R* and Convergence

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Abstract

We explore the natural rate of interest, shortly r^*, in emerging economies. If economic growth originates from convergence, then growth, say, from technological progress will be lower than we find in the data and, hence, r^* will be lower. Ignoring convergence upwardly biases our estimates of r^*. We extend the New Keynesian small open economy model to take account of convergence. The model is estimated with Bayesian techniques for four emerging economies in Central and Eastern Europe: Poland, Czech Republic, Hungary and Romania. The estimation process is informed by empirical evidence about a rapid catch-up of our example economies during the period from 2003 to 2019. We confirm the decline in r^* over the last decades. When we account for capital deepening, we find meaningful differences with non-negligible implications for monetary policy.

Keywords: natural rate of interest; convergence; New Keynesian DSGE model; Central and Eastern Europe

JEL classification: E3, E4, E5

Declarations:

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1 Introduction

Neoclassical growth theory predicts that economic convergence across countries arises from capital deepening. Economies that have less capital per worker (relative to their long-run capital per worker) tend to have higher growth rates and higher rates of return; a property that derives from the assumption of diminishing marginal returns to capital. Capital accumulation drives down the rate of return and, hence, the real rate of interest. As an economy develops, there is a tendency for the real rate of interest to fall over time. In a business cycle framework such as the New Keynesian model, the equilibrium real interest rate of the counterfactual economy without frictions is often referred to as the natural rate of interest, or Wicksellian rate or just r^*. This paper investigates the relationship between economic convergence and the natural rate of interest.

The accession to the European Union (EU) during the 2000s of emerging economies in Central and Eastern Europe (CEE) and the subsequent decade is a historical episode of rapid convergence that allows us to study the interaction between economic catch-up and the natural rate of interest. For this purpose, we present empirical evidence of beta convergence in a panel of European countries. Robust estimates of beta, in line with the iron law of convergence (Barro, 2012), inform our approximate level of the capital stocks of EU accession countries in the years after the end of the iron curtain.

We estimate the natural rate of interest in a New Keynesian dynamic stochastic general equilibrium (DSGE) model for small open economies with capital accumulation. The Bayesian estimation takes into account the transitional dynamics for the period between the years 2003 and 2019 for four emerging economies in CEE: Poland, Czech Republic, Hungary and Romania. In a way, the approach enables us to study long run growth and business cycles as well as its implications for monetary policy within a unified framework. We show that the evolutions of estimated equilibrium capital stocks match official capital stock calculations reasonably well. Ignoring convergence would lead to estimated steady state economic growth rates which are on average 20 % higher compared to the convergence model, i. e. growth is attributed erroneously to productivity growth rather than capital accumulation. In order to isolate the effects of convergence, we confront our estimates with a counterfactual model without convergence and show meaningful differences in the trajectories of the natural rates of interest. Furthermore, we gain new insights about the relationships between the natural rate of interest, the rental rate of capital and the return on capital. Finally, we discuss the implications for monetary policy in emerging economies if convergence is neglected.

Recently, it has been found that the open economy framework provides a better fit to the data than the closed economy counterpart (Zhang et al., 2021). Our four example economies are significantly open to international trade, foremost with the Euro Area, but small enough that domestic shocks or policies would not influence the world economy. While r^* has frequently been considered in an open economy set-up (Mesonnier and Renne, 2007; Berger and Kempa, 2014;

Pedersen, 2015; Wynne and Zhang, 2018), so far emerging economies in CEE are underrepresented (Grafe et al., 2018; Hledik and Vlček, 2018; Arena et al., 2020; Kupkovič et al., 2020).

Our exploration of economic convergence suggests a new perspective towards the secular drivers of r^*. While the literature about the natural rate of interest has grown rapidly during the last decade, the research focus has mostly been on the secular decline of r^* in advanced economies and its drivers.[1] The long-term decline of global real interest rates coincides with a fall in trend growth (Laubach and Williams, 2003; Del Negro et al., 2017,0; Gagnon et al., 2021; Holston et al., 2021). Demographic transition is a main determinant of the long-term decline in r^* (Kara and von Thadden, 2014; Carvalho et al., 2016; Lisack et al., 2017; Bielecki et al., 2020; Gagnon et al., 2021). Rachel and Smith (2017) take into account several drivers of the decline, including demographic changes, rising inequality, increased saving in emerging markets, the fall in the relative price of capital goods and lower demand for public investment. Summers (2014) notion of a new area of secular stagnation invoked research on the decline in r^* (Eggertsson et al., 2019; Rachel and Summers, 2019). Secular stagnation, coined originally by Hansen (1939), is associated with a reduction of investment demand, a declining rate of population growth, slowing technological progress, changes in the income distribution and a substantial decline or even permanently negative equilibrium rate of interest. Other branches in the literature emphasize a shortage in safe assets (Kirshnamurthy and Vissing-Jorgensen, 2012; Del Negro et al., 2017; Neri and Gerali, 2019; Ferreira and Shousha, 2023) or the 'global savings glut' resulting from an increase in desired savings and demand for safe assets in emerging economies (Bernanke, 2005; Bernanke et al., 2011). Taking stock of the prolonged periods of expansionary monetary policies in many economies, researchers investigate how (in contrast to the standard New Keynesian model) monetary policy can influence productivity growth and, hence, the natural rate of interest (Aghion et al., 2019; Bergeaud et al., 2019). Other, newer strands in the literature investigate the interaction of r^* and market concentration (Liu et al., 2022), wealth inequality (Fernández-Villaverde et al., 2021) or capital misallocation (Monacelli et al., 2018; Acharya et al., 2021; Asriyan et al., 2021; González et al., 2021).

The rest of the paper is organized as follows: Section 2 provides introductory empirical evidence of economic convergence. In section 3 we derive the New Keynesian small open economy framework. Section 4 describes the empirical estimation of the model. and section 5 present the results and discussion. The last section concludes.

2 Evidence of convergence

In this chapter, we provide evidence of economic convergence in Europe since the late 1990s. In the neoclassical growth model (Solow, 1956) convergence results from capital deepening. Capital

[1] A comprehensive overview about estimates of r^* and its drivers can be found, for example, in Brand et al. (2018).

accumulation leads to higher capital per worker and to a decrease of the marginal product of capital. The marginal product of capital equals the real interest rate, which equals r^* in the frictionless growth model. Hence, the convergence process coincides with a decline in r^*. Figure 1 shows facts about convergence in the four emerging economies in CEE, which we investigate: Poland, Czech Republic, Hungary and Romania. Since the turn of the millenium, the four countries show a substantial catch-up in real per capita gross domestic product (GDP). Between 1995 and 2019, real per capita GDP converged to Germany's GDP per capita by 30 % in Poland, 19 % in the Czech Republic, 19 % in Hungary and 24 % in Romania.

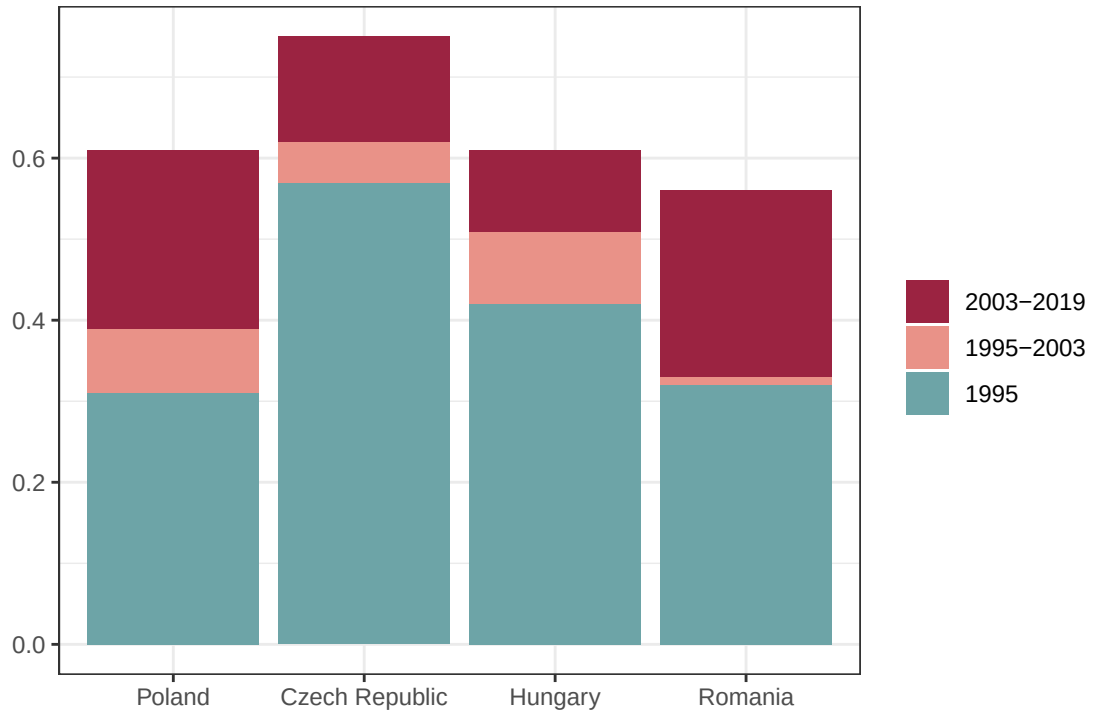


Figure 1: Convergence. The graph depicts real GDP per capita at purchasing power parities relative to Germany' GDP p. c.. Source: IMF World Economic Outlook (2021).

Next, we estimate growth regressions for a panel of European countries. Recently, Kremer et al. (2022) revisited the empirical tests of convergence in a global sample and cast doubt on the disillusion about convergence, which had spread during the 1990s. At this time, the data rather spoke for divergence in incomes across countries and time (see, for example Barro, 1991). Now that there are additional 25 years of economic development, Kremer et al. (2022) show evidence in favor of convergence, particularly after the turn of the millenium.

In table 1, we add evidence for a panel of 42 European countries and four periods, each of which spans five years starting in 1997 and ending in 2017.[2] We find that unconditional (absolute)

[2]We follow the most standard approach, testing for beta convergence by estimating OLS-regressions with fixed effects for periods (5-year), clustered at the country level, see Durlauf et al. (2005). The dependent variable is the average annual GDP per capita growth rate of the subsequent five-year period of the log GDP per capita variable. A detailed description of the sample and the definition and the sources of the variables is included in Appendix A.1.

convergence is broadly consistent with the "iron law" of convergence of 2 % per year (Barro, 2012). The unconditional convergence coefficient in specification (1) is 1.5 % and statistically significant. Specification (2) shows that convergence was fastest during the Eastern EU-enlargement between the years 2002 and 2007 (Poland, Czech Republic, and Hungary joined the EU in 2004 and Romania in 2007), when the convergence coefficient increases to 2.2 % (adding up 0.9 % and 1.3 %). It remains statistically significant and sizeable at 1.8 % (adding up 0.9 % and 0.9 %) during the subsequent five years (2008-2012). Specification (3) reveals that annual absolute convergence was of the magnitude of 2.3 % for EU countries (summing up 1.2 % and 1.1 %). Compared to Kremer et al. (2022), who find a coefficient of 0.7 % between 2005 and 2015 in a global sample, unconditional convergence in Europe appears higher for that time. Furthermore, specification (4) reveals that convergence was driven by emerging countries in CEE. The convergence coefficient increases to 2.7 % (adding up -0.1 % and 2.8 %).

Table 1: Absolute and conditional convergence in Europe between 1997 and 2017

	(1)	(2)	(3)	(4)	(5)	(6)
Log GDP p.c.	-0.015***	-0.009*	-0.012***	-0.013***	-0.020***	-0.014**
	(0.003)	(0.005)	(0.003)	(0.003)	(0.007)	(0.007)
2003-2007	0.012***	0.145***	0.013***	0.013***	0.011**	0.013***
	(0.004)	(0.050)	(0.004)	(0.004)	(0.005)	(0.005)
2008-2012	-0.027***	0.063	-0.025***	-0.025***	-0.026***	-0.024***
	(0.004)	(0.049)	(0.004)	(0.004)	(0.005)	(0.005)
2013-2017	-0.006*	-0.036	-0.005	-0.005	-0.004	-0.004
	(0.003)	(0.070)	(0.004)	(0.004)	(0.006)	(0.006)
2003-2007 × Log GDP p.c.		-0.013***				
		(0.005)				
2008-2012 × Log GDP p.c.		-0.009*				
		(0.005)				
2013-2017 × Log GDP p.c.		0.003				
		(0.007)				
EU × Log GDP p.c.			-0.011*			
			(0.006)			
EU			0.117*			
			(0.064)			
EU_CEE × Log GDP p.c.				-0.016*		
				(0.008)		
EU_CEE				0.170**		
				(0.084)		
Constant	0.176***	0.123**	0.147***	0.155***	0.204***	0.176***
	(0.028)	(0.051)	(0.030)	(0.027)	(0.065)	(0.067)
Growth correlates (controls)	no	no	no	no	yes	yes
Instrumental variable	no	no	no	no	no	yes
Observations	166	166	166	166	135	135

Cluster-robust standard errors are reported in parentheses. Time fixed effects. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Sources: own calculations, data from IMF WEO and IFS, Penn World Table, World Bank, Barro and Lee (2013).

The specifications (5) to (6) in table 1 show evidence of conditional convergence. The Solow fundamentals, i. e. the average annual investment rate, the population growth rate and the growth rate of the labor force, are added to the regression. Further growth correlates in specifications (5) and (6) are annual averages of a proxy for institutions, years of schooling, trade openness, growth of credit to the private sector, foreign direct investment (FDI) and public debt to GDP. The convergence coefficient remains statistically significant and around 2.0 % (specification (5)). Applying a two-stage-least-squares approach in specification (6) with base year values as instruments, except for the initial GDP per capita variable in which case the lag is used, shows consistent results with a convergence coefficient of 1.4 %.[3] Since we have now presented some evidence of economic convergence, we return to the analysis of the natural rate of interest in a model framework and estimation procedure allowing for convergence.

3 The New Keynesian small open economy model

We consider a model of a small open economy with staggered price setting that builds on the framework developed by Galí and Monacelli (2005). In this framework, the size of the home economy is negligible relative to that of the world economy, therefore world aggregates (output, inflation) can be taken as exogenous. We extend the model by capital accumulation that is subject to adjustment costs (see Galí and Monacelli (2016)). A similar framework for studying the natural rate of interest but without capital accumulation is derived in Zhang et al. (2021). We incorporate a preference shock, a markup shock, a terms of trade shock and a non-stationary shock process for technological progress as in Zhang et al. (2021); apart from a standard monetary policy shock. Additionally, our model features an investment shock as in Justiniano et al. (2010), Justiniano et al. (2011)), which has been found recently to play an important role also in emerging economies (Dogan, 2019). For simplicity, we stick to a version of the small open economy model in which the law of one price holds under producer currency pricing. For a richer small open economy model featuring imperfect pass-through, Caraiani (2013) finds that the estimation results for CEE are generally similar. Furthermore, we assume complete international assets markets, for which McKnight et al. (2020) find favorable evidence among emerging economies in Latin America. The Bayesian estimation is described in the subsequent section 4.

[3]The detailed regression tables including all control variables are in appendix A.1. Particularly, in specification (5) in table 1 higher investment and more rapid growth of the labor force are positively (and statistically significantly) associated with GDP per capita growth while population growth shows a negative correlation. Years of schooling and FDI are positively and stastically significantly associated with p. c. GDP growth. High public debt ratios are associated with lower GDP p. c. growth. Credit to the private sector is negatively correlated with GDP per capita growth, which might be due to the fact that credit to GDP ratios are higher in more advanced countries as well as Southern European countries. The measures of institutional quality and trade openness are not found to be statistically significant.

