze the economic welfare costs of the different oil shocks, we model and calibrate a two-sector production economy. The economy consists of a standard production sector that takes oil as an input and another sector where oil drilling and extraction takes place. Households consume final goods but also value oil as part of their consumption bundle. The model includes three kinds of shocks: macroeconomic productivity shocks, domestic oil production shocks, and foreign oil supply shocks. It turns out to be challenging for an otherwise standard two-sector model to reproduce the large impact of foreign oil supply shocks — which we identify with the oil price shocks in the VECM — that is observed empirically. To resolve this issue, we consider two amplification mechanisms proposed by the literature, on the one hand imperfect competition and time-varying markups (see Rotemberg and Woodford 1996), and on the other hand variable depreciation in connection with oil-dependent capital utilization as proposed by Finn (2000).[1]

Combining both mechanisms, we are able to generate a sizeable impact of persistent foreign oil supply shocks on macroeconomic aggregates, in line with the oil price shocks in our estimated VECM. As households in our model have Epstein and Zin (1991) preferences with a preference for early resolution of uncertainty, the persistence of the response to different shocks plays a key role for their welfare costs for the economy. In addition to that, the model also reproduces the effect of macroeconomic productivity shocks and domestic oil production shocks as observed empirically, the most important macro facts regarding general and oil-related investment, output, and consumption, and key asset pricing facts.

Having calibrated the model, we use its framework to ask several welfare and policy questions. First, we ask how much shutting down oil shocks would contribute to the welfare of the

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[1] The amplification mechanism based on oil-dependent capital utilization is widely used in the oil-related macro literature, see Leduc and Sill (2004) and Kormilitsina (2011), for example.

domestic economy. We show that the welfare cost of uncertainty related to foreign oil supply shocks — the oil shocks with the largest impact — is in the order of 2% of consumption certainty equivalent, which is similar to the cost of short-run macro shocks. This is quite remarkable given that the overall share of oil in the economy's production and consumption is only about 3%. The reason that oil productivity shocks have such important effect is their high persistence, which is critical to agents with recursive preferences.

Second, our modeling framework allows for a number of additional experiments. These include asking what is the value of decreasing the oil intensity in the economy (as the government can in principle encourage production and consumption that is less oil dependent), how much oil inventories and the Strategic Petroleum Reserve contribute to the economy's welfare, and how oil-related technological innovations such as fracking may help reducing the economy's exposure to oil shocks.

Our paper contributes to the literature that analyzes the role of oil for the general macroeconomy (see Rogoff 2006 for a survey of this literature). On the empirical side, Hamilton (1983), Barsky and Kilian (2004), and Hamilton (2008), quantify the effect of oil shocks on macroeconomic variables by estimating VAR models. The general takeaway of this research is that oil shocks have a significant impact on the general economy. Theoretical contributions such as Rotemberg and Woodford (1996), Finn (2000), Wei (2003), and Lippi and Nobili (2012) aim at rationalizing these effects by considering various different economic channels. In a more recent line of work, Blanchard and Galí (2010) and Blanchard and Riggi (2013) investigate the possibility that the economic impact of oil shocks has changed over time.

The remainder of this paper continues as follows: Section 2 provides our empirical analysis of the impact of oil shocks on the US economy. Section 3 describes our general equilibrium model. Section 4 discusses our calibration. Section 5 presents the welfare analysis by shutting down different sources of uncertainty in the model. Section 6 provides concluding remarks.

2 Impact of Oil Shocks on the US Economy

2.1 Econometric Framework

To analyze the impact of oil shocks on the US economy, we consider a VECM of the form

$$\Delta y_t = \Pi y_{t-1} + \Gamma_1 \Delta y_{t-1} + \ldots + \Gamma_{p-1} \Delta y_{t-p+1} + u_t, \tag{1}$$

with structural innovations $\varepsilon_t = B^{-1} u_t \sim N(0, I_K)$, in the four variables

$$\begin{bmatrix} \text{Real Consumption US} \\ \text{Real Industrial Production US} \\ \text{Real Oil Price} \\ \text{Oil Production US} \end{bmatrix}.$$

The choice of variables that we consider is motivated as follows: We capture business cycle fluctuations in the US by including consumption and industrial production into the VECM, as motivated by Beaudry, Collard, and Portier (2011). On the other hand, we consider the domestic production of oil in the US and the real oil price to identify oil-related shocks that are orthogonal to genuine business cycle fluctuations. While we explicitly capture shocks to the domestic production of oil in the United States, we think of oil price shocks as changes of supply and demand in the global oil market that affect the amount of oil imported to the US. Typical examples for oil price shocks are on the one hand the oil crises in the 1970s, which were characterized by a considerable decrease of global oil supply, or on the other hand the strong economic growth in the emerging Asian countries in the 2000s, which led to an increase in oil prices due to the rising oil demand (Kilian and Murphy 2014).

Our econometric approach is structurally similar to Kilian (2009), but there are some crucial differences: First, that author focuses on the question how oil prices are driven by global supply and demand shocks, characterized as changes in world economic activity and oil production. In contrast, we are interested in the question how fluctuations of the scarcity of oil affect economic welfare in the United States as a large oil consuming country. Second, we consider a VECM instead of a simple VAR to account for possible cointegration relations between different variables of our system. Economically, it is obvious that most of the four variables considered share a common trend as they grow with the US economy, and are therefore cointegrated. In the benchmark specification, we assume that there is only one non-stationary trend in the system, which means that the number of cointegration relations is 3. We show in Section 2.2 that ignoring these cointegration relations leads to qualitatively and quantitatively different results.

Finally, we orthogonalize the shocks of the model by setting six elements of B to zero, while the $*$ elements are estimated. Particularly, we set

$$B = \begin{pmatrix} * & 0 & 0 & * \\ * & * & 0 & * \\ * & * & * & * \\ 0 & 0 & 0 & * \end{pmatrix}. \tag{2}$$

A zero element in the i-th entry of the j-th column means that the shock corresponding to variable i has no *contemporaneous* impact on variable j of the system. Our choice of zero elements is in line with the literature: According to Kilian (2009), the oil production is predetermined and cannot be contemporaneously influenced by one of the other variables (last row of B). Similarly, the oil price does not influence one of the other variables contemporaneously (third column of B). In addition, we take from Beaudry, Collard, and Portier (2011) the restriction that industrial production does not have a contemporaneous impact on consumption (second column of B, first entry). In addition to this short-run orthogonalization, we also consider alternative identification schemes for robustness, especially also long-run identification in the style of Blanchard and Quah (1989).

2.2 Empirical Results

We estimate our econometric model based on monthly data from 1974 to 2013. Our data on household consumption is obtained from the National Income and Product Accounts (NIPA) tables published by the Bureau of Economic Analysis (BEA), and we use industrial production data as provided by the St. Louis Federal Reserve Bank database FRED. Further, we use oil prices and data on the oil production in the United States from the Energy Information Administration (EIA). All variables considered are in real units and deterministically detrended.

Let us first discuss the business cycle shocks as illustrated by the impulse response functions in Figure 1. The effect of business cycle shocks on the economy's consumption and industrial production is almost identical to the results in Beaudry, Collard, and Portier (2011), where a system of only these two variables is considered. Therefore, the addition of oil-related variables to the system does not negatively affect the capabilities of the econometric model to capture business cycle fluctuations properly. In addition to that, we observe that a positive business cycle shock leads to a positive and significant oil price increase, providing further evidence that the business cycle shocks are correctly identified. The effect on domestic oil production is ambiguous — while oil production increases for a positive shock attributed to industrial production, it falls for a positive consumption shock.

[Figure 1 about here.]

Figure 2 presents the impulse response functions for the effect of oil shocks on the US economy. It is eye-catching that the impact of the two different oil shocks on consumption and industrial production is very different: While domestic oil production shocks only have a weak and temporary impact on the economy, the effect of oil price shocks is persistent and economically and statistically significant. In particular, a one standard deviation — or about 10 percent — increase in oil prices leads to a fall in US industrial production by about 1%, and a drop in consumption by about 0.5%. The persistence of this type of shocks is very high, as the effect still lasts 50 months after the shock has materialized. In line with intuition, the increase in oil prices also leads to a surge of domestic oil production. The adjustment to a higher level of domestic production takes, however, a very long time, which can be explained by considerable investment lags in this industry.

[Figure 2 about here.]

We analyze several alternative specifications of our econometric model. First, we vary the number of cointegration relations and the type of restrictions that are imposed on the orthogonalization matrix B. In particular, we replace some of the short-run restrictions that are imposed in our benchmark specification by long-run restrictions that set the persistent impact of certain shocks to zero. Appendix A provides an overview of the specifications that we consider. As Figure 3 illustrates, the impact of oil shocks on the economy in the alternative specifications is very similar to the benchmark, and almost always within the corresponding significance bounds.

