

CAMP Working Paper Series
No 5/2014

MONETARY POLICY IN OIL EXPORTING ECONOMIES

Drago Bergholt



© Authors 2014.

This paper can be downloaded without charge from the CAMP website <http://www.bi.no/camp>

MONETARY POLICY IN OIL EXPORTING ECONOMIES*

DRAGO BERGHOLT[†]

July 15, 2014

Abstract

How should monetary policy be constructed when national income depends on oil exports? I set up a general equilibrium model for an oil exporting small open economy to analyze this question. Fundamentals include an oil sector and domestic non-oil firms – some of which are linked to oil markets via supply chains. In the model, the intermediate production network implies transmission of international oil shocks to all domestic industries. The presence of wage and price rigidities at the sector level leads to non-trivial trade-offs between different stabilization targets. I characterize Ramsey-optimal monetary policy in this environment, and use the framework to shed light on i) welfare implications of the supply chain channel, and ii) costs of alternative policy rules. Three results emerge: First, optimal policy puts high weight on nominal wage stability. In contrast, attempts to target impulses from the oil sector can be disastrous for welfare. Second, while oil sector activities contribute to macroeconomic fluctuations, they do not change the nature of optimal policy. Third, operational Taylor rules with high interest rate inertia can approximate the Ramsey equilibrium reasonably well.

Keywords: *Monetary policy, oil exports, small open economy, Ramsey equilibrium, DSGE.*

JEL Classification: *E52, F41, Q33, Q43.*

*This work has benefited from discussions with Tommy Sveen, Martin Seneca, Lars E. O. Svensson, Jordi Galí, and Ipeei Fujiwara. I am also grateful for comments and suggestions by participants at the Review of Flexible Inflation Targeting (ReFIT) Workshop in Norges Bank, the research seminar at the BI Norwegian Business School. I thank Junior Maih for much appreciated help with the programming. This paper is part of the research activities at the Centre for Applied Macro- and Petroleum Economics (CAMP). The views expressed in this paper are those of the author and do not necessarily reflect the views of Norges Bank. All errors are mine.

[†]Centre for Applied Macro- and Petroleum Economics, BI Norwegian Business School, and Norges Bank. E-mail: Drago.Bergholt@bi.no.

“Norges Bank’s conduct of monetary policy is geared towards low and stable inflation. ... When setting the key policy rate, we also take into account the impact of the interest rate on output and employment. ... Our framework has still not been tested against a large and persistent negative oil price shock. From a high starting point, wages have grown faster in Norway than among our trading partners for the past ten years. Our currency has appreciated considerably in real terms. I believe the real test of our framework will come when the present boom in the petroleum industry – at some point – is reversed.”

Øystein Olsen, Governor of Norges Bank, 19 November 2012

1 INTRODUCTION

The economic forces inherent in resource rich economies represent particular challenges for stabilization policy. Commodity prices, which are volatile time series processes, influence both exchange rates and the terms of trade of commodity exporters. In turn, these impulses map into price and quantity movements in labor and product markets outside the commodity sector – both along extensive margins and in form of sectoral reallocations. The spillover from commodity markets can be substantial. Norway, a petroleum rich small open economy, serves as a prime example. Even though all oil and gas revenues are saved abroad and only about 4% of the fund is spent each year, [Bjørnland and Thorsrud \(2013\)](#) find that movements in the petroleum sector explain about 30% of the medium term fluctuations in mainland (non-oil) GDP. It is, therefore, not surprising that policy makers and market participants have raised concerns regarding spillover from the petroleum sector, and the room for policy.

What are the implications, if any, of commodity exports for optimal policy design? This paper analyzes monetary policy in an economy with a large oil sector. I set up a New Keynesian model where the oil sector exists side by side with domestic traded and non-traded firms. Oil market shocks, as well as domestic and foreign productivity, create macroeconomic fluctuations in the economy. A key feature of the model is a supply chain where firms in the oil sector buy productive inputs from the non-oil economy. The supply chain gives rise to spillover from the oil sector in a way that limits the scope for fiscal insulation policies.¹ In the model, a rise in oil sector activity induces higher demand for oil inputs. In turn, this affects labor markets across the entire economy, because labor is an important ingredient in the production of inputs supplied to the oil sector. This implies that oil shocks are responsible for fluctuations in the non-oil economy even without spending of oil revenues. The impulses through the supply chain can be large and volatile, as international data on commodity prices suggest. To provide a role for monetary policy, I introduce monopolistic competition as well as nominal wage and price rigidity in labor and goods markets. These frictions generate time varying deviations from optimal capacity utilization. The question then is how, and to what extent, the use of active monetary policy can mitigate resulting inefficiencies.

¹E.g. sovereign wealth funds and public spending rules.

I analyze Ramsey optimal monetary policy in this environment, and contrast optimal responses with those that follow from an interest rate rule designed to fit data. Following a boom in the oil sector, the frictions in the model prevent sufficient real wage growth and exchange rate appreciation on the one side, but create too much expansion in non-oil GDP and hours worked on the other. The combination of limited real wage growth and substantial increase in hours gives rise to nominal wage inflation, causing inefficient wage dispersion in the non-oil economy. Consequently, optimal policy assigns a relatively large weight to nominal wage stability. How is this achieved? During an oil boom, the Ramsey planner responds with an aggressive increase in the policy rate. This amplifies the appreciation of exchange rates. In turn, the appreciation brings down import prices and the consumer price index. The gain of low prices is real wage growth even without substantial nominal wage inflation. Thus, optimal policy prevents most of the cross-sectional wage dispersion caused by a boom in the oil sector. Regarding optimal responses to domestic and foreign non-oil shocks, wage stability turns out to be important also for these shocks.

At this point, a number of questions arise that are relevant for policy making in practice. To what extent should monetary authorities care about spillover from the oil sector? What are the implications of alternative stabilization targets such as a fixed exchange rate? How well can one approximate Ramsey optimal policy by an operational targeting rule? I tackle these questions by quantifying the welfare losses associated with a large set of alternative stabilization targets. In contrast to suggestions put forward in the literature ([Frankel, 2003, 2011](#); [Catão and Chang, 2013](#)), I find that stabilizing price impulses from the oil sector (or equivalently, stabilizing the local currency export price) is disastrous from a welfare perspective. Intuitively, such a policy i) amplifies the oil sector demand towards non-oil firms, and ii) requires enormous nominal and real interest rate movements. In turn, these features lead to excessive volatility in the domestic non-oil economy. This is true both with strict and flexible targeting rules. The analysis also reveals that wage stability is optimal even in the absence of oil, confirming [Campolmi \(2014\)](#). In fact, while differences in welfare across policies can be mounting, they are generally not much affected by the size of the oil sector. Finally I study a set of optimized, flexible targeting rules. It is found that rules involving high interest rate inertia and combinations of wage and consumer price targeting can approximate Ramsey optimal policy reasonably well.

Recent swings in international commodity prices have inspired renewed interest in how commodity exporters should conduct policy. [Pieschacon \(2012\)](#) investigates fiscal spending plans through the lenses of a real business cycle model, and concludes that insulation of the economy from oil price shocks is welfare improving. However, the analysis abstracts from the supply chain channel linking non-oil firms directly to the oil sector. It is exactly this transmission channel that makes the insulation of oil price shocks inferior to other policies in my framework. Probably the most closely related papers are [Hevia and Nicolini \(2013\)](#) and [Catão and Chang \(2013\)](#). The former study looks at Ramsey optimal combinations of fiscal and monetary policy, where the social planner has access to a wide set of taxes and transfers in addition to the policy rate. [Catão and Chang \(2013\)](#) analyze an arguably more realistic environment without extensive fiscal-monetary coordination. Both of these studies point to welfare gains if the central bank targets producer prices, although [Catão and Chang \(2013\)](#) find that exchange rate stability is preferred if trade elasticities are high. An important assumption in these models is that domestic non-oil firms use oil as intermediate input in production. In contrast, I propose

that oil production requires non-oil inputs, i.e. that flows in the supply chain go the other way. This departure from previous literature is crucial for policy: Non-oil firms in existing models see oil prices movements as cost-push shocks, instead of demand shocks as in my framework. The positive spillover from oil to non-oil firms found in data (see [Bjørnland and Thorsrud \(2013\)](#)) supports the latter view. I also use a richer model with labor market frictions, sectoral reallocations, and joint determination of oil prices and other foreign variables. All these features are relevant for the description of optimal policy.²

I make two contributions to existing literature: First, the model I present here is tailored to describe dynamics in an oil exporting small open economy, and advances the traditional one- or two-sector setup. In particular, it can account for the positive spillover from the oil sector to non-oil GDP and other macro-variables found in empirical literature (see e.g. [Charnavoki and Dolado \(2014\)](#) and [Bjørnland and Thorsrud \(2013\)](#)). In existing DSGE models on the other hand, a boom in the oil sector constrains factor markets and crowds out non-oil activity. Consistent with data, the model also generates real appreciation of local currency, substantial terms of trade improvements, and a fall in non-oil trade balances. Second, the analysis sheds light on the welfare implications of monetary policy in this environment. An important point in that respect is that any attempts at stabilizing impulses from the oil sector, comes at the cost of producing volatility somewhere else. This leads to a trade-off which complicates the task of monetary authorities.

The rest of the paper is organized as follows. In [section 2](#) I present a two-country, three-sector small open economy model similar in spirit to those developed by [Petrella and Santoro \(2011\)](#) and [Bergholt and Sveen \(2014\)](#), but extended with an oil exporting sector in the home economy. [Section 3](#) presents the Ramsey optimal monetary policy, and contrasts implied dynamics with a more standard Taylor rule for the interest rate. I pay particular attention to the way in which optimal policy is achieved by the central bank. Welfare implications of alternative rules are analyzed in [section 4](#). I study strict stabilization rules, simple Taylor type rules, and optimized flexible inflation targets. [Section 5](#) presents a battery of robustness tests while [section 6](#) concludes.

2 THE MODEL

Consider a world with two economies – a small commodity exporting economy (SOE) and the rest of the world (ROW). The SOE consists of three production sectors. The first two are so called non-commodity sectors – I refer to them as the manufacturing and service sector, respectively.³ Firms in these sectors produce consumption goods, which they sell to households, and production inputs, which they sell to other firms. Some of the output is sold in domestic markets, some is exported to the ROW. The third sector in the SOE specializes in commodity exports – I refer to it as the oil sector. Firms in the oil sector use labor and intermediate inputs (produced by non-oil firms) in order to produce and supply oil in an international, competitive oil market. The ROW has a similar setup, except that I largely abstract from the interactions between foreign oil producers and the

²[Benkhodja \(2014\)](#) compares welfare when the oil exporter either commits to strict consumer price targeting or an exchange rate peg. However, the supply chain channel is completely abstracted from in that study, as well as the characterization of Ramsey optimal policy.

³These sectors can also be labeled as traded and non-traded industries. However, I take a more agnostic approach to the question of trade openness and calibrate both sectors' trade shares to data.

rest of the foreign economy. In doing so, I implicitly assume that oil producing countries such as Saudi Arabia have a negligible impact on the world economy. Still, I treat the international oil price as “semi-endogenous” in the sense that it is determined by global business cycles in addition to exogenous oil price shocks. Finally, this paper is concerned with monetary policy implications of the supply chain, not with fiscal policy. To obtain clear predictions and facilitate comparison with existing literature on monetary policy, I assume that oil firms are owned by foreign agents. This allows me to abstract from issues such as government spending of oil revenues. Below I describe the model block that constitutes the SOE.

2.1 HOUSEHOLDS

First I describe the behavior by domestic household members. There is a measure one of symmetric households. The representative household consists of a continuum of members indexed by $h \in (0, 1)$. Let subscript M refer to manufacturing sector variables, subscript S refer to service sector variables, and subscript O refer to oil sector variables. Also, let $j \in \{M, S\}$ index the two non-oil sectors. A fraction μ_j of the household members work in each non-oil sector j , while the fraction μ_O work in the oil sector. The measure of workers in the SOE is $\mu_M + \mu_S + \mu_O = 1$. Household member h working in sector j maximizes expected lifetime utility given at time t by

$$\mathcal{W}_{j,t}(h) = \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\log(C_s(h)) - \chi_N \frac{L_{j,s}(h)^{1+\varphi}}{1+\varphi} \right].$$

\mathbb{E}_t is the expectation operator conditional on the information set in period t . $\beta \in (0, 1)$ is a constant time discount factor. $C_s(h)$ denotes period s consumption while $L_{j,s}(h)$ denotes hours worked. A worker employed in the oil sector has similar preferences, and his hours is denoted by $L_{O,s}(h)$. Under the assumption of full consumption risk sharing within the household, individual member h consumption is also aggregate consumption ($C_t(h) = C_t$). I drop the h -subscript whenever possible from now on.

2.1.1 CONSUMPTION ALLOCATIONS AND BOND HOLDINGS

Aggregate consumption consists of the quantities C_M and C_S produced by manufacturing and service firms, respectively.⁴ A fraction of consumption in each sector is imported. I denote domestically produced sector j consumption by C_{Hj} , and imported consumption by C_{Fj} . Both of these quantities consist of a continuum of products from each firm in the domestic and foreign economy, respectively. All functional forms are assumed to exhibit constant elasticity of substitution (CES). Cost minimizing demand for goods and service consumption, and for domestic and imported consumption in sector j , are given in the home economy by the following equations:⁵

$$\frac{C_{M,t}}{C_{S,t}} = \frac{\xi}{1-\xi} \left(\frac{P_{rM,t}}{P_{rS,t}} \right)^{-\nu} \quad \frac{C_{Hj,t}}{C_{Fj,t}} = \frac{\bar{\alpha}_j}{1-\bar{\alpha}_j} \left(\frac{P_{rHj,t}}{P_{rFj,t}} \right)^{-\eta} \quad (1)$$

⁴Note that I abstract from the domestic consumption of oil goods.

⁵Unless stated explicitly, I deflate all nominal prices by the aggregate consumer price index P_t . Thus, $P_{rM,t} \equiv \frac{P_{M,t}}{P_t}$ refers to the real goods consumer price, $P_{rS,t} \equiv \frac{P_{S,t}}{P_t}$ refers to the real service consumer price, and so on.

Preferences for consumption goods from manufacturing (relative to services) in the total consumption basket is determined by ξ , while the elasticity of substitution across sectors is ν . The domestic weight in C_j is defined as $\bar{\alpha}_j = 1 - (1 - \varsigma)(1 - \alpha_j)$, where $\varsigma \in [0, 1]$ represents the size of the SOE relative to the ROW. The degree of bias towards domestic products in sector j is captured by $\alpha_j \in [0, 1]$.⁶ Demand for firm specific consumer products from each country's sector j are given by $C_{Hj,t}(f) = \left(\frac{P_{Hj,t}(f)}{P_{Hj,t}}\right)^{-\frac{1+\epsilon_p}{\epsilon_p}} C_{Hj,t}$ and $C_{Fj,t}(f) = \left(\frac{P_{Fj,t}(f)}{P_{Fj,t}}\right)^{-\frac{1+\epsilon_p}{\epsilon_p}} C_{Fj,t}$, respectively. The foreign economy allocates consumption expenditures according to similar first order conditions.

Besides these intratemporal decisions, households also choose how much to save in domestic (risk free) bonds, and their supply of labor to domestic firms. Maximization of lifetime utility with respect to aggregate consumption and bond holdings (subject to a sequence of budget constraints) implies the following optimality conditions in period t :

$$\Lambda_t = \frac{1}{C_t} \quad (2)$$

$$R_t^{-1} = \beta \mathbb{E}_t \left(\frac{\Lambda_{t+1} \Pi_{t+1}^{-1}}{\Lambda_t} \right) \quad (3)$$

Equation (2) states that maximization of lifetime utility implies equating the marginal utility of consumption with Λ_t , the shadow value of the budget constraint. Equation (3), the optimality condition for bond holdings, defines the optimal intertemporal consumption path by equating the marginal utility loss from less consumption today with the marginal utility gain from more consumption next period. The stochastic discount factor $\mathcal{Z}_{t,t+1}$ is linked to the gross nominal interest rate by the identity $R_t = \frac{1}{E_t(\mathcal{Z}_{t,t+1})}$. By combining the Euler equation in the world economy with equation (3), we get a standard risk-sharing condition:

$$\Lambda_t \mathcal{S}_t = \Lambda_t^F \mathcal{A}_0 \quad (4)$$

\mathcal{S}_t is the real exchange rate, i.e. the price of foreign consumption in terms of domestic consumption. $\mathcal{A}_0 = \frac{\Lambda_0 \mathcal{S}_0}{\Lambda_0^F}$, which is determined by relative levels of initial wealth, is normalized to its non-stochastic steady state value without loss of generality.⁷

2.1.2 LABOR MARKETS

Next I move to the labor market in sector $j \in \{G, S\}$, which is similar to that in [Erceg, Henderson, and Levin \(2000\)](#). The labor market in each sector is populated by a competitive labor bundler and the measure μ_j of workers. Workers cannot move between sectors at within the business cycle. Still, I calibrate the model such that all workers earn identical

⁶The foreign counterpart is defined as $\bar{\alpha}_j^F = 1 - \varsigma(1 - \alpha_j^F)$, where α_j^F is the sector specific home bias in the ROW.