3.1 Domestic households

The small open economy is inhabited by a representative household who solves the lifetime utility maximization problem

$$E_0 \sum_{t=0}^{\infty} \beta^t e^{-g_t} \left[\frac{C_t^{1-\frac{1}{\tau}}}{1-\frac{1}{\tau}} - \frac{N_t^{1+\varphi}}{1+\varphi} \right], \tag{1}$$

where N_t are the hours worked and C_t is the aggregate consumption index,

$$C_t \equiv \left[(1-\gamma)^{\frac{1}{\eta}} (C_{H,t})^{\frac{\eta-1}{\eta}} + \gamma (C_{F,t})^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}, \tag{2}$$

and $C_{H,t}$ is a composite of differentiated domestic goods,

$$C_{H,t} \equiv \left(\int_0^1 C_{H,t}(i)^{\frac{\epsilon_t-1}{\epsilon_t}} di \right)^{\frac{\epsilon_t}{\epsilon_t-1}}, \tag{3}$$

and $C_{F,t}$ an analogous composite of imported goods, where $i \in [0, 1]$ denotes the home goods varieties. The parameter τ is the elasticity of intertemporal substitution, $\varphi > 0$ denotes the inverse of the Frisch elasticity of labor supply, $\eta > 0$ is the substitution between home and foreign goods, $0 < \gamma < 1$ is a measure for the degree of openness, and $\epsilon_t > 1$ is the elasticity of substitution between product varieties. The discount factor is denoted by $0 < \beta < 1$.[4] The investment index, I_t, can be defined in analogy to the consumption index (with identical weights and substitution elasticities). An exogenous preference shock g_t is introduced following a stationary AR(1) process:

$$g_t = \rho_g g_{t-1} + \varepsilon_{g,t},\ \varepsilon_{g,t} \sim N(0, \sigma_g), \tag{4}$$

where $-1 < \rho_g < 1$ and σ_g measures persistence and volatility. The representative household invests in financial assets and accumulates physical capital, which it rents out to firms. The household's optimization problem is subject to the budget constraint that is

$$P_t C_t + P_t I_t + E_t(\Lambda_{t,t+1} D_{t+1}) \leq W_t N_t + R_t^K K_{t-1} + D_t + T_t + Pr_t. \tag{5}$$

where $P_t \equiv \left[(1-\gamma)(P_{H,t})^{1-\eta} + \gamma (P_{F,t})^{1-\eta} \right]^{\frac{1}{1-\eta}}$ is the price level of the domestic bundle of consumption goods, C_t, and $P_{H,t}$ and $P_{F,t}$ are the sub-indices of the domestically-produced and imported goods. I_t is an equivalent bundle of investment goods, W_t is the nominal wage, and Pr_t denotes the profits accrued from the ownership of the domestic firms. The nominal holdings of Arrow-Debreu securities are denoted by D_t and $\Lambda_{t,t+1}$ is the state-contingent price of the security. K_{t-1} denotes capital and R_t^K is the rental rate of capital. T_t is a lump-sum tax raised by the

[4] In order to avoid misunderstanding, the beta referring to convergence of the growth regressions in section 2 is written out, the discount factor is the greek letter, β, and the Beta distribution, appearing later, is written with a capital.

domestic government. The accumulation of capital subject to investment adjustment costs obeys

$$K_t = (1-\delta) K_{t-1} + I_t \nu_t \left[1 - \frac{\kappa_I}{2}\left(\frac{I_t}{I_{t-1}} - \widetilde{\Gamma}_A\right)^2\right], \tag{6}$$

where $\widetilde{\Gamma}_A = \Gamma_A^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}$, which is the gross steady-state growth rate of productivity. Investment in a final composite good is denoted by I_t, $0 \leq \delta \leq 1$ is the rate of physical depreciation, and $\kappa_I \geq 0$ is a parameter that scales the size of (quadratic) adjustment costs in investment. Additionally, we introduce an investment shock, ν_t, as in Justiniano et al. (2010,0). It is a shock to the marginal efficiency of investment and represents an exogenous disturbance to the process by which investment goods are transformed into installed capital or technological factors specific to the production of investment goods. It follows an AR(1) process,

$$\nu_t = \rho_\nu \nu_{t-1} + \varepsilon_{\nu,t},\ \varepsilon_{\nu,t} \sim N(0, \sigma_\nu), \tag{7}$$

where $-1 < \rho_\nu < 1$ and σ_ν measures persistence and volatility.

3.2 Domestic firms

Each intermediate goods producing domestic firm j produces a homogenous good according to the CRS production function

$$Y_t(j) = K_{t-1}(j)^\alpha \left[A_t N_t(j)\right]^{1-\alpha}, \tag{8}$$

where A_t is labor-augmenting, aggregate total factor productivity (TFP) and $K_{t-1}(j)$ and $N_t(j)$ denote capital and labor employed by the j-th firm. Productivity grows at a rate $z_t = ln(\Gamma_{A,t})$, where $\Gamma_{A,t} = \frac{A_t}{A_{t-1}}$ and z_t follows an AR(1) process

$$z_t = \rho_z z_{t-1} + \varepsilon_{z,t},\ \varepsilon_{z,t} \sim N(0, \sigma_z), \tag{9}$$

where $-1 < \rho_z < 1$ and σ_z measure persistence and volatility.

With $Y_t \equiv \left(\int_0^1 Y_t(j)^{\frac{\epsilon_t - 1}{\epsilon_t}} dj\right)^{\frac{\epsilon_t}{\epsilon_t - 1}}$ representing the aggregate index for domestic output, firm j faces demand equal to $Y_t(j) = \left(\frac{P_{H,t}(j)}{P_{H,t}}\right)^{-\epsilon_t} Y_t^d = \left(\frac{P_{H,t}(j)}{P_{H,t}}\right)^{-\epsilon_t} \left(C_{H,t} + C_{H,t}^f\right)$. The last step assumes that firms operate under producer-currency pricing such that they set the same price in units of the domestic currency irrespective of whether the goods are sold locally or exported. This assumption implies that the law of one price holds at the variety level, i. e. $P_{H,t}(j) = S_t P_{H,t}^f(j)$, where S_t is the bilateral exchange rate.

Firms set prices in a staggered fashion as in Calvo (1983), where $0 < \theta < 1$ is the constant probability that a firm keeps its price fixed in a given period. Following Del Negro and Schorfheide (2013) we depart from Calvo (1983) in assuming that for those firms that cannot adjust prices,

$P_{H,t}(j)$ will increase at the geometric weighted average with weights $1-\iota_P$ and ι_p, respectively, of the steady state inflation, $\bar{\pi}_H$, and of last period's inflation. Firms that are able to optimally update their price in period t choose the reset price $\widetilde{P}_{H,t}(j)$ to maximize the expected value of current and future profits,

$$\left(\widetilde{P}_{H,t}(j)-(1-\phi)\,mc_t P_{H,t}\right)Y_t(j)+$$
$$E_t\sum_{s=0}^{\infty}\theta^s\Lambda_{t,t+s}\left[\widetilde{P}_{H,t}(j)\left(\prod_{l=1}^{s}\pi_{H,t+l-1}^{\iota_P}\bar{\pi}_H^{1-\iota_P}\right)-(1-\phi)\,mc_{t+s}P_{H,t+s}\right]Y_{t+s}(j), \tag{10}$$

where $\Lambda_{t,t+s}=\beta^s e^{-\frac{g_{t+s}}{g_t}}\left(\frac{C_{t+s}}{C_t}\right)^{-\frac{1}{\tau}}\frac{P_t}{P_{t+s}}$ and ϕ refers to a labor subsidy funded by the domestic government (see Zhang et al. (2021)). The sequence of demand constraints that the re-optimizing firm is facing reads:

$$Y_{t+s}(j)\leq\left(\frac{\widetilde{P}_{H,t}(j)\left(\prod_{l=1}^{s}\pi_{H,t+l-1}^{\iota_P}\bar{\pi}_H^{1-\iota_P}\right)}{P_{H,t+s}}\right)^{-\epsilon_t}\left(C_{H,t+s}+C_{H,t+s}^{f}\right), \tag{11}$$

where $C_{H,t}^{f}$ refers to the foreign consumption of domestic goods. The domestic government sets the labor subsidy such that it compensates the price markup in the steady state, $\mu\equiv(1-\phi)\frac{\epsilon}{\epsilon-1}=1$. Therefore, the markups can vary over time in the short-run but do not have an effect in the long-run. We define $u_t=ln(\mu_t)$ following an AR(1) process,

$$u_t=\rho_u u_{t-1}+\varepsilon_{u,t},\ \varepsilon_{u,t}\sim N(0,\sigma_u), \tag{12}$$

where $-1<\rho_u<1$ and σ_u measure persistence and volatility. The law of motion for prices is then given by:

$$P_{H,t} = \left[(1-\theta)\widetilde{P}_{H,t}^{1-\epsilon}+\theta\left(\pi_{H,t-1}^{\iota_P}\bar{\pi}_H^{1-\iota_P}P_{H,t-1}\right)^{1-\epsilon}\right]^{\frac{1}{1-\epsilon}} \tag{13}$$

3.3 Other equilibrium conditions and market clearing

The foreign economy is assumed to be large and an almost closed economy. The foreign country's demand for domestic goods is set up symmetrically to home goods and under the assumption of complete international asset markets, the foreign country has access to the domestic (currency denominated) Arrow-Debreu securities. Together with the definition of the bilateral real exchange rate, $RER_t=\frac{P_t^f S_t}{P_t}$, we can write

$$C_t=\upsilon C_t^f\left(RER_t\right)^{\tau}, \tag{14}$$

where υ is a constant that depends on the initial conditions regarding relative net asset positions. If the law of one price holds under producer-currency pricing, the terms of trade are defined as

$$TOT_t \equiv \frac{P_{F,t}}{S_t P^f_{H,t}} = \frac{P_{F,t}}{P_{H,t}}. \tag{15}$$

Given that the law of one price holds, goods market clearing in the foreign and in the domestic economy yields the risk sharing condition,

$$Y_t = \left(\frac{P_{H,t}}{P_t}\right)^{-\eta} \left[(1-\gamma)(C_t + I_t) + \gamma (RER_t)^{\eta} Y^f_t\right]. \tag{16}$$

Furthermore, the foreign economy inflation, π^f_t, and output, Y^f_t, are assumed to follow AR(1) processes,

$$\pi^f_t = \rho_\pi \pi^f_{t-1} + \varepsilon_{\pi,t},\ \varepsilon_{\pi,t} \sim N(0,\ \sigma_\pi), \tag{17}$$

respectively

$$Y^f_t = \rho_{Yf} Y^f_{t-1} + \varepsilon_{Yf,t},\ \varepsilon_{Yf,t} \sim N(0,\ \sigma_{Yf}). \tag{18}$$

Monetary policy is set according to a standard Taylor-rule specified as

$$\frac{1+i_t}{1+i} = \left(\frac{1+i_{t-1}}{1+i}\right)^{\rho_i} \left[\left(\frac{\pi_t}{\pi}\right)^{\psi_\pi} \left(\frac{Y_t}{Y^n_t}\right)^{\psi_Y}\right]^{1-\rho_i} \varepsilon^{\sigma_i}_{i,t}. \tag{19}$$

The response of the monetary policy interest rate (i. e. the short term interest rate) to inflation and the ouput gap is given by $\psi_\pi > 0$ and $\psi_Y \geq 0$. The inertia parameter ρ_i links the monetary policy rate to its lagged value and $\varepsilon_{i,t}$ is a monetary policy shock with standard deviation σ_i. Inflation is defined as the percent deviation from steady-state inflation and the output gap is defined the percent deviation form the natural output Y^n_t. Since domestic aggregate total factor productivity has a growing trend A_t, the model is stationarized by defining variables in relation to A_t. The full set of the stationarized first order and equilibrium conditions and the equations of the natural output of the economy are listed in appendix A.2.

4 Empirical estimation

In this chapter, we present the econometric methodology and describe the data set. Then, we briefly explain how we allow for economic convergence in the estimation of the model and present the choice of prior assumptions for Bayesian inference.

4.1 Methodology

The Bayesian estimation mainly follows the methodology of Lubik and Schorfheide (2007) for small open economies as in Galí and Monacelli (2005). The vector of observed variables Y_t includes quarterly growth rates in real output, real gross fixed capital formation, the (annualized) inflation rate, the nominal exchange rate and the terms of trade, and the nominal 3-months interbank interest rate and relates to the model variables as follows:

$$Y_t = \begin{bmatrix} \frac{\tau+\tau\varphi}{1+\tau\varphi}\Gamma_Q + \left(\Delta\frac{Y_{A,\,t}}{Y_A^{ss}} + \frac{\tau+\tau\varphi}{1+\tau\varphi}\frac{A_t}{A^{ss}}\right) * 100, \\ \frac{\tau+\tau\varphi}{1+\tau\varphi}\Gamma_Q + \left(\Delta\frac{I_{A,\,t}}{I_A^{ss}} + \frac{\tau+\tau\varphi}{1+\tau\varphi}\frac{A_t}{A^{ss}}\right) * 100, \\ \pi_A + ln\left(\frac{\pi_t}{\pi^{ss}}\right) * 400, \\ ConsNER + \left(\Delta\frac{RER_t}{RER^{ss}} + ln\frac{\pi_t}{\pi^{ss}} - ln\frac{\pi_t^f}{1}\right) * 100, \\ ConsTOT - (TOT_t - TOT_{t-1}) * 100, \\ \pi_A + r_A + \frac{\tau+\tau\varphi}{1+\tau\varphi}\Gamma_Q * 4 + ln\left(\frac{i_t}{i^{ss}}\right) * 400 \end{bmatrix}$$

The observables enter the model in levels, i. e. the observed variables are not demeaned as in Lubik and Schorfheide (2007). Recall that the model variables enter in their stationarized form, i. e. adjusted by productivity A_t. Hence, the observed output growth corresponds to the sum of output growth and productivity growth, Γ_Q. Γ_Q is estimated and linked to the structural parameters of the model. Further steady state-related parameters, which have to be estimated, are π_A, $ConsNER$, $ConsTOT$ and r_A relating to the inflation rate, the nominal exchange rate, the terms of trade and the interest rate.[5] Therefore, the model takes into account non-zero growth and inflation in the steady state and the discount factor, β is estimated as well. The likelihood function is constructed using the Kalman filter based on the state-space representation of the model. Through the likelihood function the data is used to update a prior distribution (section 4.3). Markov Chain Monte Carlo (MCMC) simulation is used to generate parameter draws from the posterior distributions. The posterior mode, obtained by maximizing the log posterior kernel, is chosen as the starting point for the the Metropolis-Hastings algorithm sampling the posterior distribution of the parameters. The number of replications of the Metropolis-Hastings sampler is set to 250,000 and the number of parallel chains for the Metropolis-Hastings algorithm is set at 2. Drawing the proposal from a jumping distribution, the scale factor that multiplies the inverse of the Hessian matrix that is computed at the posterior mode (i. e. the variance) is chosen as 0.35, which leads to an acceptance rate between around 0.2 to 0.25.

[5] Here, Δ is defined as the log-dfference.

4.2 Data description

The sample covers 68 observations at quarterly frequency and spans the period between Q1 2003 and Q4 2019. Real gross domestic product (output) and real gross fixed capital formation (investment) are calendar and seasonally adjusted (chained, 2010 reference year). Inflation rates are based on the seasonally-adjusted Harmonized Index of Consumer Prices (HICP) at constant taxes (all-items) and defined as log differences multiplied by 400 to obtain annualized percentage changes. Since the Euro Area is the main trading partner of the four countries, nominal exchange rates are expressed in local currency per Euro and extracted from Macrobond Financial AB. The terms of trade are calculated by dividing the calendar and seasonally adjusted price index of imports of goods and services by the price index of exports of goods and services; both in local currencies. Percentage changes in output, investment, the terms of trade, and the nominal exchange rates are obtained by multipliying the quarterly log differences by 100. The main monetary policy interest rates are approximated by 3-month interbank interest rates and extracted from Refinitiv Eikon (expect for the Czech 3-month interbank rate (PRIBOR), which is downladed directly from the Czech National Bank). Note that the time series are not demeaned. Except for the 3-month interbank interest rates, and nominal exchange rates, the data source is Eurostat (ESA 2010) and, therefore, consistent across the four EU member countries. While r^*-estimates for advanced economies often cover considerably longer periods (for example, the time series of Holston et al. (2017) start in 1961), the four countries officially adopted inflation-targeting regimes in 1998 (Czech Republic), 1999 (Poland), 2001 (Hungary) and 2005 (Romania), partly following periods of stark disinflation after the fall of the iron curtain in 1989 and preparing for European Union membership in 2004 (Poland, Czech Republic, Hungary) and 2007 (Romania). The data description is summarized in Table 11 in the appendix.

4.3 Choice of priors

The prior distributions are mostly chosen in accordance with Lubik and Schorfheide (2007) and Zhang et al. (2021) and summarized in table 2. Basically, prior densities, means and standard deviations are set identical for all four countries, although some country-specific differences arose during the estimation process, which are discussed below (section 5.1). For the inverse Frisch elasticity of labor supply and the elasticity of substitution between home and foreign goods we choose Gamma distributions with prior means of 1.5 respectively 1.0, as in Zhang et al. (2021). The priors of the parameters of the monetary policy rule are centered around values, which are typically associated with standard Taylor rules (0.5 and 1.5 for ψ_x respectively ψ_π). The smoothing parameter of the monetary policy rule, ρ_i, has a prior mean of 0.5.