Second, we consider a simple VAR in first differences, i.e., we do not account for any cointegration relations between the variables of our system. Figure 3 shows that ignoring the cointegration relations leads to qualitatively and quantitatively different results. First, a simple VAR delivers a persistent effect of a domestic oil production shock on industrial production, while the impact is only temporary in our benchmark specification. The reason is that the long-run relations between the variables of the system are not accounted for by a VAR in first differences, and therefore all shocks — also the business cycle shocks — are by definition persistent. Second, the VAR leads to an effect of the oil price shock that is quantitatively only half the size of the one observed in the benchmark model.

[Figure 3 about here.]

3 Model Setup

We analyze the welfare costs of oil shocks within a general equilibrium framework with a general macro sector and an oil sector, building on Hitzemann (2015). Oil is used in the model both as an input factor for industrial production as well as as part of the household's consumption bundle. Oil producers make endogenous oil drilling and inventory decisions and are subject to oil productivity risk. We account for the persistent oil shocks that are *not* due to domestic productivity fluctuations — as identified in the previous section — by introducing a foreign oil producer whose oil production is imported by the domestic firm. The impact of these shocks on the general macroeconomy is enhanced by two propagation mechanisms: imperfect competition and time-varying markups in line with Rotemberg and Woodford (1996), and energy-dependent capital utilization as proposed by Finn (2000).

3.1 Household

The household in our model consumes a bundle of general consumption goods C, oil barrels B, and leisure L, given by

$$u(C, B, L) = L_t^{1-\varsigma} \left[(1-\theta) C^{1-\frac{1}{\rho}} + \theta B^{1-\frac{1}{\rho}} \right]^{\frac{\varsigma}{1-\frac{1}{\rho}}}, \tag{3}$$

where $\tilde{\theta} = \theta^{\rho}$ is the oil share of non-durable goods consumption, ρ is the constant elasticity of substitution between oil consumption and consumption of the general good, and $1 - \varsigma$ describes the share of leisure in the household's utility. More precisely, $L_t = A_t l_t$ is growth-adjusted leisure to ensure balanced growth of the economy. The household maximizes Epstein and Zin (1991) preferences

$$V_t = \left[(1-\beta) u(C_t, B_t, L_t)^{1-\frac{1}{\psi}} + \beta \mathbb{E}_t \left[V_{t+1}^{1-\gamma} \right]^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{1}{1-\frac{1}{\psi}}}, \tag{4}$$

which allow to separate the intertemporal elasticity of substitution ψ from the relative risk aversion γ, and is subject to the wealth constraint

$$W_{t+1} = (W_t - C_t - P_t B_t - W_t^N L_t) R_{t+1}^W, \tag{5}$$

where P_t is the oil price and W_t^N denotes labor wages.

3.2 Production Sector

The production sector consists of final goods producers, intermediate goods producers, and capital producers. Final goods producers compose the intermediate goods and are perfectly competitive. Intermediate goods are produced using capital and oil as an input. The firms in this sector are monopolistically competitive, which leads to price markups in line with Rotemberg and Woodford (1996). Capital producers accumulate physical capital and rent it to the intermediate goods producers.

Final Goods Final goods Y_t are composed of a continuum of intermediate goods $Y_{i,t}$ according to the production function

$$Y_t = \left(\int_0^1 Y_{i,t}^{\frac{\nu-1}{\nu}} di \right)^{\frac{\nu}{\nu-1}}. \tag{6}$$

Firms in this sector are perfectly competitive, and choose the intermediate goods inputs $Y_{i,t}$ with the goal of maximizing

$$\mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s} (\pi_{t+s} Y_{t+s} - \int_0^1 \pi_{i,t+s} Y_{i,t+s} di), \tag{7}$$

where π_t is the price of the produced final goods, $\pi_{i,t}$ denotes the price of intermediate good i, and M_{t+s} is the s-period stochastic discount factor.

Intermediate Goods The production of intermediate goods $Y_{i,t}$ involves the input of capital $K_{i,t}$, labor $n^Y_{i,t}$, and oil $J_{i,t}$. In line with the literature (Kim and Loungani 1992; Backus and Crucini 2000), oil is combined with physical capital first,

$$X_{i,t} = \left[(1-\iota)K_{i,t}^{1-\frac{1}{o}} + \iota J_{i,t}^{1-\frac{1}{o}}\right]^{\frac{1}{1-\frac{1}{o}}}, \tag{8}$$

where $\tilde{\iota} = \iota^o$ is the share of oil and o is the constant elasticity of substitution between oil and capital for industrial production. After that, the additional input of labor $n^Y_{i,t}$ leads to the intermediate goods

$$Y_{i,t} = (A_t n^Y_{i,t})^{1-\alpha} X^{\alpha}_{i,t}, \tag{9}$$

with $1-\alpha$ defining the labor share of production in the economy.

The intermediate goods producing firms are monopolistically competitive and optimize

$$\mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s}(\pi_{i,t+s}(Y_{i,t+s})Y_{i,t+s} - R^K_{t+s}K_{i,t+s} - W^N_{t+s}n^Y_{i,t+s} - P_{t+s}J_{i,t+s}), \tag{10}$$

subject to the final goods producer's demand functions $\pi_{i,t}$ for intermediate goods, where R^K_t is the rental rate for capital and P_t is the oil price.

Capital The capital stock of the economy evolves according to

$$K_{t+1} = (1-\delta(J_t, K_t))K_t + I_t - G_tK_t. \tag{11}$$

Here, we use the idea of Finn (2000), who proposes that the depreciation rate δ is a function of capital and industrial oil consumption, defined as

$$\delta(J_t, K_t) = c_0(J_t/K_t)^{c_1}. \tag{12}$$

Intuitively, capital depreciates more when the relative energy input is higher, as this means that the capital is utilized more intensely.

Investments I_t into the capital stock are subject to adjustment costs, which we define in line with Jermann (1998) as

$$G_t(I_t/K_t) = I_t/K_t - (a_0 + \frac{a_1}{1-\frac{1}{\xi}} (I_t/K_t)^{1-\frac{1}{\xi}}), \tag{13}$$

with parameter ξ. We choose the parameters a_0 and a_1 such that the adjustment costs and their first derivative are zero at the deterministic steady state.

With these ingredients, the capital goods producer maximizes its cash-flows

$$\mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s}(R_{t+s}K_{t+s} - I_{t+s}). \tag{14}$$

3.3 Oil Production

Domestic Oil Sector The domestic oil producer owns an amount of oil wells U_t that evolves as

$$U_{t+1} = (1-\eta)U_t + Z_t - G_t^Z U_t. \tag{15}$$

Oil wells depreciate at a rate of η, which is also the mean oil extraction rate, such that on average the depreciation is only the amount of oil that is extracted. The oil firm drills new wells by using an input of labor n_t^Z, of the general good H_t, and of existing machinery O_t, aggregated as

$$Z_t = (A_t n_t^Z)^{1-\tau} H_t^{\tau} O_t. \tag{16}$$

We assume that the machinery input is exogenous with $O_t = \overline{O}$. Furthermore, G_t^Z is an adjustment cost function that has the same form as the adjustment costs for capital,

$$G_t^Z(Z_t/U_t) = Z_t/U_t - (a_0^Z + \frac{a_1^Z}{1-\frac{1}{\xi^Z}}(Z_t/U_t)^{1-\frac{1}{\xi^Z}}). \tag{17}$$

The extraction of oil from existing wells takes place at an average extraction rate of η according to

$$E_t = \eta \kappa_t U_t, \tag{18}$$

but is subject to oil shocks κ_t, which are specified below in more detail.

Finally, the oil firm manages oil inventories evolving as

$$S_{t+1} = (1-\omega)S_t - \Pi_t A_t + E_{t+1} - B_{t+1} - J_{t+1} + E_{t+1}^*. \tag{19}$$

The inventory stock at time $t+1$ consists of the stock at time t, depreciated by inventory costs ω, plus the amount of oil extracted at time $t+1$, minus the amount of oil that is used for household consumption and industrial production. Furthermore, we assume that the oil firm imports an amount of E_{t+1}^* from a foreign oil producer that is specified below. Finally, Π_t describes a stock-out cost function that approximates the non-negativity constraint on oil inventories, which we specify in line with Hitzemann (2015) as

$$\Pi_t(S_t/A_t) = \frac{\pi}{2}(S_t/A_t)^{-2}, \tag{20}$$

with parameter π.

Overall, the domestic oil firm maximizes its expected discounted cash-flows

$$\mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s}(-H_{t+s} - W_{t+s}^N n_{t+s}^Z + P_{t+s}((1-\omega)S_{t+s-1} - \Pi_{t+s-1}A_{t+s-1} - S_{t+s} + E_{t+s})). \tag{21}$$

In particular, the oil firm has to pay for the oil drilling investment H_t, and for the workers' labor input n_{t+s}^Z. On the other hand, the amount of oil that is not inventoried generates revenues, as it is sold to the household and the intermediate goods producers. The oil imports E_t^* do not contribute to the cash-flows, as they are bought from the foreign oil producer at price P_t and sold again at the same price.

