Taming Volatility: Evaluating NGDP Targeting

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Abstract

I embed a nominal GDP level target in a Taylor-type rule and compare the volatilities of output, inflation, and the nominal rate to a standard, inflation-targeting Taylor rule. I demonstrate analytically that the source of the shock matters for relative variances. NGDP level targeting delivers more stable output and more volatile inflation under productivity shocks, but it generates more stable output and inflation under supply and demand shocks. These results are generally confirmed in an estimated quantitative model. Last, I impose a zero lower bound (ZLB) and simulate the model under both targets. NGDP level targeting hits the ZLB less often than inflation targeting at the cost of longer sessions at the ZLB. Switching to an NGDP level target while at the ZLB leads to quicker economic recovery through the Fed's use of forward guidance.

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1 Introduction

The Federal Reserve Act of 1913 established a dual mandate of full employment and price stability for the Federal Reserve. The Federal Open Market Committee (FOMC) regards an inflation target of “2 percent over the longer run” as satisfying price stability and, in turn, contributing to full employment (Board of Governors, 2021). During the Great Recession and COVID-19 recession, economists and popular media analysts asserted that inflation targeting was failing to accomplish the dual mandate. In a 2011 op-ed in the New York Times, for example, Christina Romer wrote that “Today, inflation is still low, but unemployment is stuck at a painfully high level.” As an alternative policy rule, Romer proposed nominal GDP (NGDP) as a target, “Because it directly reflects the Fed’s two central concerns — price stability and real economic performance.” Romer is not alone in her assertion. Economists Paul Krugman (2011) and Scott Sumner (2012) both argue for NGDP targets. Fed Chairs Ben Bernanke (Yglesias, 2015) and Jerome Powell (2022) have both considered NGDP targeting as a beneficial policy change.

This paper evaluates how well NGDP level targeting satisfies the Fed’s dual mandate compared to its current inflation target. I first analytically study an NGDP level target embedded in a Taylor-type rule in the canonical three-equation New Keynesian model in Gali (2015). I then construct a quantitative DSGE model in the vein of Smets & Wouters (2007) and Christiano et al. (2005).

In the three-equation model, I derive policy functions for output, inflation, and the nominal rate under three shocks: productivity, supply (cost-push), and demand shocks. Under a productivity shock, NGDP level targeting delivers more stable output and more volatile inflation than an inflation target; the nominal rate moves less. Under a supply or demand shock, both output and inflation are more stable. Under a supply shock, the nominal rate is less volatile than under inflation targeting, while under a demand shock, the nominal rate is more volatile.

I then estimate a standard medium-scale New Keynesian model to ground the parameters in data. The analysis from the three-equation model generally holds. Output is more stable under NGDP level targeting in response to productivity and demand shocks. The inclusion of habit in the model causes output to be more volatile under NGDP targeting in response to cost-push shocks. Inflation is more volatile under the productivity shock but more stable under cost-push and demand shocks. The nominal rate's response is more muted under the first two shocks but more pronounced under the demand shock. Conducting a long-run simulation with all the shocks in the model demonstrates that NGDP level targeting leads to more stable output, inflation, and nominal rates.

Last, I analyze performance at the zero lower bound (ZLB), since the ZLB inspired much of the writing on NGDP targeting (see Beckworth, 2019, for example). I simulate the model with an occasionally binding constraint, preventing the nominal rate from going negative. NGDP level targeting hits the ZLB less often than inflation targeting at the cost of longer stints at the ZLB. An economy that starts with inflation targeting and hits the ZLB recovers more quickly when the monetary authority switches to an NGDP level target while at the ZLB. This recovery is a result of forward guidance – the Fed commits to keeping interest rates low well into the future to boost NGDP levels back to target, immediately increasing inflation and output.

Literature Review

My paper is most similar to Garin et al. (2016), who analyze a strict NGDP rate target in a quantitative New Keynesian model. They find that NGDP targeting minimizes consumption-equivalent welfare loss under productivity shocks relative to inflation targeting and a Taylor rule. Additionally, NGDP targeting outperforms output gap targeting when potential output is observed with a small measurement error. I innovate on their paper by establishing analytical results and imposing nominal rate instrument rules rather than strict targeting rules.

Beckworth & Henderson (2019) use a canonical New Keynesian model to study nominal income targeting compared to inflation and output gap targeting. They introduce a shock to the output gap that the central bank observes to evaluate the role of information in monetary policy. They find that uncertainty in the output gap is empirically important in explaining actual output gap fluctuations and that nominal income targeting, if observed perfectly, reduces those fluctuations. I extend modeling an NGDP targeting rule in the New Keynesian literature and, since I do not use the output gap, can abstract from information problems facing the Fed.

Beckworth (2019) argues that NGDP targeting would relieve ZLB issues, saying that "NGDP [level targeting], in short, generates the temporary rise in inflation needed to escape a [zero lower-bound], something that is difficult to do with the Fed's current inflation target." According to Beckworth (2019), the ZLB is alleviated because inflation would become countercyclical. As such, real debt burdens would ease and lower real interest rates to their market-clearing levels.

Hall & Mankiw (1994) use a structural time-series counterfactual to evaluate nominal income targeting. They find that the primary benefit of nominal income targeting is reduced volatility in the price level and the inflation rate. Romer (2011) cites Hall & Mankiw (1994) on the benefits of NGDP targeting. I extend this analysis by evaluating inflation volatility in a DSGE model.

Mitra (2003) demonstrates that under NGDP targeting, a unique equilibrium exists in the three-equation New Keynesian model. Sumner (2012) argues for NGDP targeting from economic principles, saying that higher inflation under cost-push shocks can improve economic performance. Sheedy (2014) finds that NGDP targeting leads to efficient risk-sharing by stabilizing debt-to-GDP ratios. My paper also speaks to the optimal monetary policy literature such as Khan et al. (2003), who analyze the goals of optimal policy, and Woodford (2001), who analyzes the optimality of the Taylor rule. I also examine the ZLB, relating my paper to Wu & Xia (2016) and Sims & Wu (2021).

My paper also relates to articles in public policy. Crook (2022) states that NGDP targeting is "the simplest way to improve monetary policy." Bowman (2014) argues that NGDP targeting would stabilize the real economy by ensuring that nominal wage contracts would be fulfilled regardless of macroeconomic status. Employment would thus remain at potential. As mentioned above, Fed chairs Bernanke and Powell have both considered NGDP targeting to escape recessions.

I organize the rest of this paper as follows: Section II presents the analysis of the NGDP rule in the canonical, three-equation New Keynesian model. Section III outlines the quantitative DSGE model. Section IV discusses the results from the quantitative model. Section V concludes the paper.

2 Three-Equation New Keynesian Model

I begin with the canonical New Keynesian model popularized in Gali's 2015 textbook. The log-linearized model consists of the following three equations:

$$\tilde{y}_t = \mathbb{E}[\tilde{y}_{t+1}] - \frac{1}{\sigma}\left(\tilde{i}_t - \mathbb{E}_t[\tilde{\pi}_{t+1}]\right) + \varepsilon_t^d \tag{1}$$

$$\tilde{\pi}_t = \kappa(\tilde{y}_t - \tilde{y}_t^f) + \beta\mathbb{E}_t[\tilde{\pi}_{t+1}] + \varepsilon_t^s \tag{2}$$

$$\tilde{y}_t^f = \rho_a \tilde{y}_{t-1}^f + \frac{1+\eta}{\sigma+\eta}\varepsilon_t^a \tag{3}$$

$\tilde{y}_t$ denotes real output, $\tilde{\pi}_t$ denotes inflation, $\tilde{y}_t^f$ denotes potential output, and $\tilde{i}_t$ denotes the nominal interest rate. ε_t^d is a demand shock, ε_t^s is a cost-push shock and ε_t^a is a productivity shock. η denotes the inverse Frisch elasticity, σ is the CRRA parameter on the household's consumption utility, and κ is the slope parameter for the Phillips curve (Equation 2) and is a function of the price stickiness parameter θ. All variables are in their log-linearized form such that they represent deviations from their steady state. For my baseline results, I impose log-utility ($\sigma = 1$) as in Gali (2015).[1]

Equation (1) is the dynamic IS curve, Equation (2) is the New Keynesian Phillips curve, and Equation (3) is an AR(1) process for potential output, embedding the exogenous process for a productivity shock. To close the model, I need an equation to determine the nominal interest rate.

To proxy for the current monetary policy regime, I impose an inflation targeting rule:

$$\tilde{i}_t = \rho_r \tilde{i}_{t-1} + (1-\rho_r)\phi_\pi \tilde{\pi}_t + \sigma_r \varepsilon_t^r$$

where ϕ_π is the responsiveness of the central bank to deviations of inflation from steady state.

I compare this inflation rule to a rule targeting the level of NGDP:

$$\tilde{i}_t = \rho_r \tilde{i}_{t-1} + (1-\rho_r)\phi_\pi \left(\tilde{p}_t + \tilde{y}_t\right) + \sigma_r \varepsilon_t^r \tag{4}$$

where $\tilde{p}_t$ denotes the aggregate price level. Note that the weighting coefficient is the same between the two rules. This assumption allows me to derive the propositions in the next section. The system of equations that I solve to analyze the NGDP targeting rule consists of Equations (1) – (4), as well as the definition of inflation:

$$\tilde{\pi}_t = \tilde{p}_t - \tilde{p}_{t-1} \tag{5}$$

[1]Imposing log-utility eases the analysis. Varying σ does not qualitatively change the results.

2.1 Results

I derive the policy functions for $\tilde{y}_t$, $\tilde{\pi}_t$, and $\tilde{i}_t$ for the three different shocks under both NGDP level targeting and inflation targeting.

Productivity Shock

Proposition 1. *Under log-utility, an NGDP targeting rule leads to a more stable initial output response under productivity shocks given*

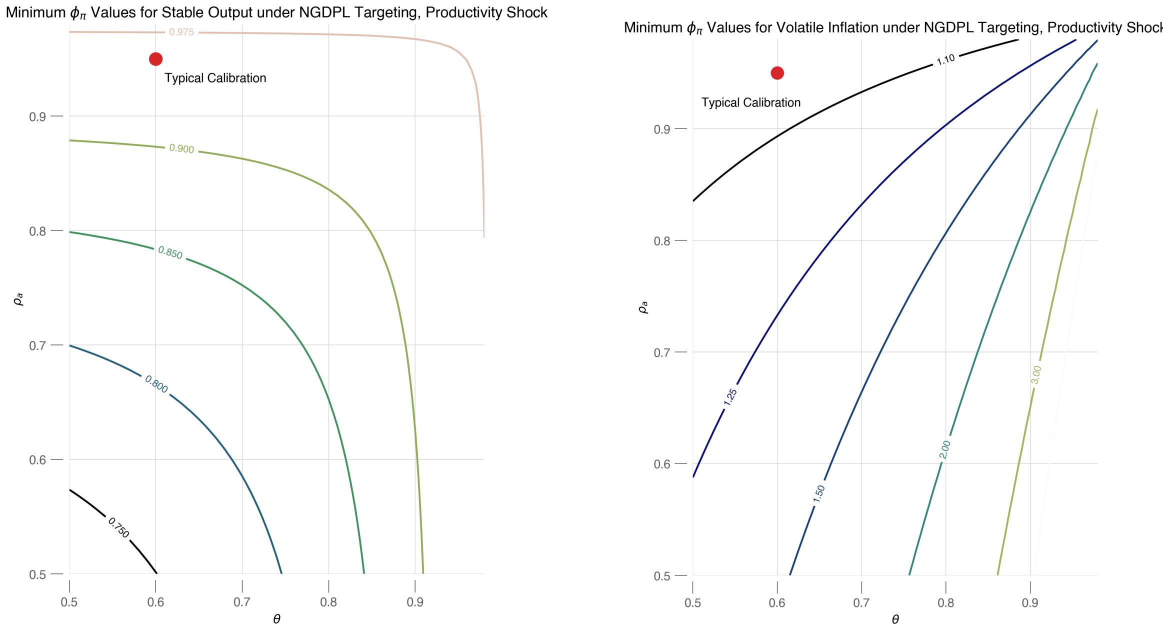
$$\phi_\pi \geq \mathcal{F}(\theta, \beta, \rho_a, \eta)$$

See Appendix A2 for the proof and form of $\mathcal{F}$.

