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# Mitigating the Impact of Fuel Subsidy Removal in an Oil-Producing Emerging Economy*

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**Abstract**

This paper examines the implications of fuel subsidy removal in an oil-producing economy, focusing on the central bank's response to volatile oil prices. Using a Markov-switching dynamic stochastic general equilibrium model, we analyze the welfare effects of this policy change under different regimes of oil price volatility and monetary policy. Our empirical findings, based on data from Nigeria (2000:2 - 2021:4), reveal time-varying switches in oil price fluctuations and monetary policy adjustments that synchronize with states of high oil price volatility. We also find that subsidy removal has welfare-reducing and heterogenous effects on households, especially when implemented in an environment of heightened volatility. The efficacy of monetary policy in mitigating the impacts of subsidy removal depends on the ability of the central bank to design a flexible framework capable of adapting to economic shifts, while balancing its stabilization objectives. Furthermore, the observed monetary policy switching endogenous to different states of oil price shocks suggests a need for the central banks of oil-producing emerging economies to consider the prospects of a dual-mandate regime.

**JEL Classification**: C32; E37; Q43

**Keywords**: Fuel subsidy; DSGE model; Regime switching; Policy analysis; Nigeria

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# Contents

# 1 Introduction

In the context of global debates surrounding fossil fuel consumption subsidies, particularly in resource-rich emerging economies which are exposed to high volatility of international commodity prices, this paper addresses two critical research questions: How should monetary policy respond to the macroeconomic implications of fuel subsidy removal in an oil-producing emerging economy, considering regime-switching dynamics in oil price volatility? How should central bank policy rules adapt to mitigate the adverse effects of subsidy removal?

Fuel consumption subsidies, a widespread global phenomenon, have been implemented to stimulate production, reduce inequality, alleviate energy poverty, and stabilize domestic prices (Estache and Leipziger, 2009; Taylor, 2020). In 2017, a total of 191 countries accounted for global fossil fuel subsidies amounting to USD 5.2 trillion, representing 6.5% of global GDP (Coady *et al.*, 2019). In line with the continued relevance of oil as a source of energy for households and firms, the amount of energy subsidies increased to USD 6 trillion (7% of global GDP) in 2020, with the top three subsidizers being China (USD 2.2 trillion), the US (USD 0.66 trillion), and Russia (USD 0.52 trillion). Interestingly, oil-producing developing countries accounted for about 48.3% of total pre-tax global subsidies in 2017, highlighting the significance of fossil fuel subsidies for those countries (Estache and Leipziger, 2009).

However, concerns have emerged regarding the fiscal costs and negative externalities of fuel consumption subsidies, prompting calls for reforms.[1] Indeed, fuel subsidies involve sizeable fiscal costs which hinder growth, especially in oil-producing developing countries; thus, limiting the capacity of such countries to mobilize the needed fiscal resources for addressing their developmental challenges.[2] More importantly, ineffective fuel consumption subsidies distort domestic price signals and complicate the monetary policy environment. The complete removal of fuel subsidies in Nigeria in May 2023 has intensified policy debates, reflecting the ongoing challenge of balancing macroeconomic stability with the imperative for reform.

Historically, subsidy reforms have been among the most challenging fiscal adjustments for governments, primarily due to the complex political economy surrounding such reforms (Inchauste and Victor, 2017). The reluctance to implement reforms stems from potential socio-political implications, especially in the absence of safety nets for vulnerable populations.[3] In Nigeria, while the calls for subsidy removal have been largely driven by the inefficiencies in its implementation, the associated fiscal costs, and its roles in widening the already existing wealth disparity and worsening the country's debt profile have indeed intensified the debate (Omotosho, 2019b).[4] While there is uncertainty as to the macroeconomic implications of subsidy removal, one thing that is clear is that the debate on the appropriateness of necessary complementary

[1]Fuel consumption subsidies have been documented to be associated with the issues of widening inequality, triggering inefficient energy consumption, negative environmental effects, market distortions, crowding-out effects in public spending, as well as balance of payments and fiscal imbalances (Clements *et al.*, 2013; Coady, 2015; Taylor, 2020).

[2]For example, the size of fuel subsidies in Nigeria posed a significant fiscal burden on the distribution of resources to the state governments.

[3]For instance, reforms that could result in higher retail energy prices could have non-trivial socio-political implications, especially in situations where there are no safety nets for the poor and vulnerable.

[4]Several attempts made under different administrations to abolish the country's fuel subsidy program have been unsuccessful. For instance, the attempt in January 2012 to introduce total subsidy removal was met with fierce resistance by the citizens, causing the decision to be rescinded within two weeks.

policies to support the reform continues to evolve.

To explore this issue, we choose Nigeria, which is a large net oil exporter, for two main reasons. First, Nigeria characterizes the typical resource-rich emerging markets. According to the Central Bank of Nigeria (CBN) Statistical Bulletin, since 2000, the oil and gas sector in Nigeria has accounted for about 40% of GDP, 72% of government revenue, and 95% of exports earnings. Nigeria continues to depend heavily on oil with less diversification towards non-oil exports and industrialization. Thus, the economy is considerably vulnerable to oil price fluctuations. The mono-product nature of exports and fiscal revenue makes macroeconomic outcomes susceptible to the vagaries of oil prices. Second, our focus is on monetary policy. Resource abundance can be a major cause of weak institutions and economic mismanagement since the fiscal authorities often face the political incentives generated by a resource endowment. Given the political expediencies faced by Nigeria's fiscal authority, combined with the country's low level of export diversification, policy for maintaining macroeconomic stability and managing aggregate demand may largely lie with the monetary authority.

Furthermore, large external price shocks have been a major force behind the recent inflationary pressures in Nigeria, given the openness of the small open-economy (SOE) and the country's fuel imports requirements. The recent episodes of heightened volatility in relative price movements which get factored into inflationary expectations have made it difficult for central banks to achieve price stability while maintaining economic growth. Indeed, Kilian and Vigfusson (2017) and Hwang and Zhu (2024) find that monetary policy behaves differently depending on how inflation is affected by oil price shocks. Meanwhile, in the face of increasing uncertainty about future prices which appears to be emanating from the supply side, a major challenge before policymakers remains the need to maintain macroeconomic stability and a stable fiscal profile while discounting volatile oil sector developments so that the effect of fuel subsidy reforms can be transformed into development gains.

Many studies have focused on assessing the macroeconomic implications of subsidy reforms on the assumption of Gaussianity of the shocks that characterize the domestic economy.[5] However, relatively little exists on the optimal interactions of monetary policy and the economic consequences of oil price volatility using micro-founded macroeconomic analysis for an emerging SOE and no consensus has emerged in the literature. Additionally, one of the issues that remains open to debate is whether the welfare consequences and stabilization incentives are expected to be different as regime-switching occurs in oil price fluctuations. Existing studies primarily focus on the macroeconomic response to subsidy reforms but often overlook the dynamic nature of economic conditions, particularly the role of stochastic regime shifts, which are essential considerations in the design of subsidy policies.

Indeed, past research in the empirical literature studying the consequences of fuel subsidy reforms is relatively silent on the mechanisms through which oil price shocks affect the economy through, for example, the connection between regime-switching and monetary policy. It leaves unanswered, the more fundamental question of what leads the policymaker to behave differently over time. Answering this question requires a model with richer dynamics, accounting for both the key features of resource-rich emerging economies and the possibility of the variance of shocks

[5]See Omotosho (2019b) and Omotosho (2022) for an overview of this literature.

changing over time.

To fill this gap, we incorporate regime-switching dynamics into a dynamic stochastic general equilibrium (DSGE) model tailored to the Nigerian context. Within this framework, we model the heteroskedasticity of oil prices in order to account for the distinct periods of oil price volatility, and thus the considerable uncertainty about the nature of the shock faced by policymakers. Our approach, directly linking the significant increase in price volatility and the behavior of policymakers responding to these dynamics, plays a central role in our analysis and is completely novel in the context of an estimated two-bloc regime-switching model. This study aims at gauging the empirical relevance of fuel subsidies and how they affect macroeconomic volatility and monetary policy. Our primary objectives include evaluating optimal monetary policy responses to an oil price shock, assessing welfare implications of alternative policy scenarios, assessing the historical implications of fuel subsidy policies on economic performances, and understanding the potential impacts of reforms on macroeconomic stability.

To achieve our objectives, we employ empirical analysis based on data from 2000:2 - 2021:4. The model parameterization considers the distinctive features of emerging economies, particularly oil-producing ones, to capture the dynamic interactions among oil price innovations, economic variables, and policy interventions. The model features an oil producer and a fiscal authority that governs the level of fuel subsidies. The subsidy program determines the pass-through effect of international oil price into domestic prices. The monetary authority follows a simple Taylor rule responding gradually to aggregate inflation, domestic output and the exchange rate.[6] To examine the interactions between oil price volatility and monetary policy adjustments, our model incorporates stochastic regime shifts in the oil price volatility and monetary policy rule coefficients, highlighting the link between switching dynamics and policy implications. Thus, we make contributions to the existing literature by discussing a range of practical and theoretical implications, shedding more light on the underlying mechanism that guides policy choices for a successful fuel subsidy reform. The main findings of this paper are summarized as follows.

We start by examining the implications for dynamic monetary policy response. The paper finds substantial empirical support for time-varying switches between major volatile episodes in oil prices and monetary policy adjustments that synchronize with states of high oil price volatility. The results show that the major volatile episodes are observed during 2008-2009, 2014-2016, and 2020-2021, corresponding to the US credit crisis of 2008, the supply-driven collapse in oil prices that led to an economic recession in Nigeria in 2016, and the more recent drop in oil demand starting from 2019Q4 triggered by the pandemic, respectively.

Next, we examine the estimation results and discuss the extent to which the central bank adjusts its behavior in response to oil price volatility. First, during highly volatile oil price periods with heightened uncertainty faced by policymakers, the central bank is less sensitive to movements in headline inflation, focuses less on exchange rate stabilization, but places greater emphasis on the output gap and adjusts interest rates more quickly. Second, we compare the economic performances under the estimated policy rule and the counterfactual scenario where

[6]The modeling of monetary policy is consistent with the operations of the CBN which currently adopts a monetary targeting framework, uses the Monetary Policy Rate as a key instrument for signalling monetary policy stance, and has recently moved to a regime of market-based exchange rate determination.

subsidies were not in place historically. The macroeconomy would have been more volatile with the realized shocks and policy rule. With the additional income available, consumption rises initially, but low-income consumers experience comparatively smaller increases.

To further understand the implications of removing fuel subsidies, we solve the model for given policy and then evaluate welfare using this solution. We find that a complete, one-off removal is welfare-reducing in an environment with recurrent periods of exogenous, volatile oil price shocks. Counterfactual simulations reveal that subsidy removal leads to higher macroeconomic instabilities and welfare cost of the business cycle. The effects of subsidy removal on private consumption and future retail energy prices are possible explanations for the different welfare consequences, implying that this policy change has non-trivial socio-political implications.

Finally, the optimal policy operation that accommodates oil price volatility has interesting implications for macroeconomic policy. In the regime of high oil price volatility, the optimal monetary response prescribes a more aggressive inflation response compared to the regime characterized by low price volatility. The impulse responses of the interest rate to economic shocks based on the realized rule differ from those generated in an economy when the central bank adopts optimal policy. When shocks are large and volatile, the best response prescribes an initial cut to interest rates, which is in contrast with the results generated by the estimated rule. In addition, monetary policy faces a less severe trade-off between price stability and output stabilization in the absence of fuel subsidy but a regime of high oil price volatility is associated with worsening policy trade-offs.

The paper is organized as follows. Section 2 reviews related literature to provide context for our study. Section 3 outlines the baseline model and introduces the Taylor-type monetary policy rules. Section 4 presents the model parameterization and filtration implications. Section 5 discusses the historical and counterfactual implications of fuel subsidy policies on economic performances. While Section 6.1 details the central bank's role and its linear-quadratic problem, Sections 6.2 and 6.5 discuss results and analysis, including optimal monetary policy, welfare assessment, and impulse responses. Section 7 explores the statistical validation of the model and robustness of the results based on posterior simulations. Section 8 discusses the implications of our results for macroeconomic policy. Finally, Section 9 concludes, summarizing key findings and suggesting avenues for future research.

## 2 Related literature

There are four strands of literature related to our paper, which are discussed in this section. Additionally, we discuss the contrast between these relevant pieces of literature and our approach to further clarify the contribution of this paper.

### 2.1 Nonlinearities of oil price shocks

The first strand is a largely econometrics literature studying oil price shocks, which have been known to generate macroeconomic instability in many resource-rich countries. This strand of literature explores the econometric aspects of oil price shocks, dissecting their asymmetric output effects and state dependence. Notable studies such as Barsky and Kilian (2004), Kilian (2009) and Ramey and Vine (2011) delve into the sources of these shocks, while others like Rahman and Serletis (2010), Holm-Hadulla and Hubrich (2017) and Hwang and Zhu (2024) investigate central banks' responses, accounting for time-varying impacts.

The major discussion under this strand of literature is around the changing estimated effects of oil price shocks, and the use of alternative methods for studying these changing effects. This motivates us to take account of time-dependent nonlinearities in modeling the impact of oil shocks. However, studying episodic nonlinearities of macroeconomic shocks is difficult and requires nonlinear techniques. SVAR-based studies that explicitly allow for nonlinearities find mixed evidence but the existence of a VAR representation can be compromised due to non-invertibility/-fundamentalness.[7]

Although useful for understanding the degree of macroeconomic co-movements, nonlinear multivariate models and dynamic factor models do not provide much information about the mechanisms through which oil price shocks affect the macroeconomy. Furthermore, to be useful for optimal policy design, we must require a data-based DSGE model that provides the structural investigation from the richer dynamics and model-implied moments behind the estimated parameters. Invariably, the contradicting findings earlier mentioned allude to the importance of a need to ascertain the appropriate transmission channel(s) through which oil price shocks affect both the oil and non-oil sectors of the economy in order to proffer optimal policies using open-economy DSGE models.