Foreign Oil Sector The structure of the foreign oil sector is very similar to the domestic one. The oil wells evolve as

$$U_{t+1}^* = (1-\eta)U_t^* + Z_t^*, \tag{22}$$

with the same depreciation rate, and oil extraction is given by

$$E_t^* = \eta \kappa_t^* U_t^*. \tag{23}$$

We assume that oil drilling in the foreign oil sector is proportional to the domestic sector, $Z_t^* = \zeta^* Z_t$, with scaling parameter ζ^*. The foreign oil producer sells all the oil extracted to the domestic oil firm.

3.4 Shocks

For the general macroeconomic sector, we consider short-run and long-run shocks to productivity growth $\Delta a_{t+1} = \ln(A_{t+1}/A_t)$, as specified by

$$\Delta a_{t+1} = \mu + \Delta x^s_{t+1} + x^l_t, \tag{24}$$

$$x^s_{t+1} = \phi_s x^s_t + \varepsilon^A_{t+1}, \tag{25}$$

$$x^l_{t+1} = \phi_l x^l_t + \varepsilon^x_{t+1}, \tag{26}$$

with $\Delta x^s_{t+1} = x^s_{t+1} - x^s_t$. The long-run shocks $\varepsilon^x_{t+1} \sim N(0, \sigma^2_x)$ are persistent shocks to productivity *growth* and command large risk premia in an economy where agents have a preference for the early resolution of uncertainty. On the other hand, we specify the short-run shocks $\varepsilon^A_{t+1} \sim N(0, \sigma^2_A)$ as transitory *level* shocks, different to Croce (2014) who introduces them as persistent level shocks. However, our empirical analysis in Section 2.2 clearly shows that business cycle shocks are transitory. Therefore, we transfer the specification of Bansal, Kiku, and Yaron (2010) to the production-based framework.

In the oil sector, productivity shocks affect the extraction rate κ_t or κ^*_t from existing oil wells. In case of a positive oil productivity shock, the extraction rate is higher than the depreciation rate η of oil wells and therefore increases the current and future oil supply to the economy. For the domestic oil sector, we specify

$$\kappa_{t+1} = (1 - \chi) + \chi \kappa_t + \varepsilon^\kappa_{t+1} \tag{27}$$

with short-run oil productivity shocks $\varepsilon^{\kappa}_{t+1} \sim N(0, \sigma^2_{\kappa})$. The extraction rate of the foreign oil sector is specified as

$$\kappa^*_{t+1} = (1 - \chi) + \chi \kappa^*_t + x^*_{t+1} + \varepsilon^{\kappa^*}_{t+1}, \tag{28}$$

$$x^*_{t+1} = \phi_{x^*} x^*_t + \varepsilon^{x^*}_{t+1}, \tag{29}$$

with the same mean-reversion rate χ and short-run shocks $\varepsilon^{\kappa^*}_{t+1} \sim N(0, \sigma^2_{\kappa})$ with the same standard deviation. In addition to that, we also consider persistent shocks $\varepsilon^{x^*}_{t+1} \sim N(0, \sigma^2_{x^*})$ to the foreign oil sector's extraction rate. We identify these shocks with the oil price shocks in our empirical analysis, which are also characterized by a persistent impact on the economy. As we do not observe a persistent effect of domestic oil shocks in our empirical analysis, we do not consider this kind of shock for the domestic oil sector, as its magnitude would be very marginal and not influence the results of our model.

We assume that all shocks in our model are mutually independent and independently normally distributed.

3.5 Equilibrium Conditions

We derive the model's equilibrium conditions, which comprise the household's and firms' first order conditions as well as the market clearing conditions. Detailed calculations for the firms' conditions are provided in Appendix B — the household's conditions are the same as for an analogous endowment economy.

To begin with, we obtain the intratemporal conditions for the oil price and for labor wages.

For the oil price, we have

$$P_t = \frac{\theta}{1-\theta}\left(\frac{B_t}{C_t}\right)^{-\frac{1}{\rho}} = \frac{\alpha\iota}{\varnothing(Y_t)}\frac{Y_t}{J_t^{\frac{1}{o}}X_t^{1-\frac{1}{o}}} - Q_t^I c_1 \delta(J_t, K_t)\frac{K_t}{J_t} \tag{30}$$

in equilibrium, with $Q_t^I = \frac{1}{1-G_t'}$. The first equation is the household's condition that the price of oil is equal to the marginal rate of substitution between oil and the general good for household's consumption. The second equation relates the oil price to the marginal contribution of oil to the industrial production of the general good. Due to the imperfect competition of firms in the intermediate goods sector, there is a price markup $\varnothing$. We assume that the markup depends on the output level Y_t by specifying it as $\varnothing(Y_t) = \mu_\varnothing Y_t^{\varepsilon\varnothing}$, where the elasticity ε determines the cyclicality of markups.

For labor wages, we obtain the household's first order condition

$$W_t^N = \frac{\partial u(C_t, B_t, L_t)}{\partial L_t} \Big/ \frac{\partial u(C_t, B_t, L_t)}{\partial C_t} = \frac{1-\varsigma}{\varsigma(1-\theta)}\left(\frac{u(C_t, B_t, L_t)}{L_t}\right)^{\frac{1}{\varsigma}(1-\frac{1}{\rho})}\left(\frac{C_t}{L_t}\right)^{\frac{1}{\rho}}, \tag{31}$$

and the firm's first order conditions are

$$W_t^N = \frac{1-\alpha}{\varnothing(Y_t)}\frac{Y_t}{N_t^Y} = Q_t^H(1-\tau)\frac{Z_t}{N_t^Z}, \tag{32}$$

with $Q_t^H = \frac{1}{\tau \cdot Z_t/H_t \cdot (1-G_t^{Z\prime})}$.

Intertemporally, the standard Euler equation

$$\mathbb{E}_t\left[M_{t+1}R_{t+1}\right] = 1 \tag{33}$$

holds for the returns R_{t+1} of all assets traded in the economy, where the pricing kernel is given by

$$M_{t+1} = \beta \left(\frac{u(C_{t+1}, B_{t+1}, L_{t+1})}{u(C_t, B_t, L_t)} \right)^{-\frac{1}{\psi}} \frac{\frac{\partial u(C_{t+1}, B_{t+1}, L_{t+1})}{\partial C_{t+1}}}{\frac{\partial u(C_t, B_t, L_t)}{\partial C_t}} \left(\frac{V_{t+1}}{\mathbb{E}_t \left[V_{t+1}^{1-\gamma} \right]^{\frac{1}{1-\gamma}}} \right)^{\frac{1}{\psi} - \gamma} . \tag{34}$$

The Euler equation especially holds for the returns on investment in the general macro sector, for oil drilling investment, and for oil inventories, as given by

$$R_{t+1}^I = \frac{\frac{\alpha(1-\iota)}{\varnothing(Y_t)} \frac{Y_{t+1}}{K_{t+1}^{\frac{1}{o}} X_{t+1}^{1-\frac{1}{o}}} + (1 - \delta(J_t, K_t)(1 - c_1) + {G_{t+1}}' \frac{I_{t+1}}{K_{t+1}} - G_{t+1}) Q_{t+1}^I}{Q_t^I}, \tag{35}$$

$$R_{t+1}^H = \frac{(1 - \eta + G_{t+1}^{Z'} \frac{Z_{t+1}}{U_{t+1}} - G_{t+1}^Z) Q_{t+1}^H + \eta \kappa_{t+1} P_{t+1}}{Q_t^H}, \tag{36}$$

$$R_{t+1}^S = \frac{(1 - \omega - \Pi_t') Q_{t+1}^S}{Q_t^S}, \tag{37}$$

where $Q_t^S = P_t$.

The equity market return is then defined as the weighted average of R^I, R^H, and R^S, according to

$$R_{t+1}^M = \frac{K_t Q_t^I R_{t+1}^I + U_t Q_t^H R_{t+1}^H + S_t Q_t^S R_{t+1}^S}{K_t Q_t^I + U_t Q_t^H + S_t Q_t^S}. \tag{38}$$

The risk-free interest rate and the equity risk premium are defined according to the standard expressions in line with Croce (2014).

Finally, we have the market clearing conditions for the general good,

$$C_t + I_t + H_t = Y_t, \tag{39}$$

and for labor and leisure,

$$l_t + n_t^Y + n_t^Z = 1. \tag{40}$$

4 Calibration

To obtain a solution of the model, we reformulate it as a central planner's problem and solve it numerically. In particular, we use perturbation methods as provided by the `dynare` package and compute a third-order approximation.

[Table 1 about here.]

We calibrate the model in line with the literature on oil markets and macroeconomic models. Table 1 provides an overview of the chosen parameter values. The general preference parameters are set in line with the long-run risk literature in endowment and production economies (Bansal and Yaron 2004; Croce 2014). The general macroeconomic sector is calibrated in line with the classical real business cycle literature and with Croce (2014). Furthermore, we set the parameters describing the oil sector roughly in line with Ready (2014) and Hitzemann (2015). Parameters that do not have standard values in the existing literature are calibrated to match important empirical moments, and particularly the magnitude and persistence of oil shocks. An overview of the quantity and price moments produced by the model compared to the data is provided by Table 2 and Table 3.