⁷The presence of home bias in consumption leads to asymmetric consumption gains of country specific shocks. This asymmetry causes exchange rate movements even with perfect risk sharing. If the consumption basket in the SOE has the same weights on domestic and foreign goods (i.e. if $\alpha_M = \alpha_S = 0$) as the ROW basket, then we get perfect synchronization of consumption across countries and a constant real exchange rate.

wage and work the same number of hours in the non-stochastic steady state. The labor bundler buys hours from all household members employed in the sector, combines these hours into an aggregate labor service $N_{j,t}$, and sells it for a competitive wage to all firms in the sector. The bundling technology is

$$N_{j,t} = \left[\left(\frac{1}{\mu_j} \right)^{\frac{\epsilon_w}{1+\epsilon_w}} \int_0^{\mu_j} L_{j,t}(h)^{\frac{1}{1+\epsilon_w}} dh \right]^{1+\epsilon_w}.$$

Optimal demand for h -type labor is $L_{j,t}(h) = \left(\frac{\Omega_{j,t}(h)}{\Omega_{j,t}} \right)^{-\frac{1+\epsilon_w}{\epsilon_w}} L_{j,t}^d$, where

$$L_{j,t}^d = \frac{N_{j,t}}{\mu_j} \quad (5)$$

is defined as the average effective labor hours per worker in sector j . $\Omega_{j,t}(h)$ and $\Omega_{j,t}$ are the individual and aggregate real wage, respectively. ϵ_w governs the degree of market power for workers.

The individual worker in sector j chooses a nominal wage rate to maximize lifetime utility of his household, subject to the intertemporal budget constraint. The worker has monopoly power, but sets wages subject to nominal wage stickiness á la [Calvo \(1983\)](#) and [Erceg et al. \(2000\)](#). Each period, only a fraction $1 - \theta_{wj}$ of the sector j workers can re-optimize wages. The remaining fraction θ_{wj} supplies labor subject to their posted wage in the previous period. Thus, when deciding the optimal wage, workers have to take into account projections about future economic states. Let $\bar{\Omega}_{j,t}$ be the optimal wage in period t . The relevant first order condition for $\bar{\Omega}_{j,t}$ equates the present value of current and expected future labor income, $D_{j,t}$, with the present value of current and future labor disutility $E_{j,t}$:

$$D_{j,t} = E_{j,t}. \quad (6)$$

$D_{j,t}$ and $E_{j,t}$ account for the risk of being stuck with old wages, as can be seen from their recursive representations:

$$D_{j,t} = \frac{1}{1 + \epsilon_w} \Lambda_t \left(\frac{\bar{\Omega}_{j,t}}{\Omega_{j,t}} \right)^{-\frac{1}{\epsilon_w}} \Omega_{j,t} L_{j,t}^d + \beta \theta_{wj} \mathbb{E}_t \left[\left(\frac{\bar{\Omega}_{j,t+1} \Pi_{t+1}}{\Omega_{j,t}} \right)^{\frac{1}{\epsilon_w}} D_{j,t+1} \right] \quad (7)$$

$$E_{j,t} = \chi_N \left(\frac{\bar{\Omega}_{j,t}}{\Omega_{j,t}} \right)^{-\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)} L_{j,t}^{d \ 1+\varphi} + \beta \theta_{wj} \mathbb{E}_t \left[\left(\frac{\bar{\Omega}_{j,t+1} \Pi_{t+1}}{\Omega_{j,t}} \right)^{\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)} E_{j,t+1} \right], \quad (8)$$

Moreover, the sectoral real wage has the following law of motion:

$$\Omega_{j,t}^{-\frac{1}{\epsilon_w}} = (1 - \theta_{wj}) \bar{\Omega}_{j,t}^{-\frac{1}{\epsilon_w}} + \theta_{wj} \left(\frac{\Omega_{j,t-1}}{\Pi_t} \right)^{-\frac{1}{\epsilon_w}} \quad (9)$$

Equation (9) collapses to $\Omega_{j,t} = \bar{\Omega}_{j,t}$ in the limit as $\theta_{wj} \rightarrow 0$, and we get $\Omega_{j,t} = (1 + \epsilon_w) \chi_N \frac{L_{j,t}(h)^\varphi}{\Lambda_t}$ from the system (6)-(8).⁸ Thus, the real wage is equated with the markup times the marginal rate of substitution (between work and consumption) for all household members in the special case with flexible sector j wages. This completes the description of household behavior in the model.

⁸Note that $\lim_{\theta_{wj} \rightarrow 0} L_{j,t}^d = L_{j,t}(h) \forall h$.

2.2 NON-OIL FIRMS

Next I describe firm behavior in domestic non-oil sectors. Firm $f \in (0, 1)$ in non-oil sector $j \in M, S$ maximizes an expected discounted dividend stream given by

$$\mathbb{E}_t \sum_{s=t}^{\infty} Z_{t,s} P_s \mathcal{D}_{j,s}(f),$$

where \mathcal{D}_j are the real dividends. Output in each period is given by

$$Y_{j,t}(f) = Z_{j,t} X_{j,t}(f)^{\phi_j} N_{j,t}(f)^{1-\phi_j} - \Phi_j,$$

where $X_{j,t}(f)$ and $N_{j,t}(f)$ are firm f 's use of materials and labor respectively. Φ_j is a fixed production cost that will be calibrated to ensure zero profit in the non-stochastic steady state. $Z_{j,t}$ follows the law of motion

$$Z_{j,t} = Z_j^{1-\rho_Z} Z_{j,t-1}^{\rho_Z} \exp(\varepsilon_{j,t}), \quad (10)$$

where $\varepsilon_{j,t} \sim N(0, \sigma_j^2)$ is referred to as a sector specific total factor productivity (TFP) shock.

2.2.1 FACTOR ALLOCATIONS

Aggregate intermediate input used by firm f in sector j is a function of manufacturing and service inputs, denoted by $X_{Mj}(f)$ and $X_{Sj}(f)$ respectively. Each of these have a domestic and imported component, $X_{HLj}(f)$ and $X_{FLj}(f)$ ($j, l \in M, S$), which again consist of a continuum of material goods from every individual firm in both economies. All functional forms are CES. Cost minimizing demand for materials from sector l , and for relative demand for imported materials, follow below:

$$\frac{X_{Mj,t}(f)}{X_{Sj,t}(f)} = \frac{\zeta_j}{1 - \zeta_j} \left(\frac{P_{rM,t}}{P_{rS,t}} \right)^{-\nu} \quad \frac{X_{HLj,t}(f)}{X_{FLj,t}(f)} = \frac{\bar{\alpha}_l}{1 - \bar{\alpha}_l} \left(\frac{P_{rHL,t}}{P_{rFL,t}} \right)^{-\eta} \quad (11)$$

The parameter ζ_j determines the steady state weight on manufactured materials in X_j . Note that the import weight $\bar{\alpha}_j$ is the same in consumption. This implies that e.g. computers have the same import weight in the SOE, regardless of whether they are used in production or consumption. However, as computers may be used more or less intensively in production, the import share in aggregate consumption and production will in general be different. Demand for materials from each country's sector j firm $g \in (0, 1)$ is given by $X_{HLj,t}(g, f) = \left(\frac{P_{HL,t}(g)}{P_{HL,t}} \right)^{-\frac{1+\epsilon_p}{\epsilon_p}} X_{HLj,t}(f)$ and $X_{FLj,t}(g, f) = \left(\frac{P_{FL,t}(g)}{P_{FL,t}} \right)^{-\frac{1+\epsilon_p}{\epsilon_p}} M_{FLj,t}(f)$, respectively. Optimality conditions with respect to $X_{j,t}(f)$ and $N_{j,t}(f)$ can be summarized by the equation

$$\frac{X_{j,t}(f)}{N_{j,t}(f)} = \frac{\phi_j}{1 - \phi_j} \frac{\Omega_{j,t}}{P_{rj,t}^x}, \quad (12)$$

where $P_{rj,t}^x$ is the real price on $X_{j,t}(f)$. It follows that real marginal costs $RMC_{j,t}$ are the same for all firms, and expressed as

$$RMC_{j,t} = \frac{1}{Z_{Aj,t}} \left(\frac{P_{rj,t}^x}{\phi_j} \right)^{\phi_j} \left(\frac{\Omega_{j,t}}{1 - \phi_j} \right)^{1-\phi_j}. \quad (13)$$

2.2.2 GOODS MARKETS

Price setting by domestic and foreign firms is subject to monopoly supply power and sticky prices. Firms set nominal prices á la Calvo (1983) and Yun (1996), and price both local goods and export goods in domestic currency. This is referred to in the literature as producer currency pricing (PCP). Each period, only a fraction $1 - \theta_{pj}$ of the firms in sector j can change prices. The remaining fraction θ_{pj} of firms supply consumption and material goods subject to their posted price in the previous period. Let $\bar{P}_{rj,t}$ be the optimal new price in period t in terms of consumption goods. It is pinned down by the identity

$$(1 + \epsilon_p) P_{rHj,t}^{\frac{1+\epsilon_p}{\epsilon_p}} G_{j,t} = H_{j,t}, \quad (14)$$

where $G_{j,t}$ is the present discounted value of current and expected future marginal costs (when $\bar{P}_{rj,t}$ is in place), and $H_{j,t}$ is the present value of current and future marginal revenues. These can be represented recursively:

$$G_{j,t} = \Lambda_t Y_{j,t}^d RMC_{j,t} + \beta \theta_{pj} \mathbb{E}_t \left(\Pi_{Hj,t+1}^{\frac{1+\epsilon_p}{\epsilon_p}} G_{j,t+1} \right) \quad (15)$$

$$H_{j,t} = \Lambda_t Y_{j,t}^d \bar{P}_{rHj,t} P_{rHj,t}^{\frac{1+\epsilon_p}{\epsilon_p}} + \beta \theta_{pj} \mathbb{E}_t \left(\frac{\bar{P}_{rHj,t}}{\bar{P}_{rHj,t+1}} \Pi_{t+1}^{\frac{1}{\epsilon_p}} H_{j,t+1} \right) \quad (16)$$

$Y_{j,t}^d$ is aggregate demand towards domestic sector j firms (see below). The law of motion for new prices $\bar{P}_{rHj,t}$ follows below:

$$P_{rHj,t}^{-\frac{1}{\epsilon_p}} = (1 - \theta_{pj}) \bar{P}_{rHj,t}^{-\frac{1}{\epsilon_p}} + \theta_{pj} \left(\frac{P_{rHj,t-1}}{\Pi_t} \right)^{-\frac{1}{\epsilon_p}} \quad (17)$$

Equation (17) collapses to $P_{rHj,t} = \bar{P}_{rHj,t}$ in the limit as $\theta_{pj} \rightarrow 0$, and we get $P_{rHj,t} = (1 + \epsilon_p) RMC_{j,t}$ from the system (14)-(16). Thus, the real producer price is equated with the markup times the marginal cost for all firms in the special case with flexible sector j prices.

2.3 THE OIL SECTOR

Consider a representative oil firm in the SOE that takes the international oil price as given. The oil firm maximizes profits given by

$$\mathcal{D}_{O,t} = S_t P_{rO,t} Y_{O,t} - R_{qO,t} Q_{O,t} - P_{rO,t}^x X_{O,t} - \Omega_{O,t} N_{O,t},$$

where $P_{rO,t}$ is the international oil price (in ROW consumption units), $Y_{O,t}$ is the oil produced by the SOE, and $R_{qO,t} Q_{O,t} + P_{rO,t}^x X_{O,t} + \Omega_{O,t} N_{O,t}$ is the total cost of production. $Q_{O,t}$ represents all inputs used in the production of oil that do not come from the non-oil SOE, including land and physical capital (e.g. drilling rigs and pipelines). $X_{O,t}$ is the aggregate material input bought from non-oil firms in the SOE while $N_{O,t}$ is aggregate labor services. Finally, the factor prices are denoted by $R_{qO,t}$, $P_{rO,t}^x$ and $\Omega_{O,t}$ respectively. The key transmission channels between the oil sector and the rest of the economy are fluctuations in $P_{rO,t}^x X_{O,t}$ and $\Omega_{O,t} N_{O,t}$, as domestic non-oil firms and households are the sole providers of materials and labor services to the oil sector.

I let oil be produced by means of a simple Cobb-Douglas production technology:

$$Y_{O,t} = Z_O Q_O^{1-\alpha_o} \left(X_{O,t}^{\phi_o} N_{O,t}^{1-\phi_o} \right)^{\alpha_o} \quad (18)$$

Note the assumption that Q_O is a constant, implying diminishing returns to scale in oil production as long as $\alpha_o < 1$. I also abstract from oil specific technology shocks by treating Z_O as constant.⁹ The aggregate material input in the oil sector is a CES function of inputs from domestic non-oil sectors.

Let ζ_O be the fraction of total oil materials that is produced by the goods sector. Profit maximizing behavior then implies that the following set of conditions must hold in the oil sector:

$$\frac{X_{MO,t}}{X_{SO,t}} = \frac{\zeta_O}{1 - \zeta_O} \left(\frac{P_{rHM,t}}{P_{rHS,t}} \right)^{-\nu_o} \quad (19)$$

$$X_{O,t} = \alpha_o \phi_o \mathcal{S}_t P_{rO,t} \frac{Y_{O,t}}{P_{rO,t}^x} \quad (20)$$

$$N_{O,t} = \alpha_o (1 - \phi_o) \mathcal{S}_t P_{rO,t} \frac{Y_{O,t}}{\Omega_{O,t}} \quad (21)$$

The price on Q_O is pinned down by the equation $R_{qO,t} = (1 - \alpha_o) \mathcal{S}_t P_{rO,t} \frac{Y_{O,t}}{Q_O}$. The real wage $\Omega_{O,t}$ is determined in the same way as wages in the non-oil sectors. Also, $X_{jO,t}(f) = \left(\frac{P_{rHj,t}(f)}{P_{rHj,t}} \right)^{-\frac{1+\epsilon_p}{\epsilon_p}} X_{jO,t}$ is the oil sector's demand for materials from non-oil firm f . For completeness, note that value added of oil production can be written as

$$GDP_{O,t} = \mathcal{S}_t P_{rO,t} Y_{O,t} - P_{rO,t}^x X_{jO,t} = (1 - \alpha_o \phi_o) \mathcal{S}_t P_{rO,t} Y_{O,t}. \quad (22)$$

Thus, value added in the oil sector is high when i) the foreign currency is strong (since oil is sold in foreign currency), ii) the world price of oil is high, and iii) when oil production is high.

Market clearing in the international oil market dictates that world supply equals world demand, or $Y_{O,t}^F + \frac{\varsigma}{1-\varsigma} Y_{O,t} = C_{O,t}^F$. Taking the limit as ς goes to zero, we get

$$Y_{O,t}^F = \xi_o P_{rO,t}^{-\eta_o} C_t^F, \quad (23)$$

where global demand for oil is assumed to be a downward sloping function of the real oil price. The parameter ξ_o governs the steady state share of oil in aggregate world consumption, while η_o is the price elasticity of oil demand. To keep the analysis as simple as possible, I let $Y_{O,t}^F \equiv Z_{PO,t}$ follow the process

$$Z_{PO,t} = Z_{PO}^{1-\rho_o} Z_{PO,t-1}^{\rho_o} \exp(\varepsilon_{o,t}), \quad (24)$$

where $\varepsilon_{o,t} \sim N(0, \sigma_o^2)$ is referred to as an international oil price shock. The implication of this assumption is that $P_{rO,t}$ is driven by everything that affects world consumption C_t^F , as well as the exogenous process for $Z_{PO,t}$. At this level of abstraction, a rise in $Z_{PO,t}$ is observationally equivalent with both a positive international oil supply a shock, and a negative international oil demand shock. Therefore, I do not take a stand on the relative importance of supply versus demand in oil markets. This completes the description of the oil sector.

⁹In an earlier version I allowed for stochastic innovations in Z_O , and interpreted these as domestic oil supply shocks. However, the variance decomposition revealed that fluctuations in Z_O only have a negligible impact on macroeconomic fluctuations in the rest of the economy.

2.4 MARKET CLEARING AND AGGREGATION

Next I report a set of aggregate equilibrium relationships in goods and labor markets in the SOE. Aggregate hours in sector j is given by

$$\int_0^{\mu_j} L_{j,t}(h) dh = L_{j,t}^d V_{wj,t}. \quad (25)$$

$V_{wj,t} = \int_0^{\mu_j} \left(\frac{\Omega_{j,t}(h)}{\bar{\Omega}_{j,t}} \right)^{-\frac{1+\epsilon_w}{\epsilon_w}} dh \geq \mu_j$ is a measure of cross-sectional wage dispersion. The law of motion for wage dispersion is

$$V_{wj,t} = \mu_j (1 - \theta_{wj}) \left(\frac{\bar{\Omega}_{j,t}}{\bar{\Omega}_{j,t-1}} \right)^{-\frac{1+\epsilon_w}{\epsilon_w}} + \theta_{wj} \Pi_{wj,t}^{\frac{1+\epsilon_w}{\epsilon_w}} V_{wj,t-1}, \quad (26)$$

where

$$\Pi_{wj,t} = \frac{\bar{\Omega}_{j,t}}{\bar{\Omega}_{j,t-1}} \Pi_t \quad (27)$$

is the nominal wage inflation rate. Labor in the oil market is aggregated in the same way. Total hours worked in the economy follows as $L_{M,t}^d V_{wM,t} + L_{S,t}^d V_{wS,t} + L_{O,t}^d V_{wO,t}$.