### 2.2 Episodic switches in DSGE frameworks

The second piece of literature focuses on episodic switches in DSGE frameworks, introducing Markov chains for macroeconomic volatility and structural parameters. Empirical studies, including Schorfheide (2005) and Liu *et al.* (2011), employing regime-switching DSGE models, reveal substantial evidence of structural shifts.[8]

A number of recent papers are related to the present paper. Chen and Macdonald (2012) focus on UK monetary policy and study its stabilization properties in a DSGE model that is subject to several regime shifts. Bjornland *et al.* (2018) construct and estimate a regime-switching model that studies the roles of oil prices and monetary policy in the US economy for the timing of the Great Moderation. Best and Hur (2019) evaluate the role of monetary policy with time-varying volatilities of non-policy shocks. Maih *et al.* (2021) investigate the implications of asymmetric monetary policy rules for the Euro area and the US based on a sample that encompasses the Great Recession and periods of financial distress.

In our paper, we study the macroeconomic implications under different policy scenarios that may be affected by changing oil price volatility and modeling uncertainties based on a model tailored to incorporate unique economic features for an oil-rich emerging economy. The paper elects to stay closer to the current consensus on synchronized-switching models, but offers a number of innovations that address the new challenges. In contrast to the previous

[7] See, for a detailed discussion, Levine *et al.* (2022) and Levine *et al.* (2019).

[8] Recent applications also include Liu and Mumtaz (2011), Bianchi (2013), Davig and Doh (2014), Bianchi and Ilut (2017) and Bianchi and Melosi (2017), among others.

papers, the stochastic switch in our model assumes that responses of the real economy depend on the volatility and persistence of oil price shocks.[9] In addition, we implement a hybrid, flexible framework to bridge the behavior of policy and the heteroskedasticity of oil prices. This is particularly relevant to the behavior of monetary policy adjustments that is affected by significant increases in oil price volatility.

### 2.3 SOE models for oil-importers and -exporters

The third strand of literature explores small open-economy (SOE) DSGE models investigating the macroeconomic impacts of oil price shocks and policy design, particularly in oil-importing and -exporting nations. Omotosho (2019a) estimates an open-economy model using Nigerian data and focuses on sources of macroeconomic fluctuations and inflation dynamics. A comprehensive review by Omotosho (2022) provides insights, covering various monetary policy responses, exchange rate regimes, and levels of oil intensity dependence. The variations in findings are also explained and discussed in Medina and Soto (2005), Allegret and Benkhodja (2015), Ferrero and Seneca (2019), Bergholt and Larsen (2016) and Algozhina (2022).

Different from the previous SOE studies, our paper focuses on the connection between regime-switching dynamics and policy implications, and assessing the role that the central bank can play in mitigating the consequences of fuel subsidy removal. Against inherent uncertainties, it is evident that the determination of crude oil prices exhibits a volatile process which poses considerable challenges to macroeconomic stability and demand management in oil-exporting emerging economies. Our benchmark form of an open-economy model applies to oil-producing emerging market economies. We fit the oil-exporting regime-switching model to Nigerian data using Bayesian methods. The latter provides an empirical assessment of how different stabilization actions affect the macroeconomic outcomes.

### 2.4 Macroeconomic effects of fuel subsidy reforms

Empirical evidence initiated by Hamilton (2003) and recent studies, such as Clements *et al.* (2013), Siddig *et al.* (2014), Dennis (2016), Rentschler *et al.* (2017) and Coady *et al.* (2019), delves into the macroeconomic effects of fuel subsidy reforms. Notably, Fan and Wang (2022) assess the net social welfare effect of China's petroleum pricing mechanism reform. Siddig *et al.* (2014) study the effect of subsidy reduction on consumption, income and fiscal planning in Nigeria. Much of the empirical studies finds non-trivial implications for the response and volatility of macroeconomic variables. The main predictions of these studies show that fuel subsidy reforms could cause inflation, reduce economic welfare, distort fiscal planning, reduce household income, and worsen the problem of inequality. However, research within a general equilibrium framework remains limited.

Building on the earlier contributions by Omotosho (2019b), this paper departs from previous studies and focuses on evaluating Nigeria's potential subsidy reforms by incorporating fuel subsidy into a DSGE model and is closely related to the work of Omotosho (2019b) and

[9] In line with the findings in Omotosho and Yang (2024), our assumption is based on the observation that the monetary authority in Nigeria has responded differently to different oil price shocks in the past, depending on the size and persistence of the shock and the state of the economy prior to the shock.

Omotosho and Yang (2024). These papers examine the pass-through effects of oil price shocks on domestic fuel prices, investigating macroeconomic volatility and dynamics. However, this literature lacks an exploration of policy formulation and welfare implications in the context of potential subsidy reforms, considering dynamic interactions between stochastic regime shifts in the nature of oil prices and time-varying central bank adjustments, and subsidy reforms – a gap addressed by this paper.

### 2.5 Outline of contributions

In the light of this review, our paper makes the following three main contributions to the literature. First, our paper emphasizes the crucial importance of the heteroskedasticity of oil prices in studying the behavior of monetary policy adjustments. Second, our paper constructs and estimates a benchmark form of an open-economy micro-founded macroeconomic model that captures key features of oil-producing emerging market economies. Third, in our application, we study simple Taylor-type monetary policy rules that are 'operational', in the sense that they are easy for the public to monitor, whilst approximating the stabilizing properties of complex optimal rules. Indeed, our empirically based theoretical approaches have properties that make them particularly suitable for policy analysis and the design of monetary policy frameworks should exhibit flexibility and adaptability. In addition to providing the important insights into optimal policy responses and welfare consequences drawn from Nigeria's subsidy removal, our paper offers the core guiding/controlling principles to implement fuel subsidy reforms for similar economies facing similar challenges.

## 3 The Regime-switching DSGE model

As in Omotosho and Yang (2024), the model features the SOE and the foreign economy and presents the regime-switching monetary policy. There are four categories of firms operating in the economy: the final goods firm, the intermediate goods producing firms, the foreign goods importing firms, and the oil-producing firm. The economic environments in which the first three categories of firms operate are standard. For the oil sector that is owned by the government and foreign investors, there are three departures from the standard open-economy model that lead to interesting results. First, oil enters firms' production technology and results in a direct impact of oil shocks on the supply side (Medina and Soto, 2005 and Ferrero and Seneca, 2019). Second, in the oil market, the government sells the imported fuel based on a fuel pricing rule that connotes an implicit subsidy regime as in Allegret and Benkhodja (2015). Third, there are frictions in the financial markets facing households as in Gabriel *et al.* (2023) and in the form of non-Ricardian consumers to capture credit constraints,[10] and an inefficient financial sector as in Smets and Wouters (2007). Furthermore, we allow for the law of one price (LOP) gap in imports and by implication assume incomplete exchange rate pass-through into import

[10]The presence of rule of thumb consumers who have no access to formal financial services and credit to smooth out consumption should improve the model fit for an emerging economy in the type of volatile economic environment that has been described so far (see Gabriel *et al.*, 2016 and Gabriel *et al.*, 2023, among others).

prices as in Monacelli (2005) and Senbeta (2011).[11] We assume that our model can switch exogenously between regimes of oil price volatility and the monetary policy rule over time. The main elements of the model are as follows.[12]

### 3.1 Oil production and pricing

The oil firm's profit maximization problem is similar to that of Ferrero and Seneca (2019) and Algozhina (2022). The firm is owned by the government and foreign investors and combines materials sourced from the domestic economy, $M_t$, and oil-related capital, $K_{o,t}$, to produce oil output, $Y_{o,t}$, which is exported to the rest of the world at a price, $P^*_{o,t}$, determined in the international crude oil market, using the following Cobb-Douglas technology

$$Y_{o,t} = A_{o,t} K_{o,t}^{\alpha_o^k} M_t^{\alpha_o^m} \tag{1}$$

where $A_{o,t}$ represents the oil technology. $\alpha_o^k$ and $\alpha_o^m \in (0,1)$ represent the elasticities of oil output with respect to $K_{o,t}$ and $M_t$, respectively. The former is accumulated by foreign direct investment (FDI), $FDI^*_t$, as follows

$$K_{o,t} = (1 - \delta_o) K_{o,t-1} + FDI^*_t \tag{2}$$

where $\delta_o$ is the depreciation rate. The intuition of (2) follows closely the assumption made in Melina *et al.* (2016) and Algozhina (2022). The natural resource sector in oil-exporting developing and emerging countries attracts capital inflows from the rest of the world in the form of FDI. Melina *et al.* (2016) argue that the decisions for resource production and developments in these countries typically happen via negotiations between governments and foreign multinational firms. As a result, FDI can be thought as the outcome of these negotiations and is accumulated to create $K_{o,t}$ used in (1).[13] $FDI^*_t$ inflows to the oil sector respond to the real international price of oil, $P^*_{o,t}$, as follows

$$FDI^*_t = \left(FDI^*_{t-1}\right)^{\rho_{fdi}} \left(P^*_{o,t}\right)^{1-\rho_{fdi}} \tag{3}$$

where $\rho_{fdi}$ measures the extent of inertia in the accumulation of $FDI^*_t$.

The oil firm receives its revenues net of royalties levied by the government on production

[11] As supported by empirical literature on Nigeria, there is incomplete exchange rate pass-through of imports to domestic prices. Various studies have estimated the level of exchange rate pass-through for Nigeria (see, for example, Oyinlola and Adetunji, 2009 and Adebiyi and Mordi, 2012).

[12] As is standard in most DSGE models, we assume that wages as well as prices of domestically produced goods are sticky. Also, an investment adjustment cost is incorporated into the model to generate hump-shaped investment response to shocks. For simplicity, parts of the model associated with the wage setting dynamics, behaviors of non-oil firms, interaction between the SOE and the foreign economy, and analogous 'foreign' variables are largely omitted in the exposition. See Omotosho and Yang (2024) for details.

[13] The role of FDI inflows aimed at oil and gas resource production is important in countries and regions that are new to resource development and may have weak institutions and tax systems. Previous literature that investigates the importance of FDI in the natural resource sector finds a significant correlation between FDI and resource endowments and studies the role and regulations of host governments in supporting large-scale resource developments with foreign investments. See, for example, Asiedu and Lien (2011), Teixeira *et al.* (2017) that apply the dynamic panel data analysis, and Goldwyn and Clabough (2020) that use the narrative approach based on case studies.

quantity at a rate $\tau$ as follows

$$\Pi_{o,t} = (1-\tau)\,\varepsilon_t P^*_{o,t} Y_{o,t} \tag{4}$$

where $\varepsilon_t$ is the nominal exchange rate. The oil firm's profits are fully taxed. It is clear that a shock to $P^*_{o,t}$ affects the firm's production and demand for capital and materials.

We assume that $P^*_{o,t}$ and $A_{o,t}$ evolve according to the following $AR(1)$ processes

$$P^*_{o,t} = \left(P^*_{o,t-1}\right)^{\rho_{P^*_o}(s^{vol}_t)} \exp\left(\sigma_{P^*_o}(s^{vol}_t)\xi^{P^*_o}_t\right), \quad A_{o,t} = \left(A_{o,t-1}\right)^{\rho_{A_o}} \exp\left(\sigma_{A_o}\xi^{A_o}_t\right) \tag{5}$$

In order to capture possible nonlinearities in the response of the resource-rich economy to oil price instabilities, we allow the volatility of the oil price shock, $\sigma_{P^*_o}(s^{vol}_t)$, to change from one regime to another as follows

$$s^{vol}_t \in \{High, Low\} \tag{6}$$

To take into consideration the possibility where the responses of the real economy may depend also on the persistence of the shock, we also restrict the persistence parameter, $\rho_{P^*_o}(s^{vol}_t)$, to follow a Markov chain that switches at the same time, but not necessarily in the same direction.

### 3.2 Fuel subsidy and fiscal policy

We assume that the government respects a budget constraint given by

$$TX_t + OR_t + B_t = P_{g,t}G_{c,t} + OS_t + \frac{B_{t+1}}{R_t} \tag{7}$$

where (7) shows that an increase in government expenditure, $G_{c,t}$, consisting of imported goods and domestically produced goods, can be financed either by increasing per-capita lump-sum taxes levied on households, $TX_t$, generating more oil revenues collected from oil royalties, $OR_t$, or issuing more debt, $B_t$. On the payment side of (7), $\frac{B_{t+1}}{R_t}$ represents the interest payments on $B_t$. When the need arises, the government makes refined oil subsidy payments, $OS_t$, within a framework that allows for the stabilization of domestic fuel price. $P_{g,t}$ is the deflator of government expenditure.

As in Medina and Soto (2007), we assume that the government consumption basket consists of imported goods, $G_{f,t}$, and domestically produced goods, $G_{h,t}$

$$G_{c,t} = \left[(1-\gamma_g)^{\frac{1}{\eta_g}} G_{h,t}^{\frac{\eta_g-1}{\eta_g}} + \gamma_g^{\frac{1}{\eta_g}} G_{f,t}^{\frac{\eta_g-1}{\eta_g}}\right]^{\frac{\eta_g}{\eta_g-1}} \tag{8}$$

where $\eta_g$ is the elasticity of substitution between $G_{f,t}$ and $G_{h,t}$. $\gamma_g$ is the share of foreign goods in the consumption basket.

Standard results from the government optimal intra-temporal decisions subject to (8) and the usual Dixit-Stigitz aggregation yield the demand functions for $G_{h,t}$ and $G_{f,t}$, respectively

$$G_{h,t} = (1-\gamma_g)\left(\frac{P_{h,t}}{P_{g,t}}\right)^{-\eta_g} G_{c,t}, \quad G_{f,t} = \gamma_g \left(\frac{P_{f,t}}{P_{g,t}}\right)^{-\eta_g} G_{c,t} \tag{9}$$

and the government consumption price index given by

$$P_{g,t} = \left[(1-\gamma_g) P_{h,t}^{1-\eta_g} + \gamma_g P_{f,t}^{1-\eta_g}\right]^{\frac{1}{1-\eta_g}} \tag{10}$$

Following Allegret and Benkhodja (2015), we assume that aggregate refined oil, $O_t$, is produced abroad and imported into the SOE at a landing price, $P_{lo,t}$, by the government. In turn, the government sells the imported fuel to households and domestic firms, at a regulated price, $P_{ro,t}$, based on a fuel pricing rule given by

$$P_{ro,t} = P_{ro,t-1}^{1-\nu} P_{lo,t}^{\nu} \tag{11}$$

where $0 \leq \nu \leq 1$ governs the extent to which the government subsidizes fuel consumption. When $\nu = 1$, the implicit subsidy regime ceases to exist whereas $\nu = 0$ implies complete price regulation. $P_{lo,t}$, which is the prevailing landing price of refined oil expressed in domestic currency, is given by[14]

$$P_{lo,t} = \varepsilon_t \frac{P_{o,t}^*}{P_t^*} \Psi_t^o \tag{12}$$

where $P_{o,t}^*$ is the foreign currency price of oil abroad, $\Psi_t^o$ is the LOP gap associated with the import price of fuel, and $P_t^*$ is aggregate consumer price index of the foreign economy.