[Table 2 about here.]

[Table 3 about here.]

Let us compare the empirical business cycle shocks in Figure 1 with the effect of a short-run macroeconomic productivity shock in the model, as presented in Figure 4. We see that the magnitude and persistence of the effect on consumption and industrial production is very much in line with what is observed empirically. Furthermore, a positive business cycle shock causes a moderate oil price increase of about 1% which is reverted quickly, similar to the effect observed in the data. The impact of business cycle shocks on domestic oil production is very low in the model, which explains why a clear effect can also not be found empirically. Overall, we see that the short-run macroeconomic productivity shock in the model properly captures the effect of business cycle shocks on the macroeconomy and the oil sector.

In the oil sector, we identify the domestic oil production shocks observed in the data with the ε^{κ} shocks in the model, while the oil price shocks are identified with the ε^{x^*} shocks. Figure 5 shows the model-based impulse response functions for both kinds of oil shocks, corresponding to the empirical effects presented by Figure 2. As in the data, the effect of domestic oil extraction shocks on macroeconomic consumption and industrial production is very small. In the same way, there is also only a marginal impact on oil prices.

In contrast to that, the impact of an oil price shock ε^{x^*} on macroeconomic variables is large and very persistent in the model, in line with the data. Consumption decreases more than 0.2% and industrial production falls by almost 0.8% in response to a one standard deviation oil price increase that is caused by a persistent shock to foreign oil production. Thus, the empirically observed response to oil price shocks is captured by the model very well. To obtain this close fit to the data, both amplification mechanisms in the model — time-varying markups and energy-dependent capital utilization —are of critical importance. Without these ingredients, the decline of consumption and production in the model would only be in the order of 0.1% or less. Finally, one should note that the slowly increasing domestic oil production is qualitatively also very well captured by the model, but quantitatively larger than in the data.

[Figure 4 about here.]

[Figure 5 about here.]

5 Welfare Analysis

5.1 Costs of Oil Shocks

Based on our calibration, we quantify the welfare costs of oil shocks within our model, where we proceed in the same way as Lucas (2003) and Croce (2013). Let Λ be the increase in time-zero consumption that the representative agent would require to make him indifferent between the consumption process (C_t, B_t, L_t) in the benchmark model and the process $(\tilde{C}_t, \tilde{B}_t, \tilde{L}_t)$ in an alternative model where some sources of risk are shut down. We describe the welfare costs of different types of shocks by considering $\lambda = \ln(1 + \Lambda)$, which can be calculated based on the corresponding utility-consumption ratios as

$$\lambda = \ln\left(\frac{\tilde{V}_0}{u(\tilde{C}_0, \tilde{B}_0, \tilde{L}_0)}\right) - \ln\left(\frac{V_0}{u(C_0, B_0, L_0)}\right). \tag{41}$$

As our empirical analysis clearly shows that oil price shocks ε^{x^*} have the most significant effect on the macroeconomy, we focus on the welfare costs of these shocks and compare them to the cost of short-run and long-run macroeconomic productivity shocks ε^A and ε^x.

[Table 4 about here.]

Table 4 presents the λs for oil shocks compared to macroeconomic shocks. Our analysis reveals that the representative agent would be willing to give up more than 2% of time-zero consumption for shutting down the uncertainty coming from persistent foreign oil supply shocks. This is actually slightly more than the cost of uncertainty from short-run macro shocks, which we quantify to 1.5%. This result is economically plausible according to the large and persistent effect of oil shocks on macroeconomic variables, together with the fact that short-run macro shocks are transitory in our calibrated model ($\phi_s < 1$). For the case of permanent short-run macro shocks ($\phi_s = 1$), the corresponding growth uncertainty leads to welfare costs of about 12.5% and therefore clearly exceeds the cost of oil shocks. However, the results of our empirical analysis in Section 2.2 suggest that the benchmark calibration is a more accurate description of reality, which means that the welfare cost of oil shocks is in a similar order of magnitude as the cost of short-run macro shocks.

On the other hand, the uncertainty coming from oil shocks is — in either calibration — much less costly for the economy than uncertainty about long-run macroeconomic growth (see also Croce 2013). The effect of oil price shocks is not as long-lasting as the one of long-run macro shocks as the former ones can be mitigated over the longer run by adjustments in oil drilling and subsequent oil production. Therefore, the welfare costs of long-run macro uncertainty are much higher than of oil price uncertainty, especially when agents have a preference for early resolution of uncertainty ($\psi > 1/\gamma$). We see that the costs of long-run macro shocks become smaller for a lower intertemporal elasticity of substitution, $\psi = 0.9$, and the costs of short-macro macro shocks and oil shocks increase. Nevertheless, the result that oil-related uncertainty is much less costly than long-run macro uncertainty also holds for this case.

5.2 Policy Analysis

The model framework of this paper allows us to analyze the implications of policies and structural changes to the oil sector for the welfare of the overall economy. We consider three important issues related to the oil sector that have an effect on the economy's exposure to oil shocks and their propagation.

[Table 5 about here.]

Oil share of industrial production and household consumption. Environmental policies aiming at reducing the oil share of the economy, e.g., by replacing fossil fuels with renewable energy, are implemented around the world. Besides the environmental aspect, changing the economy's oil share also alters the exposure to oil shocks, with potential positive effects for economic welfare. Our model allows us to analyze the welfare implications of a reduced oil share by considering a change of the corresponding parameters for household consumption θ and industrial production ι.

In particular, we consider a scenario of a 20% lower oil intensity of industrial production, i.e., $\widetilde{\theta} = 0.8\,\theta$, and a scenario where the oil intensity of household consumption is 20% lower than in the benchmark case, i.e., $\widetilde{\iota} = 0.8\,\iota$. As Table 5 reveals, a reduced oil intensity of industrial production leads to significant welfare gains for the economy, quantified as 1.67% of time-zero consumption. This result reflects that oil shocks mostly propagate through the production sector, where the effect is amplified by time-varying markups and energy-dependent capital utilization. Accordingly, a lower oil share in production considerably reduces the economy's exposure to oil shocks and increases welfare. Consistent with this finding, the additional welfare gain λ^{x^*} of shutting off oil uncertainty is also *smaller* in the model with reduced oil share in production than in the benchmark model.

On the other hand, reducing the oil intensity of consumption by 20% does not lead to significant welfare gains — in fact, we even observe a slight reduction of economic welfare in the amount of 0.07%. Given that oil shocks mostly propagate through the production sector, it is not surprising that a changed oil intensity of household consumption has only limited welfare effects. The finding that welfare is even slightly reduced might, though, seem puzzling at first sight. However, there are several possible explanations for this result. Similar to Dhawan and Jeske (2008), agents in our model have two margins of adjustment when an oil shock materializes, as oil is used in both production and consumption. Reducing the oil share of consumption shifts the weight towards the production side, where the impact of oil shocks is more incisive, resulting in a negative effect on welfare. More generally, Cho, Cooley, and Kim (2015) show that uncertainty can be welfare-enhancing in the presence of endogenous labor or investment choices if agents are able to "make use of the uncertainty in their favor". Accordingly, a reduction of the oil share in consumption might reduce this opportunity to profit from uncertainty, leading to lower economic welfare.

Overall, our findings show that a reduced oil intensity of the economy only leads to notable welfare gains if the reduction happens in the production sector. A smaller oil intensity of household consumption has only marginal implications for economic welfare.

Strategic petroleum reserve. Oil inventories serve as a cushion to oil shocks and alleviate the effect of oil supply fluctuations on the economy. In addition to that, several countries maintain an oil stock that is managed by the government, for example the *Strate-*

gic Petroleum Reserve in the United States. We can analyze the welfare contribution of holding oil inventories based on our framework. For that, compare the economy's welfare in the full model to the welfare in a model variant where the inventories are shut down. Table 5 shows that shutting down inventories only leads to a marginal reduction of economic welfare. As oil inventories in the US only amount to 15% of annual oil imports (see Table 2), they are just to small to take away much of the extremely persistent effect of oil price shocks on the economy. Therefore, the difference of economic welfare compared to the case with no inventories is also very limited. It should be noted, however, that our analysis might at this point underestimate the role of inventories for economic welfare, as we do not consider oil supply *volatility* shocks in our model. Gao, Hitzemann, Shaliastovich, and Xu (2016) show that oil volatility risk has a considerable impact on macroeconomic variables, where the effect propagates through the inventory channel. Therefore, it might be interesting to extend our analysis to a model with fluctuating oil supply uncertainty.

Fracking and other technological innovations. Technological innovations in the oil sector may have an effect on the exposure of the economy to oil price shocks. As the most important recent example, the technology of hydraulic fracturing — better known as *fracking* — has increased the domestic oil production in the United States significantly, and therefore reduced the exposure towards foreign oil supply shocks. Gilje, Ready, and Roussanov (2015) find that fracking has been an important driver of productivity in the US in the recent years. Our model enables us to quantify the welfare effects of such technological innovations by considering changes of the parameters ζ and τ of the oil drilling function. We will provide a detailed analysis of this aspect in a future version of this paper.