Market clearing in factor markets implies that $N_{j,t} = \int_0^1 N_{j,t}(f) df$ and $M_{j,t} = \int_0^1 M_{j,t}(f) df$. Together with (12), these equations allow us to write aggregate gross output in sector j as $\int_0^1 Y_{j,t}(f) df = Z_{j,t} M_{j,t}^{\phi_j} N_{j,t}^{1-\phi_j} - \Phi_j$. Aggregate demand on the other hand is

$$Y_{j,t}^d = Y_{Hj,t}^d + Y_{Hj,t}^{dF} + X_{jO,t}, \quad (28)$$

where $Y_{Hj,t}^d$ is total domestic demand (for sector j home goods) and $Y_{Hj,t}^{dF}$ is total exports.¹⁰ Thus, market clearing in the goods market in sector j is given by

$$Z_{j,t} X_{j,t}^{\phi_j} N_{j,t}^{1-\phi_j} - \Phi_j = Y_{j,t}^d V_{pj,t}. \quad (29)$$

Cross-sectional price dispersion, $V_{pj,t} = \int_0^1 \left(\frac{P_{rHj,t}(f)}{\bar{P}_{rHj,t}} \right)^{-\frac{1+\epsilon_p}{\epsilon_p}} df \geq 1$, is

$$V_{pj,t} = (1 - \theta_{pj}) \left(\frac{\bar{P}_{rHj,t}}{\bar{P}_{rHj,t-1}} \right)^{-\frac{1+\epsilon_p}{\epsilon_p}} + \theta_{pj} \Pi_{Hj,t}^{\frac{1+\epsilon_p}{\epsilon_p}} V_{pj,t-1}, \quad (30)$$

where

$$\Pi_{Hj,t} = \frac{\bar{P}_{rHj,t}}{\bar{P}_{rHj,t-1}} \Pi_t \quad (31)$$

is defined as the nominal producer price inflation on domestically produced sector j goods.

¹⁰ $Y_{Hj,t}^d = C_{Hj,t} + X_{HjG,t} + X_{HjS,t}$ and $Y_{Hj,t}^{dF} = C_{Hj,t}^F + X_{HjG,t}^F + X_{HjS,t}^F$, respectively, where $j, l = [M, S]$.

Regarding market clearing in goods markets, I restrict the analysis to the limiting case where $\varsigma \rightarrow 0$, i.e. where trade between the ROW and the SOE becomes negligible from the world economy's point of view.¹¹ Then, using the CES specifications, we can write total absorption of domestically produced and imported sector j goods, respectively, as follows:

$$Y_{Hj,t}^d = \alpha_j \left(\frac{P_{rHj,t}}{P_{rj,t}} \right)^{-\eta} (C_{j,t} + X_{jM,t} + X_{jS,t}) \quad (32)$$

$$Y_{Fj,t}^d = (1 - \alpha_j) \left(\frac{P_{rFj,t}}{P_{rj,t}} \right)^{-\eta} (C_{j,t} + X_{jG,t} + X_{jS,t}), \quad (33)$$

Finally, total foreign absorption of domestic exports is

$$Y_{Hj,t}^{dF} = (1 - \alpha_j^F) \left(\frac{P_{rHj,t}^F}{P_{rj,t}^F} \right)^{-\eta} (C_{j,t}^F + X_{jM,t}^F + X_{jS,t}^F). \quad (34)$$

Nominal gross sales in sector j is $P_{Hj,t} Y_{j,t}^d$. Real value added, which is the nominal value added denominated by the CPI, is obtained by subtracting expenditures on intermediate inputs:

$$\begin{aligned} GDP_{j,t} &= P_{rHj,t} Y_{j,t}^d - P_{rj,t}^x X_{j,t} \\ &= P_{rj,t} (C_{j,t} + X_{jM,t} + X_{jS,t}) + P_{rHj,t} X_{jO,t} + TB_{j,t} - P_{rj,t}^x X_{j,t} \end{aligned} \quad (35)$$

The first line defines GDP in sector j according to the production approach, i.e. as the value of gross output minus the value of intermediate inputs. The second line above is GDP defined by the expenditure approach, and is obtained by combining $P_{rHj,t} Y_{j,t}^d - P_{rj,t}^x X_{j,t}$ with equations (32)-(34). The trade balance in sector j is given by

$$TB_{j,t} = P_{rHj,t} Y_{Hj,t}^{dF} - P_{rFj,t} Y_{Fj,t}^d. \quad (36)$$

For completeness, note that total value added in the SOE is $VA = GDP_t + GDP_{O,t}$, where

$$\begin{aligned} GDP_t &= GDP_{M,t} + GDP_{S,t} \\ &= C_t + TB_t + \alpha_o \phi_o \mathcal{S}_t P_{rO,t} Y_{O,t} \end{aligned} \quad (37)$$

is non-oil value added and $TB_t = TB_{M,t} + TB_{S,t}$ is the non-oil trade balance. The foreign economy is characterized by a similar system of equations, except that trade constitutes a negligible part of economic activity.

The model is completed with the determination of monetary and fiscal policy. I make the conventional assumption that fiscal policy is passive (see [Leeper \(1991\)](#)). That is, fiscal authorities credibly commit to stabilization of public debt by means lump sum taxes. However, I relax the popular assumption that fiscal tax systems are designed to neutralize the steady state inefficiency due to monopoly power in labor and goods markets. Regarding the monetary policy regime, I describe interest rate determination in detail below. This completes the description of the model.

¹¹ $\varsigma \rightarrow 0$ implies that imports and exports per capita in the ROW approaches zero.

3 RAMSEY OPTIMAL MONETARY POLICY

Next I set out to characterize optimal monetary policy. One popular approach to this end, is to assume that fiscal authorities possess technologies (usually tax subsidies) that neutralize steady state distortions from monopolistic competition. Under certain restrictions, this assumption allows one to compute welfare by means of linear approximation methods. However, such technologies are clearly not widespread in data. Also, as emphasized by [Schmitt-Grohé and Uribe \(2007\)](#), they undermine the actual role of monetary authorities – to stabilize costly movements around potentially distorted trends. Thus, I do not resort to subsidies of this sort. Rather, I solve for Ramsey optimal policy using a second order approximation to policy functions. The Ramsey problem of the social planner in the SOE is to maximize expected lifetime utility of households subject to i) the behavior of private agents, ii) resource constraints in the SOE, and iii) the ROW counterparts of i) and ii). Formally, the problem is

$$\max \mathcal{W}_t \quad \text{subject to} \quad \mathbb{E}_t F(\mathcal{Y}_{t+1}, \mathcal{Y}_t, \mathcal{Y}_{t-1}, e_t) = 0, \quad (38)$$

where \mathcal{Y} is the vector of all domestic and foreign endogenous variables and e is the vector of exogenous shocks. The function F consists of all equilibrium conditions in the SOE and the ROW, except for an equation describing the law of motion for R . The objective function of the social planner is defined as the expected sum of all domestic households' lifetime utility:

$$\mathcal{W}_t \equiv \mathbb{E}_t \int_0^1 \mathcal{W}_{j,t}(h) dh = \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\log(C_s) - \chi_N \frac{\sum_{\{G,S,O\}} L_{j,s}^{1+\varphi} V_{uj,s}}{1+\varphi} \right] \quad (39)$$

The presence of wage stickiness introduces a cross-sectional wage dispersion term $V_{uj,t} \equiv \int_0^{\mu_j} \left(\frac{\Omega_{j,t}(h)}{\Omega_{j,t}} \right)^{-\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)} dh \geq \mu_j$ in the aggregate welfare function. It is similar to the dispersion measure in (26), except for the presence of a curvature parameter φ . The law of motion for $V_{uj,t}$ is

$$V_{uj,t} = \mu_j (1 - \theta_{wj}) \left(\frac{\bar{\Omega}_{j,t}}{\Omega_{j,t}} \right)^{-\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)} + \theta_{wj} \Pi_{wj,t}^{\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)} V_{uj,t-1}.$$

I use perturbation methods to obtain a second order approximation of the first order conditions for the problem in (38). The approximation is taken around a non-stochastic steady state described in the appendix. The model solution is derived from the resulting system, see e.g. [Schmitt-Grohé and Uribe \(2004\)](#) for details.

3.1 CALIBRATION

The non-stochastic steady state is one in which all relative prices (including the real exchange rate), as well as consumption in both economies, are normalized to unity. Hours is normalized to $\frac{1}{3}$. Given these values, I solve recursively for all the remaining endogenous variables including sector specific productivity. The steady state is described in the appendix. Calibration choices are summarized in [Table 1](#). $\beta = 0.99$ implies an annual steady state real interest rate of about 4%. Is set φ consistent with a Frisch elasticity of

Table 1: Benchmark calibration

<i>Parameter</i>	<i>Description</i>	<i>Value</i>	
β	Time discount factor	0.99	
φ	Inverse Frisch elasticity of labor supply	2	
χ_N	Set to fit steady state hours equal to 1/3	23.9	
ϵ_p	Steady state mark-up, individual goods	20%	
ϵ_w	Steady state mark-up, labor types	20%	
η	Elasticity of substitution, countries	0.9	
ν	Elasticity of substitution, sectors	0.9	
<i>Non-oil industries</i>		(1)	(2)
θ_{wj}	Calvo probability of no wage change	0.75	0.75
θ_{pj}	Calvo probability of no price change	0.25	0.75
α_j, α_j^F	Steady state import/export share of GDP	0.60	0.15
ξ	Steady state share of sector consumption	0.35	0.65
ϕ_j	Steady state materials share in gross output	0.6	0.4
ζ_j	Steady state manufacturing share in materials	0.7	0.3
<i>Oil sector and oil markets</i>			
ξ_o	Steady state world oil share in GDP	0.02	
η_o	Price elasticity of oil demand	0.35	
ν_o	Elasticity of substitution, oil material input	0.9	
α_o	Steady state labor and material share in oil production	0.2	
ϕ_o	Steady state material share in variable oil input	0.7	
ζ_o	Steady state manufacturing share in oil materials	0.4	
<i>Shocks</i>			
σ_{ε_j}	Standard deviation, TFP	0.018	0.006
ρ_A	Persistence, TFP	0.7	
σ_{ε_o}	Standard deviation, oil price shock	0.06	
ρ_O	Persistence, oil price shock	0.95	

Note: This table presents calibrated values in the benchmark model. The non-oil industries are (1) manufacturing and (2) services.

0.5, in the mid range of micro and macro estimates. I follow the estimates by [Molnarova and Reiter \(2014\)](#) and set the elasticity of substitution across sectors (for consumption and materials) to 0.9. It is in the upper range of estimates by [Atalay \(2013\)](#), but below the conventional value of unity (Cobb-Douglas) used in much previous literature. I choose the same value for η , based on estimates by e.g. [Corsetti, Dedola, and Leduc \(2008\)](#) and [Bergholt \(2014\)](#).

Turning to sector parameters, I calibrate θ_{pj} to match an average price duration in manufacturing and services equal to $\frac{4}{3}$ and 4 quarters, respectively. This is broadly consistent with various estimates of price stickiness at the sector level ([Nakamura and Steinsson,](#)

Table 2: Benchmark steady state ratios

	<i>Description</i>	<i>Value</i>
μ_M	Share of labor force in manufacturing	0.33
μ_S	Share of labor force in services	0.65
μ_O	Share of labor force in oil sector	0.02
$Y_M/(Y_M + Y_S)$	Manufacturing share in gross non-oil output	0.43
$Y_S/(Y_M + Y_S)$	Service share in gross non-oil output	0.57
GDP_M/GDP	Manufacturing share in non-oil GDP	0.33
GDP_S/GDP	Service sector share in non-oil GDP	0.67
GDP_O/VA	Oil sector share in aggregate GDP	0.20
$(X_{FM} + X_{FS})/GDP$	Import (and export) share in non-oil GDP	0.30
$(C_{FM} + C_{FS})/C$	Import (and export) share in consumption	0.15

Note: This table presents ratios in the non-stochastic steady state as implied by the calibration in [Table 1](#).

2008; [Bouakez, Cardia, and Ruge-Murcia, 2009](#)). Wages in all sectors are assumed to adjust on average once every year. Regarding trade openness, I let most exports and imports take place in the manufacturing sector. I assume that the non-oil trade balances are zero in each sector, and set the export/import share of GDP to 0.6 and 0.15, respectively. These numbers are similar to the trade shares in Norway the last 30 years. Moreover, consistent with Norwegian data I let most consumption goods be produced by the service sector.

Parameters related to oil markets are calibrated as follows: The oil share in world consumption is set to 2%, while the elasticity of substitution between oil and non-oil consumption is set to 0.35. The former number is consistent with IEA data, the latter with estimates in the oil literature ([Hamilton, 2009](#); [Bodenstein and Guerrieri, 2012](#)). I calibrate the share of oil GDP in total GDP in the SOE to be broadly consistent with Norwegian data (20%). The calibration choices for α_o and ϕ_o imply that about 14% of total production expenditures in the oil sector is on mainland inputs. Out of those expenditures, 40% is on input from the manufacturing sector. Finally, implied wage costs in the oil sector amounts to about 6% of total production costs. These shares are similar to those reported in the OECD-STAN dataset for the Norwegian SIC industries 10-14.

The dynamics in the model are driven by 5 shocks – 2 sector specific TFP shocks in each economy and 1 oil market shock. The TFP shocks are calibrated to match a quarterly standard deviation of GDP of about 2.75%, given that monetary authorities follow a modified Taylor rule (see below). Motivated by previous literature ([Bouakez et al., 2009](#); [Bergholt, 2014](#)), I let TFP be three times more volatile in the manufacturing sector compared to the service sector. Finally, the oil price shock is set to match the standard deviation in real oil prices of about 55%, and a first order autocorrelation of about 0.95. Regarding the calibration of structural parameters belonging to the ROW, I assume they take the same values as in the SOE. Thus, in the absence of oil, and with balanced trade, all steady state variables take the same values in both economies (in terms of per capita units).

[Table 2](#) reports implied steady state ratios in the model. A few remarks are in place: First, the large majority of the work force is employed in non-oil industries, even though

oil represents a significant fraction of total GDP. This reflects the view that oil production requires little labor. Second, manufacturing represents a larger fraction of gross output than of value added in the economy. The main reason is that intermediate inputs are more important in manufacturing production in the data. Third, the import share in consumption is substantially lower than the import share in GDP. This is because the service sector, which has a low import share, accounts for most of the consumption output.

3.2 A BENCHMARK EVALUATION OF RAMSEY OPTIMAL POLICY

What are the implications of Ramsey optimal monetary policy in the model? To answer this question, I compare the economy under Ramsey policy with the economy when the interest rate is set according to a Taylor-type rule. The latter is often used as an approximation to interest rate policy in estimated New Keynesian models. The interest rate rule takes the form

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_r} \left[\left(\frac{\Pi_t}{\Pi} \right)^{\rho_\pi} \left(\frac{GDP_t}{GDP_{t-1}} \right)^{\rho_y} \right]^{1-\rho_r},$$

where the implicit assumption is that monetary authorities only respond to non-oil GDP. Response coefficients are set as follows: $\rho_r = 0.75$, $\rho_\pi = 2$, and $\rho_y = 0.05$. These numbers are similar to those estimated by [Bergholt \(2014\)](#) for Canada and the US in a medium scale DSGE model. The open economy dimension of the model complicates the task of comparing policies because one has to consider how foreign interest rates are determined. In the main analysis, I suppose that monetary policy in the ROW follows a Taylor rule symmetric to the one described above. As pointed out by [De Paoli \(2009\)](#), policy choices in the ROW influence how (ROW) shocks affect foreign variables, but they do not modify the way in which foreign variables affect the SOE.