I create a contour plot, fixing β at 0.99 and η at 1, two common values in the literature, for the values of ϕ_π that satisfy the inequality. The results are shown in Figure 1, Panel (a). For all values of θ, the Calvo parameter for price stickiness, and ρ_a, the persistence of the shock, the minimum value of ϕ_π is less than one.
Therefore, as long as the Taylor principle holds for determinacy, NGDP level targeting would stabilize output better than inflation targeting.[2]

The intuition here is straightforward: NGDP targeting places weight on output deviations from steady state, while inflation targeting does not (NGDP targeting places greater weight on output deviations than even the typical parameterization of the Taylor rule (Taylor, 1993)). Therefore, a central bank targeting NGDP will keep output closer to steady state than a central bank targeting only inflation.

[2]Note that this is not the output gap. As is well known, inflation targeting closes the output and inflationary gaps under productivity shocks. One justification for considering output stability is that, in reality, it is difficult for the central bank to determine which shock, or combination of shocks, is hitting the economy. A rule that stabilizes output then not only decreases risk but could also be beneficial in practical policymaking.



(a) Minimum values of ϕ_π required for output to be more stable under NGDP level targeting than under inflation targeting when the economy is hit with a productivity shock. As long as the Taylor principle is satisfied, this proposition holds.

(b) Minimum values of ϕ_π required for output to be more stable under NGDP level targeting than under inflation targeting when the economy is hit with a productivity shock. As long as the Taylor principle is satisfied, this proposition holds.

Figure 1: Comparison of stability under NGDP level targeting vs. inflation targeting when hit with a productivity shock. $\beta = 0.99$, $\eta = 1$.

I next derive a similar result for inflation:

Proposition 2. *Under log-utility, an NGDP targeting rule leads to a more volatile inflation response under productivity shocks given a monetary policy authority that satisfies:*

$$\phi_\pi \geq \mathcal{G}(\kappa, \rho_a, \beta, \eta)$$

See Appendix A3 for the proof and functional from of $\mathcal{G}$.

Figure 1, Panel (b) displays the contour graph for Proposition 2. As prices become stickier (θ approaches one) and the persistence of the productivity process decreases, the central bank must respond more strongly to deviations from steady state for inflation to be more volatile under an NGDP rule. Importantly, the minimum value of ϕ_π is not unreasonable. A ϕ_π value of 1.5 is standard in the literature. Estimates of θ tend to be around 0.65, with Smets & Wouters (2007) estimating a credible set range of 0.56 to 0.74. Estimates of ρ_a are tightly estimated around 0.95.

The contour plot in Panel (b) shows that at the $(\theta,\ \rho_a)$ coordinate pair of $(0.65,\ 0.95)$, the minimum ϕ_π value is approximately 1.05. Therefore, under typical calibration of New Keynesian models, NGDP targeting leads to more volatile inflation under productivity shocks. Intuitively, Proposition 2 occurs because the relative weight on inflation has decreased under NGDP targeting. The central bank focuses only on inflation under inflation targeting.

Last, I consider the nominal rate:

Proposition 3. *Under log-utility, an NGDP targeting rule leads to no movement in the nominal interest rate in response to productivity shocks.*

Proof: See Appendix A1.

For intuition, I consider the dynamic IS equation. Substitute the NGDP targeting rule in to derive, in general, the following relationship:

$$\mathbb{E}_t[\tilde{i}_{t+1}] = \phi_\pi \tilde{i}_t + \phi_\pi (1-\sigma)\left(\mathbb{E}_t[\tilde{y}_{t+1}] - \tilde{y}_t\right) \tag{6}$$

The expected nominal interest rate tomorrow is a function of σ, the coefficient of relative risk aversion. σ is attached to the expected change in real income. A productivity shock increases real income. When $\sigma > 1$, an expected increase in income will reduce the interest rate. The larger σ is, the more the NGDP rule allows the nominal rate to move. Even with larger σ values, the movement in the nominal rate remains more muted than under inflation targeting (see Appendix A4). This suggests more muted movement in the central bank's primary instrument.

Cost-Push Shock

Turning now to a supply shock, I can derive similar propositions.

Proposition 4. *Under log-utility, an NGDP targeting rule leads to a more stable initial output response under cost-push shocks given:*

$$\phi_\pi \geq \frac{\beta\psi_2 + \sqrt{\beta^2\psi_2^2 + 4(1-\beta\psi_2)}}{2(1-\beta\psi_2)}$$

where ψ_2 is the inflation policy function weight on lagged prices.

See Appendix A5 for proof.

Figure 2, Panel (a) demonstrates that Proposition 4 holds as long as the Taylor principle is satisfied. The intuition remains from the productivity shock. Because the central bank now explicitly places weight on output, output stabilizes. Surprisingly, however, inflation is not more volatile:

Proposition 5. *Under log-utility, an NGDP targeting rule leads to more volatile inflation given:*

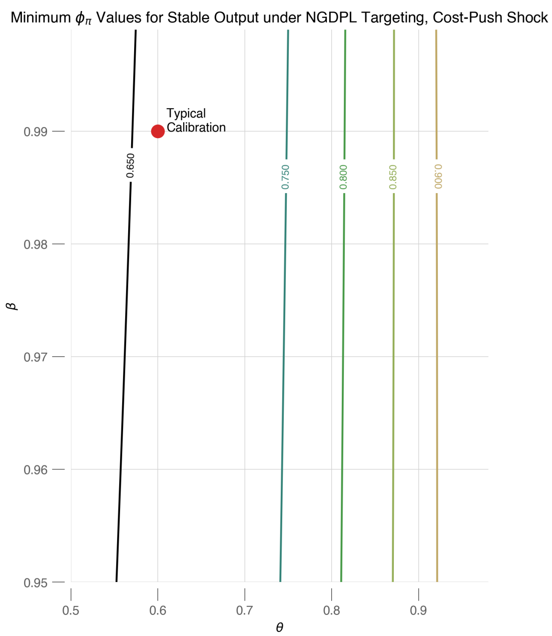
$$\phi_\pi \geq \frac{-\beta\psi_2 + \kappa}{\kappa}$$

See Appendix A6 for proof.

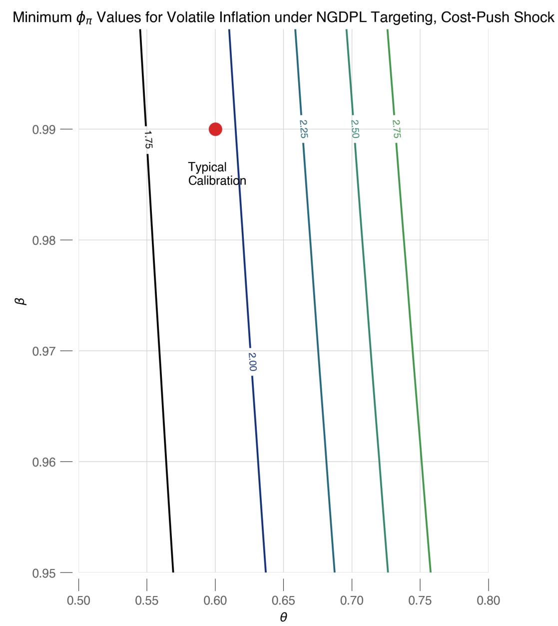
Figure 2, Panel (b) shows that ϕ_π would need to be approximately 1.9 to stabilize inflation more under inflation targeting than under NGDP targeting. It is well known that cost-push shocks break the divine coincidence in New Keynesian models. NGDP targeting prevents output from falling excessively, which in turn prevents marginal costs from increasing and inflation from rising. This occurs despite the nominal rate not moving:

Proposition 6. *Under log-utility, an NGDP targeting rule leads to no movement in the nominal interest rate in response to cost-push shocks.*

Proof: See Appendix A1.



(a) Minimum values of ϕ_π required for output to be more stable under NGDP level targeting than under inflation targeting. As long as the Taylor principle is satisfied, output will be more stable under NGDP targeting.



(b) Minimum values of ϕ_π required for output to be more stable under NGDP level targeting than under inflation targeting. Under the standard value of $\phi_\pi = 1.5$, inflation will be more stable under NGDP targeting.

Figure 2: Comparison of stability under NGDP level targeting vs. inflation targeting when hit with a cost-push shock. ρ_a does not enter either expression, so I let β vary and set $\eta = 1$.

Demand Shock

The last shock I analyze is a demand shock. I derive the following two propositions:

Proposition 7. *Under log-utility, an NGDP targeting rule leads to a more stable initial output response under demand shocks given:*

$$\phi_\pi \geq \frac{-\theta_2\kappa - \kappa\psi_2}{\beta\psi_2 - 1 - \beta\psi_2\kappa}$$

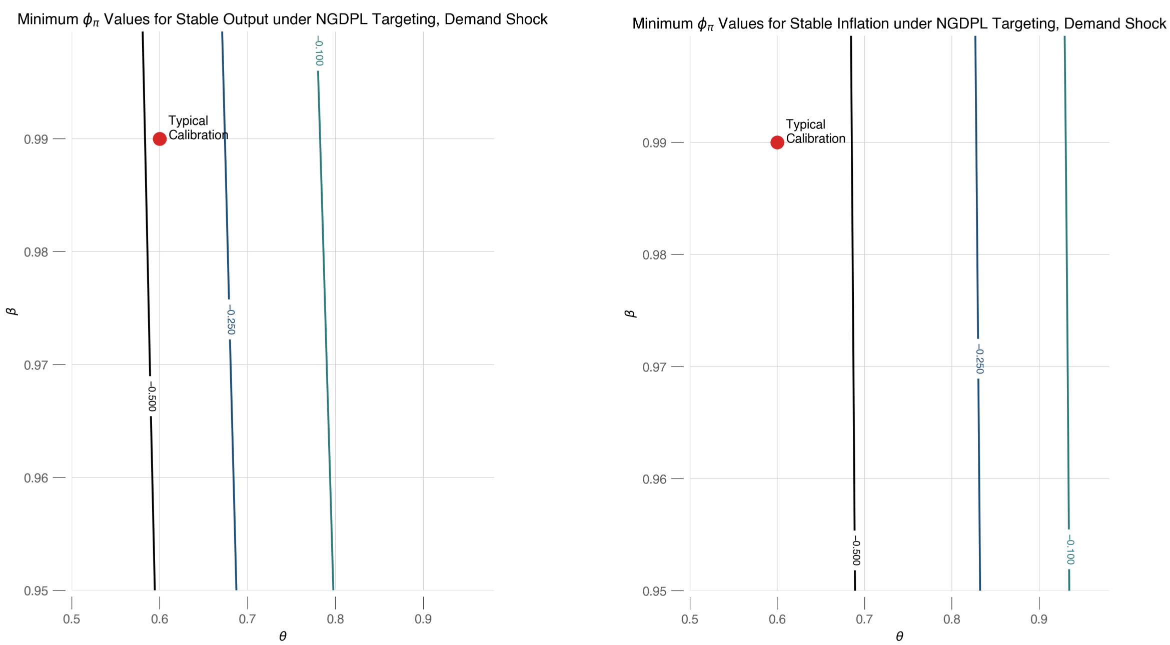
where θ_2 is the output policy function weight on lagged prices.

See Appendix A7 for proof.

Proposition 8. *Under log-utility, an NGDP targeting rule leads to more stable inflation given:*

$$\phi_\pi \geq \frac{\beta\psi_2 + \theta_2\kappa + \kappa\psi_2}{1 - \beta\psi_2}$$

See Appendix A8 for proof.



(a) Minimum values of ϕ_π required for output to be more stable under NGDP level targeting than under inflation targeting. As long as the Taylor principle is satisfied, output will be more stable under NGDP targeting.

(b) Minimum values of ϕ_π required for output to be more stable under NGDP level targeting than under inflation targeting. Under the standard value of $\phi_\pi = 1.5$, inflation will be more stable under NGDP targeting.