Thus, the implicit fuel subsidy payment is given by the difference between the value of fuel imports expressed in domestic currency and the amount realized from fuel sales in the domestic economy as follows

$$OS_t = (P_{lo,t} - P_{ro,t}) O_t \tag{13}$$

where total imported fuel $(O_t)$ comprises fuel consumption by households, $C_{o,t}$, and consumption by domestic firms, $O_{h,t}$.

On the revenue side of the budget constraint, (7), the amount of oil revenues, $OR_t$, accruing to the government are given by

$$OR_t = \tau \varepsilon_t P_{o,t}^* Y_{o,t} \tag{14}$$

Following Algozhina (2022), we consider backward looking fiscal policy reaction functions that allow government consumption and taxes to respond to lagged debt, $OR_t$ and $OS_t$

$$\frac{G_{c,t}}{\bar{G}} = \left(\frac{G_{c,t-1}}{\bar{G}}\right)^{\rho_g} \left[\left(\frac{Y_{o,t}}{\bar{Y}_o}\right)^{\omega_{yo}} \left(\frac{B_{t-1}}{\bar{B}}\right)^{-\omega_b} \left(\frac{OR_t}{\overline{OR}}\right)^{\omega_{or}}\right]^{1-\rho_g} \exp\left(\sigma_{gc}\xi_t^{gc}\right) \tag{15}$$

$$\frac{TX_t}{\overline{TX}} = \left(\frac{G_{c,t}}{\bar{G}}\right)^{\varphi_g} \left(\frac{B_{t-1}}{\bar{B}}\right)^{\varphi_b} \left(\frac{OS_t}{\overline{OS}}\right)^{\varphi_{os}} \left(\frac{OR_t}{\overline{OR}}\right)^{-\varphi_{or}} \exp\left(\sigma_{tx}\xi_t^{tx}\right) \tag{16}$$

where $\rho_g \in [0,1]$ represents the degree of smoothing in the government spending rule. $\omega_{yo}$, $\omega_b$ and $\omega_{or}$ are the government consumption feedback coefficients with respect to oil output, lagged domestic debt and $OR_t$, respectively. In (16), lump-sum taxes respond to government consumption, lagged debt, $OS_t$ and $OR_t$ with the feedback parameters, $\varphi_g$, $\varphi_b$, $\varphi_{os}$ and $\varphi_{or}$, respectively. The tax shock, $\xi_t^{tx}$, and government spending shock, $\xi_t^{gc}$, are given by an $AR(1)$ exogenous process.

[14]This is similar to the specification in Poghosyan and Beidas-Strom (2011).

### 3.3 Monetary policy and the switching Taylor rule

In setting the short-term nominal interest rate, $R_t$, the central bank follows a simple time-varying Taylor rule by gradually responding to aggregate inflation, $\pi_t = \frac{P_t}{P_{t-1}}$, domestic output, $Y_{h,t}$, and the exchange rate depreciation, $\Delta\varepsilon_t$

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\rho_r(s_t^{vol})} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\omega_\pi(s_t^{vol})} \left(\frac{Y_{h,t}}{\bar{Y}_h}\right)^{\omega_y(s_t^{vol})} \left(\frac{\Delta\varepsilon_t}{\overline{\Delta\varepsilon}}\right)^{\omega_\varepsilon(s_t^{vol})}\right]^{1-\rho_r(s_t^{vol})} \exp\left(\sigma_r \xi_t^r\right) \quad (17)$$

where $\rho_r \in [0,1]$ is the interest rate smoothing parameter capturing monetary policy inertia. $\omega_\pi$, $\omega_y$ and $\omega_\varepsilon$ are the policy coefficients chosen by the central bank with respect to inflation, domestic output and the exchange rate, respectively. These policy parameters are assumed to be governed by the same Markov process and switch together with $\sigma_{P_o^*}(s_t^{vol})$.

To bridge the behavior of policy and the heteroskedasticity of oil prices, we implement a hybrid framework

$$\rho_r(s_t^{vol}) = \bar{\rho}_r + \hat{\rho}_r(s_t^{vol}) \quad (18)$$

$$\omega_x(s_t^{vol}) = \bar{\omega}_x + \hat{\omega}_x(s_t^{vol}) \quad (19)$$

where $x = \pi, y, \varepsilon$. This specification postulates that the behavior of policy responses is made up of a systematic component, $\bar{\rho}_r$ and $\bar{\omega}_x$, and a regime-dependent component, $\hat{\rho}_r(s_t^{vol})$ and $\hat{\omega}_x(s_t^{vol})$. The setup is very flexible and nests as special cases the structures which characterize the systematic response of monetary policy that is consistent regardless of the regimes of oil price volatility and those which are typically thought to motivate the assumption of regime shifts in policy stance. In doing so, it not only gives an explicit role to oil price volatility, capturing the increasing uncertainty faced by policymakers and making these variances affect the behavior of policy directly, but also allows us to take an agnostic approach in regime-switching of volatility and policy adjustments.

### 3.4 Perturbation solution of the model

The generic problem of our rational expectations nonlinear DSGE model with Markov-switching can be written as

$$E_t \sum_{s_{t+1}=1}^{h} p_{s_t,s_{t+1}}\left(\mathcal{I}_t\right) f_{s_t}\left(x_{t+1}\left(s_{t+1}\right), x_t\left(s_t\right), x_{t-1}, \theta_{s_t}, \theta_{s_{t+1}}, \epsilon_t\right) = 0 \quad (20)$$

where $E_t$ is the expectation operator. $p_{s_t,s_{t+1}}\left(\mathcal{I}_t\right)$ is the transition probability of going from state $s_t$ in the current period to state $s_{t+1}$ in the next period. $f_{s_t}$ is a vector of (potentially) nonlinear functions. $x_t\left(s_t\right)$ is a vector of all the endogenous variables in the current regime $s_t$. $\theta_{s_t}$ contains the parameters in the current regime. $\epsilon_t \sim N\left(0, I\right)$ is a vector of stochastic shocks.

In this paper, we follow Maih (2015), which computes the solution using the Newton algorithm and starts out with the general Markov-switching framework set out in (20). This approach also develops a perturbation solution technique that allows us to approximate the decision rules and is suitable for large systems such as our model. The exact solution can be returned in the form of a first-order VAR, utilizing the idea of a minimum state variable solution of the form

$$x_t = \mathcal{T}_{s_t}(x_{t-1}, \epsilon_t) \tag{21}$$

As the solution also depends on the regime $s_t$, a $p$-order perturbation of $x_t = \mathcal{T}^{s_t}(z_t)$ yields the following solution that approximates the decision rule in (21)

$$\mathcal{T}^{s_t}(z_t) \simeq \mathcal{T}^{s_t}(\bar{z}_{s_t}) + \mathcal{T}_z^{s_t}(z_t - \bar{z}_{s_t}) + \frac{1}{2!}\mathcal{T}_{zz}^{s_t}(z_t - \bar{z}_{s_t})^{\otimes 2} + ... + \frac{1}{p!}\mathcal{T}_{z^{(p)}}^{s_t}(z_t - \bar{z}_{s_t})^{\otimes p} \tag{22}$$

where $z_t \equiv \begin{bmatrix} x'_{t-1} & \chi & \epsilon'_t \end{bmatrix}'$ is a vector of state variables, $\bar{z}_{s_t}$ is the steady state values of the state variables in $s_t$, and $\chi$ is the perturbation parameter.

# 4 Parameterization and filtration implications

Next, we turn to Bayesian methods for estimating the parameters in the model and explain the data and calibration used in the quantitative analysis. We compute a first-order solution of (22) and estimate the parameters using the RISE toolbox in Matlab which also includes the procedure that we use for filtering the regime-switching model.[15]

## 4.1 Data and calibration

The model is estimated by Bayesian methods for the Nigerian economy using 87 quarterly observations on 15 selected macroeconomic variables over the sample period of 2000:2 - 2021:4.[16] While Nigeria represents the SOE in our model setup, the rest of the world consists of Nigeria's major trading partners of the Euro area, the US, and India.[17]

The domestic variables include real GDP growth ($\Delta y_{h,t}$), real consumption growth ($\Delta c_t$), real investment growth ($\Delta i_{no,t}$), real effective exchange rate ($q_t$), headline CPI inflation ($\Delta p_t$), core CPI inflation ($\Delta p_{no,t}$), the nominal interest rate ($R_t$), oil output ($\Delta y_{o,t}$), growth rate of government debt ($\Delta b_t$), change in tax revenue ($\Delta tx_t$) and government consumption growth ($\Delta g_{c,t}$). The foreign variables are trade-weighted real GDP growth ($\Delta y_t^*$), aggregate CPI inflation ($\Delta p_t^*$), and the interest rate ($R_t^*$), as well as log growth in the international oil price ($\Delta p_{o,t}^*$).[18]

We fix a subset of parameters by a calibration and the values of the calibrated parameters are presented in Table 1. The steady state ratios reported in Table 2 are derived using data for the Nigerian economy spanning the last three decades. The parametrization is done to

[15]See Maih (2015) for further details.

[16]The data were provided by the Statistics Department of the CBN, the Federal Reserve Bank of St. Louis, and the International Financial Statistics. This choice of the estimation sample was based on data availability for Nigeria, encompasses periods of financial distress and oil price fluctuations, but excludes any observations since the outbreak of the Russo-Ukrainian conflict.

[17]These three regions account for about 65% of Nigeria's total external trade over the last two decades. In the normalized weights for the computation of the foreign variables, the Euro area is predominant with a trade weight of 0.39 while the weights for the US and India are 0.36 and 0.25, respectively. Details about data sources and transformations are consistent with those given in Omotosho and Yang (2024).

[18]To set up the model for policy analysis, it is solved by linearizing about the steady state. The lower case variables denote the deviations of these variables from their steady state.

fit quarterly data with values borrowed from those assumed by Omotosho and Yang (2024) for Nigeria and by Gali and Monacelli (2005), Romero (2008), Wolden-Bache *et al.* (2008), Hove *et al.* (2015), Ferrero and Seneca (2019), Iklaga (2017), Allegret and Benkhodja (2015), Algozhina (2022), Ncube and Balma (2017) and Hollander *et al.* (2018) for standard calibration for small open-economies and resource-rich emerging economies.

| Parameter Definition | Symbol | Value | Source |
|---|---|---|---|
| Discount factor | $\beta$ | 0.990 | Allegret and Benkhodja (2015) |
| Depreciation rate in both the oil and non-oil sectors | $\delta_h = \delta_o$ | 0.025 | Allegret and Benkhodja (2015); Algozhina (2022) |
| Share of imports in household's consumption | $\gamma_c$ | 0.400 | Gali and Monacelli (2005) |
| Share of fuel in household's consumption | $\gamma_o$ | 0.085 | National Bureau of Statistics |
| Share of imports in household's investment | $\gamma_i$ | 0.200 | National Bureau of Statistics |
| Calvo - wages | $\theta_w$ | 0.750 | Hollander *et al.* (2018) |
| Elasticity of domestic output with respect to capital | $\alpha_h^k$ | 0.330 | Rasaki and Malikane (2015); Algozhina (2022) |
| Elasticity of domestic output with respect to oil | $\alpha_h^o$ | 0.120 | $1 - \alpha_h^k - \alpha_h^n$ |
| Elasticity of domestic output with respect to labor | $\alpha_h^n$ | 0.550 | Ncube and Balma (2017) |
| Elasticity of oil output with respect to capital | $\alpha_o^k$ | 0.700 | Algozhina (2022) |
| Elasticity of oil output with respect to materials | $\alpha_o^m$ | 0.300 | Ferrero and Seneca (2019); Algozhina (2022) |
| Share of imports in government's consumption | $\gamma_g$ | 0.120 | Algozhina (2022) |
| Elasticity of substitution between foreign & domestic goods - Govt. | $\eta_g$ | 0.600 | Hollander *et al.* (2018) |
| Share of household fuel consumption in total fuel imports | $\gamma_{co}$ | 0.750 | Hollander *et al.* (2018) |
| Persistence in oil sector foreign direct investment process | $\rho_{fdi}$ | 0.300 | Algozhina (2022) |
| Foreign relative risk aversion | $\sigma^*$ | 1.000 | Gabriel *et al.* (2023) |
| Foreign habit formation | $\phi_c^*$ | 0.500 | Gabriel *et al.* (2023) |
| Intra-temporal elasticity in foreign demand | $\eta_{c_h^*}$ | 0.790 | Medina and Soto (2005) |
| Coefficient of inflation in Taylor Rule - foreign economy | $\omega_{\pi^*}$ | 1.500 | Bhattarai *et al.* (2021); Gabriel *et al.* (2023) |
| Coefficient of output in Taylor Rule - foreign economy | $\omega_{y^*}$ | 0.500 | Bhattarai *et al.* (2021); Gabriel *et al.* (2023) |

Table 1: **Calibrated Parameters**

## 4.2 Bayesian estimation

The joint posterior distribution of the estimated parameters is then obtained in two steps. First, the posterior mode and the Hessian matrix are obtained via standard numerical optimization routines. Second, we carry out a sensitivity analysis that explores the robustness of the results based on posterior distributions.

Table 3 reports the parameter estimates, summarizing the prior and posterior distributions of the estimated parameters and 90% high posterior density intervals (HPDI). Overall, the parameter estimates are plausible. Our estimation delivers that, based on the posterior estimate of $1 - \gamma_R$, about 20% of the households are liquidity-constrained. These households in Nigeria do not trade on financial markets and consume entirely their wage income each period. This is slightly below the prior value and those usually found in earlier empirical studies. The estimate of $\nu$ implies that there is about 52% pass-through of international oil price to domestic oil prices and the government subsidizes about half of the consumption of fuel in the domestic economy.

