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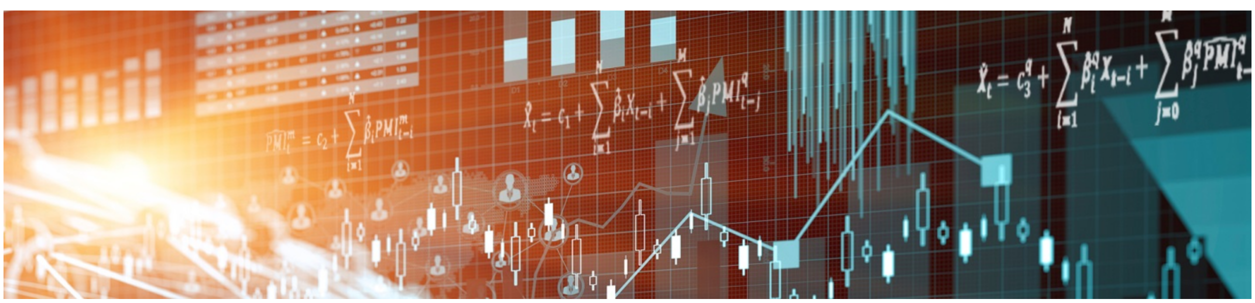
A Structural Model of the Global Oil Market



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Abstract

This note presents a structural vector autoregressive (SVAR) model of the global oil market. The model identifies four types of shocks with different economic interpretations: oil supply shocks, oil-market-specific demand shocks, storage demand shocks and shocks to global economic growth. The historical decomposition of oil price fluctuations suggests that oil supply shocks were the dominant force during the 2014–15 oil price decline. Several examples illustrate the model's usefulness for conditional forecasts of oil market variables under different scenarios for global GDP growth and oil consumption.

Bank topic: Economic models
JEL codes: Q41, Q43

Résumé

La présente note propose un modèle vectoriel autorégressif structurel (SVAR) du marché mondial du pétrole. Le modèle distingue quatre types de chocs ayant chacun leur interprétation économique : les chocs d'offre, les chocs de demande circonscrits au marché du pétrole, les chocs liés à la demande de stockage et les chocs touchant la croissance économique mondiale. La décomposition historique des fluctuations des cours du pétrole semble indiquer que la baisse survenue en 2014-2015 a été principalement causée par les chocs d'offre. À l'aide de plusieurs exemples, l'auteur montre l'utilité du modèle pour établir des prévisions conditionnelles de l'évolution des variables du marché pétrolier selon différents scénarios concernant la croissance du PIB et la consommation de pétrole à l'échelle mondiale.

Sujet : Modèles économiques
Codes JEL : Q41, Q43

1. Why build a structural model of the global oil market?

Fluctuations in oil prices can be traced back to various structural shocks with different economic interpretations**.** Identifying such shocks is important for understanding developments in the oil market and for quantifying the relationship between oil prices and macroeconomic outcomes (Kilian 2009). This note presents a structural vector autoregressive (SVAR) model that links fluctuations in oil prices, oil production, oil consumption and growth in global gross domestic product (GDP) to four types of shocks with different economic interpretations: oil supply shocks, oil-market-specific demand shocks, storage demand shocks, and global economic growth shocks.

The model can also be used to construct conditional forecasts of oil prices that are consistent with different economic growth scenarios. It is common for central banks, private sector forecasters and international organizations to generate model-based projections and scenarios for global GDP growth.[1] By linking oil market variables to global GDP growth, the SVAR model provides a convenient framework to assess how different growth scenarios affect oil prices and the oil market balance. The model is also set up to deliver forecasts based on different oil production and oil consumption scenarios.

In contrast, existing oil market models often lack the ability to incorporate specific scenarios for global GDP growth or oil consumption. Standard SVAR models of the global oil market rely on either (i) global economic activity indicators based on global freight rates (Kilian 2009; Kilian and Murphy 2014) or (ii) a global industrial production index (Caldara, Cavalla, and Iacoviella 2018; Baumeister and Hamilton, forthcoming). While these indicators are available on a higher frequency and can be more reflective of commodity-specific global demand, policy-makers are often interested in tying oil market scenarios to existing forecasts that are based on GDP growth. Another advantage of the model presented in this note is that oil demand is identified with help of global oil consumption data. This facilitates counterfactuals that are based on different oil consumption scenarios, which is particularly relevant for evaluating the impact of climate change or environmental policies on oil market variables. While dynamic stochastic general equilibrium (DSGE) models with an oil sector have similar advantages, DSGE models typically do not take account of oil inventory dynamics, which are fundamental for incorporating the forward-looking behaviour of oil market participants (Alquist and Kilian 2010; Kilian and Murphy 2014).[2]

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[1] See, e.g., Blagrave et al. (forthcoming).