Figure 3: Comparison of stability under NGDP level targeting vs. inflation targeting when hit with a cost-push shock. ρ_a does not enter either expression, so I let β vary and set $\eta = 1$.

Figure 3, Panels (a) and (b) demonstrate that Propositions 7 and 8, respectively, hold as long as ϕ_π is positive. With a demand shock, output and inflation are positively correlated. As such, a demand shock will lead to greater movement in the nominal rate under NGDP targeting, as output enters the central bank's policy decision. A higher nominal rate will counteract the demand shock, preventing inflation and output from jumping as much as they would without any weight on output deviations.

I verify this intuition by proving that the nominal rate jumps more under NGDP targeting than under inflation targeting:

Proposition 9. *Under log-utility, an NGDP targeting rule leads to larger movements in the nominal rate under a demand shock as long as:*

$$0 \leq 1 - \beta\psi_2 + \kappa\psi_2 - \kappa\beta\psi_2^2 + \kappa^2\psi_2$$

Proof: See Appendix A9.

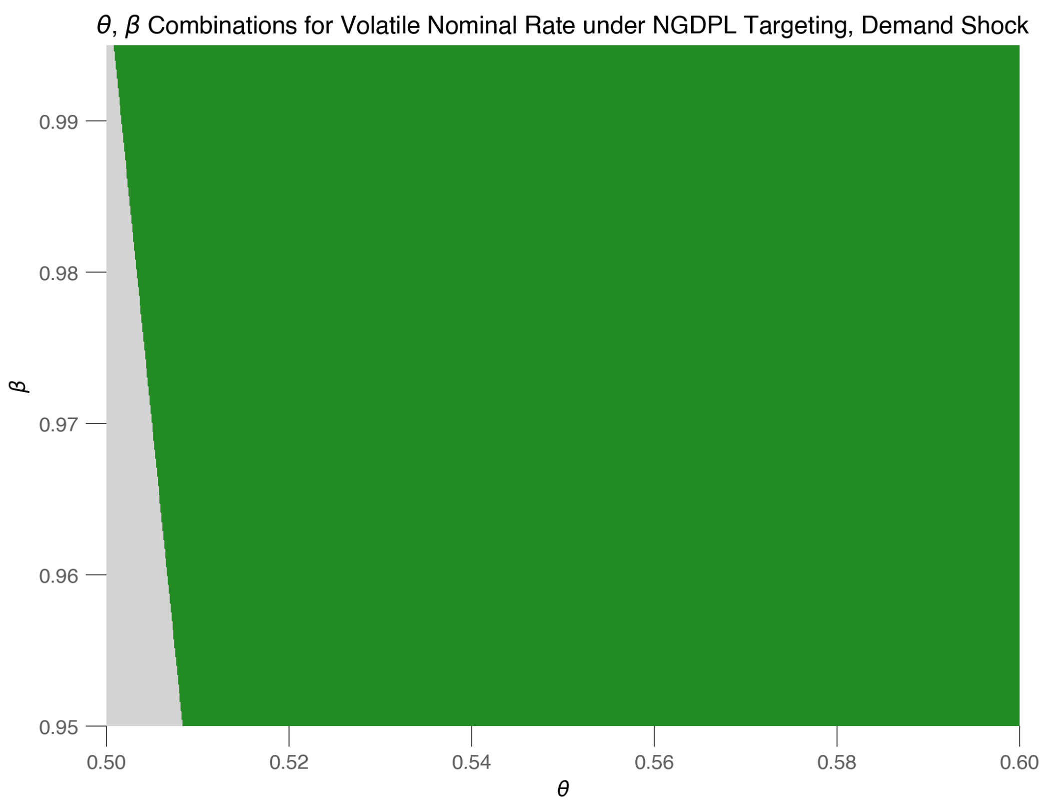


Figure 4: The green area denotes parameter combinations where the nominal rate is more volatile under NGDP targeting than under inflation targeting. The light gray area denotes areas where inflation targeting reacts more to demand shocks. All values of θ greater than 0.6 satisfy the proposition with $\beta \in [0.95, 1.00)$

Figure 4 demonstrates that for most combinations of θ and β, this result is positive. Only for relatively flexible wages and relatively low values of β does the result fail.

2.2 Summary

I have demonstrated analytically that NGDP level targeting leads to more stable output for typical calibrations. Inflation is more stable under demand and supply shocks but not under productivity shocks. The nominal rate is less volatile under productivity and cost-push shocks but must move more under demand shocks.

3 Quantitative Model

This section builds a model in the vein of Smets & Wouters (2007) and Christiano et al. (2005). Households now include external habit in their utility function. The labor market has sticky wages using standard Calvo (1983) logic and inflation indexation. The production side of the economy now has capital accumulation, capital utilization, and investment adjustment costs. Firms can also index prices to inflation. Last, a government now consumes a portion of output. For a list of equilibrium conditions, see Appendix A10. In the main body of the paper, I only highlight the shock locations.

3.1 Households

There is an infinitely lived representative agent that maximizes lifetime utility with the following form:

$$\mathbb{E}_t \left[\sum_{j=0}^{\infty} \beta^j \left\{ \ln\left(C_{t+j} - hC_{t+j-1}\right) - \frac{\chi L_{t+j}^{1+\eta}}{1+\eta} + \nu_t B(b_t) \right\} \right]$$

h designates the habit formation parameter. χ is a labor disutility scaling parameter, while η is the inverse Frisch elasticity. Households face the following real budget constraint:

$$C_t + b_t \leq mrs_t L_t + div_t - T_t + \Pi_t^{-1}(1 + i_{t-1})b_{t-1}$$

b_t denotes real government bonds, mrs_t denotes real wages the household receives, and div_t denotes profits rebated by firms to the household. T_t is a lump-sum tax enacted by the government to finance its spending. The household maximizes with respect to C_t, L_t, and b_t. $B(\cdot)$ is a bond-in-utility function following Fisher (2015), with ν_t attached as a preference shock that corresponds to the demand shock in the three-equation model.

3.2 Labor Markets

Labor markets operate in three parts. Labor unions exist on a unit measure, $h \in [0, 1]$, and purchase labor, $L_t(h)$, from households at nominal value MRS_t. Then, unions package that labor, now denoted $L_{d,t}(h)$, and sell it to a representative labor packer. Last, labor packers combine the labor from all the different unions into the final labor product, $L_{d,t}$, using a standard constant elasticity of substitution technology:

$$L_{d,t} = \left[\int_0^1 L_{d,t}(h)^{\frac{\varepsilon_{w,t}-1}{\varepsilon_{w,t}}} dh \right]^{\frac{\varepsilon_{w,t}}{\varepsilon_{w,t}-1}}$$

where $\varepsilon_{w,t}$ is the elasticity of substitution of labor. See the cost-push shock below for how wage markup varies. Labor unions face sticky wages, with a probability of adjusting wages in each period of ϕ_w. Unions that cannot update wages this period index wages back to last period's inflation with probability γ_w.

3.3 Production

The production side of the economy includes four types of firms. A competitive capital producer creates new physical capital each period, $\hat{I}_t$. I include an investment return shock on the price of capital. A representative wholesaler buys capital from the wholesaler and labor from the labor packer to create $Y_{m,t}$. A unit measure of retail firms, $f \in [0,1]$, repackage wholesale output using $Y_t(f) = Y_{m,t}(f)$. Last, a competitive final goods firm aggregates $Y_t(f)$ into Y_t using a CES aggregator:

$$Y_t = \left[\int_0^1 Y_t(f)^{\frac{\varepsilon_{p,t}-1}{\varepsilon_{p,t}}} df \right]^{\frac{\varepsilon_{p,t}}{\varepsilon_{p,t}-1}}$$

where $\varepsilon_{p,t}$ denotes the elasticity of substitution for retail output. Retail firms face sticky prices, with a probability of adjusting wages in each period of $1-\phi_p$. Firms that cannot update prices this period index prices back to last period's inflation with probability γ_p.

Note that the elasticity of substitution for retail output, $\varepsilon_{p,t}$, is time dependent. I do this to implement the cost-push shock found in Smets & Wouters (2007). Define the cost-push term, cp_t, as:

$$cp_t = \frac{1}{\varepsilon_{p,t} - 1}$$

A positive shock to cp_t increases desired markup. An increase in desired markup leads to higher prices and lower output, matching the effect of a cost-push shock in the three-equation model.

3.4 Government

The government consumes an exogenously stochastic portion of Y_t. It is financed by lump-sum taxes on the household and by nominal bonds B_t. The central bank first sets interest rates according to a zero-inflation targeting rule:

$$i_t = (1 - \rho_r)i_{ss} + \rho_r i_{t-1} + (1 - \rho_r)\phi_\pi \ln(\Pi_t) + \varepsilon_t^i$$

and I compare it to an NGDP level targeting rule:

$$i_t = (1 - \rho_r)i_{ss} + \rho_r i_{t-1} + (1 - \rho_r)\phi_N \left[\ln(P_t Y_t) - \ln(P_{ss} Y_{ss})\right] + \varepsilon_i^i$$

where P_{ss} is normalized to 1 and $\phi_\pi = \phi_N$.[3] When I analyze the model at the ZLB, the nominal interest rate is set such that:

$$(1 + i_t) = \max\{1, 1 + i_t^{rule}\} \tag{7}$$

where i_t is the prevailing interest rate in the economy and i_t^{rule} is the interest rate that the rule, either inflation or NGDP targeting, would set if unconstrained.

3.5 Estimation

I estimate my model using a random walk Metropolis Hastings algorithm. I use nominal GDP for output, PCE nondurable goods plus PCE services for consumption, PCE durable goods plus fixed private investment for investment, and the average hourly earnings of production and nonsupervisory employees for wages. I deflate each of these by the PCE deflator and detrend using log first differences. For labor, I use the employ-

[3] The price level is not stationary under the typical Taylor rule. The price level will be stationary under NGDP level targeting.

ment level, also log first-differenced. For inflation, I use the PCE price index. For the nominal rate, I use the quarterly effective federal funds rate. The resulting data run from 1975Q1 to 2007Q4. The model includes seven shocks: productivity, cost-push, investment, wage markup, government spending, nominal rate, and preference.

Table 1

Estimated Parameter Values

		Prior			**Posterior**		
Parameter	Description	Mean	SD	Distribution	Mean	5%	95%
h	habit	0.600	0.100	Beta	0.7079	0.6763	0.7396
κ	I adj. costs	4.000	1.500	Normal	7.5340	5.8948	9.1730
η	inverse Frisch	1.000	0.100	Normal	1.0660	0.9105	1.2240
ϕ_p	Calvo prices	0.500	0.100	Beta	0.7066	0.4990	0.8495
ϕ_w	Calvo wages	0.500	0.100	Beta	0.8789	0.8440	0.9129
γ_p	price index.	0.500	0.150	Beta	0.1765	0.0529	0.2978
γ_w	wage index.	0.500	0.150	Beta	0.1404	0.0674	0.2107
ϕ_π	TR inflation	1.700	0.250	Normal	1.8694	1.3161	2.4122
ϕ_y	TR output	0.120	0.050	Normal	0.1815	0.1225	0.2408

I fix β to 0.99 to roughly match the annualized rate over the time sample. I set ε^p_{ss} to 11 and ε^w_{ss} to 11 following Sims & Wu (2021). α is set to 1/3. I use the following depreciation function:

$$\delta(u_t) = \delta_0 + \delta_1(u_t - 1) + \frac{\delta_2}{2}(u_t - 1)^2$$

where δ_0 is set to 0.025, δ_2 is set to 0.01, and δ_1 is set such that steady-state utilization is equal to 1, also following Sims & Wu (2021).[4] The adjustment cost function is as follows:

$$S\left(\frac{I_t}{I_{t-1}}\right) = \frac{\kappa}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2$$

where κ is the adjustment cost multiplier. Key parameters of the estimation are displayed in Table 1. The full list of estimated parameters, including shock persistences and standard deviations, is in Appendix A11.