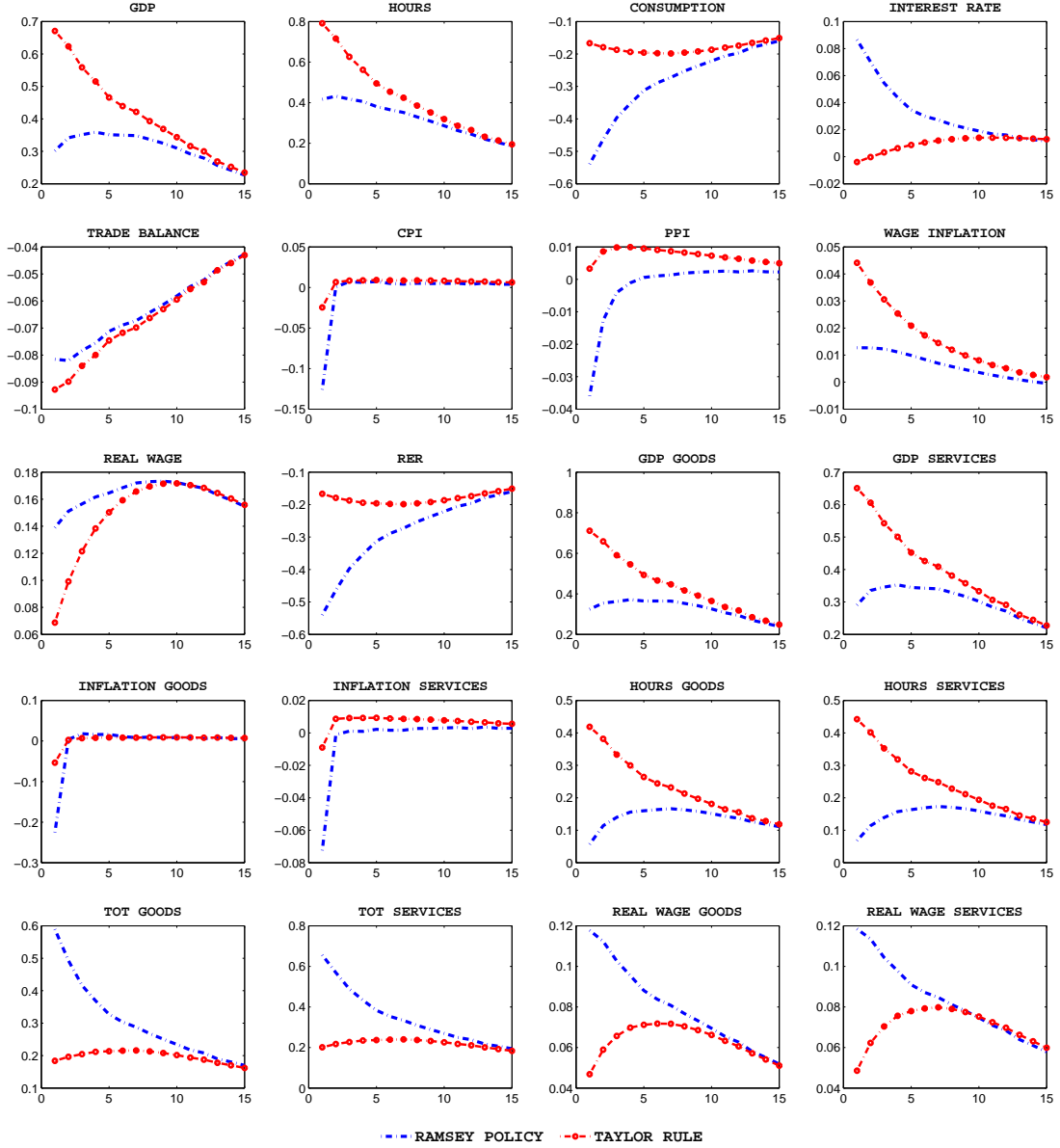
3.2.1 IMPULSE RESPONSES TO OIL SHOCKS

To understand the implications of Ramsey optimal policy, I compare impulse responses of domestic variables to shocks under the two policy regimes. I use the pruned state-space solution to avoid explosive paths, following [Kim, Kim, Schaumburg, and Sims \(2008\)](#). Impulse responses are plotted in [Figure 1-Figure 3](#), where the plots are sample averages of 200 simulations.

First I discuss impulse responses to an international oil price shock. They are plotted in [Figure 1](#). The shock leads to higher domestic (non-oil) GDP, hours and wages, both under Ramsey optimal policy (blue lines) and under the Taylor rule (red lines). Moreover, the real exchange rate appreciates and terms of trade improve in both sectors. To gain some intuition, let us for the moment restrict attention to responses under the Taylor rule: Higher oil prices create a boom in the oil sector, causing more demand for labor and materials in that sector. This maps into the non-oil economy as a demand shock, both in labor and goods markets. Non-oil firms, which are linked to the oil sector via supply chains, respond to the higher demand by increasing their prices. Consumption demand on the other hand falls because of higher real interest rates. The latter observation explains why we get a real exchange rate appreciation.¹² In fact, the appreciation is so strong

¹²Risk sharing in international asset markets implies perfect correlation between the real exchange rate

Figure 1: Impulse responses to oil shocks



Note: Impulse responses to an innovation in ε_o (one standard deviation). Measured in percentage deviations from the non-stochastic steady state. The trade balance is measured in absolute deviations and as a fraction of GDP.

that the CPI falls the first period after shock. Domestic producer price inflation and the exchange rate appreciation both cause a rise in the relative price on domestically produced goods, i.e. a terms of trade improvement. Non-oil firms also require more production inputs, so demand for labor increases in all sectors. The rise in hours worked takes the marginal rate of substitution, $\chi_N \frac{L_{j,t}^\varphi}{\Lambda_t}$, above its preferred value $\frac{1}{1+\epsilon_w} \Omega_{j,t}$. Households then respond by raising nominal wages in order to align real wages with the marginal rate of

and the relative consumption level in the SOE (see equation (4)). Thus, the model's ability to explain currency appreciation comes at the cost of counter-intuitive movements in consumption. This can in principle be overturned by assuming that households' utility is non-separable in consumption and hours worked.

substitution.¹³ This is how the oil price shock generates wage inflation in the non-oil economy. The drop in net exports is partly explained by non-oil firms' higher demand for intermediate inputs (which have an imported component), and partly explained by expenditure switching – both among households and firms, towards relatively cheaper foreign consumption and materials.

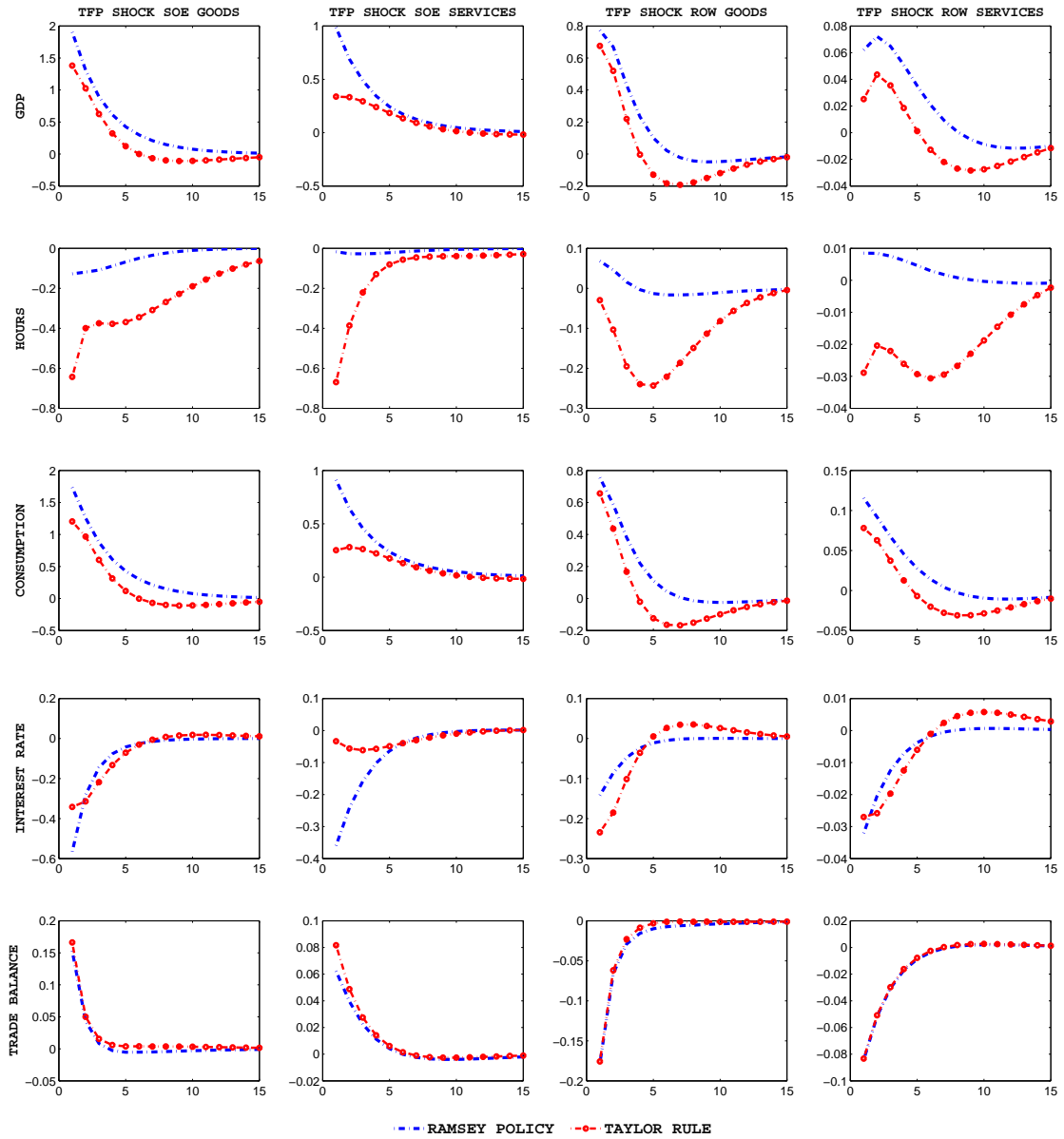
It is important to understand the inefficiencies associated with macroeconomic dynamics under the Taylor rule. Have in mind that high oil price makes it efficient to reallocate productive resources from non-oil use towards the oil sector. If wages and prices were perfectly flexible, this reallocation would have been implemented by a prolonged period with high real interest rates and appreciated domestic currency. However, wage and price stickiness prevent sufficient general equilibrium substitution, while at the same time causing i) cross-sectional wage dispersion across otherwise identical workers, and ii) cross-sectional price dispersion across otherwise identical firms. Cross-sectional dispersion arises because each worker and firm has a different history of Calvo draws. Moreover, dispersion is costly because workers and firms with same ex ante productivity level end up operating at different margins.

How are these inefficiencies dealt with by the Ramsey planner? The impulse responses allow us to draw some inference. Compared to a Taylor rule, the Ramsey optimal response is an aggressive increase of the nominal interest rate, as seen in Figure 1. This exaggerates the rise in real interest rates, implying further contraction of consumption and appreciation of the exchange rate. The gains are two-fold: First, less non-oil demand and stronger domestic currency helps to bring down the marginal costs of non-oil firms. In fact, under optimal policy real marginal costs $RMC_{j,t}$ drop below the preferred level $\frac{1}{1+\epsilon_p} P_{rHj,t}$, resulting in producer price deflation instead of inflation. Thus, more resources can be reallocated to oil via domestic supply chains, allowing oil firms to explore more of the rents associated with high oil prices. Second, optimal policy effectively neutralizes much of the incentive for households to increase nominal wages. To see this, note that both producer price deflation and exchange rate appreciation map into lower consumer prices, and consequently into higher real wages. At the same time, less non-oil demand limits the expansionary effects on hours worked and non-oil GDP. Now, because the marginal rate of substitution is increasing in both hours and consumption, and because real wages are stimulated by low consumer prices, the two move much more in line under Ramsey optimal policy. One should note that the exchange rate is a key ingredient in the transmission mechanism under optimal policy. This observation is an early warning against policies aimed at stabilizing the exchange rate. Finally, the welfare costs associated with declining producer prices are limited by the fact that producer price deflation converges back to the steady state after a few periods.

One important remark is in place at this point. The supply chain linking non-oil firms to the oil sector is crucial for the transmission of oil shocks to the non-oil economy. If one abstracts from this link by setting $\phi_o = 0$, almost all the spillover disappears. Aggregate wages and hours worked in the economy are still (mildly) affected because of workers in the oil sector, but all the remaining non-oil variables become nearly orthogonal to the

¹³This insight comes from a first order approximation of the wage inflation equation, i.e. the New Keynesian wage Phillips curve. For given expectations of future inflation, this equation predicts a negative relationship between wage inflation on the one hand, and the spread between real wages and the marginal rate of substitution on the other.

Figure 2: Impulse responses to non-oil shocks 1



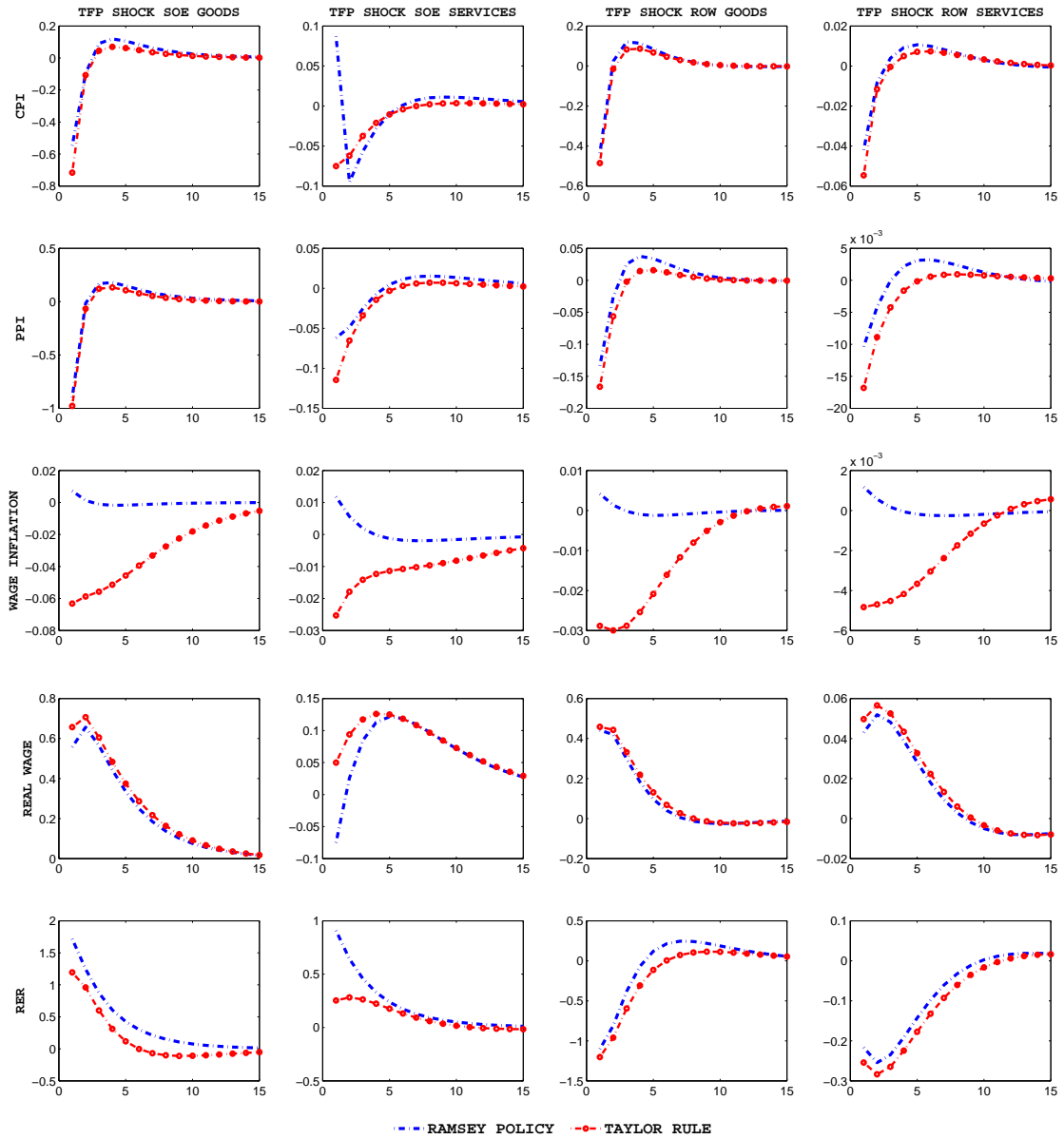
Note: Impulse responses to innovations in ε_j and ε_j^F (one standard deviation). See Figure 1.

oil price shock. Obviously, if also $\alpha_o = 0$, then even the transmission to sectoral labor markets is gone. In total we get a boom in the non-oil economy that, without resorting to spillover via e.g. government spending policies, would not take place in the absence of the supply chain linkages. We also get movements in terms of trade and the real exchange rate that at least qualitatively resemble estimates in the VAR literature.

3.2.2 IMPULSE RESPONSES TO NON-OIL SHOCKS

Next I first consider responses to domestic and foreign TFP shocks. Higher productivity causes a boom in the SOE under both policies. That is, GDP and consumption rise for a prolonged number of periods, although the responses under optimal policy are stronger.

Figure 3: Impulse responses to non-oil shocks 2



Note: Impulse responses to innovations in ε_j and ε_j^F (one standard deviation). See Figure 1.

This is true for productivity shocks in both sectors in both countries. Under the Taylor rule, both CPI and PPI inflation go down due to the drop in domestic marginal costs. As the Taylor rule assigns a high weight to CPI stability, this implies a drop in the interest rate as well. Responses of the CPI and PPI under Ramsey policy are similar, except for an initial jump in the CPI following a domestic service sector shock. This jump comes about from the large initial exchange rate depreciation associated with the Ramsey policy. The impulse responses to foreign productivity shocks are qualitatively similar to domestic shocks, except that we get a real appreciation and a negative trade balance. The real exchange rate appreciates because foreigners enjoy a relatively larger increase in consumption when foreign firms become more productive. The trade balance declines because of substitution away from domestically produced goods. However, as shown

by [Bergholt and Sveen \(2014\)](#), we still get a boom in the SOE. This has to do with the sectoral input-output linkages within and across economies, which allow cheap import of materials to domestic firms.

The most substantial difference between the Taylor rule and Ramsey optimal policy is found in labor markets. Consider first the responses of hours to productivity shocks under the Taylor rule. Hours decline – a standard feature of most New Keynesian models. The intuition is simple: Price stickiness creates too little deflation compared to real business cycle economies, thus, too little increase in aggregate demand and output. Firms (in particular those that cannot reduce their prices) then respond to the markup over preferred prices by reducing their demand for inputs. However, in a model with intermediate trade, another force drives down hours even further: The decline in prices makes materials relatively cheaper than labor, so there is substitution away from labor along the intensive margin of inputs. The large drop in hours takes the marginal rate of substitution below the real wage, leading to nominal wage deflation.