[2] For an example of a DSGE model with an oil sector, see, e.g., Lalonde and Muir (2007).

2. Model structure

The SVAR model is based on the four variables of oil production, oil consumption, the real price of oil and real global GDP. [3] Implicitly, the SVAR also models the oil market balance, since it is the difference between oil production and oil consumption. The vector

$$\mathrm{Y_t} = [\mathrm{production_t}, \mathrm{consumption_t}, \text{real price of } \mathrm{oil_t}, \mathrm{GDP}_t]'$$

is modelled as a vector autoregressive process with four lags,

$$\mathrm{Y_t} = \mathrm{D_t} + \sum_{i=1}^{4} \Phi_i \mathrm{Y_{t-i}} + \epsilon_t, \qquad (1)$$

where $\mathrm{D_t}$ comprises a constant and a set of seasonal dummies, Φ_i represents a matrix of autoregressive coefficients of lag i, and ϵ_t represents a vector of reduced-form residuals that are assumed to follow a white noise process. The model is estimated with ordinary least squares for the sample period 1988Q2–2018Q2 with quarterly variables in logs.

Four types of structural shocks are identified in the SVAR: oil supply shocks, oil-market-specific demand shocks, storage demand shocks and global economic growth shocks. The reduced form residuals from equation 1, ϵ_t, are generally correlated and do not necessarily have an economic interpretation. Instead, we assume a model structure that allows us to identify four economically meaningful shocks:

- **Positive oil supply shocks** are surprise increases to oil production that result from a rightward shift in the global oil supply curve. These shocks are associated with a fall in the real price of oil and an increase in oil consumption and global GDP growth.
- **Positive oil-market-specific demand shocks** constitute unexpected outward shifts in the global oil demand curve that are not related to changes in global GDP growth. For instance, these shocks could be driven by technological change. They result in an increase in the real price of oil and increased consumption and production, but no contemporaneous change in global GDP growth.

[3] Data on global oil production and oil consumption are drawn from the International Energy Agency's Monthly Oil Data Service. The real price of oil is constructed as the quarterly average of monthly nominal Brent prices deflated by the US consumer price index. Data on global GDP are taken from IMPACT, the Bank of Canada's International Model for Projecting Activity (Blagrave et al., forthcoming). Pre-1998 GDP data are back-casted by fitting a linear regression model to the industrial production index of Baumeister and Hamilton (forthcoming).

- **Positive storage demand shocks** reflect surprise increases in the desire to hold above-ground oil inventories. These shocks are typically related to the forward-looking behaviour of market participants, which can result from an expected shortfall of future oil supply relative to future oil demand or an increase in supply uncertainty (Alquist and Kilian 2010; Kilian and Murphy 2014). Positive storage demand shocks are associated with an increase in the oil price accompanied by a surplus of production over consumption, which constitutes an increase in total oil inventories.

- **Positive global economic growth shocks** are surprise increases in global GDP growth that lead to an outward shift of global oil demand. These shocks are associated with an increase in the real price of oil, as well as an increase in oil production and consumption.

The model assumes that the vector of reduced form residuals, ϵ_t, is linearly related to these four structural shocks via a set of structural parameters:

$$\begin{bmatrix} \epsilon_t^{\text{production}} \\ \epsilon_t^{\text{consumption}} \\ \epsilon_t^{\text{real price of oil}} \\ \epsilon_t^{\text{GDP}} \end{bmatrix} = \begin{bmatrix} 1, & \eta_S \cdot \gamma_D, & \eta_S, & \eta_S \cdot (\eta_I \cdot \gamma_D + \gamma_G) \\ \eta_D \cdot \gamma_S, & 1, & \eta_D, & \eta_I \\ \gamma_S, & \gamma_D, & 1, & \eta_I \cdot \gamma_D + \gamma_G \\ \eta_G, & 0, & 0, & 1 \end{bmatrix} \cdot \begin{bmatrix} \text{supply shock}_t, \\ \text{oil market specific demand shock}_t \\ \text{storage demand shock}_t \\ \text{economic growth shock}_t \end{bmatrix}, \quad (2)$$

where η_s denotes the contemporaneous price elasticity of oil supply, η_D the price elasticity of oil demand, η_I the income elasticity of oil demand, γ_G the GDP impact of oil supply shocks, γ_s the price impact of supply shocks, γ_D the price impact of oil-market-specific demand shocks and γ_G the part of the price impact of economic growth shocks that works through expectations rather than shifts in short-run demand alone.[4]