Before turning to the results, note that I estimate a version of the model where the nominal rate responds not only to inflation but also to deviations of output growth. If the Fed does react to output fluctuations, then I want the nominal rate rule to capture those movements in the nominal rate rather than assign them to the other estimated parameters. For the results that follow, inflation targeting still only targets inflation with the weight being the estimated ϕ_π. NGDP targeting also adopts the estimated ϕ_π weight but for deviations from steady-state nominal GDP.

4 Results

In this section, I discuss the consistency of the estimated model with the three-equation model, conduct long-run simulations, and evaluate NGDP targeting at the ZLB.

4.1 Consistency with the Propositions

Appendix A12 plots the impulse responses of output, inflation, and the nominal rate and examines differences from the analysis of the three-equation model. The results are verified for all but one of the responses. The nominal rate is less volatile on impact under the NGDP target in response to productivity and cost-push shocks and more volatile

[4] These parameters are not well-identified, which is why I fix them rather than estimate them.

in response to demand shocks. Inflation is more volatile in response to productivity shocks and less volatile in response to cost-push and demand shocks.

The result that breaks down is Proposition 4. Output is more volatile under NGDP targeting in response to a cost-push shock. This outcome occurs because of the inclusion of habit in the model. Habit smooth consumption over time. Because NGDP targeting necessarily implies deflation in future periods after a cost-push shock, the real rate rises in the future more under NGDP targeting than under inflation targeting. Households thus save more of their income, decreasing C_t and therefore Y_t. The second plot in Appendix A12 displays impulse responses in the same model but with the habit parameter set to zero. The result in Proposition 4 then carries through to the quantitative model.

In addition to impulse response analysis, I run a long-run simulation (5000 periods) with the productivity, cost-push, and demand shocks. I then take the variance of output, inflation, and the nominal rate. The results can be found in Appendix A12. Output is roughly 10% more stable under NGDP level targeting than under inflation targeting. Inflation is roughly 22% more stable. The nominal rate, however, is 45% more stable. Demand shocks drive these relative volatilities, as the nominal rate is less volatile in response to the other two shocks. Adding the rest of the shocks in the model to the simulation does not qualitatively change the relative variances, though the inclusion of investment shocks does increase the volatility of the nominal rate under NGDP targeting.

4.2 Hitting the ZLB

As mentioned in the introduction, the ZLB motivates much of the NGDP targeting policy push. I now conduct a simulation where the nominal rate is subject to an occasionally binding ZLB constraint. I generate 5000 periods of random productivity, cost-push, and demand shocks. I then calculate the proportion of time the policy rate is at the ZLB. NGDP level targeting would be "successful" if it prevented the ZLB from binding more often than inflation targeting. I conduct three different simulations: one with the supply, demand, and productivity shocks, one with all the shocks in the model, and one excluding nominal rate shocks. To ensure that the simulation hits the ZLB regularly, I scale each shock such that under inflation targeting, the ZLB binds roughly 20% of the time.[5] Table 2 reports the percentage of time spent at the ZLB.

Table 2

Time at the ZLB

	Main Shocks	All Shocks	No *I* Shock
Inflation	20.2%	20.0%	20.1%
NGDP-L	14.4%	38.6%	13.0%

The relatively low volatility of the nominal rate under NGDP level targeting means that the ZLB binds less often in a scenario where only supply, demand, and productivity shocks hit the economy. When all shocks are considered, NGDP targeting performs poorly, with the ZLB binding for roughly one-third of the simulated time span. Much of this volatility can be attributed to investment shocks. Investment shocks move output and inflation in the same direction, and hence, nominal GDP jumps. The nominal rate increase is relatively large compared to that under inflation targeting. Investment shocks act similarly to demand shocks. When output and inflation move in the same direction, the nominal rate needs to move more. However, with a binding ZLB, these large movements become problematic.

Time spent at the ZLB, while useful as a holistic picture, is too broad a measure. To get a better idea of how each target deals with the ZLB, I examine intensive and

[5]This corresponds to the amount of time the federal funds rate has been at the ZLB since 1975.

extensive margins. Table 3 displays the average duration at the ZLB per episode and the number of episodes per 40 quarters (10 years) during the simulation.

Table 3

ZLB Characteristics

	Main Shocks		**All Shocks**		**No I Shock**	
	Duration	Episodes	Duration	Episodes	Duration	Episodes
Inflation	5.6	1.7	8.0	1.7	6.3	1.9
NGDP-L	6.0	1.1	10.6	2.1	4.2	1.9

Under the main shocks, NGDP targeting leads to more quarters at the ZLB, but fewer ZLB episodes. Under all shocks, the duration is still longer, but now the number of episodes is higher. Adopting NGDP targeting means that monetary policy will hit the ZLB more often and for longer. However, when removing the investment shock, the duration of the ZLB is shorter under NGDP targeting than under inflation targeting. The investment shock thus drives monetary policy deep into the ZLB, with an unconstrained nominal rate moving strongly negative.

Now that the interest rate is constrained, the variance results from the unconstrained simulation do not necessarily hold. Table 4 lists the standard deviation of output and inflation at the ZLB in each scenario. Under the main three shocks, output is no longer less volatile under NGDP targeting. Inflation remains less volatile, in fact becoming even less volatile relative to inflation targeting. With all the shocks, output is less volatile under NGDP targeting, but inflation becomes just as volatile as under inflation targeting. Last, when removing the investment shock, the results are qualitatively similar to the results under the main shocks.

The main takeaway from these exercises is that in an economy where standard monetary policy applies, NGDP targeting will lead to less volatility in output and inflation. However, in an economy where the ZLB matters, NGDP targeting does not necessarily improve economic stability.

Table 4

Standard Deviations at the ZLB

	Main Shocks		**All Shocks**		**No *I* Shock**	
	Output	Inflation	Output	Inflation	Output	Inflation
Inflation	0.08	0.008	0.15	0.006	0.10	0.006
NGDP-L	0.08	0.006	0.12	0.006	0.10	0.005

4.3 Switching to NGDP Targeting

The New York Times op-ed by Christina Romer advocated switching to an NGDP level target when the nominal rate reaches the ZLB. Beckworth (2019) argues that NGDP level targeting would help the economy escape the ZLB. In this section, I first drive the economy into the ZLB with two large demand shocks while the central bank pursues inflation targeting.[6] I then switch to NGDP targeting in the middle of the ZLB period and compare the speed of recovery with that of an economy that maintains inflation targeting.[7] Figure 5 displays the resulting simulation.

Switching to NGDP targeting in the middle of the ZLB period causes an immediate jump in inflation, supporting the findings of Beckworth (2019). This increase in inflation is accompanied by a steeper climb in output. A switch to NGDP targeting would thus spur a sharp rise in NGDP. For policymakers seeking to jumpstart an economy out of

[6]There is considerable debate over which shocks primarily drive business cycles. I adopt a traditional view here and assume that demand drives short-run business cycles.

[7]I do this by first simulating an economy with the OCCBIN toolbox in Dynare. I then export simulated values in the middle of the ZLB period. I use those exported values as starting values in two perfect-foresight simulations: one continuing the inflation targeting rule and the other switching to an NGDP targeting rule.

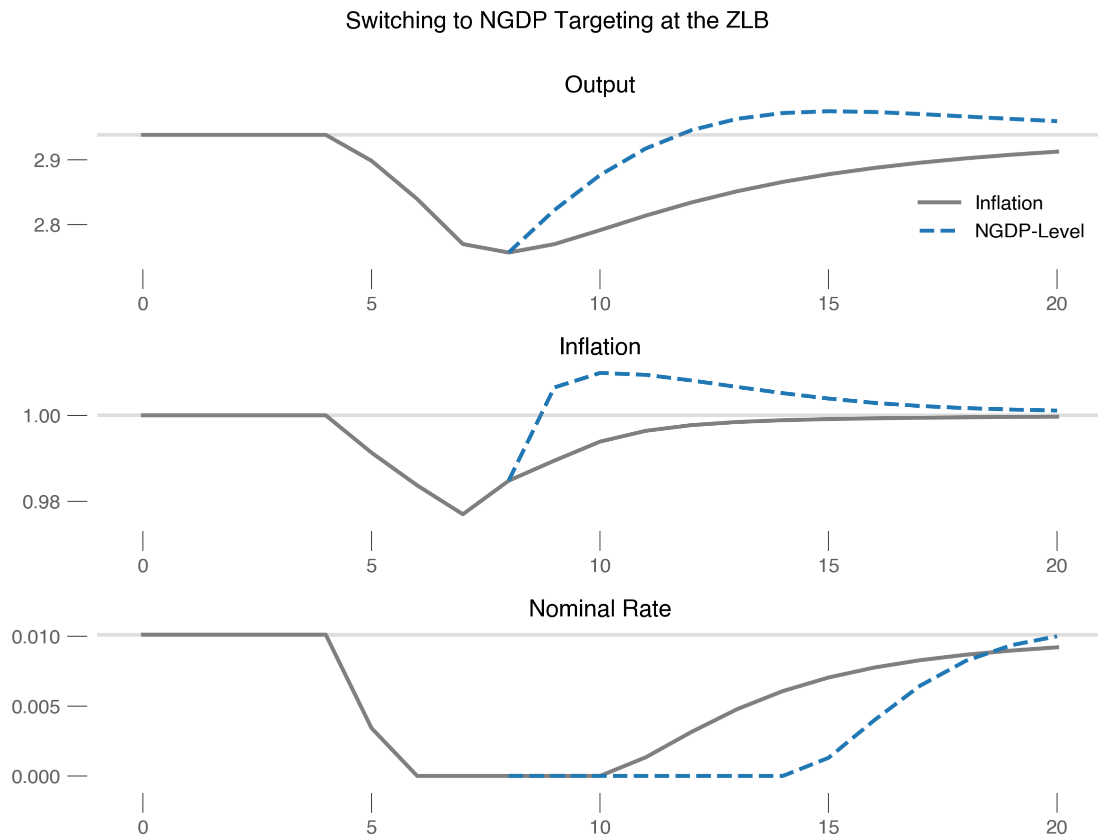


Figure 5: Simulation at the ZLB. Grey solid – Inflation targeting. Blue dashed – NGDP level targeting.

a classic recession, a switch from inflation to NGDP targeting would make sense.

The nominal rate, however, remains constrained at the ZLB for five quarters longer. This result can be viewed as forward guidance. The Fed commits itself to pursuing the targeted level of NGDP. This means higher inflation for many quarters in the future. To generate that higher inflation, the Fed promises to hold rates at zero well into the future, instead of raising them when inflation starts to recover.

5 Conclusion

This paper compares NGDP level targeting with the monetary authority's current inflation target. I show analytically that relative volatilities are shock-dependent and confirm these results quantitatively. An analysis at the ZLB demonstrates that NGDP targeting, if followed at all times, could decrease the frequency of ZLB events at the cost of prolonging the ZLB. Switching to an NGDP target while at the ZLB, however, would boost real output and inflation, driving an economy out of recession quicker than inflation targeting. The Fed uses forward guidance, promising to keep rates at the ZLB for longer, which immediately boosts inflation and output. Areas of further research should involve investigating central bank credibility on switching policy targets and reversing policy switches during booms.

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A Appendix

A1 Proof of Propositions 3 and 6

I first restate the system of four equations that I am solving, setting $\rho_r = 0$ for clarity:

$$\tilde{y}_t = \mathbb{E}[\tilde{y}_{t+1}] - \frac{1}{\sigma}\left(\tilde{i}_t - \mathbb{E}_t[\tilde{\pi}_{t+1}]\right) + \varepsilon_t^d \tag{A.1}$$

$$\tilde{\pi}_t = \kappa(\tilde{y}_t - \tilde{y}_t^f) + \beta\mathbb{E}_t[\tilde{\pi}_{t+1}] + \varepsilon_t^s \tag{A.2}$$

$$\tilde{y}_t^f = \rho_a \tilde{y}_{t-1}^f + \frac{1+\eta}{\sigma+\eta}\varepsilon_t^a \tag{A.3}$$

$$\tilde{i}_t = \phi_N\left(\tilde{p}_t + \tilde{y}_t\right) + \sigma_r \varepsilon_t^r \tag{A.4}$$

$$\tilde{\pi}_t = \tilde{p}_t - \tilde{p}_{t-1} \tag{A.5}$$

In this model, there are three forward-looking jump variables: $\tilde{y}_t$, $\tilde{\pi}_t$, and $\tilde{p}_t$. There are two state variables: $\tilde{p}_{t-1}$ and $\tilde{y}_t^f$.