The prior assumptions of the parameter of trade openness, γ, deserve some attention, since it seems that there is no consensus in the literature. Lubik and Schorfheide (2007) use a prior

Parameter	Description	Range	Density	Mean	Std. Dev.
φ	inverse Frisch	(0,10]	Gamma	1.50	0.50
η	elasticity H-F goods	(0,10]	Gamma	1.00	0.20
τ	intertemporal ES	(0,1)	Beta	0.50	0.20
γ	trade openness	[0,1)	Beta	0.30 (0.40)	0.05
θ	Calvo parameter	(0,1]	Beta	0.66	0.20
α	factor shares	[0,1)	Normal	0.30	0.05
κ_I	investment adjustment cost	[2,20]	Normal	4.00	1.50
δ	depreciation rate	(0,0.05]	Gamma	0.025	0.010
ψ_Y	monetary rule, output	(0,5]	Gamma	0.50	0.25
ψ_π	monetary rule, inflation	(1,10]	Gamma	1.50	0.50
ρ_i	monetary rule, smoothing	(0,1)	Beta	0.50	0.20
r_A	interest rate level	(0,2]	Gamma	1.00	0.20
π_A	inflation level	(0,12]	Gamma	4.00	20
Γ_Q	output level	(0,2]	Normal	0.75	0.20
$consTOT$	ToT level	[-2,2]	Normal	0.0	0.10
$consNER$	exchange rate level	[-2,2]	Normal	0.0	0.10
ι_P	inflation indexation	(0,1]	Beta	0.50	0.10
ρ_a	technology persistence	(0,1)	Beta	0.20	0.10
ρ_{y^f}	world output persistence	(0,1)	Beta	0.90	0.05
ρ_{π^f}	world inflation persistence	(0,1)	Beta	0.80	0.10
ρ_g	preference persistence	(0,1)	Beta	0.20	0.10
ρ_u	markup persistence	(0,1)	Beta	0.80	0.10
ρ_ν	investment persistence	(0,1)	Beta	0.80	0.10
σ_i	std. dev. MP rule	(0,10]	InvGamma	0.50	0.20
σ_q	std. dev. terms of trade	(0,10]	InvGamma	1.50	0.55
σ_z	std. dev. technology	(0,10]	InvGamma	1.00	0.35
σ_{y^f}	std. dev. world output	(0,10]	InvGamma	1.50	0.35
σ_{π^f}	std. dev. world inflation	(0,10]	InvGamma	0.55	0.20
σ_g	std. dev. preference	(0,10]	InvGamma	0.25	0.10
σ_u	std. dev. markup	(0,10]	InvGamma	0.55	0.20
σ_ν	std. dev. investment	(0,1]	InvGamma	0.25	0.10

Table 2: Prior distributions of the parameters.

tightly centered at 0.2, while Zhang et al. (2021) take the import shares, calculated as the average of imports of goods and services to GDP over the sample period. In our case, imports of goods and services to GDP between 2003 and 2019 averaged 43 % in case of Poland, 65 % for the Czech Republic, 75 % for Hungary and 39 % for Romania (source: World Development Indicators, World Bank). Note that these shares are much higher than the import shares of the (advanced) economies in Zhang et al. (2021), which average 0.24 across six developed economies. In CEE, firms are typically part of international supply chains, for example in the automotive sector. Intermediate goods are imported for production (assembling) and exported for final consumption abroad. However, in the model, the parameter γ is the share of foreign goods imported for domestic consumption (see equation (2)), which in our cases can differ significantly from the import share. McKnight

et al. (2020) proxy the trade openness by the ratio of the average share of real imports in GDP to the average share of real consumptions to GDP. If we used this approximation, the prior means would have to be set even higher. Alternatively, if we crosscheck with data from the last World Input-Output Database (WIOD, 2016 release) of the University of Groningen, the share of imports from all countries for final use for household consumption of total household consumption is 0.17 in case of Poland, 0.21 for Czech Republic, 0.22 for Hungary and 0.14 for Romania. In the base case, we set the mean prior of γ at 0.30 respectively 0.40; see below for further discussion.

The elasticity of intertemporal substitution, τ, has a Beta prior, which is centered at 0.5. The Calvo parameter for price stickiness is also assumed to follow a Beta distribution and has a prior mean of 0.66. The assumption of a normal prior with mean of 0.3 is applied for the factor share, α. Investment adjustment cost has a normal prior with mean 4.0 (see Smets and Wouters (2003)). For the priors of the exogenous shock processes, Lubik and Schorfheide (2007) conduct a pre-sample analysis for world output, inflation and domestic technology and we follow their prior specifications of the persistence and standard deviation parameters. The specifications of persistence and standard deviation parameters of the domestic preference shock and the domestic cost-push shock are set as in Zhang et al. (2021). Persistence and standard deviation of the investment shock is assumed to follow a Beta distribution with prior mean of 0.80 and an inverse Gamma prior with a mean of 0.25.

4.4 Convergence

As emphasized, our four example economies we estimate the model on have experienced a process of rapid convergence over our estimation horizon. Their experience is thus markedly different than for a typical advanced economy, on which model estimation is typically performed. Our model with capital allows us to explicitly capture the idea that part of the behavior of our observable macroeconomic time series of our four CEE countries is driven by a process of capital accumulation, via which these economies are catching up to their respective long run growth path, i.e. convergence taking place. In technical terms, we proceed as follows. In the estimation process, the DSGE model solution – for each parameter draw – is mapped into the format of the Kalman filter, which is a linear filter consisting of a transition equation for observables and and an equation for transition of (latent) state variables. The state vector is equal to the vector of state variables of the DSGE model itself, both exogenous (shock processes) and endogenous, which, importantly, includes the capital stock. Variables are expressed in terms of (percentage) deviations from their respective steady state.

A common choice in estimation of macroeconomic models is to initialize the state vector of the Kalman filter at the stationary distribution, i.e. to choose an initial state vector of zeros (state variables being zero percent away from their steady state) and setting the initial matrix of the

variance of the error of forecast equal to the unconditional variance of the state variables. This logic makes sense for advanced economies, for which case fluctuations in their time series largely reflect fluctuations around their growth path. For our CEE economies, however, fluctuations in the macroeconomic time series of these countries, to a large degree reflect the process of capital accumulation. To account for this, we initialize the starting value of the state vector pertaining to the capital stock to below steady state, while currently keeping the initialization of the error of forecast at the unconditional variance of the state variables as well.[6]

Since we assume that the capital stocks are not observed, we make use of the empirical beta estimates of convergence (section 2) to help us identify the approximate initial level of the capital stocks. According to our regressions, if we assume a $beta = 0.02$, i.e. annual catch-up of 2 %, for a period of 17 years between 2003 and 2019, the initial level of the capital stocks is assumed approximately 29 % below the steady state level, i. e. $K_{i,Q1\,2003} = 0.71 * K_{i,ss}$, where $K_{i,ss}$ is the steady state capital of country i. In our baseline approach to initialize capital stocks, we therefore do not allow for differences of our four CEE countries; however, in section **??** we explore an alternative approach to find guidance for initial levels of the capital stock of the four economies individually.

5 Results

5.1 Baseline estimation

In the section, the estimation results of the small open economy model allowing for convergence are presented. Table 3 shows the posterior means and 90 % posterior probaility intervals of the structural, policy and steady state-related model parameters. Table 4 shows the posterior means of the persistence parameters and standard devations of the shock processes. The parameters of the Taylor rule indicate that central banks in CEE respond strongly to changes of inflation with posterior estimates of ψ_π far beyond the prior assumption (2.6 versus 1.5), while the response to changes in the output gap appears benign. The anti-inflationary bias may be due to previously high inflation during the transition from former socialist regimes to market economies during the 1990s and the preparation for accession, respectively, membership of the EU. The mean posterior estimates for interest rate smoothing, ρ_i, average 0.79 across the four economies and are higher than the prior assumption and also higher than estimates of Caraiani (2013) for Poland, Czech Republic and Hungary (for a Taylor rule that additionally includes an exchange rate term). The estimates of the posterior mean of the intertemporal elasticity of substitution are on average above the prior means (0.69 versus 0.50) but still in line though on the higher end compared to the

[6] Alternatively, we could consider setting up the initial state covariance matrix to be a diagonal matrix where each diagonal element is set to a very large number (i.e., adopting Dynare's diffuse Kalman Filter). This choice would reflect our knowledge that the initial state of the capital stock is certainly below steady state, but leaves room for uncertainty in initialization, as precisely where the initial state of the model lies is not entirely known.

empirical evidence (Havránek, 2015). As already discussed (section 4.3), there is some ambiguity about the choice of the prior assumptions for the trade openness parameter, γ. Eventually, we set the prior mean to 0.4 (Poland, Czech Republic) respectively 0.3 (Hungary, Romania). In this order, the posterior mean estimates are 0.39, 0.35, 0.29 and 0.16. The implied Frisch elasticities come close the prior mean of 1.50, except of the posterior mean in case of Poland (0.66). The posteriors means of the elasticity of substitution between home and foreign goods range between 0.72 (Poland) and 1.45 (Czech Republic). The posterior means of the parameter of price stickiness are lower than the prior mean of 0.66, which might be due to past high inflation and to periods of rapid price adjustment during and after the transition to market economies. Three parameters are connected to the estimation of capital: capital adjustment costs, the depreciation rate and the factor share. The posterior means of the capital adjustement cost parameter, κ_I, are broadly as expected (on average 4.31 versus a prior mean of 4.00). The posterior mean estimates of the depreciation rates are also close to their prior mean (0.03). To simulate the convergence through capital accumulation, the initial values of the capital stocks are set well below the steady states (see section 4.4), therefore the posterior means of the factor share, α, which have a mean of 0.19, fall short of the assumption of a capital share of 1/3 (usually made for advanced economies). To account for this, the prior assumption of the lower bound was decreased from 0.2 to 0.1 (except for Poland), after the estimation failed to converge. Posterior estimates of the persistence parameters of the shocks are broadly in line with the prior assumption (only persistence of the technology process appears low by averaging 0.08). The volatility of the posterior means of the investment shock, σ_ν, becomes quite high, which is probably not unusual. For example, Justiniano et al. (2011) estimate a posterior median of 5.8 for the U. S.[7]

5.2 The natural rate of interest in emerging economies

Next, we are going to establish the main results concerning the natural rate of interest in small open economies in CEE. We expect that for CEE economies the natural rate is higher compared to estimates for advanced economies. Convergence drives down the real interest rate. Moreover, the drivers of a decline that were found for advanced economies are also prevailing in CEE, such as demographic change, the shortage of safe assets or secular stagnation (as described in section 1). Hence, we expect a downward trend in r^*. Figure 2 shows the estimates from the baseline estimation. R^* has been declining in all four economies since the beginning of the sample period in 2003. This is consistent with the consensus in the literature about a r^*-decline, as outlined in section 1. On average between the years 2003 and 2019, we estimate a natural rate of interest of 2.0 % for Poland, 0.4 % for the Czech Republic, 2.7 % for Hungary and 3 % for Romania.

[7]The high standard deviations of σ_ν are likely linked to the structure that we impose on capital formation with inital capital levels far away from steady states and with the observed gross fixed investment time series. For example, one could possibly adress this by introducing capital utilization to the model.

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
τ	0.50	0.68	[0.49,0.89]	0.50	0.66	[0.45,0.89]
γ	0.40	0.39	[0.29,0.48]	0.40	0.35	[0.27,0.43]
η	1.00	0.72	[0.5,0.93]	1.00	1.45	[1.11,1.77]
φ	1.50	0.66	[0.25,1.07]	1.50	1.12	[0.55,1.67]
θ	0.66	0.09	[0.02,0.15]	0.66	0.20	[0.07,0.32]
κ_I	4.00	3.88	[2.85,4.92]	4.00	6.07	[4.78,7.36]
δ	0.03	0.03	[0.02,0.04]	0.03	0.04	[0.03,0.05]
α	0.30	0.22	[0.2,0.23]	0.30	0.18	[0.14,0.21]
ψ_Y	0.50	0.10	[0.03,0.17]	0.50	0.06	[0.02,0.11]
ψ_π	1.50	3.08	[2.22,3.87]	1.50	2.77	[1.96,3.54]
ρ_i	0.50	0.83	[0.77,0.89]	0.50	0.84	[0.78,0.9]
r_A	1.00	0.79	[0.54,1.04]	1.00	0.69	[0.46,0.91]
π_A	4.00	2.08	[1.17,3]	4.00	1.14	[0.57,1.72]
Γ_Q	0.75	0.42	[0.24,0.6]	0.75	0.09	[0,0.17]
$consTOT$	0.00	-0.06	[-0.22,0.11]	0.00	-0.03	[-0.12,0.06]
$consNER$	0.00	0.01	[-0.16,0.17]	0.00	-0.01	[-0.18,0.15]
ι_P	0.50	0.48	[0.32,0.65]	0.50	0.47	[0.3,0.64]
	Hungary			Romania		
τ	0.50	0.73	[0.55,0.92]	0.50	0.68	[0.44,0.93]
γ	0.30	0.29	[0.22,0.37]	0.30	0.16	[0.1,0.23]
η	1.00	1.28	[0.94,1.64]	1.00	1.01	[0.68,1.36]
φ	1.50	1.14	[0.57,1.72]	1.50	1.35	[0.64,2.01]
θ	0.66	0.42	[0.3,0.54]	0.66	0.46	[0.08,0.79]
κ_I	4.00	4.10	[2.83,5.33]	4.00	3.21	[2.19,4.21]
δ	0.03	0.04	[0.03,0.05]	0.03	0.02	[0.01,0.03]
α	0.30	0.17	[0.14,0.2]	0.30	0.20	[0.16,0.24]
ψ_Y	0.50	0.24	[0.1,0.37]	0.50	0.24	[0.08,0.37]
ψ_π	1.50	2.22	[1.47,2.96]	1.50	2.50	[1.55,3.45]
ρ_i	0.50	0.79	[0.72,0.87]	0.50	0.71	[0.61,0.81]
r_A	1.00	0.89	[0.6,1.17]	1.00	0.92	[0.63,1.22]
π_A	4.00	2.24	[0.88,3.52]	4.00	2.71	[1.16,4.29]
Γ_Q	0.75	0.37	[0.21,0.53]	0.75	0.56	[0.33,0.78]
$consTOT$	0.00	-0.06	[-0.17,0.05]	0.00	0.15	[-0.01,0.3]
$consNER$	0.00	0.00	[-0.16,0.16]	0.00	0.02	[-0.15,0.18]
ι_P	0.50	0.44	[0.28,0.61]	0.50	0.42	[0.24,0.6]

Table 3: Posterior estimation results of the model with convergence: Posterior mean, lower and upper bound of 90 % HPD interval.

The magnitudes appear consistent with estimates of TFP growth during 2003 to 2019 (AMECO). Consistent with our r^*-estimates, TFP growth was highest for Romania with 2.2 % and second-highest for Poland with 1.5 %. For Czech Republic average TFP growth was also 1.5 %, while the

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
ρ_a	0.20	0.06	[0.01,0.1]	0.20	0.04	[0.01,0.08]
ρ_{yf}	0.90	0.98	[0.96,0.99]	0.90	0.96	[0.93,0.98]
$\rho_{\pi f}$	0.80	0.49	[0.35,0.64]	0.80	0.54	[0.39,0.69]
ρ_g	0.20	0.25	[0.06,0.43]	0.20	0.26	[0.06,0.45]
ρ_u	0.80	0.87	[0.79,0.96]	0.80	0.79	[0.69,0.89]
ρ_ν	0.80	0.69	[0.54,0.83]	0.80	0.81	[0.71,0.91]
σ_i	0.50	0.25	[0.19,0.32]	0.50	0.21	[0.16,0.25]
σ_a	1.00	1.68	[1.14,2.2]	1.00	1.60	[1.2,2.01]
σ_{yf}	1.50	2.05	[1.48,2.63]	1.50	1.12	[0.89,1.37]
$\sigma_{\pi f}$	0.55	3.89	[3.32,4.47]	0.55	2.29	[1.94,2.64]
σ_g	0.25	0.18	[0.12,0.23]	0.25	0.16	[0.11,0.2]
σ_u	0.55	2.17	[1.29,3.03]	0.55	1.55	[0.95,2.11]
σ_q	1.00	0.45	[0.31,0.59]	1.00	0.41	[0.31,0.52]
σ_ν	0.25	8.53	[7.06,10]	0.25	4.24	[3.17,5.29]
	Hungary			Romania		
ρ_a	0.20	0.07	[0.02,0.11]	0.20	0.14	[0.01,0.32]
ρ_{yf}	0.90	0.91	[0.87,0.96]	0.90	0.95	[0.92,0.99]
$\rho_{\pi f}$	0.80	0.46	[0.32,0.62]	0.80	0.66	[0.49,0.84]
ρ_g	0.20	0.23	[0.05,0.4]	0.20	0.42	[0.09,0.83]
ρ_u	0.80	0.92	[0.86,0.98]	0.80	0.74	[0.56,0.94]
ρ_ν	0.80	0.50	[0.35,0.63]	0.80	0.57	[0.42,0.72]
σ_i	0.50	0.42	[0.31,0.51]	0.50	0.60	[0.45,0.75]
σ_a	1.00	1.50	[1.16,1.85]	1.00	2.30	[1.51,3.13]
σ_{yf}	1.50	1.11	[0.9,1.32]	1.50	1.54	[1.15,1.93]
$\sigma_{\pi f}$	0.55	3.04	[2.58,3.49]	0.55	1.53	[0.94,2.07]
σ_g	0.25	0.20	[0.12,0.27]	0.25	1.05	[0.12,2.49]
σ_u	0.55	1.73	[1.05,2.41]	0.55	2.84	[0.3,5.12]
σ_q	1.00	0.45	[0.33,0.56]	1.00	1.78	[1.36,2.22]
σ_ν	0.25	15.22	[11.55,20]	0.25	16.82	[13.55,20]

Table 4: Posterior estimation results of the model with convergence: Shock parameters. Posterior mean, lower and upper bound of 90 % HPD interval.

average r^* was lower. This could be due to a safe asset shortage, respectively the low supply of goverment bonds of a small country with low public debt. In case of Hungary the average TFP growth was low (0.4 % according to AMECO). R^* turned out statistically significantly negative in the Czech Republic in 2012 and remained negative until mid-2018, before we see a pick-up. Hledik and Vlček (2018) estimate a natural interest rate for the Czech Republic, that neither has a sustained downward trend but has been hoovering around 1 % since 2000 and never dropped into negative territory, while according to our results, r^* was negative for several years. An increase in r^* is also visible in case of Hungary towards the end of the etimation period. There is a considerable

drop mostly in the aftermath of the Global Finanical Crisis (GFC), which is not unusual for r^*-estimates as, for example, noted in Del Negro et al. (2017) for the US. Therefore, we take the GFC as a cut-off point (Q3 2008) for comparison. Then, before the GFC r^* averaged 2.7 %, 1.0 %, 3.7 % and 6.0 % in Poland, Czech Republic, Hungary and Romania, while during the last five years of the total period (after Q4 2014) it averaged 1.0 %, 0.0 %, 1.2 % and -0.1 %.