This structure has an intuitive economic interpretation, which is consistent with the features of the structural shocks:

- Surprise changes in oil production can arise from unanticipated shifts in the oil supply curve and from movements along the supply curve in reaction to oil price changes induced by the other three structural shocks.
- In a similar fashion, surprise changes in oil consumption arise from shifts in the demand curve—either because of economic growth shocks or because of shifts in oil-market-specific demand—and from movements along the demand curve.
- Surprise changes in oil prices arise from shifts in the oil supply curve and the oil demand curve, or in inventory demand. In addition to shifting contemporaneous demand for oil,

[4] This setup is similar to the one in Baumeister and Hamilton (forthcoming). It features some additional restrictions that facilitate identification of the structural shocks.

economic growth shocks can affect oil prices through changes in expectations about future oil demand. The price impact of economic growth shocks thus accounts for shifts in forward-looking behaviour of oil market participants that are correlated with economic growth shocks (Kilian and Zhou 2018).

- In the short run, i.e., within the same quarter, surprise changes in GDP are mainly due to shocks to global economic growth, but they can also result from shifts in oil supply that change the availability of oil.[5]

Equation 2 contains several implicit restrictions on the reaction of variables to structural shocks**.** The first row of equation 2 requires that the short-run price elasticity of oil supply is identical for all non-supply shocks, i.e., for economic growth, oil-market-specific demand and storage demand shocks. Similarly, the model imposes an identical short-run price elasticity of demand for supply and for storage demand shocks. These restrictions imply that shifts along the short-run supply and demand curve depend on the size of the price change but not on the nature of the underlying shock. Finally, the model only allows the effects of oil-market-specific demand shocks and of storage demand shocks on global GDP growth to occur with a lag. This assumption reflects the definition of oil-market-specific demand shocks, which are shifts in oil demand that are independent from contemporaneous shocks to global economic growth. It also reflects the idea that storage demand shocks are generally a combination of changes in expectations about future oil supply and future oil demand, which tend to be, on average, uncorrelated with short-run fluctuations in global economic activity (Bilgin and Ellwanger 2017; Baumeister and Hamilton forthcoming).

3. Quantitative features

We impose a short-run oil supply elasticity that is consistent with existing evidence to identify the remaining structural parameters. The restrictions implied by the economic structure in equation 2 are not sufficient to identify all seven structural parameters. Given that six distinct covariances can be estimated from the four reduced-form shocks, identification requires at least one additional restriction (Kilian and Lütkepohl 2017). To estimate the structural model, the short-run price elasticity of oil supply, η_s, is set to 1 per cent. This value of the short-run supply elasticity is within the range of existing estimates (Kilian and Murphy 2014; Bilgin and Ellwanger 2017). Moreover, the empirical results are reasonably robust to alternative, plausible values of $\eta_{s.}$ The remaining structural parameters are then uniquely identified by the data.

[5] Since the model is estimated on quarterly data, *short-run* or *contemporaneous* refers to the occurrence within the same quarter throughout this note.

The estimated structural parameters and impulse responses provide plausible interpretation of oil market dynamics:

- A 1 per cent shock to oil supply is estimated to increase the real price of oil by about 6 per cent within the same quarter and about 9 per cent at peak after two quarters. This impact is larger than in most existing SVAR models, which are estimated at a monthly frequency (Herrera and Rangaraju 2018).
- The within-quarter price impact of a 1 percentage point surprise increase in global GDP growth is estimated to be around 18 per cent. This effect occurs through both a shift in the contemporaneous demand curve (7 per cent) and an additional shift in expectations (11 per cent).
- The short-run price elasticity of oil demand is about -2 per cent, which is almost identical to the estimates provided by Bilgin and Ellwanger (2017). The short-run price elasticity of oil supply is restricted to 1 per cent.[6]
- The estimate of the short-run income elasticity of oil consumption is about 0.95 and thus of a magnitude similar to existing estimates of the long-run income elasticity (Hamilton 2009).
- Supply shocks, oil-market-specific demand shocks and storage demand shocks that raise the price of oil have a negative but very modest impact on global GDP growth.