Notably, most of the drop in hours under the Taylor rule is removed by the Ramsey policy – hours even rise slightly after foreign TFP shocks. More importantly, we get a small nominal wage increase instead of deflation. The intuition follows along the lines of Ramsey optimal response to oil price shocks: Nominal interest rates decline more, implying lower real interest rates. This stimulates consumption demand via the Euler equation, causing higher aggregate demand than with the Taylor policy. High demand prevents the large decline in hours worked. Finally, the combination of high demand and limited movements in hours removes most of the wedge between the marginal rate of substitution and the real wage.

3.2.3 BUSINESS CYCLE MOMENTS

[Table 3](#) reports simulated moments and variance decompositions. Consistent with the impulse response analysis, we get more volatile GDP, consumption and real exchange rate under Ramsey optimal policy. Wage inflation and hours on the other hand are less volatile. The small differences in PPI inflation volatility under the two policies are consistent with the view that wage inflation stability is most important in the model. Aggregate consumption, hours and real wages are pro-cyclical under both policies, while nominal CPI and PPI inflation, as well as the interest rate, are counter-cyclical. Counter-cyclicity of inflation rates is a result of the predominance of TFP shocks in the model. The non-oil trade balance is countercyclical – as in the data. Note that the ability of Ramsey optimal policy to insulate wage inflation from TFP shocks turns it from counter-cyclical to pro-cyclical.

The variance decomposition shows that the oil price shock is an important source of business cycle fluctuations in the model. It explains about 36% the fluctuations in non-oil GDP under the Taylor rule, comparable to the 31-36% found by [Bjørnland and Thorsrud \(2013\)](#) for Norway.¹⁴ The same study estimates that 16-24% of wage fluctuations are caused by oil shocks. The contribution of oil price shocks to trade balance fluctuations in the model is about 40%, while more than half of the fluctuations in hours worked stems from oil prices when the Taylor rule is in place.

¹⁴The authors separate between oil price shocks and oil activity shocks. The numbers are the sum of these two. Also, they report variance decompositions 4 and 8 horizons ahead, while I report stationary variance decompositions.

Table 3: Business cycle statistics – Taylor rule versus Ramsey optimal policy

	<i>Moments</i>		<i>Variance decomposition</i>				
	σ_x	$\rho_{x,y}$	ε_m	ε_s	ε_m^F	ε_s^F	ε_o
<i>Panel A – Taylor rule</i>							
GDP	2.76	1.00	46.38	5.73	11.31	0.12	36.45
Consumption	2.14	0.52	62.03	7.10	16.64	0.38	13.86
Hours	2.34	0.10	28.36	12.84	5.56	0.13	53.10
Trade balance	0.42	-0.20	21.39	5.74	25.08	6.18	41.61
Interest rate	0.64	-0.73	69.04	4.12	25.59	0.53	0.72
CPI Inflation	0.88	-0.57	66.21	1.46	31.70	0.43	0.20
PPI inflation	1.02	-0.52	95.11	1.81	2.96	0.04	0.09
Wage inflation	0.18	-0.29	61.76	6.58	12.88	0.37	18.40
Real wages	1.76	0.81	58.50	3.71	18.71	0.41	18.66
Real exchange rate	2.65	0.11	40.76	4.66	40.75	4.71	9.11
Oil price inflation	18.03	0.16	0.00	0.00	7.04	0.26	92.70
<i>Panel B – Ramsey optimal policy</i>							
GDP	3.46	1.00	59.79	16.16	10.30	0.16	13.60
Consumption	3.25	0.73	59.26	16.05	10.85	0.29	13.55
Hours	1.29	0.22	3.40	0.22	0.38	0.02	95.98
Trade balance	0.41	-0.04	18.76	3.84	28.96	6.95	41.50
Interest rate	0.90	-0.83	64.40	28.77	4.35	0.21	2.28
CPI Inflation	0.76	-0.44	56.23	3.79	37.09	0.39	2.50
PPI inflation	0.96	-0.48	96.53	0.90	2.39	0.02	0.16
Wage inflation	0.04	0.42	6.10	15.27	2.03	0.15	76.44
Real wages	1.64	0.86	54.21	3.70	18.41	0.38	23.30
Real exchange rate	3.45	0.46	52.75	14.29	18.87	2.02	12.06
Oil price inflation	18.03	0.04	0.00	0.00	7.04	0.26	92.70

Note: σ_x is the standard deviation of variable x (in %), $\rho_{x,y}$ is the correlation with GDP. The remaining columns report the variance decomposition of each variable (in %). Business cycle statistics at the sector level are provided in [Table B.1](#) in the appendix.

Ramsey optimal policy shifts the importance of oil shocks from GDP to domestic labor markets. In fact, almost all the variation in hours is explained by these shocks under optimal policy. This is also apparent from the impulse response functions. The oil price shock not only creates a substantial jump in hours on impact, it also passes on the high persistence. The main contribution to aggregate hours comes from labor in the oil sector, which inherits much of the volatility in oil prices. Also wage inflation is substantially affected by the oil price under optimal policy. This raises the question of whether the central bank should be particularly concerned with the wage and price impulses coming from the oil sector. That question is analyzed in detail in the next section.

4 WELFARE IMPLICATIONS OF ALTERNATIVE POLICIES

Having described transmission mechanisms under optimal monetary policy, I next set out to analyze the welfare implications of alternative policy rules. To this end I follow [Schmitt-Grohé and Uribe \(2007\)](#), and rank different policy regimes based on their consumption equivalent losses relative to the Ramsey policy. Let \mathcal{W}_t^i be the expected lifetime utility associated with some policy i . Moreover, let λ^i be the increase in period consumption that the representative household would require in order to be indifferent between Ramsey equilibrium and equilibrium under policy i . Expected lifetime utility under Ramsey optimal monetary policy \mathcal{R} can then be written as

$$\mathcal{W}_t^{\mathcal{R}} = \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\log (C_s^i (1 + \lambda^i)) - \chi_N \frac{\sum_{\{M,S,O\}} L_{j,s}^i {}^{1+\varphi} V_{uj,s}^i}{1 + \varphi} \right],$$

where $\{C_s^i, L_{M,s}^i, L_{S,s}^i, L_{O,s}^i\}_{s=t}^{\infty}$ are the paths for consumption and labor under policy i . Given the assumed functional form for period utility, we can solve for λ^i to get

$$\lambda^i = \exp [(1 - \beta) (\mathcal{W}_t^{\mathcal{R}} - \mathcal{W}_t^i)] - 1,$$

where $\mathcal{W}_t^i \equiv \mathbb{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\log (C_s^i) - \chi_N \frac{\sum_{\{M,S,O\}} L_{j,s}^i {}^{1+\varphi} V_{uj,s}^i}{1 + \varphi} \right]$. It is clear from the expression for λ that $\lambda^i > 0$ if and only if $\mathcal{W}_t^{\mathcal{R}} > \mathcal{W}_t^i$.

The analysis of alternative targeting rules is done in three steps. First I study a set of strict targeting rules, where the interest rate is set to neutralize all movements in some target variable. This allows us to identify variables in the model that are promising candidates for more operative policy rules. Second I study a set of simple Taylor type rules, where the interest rate responds linearly to some target variable. I compare different degrees of responsiveness, with strict targeting as the limiting case. I also compare different sizes of the oil sector's supply chain in order to shed light on the role of oil exports for optimal policy. Third, I search for response coefficients that maximize welfare within a large set of Taylor rules. A set of six variables is analyzed. These are (quarter-to-quarter) CPI inflation $\Pi_{c,t}$, PPI inflation $\Pi_{p,t}$, wage inflation $\Pi_{w,t}$, nominal exchange rate depreciation $\Delta \mathcal{E}_t$, nominal non-oil GDP growth $\Delta GDP_{n,t}$, and the cost deflator for the oil supply chain, $\Pi_{O,t}^{def}$.

4.1 STRICT TARGETING RULES

To shed light on the partial effects of stabilizing specific economic variables, I first consider a set of strict targeting rules. Suppose the central bank sets the nominal interest rate in order to prevent any movement in some variable Z_t . A policy dedicated to hit the target $\sigma_Z^2 = 0$ is referred to as a strict targeting rule.

[Table 4](#) reports the results for different strict targeting rules in the oil exporting SOE. Panel A presents the results when the oil supply chain is in place, panel B shows the results when $\alpha_o = 0$. Consider first the top rows in the panels. An interesting starting point is the natural equilibrium, defined as the equilibrium associated with full wage and price flexibility ($\theta_{pj} = \theta_{wj} = \theta_{wo} = 0$). Monopoly power is still in place in the natural equilibrium, as I do not resort to subsidies aimed at shifting the steady state to the first

Table 4: Welfare under strict targeting rules

Z	WL (%)	λ (%)	W	σ_x				
				GDP	C	N	Π_c	Π_w
<i>Panel A – Benchmark: Oil supply chain</i>								
Nat. eq.	0.20	-0.06	-30.27	3.46	3.33	1.10	1.27	0.91
Ramsey	0.00	0.00	-30.34	3.46	3.25	1.29	0.76	0.04
Π_c	-1.78	0.55	-30.89	7.57	7.31	4.77	0.00	0.23
Π_p	-18.65	7.20	-37.29	20.94	20.99	18.23	3.38	0.62
Π_w	-0.04	0.01	-30.35	2.99	2.94	1.27	0.83	0.00
$\Delta\mathcal{E}$	-1.01	0.31	-30.65	3.12	2.37	2.95	0.92	0.23
ΔGDP_n	-0.26	0.08	-30.42	2.03	2.22	2.15	1.01	0.05
Π_O^{def}	-18.34	7.05	-37.15	17.76	18.42	15.16	2.94	0.78
<i>Panel B – Counterfactual: No oil supply chain</i>								
Nat. eq.	0.35	-0.10	-28.00	3.14	3.23	0.39	1.29	0.78
Ramsey	0.00	0.00	-28.10	3.19	3.11	0.29	0.74	0.02
Π_c	-1.86	0.53	-28.63	7.32	7.41	4.23	0.00	0.22
Π_p	-20.17	7.36	-35.20	21.04	21.41	18.05	3.37	0.61
Π_w	-0.02	0.01	-28.11	2.78	2.69	0.72	0.80	0.00
$\Delta\mathcal{E}$	-0.93	0.27	-28.36	2.29	2.30	2.14	0.92	0.20
ΔGDP_n	-0.24	0.07	-28.17	1.74	1.71	1.97	0.98	0.05
Π_O^{def}	-19.46	7.03	-34.89	18.47	18.78	15.70	2.96	0.76

Note: The first column reports the relative difference in welfare between policy i and the Ramsey policy, i.e. $WL = 100 \left(\frac{W_t^i}{W_t^R} - 1 \right)$, given that policy stabilizes the target Z . The second column shows the loss in consumption units. The third column reports the expected welfare level. The remaining columns report the standard deviation of non-oil GDP, consumption, hours, CPI inflation, and wage inflation.

best. The welfare level in natural equilibrium is about 0.2% higher than the optimal policy when the supply chain is present. This corresponds to a consumption gain of less than 0.1%. Thus, Ramsey optimal policy is able to approximate the natural equilibrium welfare fairly well in this case. However, the volatility of wages and prices are very different. Wage and price inflation volatility is low in the Ramsey equilibrium because i) wages and prices are sticky, and ii) because optimal policy stabilizes wages and prices. Apparently, natural equilibrium and the Ramsey equilibrium display similar welfare differences when I shut down the supply chain. This demonstrates that the ability of the Ramsey planner to approximate welfare in absence of wage and price stickiness, does not hinge on the oil sector. However, one should note that the welfare relevant benchmark in open economies in general differs from the natural equilibrium. The reason is that monetary authorities can

affect expected real exchange rates via their influence on the exchange rate volatility. This leads to a terms of trade externality with implications for welfare, see [De Paoli \(2009\)](#) for a detailed analysis. Thus, welfare under Ramsey optimal policy serves as a benchmark reference point when I evaluate alternative policy rules.

One important result emerges when we compare the remaining rows in the two panels: The oil supply chain has very limited effects of welfare. That is, the welfare ranking of different strict targets is not altered by the presence of the supply chain. Moreover, the absolute welfare level for a given target is not much affected either. This is true for all targets under consideration. However, there are potentially large welfare differences across different targets. Strict wage inflation targeting is ranked on top, followed by nominal GDP targeting. The performance of strict wage targeting is not surprising given the low wage inflation volatility in Ramsey equilibrium. Stabilization of nominal GDP implies very low wage inflation volatility as well. Thus, the results in [Table 4](#) provides further evidence of the gains related to wage stability. The worst targets are the PPI and the supply chain deflator. Strictly stabilizing any of these variables is disastrous from a welfare perspective. About 18% of welfare is lost, implying that households would need a 7% increase in consumption to be as well off as under the Ramsey policy. These policies also lead to enormous movements in most macroeconomic variables, e.g. GDP 6 times as volatile as in the Ramsey case. This comes about from the movements in nominal interest rates needed to stabilize the two targets. Excessive macroeconomic volatility can be problematic for agents in the economy for reasons that are not captured in the current framework. In any case, the results suggest that one should accommodate rather than trying to fight the price impulses from oil to non-oil variables.

Oil exports aside, the results presented here contrast those in [Galí and Monacelli \(2005\)](#), where strict producer price targeting is optimal. Several arguments work against PPI stability in the current model: First, sector specific shocks and rigidities create trade-offs between disaggregate prices, as in [Aoki \(2001\)](#). Second, wage stickiness creates a trade-off between wage and price stability, as in [Campolmi \(2014\)](#). Third, the ability of policy makers to influence average terms of trade takes optimal policy away from the natural equilibrium, as shown by [De Paoli \(2009\)](#). Finally, trade in intermediate goods changes the dynamics of labor market variables in a way that, coupled with wage stickiness, amplifies the importance of wage stability.

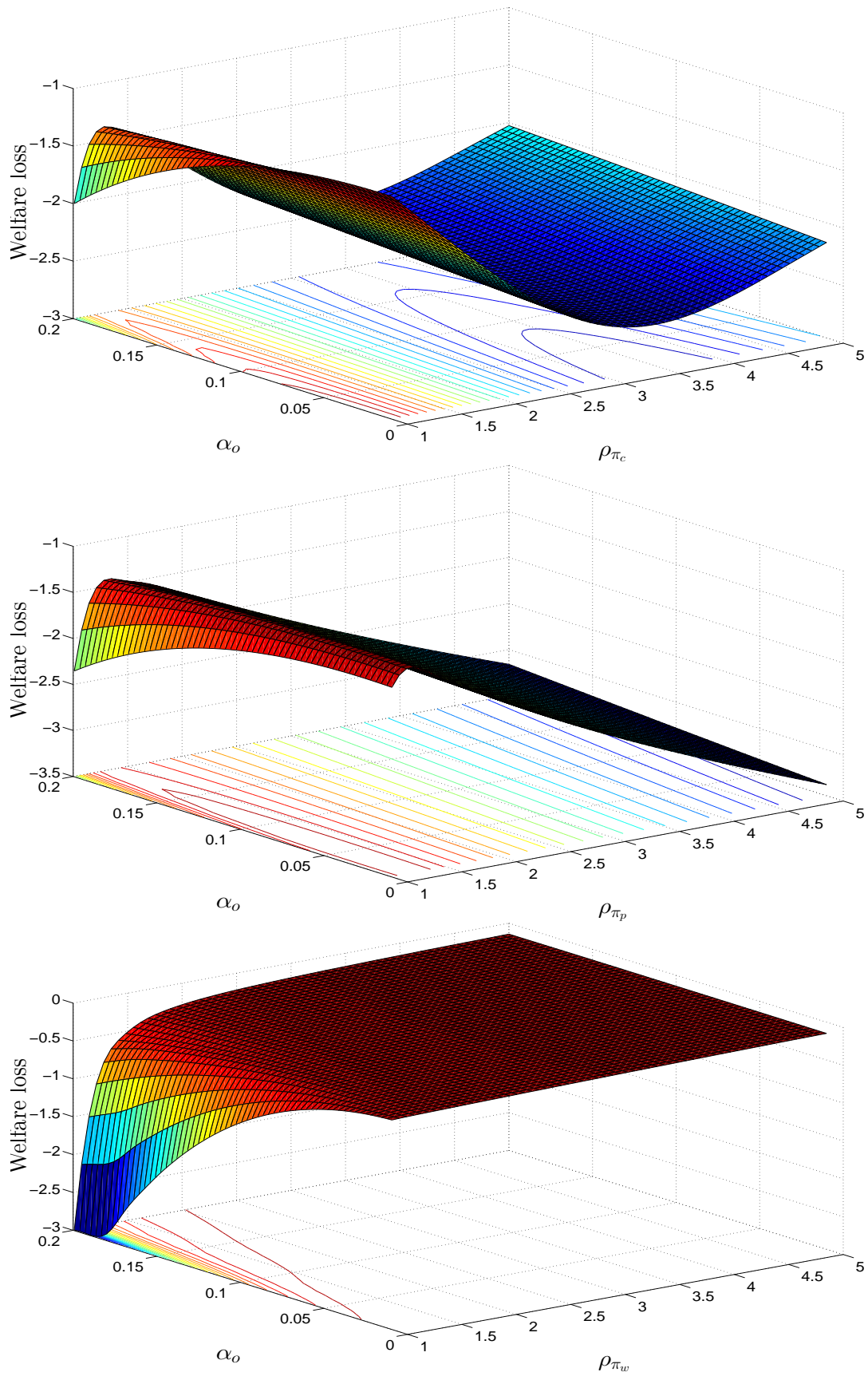
4.2 FLEXIBLE SIMPLE TAYLOR RULES

Implementing strict targeting rules requires knowledge about the true feedback system (the policy rules of private agents) that determines macroeconomic dynamics. It also requires that the central bank can infer the true state of the economy, including unobserved shadow prices as well as all the exogenous shocks. These considerations make strict targeting rules difficult to implement in practice. A common response to this concern in the literature is to analyze simple rules, typically some types of Taylor rules. Next I analyze a policy rule given by