Before focusing on monetary policy rules in the following section, the role of fiscal policy needs to be briefly discussed here in the context of the present paper as the implicit subsidy expenditure determined by the fuel pricing rule is closely associated with the conduct of fiscal policy and planning. The feedback parameter with respect to oil output, $\omega_{yo}$, defines the cyclicality of government spending. The estimate suggests evidence of counter-cyclical fiscal policy. In other words, the fiscal policy is 'active' for demand stabilization, implying that the country is able to sustain increased government spending even during the periods of oil price falls. The tax policy response is, on the other hand, 'passive' so that the fiscal authority

| Ratio | Symbol | Value |
|---|---|---|
| Domestic consumption to domestic output | $\bar{C}_h/\bar{Y}_h$ | 0.690 |
| Investment to domestic output | $\bar{I}_{no}/\bar{Y}_h$ | 0.150 |
| Domestic materials to domestic output | $\bar{M}/\bar{Y}_h$ | 0.010 |
| Government consumption to domestic output | $\bar{G}_c/\bar{Y}_h$ | 0.070 |
| Non-oil export to output | $\bar{C}_h^*/\bar{Y}_h$ | 0.070 |
| Import to domestic output | $\overline{IM}/\bar{Y}_h$ | 0.150 |
| Share of non-oil export in aggregate export | $1-\bar{Y}_o/\overline{EX}$ | 0.050 |
| Share of oil in GDP | $\bar{Y}_o/\bar{Y}$ | 0.260 |
| Fiscal debt to oil revenue | $\bar{B}/\overline{OR}$ | 0.700 |
| Taxes to oil revenue | $\overline{TX}/\overline{OR}$ | 0.050 |
| Government consumption to oil revenue | $p_g\bar{G}_c/\overline{OR}$ | 0.700 |
| Non-oil imports to total import | $\bar{C}_f/\overline{IM}$ | 0.400 |
| Fuel import to total import | $\bar{O}/\overline{IM}$ | 0.300 |
| Oil sector foreign direct investment to net exports | $q\overline{FDI}/\overline{NX}$ | 0.300 |
| Exports to net exports | $\overline{EX}/\overline{NX}$ | 0.600 |
| Imports to net exports | $1-\overline{EX}/\overline{NX}$ | 0.400 |
| Foreign debt service payments to net exports | $q\bar{B}^*\bar{R}^*/\overline{NX}$ | 0.020 |
| Foreign debt to net exports | $q\bar{B}^*/\overline{NX}$ | 0.3112 |
| Oil profit repatriation to net exports | $(1-\tau)q\bar{P}_o^*\bar{Y}_o/N\bar{X}$ | 0.600 |
| Public goods imports to total import | $\bar{G}_f/\overline{IM}$ | 0.050 |
| Fuel subsidy payments to oil revenue | $\overline{OS}/\overline{OR}$ | 0.200 |
| Fuel sales value to fuel subsidy payments | $\bar{P}_{ro}\bar{O}/\overline{OS}$ | 0.300 |
| Domestic debt service payments to oil revenue | $\bar{B}/\bar{R}/\overline{OR}$ | 0.020 |
| Fuel import value to fuel subsidy payments | $q\bar{P}_o^*\bar{O}/\overline{OS}$ | 0.300 |

Table 2: **Steady State Ratios**

*Notes*: The implied steady state ratios are derived based on the National Accounts Statistics, National Bureau of Statistics and the Balance of Payments Statistics, Central Bank of Nigeria.

strongly adjusts lump-sum taxes in order to ensure debt stability in the regime that passively accommodates the monetary authority.

It is interesting to note that the estimated values of the key switching parameters are very different between the various regimes. The standard deviation of the oil price shock, $\xi_t^{P_o^*}$, is estimated to be over two times higher in the high volatility regime than in the low volatility regime. The probability of moving from the low volatility regime to the high volatility regime is higher than the probability of switching from high to low volatility but the periods of major oil price fluctuations do not tend to be long-lasting. The difference clearly suggests evidence of distinct oil price movements that are time-varying in our model-implied dynamics.

To understand the central bank behavior, our empirical analysis evaluates the extent of its adjustments that interact with the varying oil price volatility. There is no prior information about the regime-dependent policy parameters which are assumed to be normally distributed and centered at 0 with standard deviations of 0.25. Our posterior maximization identifies several observed switches in monetary policy. During highly volatile oil price periods ($s_2$) with heightened uncertainty faced by policymakers, the central bank is less sensitive to movements in headline inflation, focuses less on exchange rate stabilization, but places greater emphasis on the output gap and adjusts interest rates more quickly.

### 4.3 Smoothed transition probabilities

There is ample evidence in favor of stochastic regime switches in the parameters. Figure 1 plots the smoothed state probabilities for being in the high volatility regime ($s_2$) in the model (based on the posterior mode) and clearly shows recurrent spikes in the oil price movements

| Parameter | | Prior distribution | | | Posterior distribution | | |
|---|---|---|---|---|---|---|---|
| | | Density | Mean | SD/DoF | Mode | Median | 90% HPDI |
| Ricardian consumers | $\gamma_R$ | $\mathcal{B}$ | 0.60 | 0.10 | 0.811 | 0.807 | [0.739: 0.877] |
| Labour supply elasticity | $\varphi$ | $\mathcal{G}$ | 1.45 | 0.10 | 1.424 | 1.397 | [1.252: 1.547] |
| Relative risk aversion | $\sigma$ | $\mathcal{IG}$ | 2.00 | 0.40 | 1.271 | 1.304 | [1.021: 1.549] |
| External habit | $\phi_c$ | $\mathcal{B}$ | 0.70 | 0.10 | 0.388 | 0.400 | [0.281: 0.503] |
| Investment adjustment cost | $\chi$ | $\mathcal{G}$ | 4.00 | 3.00 | 16.866 | 18.050 | [17.043: 18.619] |
| Fuel pricing parameter | $\nu$ | $\mathcal{B}$ | 0.30 | 0.10 | 0.526 | 0.522 | [0.387: 0.625] |
| Oil-core consumption elasticity | $\eta_o$ | $\mathcal{G}$ | 0.20 | 0.10 | 0.151 | 0.189 | [0.059: 0.318] |
| Foreign-domestic consumption elasticity | $\eta_c$ | $\mathcal{G}$ | 0.60 | 0.20 | 0.560 | 0.586 | [0.435: 0.784] |
| Foreign-domestic investment elasticity | $\eta_i$ | $\mathcal{G}$ | 0.60 | 0.20 | 0.561 | 0.586 | [0.257: 0.807] |
| Calvo - domestic goods | $\theta_h$ | $\mathcal{B}$ | 0.70 | 0.10 | 0.616 | 0.621 | [0.557: 0.678] |
| Calvo - imported goods | $\theta_f$ | $\mathcal{B}$ | 0.70 | 0.10 | 0.691 | 0.664 | [0.498: 0.822] |
| Calvo - exports goods | $\theta_{hf}$ | $\mathcal{B}$ | 0.70 | 0.10 | 0.716 | 0.717 | [0.522: 0.867] |
| ***Monetary policy: systematic*** | | | | | | | |
| Taylor rule - inflation | $\bar{\omega}_\pi$ | $\mathcal{G}$ | 1.50 | 0.25 | 3.492 | 3.234 | [2.831: 3.719] |
| Taylor rule - output | $\bar{\omega}_y$ | $\mathcal{G}$ | 0.125 | 0.05 | 0.108 | 0.115 | [0.051: 0.186] |
| Taylor rule - exchange rate | $\bar{\omega}_\varepsilon$ | $\mathcal{G}$ | 0.125 | 0.05 | 0.177 | 0.199 | [0.087: 0.341] |
| Interest rate smoothing | $\bar{\rho}_r$ | $\mathcal{B}$ | 0.50 | 0.25 | 0.162 | 0.146 | [0.020: 0.272] |
| ***Monetary policy: regime-dependent*** | | | | | | | |
| Taylor rule - inflation (L) | $\hat{\omega}_\pi(s_1)$ | $\mathcal{N}$ | 0.00 | 0.25 | 0.609 | 0.632 | [0.378: 0.923] |
| Taylor rule - inflation (H) | $\hat{\omega}_\pi(s_2)$ | $\mathcal{N}$ | 0.00 | 0.25 | 0.206 | 0.011 | [-0.360: 0.302] |
| Taylor rule - output (L) | $\hat{\omega}_y(s_1)$ | $\mathcal{N}$ | 0.00 | 0.25 | -0.077 | 0.008 | [-0.144: 0.200] |
| Taylor rule - output (H) | $\hat{\omega}_y(s_2)$ | $\mathcal{N}$ | 0.00 | 0.25 | 0.161 | 0.029 | [-0.151: 0.258] |
| Taylor rule - exchange rate (L) | $\hat{\omega}_\varepsilon(s_1)$ | $\mathcal{N}$ | 0.00 | 0.25 | 0.866 | 1.071 | [0.844: 1.327] |
| Taylor rule - exchange rate (H) | $\hat{\omega}_\varepsilon(s_2)$ | $\mathcal{N}$ | 0.00 | 0.25 | 0.363 | 0.152 | [-0.167: 0.433] |
| Interest rate smoothing (L) | $\hat{\rho}_r(s_1)$ | $\mathcal{N}$ | 0.00 | 0.25 | 0.002 | 0.030 | [-0.090: 0.131] |
| Interest rate smoothing (H) | $\hat{\rho}_r(s_2)$ | $\mathcal{N}$ | 0.00 | 0.25 | -0.092 | -0.009 | [-0.191: 0.189] |
| ***Fiscal policy*** | | | | | | | |
| Government consumption - output | $\omega_{yo}$ | $\mathcal{N}$ | 0.40 | 0.50 | -0.388 | -0.388 | [-0.440: -0.322] |
| Government consumption - fiscal debt | $\omega_b$ | $\mathcal{N}$ | 0.30 | 0.50 | 0.079 | 0.086 | [0.000: 0.178] |
| Government consumption - oil revenue | $\omega_{or}$ | $\mathcal{N}$ | 0.80 | 0.50 | 0.778 | 0.758 | [0.603: 0.929] |
| Government consumption smoothing | $\rho_{g_c}$ | $\mathcal{B}$ | 0.50 | 0.25 | 0.310 | 0.307 | [0.161: 0.466] |
| Tax - fiscal debt | $\varphi_b$ | $\mathcal{N}$ | 0.40 | 0.50 | 0.205 | 0.207 | [0.006: 0.384] |
| Tax - government consumption | $\varphi_g$ | $\mathcal{N}$ | 0.95 | 0.50 | 0.630 | 0.680 | [0.507: 0.853] |
| Tax - subsidies | $\varphi_{os}$ | $\mathcal{N}$ | 0.10 | 0.50 | 0.531 | 0.604 | [0.239: 0.809] |
| Tax - oil revenue | $\varphi_{or}$ | $\mathcal{N}$ | 0.30 | 0.50 | 0.077 | 0.130 | [0.007: 0.241] |
| ***Standard deviation and persistence of shock*** | | | | | | | |
| Oil price (L) | $\sigma_{P_o^*}(s_1)$ | $\mathcal{IG}$ | 0.10 | 4.00 | 0.100 | 0.126 | [0.114: 0.137] |
| Oil price (H) | $\sigma_{P_o^*}(s_2)$ | $\mathcal{IG}$ | 0.01 | 4.00 | 0.226 | 0.325 | [0.214: 0.475] |
| Oil price (L) | $\rho_{P_o^*}(s_1)$ | $\mathcal{B}$ | 0.50 | 0.28 | 0.994 | 0.957 | [0.907: 0.999] |
| Oil price (H) | $\rho_{P_o^*}(s_2)$ | $\mathcal{B}$ | 0.50 | 0.28 | 0.548 | 0.587 | [0.371: 0.888] |
| ***Transition probability*** | | | | | | | |
| [L, H] | $p_{12}^{vol}$ | $\mathcal{B}$ | 0.50 | 0.28 | 0.045 | 0.043 | [0.006: 0.084] |
| [H, L] | $p_{21}^{vol}$ | $\mathcal{B}$ | 0.50 | 0.28 | 0.178 | 0.280 | [0.103: 0.476] |

Table 3: **Prior and Posterior Distributions**

*Notes*: Two chains of 100,000 draws are generated and the first half of these draws is discarded. The variance-covariance matrix of the perturbation term for the jumping distribution in the Metropolis-Hastings algorithm is adjusted so that an acceptance rate of 0.2469% is obtained. In the estimation the number of draws that we choose is sufficient to allow for convergence. To formally check the convergence of the parameters, we use the convergence indicators such as the scale reduction factor statistic recommended by Brooks and Gelman (1998) and Gelman *et al.* (2004).

and the ensuing policy responses that are time-varying and contribute to their nonlinear effect on the real economy. The economy has stayed in the high oil price volatility regime with a high probability of occurrence which is mostly responsible for the macroeconomic instability that we observe and coincides with monetary policy adjustments.

Interestingly, major volatile episodes in oil prices are observed during 2008-2009, 2014-2016, and 2020-2021. These high oil price volatility states are mostly related to historical events and are clearly triggered by a plunge in oil prices in these distinct periods. The first period of a huge price swing coincides with the US credit crisis of 2008. The second episode of heightened volatility saw crude oil spot prices drop from as high as USD115 a barrel in June 2014 to a low of USD45 in January 2015.[19] This may be explained by the booming US shale oil production causing the sharp and persistent price fall starting from the third quarter of 2014 that culminated into an economic recession in Nigeria in 2016.[20] The third break date is estimated to occur in 2019/2020. We find that oil prices have displayed a more recent surge of volatility since then, coinciding with the demand-driven collapse in oil prices starting from the fourth quarter of 2019 due to the COVID-19 outbreak.