The complete set of impulse response functions is displayed in **Chart A-1** in the Appendix.

4. Model applications: Historical decomposition of oil price fluctuations and scenario analysis

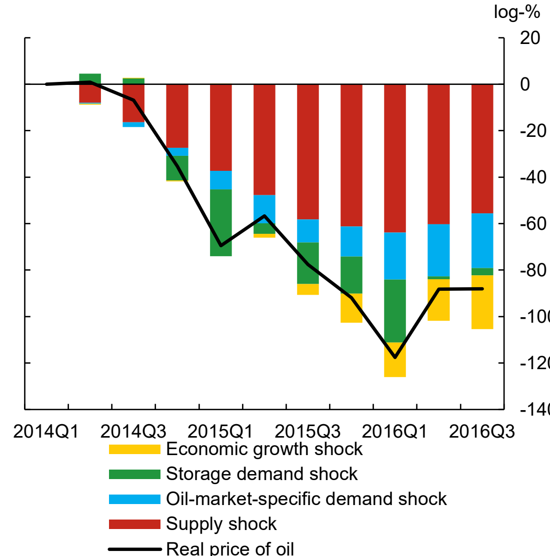
The model provides historical decompositions of oil price fluctuations. These decompositions are useful to disentangle the underlying drivers of changes in oil prices. Consistent with existing evidence, the model suggests that the 2014–15 oil price decline was initially driven by shocks to oil supply, while economic growth shocks and oil-market-specific demand shocks become

[6] The demand elasticity estimated in this model differs from those of standard SVAR models in that it relates to the demand for finished petroleum products instead of the standard demand for crude oil. See Bilgin and Ellwanger (2017) for a detailed discussion about this distinction.

relatively more important later in 2015 and in 2016 (**Chart 1**) (see Ellwanger, Sawatzky and Zmitrowicz 2017).

The model can also provide conditional forecasts that are consistent with pre-defined paths of model variables. Scenario analysis in oil market SVARs traditionally relies on specifying a particular scenario as a sequence of structural shocks (Baumeister and Kilian 2014). However, in many applications, it might be more natural for policy-makers to conduct scenario analysis for a pre-specified path of an observable model variable. For example, policy-makers might want to condition forecasts of oil market variables on different scenarios for global GDP growth.

Chart 1: Cumulative log-percentage changes in the real price of oil since 2014Q1



Source: Bank of Canada Last observation: 2016Q3

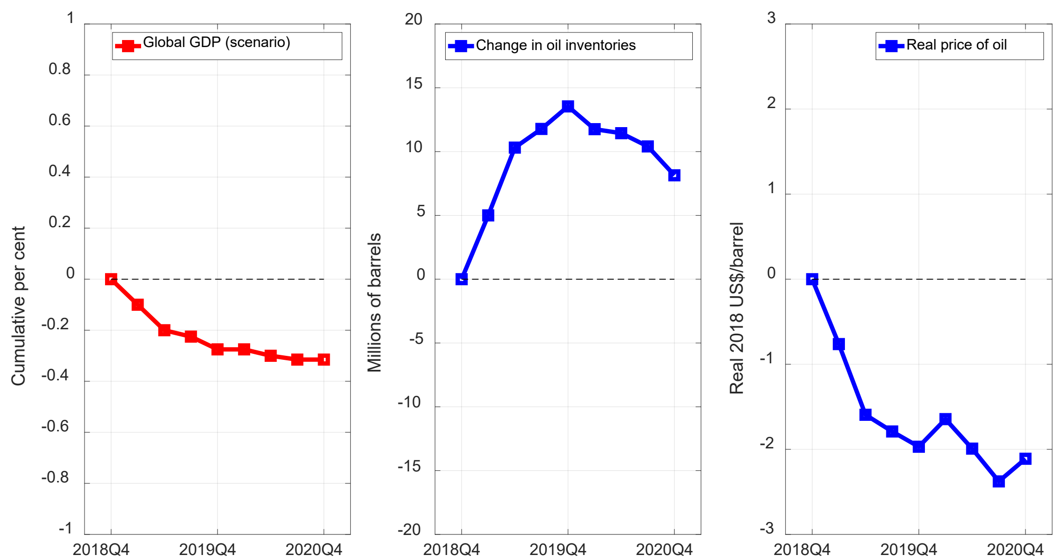
Generally, a specific path of any model variable could reflect many different possible combinations of structural shocks. However, since the estimated short-run elasticities of oil supply, oil demand and global economic growth are very low, specific paths of observable variables are naturally associated with a sequence of specific structural shocks:

- Specific paths for global GDP are primarily associated with economic growth shocks.
- Specific paths for global oil production are primarily associated with oil supply shocks.
- Specific paths for global oil consumption that are not accounted for by global growth are primarily associated with oil-market-specific demand shocks.