$$\frac{R_t}{R} = \left(\frac{Z_t}{Z} \right)^{\rho_z},$$

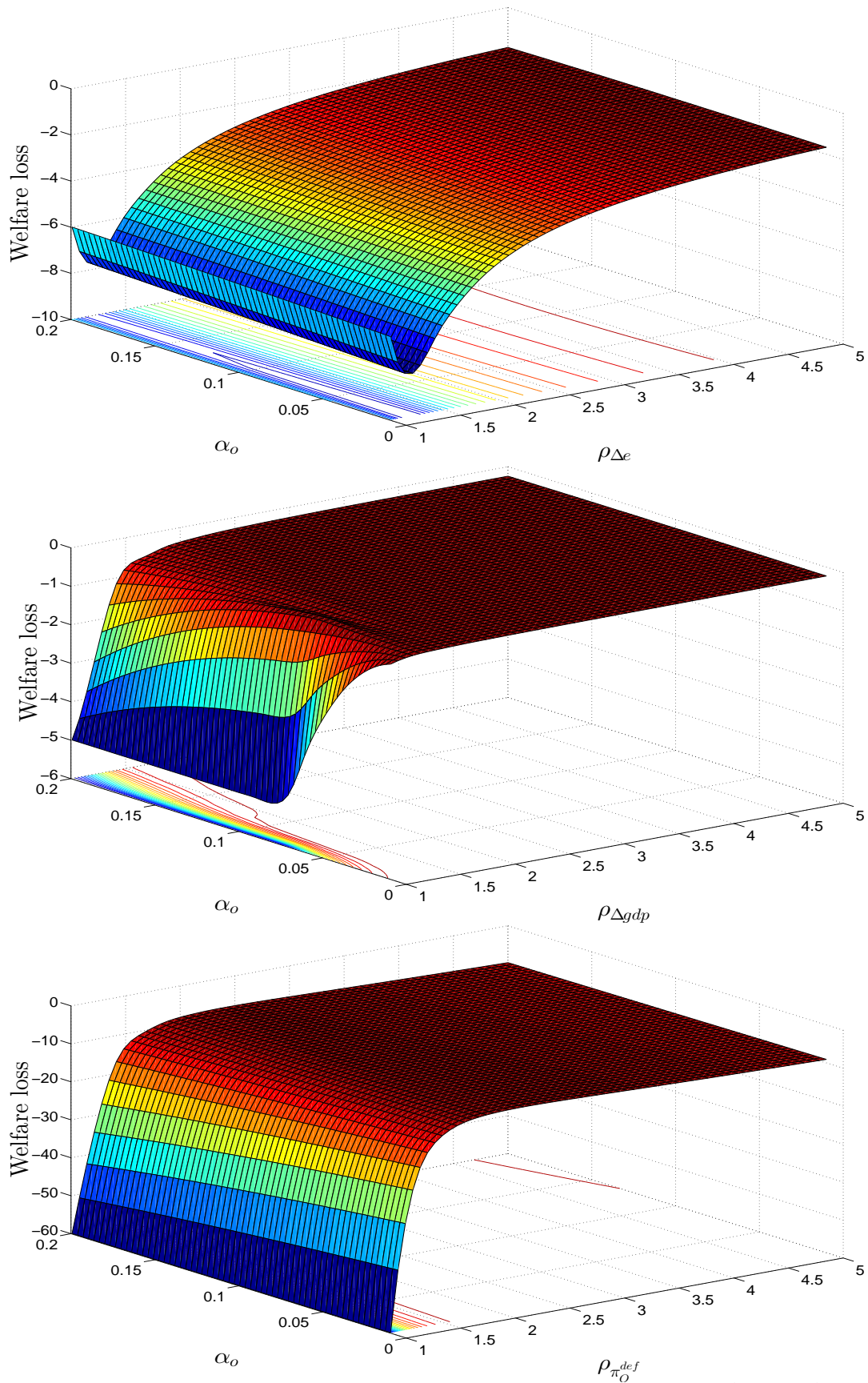
where Z is the targeting variable. This rule is simple in the sense that policy actions only requires knowledge about Z .

Figure 4: Simple Taylor rules and the role of oil supply chains 1



Note: Welfare losses in a) the (α_o, ρ_{π_c}) -space, b) the (α_o, ρ_{π_p}) -space, and c) the (α_o, ρ_{π_w}) -space.

Figure 5: Simple Taylor rules and the role of oil supply chains 2



Note: Welfare losses in a) the $(\alpha_o, \rho_{\Delta e})$ -space, b) the $(\alpha_o, \rho_{\Delta gdp})$ -space, and c) the $(\alpha_o, \rho_{\pi_o}^{def})$ -space.

Two observations are important: First, for all the target variables under consideration, determinacy requires that $\rho_z > 1$. Second, for all the variables under consideration, this rule converges to strict targeting in the limit as ρ_z goes to infinity. Thus, the simple Taylor rule allows us to shed light on how the degree of responsiveness to specific macroeconomic fluctuations affect welfare. To provide insights regarding the importance of oil for policy, I set up a grid of size 20×20 in the (α_o, ρ_z) -space, and simulate the model for each point on the grid. The bounds on the parameters are $\alpha_o = [0.01, 0.2]$ and $\rho_z = [1.01, 5]$, respectively.

Figure 4-Figure 5 plot the resulting welfare losses (in %) relative to Ramsey optimal policy, against pairs of (α_o, ρ_z) . Consider first the top panel in Figure 4, which shows results when the Taylor rule includes CPI inflation. Welfare losses are smallest when ρ_{π_c} either takes a relatively low value, or when the policy response implies something close to full CPI stability (see Table 4). However, differences in welfare between the “best” and “worst” choice of ρ_{π_c} are rather small – about 1-2%. Importantly, this conclusion seems fairly robust to the size of the supply chain. Next, consider a simple Taylor rule with producer price inflation only. The optimal response coefficient is about 1.4, regardless of spillover from the oil sector. For higher values of ρ_{π_p} welfare decreases monotonically towards the level associated with a strict target. The optimal response coefficient with $\alpha_o = 0.2$ leads to a welfare loss close to 1.4%. Thus, the large welfare loss associated with strict PPI targeting does not carry over in general. Turning to wage inflation, I find that the relationship between welfare and ρ_{π_w} is strictly positive. Moreover, the figure suggests that one can approximate Ramsey optimal policy reasonably well with a reasonable wage inflation response, because the marginal gain of a more aggressive wage inflation response quickly diminishes as ρ_{π_w} increases. The role of α_o is also fairly small for $\rho_{\pi_w} > 2$. The story is similar for the last three targets. Stronger responses are better across most of the parameter space, and the role of α_o is usually minor except in regions close to indeterminacy.¹⁵ These results add to the idea that optimal policy is not affected in any fundamental sense by the presence of an oil exporting sector.

4.3 OPTIMIZED TARGETING RULES

Finally I analyze a large set of modified Taylor rules of the form

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_r} \left[\left(\frac{Z_{1,t}}{Z_1} \right)^{\rho_{z_1}} \left(\frac{Z_{2,t}}{Z_2} \right)^{\rho_{z_2}} \right]^{1-\rho_r}.$$

For each pair of flexible targets (Z_1, Z_2) , I search for the coefficients $(\rho_r, \rho_{z_1}, \rho_{z_2})$ that minimize the welfare loss relative to Ramsey optimal policy. The resulting interest rate equation is referred to as an optimized Taylor rule. In general this rule covers as special cases both the simple Taylor rules in subsection 4.2 ($\rho_r = \rho_{z_2} = 0$) and the strict targeting rules in subsection 4.1 ($\rho_r = \rho_{z_2} = 0, \rho_{z_1} = \infty$). The search grid is an array of size $10 \times 11 \times 11$ with equally spaced nodes. The bounds are $\rho_r = [0, 0.9]$, $\rho_{z_1} = [0, 3]$, and $\rho_{z_2} = [0, 3]$. Parameter combinations implying indeterminacy are disregarded. The aim here is not to identify a “best rule” (model uncertainty aside, that would require a much finer grid and wider bounds). Instead, I attempt to shed some light on a set of simple, operational rules that can approximate optimal policy reasonably well.

¹⁵The results become prone to numerical approximation errors when $\rho_z \rightarrow 1$.

Table 5: Optimized Taylor rules

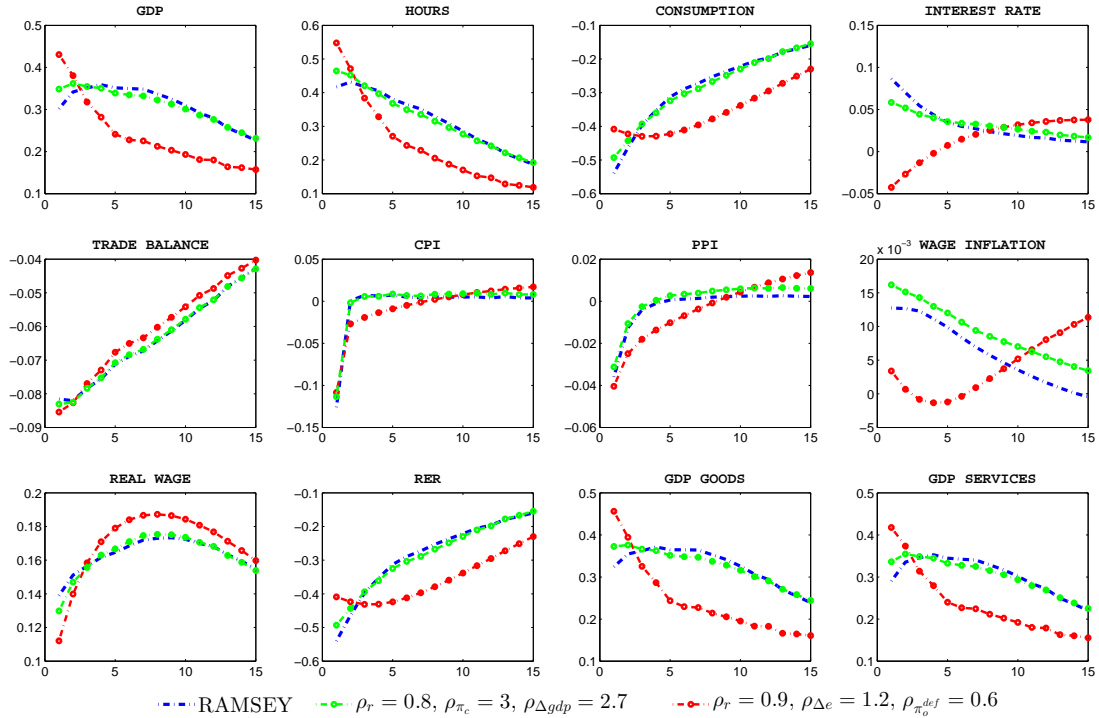
$Z_1 \setminus Z_2$	Π_c	Π_p	Π_w	$\Delta\mathcal{E}$	ΔGDP_n	Π_O^{def}
Π_c	–	$\rho_r = 0.9$ $\rho_{\pi_c} = 3$ $\rho_{\pi_p} = 2.7$	$\rho_r = 0.9$ $\rho_{\pi_c} = 3$ $\rho_{\pi_w} = 3$	$\rho_r = 0.9$ $\rho_{\pi_c} = 3$ $\rho_{\Delta e} = 0$	$\rho_r = 0.8$ $\rho_{\pi_c} = 3$ $\rho_{\Delta gdp} = 2.7$	$\rho_r = 0.9$ $\rho_{\pi_c} = 3$ $\rho_{\pi_o^{def}} = 0.3$
Π_p	–0.17	–	$\rho_r = 0.9$ $\rho_{\pi_p} = 3$ $\rho_{\pi_w} = 3$	$\rho_r = 0.9$ $\rho_{\pi_p} = 3$ $\rho_{\Delta e} = 0.3$	$\rho_r = 0.8$ $\rho_{\pi_p} = 3$ $\rho_{\Delta gdp} = 2.7$	$\rho_r = 0.9$ $\rho_{\pi_p} = 3$ $\rho_{\pi_o^{def}} = 0.3$
Π_w	–0.10	–0.09	–	$\rho_r = 0.8$ $\rho_{\pi_w} = 3$ $\rho_{\Delta e} = 0$	$\rho_r = 0$ $\rho_{\pi_w} = 3$ $\rho_{\Delta gdp} = 0.6$	$\rho_r = 0.8$ $\rho_{\pi_w} = 3$ $\rho_{\pi_o^{def}} = 0$
$\Delta\mathcal{E}$	–0.24	–0.25	–0.17	–	$\rho_r = 0.9$ $\rho_{\Delta e} = 0$ $\rho_{\Delta gdp} = 3$	$\rho_r = 0.9$ $\rho_{\Delta e} = 1.2$ $\rho_{\pi_o^{def}} = 0.6$
ΔGDP_n	–0.10	–0.09	–0.16	–0.21	–	$\rho_r = 0.9$ $\rho_{\Delta gdp} = 3$ $\rho_{\pi_o^{def}} = 0$
Π_O^{def}	–0.18	–0.21	–0.17	–0.74	–0.21	–

Note: The upper triangle of the table shows the optimized combination of policy coefficients for a given pair (Z_1, Z_2) . The lower triangle reports welfare losses (in %) relative to Ramsey optimal policy.

Results are provided in [Table 5](#). In all cases the optimum is identified in the upper bound of at least one dimension of the grid. Moreover, the upper bounds are always optimal for the coefficients ρ_{π_c} and ρ_{π_w} , while $\rho_{\pi_o^{def}}$ and $\rho_{\pi_{\Delta e}}$ usually are close to the lower bound. The optimal rule implies high interest rate persistence for or all response combinations except the one involving wages and nominal GDP growth. For all rules, we see that one is able to do reasonably well compared to the more extreme scenarios analyzed in [subsection 4.1](#) and [subsection 4.2](#). In particular, with high interest rate inertia and a large weight on either wage or CPI inflation, even a rule involving Π_O^{def} can lead to welfare losses around 0.2% compared to the Ramsey optimal policy. The smallest welfare losses in [Table 5](#) are associated with rules involving either CPI or PPI inflation on the one side, and either wage inflation or nominal GDP growth on the other. This is not surprising, as these variables also generate the smallest welfare losses with $\alpha_o = 0.2$ in [Figure 4](#) and [Figure 5](#). Also, while strict producer price targeting turned out to generate large losses in [subsection 4.1](#), the presence of interest rate inertia removes the majority of these losses. In contrast to Π_O^{def} , the optimized rule actually places a high weight on Π_{pj} . This is true for all combinations involving producer prices. Thus, one should not conclude that producer price targeting in general is inferior to other targets in the model.

[Figure 6](#) plots impulse responses following an oil price shock for two of the rules in

Figure 6: Impulse responses to oil shocks – Optimized Taylor rules



Note: Impulse responses to an innovation in ε_o (one standard deviation) under different flexible targeting rules. See Figure 1.

Table 5, in addition to Ramsey optimal responses. The first Taylor rule is the one targeting CPI inflation and nominal GDP growth. These variables are conventional targets in many central banks. This rule also does well in minimizing the welfare losses. The second rule is the one targeting the exchange rate and the price impulse from the oil sector. This rule performs worst of those considered in Table 5. The difference between the two stems from the interest rate path – the second rule generates a muted response the first periods (due to nominal the exchange rate appreciation), but then takes off for a prolonged time. In the first periods after the shock, this leads to more hours worked and a higher consumption level. The gain is lower wage inflation. However, things turn around after some periods, and it takes a long time before wage inflation settles down. The CPI-GDP target on the other hand is able to track optimal policy reasonably well, although it tends to overshoot Ramsey optimal wage inflation.