Finding the Policy Functions

Focusing only on productivity shocks for now, assume that the jump variables are linear in the state variables:

$$\tilde{y}_t = \theta_1\tilde{y}_t^f + \theta_2\tilde{p}_{t-1} \qquad \tilde{\pi}_t = \psi_1\tilde{y}_t^f + \psi_2\tilde{p}_{t-1} \qquad \tilde{p}_t = \tau_1\tilde{y}_t^f + \tau_2\tilde{p}_{t-1}$$

Starting with Equation A.2, I plug in the conjectures:

$$\tilde{\pi}_t = \kappa(\tilde{y}_t - \tilde{y}_t^f) + \beta E_t[\tilde{\pi}_{t+1}]$$
$$\psi_1\tilde{y}_t^f + \psi_2\tilde{p}_{t-1} = \kappa(\theta_1\tilde{y}_t^f + \theta_2\tilde{p}_{t-1} - \tilde{y}_t^f) + \beta\mathbb{E}_t[\psi_1\tilde{y}_{t+1}^f + \psi_2\tilde{p}_t]$$
$$\tilde{y}_t^f(\psi_1 - \kappa\theta_1 + \kappa - \beta\psi_1\rho_a - \beta\psi_2\tau_1) = \tilde{p}_{t-1}(\kappa\theta_2 - \psi_2 + \beta\psi_2\tau_2)$$

I now have two equations:

$$\psi_1 - \kappa\theta_1 + \kappa - \beta\psi_1\rho_a - \beta\psi_2\tau_1 = 0 \tag{A.6}$$

$$\kappa\theta_2 - \psi_2 + \beta\psi_2\tau_2 = 0 \tag{A.7}$$

Next, I substitute the NGDP rule and the policy guesses into A.1:

$$\tilde{y}_t = \mathbb{E}_t[\tilde{y}_{t+1}] - \frac{1}{\sigma}(\tilde{i}_t - \mathbb{E}_t[\tilde{\pi}_{t+1}])$$
$$\theta_1\tilde{y}_t^f + \theta_2\tilde{p}_{t-1} = \mathbb{E}_t[\theta_1\tilde{y}_{t+1}^f + \theta_2\tilde{p}_t] - \frac{1}{\sigma}(\phi_N\tilde{p}_t + \phi_N\tilde{y}_t - \psi_1\tilde{y}_{t+1}^f - \psi_2\tilde{p}_t)$$

Plugging in the policy guesses again and sorting by term yields:

$$\tilde{y}_t^f\left(-\sigma\theta_1 + \sigma\theta_1\rho_a + \sigma\theta_2\tau_1 - \phi_N\tau_1 - \phi_N\theta_1 + \psi_1\rho_a + \psi_2\tau_1\right) +$$
$$\tilde{p}_{t-1}\left(-\sigma\theta_2 + \sigma\theta_2\tau_2 - \phi_N\tau_2 - \phi_N\theta_2 + \psi_2\tau_2\right) = 0$$

which produces another two equations:

$$-\sigma\theta_1 + \sigma\theta_1\rho_a + \sigma\theta_2\tau_1 - \phi_N\tau_1 - \phi_N\theta_1 + \psi_1\rho_a + \psi_2\tau_1 = 0 \tag{A.8}$$

$$-\sigma\theta_2 + \sigma\theta_2\tau_2 - \phi_N\tau_2 - \phi_N\theta_2 + \psi_2\tau_2 = 0 \tag{A.9}$$

Last, use Equation A.5:

$$\tilde{pi}_t = \tilde{p}_t - \tilde{p}_{t-1}$$
$$0 = \tilde{y}_t^f(\psi_1 - \tau_1) + \tilde{p}_{t-1}(\psi_2 - \tau_2 + 1)$$

which yields the last two equations:

$$\tau_1 = \psi_1 \tag{A.10}$$

$$\tau_2 = \psi_2 + 1 \tag{A.11}$$

Equations A.6 through A.11 yield six equations with six unknowns. I can now solve the system. Starting with Equation A.7:

$$\kappa\theta_2 - \psi_2 + \beta\psi_2\tau_2 = 0$$

$$\theta_2 = \frac{\psi_2(1-\beta(\psi_2+1))}{\kappa} \tag{A.12}$$

Moving to Equation A.9:

$$-\sigma\theta_2 + \sigma\theta_2\tau_2 - \phi_N\tau_2 - \phi_N\theta_2 + \psi_2\tau_2 = 0$$

$$\frac{-\sigma\psi_2(1-\beta(\psi_2+1))}{\kappa(\psi_2+1)} + \frac{\sigma\psi_2(1-\beta(\psi_2+1))}{\kappa} - \phi_N - \phi_N\frac{\psi_2(1-\beta(\psi_2+1))}{\kappa(\psi_2+1)} + \psi_2 = 0$$

This is a cubic equation. I now impose log-utility, setting $\sigma = 1$. Using a cubic-root solver, I find that the only solution for ψ_2 that satisfies Equations A.6–A.11 is:

$$\psi_2^* = \frac{-\sqrt{\beta^2 + 2\beta(\kappa-1) + (\kappa+1)^2} - \beta + \kappa + 1}{2\beta} \tag{A.13}$$

Plugging A.13 into A.12 yields a closed-form expression for θ_2:

$$\theta_2^* = \frac{\psi_2^*(1-\beta(\psi_2^*+1))}{\kappa} \tag{A.14}$$

I also now have $\tau_2^* = \psi_2^* + 1$. Move to Equation A.6:

$$\psi_1 - \kappa\theta_1 + \kappa - \beta\psi_1\rho_a - \beta\psi_2\tau_1 = 0$$
$$\theta_1 = \frac{\psi_1 + \kappa - \beta\psi_1\rho_a - \beta\psi_2^*\psi_1}{\kappa}$$

Plugging this into Equation A.8 and solving for ψ_1:

$$0 = -\sigma\theta_1 + \sigma\theta_1\rho_a + \sigma\theta_2\tau_1 - \phi_N\tau_1 - \phi_N\theta_1 + \psi_1\rho_a + \psi_2\tau_1$$
$$\psi_1^* = \frac{\kappa(1 - \rho_a + \phi_N)}{(\rho_a - \phi_N + 1)(1 - \beta\rho_a - \beta\psi_2^*) + \psi_2^*\left(1 - \beta(\psi_2^* + 1) + \kappa\right) - \kappa(\phi_N - \rho_a)} \tag{A.15}$$

A.6 is now solved:

$$\theta_1^* = \frac{\psi_1^* + \kappa - \beta\psi_1^*\rho_a - \beta\psi_2^*\psi_1^*}{\kappa}$$

I also have $\tau_1^* = \psi_1^*$. All coefficients are composed only of parameters, so the guess is verified.

Solving for the Nominal Rate

I substitute the policy functions into the NGDP targeting rule:

$$\tilde{i}_t = \phi_N\left(\tilde{p}_t + \tilde{y}_t\right)$$
$$= \phi_N\left[\tilde{y}_t^f \underbrace{\left(1 + \psi_1 + \frac{\psi_1(1 - \beta\rho_a - \beta\psi_2)}{\kappa}\right)}_{\equiv A} + \tilde{p}_{t-1}\underbrace{\left(\psi_2 + 1 + \frac{\psi_2}{\kappa}(1 - \beta(\psi_2 + 1))\right)}_{\equiv B}\right]$$

Considering only term A, I plug in for the coefficients and simplify to obtain:

$$\frac{\kappa(1+\psi_1)+\psi_1-\psi_1\beta\rho_a-\beta\psi_2\psi_1}{\kappa} = \frac{\psi_2-\beta\psi_2(\psi_2+1)+\psi_2\kappa+\kappa}{(\rho_a-\phi_N-1)(1-\beta\rho_a-\beta\psi_2)+\psi_2(1-\beta(\psi_2+1)+\kappa)-\kappa(\phi_N-\rho_a)}$$

which, after plugging in for ψ_2, simplifies to 0. Regarding term B:

$$\psi_2+1+\frac{\psi_2}{\kappa}(1-\beta(\psi_2+1)) = \psi_2+1+\frac{\psi_2}{\kappa}-\frac{\beta}{\kappa}\psi_2^2-\frac{\beta\psi_2}{\kappa}$$

which, after plugging in for ψ_2 also simplifies to 0. Therefore:

$$\tilde{i}_t = \sigma_r\varepsilon_t^r$$

With Cost-Push Shocks

As before, assume linear policy functions for the jump variables. Now, ε_t^s is included instead of y_t^f:

$$\tilde{y}_t = \theta_2\tilde{p}_{t-1}+\theta_3\varepsilon_t^s \qquad \tilde{\pi}_t = \psi_2\tilde{p}_{t-1}+\psi_3\varepsilon_t^s \qquad \tilde{p}_t = \tau_2\tilde{p}_{t-1}+\tau_3\varepsilon_t^s$$

Plugging the policy function guesses into the DIS and NKPC curves yields the following new equations:

$$\kappa\theta_3-\psi_3+\beta\psi_2\tau_3+1=0 \tag{A.16}$$

$$-\sigma\theta_3+\sigma\theta_2\tau_3-\phi_N\tau_3-\phi_N\theta_3+\psi_2\tau_3=0 \tag{A.17}$$

$$\tau_3=\psi_3 \tag{A.18}$$

Solving A.16 provides an equation for θ_3:

$$\theta_3 = \frac{\psi_3 - \beta\psi_2\psi_3 - 1}{\kappa}$$

which can be used to solve A.17 for ψ_3 and verify the guess:

$$\psi_3 = \frac{-\sigma - \phi_N}{-\sigma + \sigma\beta\psi_2 - \phi_N + \beta\phi_N\psi_2 - \phi_N\kappa + \psi_2\kappa + \sigma\theta_2\kappa}$$

Solving the for the nominal rate yields:

$$\tilde{i}_t = \phi_N \left(A\tilde{y}_t^f + B\tilde{p}_{t-1} + \varepsilon_t^s \underbrace{\left(\psi_3 + \frac{\psi_3 - \beta\psi_2\psi_3 - 1}{\kappa} \right)}_{\equiv C} \right) + \sigma_r \varepsilon_t^r$$

After tedious algebra, C also simplifies to 0.