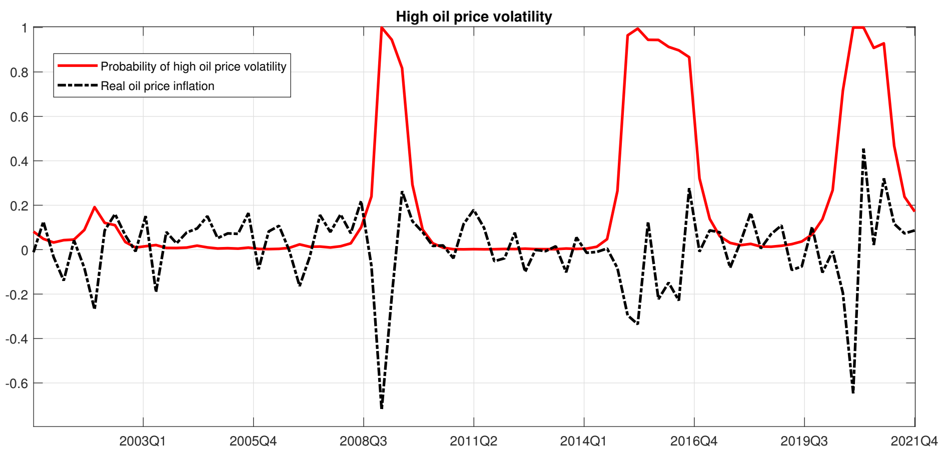


Figure 1: **Smoothed Probability of High Volatility Regime ($s_2$)**

*Notes*: The figure presents the smoothed probabilities for being in the high oil price volatility regime in the model that allows synchronized switching in the standard deviations of the oil price shock and in the monetary policy parameters. Their priors are assumed to be inverse gamma with $(0.1, 4)$ and normal with $(0, 0.25)$, respectively, between the high and low volatility regimes. Observed data: log growth in the international oil price.

# 5 Macroeconomic implications

Before conducting our policy exercises to quantify the time-varying optimized monetary policy response that depends on the volatility regimes, we simulate the model based on the posterior estimates (mode) under a condition of complete pass-through of international oil price to the retail price of fuel to assess how the economy would have responded in the absence of the subsidy program.

[19]Source: U.S. Energy Information Administration.

[20]Beyond the oil price movements in 2014-2016, oil revenue in Nigeria was subject to heightened volatility due to production shutdowns and supply disruptions, and was affected by the peculiar market demand conditions associated with the shale oil and gas revolution. As a result, the country recorded reduced patronage of its crude oil, and more so, increased disinvestment of oil-related capital by foreign investors.

### 5.1 Responses of fuel subsidy removal

Based on (11), the parameter $\nu \in [0, 1]$ governs the level to which the government subsidizes fuel consumption. A value of $\nu = 1$ provides us an alternative case where there is complete pass-through of international oil prices into the retail price of fuel and the subsidy regime ceases to exist. In Figure 2, we simulate the model based on the parameterization in Section 4 and report the impulse responses (henceforth IRFs) comparing the transmission mechanism of a *negative* oil price shock when the subsidy program is in place or 'turned off'.[21]

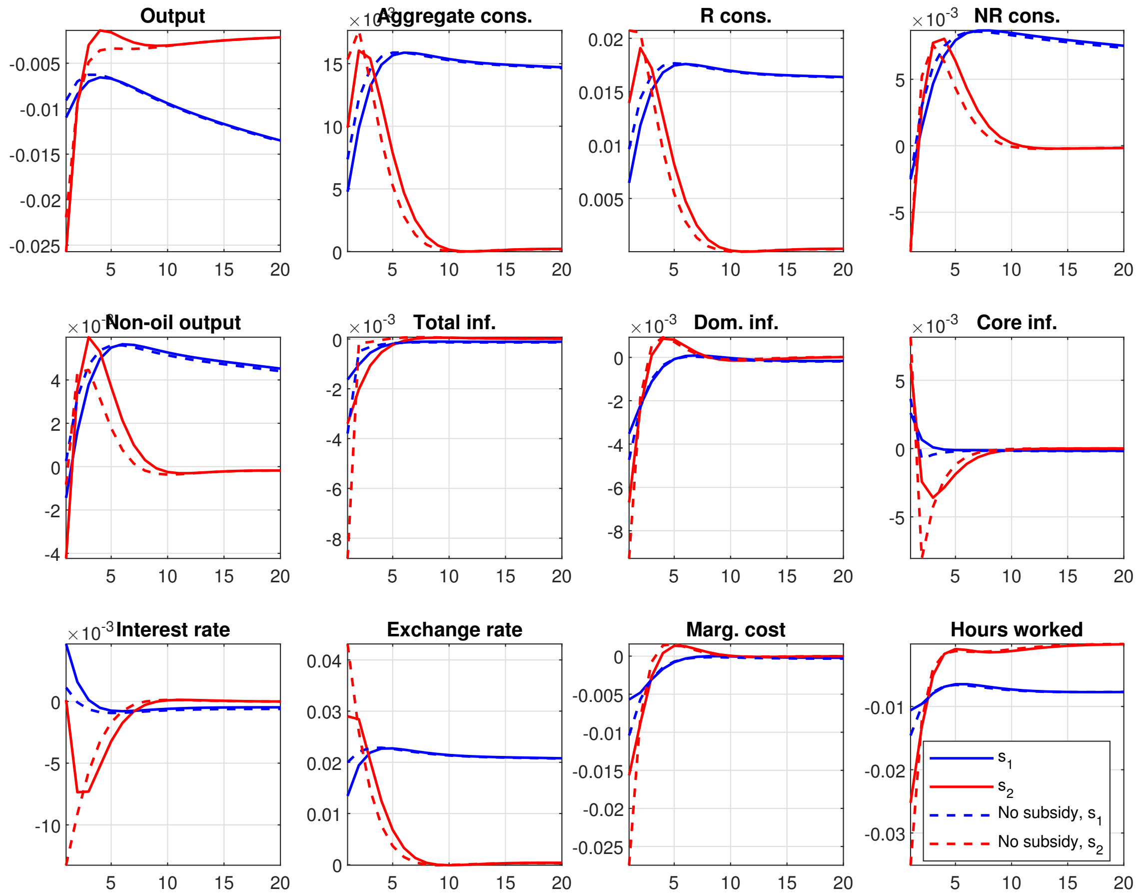


Figure 2: **Responses to a Negative Oil Price Shock**

*Notes*: The figure plots the response corresponding a *negative* one standard deviation of the oil price shock's innovation. Each response is for a 20 period (5 years) horizon. $s_1 \to$ Regime 1: Low oil price volatility; $s_2 \to$ Regime 2: High oil price volatility. Subsidy: $\nu = 0.526$; No subsidy: $\nu = 1$.

The results are briefly discussed here for the alternative economy with $\nu = 1$. The projected outcomes for GDP and private consumption are in line with the findings of Siddig *et al.* (2014). Following a negative real oil price shock, the contraction of aggregate GDP is less severe in the short run. Private consumption rises more due to more resources becoming available to consumers (and an improvement in the terms of trade), compared to the case in which the subsidy policy is in place. The increased aggregate demand arising from additional income that is available to consumers and the associated lower real marginal cost owing to the full

[21] A negative oil price shock (an unanticipated fall in oil prices) can be strongly correlated with domestic output and capital inflows. The frailties in emerging market countries can lead to sudden and sharp reversals of capital inflows during a negative oil price shock (the 'sudden stops' highlighted in Calvo, 1998).

pass-through effect ameliorates the shock's contractionary effects on non-oil GDP.

The behaviors of different measures of inflation are qualitatively and quantitatively consistent with those of Omotosho (2019b). Domestic inflation declines more as domestic prices are less sticky in their downward adjustment, while the response (decline) of aggregate inflation is less pronounced in the benchmark which can be explained by the price rigidity implied by the subsidy program. Reacting to aggregate inflation, the monetary authority is able to cut interest rates, in the aftermath of a large, negative oil price shock, ameliorating the short-run output contraction. The real exchange rate depreciates more and the inflationary effects of such depreciation on headline inflation are more than offset by the reduction in domestic inflation. Finally, labor demand decreases with an decreased cost of production (firms wishing to substitute away from labor).

More importantly, there are marked differences in IRFs when the economy moves from $s_1$ to $s_2$. Overall, the effects are generally stronger and more persistent in $s_2$. In particular, the decline in firms' real marginal cost is more fully reflected by the removal effects causing more downward adjustment in the prices of domestically produced goods which is exacerbated if the shock is large and volatile. Given an oil price shock in the high volatility period ($s_2$), the alternative economy ($\nu = 1$) is associated with a large decline in total inflation and, facing no inflationary pressures following a fall in oil prices, its central bank would cut interest rates in the bid to boost aggregate demand. As a result, it would ameliorate the contractionary effects of the negative shock and produce better outcomes for consumption. Compared to the low-variance state, the output contraction on impact in the benchmark economy is more severe in $s_2$. Interestingly, the model also predicts that there is an amplification effect in the output dynamics in $s_2$ where the policy reacts strongly to output stabilization.

Our simulations so far also reveal another interesting finding. As our model features Ricardian and Non-Ricardian households (rich and poor), we depict the responses of consumption of both types of consumers (R and NR, respectively). When we remove the subsidy program in the alternative economy, this introduces more amplified responses into the model, drives a bigger wedge between the responses of the two economies in aggregate consumption and the consumption of R households than those in the consumption of NR households, in the sense that the increase in aggregate consumption is mostly associated with that from the R consumers, arising from additional income that is available to the latter. Additionally, the magnitude of the increase is larger in $s_2$ where the shock is more volatile. Clearly, this suggests that potential fuel subsidy reforms would have mainly benefited the upper-income households exacerbating wealth inequality between these households and the working poor that are credit-constrained. These results are useful in helping us understand the issues of different welfare consequences in different policy scenarios.

### 5.2 Economic performances under counterfactual scenarios

What would the economy look like if the central bank does not change its policy when the fuel subsidy is removed? We look at the same counterfactual economy as assumed in Section 5.1 in which we impose $\nu = 1$. Table 4 corresponds to the standard deviations of observed macroeconomic variables under this alternative assumption and the estimated benchmark model, respectively. With the estimated Taylor rule, this leads to higher volatility in most of the key economic indicators. The alternative economy is associated with higher volatility in headline, core, domestic and imported inflation. Table 5 reports the cross-correlations of the observable variables *vis-à-vis* output. The alternative economy also performs poorly in capturing the countercyclicality of inflation, generating the wrong sign.

| std. dev. | $\Delta y_{h,t}$ | $\Delta c_t$ | $\Delta i_{no,t}$ | $\pi_t$ | $R_t$ | $q_t$ | $\pi_{c,t}$ | $\Delta y_{o,t}$ | $\Delta b_t$ | $\Delta tx_t$ | $\Delta g_{c,t}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | 0.146 | 0.182 | 0.092 | 0.109 | 0.429 | 0.143 | 0.107 | 0.457 | 0.551 | 0.444 | 0.233 |
| $\nu = 1$ | 0.147 | 0.186 | 0.092 | 0.113 | 0.432 | 0.159 | 0.109 | 0.458 | 0.550 | 0.454 | 0.235 |

Table 4: **Standard Deviation of Domestic Observables**

| cross-corr. | $\Delta y_{h,t}$ | $\Delta c_t$ | $\Delta i_{no,t}$ | $\pi_t$ | $R_t$ | $q_t$ | $\pi_{c,t}$ | $\Delta y_{o,t}$ | $\Delta b_t$ | $\Delta tx_t$ | $\Delta g_{c,t}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | - | 0.324 | 0.033 | 0.015 | -0.069 | 0.241 | 0.042 | 0.543 | 0.610 | 0.152 | 0.444 |
| $\nu = 1$ | - | 0.341 | 0.034 | -0.020 | -0.081 | 0.272 | 0.057 | 0.543 | 0.608 | 0.176 | 0.455 |

Table 5: **Co-Movement of Domestic Observables**

What would be the stabilization properties of the estimated policy had the subsidy removal been implemented over the last two decades? Figure 3 provides an additional comparison of the economic performances under the counterfactual scenario where subsidies were not in place historically. To this end, we plot the simulated time series from the benchmark model based on the smoothed shocks and compare those with the simulated economy from the counterfactual scenario. With the realized monetary rule, Figure 3 provides some interesting result that shows that the central bank had done well and achieved better performances in terms of stabilizing inflation and exchange rate movements and smoothing out fluctuations in output, especially during the early periods of the sample during which oil prices were relatively stable, in the presence of subsidies. In the absence of subsidies ($\nu = 1$), the macroeconomy (particularly in terms of the three policy target variables) would have been more volatile with the realized shocks and policy rule.

# 6 Macroeconomic stabilization and optimal policy

The estimated structural model set out above is well-suited for the study of policy options. In this section, we move to optimal monetary policy exercises. The policymaker may be constrained to simple rules even with commitment, thus, for transparency, information available for communications, and ease of implementation, we focus on the optimized simple Taylor-type commitment rule that minimizes the expected inter-temporal loss as given by (23) at time $t$.

## 6.1 The central bank's role

The central bank sets out to maximize a general discounted welfare criterion subject to the constraints of the DSGE model. In a no-subsidy economy, the reason why monetary policy is more important for stabilizing economic activity is two-fold. First, we do not know whether the

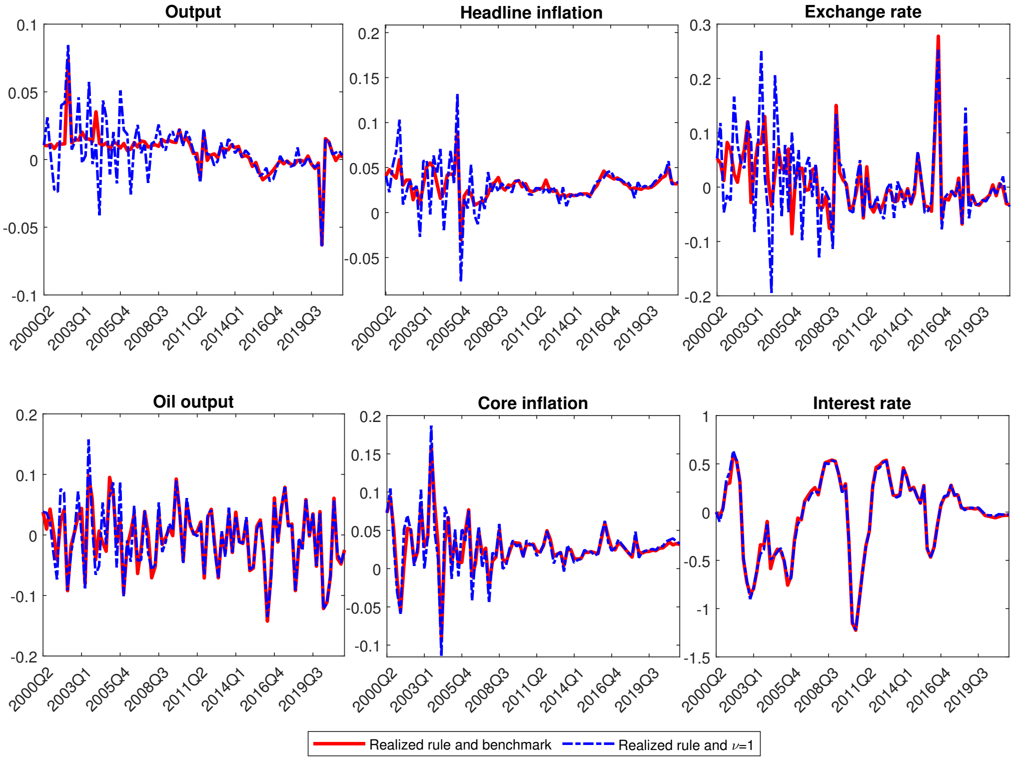


Figure 3: **Simulated Economies with Realized Rule and Shocks**

central bank has behaved optimally, in terms of a Taylor rule model. Second, agents are more vulnerable to oil price fluctuations which can be exacerbated by fuel subsidy removal.