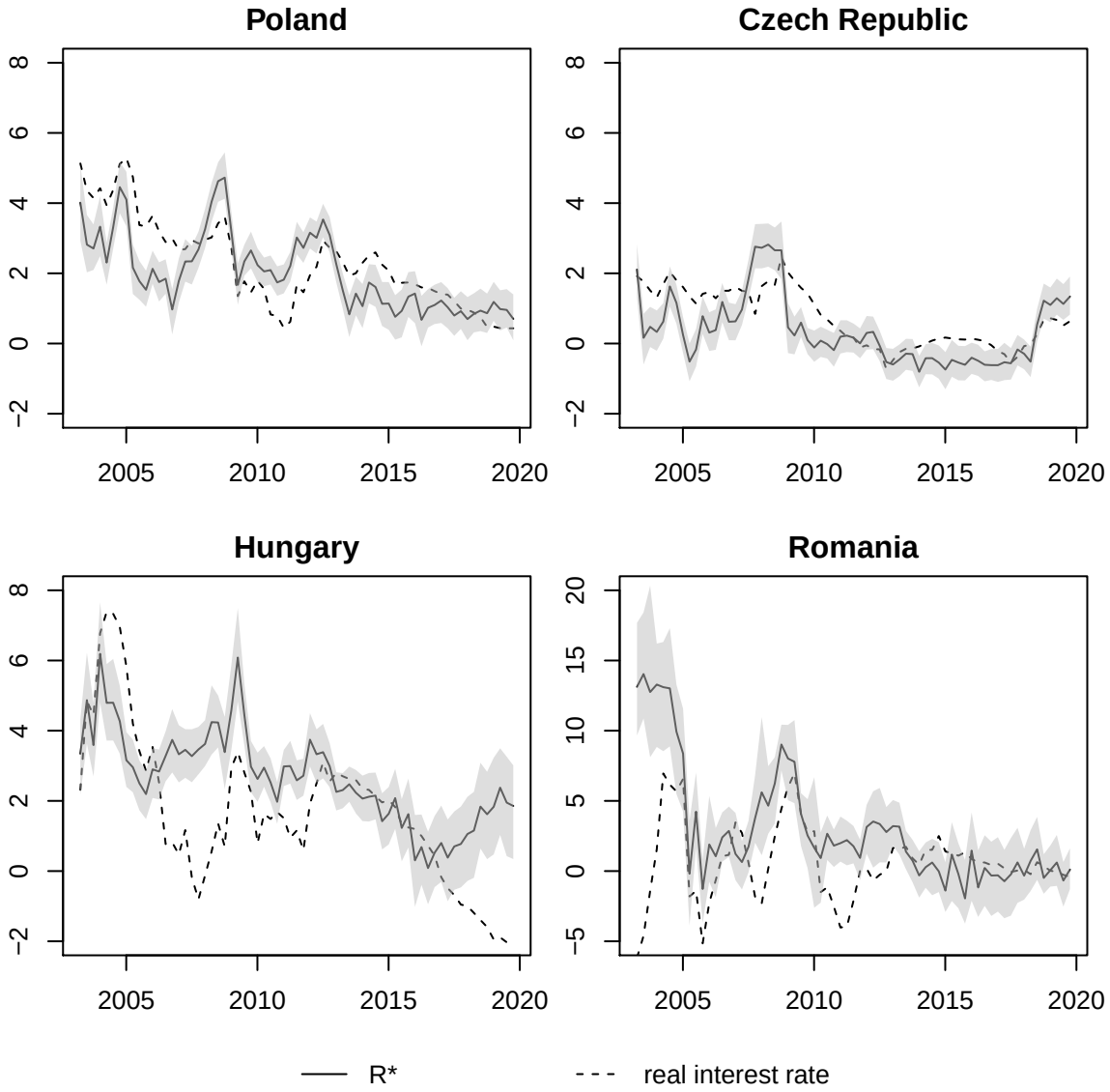


Figure 2: Natural rates of interest in converging economies. The graph shows r^* measured as the (annualized) median posterior estimates (in %). Real short-term interest rates (dotted) are calculated as the 3-months interbank interest rates minus survey inflation expectations. Inflation expectations are measured based on the European Commission's Business and Consumer Survery following the Carlson and Parkin (1975) method. The credible interval is the upper/lower bound of the 90 % highest posterior density interval. Note that the graph of Romania has a different scale on the y-axis.

The literature distinguishes between the short run natural rate of interest (sometimes called "neutral" interest rate), which is often obtained from DSGE models capturing business cycle fluctuations (such as the model presented here) and long run trends in r^* originating from low-frequency movements. Capital deepening and convergence should be seen as such a long term process. Del Negro et al. (2017) make this distinction and compute the h-step ahead forecast

to extract the low-frequency component from a comparable DSGE model. We follow them by estimating the five year ahead filtered forecast, $E_t[r^*_{t+20}]$ that is obtained by the Kalman filter. The "forward" r^*'s follow more persistent downward movements and are shown in figure 3.

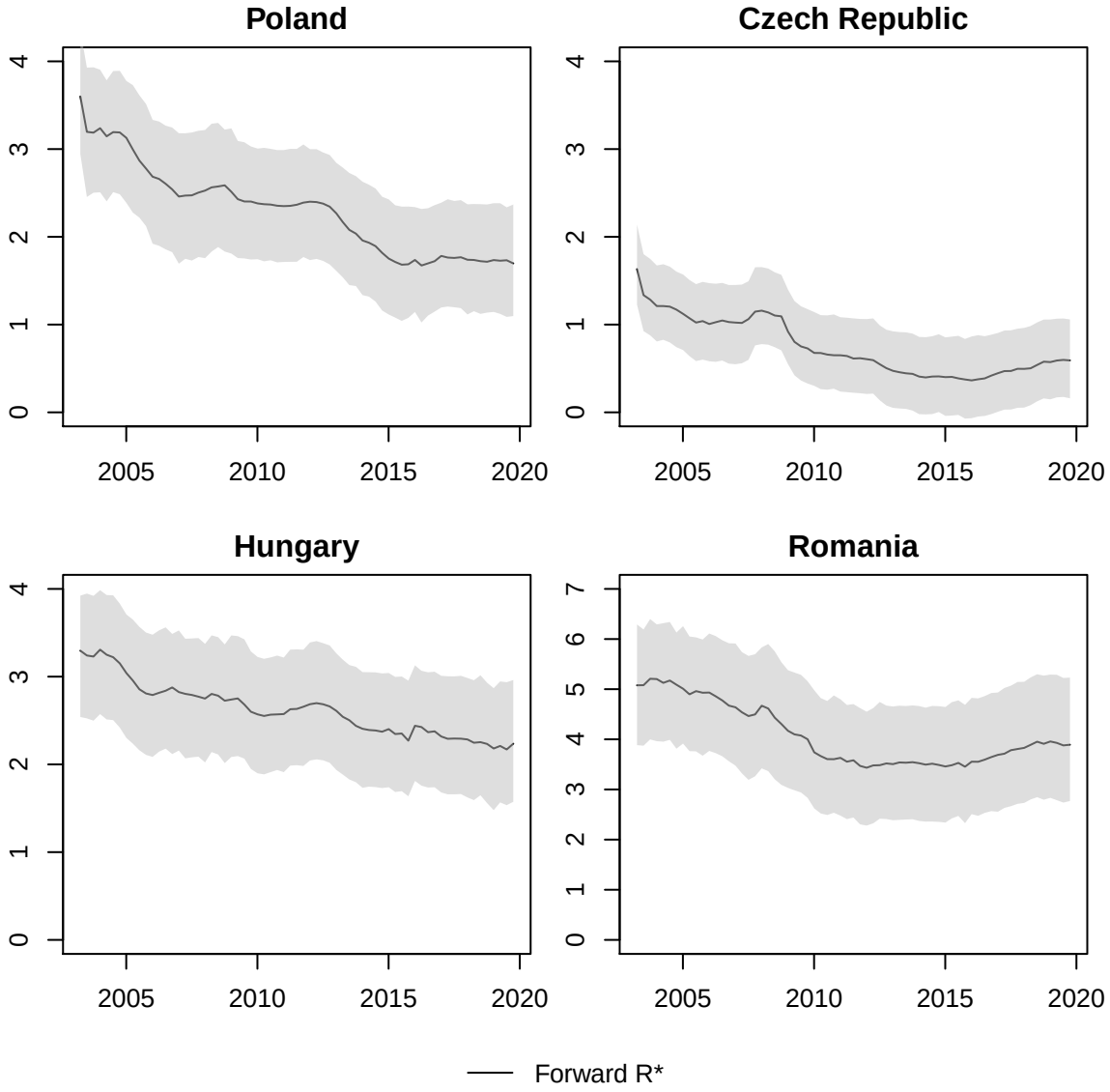


Figure 3: Natural rates of interest in converging economies. The graph shows the (annualized) median posterior estimates of the expected filtered values of r^* in five years, $E_t[r^*_{t+20}]$ (in %). The credible interval is the upper/lower bound of the 90 % highest posterior density interval. Note that the graph of Romania has a different scale on the y-axis.

The long term declines are steady though not as pronounced as in case of the short run estimates (figure 2). The short run r^*'s fall more rapidly after the GFC but for Czech Republic and Hungary they even show a pick up towards the end of the sample period. The forward r^*'s average 2.3 %, 0.7 %, 2.6 % and 4.3 % for Poland, Czech Republic, Hungary and Romania. Comparing the average levels before the GFC (until Q3 2008) and toward the end of the observations (after Q4 2014) the forward r^*-declines are 1.2, 0.7, 0.7 and 1.1 %-age points, respectively, for the four countries. The average five-year levels toward the end of the period (1.7 %, 0.4 %, 3.0 $ and 5.0 %) indicate further catch up potential (except Czech Republic) consistent with the evidence presented

in section 2 (compare figure 1). Countries with lower GDP per capita (relative to the frontier) have higher equilibrium real interest rates.

5.3 Comparing the capital stocks to official estimates

Further main results concern the evolution of the capital stocks. The empirical identification of the initial levels of the capital stock using evidence described in section 2 (29 % below the steady state) leads consistently to posterior estimates of the capital stocks, which are close to these initialization values at the start of the estimation period. All countries have in common a rather steady convergence path, although plausible differences can be observed. A rapid capital accumulation sets in after the GFC and leads to capital stocks near their steady states towards the ends of the estimation period. Poland's initial capital stock starts close to its steady state level. Given Poland maintained positive growth through the GFC as well as during the euro crisis without falling into a recession, it shows a steady convergence of the capital stocks that even goes beyond the steady state toward the end of the period. This might also be driven by the large capital inflow from the EU's structural and cohesion funds, which additionally has been fuelling capital accumulation. In 2003, living standards were highest in the Czech Republic (see figure 1), hence, also the inital capital stock is similarly close to the steady state level. For Romania, the trajectory of the posterior estimates falls below the initialization and indicates a capital stock furthest away from the steady state, which is plausible since Romania started from the lowest development stage in 2003.

As a crosscheck, we plot the evolution of the capital stocks of the baseline estimation against the estimates of the capital stocks from the European Commission's macroeconomic database AMECO (figure 4). Capital stocks are not directly observable. Attempts to construct capital stocks are based on some variant of the perpetual inventory method. The European Commission's AMECO constructs the net capital stock at constant prices ($OKND$) as $OKND_t = OKND_{t-1} + [OIGT_t - (UKCT_t/PIGT_t) * 100]$, where $OIGT$ is gross fixed capital formation at constant prices, $UKCT$ is consumption of fixed capital at current prices (depreciation), and $PIGT$ is the price deflator of gross fixed capital formation.[8] Our estimated equilibrium capital stocks match the AMECO calculations well. If anything, the comparison shows that capital accumulation was even faster in case of Poland or Romania (until around 2008) according to AMECO. If our assumption about initial levels of the capital stocks is too high, i. e. too close to the steady states, it would imply that the presented declines in the natural rates of interest are conservative. If so, the capital deepening process associated with the economic convergence episode contributed even more to the declines in r^*.

[8]See AMECO online database and list of variables: https://economy-finance.ec.europa.eu/economic-research-and-databases/economic-databases/ameco-database_en.

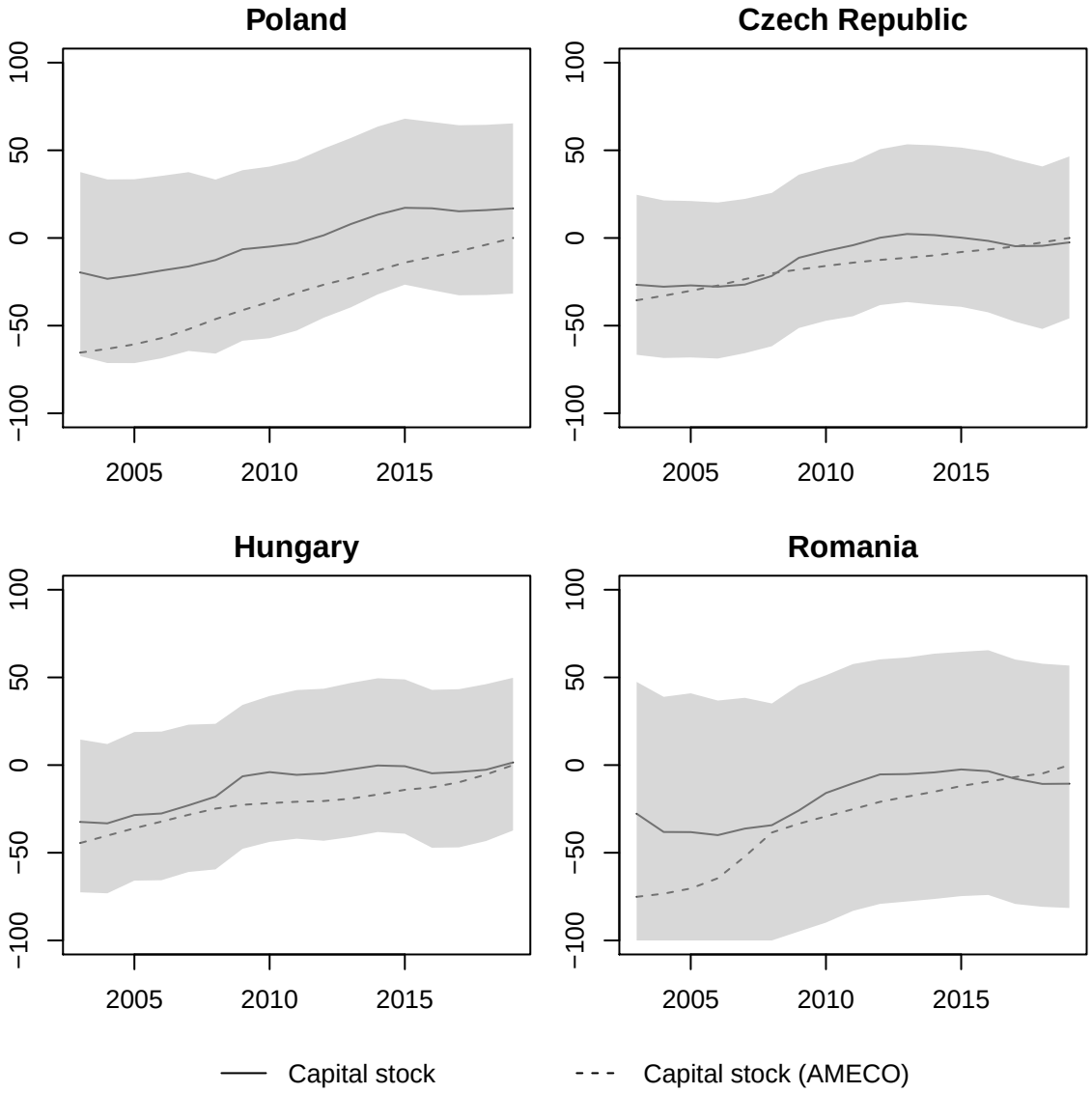


Figure 4: Capital stocks. Annual average of the median posterior estimates of capital stocks of the baseline estimation in % deviation from steady state. The graph shows a comparison to the annual capital stock (dotted) calculated by AMECO in %-deviation from the last value in 2019. The credible interval is the upper/lower bound of the 90 % highest posterior density interval.

5.4 R^* with and without convergence

In the following section, we intend to isolate the effects of convergence on the natural rate of interest. At first, we identify the main differences in the estimated parameters between a model in which capital is allowed to converge to its steady state and a model in which capital is already at its steady state. Second, we use the parameter etimates to construct r^* for a counterfactual model where capital is initially at its steady state.

5.4.1 Parameter comparison

For the model in which capital is already at its steady state, the Kalman filter is initated at the steady state level for the capital stock (as for all other variables); see section 4.4. Compared to the

baseline model with converging capital stock (section 5.1) significant differences arise particularly for the capital-related estimated parameters, which are summarized in table 5.[9] The capital adjustment cost parameter, κ_I, is closer to the prior mean assumption (except for the Czech Republic) and more in line with the literature in the case of the model with convergence (average: 4.31). In the model without convergence, κ_I is on average across the four sample economies at 2.69 and 60 % lower than in the model with convergence. The posterior estimates of the depreciation rate, δ, are on average 44 % higher for the convergence model. The posterior estimates of the capital share, α, in the case of convergence are lower than the usually assumed capital shares of around 0.3. On average, the capital shares in the model with convergence are 0.19 and 27 % lower than in the model without convergence (average: 0.26). This is not surprising: The assumption of a steady state capital share of 0.3 is more appropriate for advanced economies, while emerging economies start at a lower capital share and converge towards their steady state levels during the catch-up process. Additionally, the intertemporal elasticity of substitution, τ, shows large discrepancies. It is an important parameter that determines r^* through the Euler equation of the flexible price counterpart of the economy (equation 54 in the model appendix A.2). On average it is around 15 % higher in the model without convergence (0.69 versus 0.81).