As for the other experiments considered, it should be emphasized that our analysis only quantifies the welfare benefits for the economy. These are naturally opposed by the costs of implementing the respective policy. Especially for the case of fracking, note that the potential benefits of a lower exposure to oil shocks have to be seen in relation to the costs of related environmental damages. As pointed out by Bansal, Kiku, and Ochoa (2015), environmental damages typically have extremely long-run effects for economic growth and are associated with high costs for the economy.

6 Concluding Remarks

The goal of this paper is to quantify the welfare costs of oil shocks for the economy, based on the example of the United States as a large oil importer. For that, we consider an econometric model which allows us to analyze the effect of oil shocks on macroeconomic variables such as industrial production and household consumption. We show that accounting for cointegration relationships between the different variables considered is critical for the qualitative and quantitative results of the econometric analysis. For the welfare analysis, we set up a two-sector general equilibrium model that rationalizes the effects of different oil shocks as characterized by our empirical analysis.

Oil price shocks which are orthogonal to US business cycle shocks and domestic oil production shocks have a sizeable and persistent impact on the US macroeconomy. Our analysis reveals that the welfare cost of such shocks is in a similar order of magnitude as the transitory business cycle component. We find that a decreased oil intensity of industrial production would significantly reduce the economy's exposure to such oil shocks and promote economic welfare. On the other hand, reducing the oil intensity of household consumption to a similar extent would not have notable welfare consequences. Similarly, we do not find a significant welfare contribution of oil inventories. As this research is in a very early stage, it is left to extend and refine the results of our welfare analysis in future versions of this paper. We would also like to quantify the welfare consequences of fracking in the context of our model.

Appendix

A Alternative VECM Specifications

We consider several alternative specifications to our econometric model introduced in Section 2.1. In particular, we also consider specifications that impose long-run conditions in the style of Blanchard and Quah (1989), which allows us to resolve some of the short-run conditions instead. Technically, long-run identification imposes conditions on the matrix ΞB, where

$$\Xi = \beta_\perp \left(\alpha_\perp' (I_K - \sum_{i=1}^{p-1} \Gamma_i) \beta_\perp \right)^{-1} \alpha_\perp', \tag{42}$$

with $\perp$ indicating the orthogonal complement. Setting a column of ΞB to zero defines the corresponding structural shock as purely transitory, not contributing to the common long-run trends of the system.

We consider the following alternative econometric specifications.

3 cointegration relations, short- and long-run restrictions (—)

$$B = \begin{pmatrix} * & 0 & * & * \\ * & * & 0 & * \\ * & * & * & * \\ 0 & 0 & 0 & * \end{pmatrix}, \quad \Xi B = \begin{pmatrix} * & 0 & * & 0 \\ * & 0 & * & 0 \\ * & 0 & * & 0 \\ * & 0 & * & 0 \end{pmatrix}$$

In this specification, we assume the industrial production shock to be only transitory (as in Beaudry, Collard, and Portier 2011), and we also define the oil production shock as a transitory shock. These long-run restrictions give us the flexibility to impose less short-run restrictions. We use that to allow the oil price to have a contemporaneous effect on consumption, in contrast to the benchmark variant.

2 cointegration relations, short- and long-run restrictions (—)

$$B = \begin{pmatrix} * & * & * & * \\ * & * & 0 & * \\ * & * & * & * \\ 0 & 0 & 0 & * \end{pmatrix}, \quad \Xi B = \begin{pmatrix} * & 0 & * & 0 \\ * & 0 & * & 0 \\ * & 0 & * & 0 \\ * & 0 & * & 0 \end{pmatrix}$$

We further vary the number of cointegration relations. In this variant, we assume only 2 cointegration relations. We also remove another restriction from the short-run impact matrix.

VAR in first differences, short- and long-run restrictions (—)

$$B = \begin{pmatrix} * & 0 & 0 & * \\ * & * & 0 & * \\ * & * & * & * \\ 0 & 0 & 0 & * \end{pmatrix}, \quad \Xi B = \begin{pmatrix} * & * & * & * \\ * & * & * & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

Finally, we consider a VAR in first differences with the short-run impact matrix as in the benchmark variant.

B Firms' First Order Conditions

We explicitly derive the firm's first order conditions in our model.

Final Goods Firm The final goods firm solves the optimization problem

$$\max_{Y_{i,t}} \mathbb{E}_t \sum_{s=0}^{\infty} M_{t+s}(\pi_{t+s} Y_{t+s} - \int_0^1 \pi_{i,t+s} Y_{i,t+s} di). \tag{43}$$

subject to (6). As a result, we obtain the demand curve for good Y_i as

$$Y_{i,t} = \left(\frac{\pi_{i,t}}{\pi_t}\right)^{-\nu} Y_t. \tag{44}$$

Intermediate Goods Firm We consider the optimization problem (10) of intermediate goods producers and attach condition (9) with Lagrange multiplier $\phi_{i,t}$, obtaining

$$\begin{aligned}\max_{Y_{i,t},K_{i,t+1},n^Y_{i,t},J_{i,t}} \mathbb{E}_t \sum_{t=0}^{\infty} M_t(\pi_{i,t}(Y_{i,t})Y_{i,t} - R^K_t(J_{i,t})K_{i,t} - W^N_t n^Y_{i,t} - P_t J_{i,t} \\ - \phi_{i,t}(Y_{i,t} - (A_t n^Y_{i,t})^{1-\alpha} X^{\alpha}_{i,t})).\end{aligned} \tag{45}$$

Setting the derivative by $Y_{i,t}$ to zero yields

$$\pi'_{i,t}(Y_{i,t})Y_{i,t} + \pi_{i,t}(Y_{i,t}) = \phi_{i,t}. \tag{46}$$

Now we formulate the demand curve for $Y_{i,t}$ derived before as a function of $Y_{i,t}$, obtaining

$$\pi_{i,t}(Y_{i,t}) = \left(\frac{Y_{i,t}}{Y_t}\right)^{-\frac{1}{\nu}} \pi_t, \quad \pi'_{i,t}(Y_{i,t}) = -\frac{1}{\nu}\frac{\pi_{i,t}(Y_{i,t})}{Y_{i,t}}. \tag{47}$$

Inserting this into (46) yields the condition

$$\pi_{i,t}(Y_{i,t}) = \phi_{i,t}(\frac{\nu}{\nu-1}) \tag{48}$$

Defining $\varnothing = \frac{\nu}{\nu-1}$ as the price markup, we obtain

$$\phi_{i,t} = \frac{\pi_{i,t}(Y_{i,t})}{\varnothing}. \tag{49}$$

Furthermore, we obtain the first order equations by $K_{i,t}$, $n^Y_{i,t}$, and $J_{i,t}$ as

$$R^K_{t+1} = \phi_{i,t+1}\alpha(1-\iota)\frac{Y_{i,t+1}}{K^{\frac{1}{o}}_{i,t+1}X^{1-\frac{1}{o}}_{i,t+1}}, \tag{50}$$

$$W^N_t = \phi_{i,t}(1-\alpha)\frac{Y_{i,t}}{n^Y_{i,t}}, \tag{51}$$

$$P_t = \phi_{i,t}\alpha\iota\frac{Y_{i,t}}{J^{\frac{1}{o}}_{i,t}X^{1-\frac{1}{o}}_{i,t}} - \frac{\partial R^K_t(J_{i,t})}{\partial J_{i,t}}K_{i,t}. \tag{52}$$

Aggregation We insert (49) into the first order conditions (50), (51), (52) and aggregate them, normalizing the $\pi_{i,t}$ to 1. Consequently, we obtain

$$R^K_{t+1} = \frac{1}{\varnothing}\alpha(1-\iota)\frac{Y_{t+1}}{K_{t+1}^{\frac{1}{o}} X_{t+1}^{1-\frac{1}{o}}}, \tag{53}$$

$$W^N_t = \frac{1}{\varnothing}(1-\alpha)\frac{Y_t}{n^Y_t}, \tag{54}$$

$$P_t = \frac{1}{\varnothing}\alpha\iota\frac{Y_t}{J_t^{\frac{1}{o}} X_t^{1-\frac{1}{o}}} - \frac{\partial R^K_t(J_t)}{\partial J_t}K_t. \tag{55}$$

Capital Producers Capital producers optimize (14), and we attach (11) with Lagrange multiplier Q^I_t:

$$\max_{K_{t+1},I_t,J_t} \mathbb{E}_t \sum_{t=0}^{\infty} M_t(R^K_t(J_t)K_t - I_t - Q^I_t(K_{t+1} - (1-\delta(J_t,K_t))K_t - I_t + G_tK_t)). \tag{56}$$