Under these assumptions, there exists a unique set of structural shocks that is consistent with the specific path of any model variable. Moreover, these assumptions readily extend to forecasts that condition on paths of more than one variable. By combining the corresponding structural impulse responses, there exists also a unique combination of two structural shocks associated with a pre-specified path of two model variables, and a unique combination of three structural shocks associated with a pre-specified path of three model variables. Sequences of structural shocks that are consistent with a specific scenario are obtained by computing the difference between the model-implied forecast and the path of the respective variables.

Policy institutions often provide forecasts for global GDP, which can be used as pre-specified paths for the variables in our model.[7] Such paths can then be used to understand the potential impact on other variables in the model. We highlight an example of this, which looks at the revisions to the International Monetary Fund's *World Economic Outlook* between October 2018 and January 2019. The revision projects the global economy to grow at 3.5 per cent in 2019 and 3.6 per cent in 2020, respectively 0.2 and 0.1 percentage point below the October 2018 projections (IMF 2019). The model can trace the estimated effects of the change in the forecast on oil market variables (**Chart 2**).[8] It estimates that relative to the projections from October 2018, real oil prices would be around US$2 lower by the fourth quarter of 2020. Most of the price difference appears in 2019, along with an accumulation of total oil inventories relative to the base-case scenario.

Chart 2: Response of the oil market balance and the real price of oil to revisions in GDP projections



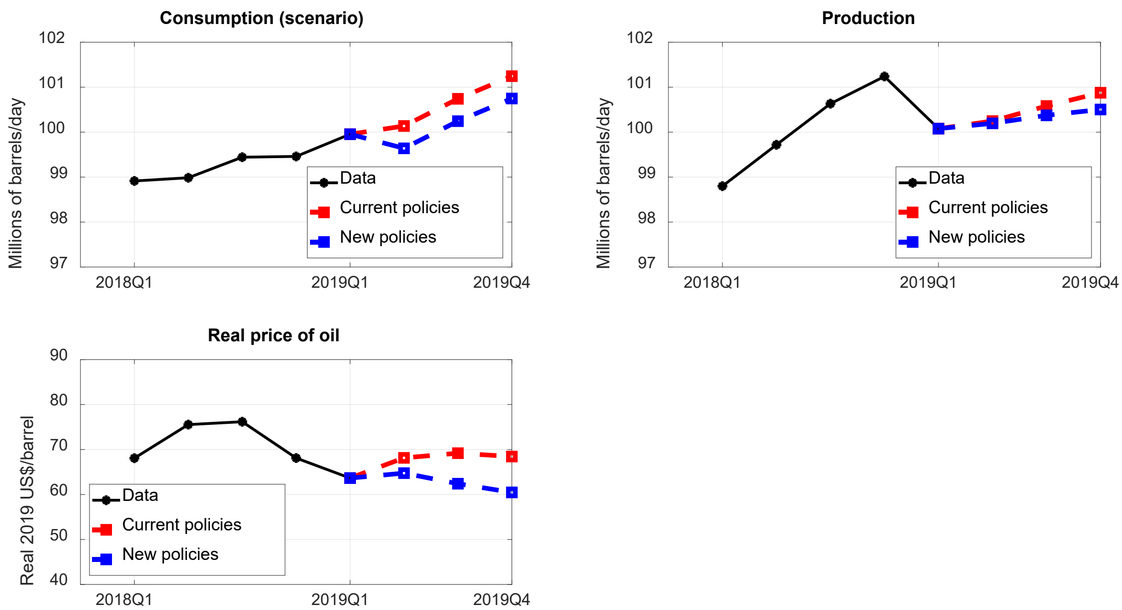
Source: Bank of Canada

The model can also be used to estimate the effect of different scenarios of oil production and consumption on the global oil market.[9] Like existing oil market models, the SVAR can gauge the effect of shortfalls or increases in global oil production on oil market variables (Baumeister and Kilian 2014). Moreover, it is straightforward to apply the model to scenarios that are based on an