Striking differences arise also with respect to the steady state growth rate, Γ_Q, which is estimated in our model and, thereby, linked to the structural parameters. In the case without convergence, Γ_Q is on average 20 % higher compared to the convergence model, i. e. growth is attributed to productivity growth rather than capital accumulation. The model interprets convergence as technological growth. Note that this implies that the level of r^* is on average over time too high if the estimation does not account for convergence. For the period considered, the quarterly growth differential would on average imply more than 5 % productivity differential. Furthermore, average growth rates of the capital stocks appear implausibly low (close to zero for Czech Republic, Hungary and Romania) in the model without convergence, while in the model with convergence the quarterly capital growth rate averages 0.41 % and is therefore more consistent with the data. This clearly indicates that too much growth is (incorrectly) attributed to productivity if capital formation is not considered appropriately.

5.4.2 Counterfactual experiment

Next, we conduct a counterfactual experiment to understand better the influence of these key parameters (5). We fix the parameters of the model without convergence at the estimated mean posterior parameter values of the model with convergence (the "true" parameter values). Specifically, two changes are made:

[9] The tables with the complete lists of the posterior estimates of the parameters are in the appendix, see tables 12 and 13.

	Prior	PL	CZ	HU	RO	PL	CZ	HU	RO	∅-Change
		with convergence:				without convergence:				in %
κ_I	4.00	3.88	6.07	4.10	3.21	2.88	3.47	2.22	2.18	-60.21
δ	0.03	0.03	0.04	0.04	0.02	0.02	0.03	0.02	0.02	-44.35
α	0.30	0.22	0.18	0.17	0.20	0.26	0.29	0.25	0.25	26.55
τ	0.50	0.68	0.66	0.73	0.68	0.76	0.79	0.88	0.82	14.88
Γ_Q	0.75	0.42	0.09	0.37	0.56	0.58	0.13	0.42	0.60	20.47

Table 5: Comparison of the mean posterior estimates of key parameters for the models with and without convergence. The second column shows the prior mean. The last columns contains the mean of the %-differences between the models compared.

– The intertemporal elasticity of substitution, τ, and the steady state growth rate, Γ_Q are fixed at the mean posterior estimated levels of the model with convergence. They are not estimated.

– The parameters most relevant for the capital accumulation (κ_I, δ, α) are estimated with prior means set at the mean posterior estimates of the "true" model with convergence.

We focus on these key parameters, since the differences are minor for the remaining structural parameters. Given that investment is an observable, completely fixing the capital-relevant parameters, i.e. excluding them from the Bayesian estimation, leads to estimation problems, that is why we decide to estimate them as described above. Table 6 summarizes the differences in the r^*-estimates and compares the average levels between Q2 2003 and Q4 2008 to the average levels between Q4 2014 to Q4 2019. If we compare the mean of r^* in the case of Poland, we can see that ignoring convergence upwardly biases the estimates of r^* (mean of 2.0 versus 2.3 %-age points). Moreover, the decline of r^* is underestimated (-1.7 versus -0.9 %-age points). Basically, the same holds true for the Czech Republic, with higher levels in the counterfactual case (0.4 versus 0.5 %-age points). However, the magnitude of the decline is similar, what is likely du to the generally low level of r^* in the country. For Hungary and Romania, the decline in r^* is also underestimated. The counterfactual model shows smaller declines than the "true" model with convergence (Hungary: -2.4 versus -1.7 %-age points, Romania: -6.1 versus -1.6 %-age points). On average, the mean level of the counterfactual r^*-estimates is 8 % too high. In the early years of the total period, the average estimates of the "true" model are 14 % higher, while towards the end of the period, they are 48 % lower than the counterfactual estimates. On average, the decline in r^* is underestimated by 48% in the counterfactual model.

Figure 5 summarizes the counterfactual experiment. In the first column, we plot the median posterior estimates of r^* of the baseline model. To highlight differences we juxtapose the trend components obtained by the Hodrick-Prescott (HP) filter for the baseline model and the counterfactual model. For Poland, Hungary and Romania, the r^*-trajectories are higher in the beginning when accounting for convergence, only for the Czech Republic levels are similar during the first several years. Considerable gaps between the two variants arise after around 2008 to 2010, when

	PL	CZ	HU	RO	PL	CZ	HU	RO	∅-Difference
	with convergence:				without convergence:				in %
$mean_{2003Q2-2019Q4}$	2.0	0.4	2.7	3.0	2.3	0.5	2.7	3.1	-7.97
$mean_{2003Q2-2008Q3}$	2.7	1.0	3.7	6.0	2.5	1.0	3.4	4.8	14.37
$mean_{2014Q4-2019Q4}$	1.0	0.0	1.2	-0.1	1.6	0.0	1.7	0.7	-48.45
$mean_{2014Q4-2019Q4} - mean_{2003Q2-2008Q3}$	-1.7	-1.0	-2.4	-6.1	-0.9	-1.0	-1.7	-4.0	48.46

Table 6: Comparision of historical means of median posterior estimates of r^* in the (baseline) estimation with convergence and the counterfactual scenario without convergence.

the estimates from the counterfactual models remain too high for several years.

In column 2 of figure 5 we plot the baseline five-year forward r^* against its counterfactual forward r^*. Again, we observe steeper curves for the baseline model reflecting the convergence effect. Generally, forward r^*'s start higher, then cross the counterfactual estimates and run below them towards the end of the period. In case of Romania, the forward r^* declines faster in the beginning but remains close to the counterfactual estimate for the rest of the period.

The third column of figure 5 combines the evolutions of the capital stocks in the two models. The four examples highlight consistently the catch-up processes of the capital stocks in the baseline models versus the capital stocks of the counterfactual variants which fluctuate around their steady states, as expected.

5.5 Alternative initial capital stocks

In this section, we conduct a couple of robustness tests. First, we calculate the GDP p. c. of the emerging economy in relation to Germany's GDP p. c. in the years 2003 and 2019. For example, Poland's GDP p. c. was 0.40 and 0.62 of Germany's GDP p. c. in 2003 respectively 2019.[10] Hence, the catch-up was 0.22 and the initial capital stock is set at $0.78 * K_{i,ss}$. The other economies caught up from 0.62 to 0.76 (Czech Republic), from 0.51 to 0.61 (Hungary) and from 0.33 to 0.56 (Romania) of Germany's GDP p. c. The initial capital stocks are set accordingly at 0.87, 0.90 and 0.77 of the steady state value of capital.[11] The posterior estmation results of the model parameters with alternative initial values of the capital stocks are similar to the baseline estimation (appendix A.4, tables 16 and 17). Figure 6 depicts the median posterior estimates for r^* (first row) and for the capital stocks (second row). The alternative trajectories are similar to the r^*-estimates of the baseline estimation. Differences arise with respect to the evolution of the capital stocks. As expected, given higher initial values, capital accumulation starts consistently closer to the steady states though the trajectories appear similar to the capital stocks of the baseline estimation.

[10] The data source is the IMF World Economic Outlook, April 2021, GDP per capita at purchasing power parities.

[11] The initial level of the capital stock of country i is given by

$$K_{i,Q1\,2003} = K_{i,ss} * \left[1 - \left[\frac{GDPpc_{i,2019}}{GDPpc_{DE,2019}} - \frac{GDPpc_{i,2003}}{GDPpc_{DE,2003}}\right]\right].$$

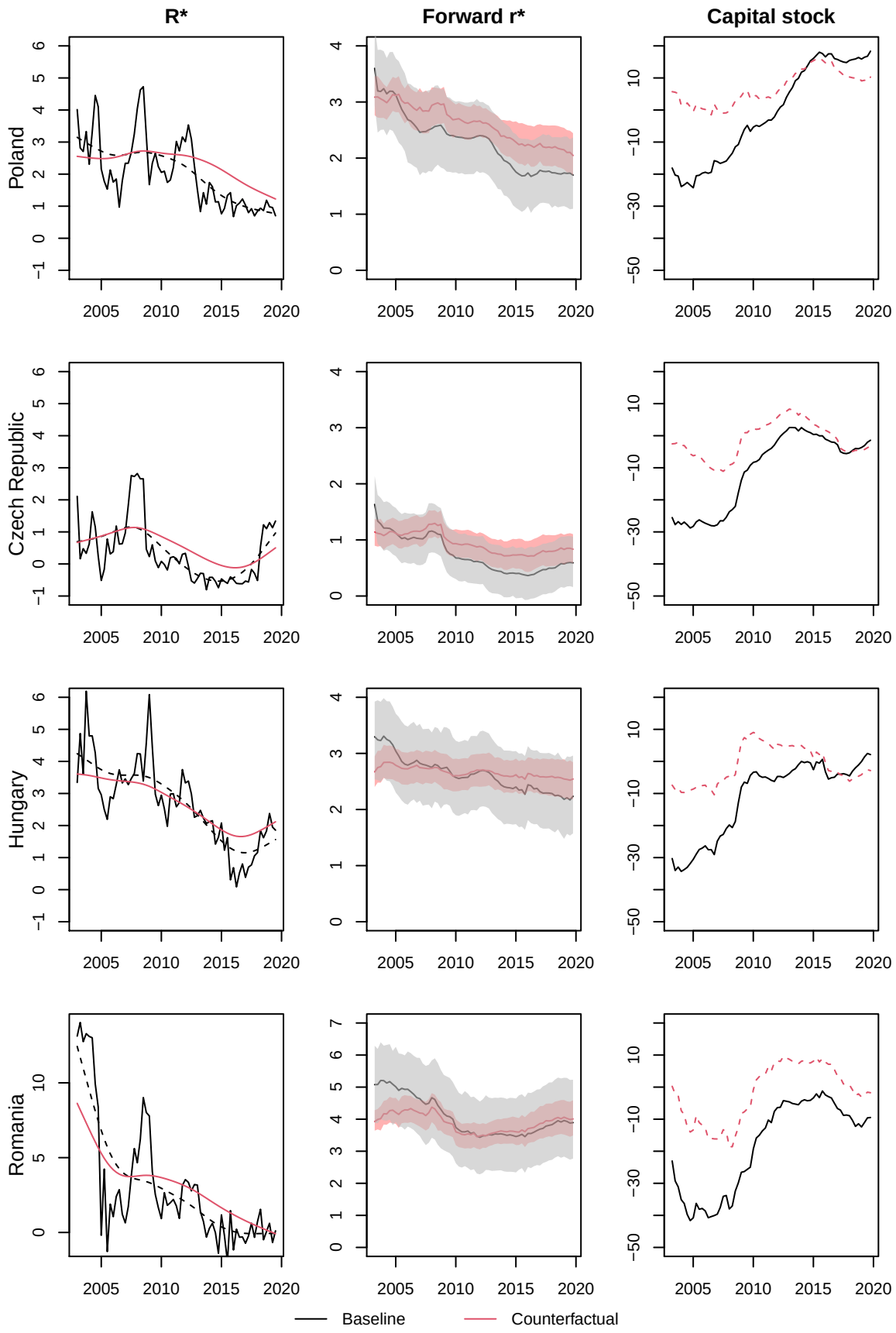


Figure 5: Counterfactual experiment. First column shows r^* measured as the (annualized) median posterior estimates (in %). Trajectories with and without convergence (counterfactual) are trend components using the HP-filter. Second column shows expected filtered values of r^* in five years, $E_t[r^*_{t+20}]$ (in %) with and without convergence (counterfactural). The credible interval is the upper/lower bound of the 90 % highest posterior density interval. Third column shows capital stocks measured as the deviation from steady state in %. Note that the graphs of Romania have different scale on the y-axis.

Second, there is evidence the Poland and Romania had very strong economic catch-up phases. Figure 1 reveals that real per capita GDPs converged fastest among the four example economies. The capital stock estimates of AMECO in figure 4 indicate that we could assume lower initial capital stock levels for the estimation. The CEE dummy in the growth regressions in table 1 indicates an annual catch-up of 2.7 %, which implies an level of 0.64 of the steady state for the initial capital stock, i. e. 36 % below the steady state. Compared to that in the baseline we assumed conservatively that convergence followed the "iron law" of convergence of 2 % per year or a level of 0.71 of the steady state (as implied by the main regression results; see also section 4.4). The results based on the "fast" catch-up for Poland and Romania as depicted in blue color in figure 6. While the evolutions of the capital stocks are consistently below or steeper than the baselines, the estimates of r^* appear fairly robust against alternative capital stock convergence paths.

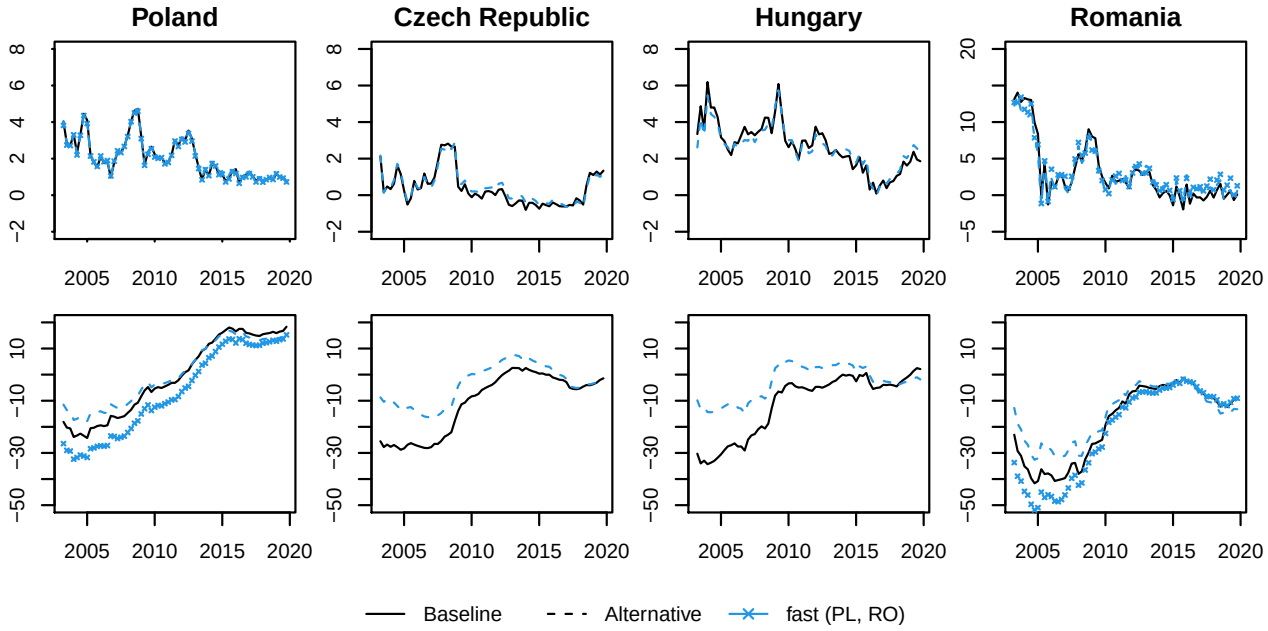


Figure 6: Robustness: Natural Rates of Interest (upper panel) and capital stocks (lower panel). The first row shows median posterior esimates of r^* for the baseline estimation and alternative estimations based on different assumptions about the initial levels of the capital stocks. The second row shows the corresponding median posterior estimates of the capital stocks.

5.6 R^* and the return on capital

The framework allows us to gain insights about the relationships between the natural rate of interest, the rental rate of capital and the return on capital. It is a well known fact (Gomme et al., 2011,0; Caballero et al., 2017; Marx et al., 2021; Reis, 2022) that measures of the return on capital have been remarkably stable over the last decades. The deviation between the dramatic decline in the natural rates of interest and the stable (measured or observed) rates of return on capital is an unsolved puzzle in the literature. This literature focuses mostly on advanced economies, foremost the U.S. We present measures of the real return on capital based on time series from the European

Commission's AMECO database in figure 7, documenting that in our CEE countries we similarly did not observe a decline compared to the paths of real natural rates, but instead they are rather stable.