Setting the first derivatives with respect to K_{t+1}, I_t, and J_t to zero yields

$$\mathbb{E}_t[M_{t+1}\frac{R^K_{t+1}(J_{t+1}) + (1-\delta(J_{t+1},K_{t+1}) - \frac{\partial\delta(J_{t+1},K_{t+1})}{\partial K_{t+1}}K_{t+1} + G'_{t+1}\frac{I_{t+1}}{K_{t+1}} - G_{t+1})Q^I_{t+1}}{Q^I_t}] = 1, \tag{57}$$

$$Q^I_t = \frac{1}{1-G'_t}, \tag{58}$$

$$\frac{\partial R^K_t(J_t)}{\partial J_t}K_t = Q^I_t\frac{\partial\delta(J_t,K_t)}{\partial J_t}K_t, \tag{59}$$

where the derivatives of $\delta(J_t,K_t)$ are given by

$$\frac{\partial\delta(J_t,K_t)}{\partial K_t} = -c_1\frac{\delta(J_t,K_t)}{K_t} \quad \text{and} \quad \frac{\partial\delta(J_t,K_t)}{\partial J_t} = c_1\frac{\delta(J_t,K_t)}{J_t}. \tag{60}$$

Oil Firm Finally, we consider the maximization problem of the oil firm (21) and attach condition (15) with Lagrange multiplier Q_t^H:

$$\max_{H_t, N_t^Z, S_t, U_{t+1}} \mathbb{E}_0 \sum_{t=0}^{\infty} M_t(-H_t - W_t^N N_t^Z - Q_t^H(U_{t+1} - (1-\eta)U_t - Z_t + G_t^Z U_t) \\ + P_t((1-\omega)S_{t-1} - \Pi_{t-1}A_{t-1} - S_t + E_t)) \quad (61)$$

Taking the first derivatives by H_t, N_t^Z, S_t, and U_{t+1}, and setting them to zero yields the first order conditions

$$Q_t^H = \frac{1}{\tau \cdot Z_t/H_t \cdot (1 - G_t^{Z\prime})}, \quad (62)$$

$$W_t^N = Q_t^H(1-\tau)\frac{Z_t}{N_t^Z}, \quad (63)$$

$$\mathbb{E}_t[M_{t+1}\frac{(1-\omega-\Pi_t')P_{t+1}}{P_t}] = 1, \quad (64)$$

$$\mathbb{E}_t[M_{t+1}\frac{(1-\eta+G_{t+1}^{Z\prime}\frac{Z_{t+1}}{U_{t+1}} - G_{t+1}^Z)Q_{t+1}^H + \eta\kappa_{t+1}P_{t+1}}{Q_t^H}] = 1. \quad (65)$$

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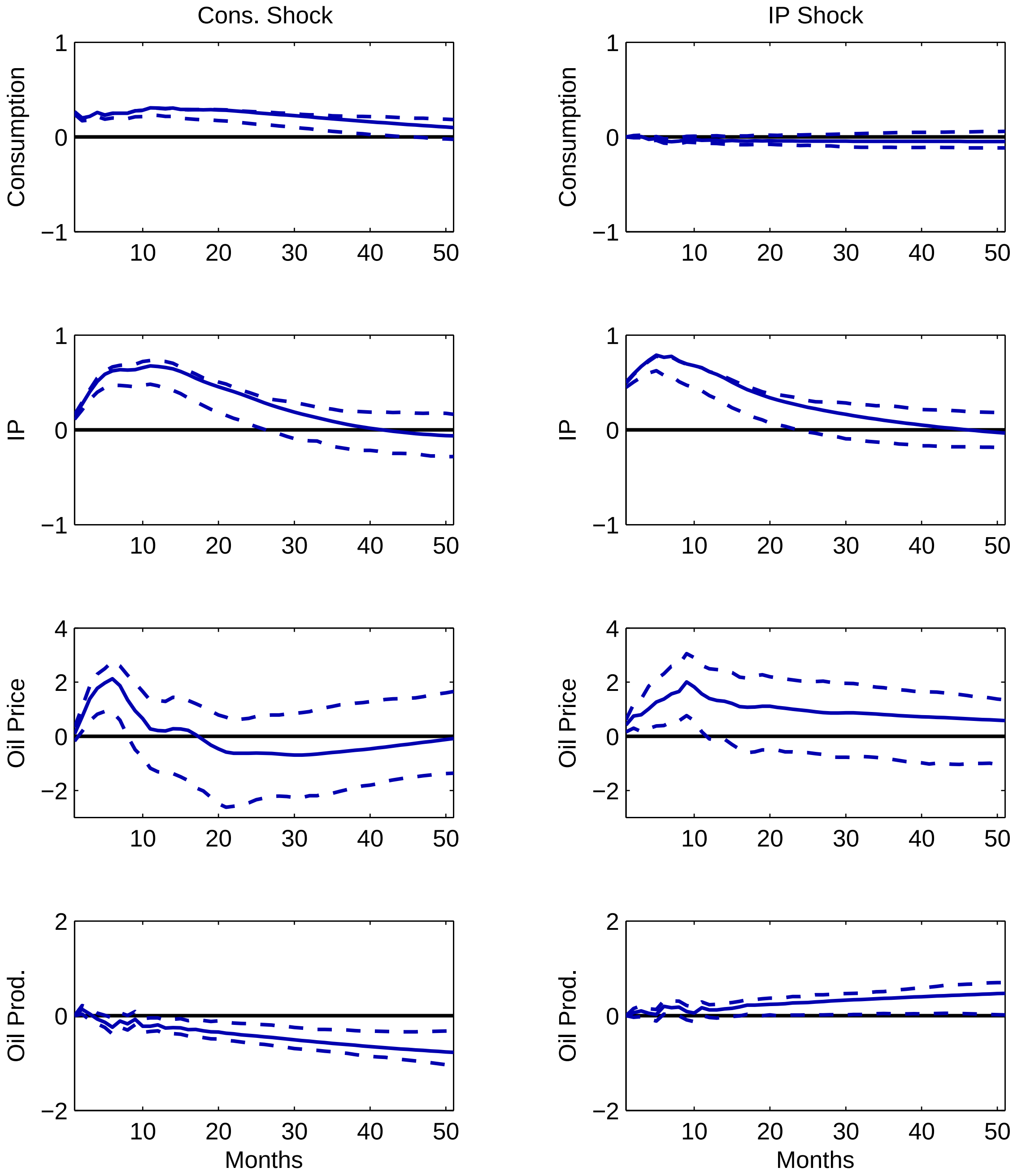

Figure 1: Empirical impulse response functions with respect to business cycle shocks. We compute impulse response functions based on the VECM model specified in Section 2.1.