There are generally two approaches to optimally evaluate policies for welfare analysis in DSGE models. The welfare loss function can be either utility-based or derived through a standard ad-hoc quadratic loss function. We examine the potential consequences of removing fuel subsidies in Nigeria from the viewpoint of a central banker, focusing on their role in managing the adverse effects of oil price shocks and the removal. Therefore, we opt for the latter approach and evaluate monetary policy rules based on the linearized model of (20) with a simple quadratic loss function that penalizes variability in an observed subset of key macroeconomic variables (i.e. welfare-relevant variables).

The estimated structural parameters of the model, other than the monetary policy parameters, are used to seek optimized simple monetary policy rules, based on the time-varying Taylor interest rate rule set out in Section 3.3, that can accommodate the Markov-switching parameters. We consider the standard ad-hoc quadratic period loss function in deviation form which is given by

$$\begin{aligned} \Omega_0 &= (1-\beta)E_0\left[\sum_{t=0}^{\infty}\beta^t(\lambda_\pi\pi_t^2+\lambda_y y_{h,t}^2+\lambda_r\Delta R_t^2+\lambda_\varepsilon\Delta\varepsilon_t^2)\right] \\ &\simeq \lambda_\pi \text{var}(\pi_t)+\lambda_y\text{var}(y_{h,t})+\lambda_r\text{var}(\Delta R_t)+\lambda_\varepsilon\text{var}(\Delta\varepsilon_t) \text{ as } \beta\to 1 \end{aligned} \quad (23)$$

where the variances above are unconditional variances of the target variables and the period utility $\Omega_0$ is an unconditional welfare loss function where $\beta \to 1$. We also carry out a search over a grid on a range of different weights on the variances in terms of $(1, \lambda_y, \lambda_r, \lambda_\varepsilon)$.

We use the estimated structural parameters of the model to derive optimized simple monetary policy rules that can accommodate the Markov-switching behavior that we set out in our model, assuming that, like agents in the model, the central bank can observe the different regimes (i.e. they observe $s_t$). We compare the result with counterfactual simulations in terms of their abilities in stabilizing inflation, output and exchange rates.

### 6.2 Optimized Taylor rules

To optimize the policy parameters in (17), we set bounds (priors) on the parameters to discipline the process with the wide 90% ranges within which the optimization searches for the parameters. Our focus is on linear-quadratic problems that are available for different forms of policy, and we use the ad-hoc approach for the (central bank's) loss as the welfare criterion assuming that they dislike inflation, output gap, and exchange rate movements to assess the welfare-reducing effects implied by the model features. Table 6 uses the same prior densities as in Table 3 but imposes more prior uncertainty and uses quantiles of the distributions, allowing such priors to have more diffuse distributions.

We carry out the policy simulations that compare the expected inter-temporal losses and macroeconomic volatilities for periods of varying economic conditions (changing variances of oil prices), and for cases of zero or partial subsidy. In a sense, we have designed and derived 'robust' simple policy rules with respect to exogenous uncertainty incorporated into the AR(1) shock process of oil price for the estimated model and a counterfactual (i.e. $\nu = 1$).

| **Parameter** | **Prior distribution** | | | **Posterior mode** | | |
|---|---|---|---|---|---|---|
| | Density | Lower quartile | Upper quartile | Estimated rule | OSR $\nu = 0.526$ | OSR $\nu = 1$ |
| $\bar{\omega}_\pi$ | $\mathcal{G}$ | 1 | 10 | 3.492 | 6.782 | 6.897 |
| $\bar{\omega}_y$ | $\mathcal{G}$ | 0.1 | 4 | 0.108 | 0.153 | 0.144 |
| $\bar{\omega}_\varepsilon$ | $\mathcal{G}$ | 0.1 | 4 | 0.177 | 0.824 | 0.801 |
| $\bar{\rho}_r$ | $\mathcal{B}$ | 0.5 | 0.95 | 0.162 | 0.783 | 0.781 |
| | Density | Mean | SD | | | |
| $\hat{\omega}_\pi(s_1)$ | $\mathcal{N}$ | 0 | 0.5 | 0.609 | 0.060 | 0.060 |
| $\hat{\omega}_\pi(s_2)$ | $\mathcal{N}$ | 0 | 0.5 | 0.206 | 0.023 | 0.024 |
| $\hat{\omega}_y(s_1)$ | $\mathcal{N}$ | 0 | 0.5 | -0.077 | -0.036 | -0.047 |
| $\hat{\omega}_y(s_2)$ | $\mathcal{N}$ | 0 | 0.5 | 0.161 | -0.008 | -0.012 |
| $\hat{\omega}_\varepsilon(s_1)$ | $\mathcal{N}$ | 0 | 0.5 | 0.866 | 0.115 | 0.114 |
| $\hat{\omega}_\varepsilon(s_2)$ | $\mathcal{N}$ | 0 | 0.5 | 0.363 | 0.044 | 0.043 |
| $\hat{\rho}_r(s_1)$ | $\mathcal{N}$ | 0 | 0.5 | 0.002 | -0.345 | -0.351 |
| $\hat{\rho}_r(s_2)$ | $\mathcal{N}$ | 0 | 0.5 | -0.092 | -0.232 | -0.235 |
| $\Omega_0$ | | | | 0.0417 | 0.0251 | 0.0262 |

Table 6: **Estimated and Optimized Simple Rule Coefficients**

*Notes*: $s_1 \rightarrow$ Regime 1: Low oil price volatility; $s_2 \rightarrow$ Regime 2: High oil price volatility. $\nu = 0.526$: estimated partial subsidy; $\nu = 1$: zero subsidy. We assume that $\lambda_\pi = 1$, $\lambda_y = 0.2$, $\lambda_r = 0.1$ and $\lambda_\varepsilon = 0.1$ in (23) for the policymaker's linear-quadratic problem. Following Chen and Macdonald (2012), we carry out a search over a grid on a range of different weights. We allow $(\lambda_y, \lambda_r)$ to vary over a grid of $[0, 1]$ and compute the optimized simple rules and the unconditional variances of the target variables which compares the output-inflation volatilities associated with each set of $(\lambda_y, \lambda_r)$ used. Our result shows that a conservative banker's policy preference increases the variance of output and clearly faces a policy trade-off which moves to the upper-left corner when $\lambda_r$ increases. To derive an optimal monetary policy rule, we also choose the above parameter configuration in the loss function that generates a low level of exchange rate volatility, whilst keeping the output-inflation volatility low at the same time.

In Table 6, we benchmark the optimized simple rules (OSR) against the estimated policy rule. The OSR prescribes larger responses to all three target variables and has a much higher degree of interest rate smoothing compared to the realized rule. These results suggest that, had the central bank acted optimally, it would more aggressively respond to fluctuations in inflation and exchange rates and be much more inertial whether we use subsidies or not. Such a rule would achieve the best welfare outcome under the subsidy program (i.e. we use $\Omega_0 = 0.0251$ as our performance metric). In addition, the OSR responses are more symmetric between regimes and under the OSR the central bank behaviors are relatively systematic regardless of regime shifts, except for stabilizing exchange rates. In the no-subsidy economy, optimal monetary policy is more focused on preserving price stability and anchoring inflation expectations.

### 6.3 Unconditional standard deviations

Under different optimized rules, aggregated standard deviations of the key domestic variables are computed by re-weighting the system with appropriate probabilities (i.e. the ergodic distribution of the regimes) and presented in Table 7 with one exception: "$s_2$" indicates the scenario where the regime-specific volatilities are computed. It shows the level of macroeconomic instabilities conditional on regimes, for example, if the economy had stayed in the high-variance state ($s_2$).

| | sd($\Delta y_{h,t}$) | sd($\Delta c_t$) | sd($\Delta i_{no,t}$) | sd($\Delta y_{no,t}$) | sd($\pi_t$) | sd($\pi_{c,t}$) | sd($\pi_{d,t}$) | sd($\pi_{f,t}$) | sd($R_t$) | sd($\Delta \varepsilon_t$) | sd($c_t^R$) | sd($c_t^{NR}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Estimated rule | 0.146 | 0.182 | 0.092 | 0.190 | 0.109 | 0.107 | 0.111 | 0.091 | 0.429 | 0.204 | 0.298 | 0.215 |
| OSR $\nu = 0.526$ | 0.142 | 0.178 | 0.092 | 0.186 | 0.068 | 0.070 | 0.088 | 0.064 | 0.388 | 0.168 | 0.285 | 0.207 |
| OSR $\nu = 1$ | 0.144 | 0.183 | 0.092 | 0.186 | 0.070 | 0.072 | 0.088 | 0.064 | 0.392 | 0.177 | 0.288 | 0.209 |
| OSR $\nu = 1$, $\lambda_y = 0.5$ | 0.144 | 0.182 | 0.092 | 0.186 | 0.072 | 0.073 | 0.089 | 0.064 | 0.391 | 0.158 | 0.287 | 0.208 |
| OSR $\nu = 1$, $s_2$ | 0.145 | 0.181 | 0.092 | 0.183 | 0.079 | 0.079 | 0.089 | 0.065 | 0.383 | 0.194 | 0.245 | 0.198 |

Table 7: **Standard Deviation of Macroeconomic Variables**

*Notes*: $\nu = 0.526$: estimated partial subsidy; $\nu = 1$: zero subsidy. $s_2 \rightarrow$ Regime 2: High oil price volatility. $\lambda_y = 0.5$ is the weight on the output gap variance. The variables include real GDP growth ($\Delta y_{h,t}$), real consumption growth ($\Delta c_t$), real investment growth ($\Delta i_{no,t}$), non-oil output growth ($\Delta y_{no,t}$), headline inflation ($\pi_t$), core inflation ($\pi_{c,t}$), domestic inflation ($\pi_{d,t}$), imported inflation ($\pi_{f,t}$), nominal interest rate ($R_t$), real effective exchange rate ($\Delta \varepsilon_t$), consumption by Ricardian household ($c_t^R$), and consumption by Non-Ricardian household ($c_t^{NR}$).

The first two rows of Table 7 compute the cost of following the estimated rule relative to the optimal rule in the benchmark economy (OSR $\nu = 0.526$). In line with the results that compare the welfare losses, which represent the expectation of all future outcomes, the computed OSR in the alternative economy (OSR $\nu = 1$) is able to more effectively stabilize the economy, compared to the estimated rule in the benchmark economy, with the exception of aggregate consumption. Table 7 also presents a scenario under which we can achieve better policy outcomes than the estimated rules when $\nu = 1$. To do so, the central banker sets the weight on the output gap variance to $\lambda_y = 0.5$. This result shows the potential welfare gains from eliminating business cycle fluctuations in the alternative economy ($\nu = 1$). Putting a higher weight on controlling output volatility increases inflation variance. Nevertheless, this policy scenario generates an optimized Taylor rule that can achieve better policy outcomes than the estimated rules in the $\nu = 1$ economy. Finally, we investigate the level of macroeconomic instabilities that is regime-specific, that is, we compute the model-implied moments conditional on the alternative economy staying in the high-variance state (OSR $\nu = 1$, $s_2$). The OSR in this economy generates higher volatility for inflation and exchange rate movements.

### 6.4 Volatility implications of optimized rules

As in Section 6.3, we allow $\lambda_y$ to vary and compute the optimized simple rules and the unconditional variances of the target variables in Table 8 which compares the output-inflation volatilities associated with $\lambda_y = 0.1$ and $\lambda_y = 0.5$, respectively. By increasing $\lambda_y$, we show that the central banker's policy preference decreases the variance of output growth, whilst facing a clear policy trade-off which generates a higher level of inflation volatility. For this exercise, our focus is on comparing the following four cases: the benchmark economy (Bench: $\nu = 0.526$), the alternative economy (Alter: $\nu = 1$), the benchmark economy staying in the high-variance state (Bench in $s_2$: $\nu = 0.526$), and the alternative economy staying in the high-variance state (Alter in $s_2$: $\nu = 0.526$). Our results show that the monetary policy trade-offs can be less severe under optimized rules with an aggressive response to inflation in the alternative economy when subsidy is removed but are amplified in states of highly volatile oil prices.

| $\lambda_y = 0.1$ | sd($\Delta y_{h,t}$) | sd($\pi_t$) | $\lambda_y = 0.5$ | sd($\Delta y_{h,t}$) | sd($\pi_t$) | $\downarrow$ sd($\Delta y_{h,t}$) | $\uparrow$ sd($\pi_t$) |
|---|---|---|---|---|---|---|---|
| Bench | 0.14226 | 0.06838 | Bench | 0.14210 | 0.06950 | 0.00016 | 0.00112 |
| Alter | 0.14423 | 0.07027 | Alter | 0.14397 | 0.07171 | 0.00026 | 0.00143 |
| Bench in $s_2$ | 0.14387 | 0.07690 | Bench in $s_2$ | 0.14377 | 0.07780 | 0.00010 | 0.00090 |
| Alter in $s_2$ | 0.14496 | 0.07930 | Alter in $s_2$ | 0.14478 | 0.08051 | 0.00018 | 0.00121 |

Table 8: **Output-Inflation Volatility for Optimized Simple Rules**

*Notes*: $\nu = 0.526$: estimated partial subsidy; $\nu = 1$: zero subsidy. $s_2 \rightarrow$ Regime 2: High oil price volatility. $\lambda_y = 0.1, 0.5$ is the weight on the output gap variance. The policy variables are real GDP growth ($\Delta y_{h,t}$) and headline inflation ($\pi_t$).