5 SENSITIVITY ANALYSIS

In this section I analyze how robust the findings are to alternative calibration choices and modeling assumptions. The results of this exercise are reported in Table 6. The first column in the table presents the welfare level associated with Ramsey optimal monetary policy. The remaining columns show the welfare losses (in %) of deviating from optimal policy. To save space, I restrict attention to a set of simple Taylor rules identical to those analyzed in subsection 4.2. The response coefficient ρ_z is set to 1.5, a number located in a fairly flat region of the parameter space for most targets (see Figure 4-Figure 5). To

Table 6: Welfare under alternative model specifications

	Ramsey	Π_c	Π_p	Π_w	$\Delta\mathcal{E}$	ΔGDP_n	Π_O^{def}
<i>Panel A – Benchmark model</i>							
	-30.34	-1.46	-1.46	-0.50	-5.60	-0.85	-12.06
<i>Panel B – Alternative specifications</i>							
$\varphi = 3$	-22.97	-2.54	-2.55	-1.06	-9.25	-1.58	-23.14
$\phi_j = 0$	-30.33	-0.87	-0.60	-0.41	-4.84	-0.78	-10.54
$\alpha_j = \alpha_j^F = 1$	-30.44	-2.40	-2.33	-0.84	-7.09	-1.36	-15.93
$\eta = 2$	-30.33	-1.21	-1.09	-0.33	-5.09	-2.08	-9.71
$\phi_o = 0$	-29.71	-1.42	-1.37	-0.49	-5.60	-0.25	-53.25
<i>Coordination</i>	-30.27	-1.75	-1.49	-0.51	-4.69	-0.89	-12.10
<i>PTM</i>	-30.34	-1.46	-1.45	-0.50	-5.59	-0.85	-12.08
<i>PTM-LCP</i>	-30.34	-1.42	-1.42	-0.51	-5.53	-0.82	-11.91

Note: The first column row reports i) the welfare level under Ramsey optimal policy in the benchmark model, and ii) welfare losses when monetary authorities follow a simple Taylor rule of the form $\frac{R_t}{R} = \left(\frac{Z_t}{Z}\right)^{\rho_z}$, where $\rho_z = 1.5$. The remaining rows show the same under different calibration and modeling assumptions.

facilitate comparison, the first row reports the welfare level of Ramsey optimal policy in the benchmark model, as well as welfare losses associated with alternative flexible targets. The numbers correspond to those in [Figure 4-Figure 5](#) for $\alpha_o = 0.2$ and $\rho_z = 1.5$.

The remaining rows show results from the robustness tests. First, I change the sensitivity of labor supply to wage changes. The value of $\varphi^{-1} = 1/3$ lies below typical estimates in the macro literature, but within the range of 0-0.5 found in microeconomic studies (see e.g. [Peterman \(2012\)](#)). The Frisch elasticity has potentially important effects on welfare in models with wage rigidity. In particular, a low value implies that an increase in the wedge between optimal and average wages contributes more to the welfare loss associated with wage dispersion in equation (39). The results show that welfare is indeed reduced more under alternative rules with this calibration. However, the ranking across policies is unchanged.¹⁶

Second, I abstract from trade between firms in the non-oil economy by setting $\phi_j = 0$. Under this scenario the model collapses to a standard multi-sector, small open economy model. While welfare associated with Ramsey optimal policy is nearly unchanged, we see that the losses from alternative rules are smaller. This is particularly true for PPI targeting, which is ranked above CPI targeting under this calibration.

Third, I report results when the open economy dimension of the model is abstracted from. That is, I assume that the only link between the SOE and the ROW is the oil sector. One can think of this as the special case with complete home bias in both economies, i.e.

¹⁶The high level of welfare under Ramsey optimal policy comes about from the non-stochastic steady state solution, which reduces the scaling parameter χ_N when φ rises.

$\alpha_j = \alpha_j^F = 1$. All policies produce larger welfare losses under this scenario, even though the non-stochastic steady state welfare level is unchanged. One reason might be that second order gains of exchange rate volatility on welfare are removed when the economy is closed, see [De Paoli \(2009\)](#) for a detailed analysis. Still, the welfare ranking of different policies is similar to the benchmark case.

Fourth, I increase the substitution elasticity between domestic and foreign goods. The literature has still not settled on a value for this parameter. Values used in DSGE models typically span from about 0.3 to 2, and microeconomic estimates lie even higher. I report results when $\eta = 2$. Welfare rankings are as before, except for relatively larger losses associated with the nominal GDP growth target.

Fifth, I shut down the direct channel between domestic non-oil firms and the oil sector. This is done by assuming that labor and land (Q) constitutes all non-oil inputs used in oil production. Compared to the benchmark case, this leads to smaller welfare losses of targeting GDP growth, and substantially larger welfare losses associated with the oil impulse deflator. The intuition for the latter result is found in labor markets. When $\phi_o = 0$, the price impulse deflator collapses to $\Pi_{O,t}^{def} = \Pi_{wO,t}$, i.e. the nominal wage inflation of oil workers. Targeting this variable leads to excessive fluctuations in hours worked, which spill over to labor markets in the non-oil economy.

Next, I investigate alternative modeling assumptions. First I change the design of foreign policy. So far, I have abstracted from the question of optimal policy in the rest of the world. How do the results change if foreign monetary authorities follow an optimal policy rule as well? To shed light on this question, I make the assumption that foreign and domestic monetary authorities engage in policy cooperation in order to maximize welfare – both in the SOE and in the ROW. This analysis follows along the lines of [Benigno and Benigno \(2006\)](#). The cooperation problem can be formalized as follows:

$$\max \mathcal{W}_t^C \quad \text{subject to} \quad \mathbb{E}_t^F (\mathcal{Y}_{t+1}, \mathcal{Y}_t, \mathcal{Y}_{t-1}, e_t) = 0,$$

where

$$\mathcal{W}_t^C \equiv \varsigma \mathcal{W}_t + (1 - \varsigma) \mathcal{W}_t^F$$

denotes the weighted sum of expected lifetime utility in the SOE and the ROW. As before, the weight ς measures the relative size of the SOE, while F is the system of (private agents’) equilibrium conditions in both economies. e_t is the vector of structural shocks. \mathcal{W}_t^F denotes the ROW equivalent to equation (39). Note that the coordination problem described above is equivalent to a problem faced by one “global” Ramsey-planner that attempts to maximize world welfare. To solve the maximization problem, I equip the cooperative planners with two instruments – the nominal interest rate at home and abroad. The solution procedure is as before.¹⁷ Results are reported in sixth row in [Table 6](#). Compared to the benchmark case, we see that Ramsey optimal welfare is higher in the SOE with international policy cooperation. Gains from cooperation are consistent with the findings by [Benigno and Benigno \(2006\)](#) in a two-country model without oil and intermediate goods. Columns 2-7 report the welfare losses associated with alternative targeting

¹⁷In the limit as $\varsigma \rightarrow 0$, the coordination problem collapses to the Ramsey problem of the ROW. But this problem totally neglects the impact of domestic interest rates on welfare in the SOE, implying an indeterminate solution. Thus, for numerical reasons, I set ς to a small, but positive number. Results for welfare in the ROW are identical if I instead maximizes \mathcal{W}_t^F only.

rules in the SOE, maintaining the assumption that policy is Ramsey-optimal in the ROW. Interestingly, most of the welfare losses are similar to those in the benchmark model, except for a slightly higher loss in the case of CPI targeting. Thus, the analysis seems to be robust to the choice of Ramsey-optimality in the ROW.

Finally, I change the assumptions regarding the pricing behavior of firms. In the benchmark model, it is assumed that non-oil firms charge the same price in all markets, including export markets and the oil supply chain. The latter assumption is relaxed next, where I allow domestic firms to price discriminate between non-oil buyers and the oil sector firm. This is referred to in the literature as pricing to market (PTM) behavior. Pricing to the oil market is obtained by substituting equations (29) and (35) with the following:

$$\begin{aligned} Z_{j,t}M_{j,t}^{\phi_j}N_{j,t}^{1-\phi_j} - \Phi_j &= (X_{Hj,t} + X_{Hj,t}^F)V_{pj,t} + M_{jO,t}V_{pj,t}^o \\ GDP_{j,t} &= P_{rHj,t}(X_{Hj,t} + X_{Hj,t}^F) + P_{rHj,t}^oM_{jO,t} - P_{rj,t}^mM_{j,t} \end{aligned}$$

In addition, we get price inflation and corresponding price dispersion terms that are specific to the inputs purchased by the oil sector. Optimal new prices specific to $M_{jO,t}$ are found from a system similar to (14)-(16), while $P_{rHj,t}^o$ is determined as in equation (17). The spread between $P_{rHj,t}$ and $P_{rHj,t}^o$ is in general determined by differences in non-oil demand and demand from the oil sector. Results with PTM in the oil sector are shown in Table 6. We see that the welfare results are almost identical to those obtained in the benchmark model without PTM.

The last robustness test is to also model PTM of export goods. In particular, I allow domestic firms to price discriminate between domestic and foreign buyers. I also make the assumption that exports from the SOE are priced in the currency of buyers, so-called local currency pricing (LCP). LCP can be motivated by the observation that most export goods in small open economies are priced in foreign currency (Gopinath, Itskhoki, and Rigobon, 2010). I refer to the combination of active export price discrimination and local currency pricing as PTM-LCP. Under PTM-LCP, the export prices deviate from local producer prices because of i) asymmetric market conditions between the SOE and the ROW, and ii) exchange rate movements which produce a spread between the two. PTM-LCP implies that we have to substitute equations (29) and (35) with the following:

$$\begin{aligned} Z_{j,t}M_{j,t}^{\phi_j}N_{j,t}^{1-\phi_j} - \Phi_j &= X_{Hj,t}V_{pj,t} + X_{Hj,t}^FV_{Hpj,t}^F + M_{jO,t}V_{pj,t}^o \\ GDP_{j,t} &= P_{rHj,t}X_{Hj,t} + P_{rHj,t}^FX_{Hj,t}^F + P_{rHj,t}^oM_{jO,t} - P_{rj,t}^mM_{j,t} \end{aligned}$$

As before we get price inflation and corresponding price dispersion terms that are specific to the export markets. Results with PTM-LCP are shown in the last row in Table 6. Again, we see that the implications are minor compared with the benchmark model. There are some small gains associated with all alternative rules except wage targeting, but they are negligible compared with the welfare differences across different targets. In total, I do not find that assumptions regarding the pricing behavior of firms matter for the results.

6 CONCLUSIONS

This paper studies optimal monetary policy in a small open economy with oil exports. I identify the way in which a social planner sets the interest rate to maximize welfare,

and ask how the presence of an oil sector affects optimal policy. Several results are provided: First, because of wage stickiness in labor markets, Ramsey optimal policy assigns a high weight to nominal wage stability. Such stability is accomplished by an aggressive increase (decrease) in nominal interest rates when the marginal rate of substitution lies above (below) the real wage. Second, the properties of optimal policy are not turned around because of spillover from the oil sector (except from parts of the parameter space close to the indeterminacy region). The supply chain represents a new source of macroeconomic fluctuations in the economy, but it does not change the importance of wage stability. Third, policies aimed at stabilizing price and wage impulses from the oil sector can be disastrous. This conclusion is backed up by two simple observations: If one succeeds in stabilizing oil sector wages, or the price on intermediate oil inputs, then this comes at the cost of shutting down the automatic stabilization mechanisms embedded in these variables. When demand for inputs in the oil sector goes up, prices and wages should increase in order to prevent excessive tightening of resource constraints in the non-oil economy. Otherwise, one can get enormous movements in non-oil wages and prices – movements that are unwarranted from a welfare perspective. The second observation that speaks against such a policy, is the fact that nominal interest rates would have to undertake drastic swings in order to achieve stability of the target variable.

Although the model presented here provides a step forward for our understanding of macroeconomic dynamics in oil exporting economies, it comes with important limitations. One is the observation that oil production is relatively intensive in capital. To the extent that investment goods used to accumulate capital are produced in the non-oil economy, this will certainly add to the impulses through the supply chain. Also, I have restricted the study to the spillover from oil to domestic factor markets. Oil revenues, the flip-side of oil sector activity, are abstracted from. How does this affect the results? In most oil exporting economies, the oil revenues accrue to the government. Suppose these are spent on an as-you-go basis. If an increase in revenues leads to an increase in public spending, then I expect that impulse responses in [Figure 1](#) are amplified. That is, higher non-oil demand (due to public spending) would further increase domestic prices and real interest rates, causing stronger pressure on labor as well as additional exchange rate appreciation. On the contrary, non-oil responses might be smaller if fiscal spending is countercyclical. A related concern to public spending is the way in which the tax system is formed. I leave the question of optimal fiscal policy for future research, although [Hevia and Nicolini \(2013\)](#) provide insights along these lines. Finally, I have abstracted from concerns regarding the zero lower bound. Indeed, many of the policies under consideration in this paper generates large movements in the nominal interest rate, implying that the zero lower bound might bind quite often. However, dealing with this issue requires a considerably more complex framework, involving non-linear, global approximation algorithms (see e.g. [Adam and Billi \(2006\)](#) and [Nakov \(2008\)](#)). Thus, I see this as a preliminary, but productive step towards understanding monetary policy trade-offs in oil exporting economies.

APPENDIX

A THE NON-STOCHASTIC STEADY STATE

In this appendix, I derive an analytical solution for the non-stochastic steady state system of the SOE. I restrict attention to an equilibrium with relative prices equal to unity, i.e. $P_{Hrj} = P_{Frj} = P_{rj}^F = P_{ro} = \mathcal{S} = 1$. I also restrict attention the benchmark model without PTM or PTM-LCP (see [section 5](#)). The solution for these alternative models is found following a similar procedure as the one below. A few remarks about the steady state: First, I cannot follow common practice and normalize steady state TFP to unity, because one degree of freedom has already been used by normalizing the measure of firms in each sector to unity. Thus, Z_j will be part of the steady state solution. Second, to control the size of the oil sector relative to aggregate GDP, I introduce a free parameter γ_o . This implies that I have to solve for steady state TFP in the oil sector as well. Third, to control import and export shares in each non-oil sector, I introduce the free parameters γ_j^{im} and γ_j^{ex} . This means I have to solve for α_j and α_j^F . Finally, I restrict steady state wages and hours per worker to be the same across sectors. This removes the incentive to change sectoral working occupation (implying no-arbitrage in the labor markets), but implies that I have to solve for the fractions of employed workers in each sector, μ_j and μ_o .

A.1 THE REST OF THE WORLD (CLOSED ECONOMY)

The ROW has a steady state solution similar to the SOE, except that the exports, imports and oil production is negligible. The steady state for the ROW can be found using the same recursive procedure as showed below for the SOE.

A.2 THE SMALL OPEN ECONOMY

Here I solve for the non-stochastic steady state in the SOE, taking as input the i) vector of structural parameters ii) the steady state CPI inflation rate Π_c , and iii) the steady state solution for the ROW. The nominal interest rate is found from (3):

$$R = \frac{\Pi_c}{\beta} \quad (\text{A.1})$$

Marginal utility of aggregate consumption is found from (4):

$$\Lambda = \Lambda^F \quad (\text{A.2})$$

Aggregate consumption is found from (2):

$$C = \Lambda^{-1} \quad (\text{A.3})$$

Consumption in sector j from (1):

$$C_M = \xi C, \quad C_S = (1 - \xi) C \quad (\text{A.4})$$

Next, I set out to derive sector level output. A few observations are needed: First, the definition of GDP in sector j implies that GDP and gross output are linked by the identity $GDP_j = Y_j^d - M_j = (1 - \phi_j) Y_j^d$, implying that aggregate non-oil GDP is $GDP = \sum_{j=M,S} (1 - \phi_j) Y_j^d$. Oil GDP on the other hand can be written $GDP_O = (1 - \alpha_o \phi_o) Y_O$. Second, total absorption of sector j -goods, including demand from the oil sector, is

$$Y_{Hj}^d + Y_{Fj}^d = C_j + X_{jM} + X_{jS} + X_{jO}.$$

Using the expression for GDP_j , we can write the left hand side as

$$\begin{aligned} Y_{Hj}^d + Y_{Fj}^d &= Y_j^d - Y_{Hj}^{dF} + Y_{Fj}^d \\ &= Y_j^d - \gamma_j^{ex} (1 - \phi_j) Y_j^d + \gamma_j^{im} (1 - \phi_j) Y_j^d, \end{aligned}$$

where γ_j^{ex} and γ_j^{im} are the export and import shares of GDP in sector j . The right hand side of the expression above can be written (see below)

$$\begin{aligned} C_j + X_{jM} + X_{jS} + X_{jO} &= C_j + \zeta_{jM} \phi_M Y_M^d + \zeta_{jS} \phi_S Y_S^d + \zeta_{jO} \phi_o \alpha_o Y_O \\ &= C_j + \sum_{l=M,S} \left[\zeta_{jl} \phi_l + \frac{\zeta_{jO} \phi_o \alpha_o \gamma_o}{(1 - \phi_o \alpha_o) (1 - \gamma_o)} (1 - \phi_l) \right] Y_l^d, \end{aligned}$$

where γ_o is oil share in total GDP in the economy. Thus, by combining the left hand side and the right hand side, we can express the production network in the SOE in compact form:

$$\Psi'_{NX} \mathbf{Y} = \mathbf{C} + \Psi \mathbf{Y}$$

The output vector is denoted by $\mathbf{Y} = [Y_M^d, Y_S^d]'$, and the consumption vector by $\mathbf{C} = [C_M, C_S]'$. The j 'th element in Ψ_{NX} is

$$\Psi_{NX}(j) = 1 - (\gamma_j^{ex} - \gamma_j^{im}) (1 - \phi_j),$$

while the (j, l) 'th element of the matrix Ψ is equal to

$$\Psi(j, l) = \zeta_{jl} \phi_l + \frac{\zeta_{jO} \phi_o \alpha_o \gamma_o}{(1 - \phi_o \alpha_o) (1 - \gamma_o)} (1 - \phi_l).$$

The solution for Y_j^d follows:

$$\mathbf{Y} = \tilde{\Psi} \mathbf{C} \tag{A.5}$$

$\tilde{\Psi} = [\mathbf{1} \times \Psi'_{NX} - \Psi]^{-1}$ is referred to as the steady state influence matrix. Next, optimal new price in sector j is found from (17):

$$\bar{P}_{rHj} = \left(\frac{1 - \theta_{pj}}{1 - \theta_{pj} \Pi_c^{\frac{1}{\epsilon_p}}} \right)^{\epsilon_p} \tag{A.6}$$