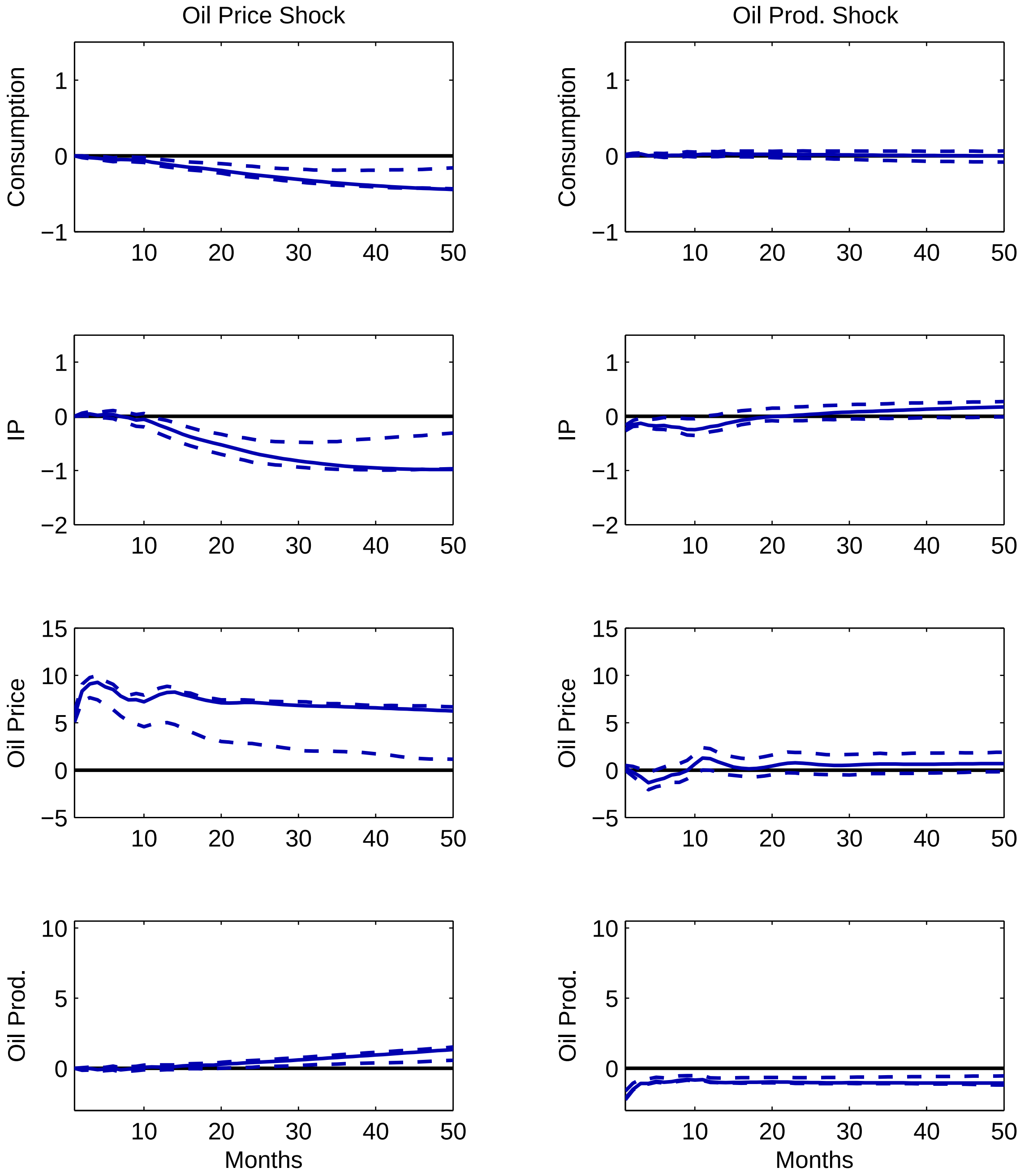

Figure 2: Empirical impulse response functions with respect to oil shocks. We compute impulse response functions based on the VECM model specified in Section 2.1.

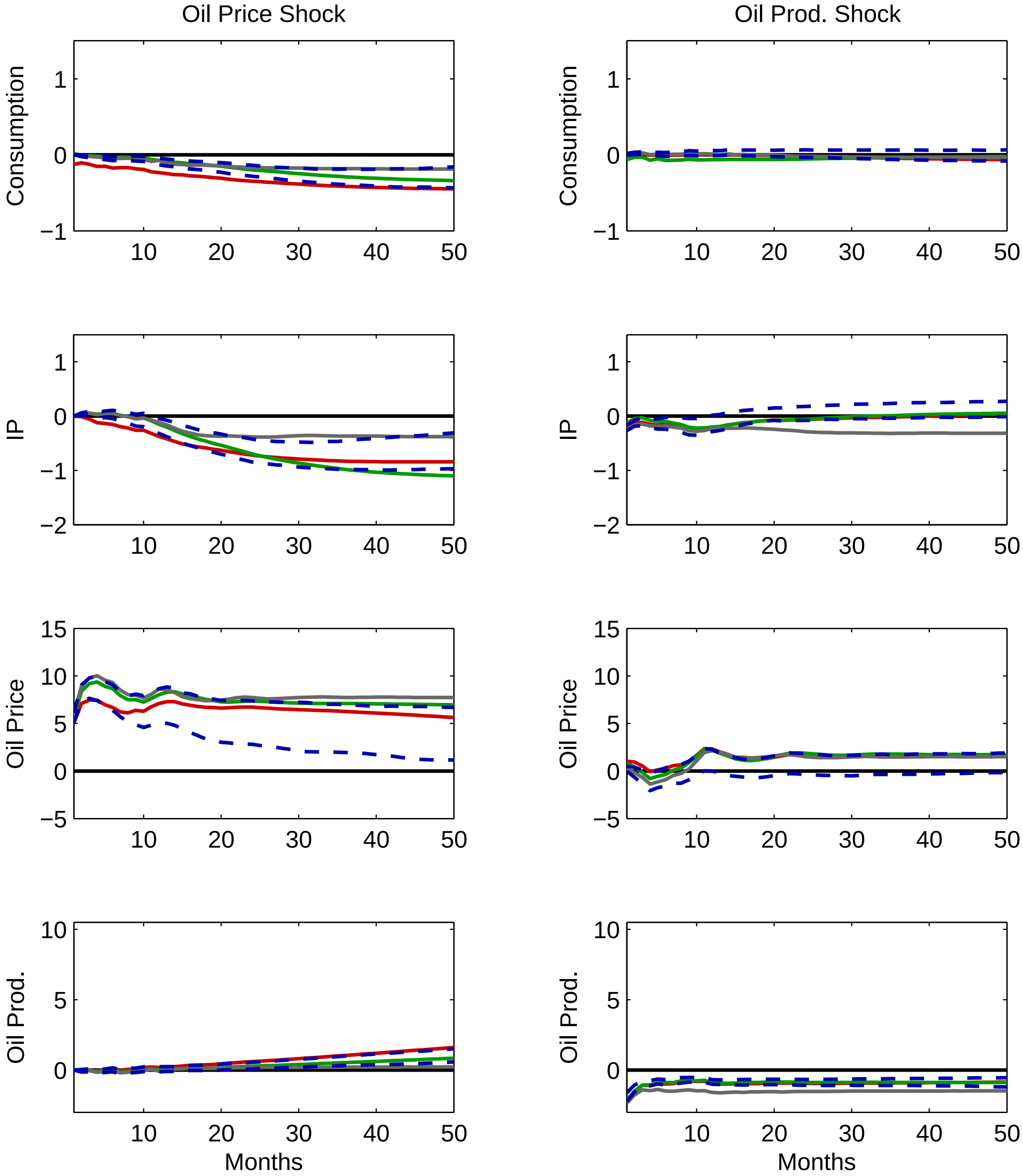

Figure 3: Empirical impulse response functions with respect to oil shocks for alternative specifications of the econometric model. The alternative specifications considered are described in Appendix A. The blue dashed lines stand for the significance bounds of the benchmark specification.

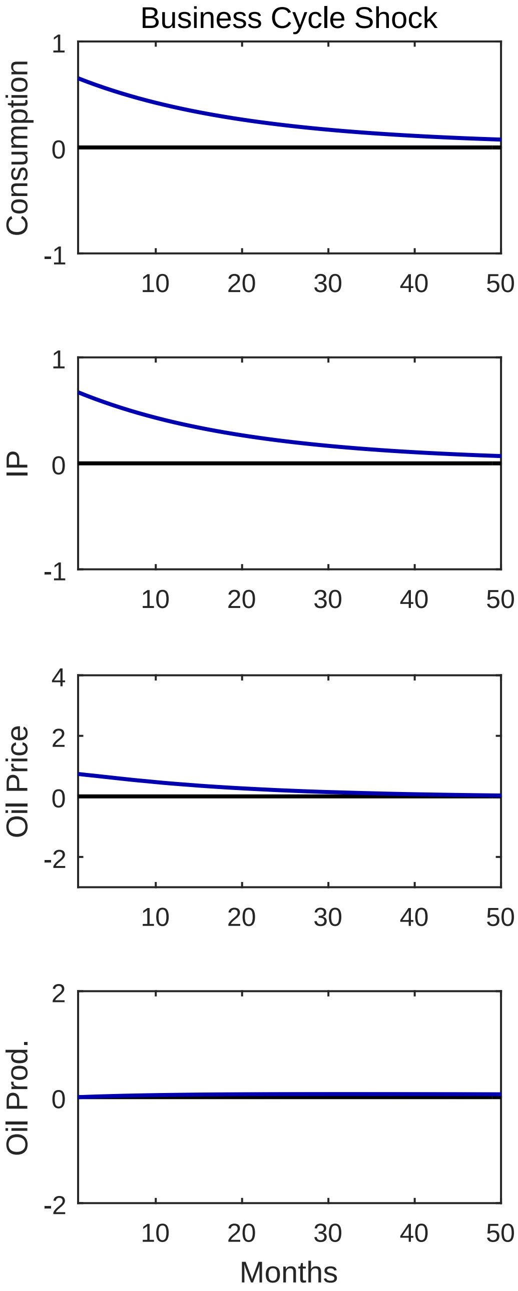

Figure 4: Model-based impulse response functions with respect to short-run macroeconomic productivity shocks ε^A. The parameter values of the calibrated model are provided by Table 1.