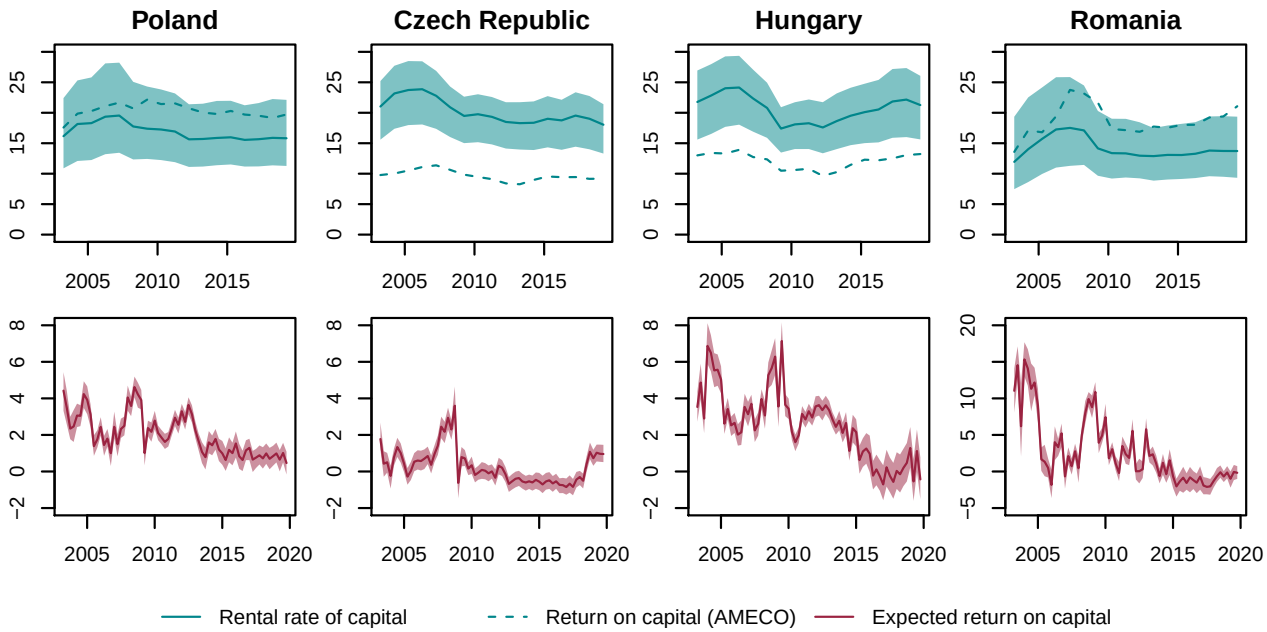


Figure 7: R^* and returns on capital in converging economies. The graph shows median posterior estimates of the rental rate of capital and the (annualized) expected return on capital in % (including 90 % HPD intervals). The observed annual return on capital is constructed by dividing the series 'Net operating surplus, total economy' by the 'Net capital stock at constant prices; total economy', which is multiplied by the 'Price deflator gross fixed capital formation: total economy' from the AMECO database

Gomme et al. (2011) discuss constructing returns on capital from national accounts. Here, the observed (average) return on capital is constructed by dividing the series 'Net operating surplus, total economy' by the 'Net capital stock at constant prices; total economy', which is multiplied by the 'Price deflator gross fixed capital formation: total economy' from the AMECO database (for example, as in Broner et al. (2021)). To evaluate our model implications on these time series, we juxtapose the posterior median estimates of the rental rates of capital and of the expected returns on capital with measures of the real return on capital based on the time series contructed from AMECO data in figure 7. The figure suggests that these time series share similar dynamics. By eyeballing, the estimated rental rate of capital, r_t^K, resembles approximately the observed returns on capital with regards to size and shape. In the case of Poland and Romania, the observed rates of return lie within the 90 % credible intervals of r_t^K, although our model framework does not take into account the riskiness of capital investment. We also estimate the expected return on capital, given by the term in squared brackets of equation 27, $r_{t+1}^K + q_{t+1}(1-\delta)$, divided by marginal value of installed capital, q_t, respectively its shadow price or Tobin's q. However, in this case, the similarity to the AMECO based time series vanishes and the DSGE-model implied estimated expected rate of return on capital resembles closely the path of natural rates of interest. Table 7 provides a summary. When we compare again the periods before 2008 and after 2014, on average

	PL	CZ	HU	RO
Natural rate of interest	2.0	0.4	2.7	3.0
Expected return on capital	2.0	0.2	2.5	2.6
Rental rate of capital	17.0	20.3	20.7	14.3
Return on capital (AMECO)	20.3	9.7	12.1	18.7

Table 7: R^* and the return on capital

across the four economies the declines in r^* and the estimated returns on capital are around 83 % and 99 %. Then again, the declines of the estimated rental rates of capital are much lower averaging about 15 % and the observed returns on capital decrease by about 3 %. So, in our framework, the rental rates of capital come close to empirically observed returns on capital, while estimated returns on capital are close to the natural rates of interest. We believe that this finding is a result of the fact that the real interest rate shares the low-frequency dynamics of the real natural rate, and of the fact that rates of return on capital and real interest rates are necessarily equivalent in our DSGE model at steady state and at a first-order (linear) solution and estimation of the model.[12]

5.7 Monetary policy implications

Taking stock of the presented results we find significant implications for monetary policy. Figure 8 depicts the gap between the actual real interest rate and the real natural rate of interest, which acts as a guide to monetary policy. In times the actual real interest rate is higher than r^*, monetary policy is contractionary, whereas when the actual real interest rate is lower than r^*, the monetary policy stance is expansionary. The interest rate gap is shown for the baseline model, the counterfactual model and a labor-only version of the model similar to the version in Zhang et al. (2021). There are times of agreement and times of disagreement between the three different models. Until around 2006, the models agree in signaling that monetary policy was tight in Poland, Czech Republic, and Hungary. After this period of contractionary policies, the models mostly agree that monetary policy was expansionary for some time in the three countries. Disagreement arises mostly towards the second half of the observation period. For Poland, the baseline model starts indicating a contractionary stance, while the counterfactual and the labor-only model indicate an expansionary phase. We also find ambiguous signals in the case of Czech Republic. Our baseline model turns neutral and then restrictive, the counterfactual model and the model without capital indicate an expansionary monetary policy first, and then neutral to contractionary. In case of Romania, there is agreement about a loose monetary policy stance until around 2012, afterwards, the models disagree. The baseline model indicates an neutral stance, while the counterfactual model indicates a loose and the model without capital indicates a tight stance of monetary policy.

[12] Allowing levels of returns on capital and real interest rates to be different would require a modeling framework with, e.g. financial frictions, and/ or estimation methods capable of going beyond linear approximation. We leave this interesting agenda for future research.

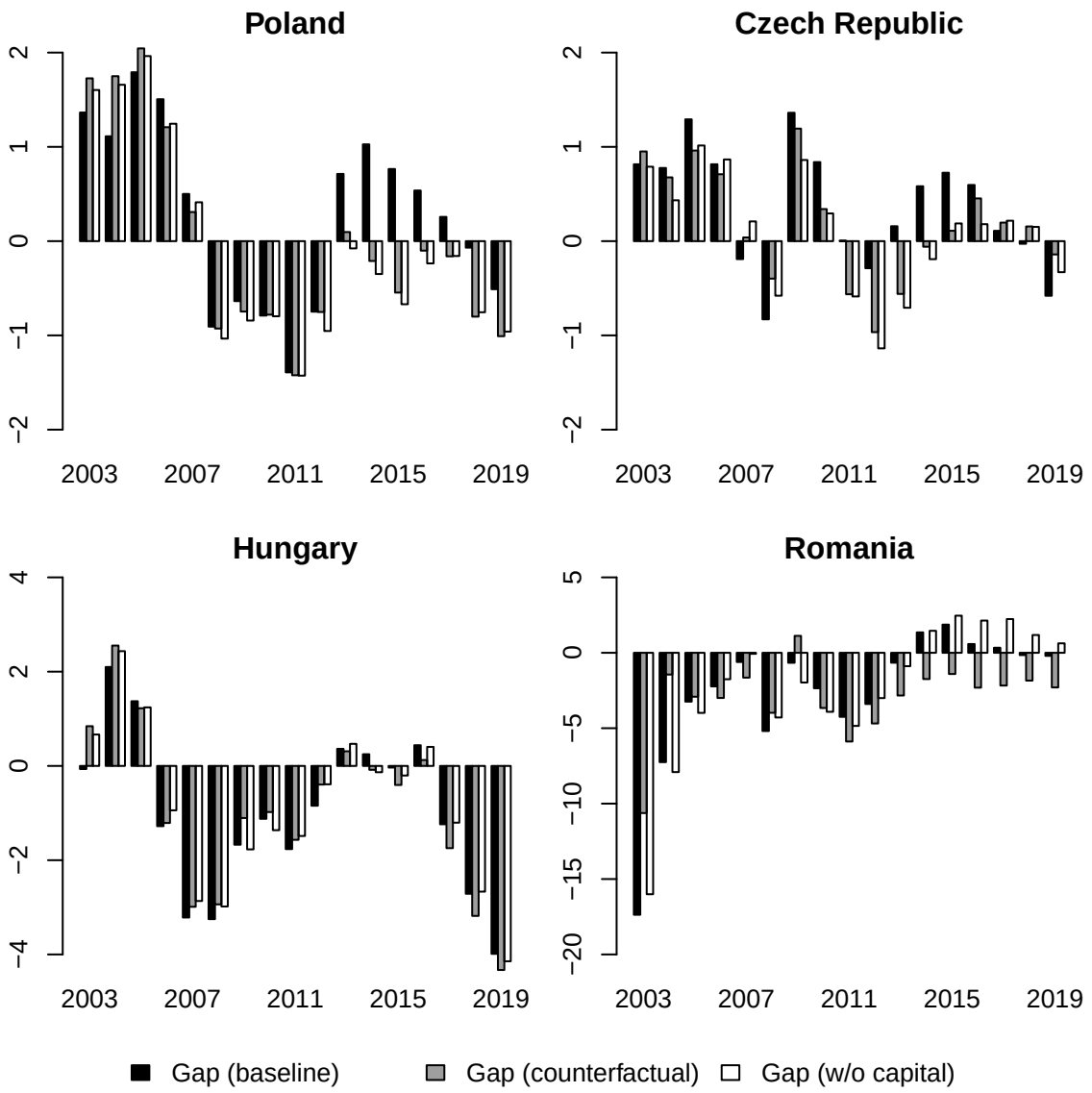


Figure 8: Interest rate gaps. The graph shows the real interest rate gaps for the benchmark model, the counterfactual scenario and without capital. Gap is defined as the difference between actual real short-term interest rate and median posterior estimate of r^*in %-age points. Note that the y-axis' have different scales.

6 Conclusions

Tracking the natural rate of interest derived from structural DSGE models can considerably improve macroeconomic stability (Barsky et al., 2014; Brand et al., 2018). Under certain circumstances (as shown for the U. S. by Justiniano et al. (2013)), setting the real key policy rate equal to r^* closes the welfare-relevant output gap and stabilizes the inflation rate around its target. So far, investigations into the natural rate of interest in emerging economies are underrepresented in the literature. We exploit the historical episode of rapid economic catch-up during almost two decades of formerly centrally-planned economies in Central and Eastern Europe to learn about the natural rate of interest under these specific circumstances. Hence, investigating economic convergence adds

a new aspect to the numerous drivers of the decline in r^* that are found in the literature.

Preliminary to estimating the structural model, we present empirical evidence of convergence in a panel of European countries and find that convergence was roughly consistent with the iron law of 2 % convergence per year (Barro, 2012). The empirical evidence helps us to identify initial stages of the capital stocks in the structural model. To build an appropriate environment for catch-up economies, we extend a New Keynesian small open economy model in several dimensions and estimate the model in a Bayesian fashion that allows for convergence. The model is estimated for Poland, Czech Republic, Hungary and Romania for the period between 2003 and 2019.

We confirm a secular decline in r^* that ranges between one to six percentage points in the period between 2003 and 2019. Real natural rates of interest appear consistent among the four economies and of reasonable magnitude and average 2.0 %, 0.4 %, 2.7 % and 3.0 % for Poland, Czech Republic, Hungary and Romania. We conduct a counterfactual experiment that helps us to identify the effects of convergence. We find evidence that growth from technological progress might be overestimated, i. e. average levels of natural rates of interest might appear too high, while the declines in r^* might be underestimated if convergence is neglected. Finally, we show that conflicting signals from the natural rate of interest might arise for monetary policy in emerging economies, when the modeling framework does not properly account for capital accumulation and convergence.

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A Appendix

A.1 Evidence of convergence: Data description and robustness

The sample for the estimation of the growth regressions includes annual data of 42 European countries for the period 1997 to 2017. The list of countries includes Albania (AL), Austria (AT), Belarus (BY), Belgium (BE), Bosnia and Herzegovina (BA), Bulgaria (BG), Croatia (HR), Cyprus (CY), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Iceland (IC), Ireland (IE), Italy (IT), Kosovo (XK), Latvia (LV), Lithuania (LT), Luxembourg (LU), Malta (MT), Macedonia (MK), Moldova (MD), Montenegro (ME), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Russia (RU), Serbia (RS), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (SW), Turkey (TR), Ukraine (UA), United Kingdom (UK).

Table 8 lists the description and sources of the variables used in the empirical section 2. To check for robustness, table **??** shows additional conditional convergence regressions.

Variable	**Description and source**
GDP p. c.	gross domestic product (GDP) per capita, at purchasing power parities (PPP), IMF World Economic Outlook (WEO)
GDP p. c. growth	average annual growth rate of GDP p. c., measured as log difference of GDP p. c. between the last year of the 5-year period and the previous year divided by 5, IMF WEO
Investment	gross capital cormation at PPP, per capita, current prices, as share of GDP, 5-year averages, Penn World Table
Population	average 5-year annual growth rate of the total population, IMF WEO
Labor Force	average 5-year annual growth rate of the labor force, IMF International Financial Statistics (IFS)
Institutions	annual average of the world governance indicators for rule of law, regulatory quality, government effectiveness and corruption, World Bank
Openess	sum of merchandise exports and imports, at PPP, per capita, current prices, as share of GDP, Penn World Table
Credit	average 5-year annual domestic credit to private sector by banks, percent of GDP, World Bank, World Development Indicators
FDI	average 5-year annual foreign direct investment, IMF IFS
Public debt	central government debt, percent of GDP, World Bank, World Development Indicators

Table 8: Evidence of convergence: Data description and sources

Table 9: Absolute and conditional convergence in Europe between 1997 and 2017

	(1)	(2)	(3)	(4)	(5)	(6)
Log GDP p.c.	-0.015***	-0.009*	-0.012***	-0.013***	-0.020***	-0.014**
	(0.003)	(0.005)	(0.003)	(0.003)	(0.007)	(0.007)
2003-2007	0.012***	0.145***	0.013***	0.013***	0.011**	0.013***
	(0.004)	(0.050)	(0.004)	(0.004)	(0.005)	(0.005)
2008-2012	-0.027***	0.063	-0.025***	-0.025***	-0.026***	-0.024***
	(0.004)	(0.049)	(0.004)	(0.004)	(0.005)	(0.005)
2013-2017	-0.006*	-0.036	-0.005	-0.005	-0.004	-0.004
	(0.003)	(0.070)	(0.004)	(0.004)	(0.006)	(0.006)
2003-2007 × Log GDP p.c.		-0.013***				
		(0.005)				
2008-2012 × Log GDP p.c.		-0.009*				
		(0.005)				
2013-2017 × Log GDP p.c.		0.003				
		(0.007)				
EU × Log GDP p.c.			-0.011*			
			(0.006)			
EU			0.117*			
			(0.064)			
EU_CEE × Log GDP p.c.				-0.016*		
				(0.008)		
EU_CEE				0.170**		
				(0.084)		
Investment					0.001**	-0.000
					(0.000)	(0.000)
Population					-0.005	-0.007*
					(0.004)	(0.004)
Labor Force					0.004	0.002
					(0.002)	(0.004)
Institutions					0.004	0.004
					(0.005)	(0.005)
Schooling					0.002*	0.001
					(0.001)	(0.001)
Openness					-0.000	0.000
					(0.000)	(0.000)
Credit					-0.000**	-0.000**
					(0.000)	(0.000)
FDI					0.000***	0.000***
					(0.000)	(0.000)
Public debt					-0.000*	-0.000
					(0.000)	(0.000)
Constant	0.176***	0.123**	0.147***	0.155***	0.204***	0.176***
	(0.028)	(0.051)	(0.030)	(0.027)	(0.065)	(0.067)
Instrumental variable	no	no	no	no	no	yes
Observations	166	166	166	166	135	135

Cluster-robust standard errors are reported in parentheses. Time fixed effects. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Sources: own calculations, data from IMF WEO and IFS, Penn World Table, World Bank, Barro and Lee (2013).