A2 Proof of Proposition 1

I first solve for the policy functions under inflation targeting. Assuming that $\rho_r = 0$ for simplicity, the four equations I need to solve are:

$$\tilde{y}_t = \mathbb{E}[\tilde{y}_{t+1}] - \frac{1}{\sigma}\left(\tilde{i}_t - \mathbb{E}_t[\tilde{\pi}_{t+1}]\right) + \varepsilon_t^d \tag{A.19}$$

$$\tilde{\pi}_t = \kappa(\tilde{y}_t - \tilde{y}_t^f) + \beta\mathbb{E}_t[\tilde{\pi}_{t+1}] + \varepsilon_t^s \tag{A.20}$$

$$\tilde{y}_t^f = \rho_a \tilde{y}_{t-1}^f + \frac{1+\eta}{\sigma+\eta}\varepsilon_t^a \tag{A.21}$$

$$\tilde{i}_t = \phi_\pi \tilde{\pi}_t + \sigma_r \varepsilon_t^r \tag{A.22}$$

Assume that the jump variables, $\tilde{y}_t$ and $\tilde{\pi}_t$, are linear in the state variable, $\tilde{y}_t^f$:

$$\tilde{y}_t = \lambda_1 \tilde{y}_t^f \qquad\qquad \tilde{\pi}_t = \lambda_2 \tilde{y}_t^f$$

Starting with A.20, substitute in the policy function guesses:

$$\begin{aligned}
\tilde{\pi}_t &= \kappa(\tilde{y}_t - \tilde{y}_t^f) + \beta\mathbb{E}_t[\tilde{\pi}_{t+1}] \\
\lambda_1 \tilde{y}_t^f &= \kappa(\lambda_1 \tilde{y}_t^f - \tilde{y}_t^f) + \beta\mathbb{E}_t[\lambda_2 \tilde{y}_t^f] \\
0 &= \lambda_2 \tilde{y}_t^f - \kappa(\lambda_1 - 1)\tilde{y}_t^f - \beta\rho_a\lambda_2\tilde{y}_t^f \\
0 &= [\lambda_2 - \kappa(\lambda_1 - 1) - \beta\rho_a\lambda_2]\,\tilde{y}_t^f
\end{aligned} \tag{A.23}$$

Now, solve A.19:

$$\begin{aligned}
\tilde{y}_t &= \mathbb{E}[\tilde{y}_{t+1}] - \frac{1}{\sigma}\left(\tilde{i}_t - \mathbb{E}_t[\tilde{\pi}_{t+1}]\right) \\
\lambda_1 \tilde{y}_t^f &= \lambda_1\rho_a\tilde{y}_t^f - \frac{1}{\sigma}(\phi_\pi\tilde{\pi}_t - \lambda_2\rho_a\tilde{y}_t^f) \\
0 &= \lambda_1\tilde{y}_t^f - \lambda_1\rho_a\tilde{y}_t^f + \frac{\phi_\pi}{\sigma}\lambda_2\tilde{y}_t^f - \frac{\lambda_2\rho_a}{\sigma}\tilde{y}_t^f
\end{aligned}$$

$$0 = \left[\lambda_1 - \lambda_1\rho_a + \frac{\phi_\pi}{\sigma}\lambda_2 - \frac{\lambda_2\rho_a}{\sigma}\right]\tilde{y}_t^f \tag{A.24}$$

Solve for the coefficient in A.24 for λ_1:

$$\begin{aligned}
\lambda_1 - \lambda_1\rho_a + \frac{\phi_\pi}{\sigma}\lambda_2 - \frac{\lambda_2\rho_a}{\sigma} &= 0 \\
\lambda_1(1-\rho_a) &= \lambda_2\left(\frac{\rho_a}{\sigma} - \frac{\phi_\pi}{\sigma}\right) \\
\lambda_1 &= \frac{\lambda_2}{1-\rho_a}\left(\frac{\rho_a}{\sigma} - \frac{\phi_\pi}{\sigma}\right) \qquad \text{(A.25)}
\end{aligned}$$

Plug A.25 into the coefficient of A.23:

$$\begin{aligned}
0 &= \lambda_2 - \kappa(\lambda_1 - 1) - \beta\rho_a\lambda_2 \\
0 &= \lambda_2 - \kappa\left(\frac{\lambda_2}{1-\rho_a}\left(\frac{\rho_a}{\sigma} - \frac{\phi_\pi}{\sigma}\right) - 1\right) - \beta\rho_a\lambda_2 \\
0 &= \lambda_2(1-\beta\rho_a) - \lambda_2\frac{\kappa(\rho_a - \phi_\pi)}{\sigma(1-\rho_a)} + \kappa \\
\lambda_2^* &= \frac{\sigma\kappa(1-\rho_a)}{\sigma(1-\beta\rho_a)(\rho_a - 1) - \kappa(\phi_\pi - \rho_a)} \qquad \text{(A.26)}
\end{aligned}$$

Plug A.26 into A.25:

$$\begin{aligned}
\lambda_1 &= \lambda_2^*\frac{\rho_a - \phi_\pi}{\sigma(1-\rho_a)} \qquad \text{(A.27)} \\
\lambda_1^* &= \frac{\kappa(\phi_\pi - \rho_a)}{(1-\beta\rho_a)(1-\rho_a) - \kappa(\rho_a - \phi_\pi)} \qquad \text{(A.28)}
\end{aligned}$$

Now, compare the output policy function weights on potential output under NGDP targeting and under inflation targeting, setting $\phi_N = \phi_\pi$ and $\sigma = 1$, assuming that output is less volatile under NGDP level targeting:

$$\frac{\kappa(\phi_\pi - \rho_a)}{(1-\beta\rho_a)(1-\rho_a) - \kappa(\rho_a - \phi_\pi)} \geq \frac{\kappa(\phi_\pi - \rho_a) - \psi_2(1+\kappa-\beta(\psi_2+1))}{(1+\phi_\pi-\rho_a)(1-\beta\rho_a-\beta\psi_2) - \kappa(\rho_a-\phi_\pi) - \psi_2(1+\kappa-\beta(\psi_2+1))}$$

Clearing fractions (both denominators are positive assuming that $\phi_\pi > 1$) and grouping by ϕ_π terms yields:

$$\phi_\pi^2 \underbrace{(\kappa - \kappa\beta\rho_a - \kappa\beta\psi_2)}_{\equiv a} + \phi_\pi \underbrace{\left(\kappa\beta\rho_a\psi_2 + \beta\psi_2^2 - \kappa\rho_a + \kappa\beta\rho_a^2 + \kappa\rho_a\beta\psi_2 - \kappa\psi_2\beta(\psi_2+1)\right)}_{\equiv b}$$
$$+ \underbrace{\psi_2(1+\kappa-\beta(\psi_2+1))(1-\rho_a-\beta\rho_a+\beta\rho_a^2-\kappa\rho_a) - \beta\kappa\rho_a^2\psi_2 + \kappa\rho_a\psi_2 + \kappa^2\psi_2\rho_a - \beta\kappa\rho_a\psi_2^2}_{\equiv c}$$

This is of a quadratic form. The quadratic formula yields:

$$\phi_\pi \geq \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

where I omit the smaller of the two ϕ_π values.

This concludes the proof of Proposition 1.

A3 Proof of Proposition 2

Compare the policy function for inflation under NGDP targeting and under inflation targeting, assuming that the NGDP response is more negative:

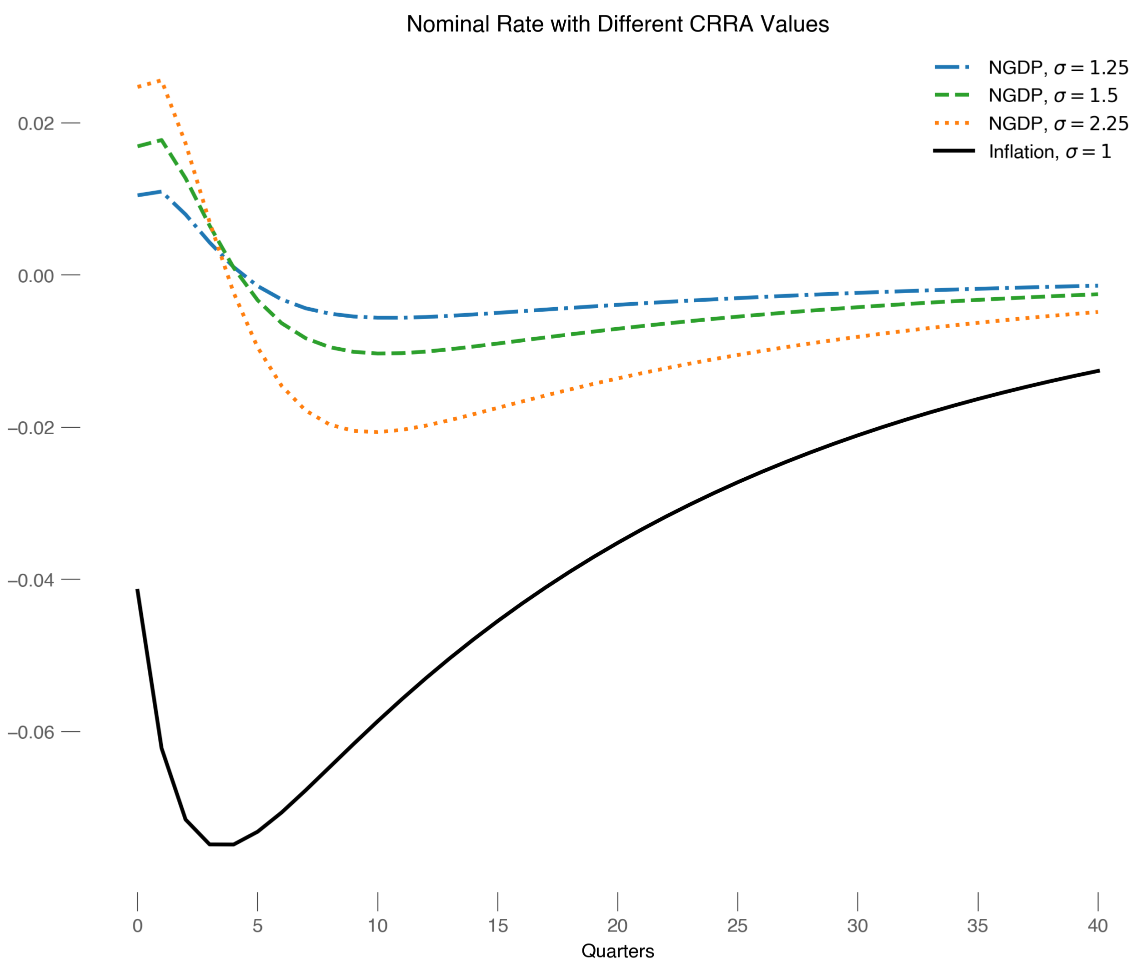
$$\frac{-\kappa(1-\rho_a)}{(1-\beta\rho_a)(1-\rho_a)-\kappa(\rho_a-\phi_\pi)} \geq \frac{-\kappa(1-\rho_a-\phi_\pi)}{(1+\phi_\pi-\rho_a)(1-\beta\rho_a-\beta\psi_2)-\kappa(\rho_a-\phi_\pi)-\psi_2(1+\kappa-\beta(\psi_2+1))}$$

Clear fractions and divide both sides by $-\kappa$. Then simplify and group by ϕ_π terms:

$$\phi_\pi^2\kappa + \phi_\pi(-\kappa\rho_a + (1-\rho_a)\beta\psi_2) + \psi_2(1-\rho_a)\left[\beta(1-\rho_a) + 1 + \kappa - \beta(\psi_2+1)\right] \geq 0$$

Applying the quadratic formula and taking the larger value verifies the proposition.

A4 Varying CRRA Parameters



A5 Proof of Proposition 4

Solving the policy functions with cost-push shocks under inflation targeting yields coefficients:

$$\lambda_1^s = \frac{-\phi_\pi/\sigma}{1+\kappa\phi_\pi/\sigma}$$

$$\lambda_2^s = 1+\kappa\theta_1$$

Compare λ_1^s to θ_3, assuming that $\theta_3 \geq \lambda_1^s$:

$$\frac{\psi_3 - \beta\psi_2\psi_3 - 1}{\kappa} \geq \frac{-\phi_\pi}{1+\kappa\phi_\pi}$$

Substitute in for ψ_3 to obtain:

$$\phi_\pi \leq \frac{1+\phi_\pi}{1+\phi_\pi - \beta\psi_2(1+\phi_\pi)}$$

Multiply the denominator across, and group by ϕ_π terms:

$$\phi_\pi^2(1-\beta\psi_2) - \phi_\pi\beta\psi_2 - 1 \geq 0$$

Applying the quadratic formula yields:

$$\phi_\pi \geq \frac{\beta\psi_2 + \sqrt{\beta^2\psi_2^2 + 4(1-\beta\psi_2)}}{2-2\beta\psi_2}$$

A6 Proof of Proposition 5

Assume that $\psi_3 \geq \lambda_2^s$:

$$\frac{-1-\phi_\pi}{-1+\beta\psi_2-\phi_\pi+\beta\phi_\pi\psi_2-\phi_\pi\kappa-\kappa} \geq 1+\frac{-\phi_\pi\kappa}{1+\kappa\phi_\pi}$$