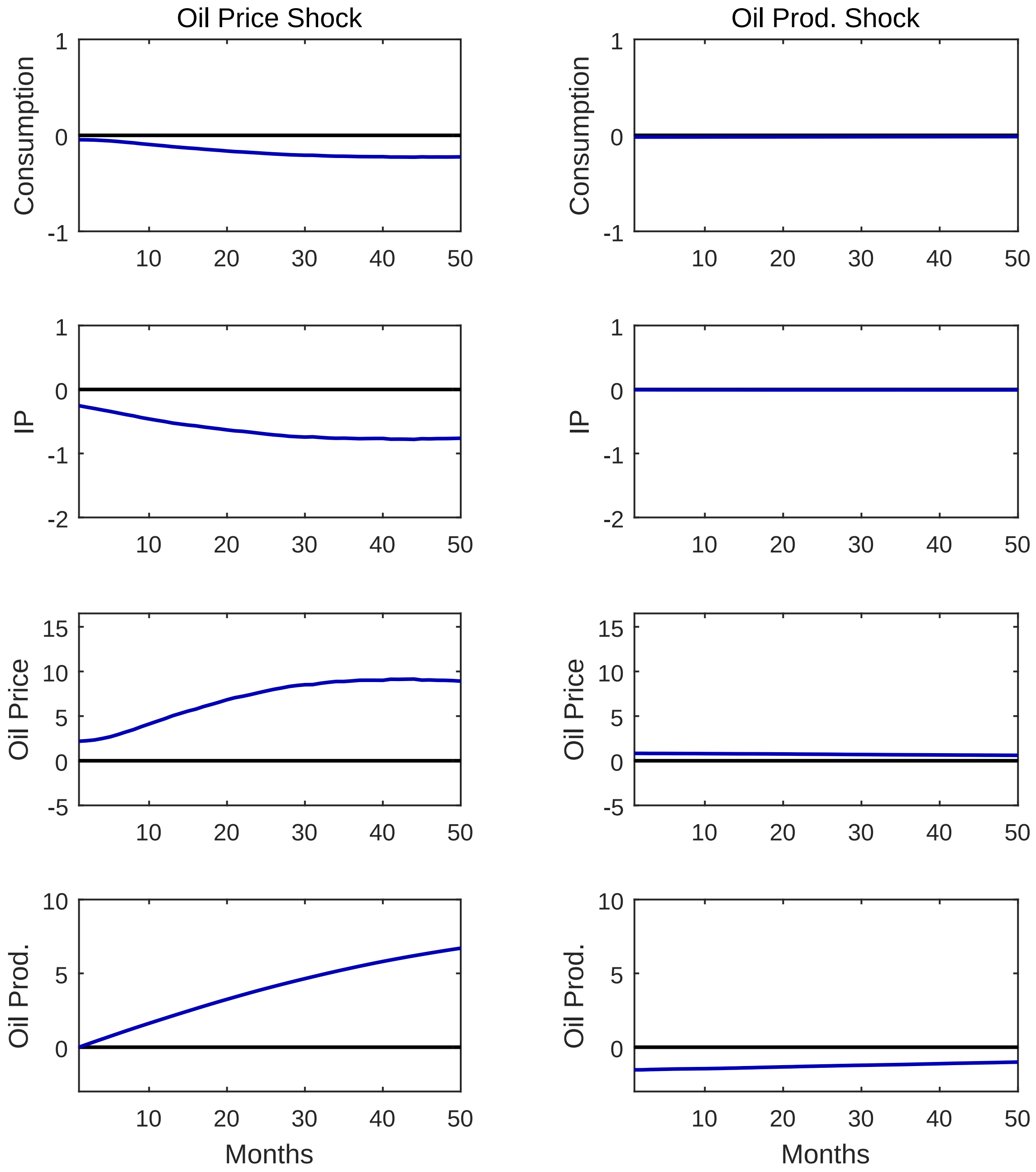

Figure 5: Model-based impulse response functions with respect to oil price shocks ε^{x^*} and domestic oil production shocks ε^{κ}. The parameter values of the calibrated model are provided by Table 1.

Table 1: Model parameters. This table reports parameters describing the household's preferences and the structure of the general macroeconomy and the oil sector for the calibrated model.

Parameter		Value
Preference Parameters		
Subjective discount factor	β	0.95
Relative risk aversion	γ	10
Intertemporal elasticity of substitution	ψ	2
Non-leisure share in consumption	ς	0.205
Oil share in consumption	$\tilde{\theta}$	0.05
Elasticity of subst. between oil and general goods in consumption	ρ	1
General macroeconomy		
Capital share in industrial production	α	0.34
Oil share in industrial production	$\tilde{\iota}$	0.37
Elasticity of substitution between oil and capital in production	o	1
Average growth rate	μ	1.8%
Depreciation rate of capital, level parameter	c_0	1.03
Depreciation rate of capital, elasticity parameter	c_1	0.66
Price markup, level parameter	$\mu_{\varnothing}$	0.77
Price markup, elasticity parameter	$\varepsilon_{\varnothing}$	-0.25
Capital adjustment costs	ξ	3.5
Autocorrelation of short-run productivity level	ϕ_s	0.54
Volatility of short-run risk	σ_A	3.35%
Autocorrelation of long-run productivity growth	ϕ_l	0.8
Volatility of long-run risk	σ_x	$0.1\sigma_A$
Domestic and foreign oil sector		
Capital share of oil drilling	τ	0.6
Machinery	$\overline{O}$	4
Oil inventory costs	ω	0.1
Oil stock-out costs	π	$2 \cdot 10^{-10}$
Average oil production rate	η	0.16
Mean-reversion of oil productivity	χ	0.87
Volatility of oil productivity risk	σ_κ	5.26%
Scaling parameter of foreign oil drilling investment	ζ^*	2
Autocorrelation of persistent foreign shocks	ϕ_{x^*}	0.75
Volatility of persistent foreign shocks	σ_{x^*}	2%

Table 2: Quantities. This table presents important macroeconomic and oil-specific quantities calculated based on the model and the data. Empirical moments are calculated based on annual data for the United States. Lowercase letters refer to log variables, and Δ is the first difference operator.

Statistic	Data	Model
Investment-output ratio $\mathbb{E}[I/Y][\%]$	18.48	20.22
Ratio of oil-related and general investment $\mathbb{E}[H/I]$ $[\%]$	2.80	4.04
Ratio of industrial oil consumption and general consumption $\mathbb{E}[P * J/C]$	0.92	1.05
Ratio of household oil consumption and general consumption $\mathbb{E}[P * B/C]$	1.80	2.66
Oil inventory-production ratio $\mathbb{E}[S/E]$	0.14	0.20
Ratio of oil imported to overall oil supply $\mathbb{E}[E^{*}/(E+E^{*})]$	0.51	0.57
Relative volatility of general consumption and output $\sigma(\Delta c)/\sigma(\Delta y)$	0.61	0.84
Relative volatility of general investment and output $\sigma(\Delta i)/\sigma(\Delta y)$	3.16	1.94
Relative volatility of oil-related and general investment $\sigma(\Delta h)/\sigma(\Delta i)$	3.87	2.39
Relative volatility of oil production and oil investment $\sigma(\Delta e)/\sigma(\Delta h)$	0.21	0.70
Relative volatility of oil inventories and oil production $\sigma(\Delta s)/\sigma(\Delta e)$	1.43	3.44
Relative volatility of oil imports and domestic oil production $\sigma(\Delta e^{*})/\sigma(\Delta e)$	1.57	4.73

Table 3: Prices. This table presents important price variables calculated based on the model and the data. Empirical moments are calculated based on annual data for the United States. Lowercase letters refer to log variables, and Δ is the first difference operator.

Statistic	Data	Model
Equity risk premium $\mathbb{E}[r^{LEV}_{ex,t+1}]$ [%]	6.47	6.40
Risk-free rate $\mathbb{E}[r^f_t]$ [%]	1.17	1.10
Volatility of risk-free rate $\sigma(r^f_t)$ [%]	2.18	1.89
Volatility of short-term oil futures $\sigma(\Delta p_t)$ [%]	37.27	36.56

Table 4: Welfare costs of oil shocks compared to macroeconomic shocks. We quantify the welfare costs of different shocks in our model as the increase in time-zero consumption that the representative agent would require to offset the related economic uncertainty, as described in Section 5.1.

	Benchmark Model	Model with $\phi_s = 1$	Model with $\psi = 0.9$
Oil price shocks (λ^{x^*})	2.19%	2.11%	3.07%
Short-run macro (λ^A)	1.48%	12.49%	2.07%
Long-run macro (λ^x)	230.92%	230.91%	170.19%

Table 5: Experiments and welfare analysis. We modify our benchmark calibration in three ways: Reducing the oil intensity of industrial production by 20%, reducing the oil intensity of household consumption by 20%, and shutting down oil inventories. The first panel reports important moments for these calibrations. In the second panel, we calculate the welfare gain compared to the benchmark calibration. The third panel documents the welfare costs of oil shocks for the modified calibrations in line with Table 4.

	20% reduced oil intensity		
	in production (ι)	in consumption (θ)	no storage
Important quantities			
Ratio of oil-related and general investment $\mathbb{E}[H/I]$ [%]	4.65	3.16	4.03
Ratio of industrial oil consumption and general consumption $\mathbb{E}[P * J/C]$	0.76	1.05	1.05
Ratio of household oil consumption and general consumption $\mathbb{E}[P * B/C]$	2.88	1.91	2.65
Oil inventory-production ratio $\mathbb{E}[S/E]$	0.17	0.24	—
Change of welfare compared to benchmark calibration			
Welfare gain	1.67%	-0.07%	-0.00%
Welfare costs of macro and oil uncertainty			
Oil price shocks (λ^{x^*})	1.98%	2.04%	2.05%
Short-run macro (λ^{A})	1.34%	1.37%	1.38%
Long-run macro (λ^{x})	230.41%	231.67%	231.61%