Table 10: Absolute and conditional convergence in Europe between 1997 and 2017

	(1)	(2)	(3)	(4)	(5)
Log GDP p.c.	-0.017***	-0.021***	-0.020***	-0.013	-0.018***
	(0.003)	(0.007)	(0.007)	(0.010)	(0.006)
2003-2007	0.012***	0.009**	0.011**	0.171**	0.012**
	(0.004)	(0.004)	(0.005)	(0.079)	(0.005)
2008-2012	-0.028***	-0.032***	-0.026***	0.000	-0.025***
	(0.004)	(0.005)	(0.005)	(0.089)	(0.005)
2013-2017	-0.006	-0.011**	-0.004	-0.131	-0.003
	(0.004)	(0.005)	(0.006)	(0.104)	(0.006)
2003-2007 × Log GDP p.c.				-0.016**	
				(0.008)	
2008-2012 × Log GDP p.c.				-0.003	
				(0.009)	
2013-2017 × Log GDP p.c.				0.012	
				(0.010)	
EU × Log GDP p.c.					-0.010*
					(0.005)
EU					0.103*
					(0.054)
Investment	0.001**	0.001**	0.001**	0.000	0.001**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Population	-0.007**	-0.005	-0.005	-0.008**	-0.003
	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)
Labor Force	0.002*	0.003*	0.004	0.006***	0.004
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
Institutions		-0.002	0.004	0.002	0.003
		(0.004)	(0.005)	(0.005)	(0.005)
Schooling		0.003**	0.002*	0.001	0.002*
		(0.001)	(0.001)	(0.001)	(0.001)
Openness		0.000	-0.000	0.000	-0.000
		(0.000)	(0.000)	(0.000)	(0.000)
Credit			-0.000**	-0.000*	-0.000**
			(0.000)	(0.000)	(0.000)
FDI			0.000***	0.000***	0.000***
			(0.000)	(0.000)	(0.000)
Public debt			-0.000*	-0.000**	-0.000*
			(0.000)	(0.000)	(0.000)
Constant	0.182***	0.193***	0.204***	0.153	0.183***
	(0.030)	(0.070)	(0.065)	(0.092)	(0.059)
Observations	152	150	135	135	135

Cluster-robust standard errors are reported in parentheses. Time fixed effects.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Sources: own calculations, data from IMF WEO and IFS, PWT, World Bank, Barro and Lee (2013)

A.2 Model appendix

A.2.1 Stationarizing the model

Since domestic aggregate total factor productivity has a growing trend A_t, the model is stationarized by defining variables in relation to A_t as follows: $C_{A,t} = \frac{C_t}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $K_{A,t-1} = \frac{K_{t-1}}{A_{t-1}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $N_{A,t} = \frac{N_t}{A_t^{\frac{\tau-1}{1+\tau\varphi}}}$, $C_{AH,t} = \frac{C_{H,t}}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $C_{AF,t} = \frac{C_{F,t}}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $C^f_{AH,t} = \frac{C^f_{H,t}}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $I_{A,t} = \frac{I_t}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $Y_{A,t} = \frac{Y_t}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $W_{A,t} = \frac{W_t}{A_t}$, $aux_{A1t} = \frac{aux_{1t}}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $aux_{A2t} = \frac{aux_{2t}}{A_t^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}}$, $mc_t = \frac{MC_t}{P_{H,t}}$. Also, we define real (relative) prices as: $w_{A,t} = \frac{W_{A,t}}{P_t} = \frac{W_t}{A_t P_t}$, $r^K_t = \frac{R^K_t}{P_t}$, $q_t = \frac{Q_t}{P_t}$, $p_{H,t} = \frac{P_{H,t}}{P_t}$, $\widetilde{p}_t = \frac{\widetilde{P}_{H,t}}{P_{H,t}}$, $\pi_t = \frac{P_t}{P_{t-1}}$, $\pi_{H,t} = \frac{P_{H,t}}{P_{H,t-1}}$, $TOT_t = \frac{P_{F,t}}{P_{H,t}}$, $RER_t = \frac{S_t P^f_t}{P_t}$ and $\widetilde{\Gamma}_A = \Gamma_A^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}$.

Households' intratemporal optimality conditions between home and foreign goods and home demand functions for H- and F-goods become

$$C_{AH,t} = (1-\gamma)\left(p_{H,t}\right)^{-\eta} C_{A,t}, \tag{20}$$

$$C_{AF,t} = \gamma\left(p_{F,t}\right)^{-\eta} C_{A,t}, \tag{21}$$

$$C^f_{AH,t} = \gamma\left(\frac{p_{H,t}}{RER_t}\right)^{-\eta} C^f_{At}. \tag{22}$$

The equations that govern the processes of home and foreign CPI become

$$\frac{1}{p_{H,t}} = \left[(1-\gamma) + \gamma\left(TOT_t\right)^{1-\eta}\right]^{\frac{1}{1-\eta}} \tag{23}$$

$$P^f_t = P^f_{F,t} \Longrightarrow \pi^f_t = \pi^f_{F,t} \tag{24}$$

Households' intertemporal conditions become

$$C_{A,t}^{\frac{1}{\tau}} N_{A,t}^{\varphi} = w_{A,t}, \tag{25}$$

$$C_{A,t}^{-\frac{1}{\tau}} e^{-g_t} = \beta E_t\left[\frac{(1+i_t)}{\pi_{t+1}} C_{A,t+1}^{-\frac{1}{\tau}} e^{-\Delta g_{t+1}}\left(\frac{A_{t+1}}{A_t}\right)^{-\left(\frac{1+\varphi}{1+\tau\varphi}\right)}\right], \tag{26}$$

$$q_t C_{A,t}^{-\frac{1}{\tau}} = \beta E_t C_{A,t+1}^{-\frac{1}{\tau}}\left(\frac{A_{t+1}}{A_t}\right)^{-\left(\frac{1+\varphi}{1+\tau\varphi}\right)} e^{-\Delta g_{t+1}}\left[r^K_{t+1} + q_{t+1}(1-\delta)\right], \tag{27}$$

$$\left[\begin{array}{c} 1+\kappa_I q_t \nu_t \left(\frac{I_{A,t}}{I_{A,t-1}}\Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A\right)\frac{I_{A,t}}{I_{A,t-1}}\Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} \\ -q_t\nu_t\left[1-\frac{\kappa_I}{2}\left(\frac{I_t}{I_{t-1}}\Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A\right)^2\right] \end{array}\right] = \kappa_I \beta E_t q_{t+1}\nu_{t+1}\frac{C_{A,t+1}^{-\frac{1}{\tau}}}{C_{A,t}^{-\frac{1}{\tau}}}e^{-\Delta g_{t+1}}$$
$$\left(\frac{A_{t+1}}{A_t}\right)^{-\left(\frac{1+\varphi}{1+\tau\varphi}\right)}\left(\frac{I_{A,t+1}}{I_{A,t}}\Gamma_{A,t+1}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A\right), \tag{28}$$

$$K_{A,t} = (1-\delta)K_{A,t-1}\left(\frac{A_{t-1}}{A_t}\right)^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} + I_{A,t}\nu_t\left[1-\frac{\kappa_I}{2}\left(\frac{I_{A,t}}{I_{A,t-1}}\Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A\right)^2\right]. \tag{29}$$

The law of one price for H-goods and F-goods and law of motion linking PPI and CPI inflation become:

$$p_{H,t} = RER_t p_{H,t}^f \tag{30}$$

$$TOT_t p_{H,t} = RER_t tot_t^{\sigma_q} \tag{31}$$

Note that we add a measurement error shock, tot_t with standard deviation σ_q, to the equation governing the law of one price.

$$\frac{P_{H,t}}{P_{H,t-1}} = \frac{P_{H,t}/P_t}{P_{H,t}/P_{t-1}}\frac{P_t}{P_{t-1}} \tag{32}$$

The market clearing and the risk sharing conditions in stationarized representation are

$$Y_{A,t} = (p_{H,t})^{-\eta}\left[(1-\gamma)(C_{A,t}+I_{A,t}) + \gamma(RER_t)^{\eta}Y_{A,t}^f\right], \tag{33}$$

$$C_{A,t} = \upsilon C_{A,t}^f (RER_t)^{\tau}, \tag{34}$$

$$C_{A,t}^f = Y_{A,t}^f. \tag{35}$$

For the estimation, foreign output $Y_{A,t}^f$ is multiplied by the consumption share (0.75) in the above equation. The stationarized equilibrium conditions of domestic firms are written as

$$\frac{1-\alpha}{\alpha} = \frac{w_{A,t}N_{A,t}}{r_t^K K_{A,t-1}}\left(\frac{A_t}{A_{t-1}}\right)^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}, \tag{36}$$

$$mc_t = \frac{\left(r_t^K\right)^{\alpha}\left(w_{A,t}\right)^{1-\alpha}}{p_{H,t}\alpha^{\alpha}\left(1-\alpha\right)^{1-\alpha}}\frac{1}{A_t}, \tag{37}$$

$$\Delta_t Y_{A,t} = \left(\frac{A_t}{A_{t-1}}\right)^{-\alpha\frac{\tau+\tau\varphi}{1+\tau\varphi}}\left(K_{A,t-1}\right)^{\alpha}\left(N_{A,t}\right)^{1-\alpha}, \tag{38}$$

$$\widetilde{p}_t = \mu_t\frac{aux_{A1,t}}{aux_{A2,t}}, \tag{39}$$

$$aux_{A1t} = mc_t Y_{A,t} + E_t\beta\theta e^{-\frac{g_{t+1}}{g_t}}\left(\frac{C_{A,t+1}}{C_{A,t}}\right)^{-\frac{1}{\tau}}\frac{\left(\pi_{H,\,t+1}^{-1}\pi_{H,\,t}^{\iota_P}\bar{\pi}_H^{1-\iota_P}\right)^{1+\epsilon}}{\pi_{t+1}}\left(\frac{A_{t+1}}{A_t}\right)^{\frac{(1+\varphi)(\tau-1)}{1+\tau\varphi}}aux_{A1t+1}, \tag{40}$$

$$aux_{A2t} = Y_{A,t} + E_t\beta\theta e^{-\frac{g_{t+1}}{g_t}}\left(\frac{C_{A,t+1}}{C_{A,t}}\right)^{-\frac{1}{\tau}}\frac{\left(\pi_{H,\,t+1}^{-1}\pi_{H,\,t}^{\iota_P}\bar{\pi}_H^{1-\iota_P}\right)^{\epsilon}}{\pi_{t+1}}\left(\frac{A_{t+1}}{A_t}\right)^{\frac{(1+\varphi)(\tau-1)}{1+\tau\varphi}}aux_{A,1t+2}, \tag{41}$$

$$\Delta_t \equiv \left(1-\theta\right)\left(\widetilde{p}_t\right)^{-\epsilon} + \theta\left(\pi_{H,\,t}^{-1}\pi_{H,\,t-1}^{\iota_P}\bar{\pi}_H^{1-\iota_P}\right)^{\epsilon}\Delta_{t-1}, \tag{42}$$

$$\widetilde{p}_t = \left[\frac{1-\theta\left(\pi_{H,\,t}^{-1}\pi_{H,\,t-1}^{\iota_P}\bar{\pi}_H^{1-\iota_P}\right)^{\epsilon-1}}{\left(1-\theta\right)}\right]^{\frac{1}{1-\epsilon}}. \tag{43}$$

Finally, the monetary policy rule becomes

$$\frac{1+i_t}{1+i} = \left(\frac{1+i_{t-1}}{1+i}\right)^{\rho_i}\left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\psi_\pi}\left(\frac{Y_{A,t}}{Y_{A,t}^n}\right)^{\psi_Y}\right]^{1-\rho_i}\varepsilon_{i,\,t}^{\sigma_i}. \tag{44}$$

The system of equations (20) to (44) together with seven exogenous shocks for $\{g_t, a_t, u_t, Y_t^f, \pi_t^f\, \varepsilon_t, tot_t, \nu_t\}$ determines 22 endogenous variables and represents the equilibrium of the small open economy.[13]

[13] Except for equations (21), (24) and (30), which are not needed.

A.2.2 Natural output in the small open economy

The flexible price level of output in the domestic economy can be derived from an equivalent system of labor supply, marginal cost, optimal price, production function, resource constraint, risk sharing condition, CPI, and law of one price for foreign goods.[14] Note that all natural variables have superscript n, accordingly the natural rate of interest $r_t^* = R_t^n$.

$$C_{A,t}^{n\frac{1}{\tau}} N_{A,t}^{n\varphi} = w_{A,t}^n, \tag{45}$$

$$\frac{1-\alpha}{\alpha} = \frac{w_{A,t}^n N_{A,t}^n}{r_t^{Kn}\ K_{A,t-1}^n} \Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}}, \tag{46}$$

$$mc_t^n = \frac{\left(r_t^{Kn}\right)^{\alpha} \left(w_{A,t}^n\right)^{1-\alpha}}{p_{H,t}^n \alpha^{\alpha} \left(1-\alpha\right)^{1-\alpha}} \frac{1}{A_t}, \tag{47}$$

$$\widetilde{p}_t^n = 1 = \frac{\epsilon}{(\epsilon-1)} \left(1-\phi\right) mc_t^n = \mu_t mc_t^n, \tag{48}$$

$$Y_{A,t}^n = \Gamma_{A,t}^{-\alpha \frac{\tau+\tau\varphi}{1+\tau\varphi}} A_t \left(K_{A,t-1}^n\right)^{\alpha} \left(N_{A,t}^n\right)^{1-\alpha} \tag{49}$$

$$Y_{A,t}^n = \left(p_{H,t}^n\right)^{-\eta} \left[\left(1-\gamma\right)\left(C_{A,t}^n + I_{A,t}^n\right) + \gamma \left(RER_t^n\right)^{\eta} Y_{A,t}^{nf}\right] \tag{50}$$

$$C_{A,t}^n = \upsilon C_{A,t}^{nf} \left(RER_t^n\right)^{\tau} \tag{51}$$

$$p_{H,\,t}^n = \left[\left(1-\gamma\right) + \gamma \left(TOT_t^n\right)^{1-\eta}\right]^{\frac{1}{\eta-1}} \tag{52}$$

$$TOT_t^n p_{H,t}^n = RER_t^n tot_n^{\sigma_q} \tag{53}$$

$$C_{A,t}^{n-\frac{1}{\tau}} e^{-g_t} = \beta E_t \left[R_t^n C_{A,t+1}^{n-\frac{1}{\tau}} e^{-g_{t+1}} \left(\frac{A_{t+1}}{A_t}\right)^{-\left(\frac{1+\varphi}{1+\tau\varphi}\right)}\right] \tag{54}$$

[14] A detailed model appendix is available upon request from the authors.

$$q_t^n C_{A,t}^{n-\frac{1}{\tau}} = \beta E_t C_{A,t+1}^{n-\frac{1}{\tau}} \Gamma_{A,t+1}^{-\left(\frac{1+\varphi}{1+\tau\varphi}\right)} e^{-\Delta g_{t+1}} \left[r_{t+1}^{Kn} + q_{t+1}^n (1-\delta)\right] \tag{55}$$

$$\begin{bmatrix} 1 + \kappa_I q_t^n \nu_t \left(\frac{I_{A,t}^n}{I_{A,t-1}^n} \Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A \right) \frac{I_{A,t}^n}{I_{A,t-1}^n} \Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} \\ -q_t^n \nu_t \left[1 - \frac{\kappa_I}{2} \left(\frac{I_{A,t}^n}{I_{A,t-1}^n} \Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A \right)^2 \right] \end{bmatrix} = \begin{bmatrix} \kappa_I \beta E_t q_{t+1}^n \nu_{t+1} \frac{C_{A,t+1}^{n-\frac{1}{\tau}}}{C_{A,t}^{n-\frac{1}{\tau}}} e^{-\Delta g_{t+1}} \Gamma_{A,t+1}^{-\left(\frac{1+\varphi}{1+\tau\varphi}\right)} \\ \left(\frac{I_{A,t+1}^n}{I_{A,t}^n} \Gamma_{A,t+1}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A \right) \end{bmatrix} \tag{56}$$

$$K_{A,t}^n - (1-\delta) K_{A,t-1}^n \left(\Gamma_{A,t}^{-\frac{\tau+\tau\varphi}{1+\tau\varphi}} \right) = I_{A,t}^n \nu_t \left[1 - \frac{\kappa_I}{2} \left(\frac{I_{A,t}^n}{I_{A,t-1}^n} \Gamma_{A,t}^{\frac{\tau+\tau\varphi}{1+\tau\varphi}} - \widetilde{\Gamma}_A \right)^2 \right] \tag{57}$$

$$GAP_t = \frac{Y_{A,t}}{Y_{A,t}^n} \tag{58}$$

A.3 Description of observables and additional data

Variable	**Description and source**
Observables:	
Output	Gross domestic product, calendar and seasonally adjusted, chained, 2010 reference year. Eurostat. ESA 2010
Inflation	Harmonized index of consumer prices (HICP) at constant taxes, all-items, seasonally adjusted. ESA 2010
Exchange rate to euro	Local currency per euro. Macrobond Financial AB
Terms of Trade	Price deflator of imports divided by price deflator of exports of goods and services. Eurostat. ESA 2010
Short term interest rates	3-month interbank interest rates. Source: Refinitv Eikon, Czech National Bank
Additional data:	
Import share	Imports of goods and services divided by gross domestic product, current prices, calendar and seasonally adjusted. World Development Indicators, World Bank
Share of imported goods in consumption	World Input-Output Database (WIOD), release 2016 for the period 2000-2014, University of Groningen
Survey inflation expecations	Inflation perceptions, Development of consumer prices in the next 12 months. European Commission (DG ECFIN) Consumer Survey

Table 11: Observables and other: Data description and sources

A.4 Alternative estimation results

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
τ	0.50	0.76	[0.6,0.93]	0.50	0.79	[0.64,0.95]
γ	0.40	0.39	[0.31,0.47]	0.40	0.35	[0.27,0.43]
η	1.00	1.10	[0.86,1.33]	1.00	1.42	[1.08,1.74]
φ	1.50	1.04	[0.49,1.56]	1.50	1.15	[0.59,1.72]
θ	0.66	0.09	[0.02,0.15]	0.66	0.11	[0.03,0.19]
κ_I	4.00	2.88	[1.84,3.91]	4.00	3.47	[1.95,4.84]
δ	0.03	0.02	[0.01,0.04]	0.03	0.03	[0.02,0.04]
α	0.30	0.26	[0.23,0.3]	0.30	0.29	[0.25,0.33]
ψ_Y	0.50	0.34	[0.15,0.52]	0.50	0.14	[0.05,0.23]
ψ_π	1.50	2.64	[1.87,3.38]	1.50	2.39	[1.68,3.09]
ρ_i	0.50	0.79	[0.72,0.87]	0.50	0.83	[0.77,0.89]
r_A	1.00	0.85	[0.58,1.12]	1.00	0.67	[0.45,0.89]
π_A	4.00	2.82	[0.98,4.5]	4.00	1.28	[0.42,2.05]
Γ_Q	0.75	0.58	[0.39,0.77]	0.75	0.13	[0,0.24]
$consTOT$	0.00	-0.15	[-0.29,0]	0.00	-0.04	[-0.12,0.04]
$consNER$	0.00	0.01	[-0.16,0.17]	0.00	-0.01	[-0.17,0.15]
ι_P	0.50	0.47	[0.31,0.64]	0.50	0.47	[0.31,0.64]
	Hungary			Romania		
τ	0.50	0.88	[0.79,0.98]	0.50	0.82	[0.67,0.97]
γ	0.30	0.25	[0.18,0.31]	0.30	0.19	[0.09,0.28]
η	1.00	1.02	[0.73,1.32]	1.00	0.99	[0.68,1.28]
φ	1.50	1.05	[0.58,1.51]	1.50	1.55	[0.85,2.19]
θ	0.66	0.35	[0.24,0.45]	0.66	0.25	[0.04,0.54]
κ_I	4.00	2.22	[0.75,3.79]	4.00	2.18	[0.82,3.44]
δ	0.03	0.02	[0.01,0.03]	0.03	0.02	[0.01,0.03]
α	0.30	0.25	[0.22,0.29]	0.30	0.25	[0.21,0.28]
ψ_Y	0.50	0.31	[0.15,0.47]	0.50	0.29	[0.13,0.45]
ψ_π	1.50	2.07	[1.48,2.63]	1.50	2.46	[1.47,3.26]
ρ_i	0.50	0.75	[0.67,0.84]	0.50	0.66	[0.55,0.77]
r_A	1.00	0.91	[0.63,1.2]	1.00	0.95	[0.65,1.26]
π_A	4.00	2.54	[0.84,4.11]	4.00	3.13	[1.39,4.64]
Γ_Q	0.75	0.42	[0.27,0.57]	0.75	0.60	[0.4,0.81]
$consTOT$	0.00	-0.04	[-0.14,0.05]	0.00	0.16	[0.01,0.31]
$consNER$	0.00	0.01	[-0.15,0.17]	0.00	0.02	[-0.14,0.18]
ι_P	0.50	0.44	[0.27,0.61]	0.50	0.45	[0.28,0.63]

Table 12: Posterior estimation results of the model without convergence: Posterior mean, lower and upper bound of 90 % HPD interval.