Clearing fractions and grouping by ϕ_π yields:

$$0 \leq \kappa\phi_\pi^2+\beta\phi_\pi\psi_2+\beta\psi_2-\kappa$$

The quadratic formula yields:

$$\phi_\pi \geq \frac{-\beta\psi_2+\kappa}{\kappa}$$

A7 Proof of Proposition 6

Following the above steps for solving the policy functions yields the NGDP targeting coefficients for $\tilde{y}_t$, $\tilde{\pi}_t$, and $\tilde{p}_t$ in response to a demand shock:

$$\theta_4 = \frac{\psi_4(1-\beta\psi_2)}{\kappa}$$
$$\psi_4 = \frac{-\sigma\kappa}{-\sigma + \sigma\beta\psi_2 - \phi_N + \phi_N\beta\psi_2 + \sigma\theta_2\kappa - \phi_N\kappa + \kappa\psi_2}$$
$$\tau_4 = \psi_4$$

and the inflation targeting coefficients for $\tilde{y}_t$ and $\tilde{\pi}_t$:

$$\lambda_1^d = \frac{1}{1 + \frac{\phi_\pi\kappa}{\sigma}}$$
$$\lambda_2^d = \frac{1}{1 + \phi_\pi\kappa}$$

Assume that output is more volatile under inflation targeting, and solve for ϕ_π:

$$\frac{1}{1 + \frac{\phi_\pi\kappa}{\sigma}} \geq \frac{\psi_4(1-\beta\psi_2)}{\kappa}$$
$$\frac{1}{1 + \phi_\pi\kappa} \geq \frac{-(1-\beta\psi_2)}{-1 + \beta\psi_2 - \phi_\pi + \phi_N\beta\psi_2 + \theta_2\kappa - \phi_\pi\kappa + \kappa\psi_2}$$
$$\phi_\pi(\beta\psi_2 - 1 - \beta\psi_2\kappa) \leq -\theta_2\kappa - \kappa\psi_2$$
$$\phi_\pi \geq \frac{-\theta_2\kappa - \kappa\psi_2}{\beta\psi_2 - 1 - \beta\psi_2\kappa}$$

A8 Proof of Proposition 7

Assume that inflation is more volatile under inflation targeting:

$$\frac{\kappa}{1+\phi_\pi\kappa} \geq \frac{-1}{-1+\beta\psi_2-\phi_\pi+\phi_\pi\beta\psi_2+\theta_2\kappa-\phi_\pi\kappa+\kappa\psi_2}$$

Clear fractions and solve for ϕ_π:

$$\frac{\beta\psi_2+\theta_2\kappa+\kappa\psi_2}{1-\beta\psi_2} \leq \phi_\pi$$

A9 Proof of Proposition 8

Plugging the policy functions into the NGDP targeting rule yields:

$$\tilde{i}_t = \phi_N \left(\varepsilon_t^d \left(\psi_4 + \frac{\psi_4 - \beta\psi_4\psi_2}{\kappa} \right) \right)$$

Simplifying the term inside parentheses yields:

$$\frac{-\sigma\kappa^2 - \sigma\kappa + \sigma\kappa\beta\psi_2}{-\sigma\kappa + \sigma\kappa\beta\psi_2 - \kappa\phi_N + \kappa\phi_N\beta\psi_2 + \sigma\kappa^2\theta_2 - \phi_N\kappa^2 + \kappa^2\psi_2}$$

As such, the nominal rate evolves according to:

$$\tilde{i}_t = \phi_N \left(\varepsilon_t^d \frac{-\sigma\kappa^2 - \sigma\kappa + \sigma\kappa\beta\psi_2}{-\sigma\kappa + \sigma\kappa\beta\psi_2 - \kappa\phi_N + \kappa\phi_N\beta\psi_2 + \sigma\kappa^2\theta_2 - \phi_N\kappa^2 + \kappa^2\psi_2} \right)$$

In comparison, inflation targeting yields:

$$\tilde{i}_t = \phi_\pi \frac{\kappa}{1 + \frac{\phi_\pi\kappa}{\sigma}} \varepsilon_t^d$$

Assume that the NGDP target leads to a more volatile nominal rate response. Then:

$$\frac{-\sigma\kappa^2 - \sigma\kappa + \sigma\kappa\beta\psi_2}{-\sigma\kappa + \sigma\kappa\beta\psi_2 - \kappa\phi_N + \kappa\phi_N\beta\psi_2 + \sigma\kappa^2\theta_2 - \phi_N\kappa^2 + \kappa^2\psi_2} \geq \frac{\kappa}{1 + \frac{\phi_\pi\kappa}{\sigma}}$$

Simplifying, and imposing $\sigma = 1$, leads to:

$$0 \leq 1 - \beta\psi_2 + \kappa\psi_2 - \kappa\beta\psi_2^2 + \kappa^2\psi_2$$

A10 Equilibrium Equations for the Quantitative Model

This model is similar to the Smets & Wouters (2007) model. It contains the typical medium-scale frictions. The model is solved for a zero-inflation and labor-of-unity steady state. Below, I list the equilibrium equations:

$$\mu_t = \frac{1}{C_t - \mathcal{H}C_{t-1}} - \beta \mathbb{E}_t \left[\frac{\mathcal{H}}{C_{t+1} - \mathcal{H}C_t} \right] \tag{A.29}$$

$$\chi L_t^{\eta} = mrs_t \mu_t \tag{A.30}$$

$$\mu_t = \mathbb{E}_t \left[\beta \mu_{t+1} \Pi_{t+1}^{-1} (1 + i_t) \right] + \nu_t \tag{A.31}$$

$$\Lambda_{t,t+1} = \beta \frac{\mathbb{E}_t[\mu_{t+1}]}{\mu_t} \tag{A.32}$$

$$w_t^* = \frac{\varepsilon_{w,t}}{\varepsilon_{w,t} - 1} \frac{f_{1,t}}{f_{2,t}} \tag{A.33}$$

$$f_{1,t} = mrs_t w_t^{\varepsilon_{w,t}} L_{d,t} + \phi_w \mathbb{E}_t \left[\Lambda_{t,t+1} \Pi_{t+1}^{\varepsilon_{w,t}} \Pi_t^{-\varepsilon_{w,t}\gamma_w} f_{1,t+1} \right] \tag{A.34}$$

$$f_{2,t} = w_t^{\varepsilon_{w,t}} L_{d,t} + \phi_w \mathbb{E}_t \left[\Lambda_{t,t+1} \Pi_{t+1}^{\varepsilon_{w,t}-1} \Pi_t^{(1-\varepsilon_{w,t})\gamma_w} f_{2,t+1} \right] \tag{A.35}$$

$$L_t = L_{d,t} v_t^w \tag{A.36}$$

$$v_t^w = (1 - \phi_w) \left(\frac{w_t^*}{w_t} \right)^{-\varepsilon_{w,t}} + \phi_w \left(\frac{\Pi_t}{\Pi_{t-1}^{\gamma_w}} \right)^{\varepsilon_{w,t}} \left(\frac{w_t}{w_{t-1}} \right)^{\varepsilon_{w,t}} v_{t-1}^w \tag{A.37}$$

$$w_t^{1-\varepsilon_{w,t}} = (1 - \phi_w)(w_t^*)^{1-\varepsilon_{w,t}} + \phi_w \left(\frac{\Pi_{t-1}^{\gamma_w}}{\Pi_t} w_{t-1} \right)^{1-\varepsilon_{w,t}} \tag{A.38}$$

$$p_t^* = \frac{\varepsilon_{p,t}}{\varepsilon_{p,t} - 1} \frac{x_{1,t}}{x_{2,t}} \tag{A.39}$$

$$x_{1,t} = p_{m,t} Y_t + \phi_p \mathbb{E}_t \left[\Lambda_{t,t+1} \Pi_t^{-\varepsilon_{p,t}\gamma_p} \Pi_{t+1}^{\varepsilon_{p,t}} x_{1,t+1} \right] \tag{A.40}$$

$$x_{2,t} = Y_t + \phi_p \mathbb{E}_t \left[\Lambda_{t,t+1} \Pi_t^{(1-\varepsilon_{p,t})\gamma_p} \Pi_{t+1}^{\varepsilon_{p,t}-1} x_{2,t+1} \right] \tag{A.41}$$

$$Y_{m,t} = Y_t v_t^p \tag{A.42}$$

$$v_t^p = (1 - \phi_p)(p_t^*)^{-\varepsilon_{p,t}} + \phi_p \Pi_t^{\varepsilon_{p,t}} \Pi_{t-1}^{-\varepsilon_{p,t}\gamma_p} v_{t-1}^p \tag{A.43}$$

$$1 = (1 - \phi_p)(p_t^*)^{1-\varepsilon_{p,t}} + \phi_p \Pi_{t-1}^{\gamma_p(1-\varepsilon_{p,t})} \Pi_t^{\varepsilon_{p,t}-1} \tag{A.44}$$

$$Y_{m,t} = A_t \left(u_t K_t\right)^{\alpha} L_{d,t}^{1-\alpha} \tag{A.45}$$

$$K_{t+1} = \hat{I}_t + (1 - \delta(u_t))K_t \tag{A.46}$$

$$w_t = (1-\alpha) p_{m,t} A_t (u_t K_t)^{\alpha} L_{d,t}^{-\alpha} \tag{A.47}$$

$$p_t^k \delta'(u_t) = p_{m,t} A_t \alpha (u_t K_t)^{\alpha-1} L_{d,t}^{1-\alpha} \tag{A.48}$$

$$p_t^k = \mathbb{E}_t \left[\alpha \Lambda_{t,t+1} p_{m,t+1} A_{t+1} u_{t+1}^{\alpha} K_{t+1}^{\alpha-1} L_{d,t+1}^{1-\alpha} + p_{t+1}^k (1 - \delta(u_t))\right] \tag{A.49}$$

$$\hat{I}_t = \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t \tag{A.50}$$

$$\ln(A_t) = \rho_a \ln(A_{t-1}) + \varepsilon_{a,t} \tag{A.51}$$

$$\ln(G_t) = (1-\rho_g)\ln(G_{ss}) + \rho_g \ln(G_{t-1}) + \varepsilon_{g,t} \tag{A.52}$$

$$\nu_t = \rho_\nu \nu_{t-1} + \varepsilon_{\nu,t} \tag{A.53}$$

$$cp_t = \frac{1}{\varepsilon_{p,t} - 1} \tag{A.54}$$

$$cp_t = (1-\rho_{cp}) cp_{ss} + \rho_{cp} cp_{t-1} + \varepsilon_{cp,t} \tag{A.55}$$

$$cpw_t = \frac{1}{\varepsilon_{w,t} - 1} \tag{A.56}$$

$$cpw_t = (1-\rho_{cpw_t}) cpw_{ss} + \rho_{cpw} cpw_{t-1} + \varepsilon_{cpw,t} \tag{A.57}$$

$$Y_t = C_t + I_t + G_t \tag{A.58}$$

$$Welf_t = \ln(C_t - hC_{t-1}) - \frac{\chi L_t^{1+\eta}}{1+\eta} + \beta \mathbb{E}_t \left[Welf_{t+1}\right] \tag{A.59}$$

$$\begin{aligned} 1 = (1+x_t) p_t^k \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] - (1+x_t) p_t^k \frac{I_t}{I_{t-1}} S'\left(\frac{I_t}{I_{t-1}}\right) \\ + \mathbb{E}_t \left[\Lambda_{t,t+1} (1+x_{t+1}) p_{t+1}^k \left(\frac{I_{t+1}}{I_t}\right)^2 S'\left(\frac{I_{t+1}}{I_t}\right)\right] \end{aligned} \tag{A.60}$$

$$\ln(1+x_t) = \rho_x \ln(1+x_{t-1}) + \varepsilon_{x,t} \tag{A.61}$$

$$\begin{aligned} \ln(1+i_t) = (1-\rho_r)\ln(1+i_{ss}) + \rho_r \ln(1+i_{t-1}) \\ + (1-\rho_r)\left[\phi_\pi \ln(\Pi_t) + \phi_y \left(\ln(Y_t) - \ln(Y_{t-1})\right)\right] + \varepsilon_{i,t} \end{aligned} \tag{A.62}$$

$$\varepsilon_{i,t} = \rho_i \varepsilon_{i,t-1} + \varepsilon_{r,t} \tag{A.63}$$

The unknown variables are μ, C, L, mrs, Π, i, Λ, w^*, f_1, f_2, L_d, v^w, w, p^*, x_1, x_2, p_m, Y, Y_m, v_p, A, u, K, $\hat{I}$, p_k, I, G, ε_p, ε_w, cp, cpw, x, ε_i, ν, and $Welf$.