[7] For example, the International Monetary Fund's *World Economic Outlook* series provides regular global GDP growth projection.
[8] The growth shock is implemented by distributing the change in yearly growth equally across all quarters of the year.
[9] The International Energy Agency's *Oil Market Report* provides regular forecasts for global oil production and consumption.

explicit specification of the volume of oil consumption. This complements existing models, which typically rely on measures of real economic activity to compare alternative scenarios of future oil demand. It is particularly relevant for evaluating the effect of climate change and environmental policies on the global oil market. For example, the model suggests that the reduction in oil consumption growth under the International Energy Agency's 2018 New Policies Scenario compared with its Current Policies Scenario could lower real oil prices from the high US$60 range to the low US$60 range over the remainder of 2019, accompanied by a slowdown in the growth of global oil production (**Chart 3**).

Chart 3: Oil production and the real price of oil under different oil consumption scenarios



Source: Bank of Canada

5. Conclusion

This SVAR model of the global oil market and global GDP provides a consistent framework for the economic interpretation of oil market developments and for conditional forecasts of oil market variables. With additional assumptions, the model generates oil market scenarios that are consistent with global GDP projections. This is particularly convenient for policy-makers whose macroeconomic projections and risk analysis already provide paths for future GDP growth. Moreover, the model can generate oil market scenarios for different oil consumption and oil intensity scenarios without the need to resort to DSGE models (Baumeister and Kilian 2014). A natural extension of the current framework would be to incorporate confidence bands to highlight the uncertainty around the point forecasts generated by the model.

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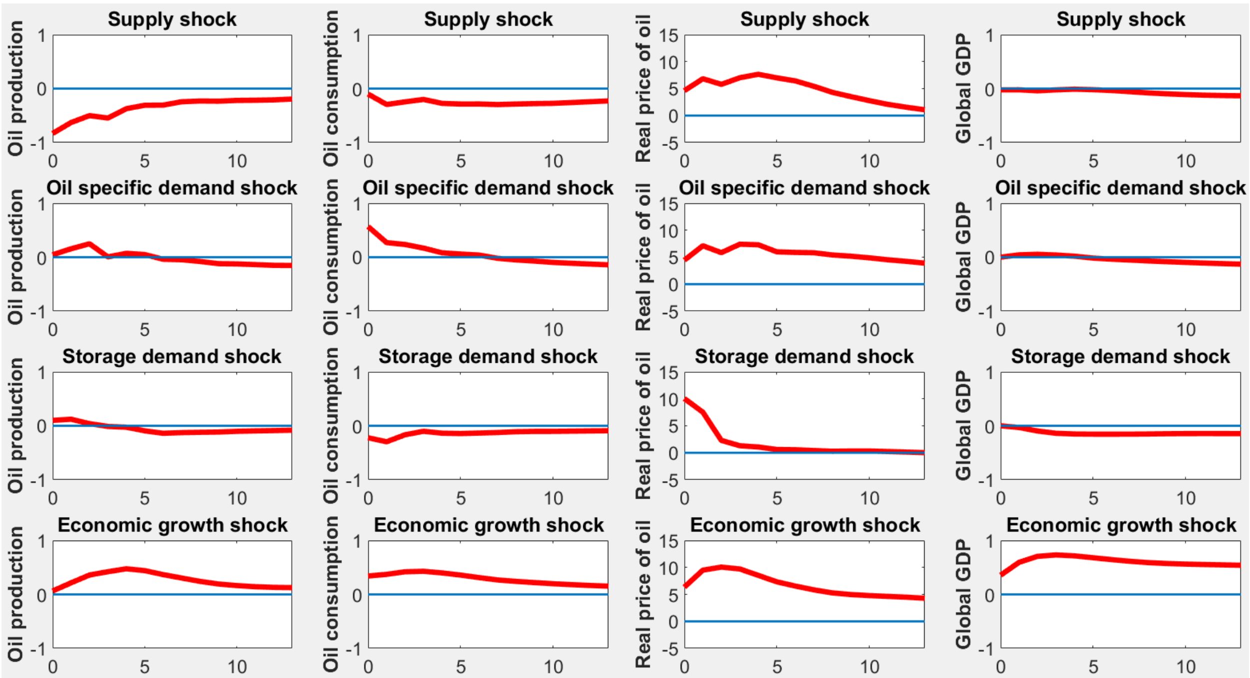
Appendix

Chart A-1: Estimated impulse responses to structural shocks



All responses are measured in per cent. The horizontal axis denotes quarters. Source: Bank of Canada