### 6.5 Impulse responses to a negative oil price shock

Insights into the working of optimal policy and of the transmission mechanism can be obtained by deriving posterior IRFs following an unanticipated 1% negative international oil price shock. The aim of this exercise is two-fold. First, we are interested in comparing the transmission of the shock when the subsidy program is 'turned on' and 'turned off'. This way, we assess the impact of imposing/removing the program on different model dynamics under different monetary policy rules. Second, we investigate the importance of shocks to the endogenous variables of interests in order to gain a better understanding of the model uncertainties faced by policymakers and the source of welfare differences. In Figures 4 and 5, we plot the IRFs for the low ($s_1$) and high volatility regimes ($s_2$), respectively. The policy rules presented are the estimated rule under the benchmark model, an optimized simple rule (OSR) derived based on the posterior mode of the model, and an OSR when we remove the subsidy program in the same model.

Qualitatively, the IRFs are broadly similar under the different monetary policy rules and under the volatility-switching assumption. Only the qualitative responses of total inflation and interest rate differ depending on the subsidy regulation. Following a negative oil price shock, output immediately falls and domestic inflation falls. This effect in turn leads to a reduction in equilibrium labor. The supply-side shock results in a fall in the marginal cost, and the fall is larger in the absence of subsidies. Domestic consumption rises due to the depreciating real exchange rate and the resultant improvement in the terms of trade.

The optimal policy (when the subsidy is in place) is to raise the interest rate a little initially

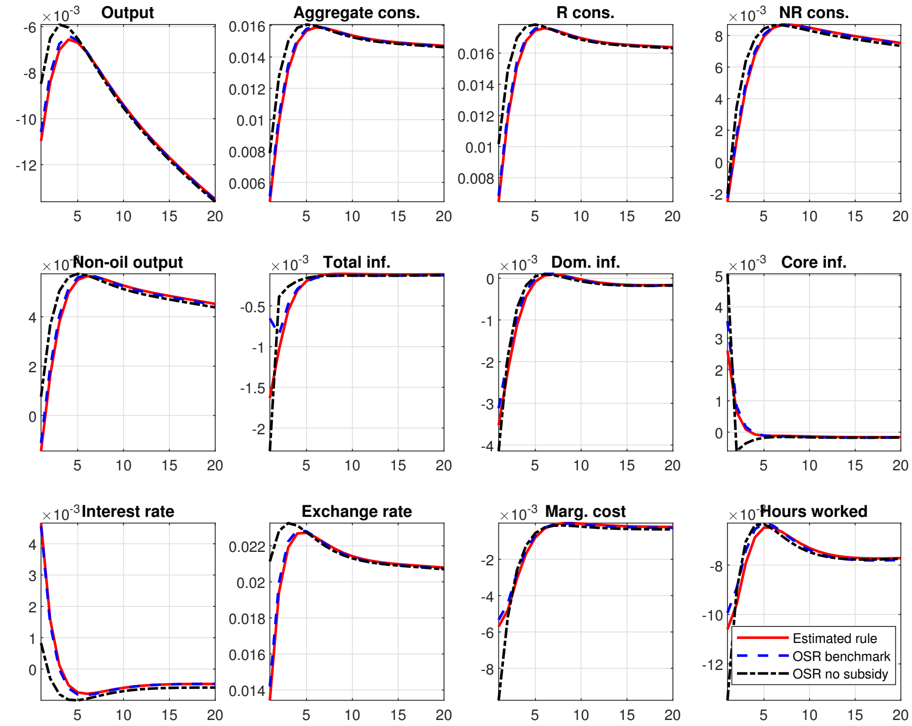


Figure 4: **Responses to a Negative Oil Price Shock with $s_1$**

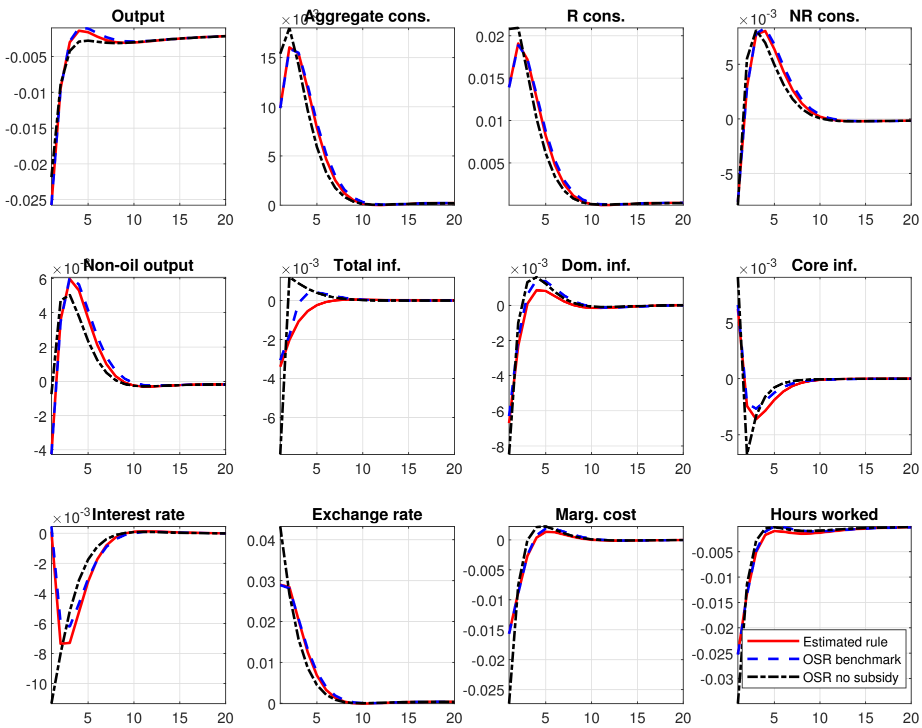


Figure 5: **Responses to a Negative Oil Price Shock with $s_2$**

to contain inflation (the headline or core measure), but then to commit to a sharp monetary relaxation before gradually returning to the steady state. The same trajectory is depicted by the estimated policy. Contrary to the situation in which the government subsidizes the consumption of fuel, but similarly to Figure 2, the OSR predicts an initial cut in the interest rate in the counterfactual case in response to the falling headline inflation rate, ameliorating the contractionary effects of a negative oil price shock on aggregate GDP. As is consistent with Table 6, the responsiveness of the initial monetary expansion to inflation is stronger in the case when the subsidy is removed (if we compare the magnitude of their responses under the two optimal rules).

As expected, the reaction to the shock is less aggressive in $s_1$ (low volatility). The three policy rules generate less contractionary effects on output and are better at containing inflation and mitigating the real exchange rate depreciation in this regime. It should be noted that, while the magnitude of the interest rate responses under the OSR are slightly larger in $s_2$, the target variables exhibit generally much larger responses to the shock in $s_2$ compared to in $s_1$ (especially those of output and aggregate inflation). This suggests that the optimal policy has a more aggressive reaction function to variations in these variables in $s_1$ – a result consistent with our Table 6 above.

As oil is an input to both production and consumption, our results can also reveal more evidence for the central bank's trade-off, i.e., in its objective to stabilize prices and fluctuations in output, and that the severity of this dilemma depends on the price volatility (uncertainty) and the impact of subsidy removal. For example, our simulations imply that, when the central bank tends to respond to increased uncertainty about future prices during an episode of persistent inflationary pressures (Figure 5) by raising the interest rate (a small rate increase), the OSR and realized policy rule predict a more severe decline in output than under the low volatility regime. Similarly, as noted, the responsiveness of the initial monetary expansion to inflation is stronger in the case when the subsidy is removed, from a central bank whose objective is to smooth out fluctuations in output, thus this helps prevent the economy from contracting drastically following the oil price shock.

Finally, as discussed initially in Section 5.1, the policy IRFs provide more interesting results. With the additional recourses available to consumers (which, as discussed, would mainly benefit the R consumers), under the OSR, consumption rises initially but the NR (poor) consumers see this happening with a *much smaller* increase in their consumption. Qualitatively, these consumption responses are similar regardless of the exogenous switching between the volatility states. The responses of real variables - output, hours and consumption - differ considerably between the benchmark OSR and the OSR in the no-subsidy economy, and between the low and high volatility regimes, following the shock, which explains the large welfare differences (for all shocks combined). Furthermore, the OSR policy derived in both regimes of price volatility and in the no-subsidy economy sees a larger increase in both output and consumption on impact and in the short run. This is a major source of the expected welfare differences noted previously.

## 7 Statistical validation and sensitivity analysis

Our analysis is based on a particular parameterization of the model which generates some interesting findings. In this section, we explore the robustness of our results based on the posterior distribution. The posterior density is approximated by using the Monte-Carlo Markov Chain Metropolis-Hastings (MCMC-MH) algorithm, starting from the posterior kernel mode, with two parallel chains of 100,000 random draws from the posterior density,[22] with the variance-covariance matrix of the perturbation term in the algorithm being adjusted in order to maintain an acceptance ratio of 25%. These draws are then used for validating the main results.

One of the great advantages of adopting a Bayesian approach is that it facilitates a formal comparison of different models through their posterior marginal likelihoods. The differences in marginal data densities (MDD) or the posterior odds ratio (Bayes Factors) are important as they help to provide decisive evidence for choosing a particular model over others. In Table 9, we compare two approximations of log MDD based on the posterior distribution.[23] The benchmark model with subsidy clearly wins the likelihood ranking and attains the highest posterior odds, thus providing the most comprehensive form of assessment that suggests that our model with switching dynamics is empirically relevant and statistically improves the fit to the Nigerian data.[24] Our finding clearly rejects the models with time-invariant parameters and complete pass-through in terms of explaining the data for Nigeria over the sample period. Indeed, the benchmark model produces tight posterior estimates.

| MDD | Non-switching | Switching (benchmark) | Switching ($\nu = 1$) |
|---|---|---|---|
| Meng and Wong's Bridge | 919.26 | 922.20 | 899.31 |
| Modified Harmonic-Mean | 915.07 | 918.30 | 893.62 |

Table 9: **Bayesian Model Comparison**

Next, we draw 10,000 random parameters from the posterior simulation above and repeat the exercises in Sections 4.3 and 5.1. In Figure 6, we compute the smoothed probabilities for being in the high oil price volatility state. The figure shows the median response, together with the shaded areas that correspond to the 90% credibility interval. The simulation identifies qualitatively the distinct periods of oil price volatility similar to the finding in Section 4.3. In line with the previous result, there are synchronized switches to a responsive policy state that are triggered by the recurrent volatility episode with a high probability. It also shows that the economy mostly stays in the more active policy regime ($\hat{\omega}_\pi(s_1)$).

However, we identify a switch to a less responsive monetary state that coincides with the first and third oil price volatility episodes with a high probability, albeit for a relatively brief period. As explained by some of the previous studies,[25] inflation in Nigeria was brought under

[22] We burn-in the first 25% of the chain to remove any dependance from the initial conditions. The number of replications is sufficiently large to explore the whole parameter space and asymptotically move to its ergodic distribution.

[23] Our computational methods for estimating the MDD are based on the Geweke (1999) Modified Harmonic-Mean estimator and the Meng and Wong (1996) Bridge Sampling estimator.

[24] Based on Kass and Raftery (1995), a Bayes factor of $10 - 100$ or a log data density range of $[2.30, 4.61]$ is "strong to very strong evidence".

[25] Similar responsive states are also detected in Omotosho and Yang (2024) based on posterior simulations

control during the 2008-09 global financial crisis, although monetary policy seems to have played a role in stabilizing output during this distinct episode. The central bank appears to have been less sensitive to movements in headline inflation since the financial crisis as the Monetary Policy Rate becomes more persistent during the period, reflecting a transition to a multiple-mandate regime.

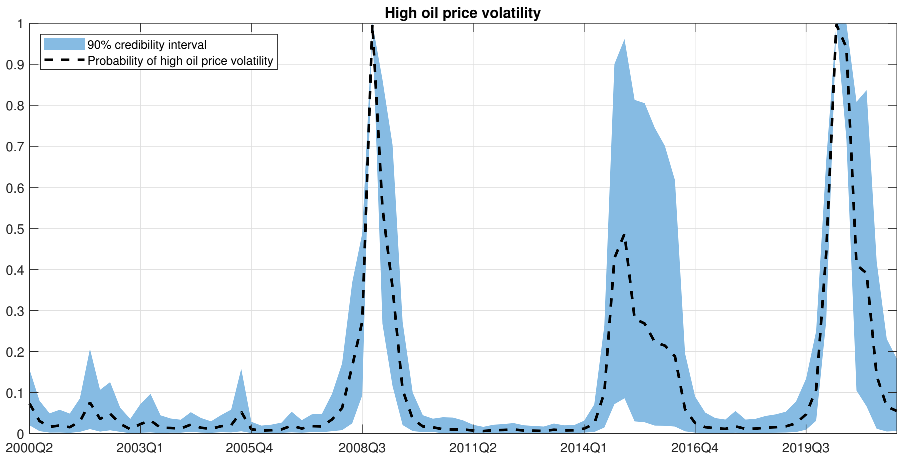


Figure 6: **Smoothed Probability of High Volatility Regime ($s_2$)**

*Notes*: The figure presents the smoothed probabilities for being in the high oil price volatility regime in the model that allows synchronized switching in the standard deviations of the oil price shock and in the monetary policy parameters. Their priors are assumed to be inverse gamma with $(0.1, 4)$ and normal with $(0, 0.25)$, respectively, between the high and low volatility regimes.

Finally, in Figures 7-10, we conduct 10,000 simulations of 20 quarters each, and plot the median responses of the key variables, along with the 90% credibility intervals, that can be compared with the impulse response simulations reported in Section 5.1 above. This robustness exercise presents similar dynamics compared with those generated by the posterior mode, with the magnitude of responses under the latter generally lying within the credibility intervals of median responses. We uphold these results with both the volatility and subsidy scenarios. Under the no-subsidy regime, when shocks are small, the central bank responds by increasing the interest rate, but when shocks are large, the simulated response predicts an initial cut to the interest rate, loosening monetary policy – a result consistent with the policy response prescribed by the OSR.