A11 Parameter Values

Table A1

Estimated Parameter Values

		Prior			Posterior		
Parameter	Description	Mean	SD	Distribution	Mean	5%	95%
h	habit	0.600	0.100	Beta	0.7079	0.6763	0.7396
κ	I adj. costs	4.000	1.500	Normal	7.5340	5.8948	9.1730
η	inverse Frisch	1.000	0.100	Normal	1.0660	0.9105	1.2240
ϕ_p	Calvo prices	0.500	0.100	Beta	0.7066	0.4990	0.8495
ϕ_w	Calvo wages	0.500	0.100	Beta	0.8789	0.8440	0.9129
γ_p	price index.	0.500	0.150	Beta	0.1765	0.0529	0.2978
γ_w	wage index.	0.500	0.150	Beta	0.1404	0.0674	0.2107
ϕ_π	TR inflation	1.700	0.250	Normal	1.8694	1.3161	2.4122
ϕ_y	TR output	0.120	0.050	Normal	0.1815	0.1225	0.2408
ρ_r	TR persist.	0.800	0.050	Beta	0.5940	0.5248	0.6598
Shock Standard Deviations							
σ_r	i	0.100	1.000	Inv. Gam.	0.0120	0.0118	0.0123
σ_g	G	0.100	1.000	Inv. Gam.	0.0171	0.0154	0.0188
σ_{cp}	cost-push	0.100	1.000	Inv. Gam.	0.0186	0.0118	0.0256
σ_v	demand	0.100	1.000	Inv. Gam.	0.0145	0.0119	0.0167
σ_a	TFP	0.100	1.000	Inv. Gam.	0.0123	0.0118	0.0128
σ_{cpw}	w markup	0.100	1.000	Inv. Gam.	0.0340	0.0273	0.0405
σ_x	I	0.100	1.000	Inv. Gam.	0.1181	0.0878	0.1463
Shock Persistence Parameters							
ρ_i	i	0.400	0.200	Beta	0.0927	0.0100	0.1747
ρ_g	G	0.850	0.050	Beta	0.8540	0.7892	0.9209
ρ_{cp}	cost-push	0.600	0.200	Beta	0.6284	0.3383	0.9788
ρ_v	demand	0.600	0.200	Beta	0.6077	0.5271	0.6880
ρ_a	TFP	0.900	0.050	Beta	0.9275	0.8963	0.9595
ρ_{cpw}	w markup	0.600	0.200	Beta	0.8646	0.8064	0.9228
ρ_x	I	0.600	0.200	Beta	0.2807	0.1387	0.4257

A12 Variance Analysis

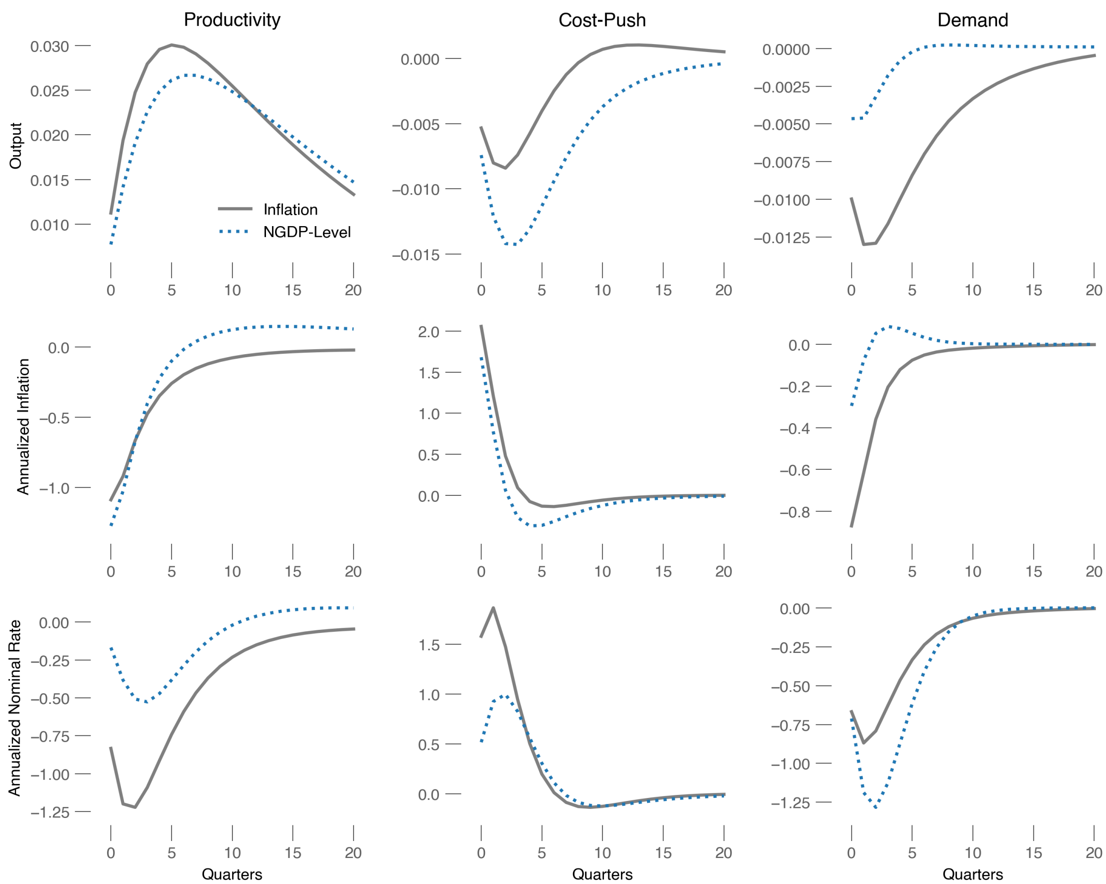


Figure 6: Impulse response functions of output, inflation, and the nominal rate to one-standard-deviation productivity, cost-push, and demand shocks.

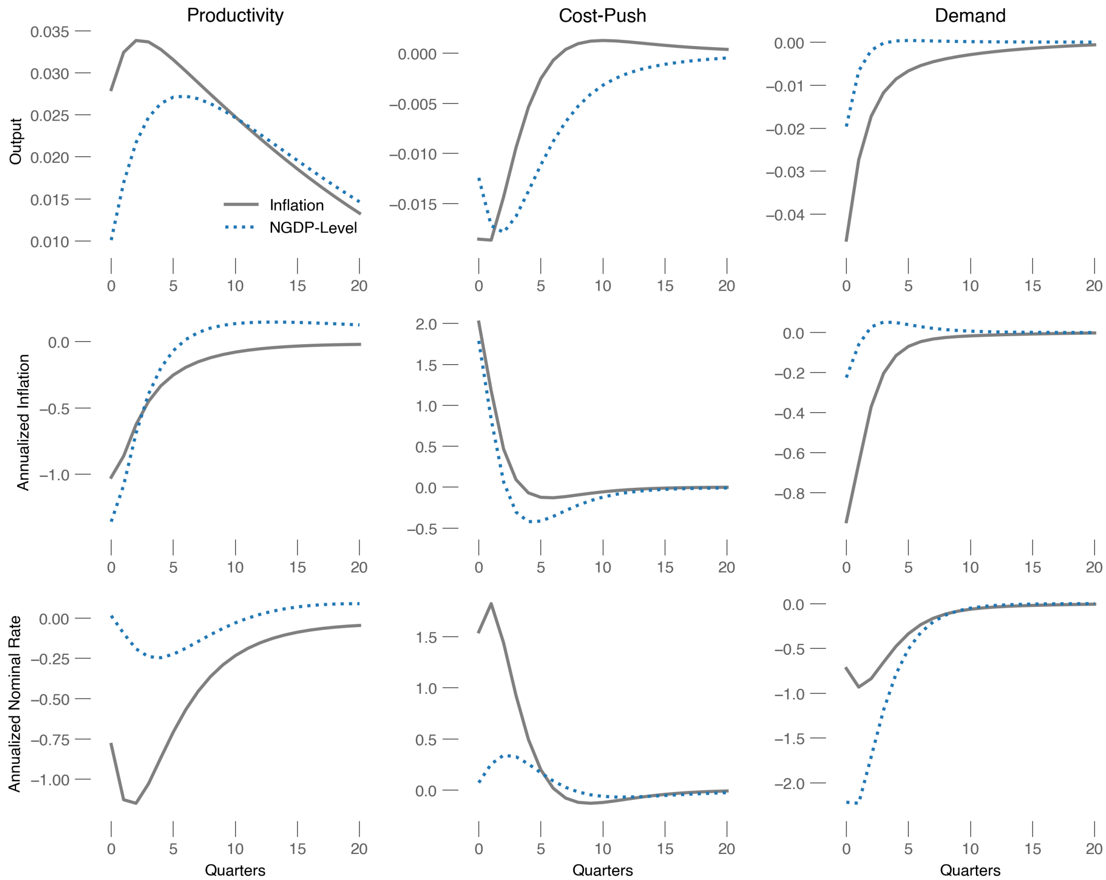


Figure 7: Impulse response functions of output, inflation, and the nominal rate to one-standard-deviation productivity, cost-push, and demand shocks. I set the habit parameter to zero.

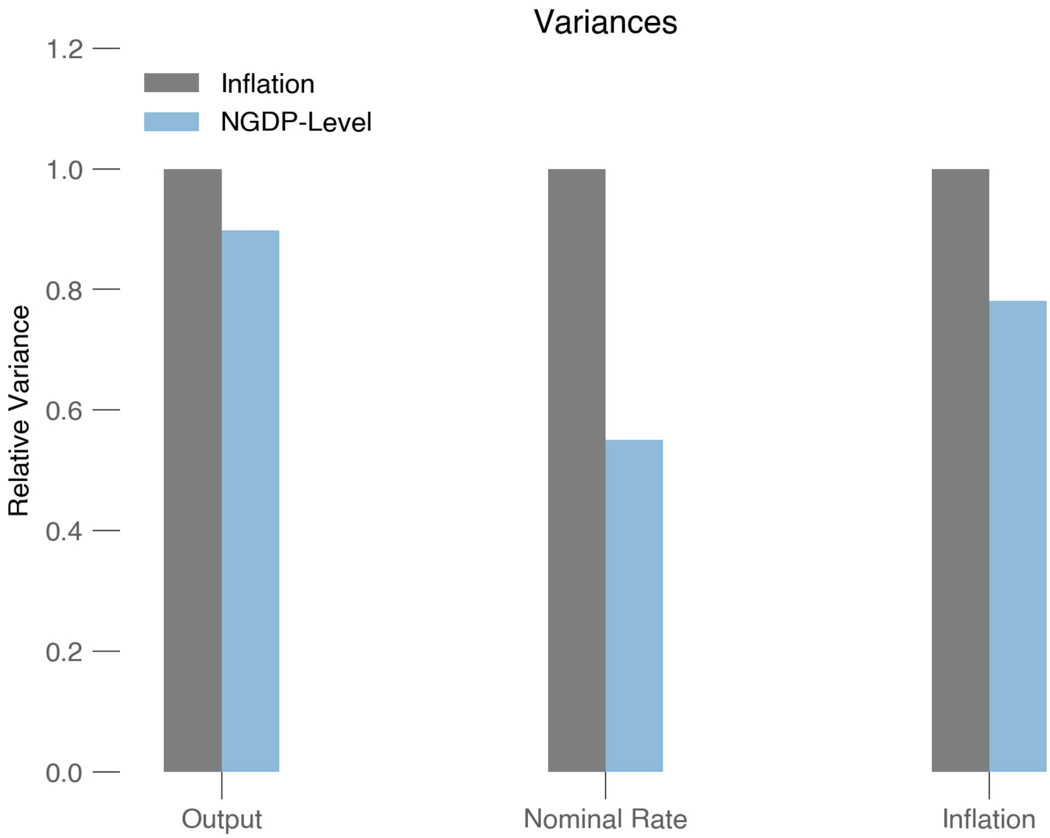


Figure 8: Variance of output, inflation, and the nominal rate relative to the respective variance under inflation targeting. Gray bar – inflation targeting. Blue bar – NGDP level targeting