Real marginal costs in sector j is found from (14):

$$RMC_j = \frac{1 - \beta \theta_{pj} \Pi_c^{\frac{1+\epsilon_p}{\epsilon_p}}}{1 - \beta \theta_{pj} \Pi_c^{\frac{1}{\epsilon_p}}} \frac{\bar{P}_{rHj}}{1 + \epsilon_p} \tag{A.7}$$

Note that equation (A.7) collapses to $RMC_j = \frac{1}{1+\epsilon_p}$ in the special case with $\Pi_c = 1$. The variables G_j and H_j that determine optimal new prices in sector j are found from (15) and (16):

$$G_j = \frac{\Lambda Y_j^d RMC_j}{1 - \beta \theta_{pj} \Pi_c^{\frac{1+\epsilon_p}{\epsilon_p}}} \quad (\text{A.8})$$

$$H_j = \frac{\Lambda Y_j^d \bar{P}_{rHj}}{1 - \beta \theta_{pj} \Pi_c^{\frac{1}{\epsilon_p}}} \quad (\text{A.9})$$

Price dispersion in sector j is found from (30):

$$V_{pj} = \frac{1 - \theta_{pj}}{1 - \theta_{pj} \Pi_c^{\frac{1+\epsilon_p}{\epsilon_p}}} \bar{P}_{rHj}^{-\frac{1+\epsilon_p}{\epsilon_p}} \quad (\text{A.10})$$

Gross output in sector j is found from (29):

$$Y_j = Y_j^d V_{pj} \quad (\text{A.11})$$

Next I solve for the fixed production cost Φ_j . The optimality conditions for firm j with respect to factors of production are as follows:

$$\begin{aligned} RMC_j \phi_j (Y_j(f) + \Phi_j) &= P_{rj}^x X_j(f) \\ RMC_j (1 - \phi_j) (Y_j(f) + \Phi_j) &= \Omega N_j(f) \end{aligned}$$

Thus, we can write the individual firm's profit as

$$\begin{aligned} \mathcal{D}_j(f) &= P_{rHj}(f) Y_j(f) - P_{rj}^x X_j(f) - \Omega N_j(f) \\ &= P_{rHj}(f) Y_j(f) - RMC_j (Y_j(f) + \Phi_j). \end{aligned}$$

Taking the sum over all firms and imposing zero profit in the aggregate, we get

$$\int_0^1 [P_{rHj}(f) Y_j(f) - RMC_j (Y_j(f) + \Phi_j)] df = Y_j^d - RMC_j (Y_j^d V_{pj} + \Phi_j) = 0,$$

where $\int_0^1 P_{rHj}(f) Y_j(f) df = P_{rHj} Y_j^d$ and $Y_j \equiv \int_0^1 Y_j(f) df = Y_j^d V_{pj}$. Solving the expression above for Φ_j :

$$\Phi_j = \left(\frac{1}{RMC_j} - V_{pj} \right) Y_j^d \quad (\text{A.12})$$

The real wage is found from aggregate labor market income $\Omega (N_M + N_S + N_O)$ and the sector specific optimality conditions with respect to labor demand (see below):

$$\Omega = \frac{\left(1 + \frac{\alpha_o \gamma_o (1 - \phi_o)}{1 - \alpha_o \phi_o} \right) \sum_{j=M,S} (1 - \phi_j) Y_j^d}{L} \quad (\text{A.13})$$

TFP in sector j is found from (13):

$$Z_j = \frac{1}{RMC_j} \left(\frac{1}{\phi_j} \right)^{\phi_j} \left(\frac{\Omega}{1 - \phi_j} \right)^{1 - \phi_j} \quad (\text{A.14})$$

Material and labor demand in sector j is found from (12):

$$X_j = \phi_j Y_j^d \quad (\text{A.15})$$

$$N_j = (1 - \phi_j) \frac{Y_j^d}{\Omega} \quad (\text{A.16})$$

Material input delivered to sector j from sector l is found from (11):

$$X_{Mj} = \zeta_j X_j, \quad X_{Sj} = (1 - \zeta_j) X_j \quad (\text{A.17})$$

Labor force share in sector j is found from (5):

$$\mu_j = \frac{N_j}{L} \quad (\text{A.18})$$

Imports in sector j :

$$Y_{Fj}^d = \gamma_j^{im} (1 - \phi_j) Y_j^d \quad (\text{A.19})$$

Exports in sector j :

$$Y_{Hj}^{dF} = \gamma_j^{ex} (1 - \phi_j) Y_j^d \quad (\text{A.20})$$

Domestically produced local goods in sector j :

$$Y_{Hj}^d = Y_j^d - Y_{Hj}^{dF} \quad (\text{A.21})$$

Home bias in sector j :

$$\alpha_j = \frac{Y_{Hj}^d}{Y_{Hj}^d + Y_{Fj}^d} \quad (\text{A.22})$$

Home bias in the ROW's sector j , where Y_j^{dF} is sectoral demand in the ROW:

$$\alpha_j^F = 1 - \frac{Y_{Hj}^{dF}}{Y_j^{dF}} \quad (\text{A.23})$$

The normalizing constant in the utility function is found from (8):

$$\chi^N = \frac{\Omega}{CL^\varphi (1 + \epsilon_w)} \quad (\text{A.24})$$

Constant real wage in all sectors requires that $\Pi_w = \Pi_c$. Optimal new real wage in sector j is found from (9):

$$\bar{\Omega}_j = \left(\frac{1 - \theta_{wj}}{\Omega^{-\frac{1}{\epsilon_w}} - \theta_{wj} \left(\frac{\Omega}{\Pi_c} \right)^{-\frac{1}{\epsilon_w}}} \right)^{\epsilon_w} \quad (\text{A.25})$$

The variables D_j and E_j that determine optimal new wages in sector j are found from (7) and (8):

$$D_j = \frac{\bar{\Omega}_j^{-\frac{1}{\epsilon_w}} \Lambda \Omega^{\frac{1+\epsilon_w}{\epsilon_w}} L}{(1 + \epsilon_w) \left(1 - \beta \theta_{wj} \Pi_c^{\frac{1}{\epsilon_w}}\right)} \quad (\text{A.26})$$

$$E_j = \chi_N \frac{L^{1+\varphi}}{\left(\frac{\bar{\Omega}_j}{\Omega}\right)^{\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)} \left(1 - \beta \theta_{wj} \Pi_c^{\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)}\right)} \quad (\text{A.27})$$

Wage dispersion in sector j is found from (26):

$$V_{wj} = \mu_j \frac{(1 - \theta_{wj}) \left(\frac{\bar{\Omega}_j}{\Omega}\right)^{-\frac{1+\epsilon_w}{\epsilon_w}}}{1 - \theta_{wj} \Pi_c^{\frac{1+\epsilon_w}{\epsilon_w}}} \quad (\text{A.28})$$

Finally, we arrive at the oil sector. Gross oil output is found from (22):

$$Y_O = \frac{\gamma_o}{(1 - \gamma_o)(1 - \alpha_o \phi_o)} \sum_{j=M,S} (1 - \phi_j) Y_j^d \quad (\text{A.29})$$

Land (with R_O^q normalized to unity):

$$Q_O = (1 - \alpha_o) Y_O \quad (\text{A.30})$$

The remaining oil sector variables are found in the same way as corresponding non-oil variables. Finally, the variables relevant for welfare are summarized as follows:

$$V_{uj} = \mu_j \frac{(1 - \theta_{wj}) \left(\frac{\bar{\Omega}_j}{\Omega}\right)^{-\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)}}{1 - \theta_{wj} \Pi_c^{\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)}} \quad (\text{A.31})$$

$$V_{uO} = \mu_O \frac{(1 - \theta_{wO}) \left(\frac{\bar{\Omega}_O}{\Omega}\right)^{-\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)}}{1 - \theta_{wO} \Pi_c^{\frac{1+\epsilon_w}{\epsilon_w}(1+\varphi)}} \quad (\text{A.32})$$

$$\mathcal{W} = \frac{1}{1 - \beta} \left[\ln(C) - \chi_N \frac{L^{1+\varphi} (V_{uM} + V_{uS} + V_{uO})}{1 + \varphi} \right] \quad (\text{A.33})$$

Note that the sum of dispersion terms in the welfare function collapses to $\mu_M + \mu_S + \mu_O = 1$ if $\Pi_c = 1$. This completes the description of the non-stochastic steady state.

B ADDITIONAL TABLES

Table B.1: Business cycle statistics – Sector level

	<i>Moments</i>		<i>Variance decomposition</i>				
	σ_x	$\rho_{x,y}$	ε_m	ε_s	ε_m^F	ε_s^F	ε_o
<i>Panel A – Manufacturing sector under Taylor rule</i>							
GDP	3.38	0.96	66.32	1.34	5.17	0.05	27.13
Consumption	4.21	0.63	77.39	0.51	19.44	0.18	2.48
Hours	2.82	-0.39	81.65	0.34	6.81	0.19	11.00
Trade balance	0.96	-0.21	23.79	3.80	27.46	4.22	40.73
Inflation	2.38	-0.51	71.97	0.10	27.72	0.14	0.07
Wage inflation	0.18	-0.48	76.01	5.23	13.64	0.40	4.73
Real wages	1.53	0.75	65.74	7.10	23.54	0.50	3.11
Terms of trade	7.44	-0.22	49.10	0.24	49.08	0.24	1.33
<i>Panel B – Manufacturing sector under Ramsey policy</i>							
GDP	4.07	0.97	77.15	7.04	4.98	0.05	10.78
Consumption	5.08	0.80	75.46	3.27	17.38	0.17	3.72
Hours	1.98	-0.45	74.05	14.51	2.79	0.06	8.59
Trade balance	0.93	-0.03	22.04	2.69	29.92	4.59	40.76
Inflation	2.18	-0.42	66.13	2.55	30.22	0.11	0.99
Wage inflation	0.04	-0.23	36.71	56.16	0.73	0.00	6.40
Real wages	1.38	0.85	62.31	7.05	24.45	0.48	5.71
Terms of trade	7.99	-0.39	58.77	2.11	36.46	0.15	2.51
<i>Panel C – Service sector under Taylor rule</i>							
GDP	2.56	0.98	33.60	10.49	15.88	0.20	39.82
Consumption	1.58	0.19	31.25	21.13	16.80	0.47	30.36
Hours	1.90	0.10	19.81	44.77	8.12	0.25	27.05
Trade balance	0.16	-0.19	15.12	13.00	18.48	13.28	40.13
Inflation	0.26	-0.47	40.39	39.79	15.56	2.67	1.59
Wage inflation	0.16	-0.36	67.98	9.93	15.10	0.49	6.51
Real wages	1.65	0.73	71.34	3.33	21.37	0.45	3.51
Terms of trade	2.01	0.11	21.47	16.65	21.86	16.78	23.24
<i>Panel D – Service sector under Ramsey policy</i>							
GDP	3.25	0.99	48.26	22.82	13.97	0.25	14.70
Consumption	2.58	0.57	34.58	34.75	4.27	0.37	26.03
Hours	0.94	0.43	31.65	26.00	1.55	0.02	40.79
Trade balance	0.15	-0.07	9.20	8.25	27.08	16.21	39.26
Inflation	0.20	-0.16	37.43	34.43	13.59	2.85	11.70
Wage inflation	0.03	0.61	78.27	2.08	5.06	0.17	14.43
Real wages	1.52	0.83	68.98	3.59	21.62	0.43	5.38
Terms of trade	3.11	-0.40	24.88	29.78	18.05	5.25	22.04

Note: σ_x is the standard deviation of variable x (in %), $\rho_{x,y}$ is the correlation with GDP. The remaining columns report the variance decomposition of each variable (in %).

REFERENCES

- Adam, K. and R. M. Billi (2006). Optimal Monetary Policy under Commitment with a Zero Bound on Nominal Interest Rates. *Journal of Money, Credit and Banking* 38(7), 1877–1905.
- Aoki, K. (2001). Optimal monetary policy responses to relative-price changes. *Journal of Monetary Economics, Elsevier* 48(1), 55–80.
- Atalay, E. (2013). How important are sectoral shocks? Manuscript.
- Benigno, G. and P. Benigno (2006). Designing targeting rules for international monetary policy cooperation. *Journal of Monetary Economics* 53(3), 473–506.
- Benkhodja, M. T. (2014). Monetary policy and the dutch disease effect in an oil exporting economy. *International Economics* 138(0), 78 – 102.
- Bergholt, D. (2014). Foreign Shocks in an Estimated Multi-Sector Model.
- Bergholt, D. and T. Sveen (2014). Sectoral Interdependence and Business Cycle Synchronization in Small Open Economies. *Norges Bank Working Paper Series* 2014(04).
- Bjørnland, H. C. and L. A. Thorsrud (2013). Boom or gloom? Examining the Dutch disease in a two-speed economy. Working Papers 0015, Centre for Applied Macro- and Petroleum economics (CAMP), BI Norwegian Business School.
- Bodenstein, M. and L. Guerrieri (2012). Oil efficiency, demand, and prices: a tale of ups and downs. 2012 Meeting Papers 25, Society for Economic Dynamics.
- Bouakez, H., E. Cardia, and F. J. Ruge-Murcia (2009). The transmission of monetary policy in a multisector economy. *International Economic Review* 50(4), 1243–1266.
- Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics* 12(3), 383–398.
- Campolmi, A. (2014). Which inflation to target? A small open economy with sticky wages. *Macroeconomic Dynamics* 18(01), 145–174.
- Catão, L. and R. Chang (2013). Monetary Rules for Commodity Traders. *IMF Economic Review* 61(1), 52–91.
- Charnavoki, V. and J. J. Dolado (2014). The Effects of Global Shocks on Small Commodity-Exporting Economies: Lessons from Canada. *American Economic Journal: Macroeconomics* 6(2), 207–37.
- Corsetti, G., L. Dedola, and S. Leduc (2008). International risk sharing and the transmission of productivity shocks. *The Review of Economic Studies* 75(2), 443–473.
- De Paoli, B. (2009). Monetary policy and welfare in a small open economy. *Journal of International Economics* 77(1), 11–22.
- Erceg, C. J., D. W. Henderson, and A. T. Levin (2000). Optimal monetary policy with staggered wage and price contracts. *Journal of Monetary Economics* 46(2), 281–313.
- Frankel, J. A. (2003). A Proposed Monetary Regime for Small Commodity Exporters: Peg the Export Price ('PEP'). *International Finance* 6(1), 61–88.

- Frankel, J. A. (2011). A Comparison Of Product Price Targeting And Other Monetary Anchor Options, For Commodity Exporters In Latin America. *Journal of LACEA Economia*.
- Galí, J. and T. Monacelli (2005). Monetary policy and exchange rate volatility in a small open economy. *Review of Economic Studies* 72(3), 707–734.
- Gopinath, G., O. Itskhoki, and R. Rigobon (2010). Currency choice and exchange rate pass-through. *American Economic Review* 100(1), 304–36.
- Hamilton, J. D. (2009). Understanding Crude Oil Prices. *The Energy Journal* 0(Number 2), 179–206.
- Hevia, C. and J. P. Nicolini (2013). Optimal devaluations. *IMF Economic Review* 61(1), 22–51.
- Kim, J., S. Kim, E. Schaumburg, and C. A. Sims (2008). Calculating and using second-order accurate solutions of discrete time dynamic equilibrium models. *Journal of Economic Dynamics and Control* 32(11), 3397 – 3414.
- Leeper, E. M. (1991). Equilibria under active and passive monetary and fiscal policies. *Journal of Monetary Economics* 27(1), 129 – 147.
- Molnarova, Z. and M. Reiter (2014). Its Not All Exogenous: Propagation of Productivity Through the Input-Output Network.
- Nakamura, E. and J. Steinsson (2008). Five facts about prices: A re-evaluation of menu cost models. *The Quarterly Journal of Economics* 123(4), 1415–1464.
- Nakov, A. (2008). Optimal and Simple Monetary Policy Rules with Zero Floor on the Nominal Interest Rate. *International Journal of Central Banking* 4(2), 73–127.
- Peterman, W. B. (2012). Reconciling micro and macro estimates of the Frisch labor supply elasticity. Finance and Economics Discussion Series 2012-75, Board of Governors of the Federal Reserve System (U.S.).
- Petrella, I. and E. Santoro (2011). Input-output interactions and optimal monetary policy. *Journal of Economic Dynamics and Control* 35(11), 1817–1830.
- Pieschacon, A. (2012). The value of fiscal discipline for oil-exporting countries. *Journal of Monetary Economics* 59(3), 250 – 268.
- Schmitt-Grohé, S. and M. Uribe (2004). Solving dynamic general equilibrium models using a second-order approximation to the policy function. *Journal of Economic Dynamics and Control* 28(4), 755–775.
- Schmitt-Grohé, S. and M. Uribe (2007). Optimal simple and implementable monetary and fiscal rules. *Journal of Monetary Economics* 54(6), 1702–1725.
- Yun, T. (1996). Nominal price rigidity, money supply endogeneity, and business cycles. *Journal of Monetary Economics* 37(2-3), 345–370.

Centre for Applied Macro - and Petroleum economics (CAMP)
will bring together economists working on applied macroeconomic issues, with special emphasis on petroleum economics.

BI Norwegian Business School
Centre for Applied Macro - Petroleum economics (CAMP)
N-0442 Oslo

<http://www.bi.no/camp>