## 8 Implications for macroeconomic policy

By generating important dynamics in the data, the results presented in the paper can be used to derive some concrete policy recommendation for an oil-producing emerging economy. On the design of monetary policy frameworks, we find that, for a welfare-maximizing central bank, the best policy rules are aggressive on inflation and exchange rates and are much more inertial whether we use fuel subsidies or not. But the trade-offs faced by the central bank in balancing its objectives such as price stability and output stabilization are less severe when the

which clearly shows that monetary responses are sensitive to the oil price variance.

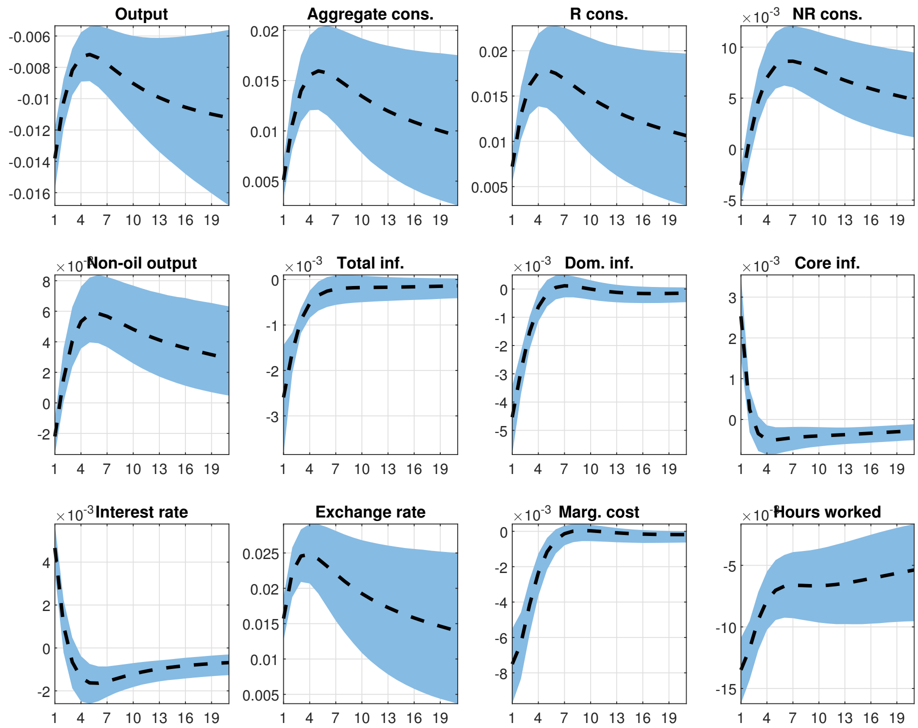


Figure 7: **Responses to a Negative Oil Price Shock with $s_1$**

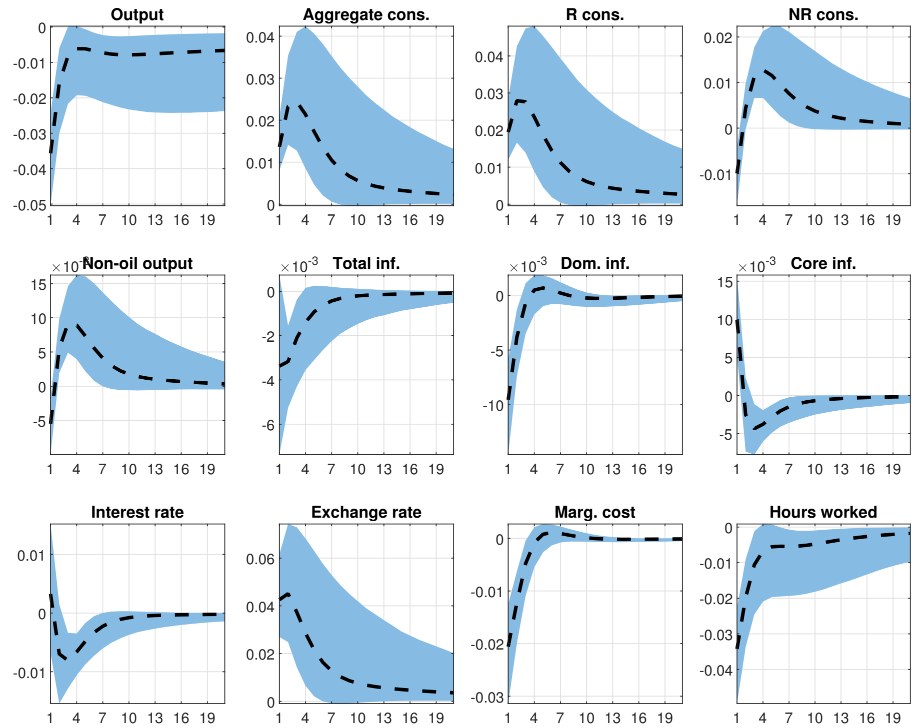


Figure 8: **Responses to a Negative Oil Price Shock with $s_2$**

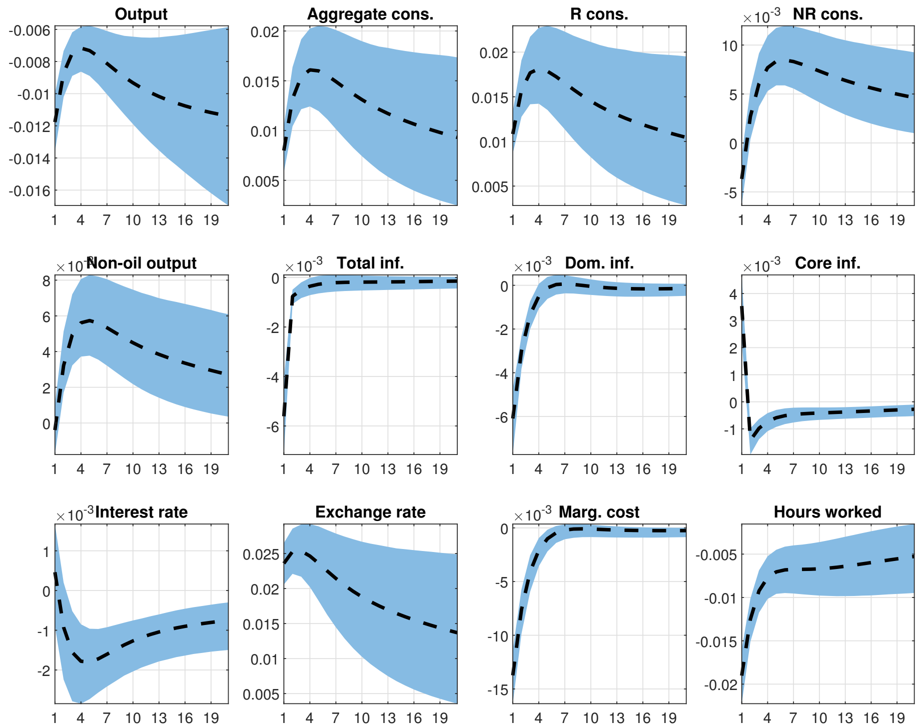


Figure 9: **Responses to a Negative Oil Price Shock with $s_1$ and $\nu = 1$**

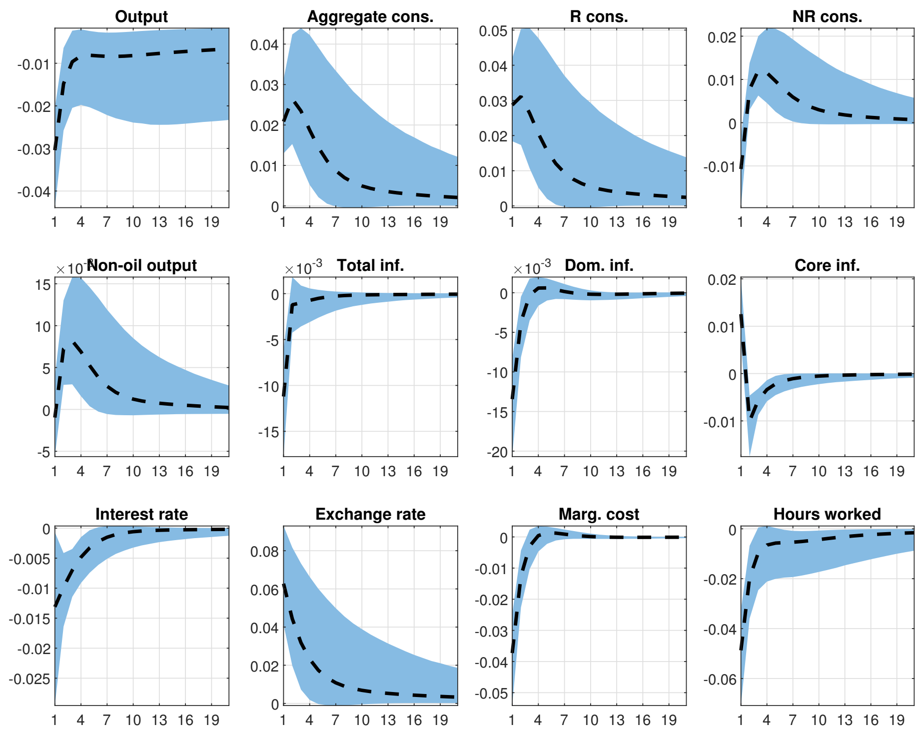


Figure 10: **Responses to a Negative Oil Price Shock with $s_2$ and $\nu = 1$**

subsidy is removed. They are however larger in the regime of high oil price volatility.[26] Due to increased economic volatility, the challenges of the central bank intervention in mitigating the impacts of subsidy removal when responding to contractionary supply shocks lie in designing a flexible framework capable of adapting to economic shifts while balancing inflation and output stabilization.

In terms of building capacity around crisis response in times of uncertainty, disentangling the impact responses from shocks whose variances are changing over time is helpful for developing the policy coordination scenarios in the context of exploring the potential benefits of coordination between monetary and fiscal authorities in achieving macroeconomic stability, particularly in periods of stress and high volatility. Our results show that monetary policy becomes more expansionary in a no-subsidy economy when oil prices are large and volatile. This is useful for policymakers to give careful consideration to the consequences of combinations of fiscal and monetary policy for jointly stabilizing the economy through scenario analysis. Furthermore, the observed switches in monetary policy appear to suggest a need for a policy transition to a multiple-mandate regime.[27] Fiscal operations (quasi-fiscal activities) aimed at boosting output would positively impact the supply-side drivers of inflation. It is clear that the best policy framework required to effectively respond to abrupt changes in global economic conditions should exhibit flexibility and adaptability.

Finally, in terms of the socio-political implications of fuel subsidy reforms, our empirical results and policy simulations show that the vast majority of the subsidy and benefits of its removal goes to better-off households. This explains why, especially during periods of high oil price volatility, subsidy reductions could widen the wealth and income gap, and be a major source of the different welfare consequences previously noted in the analysis.[28] Potential adjustments to interest rates, reserve requirements or other policy tools that could be used to counteract the contractionary effects on income and wealth distribution could be helpful to inform future policy design and implementation, particularly in navigating regime-switching dynamics in uncertain environments.

## 9 Concluding remarks and future research

We estimated a regime-switching DSGE model of the Nigerian economy. In this model, the fiscal authority sells the imported fuel using a pricing rule that connotes an implicit subsidy program and the monetary authority responds to stochastic regime shifts in shocks to oil prices. We studied the impact of fuel subsidy removal on central bank behavior and optimal monetary policy. We have three major findings.

A general finding is that monetary policy adjustments are time-varying and synchronize with high oil price volatility states. In the high volatility state, the central bank policy rule delivers a

[26]This result is in line with the finding in Natal (2012) who makes a similar argument that oil price volatility operates as a source of monetary policy trade-off amplification.

[27]See, for more discussions, Omotosho and Yang (2024) who discuss about a transition of the Central Bank of Nigeria that has been involved in quasi-fiscal operations aimed at boosting output and may explain the observed switch in the monetary policy regime after the financial crisis.

[28]The similar results can be found from previous empirical studies, such as Siddig *et al.* (2014), that have focused on examining the implications of fuel subsidy for the Nigerian economy.

lower degree of interest rate smoothing and places a greater emphasis on the output gap relative to inflation, compared to the low volatility state. Our study strengthens the connection between regime-switching dynamics and monetary policy responses in times of uncertainty.

A second finding is that a complete, one-off removal of subsidy may lead to welfare losses due to increased macroeconomic volatility, highlighting the need for careful policy consideration. The optimal monetary rules are aggressive on inflation and exchange rates regardless of the subsidy arrangement in place, and prescribe an initial monetary expansion in the absence of fuel subsidy and in high-variance states. Based on our counterfactual simulations, we find that the economy would have experienced increased macroeconomic instability with the realized shocks in the absence of subsidy. The result suggests that possible central bank interventions may be crucial in mitigating the impacts of subsidy removal, underscoring the importance of coordinated policy responses capable of adapting to economic shifts.

Third, there are marked differences between the model-implied simulations of the two alternative economies suggesting that subsidy removal would play a significant role in affecting the business cycle dynamics and economic performances. The effect on private consumption is very different across the different types of households; thus offering an explanation for its potential impact on widening the wealth and income gap, and the different welfare consequences. These effects are more pronounced when the economy is in a high volatility environment where the severity of the output contraction is amplified, thus emphasizing the importance of proactive policy measures to manage economic volatility and safeguard welfare.

We provide a flexible, novel framework for policy analysis that can be general and geared towards applications in resource-producing emerging countries. There are a number of possible avenues for future research. An issue that certainly deserves further attention is informality, in particular for emerging market economies. The heterogeneity of the model could be enriched by considering a two-sector economy allowing for informality. Gabriel *et al.* (2012) study such a model for India and find empirical evidence of a sizeable informal, low-skilled labor intensive sector. Given the significant presence of informality in resource-producing developing countries, the adverse impact of subsidy removal could be felt more by the informal sector. Incorporating an informal sector should stylize the nature of productive activity in these economies. Monetary policy actions would impact differently depending on the sector's access to financial wealth.

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