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
ρ_a	0.20	0.04	[0.01,0.08]	0.20	0.04	[0.01,0.08]
ρ_{y^f}	0.90	0.98	[0.97,0.99]	0.90	0.96	[0.95,0.98]
ρ_{π^f}	0.80	0.50	[0.35,0.65]	0.80	0.53	[0.38,0.68]
ρ_g	0.20	0.27	[0.07,0.46]	0.20	0.28	[0.07,0.49]
ρ_u	0.80	0.91	[0.83,0.99]	0.80	0.88	[0.8,0.96]
ρ_ν	0.80	0.47	[0.33,0.62]	0.80	0.75	[0.64,0.86]
σ_i	0.50	0.27	[0.2,0.34]	0.50	0.20	[0.16,0.24]
σ_a	1.00	1.42	[1.1,1.73]	1.00	1.37	[1.11,1.62]
σ_{y^f}	1.50	2.86	[2.13,3.54]	1.50	1.19	[0.94,1.44]
σ_{π^f}	0.55	3.91	[3.34,4.51]	0.55	2.35	[2.01,2.71]
σ_g	0.25	0.18	[0.11,0.24]	0.25	0.15	[0.1,0.19]
σ_u	0.55	0.98	[0.57,1.39]	0.55	0.84	[0.53,1.14]
σ_q	1.00	0.43	[0.31,0.55]	1.00	0.38	[0.29,0.48]
σ_ν	0.25	7.85	[5.82,10]	0.25	2.28	[1.37,3.13]
	Hungary			Romania		
ρ_a	0.20	0.07	[0.02,0.12]	0.20	0.08	[0.01,0.14]
ρ_{y^f}	0.90	0.92	[0.86,0.97]	0.90	0.96	[0.94,0.99]
ρ_{π^f}	0.80	0.47	[0.31,0.61]	0.80	0.65	[0.48,0.82]
ρ_g	0.20	0.23	[0.04,0.39]	0.20	0.54	[0.13,0.82]
ρ_u	0.80	0.96	[0.94,0.99]	0.80	0.86	[0.72,0.99]
ρ_ν	0.80	0.41	[0.27,0.55]	0.80	0.48	[0.35,0.61]
σ_i	0.50	0.45	[0.34,0.56]	0.50	0.64	[0.48,0.79]
σ_a	1.00	1.32	[1.09,1.54]	1.00	2.05	[1.65,2.44]
σ_{y^f}	1.50	1.00	[0.83,1.16]	1.50	1.56	[1.16,1.94]
σ_{π^f}	0.55	3.03	[2.57,3.48]	0.55	1.56	[1.04,2.08]
σ_g	0.25	0.19	[0.12,0.26]	0.25	1.36	[0.13,2.2]
σ_u	0.55	1.13	[0.69,1.54]	0.55	1.28	[0.28,2.7]
σ_q	1.00	0.45	[0.34,0.57]	1.00	1.74	[1.34,2.14]
σ_ν	0.25	9.35	[3.45,15.44]	0.25	13.19	[7.42,19.99]

Table 13: Posterior estimation results of the model without convergence: Shock parameters. Posterior mean, lower and upper bound of 90 % HPD interval.

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
γ	0.40	0.36	[0.27,0.45]	0.40	0.34	[0.27,0.42]
η	1.00	0.99	[0.82,1.16]	1.00	1.36	[1.04,1.67]
φ	1.50	1.10	[0.53,1.64]	1.50	1.45	[0.78,2.1]
θ	0.66	0.09	[0.02,0.15]	0.66	0.11	[0.04,0.19]
κ_I	3.88	2.58	[1.46,3.76]	6.07	5.09	[3.49,6.73]
δ	0.03	0.03	[0.02,0.04]	0.04	0.04	[0.03,0.05]
α	0.22	0.19	[0.16,0.23]	0.18	0.19	[0.15,0.23]
ψ_Y	0.50	0.37	[0.17,0.55]	0.50	0.20	[0.07,0.33]
ψ_π	1.50	2.47	[1.76,3.17]	1.50	2.25	[1.57,2.9]
ρ_i	0.50	0.78	[0.71,0.86]	0.50	0.82	[0.75,0.88]
r_A	1.00	0.87	[0.6,1.15]	1.00	0.72	[0.49,0.95]
π_A	4.00	2.09	[0.76,3.36]	4.00	1.31	[0.47,2.07]
$consTOT$	0.00	-0.12	[-0.27,0.03]	0.00	-0.04	[-0.11,0.04]
$consNER$	0.00	0.00	[-0.15,0.16]	0.00	-0.01	[-0.17,0.15]
ι_P	0.50	0.47	[0.3,0.64]	0.50	0.47	[0.3,0.63]
	Hungary			Romania		
γ	0.40	0.32	[0.25,0.4]	0.30	0.15	[0.08,0.23]
η	1.00	1.07	[0.78,1.36]	1.00	0.94	[0.64,1.23]
φ	1.50	1.25	[0.66,1.84]	1.50	1.70	[0.93,2.41]
θ	0.66	0.35	[0.24,0.45]	0.66	0.33	[0.07,0.58]
κ_I	4.10	2.76	[1.28,4.34]	3.21	1.70	[0.41,2.99]
δ	0.04	0.04	[0.03,0.05]	0.02	0.02	[0.01,0.03]
α	0.17	0.15	[0.11,0.19]	0.20	0.18	[0.14,0.21]
ψ_Y	0.50	0.34	[0.14,0.54]	0.50	0.36	[0.15,0.56]
ψ_π	1.50	1.84	[1.31,2.37]	1.50	2.17	[1.28,2.92]
ρ_i	0.50	0.74	[0.65,0.83]	0.50	0.65	[0.54,0.76]
r_A	1.00	0.89	[0.61,1.15]	1.00	0.90	[0.61,1.18]
π_A	4.00	2.57	[0.9,4.18]	4.00	3.05	[1.22,4.61]
$consTOT$	0.00	-0.04	[-0.13,0.05]	0.00	0.18	[0.03,0.33]
$consNER$	0.00	0.01	[-0.16,0.17]	0.00	0.02	[-0.14,0.19]
ι_P	0.50	0.44	[0.27,0.6]	0.50	0.43	[0.25,0.61]

Table 14: Posterior estimation results of the counterfactual model: Posterior mean, lower and upper bound of 90 % HPD interval.

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
ρ_a	0.20	0.04	[0.01,0.07]	0.20	0.04	[0.01,0.07]
ρ_{y^f}	0.90	0.98	[0.97,0.99]	0.90	0.95	[0.93,0.98]
ρ_{π^f}	0.80	0.49	[0.34,0.64]	0.80	0.53	[0.38,0.68]
ρ_g	0.20	0.27	[0.07,0.46]	0.20	0.29	[0.07,0.5]
ρ_u	0.80	0.93	[0.86,0.99]	0.80	0.91	[0.84,0.98]
ρ_ν	0.80	0.46	[0.31,0.6]	0.80	0.74	[0.62,0.85]
σ_i	0.50	0.27	[0.2,0.33]	0.50	0.20	[0.16,0.24]
σ_a	1.00	1.46	[1.22,1.69]	1.00	1.38	[1.17,1.58]
σ_{y^f}	1.50	2.43	[2,2.85]	1.50	1.04	[0.84,1.22]
σ_{π^f}	0.55	3.93	[3.34,4.5]	0.55	2.35	[2.01,2.69]
σ_g	0.25	0.17	[0.11,0.23]	0.25	0.15	[0.11,0.19]
σ_u	0.55	0.84	[0.48,1.19]	0.55	0.74	[0.47,0.98]
σ_q	1.00	0.45	[0.31,0.57]	1.00	0.39	[0.29,0.48]
σ_ν	0.25	7.19	[4.85,10]	0.25	3.19	[2.09,4.28]
	Hungary			Romania		
ρ_a	0.20	0.07	[0.02,0.12]	0.20	0.07	[0.01,0.13]
ρ_{y^f}	0.90	0.90	[0.84,0.97]	0.90	0.96	[0.94,0.99]
ρ_{π^f}	0.80	0.47	[0.31,0.62]	0.80	0.64	[0.47,0.82]
ρ_g	0.20	0.23	[0.05,0.4]	0.20	0.45	[0.09,0.8]
ρ_u	0.80	0.96	[0.93,0.99]	0.80	0.86	[0.67,0.99]
ρ_ν	0.80	0.44	[0.3,0.58]	0.80	0.48	[0.33,0.63]
σ_i	0.50	0.45	[0.33,0.56]	0.50	0.64	[0.49,0.78]
σ_a	1.00	1.28	[1.08,1.48]	1.00	2.03	[1.7,2.36]
σ_{y^f}	1.50	0.92	[0.76,1.07]	1.50	1.35	[1.08,1.62]
σ_{π^f}	0.55	3.06	[2.59,3.49]	0.55	1.57	[1.05,2.11]
σ_g	0.25	0.20	[0.12,0.27]	0.25	1.05	[0.13,2.1]
σ_u	0.55	1.06	[0.58,1.55]	0.55	1.24	[0.3,2.39]
σ_q	1.00	0.43	[0.32,0.54]	1.00	1.77	[1.38,2.16]
σ_ν	0.25	10.59	[5.01,16.26]	0.25	10.97	[3.97,19.12]

Table 15: Posterior estimation results of the counterfactual model: Shock parameters. Posterior mean, lower and upper bound of 90 % HPD interval.

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
τ	0.50	0.73	[0.55,0.93]	0.50	0.71	[0.52,0.91]
γ	0.40	0.38	[0.29,0.48]	0.40	0.35	[0.27,0.42]
η	1.00	0.76	[0.5,1]	1.00	1.43	[1.1,1.75]
φ	1.50	0.76	[0.29,1.23]	1.50	1.16	[0.56,1.74]
θ	0.66	0.09	[0.02,0.15]	0.66	0.13	[0.04,0.23]
κ_I	4.00	3.62	[2.54,4.68]	4.00	4.41	[3.08,5.77]
δ	0.03	0.03	[0.01,0.04]	0.03	0.04	[0.03,0.05]
α	0.30	0.23	[0.2,0.25]	0.30	0.25	[0.21,0.28]
ψ_Y	0.50	0.12	[0.04,0.21]	0.50	0.08	[0.02,0.14]
ψ_π	1.50	3.04	[2.18,3.87]	1.50	2.62	[1.89,3.35]
ρ_i	0.50	0.82	[0.76,0.89]	0.50	0.83	[0.76,0.89]
r_A	1.00	0.80	[0.54,1.04]	1.00	0.68	[0.45,0.89]
π_A	4.00	2.14	[1.1,3.21]	4.00	1.13	[0.51,1.76]
Γ_Q	0.75	0.44	[0.26,0.62]	0.75	0.10	[0,0.19]
$consTOT$	0.00	-0.07	[-0.26,0.09]	0.00	-0.05	[-0.13,0.03]
$consNER$	0.00	0.00	[-0.16,0.17]	0.00	-0.01	[-0.17,0.15]
ι_P	0.50	0.48	[0.31,0.65]	0.50	0.47	[0.31,0.63]
	Hungary			Romania		
τ	0.50	0.86	[0.75,0.98]	0.50	0.62	[0.42,0.82]
γ	0.30	0.27	[0.2,0.34]	0.30	0.14	[0.08,0.2]
η	1.00	1.16	[0.83,1.48]	1.00	1.07	[0.74,1.41]
φ	1.50	1.10	[0.59,1.61]	1.50	1.31	[0.66,1.94]
θ	0.66	0.36	[0.25,0.46]	0.66	0.61	[0.44,0.8]
κ_I	4.00	3.12	[1.66,4.65]	4.00	3.11	[2.15,4.18]
δ	0.03	0.03	[0.01,0.04]	0.03	0.02	[0.01,0.02]
α	0.30	0.23	[0.2,0.26]	0.30	0.23	[0.2,0.25]
ψ_Y	0.50	0.31	[0.14,0.47]	0.50	0.25	[0.1,0.39]
ψ_π	1.50	2.12	[1.48,2.74]	1.50	2.05	[1.43,2.64]
ρ_i	0.50	0.77	[0.69,0.85]	0.50	0.71	[0.62,0.81]
r_A	1.00	0.90	[0.62,1.18]	1.00	0.92	[0.63,1.22]
π_A	4.00	2.43	[0.82,3.99]	4.00	2.27	[0.79,3.63]
Γ_Q	0.75	0.41	[0.26,0.56]	0.75	0.54	[0.32,0.74]
$consTOT$	0.00	-0.05	[-0.15,0.04]	0.00	0.15	[0,0.3]
$consNER$	0.00	0.00	[-0.16,0.16]	0.00	0.01	[-0.15,0.17]
ι_P	0.50	0.44	[0.28,0.61]	0.50	0.39	[0.22,0.55]

Table 16: Posterior estimation results of the model with alternative inital k: Posterior mean, lower and upper bound of 90 % HPD interval.

Parameter	Prior mean	Post. mean	90 % interval	Prior mean	Post. mean	90 % interval
	Poland			Czech Republic		
ρ_z	0.20	0.06	[0.01,0.11]	0.20	0.04	[0.01,0.07]
ρ_{y^f}	0.90	0.97	[0.95,1]	0.90	0.96	[0.94,0.98]
ρ_{π^f}	0.80	0.50	[0.35,0.65]	0.80	0.54	[0.38,0.68]
ρ_g	0.20	0.25	[0.06,0.43]	0.20	0.28	[0.07,0.48]
ρ_u	0.80	0.87	[0.78,0.96]	0.80	0.82	[0.73,0.92]
ρ_ν	0.80	0.63	[0.47,0.79]	0.80	0.75	[0.64,0.86]
σ_i	0.50	0.26	[0.19,0.33]	0.50	0.21	[0.17,0.26]
σ_z	1.00	1.54	[1.07,1.99]	1.00	1.51	[1.19,1.82]
σ_{y^f}	1.50	2.19	[1.54,2.82]	1.50	1.17	[0.92,1.43]
σ_{π^f}	0.55	3.91	[3.31,4.47]	0.55	2.32	[1.96,2.66]
σ_g	0.25	0.17	[0.11,0.23]	0.25	0.16	[0.11,0.2]
σ_u	0.55	2.03	[1.14,2.91]	0.55	1.17	[0.71,1.6]
σ_q	1.00	0.45	[0.31,0.59]	1.00	0.40	[0.3,0.49]
σ_ν	0.25	8.32	[6.66,10]	0.25	2.98	[2.04,3.89]
	Hungary			Romania		
ρ_z	0.20	0.06	[0.02,0.11]	0.20	0.16	[0.02,0.31]
ρ_{y^f}	0.90	0.91	[0.86,0.97]	0.90	0.95	[0.92,0.98]
ρ_{π^f}	0.80	0.47	[0.32,0.62]	0.80	0.63	[0.46,0.81]
ρ_g	0.20	0.23	[0.05,0.41]	0.20	0.21	[0.04,0.36]
ρ_u	0.80	0.96	[0.93,0.99]	0.80	0.78	[0.62,0.96]
ρ_ν	0.80	0.40	[0.27,0.53]	0.80	0.57	[0.44,0.69]
σ_i	0.50	0.45	[0.33,0.56]	0.50	0.57	[0.45,0.68]
σ_z	1.00	1.37	[1.13,1.61]	1.00	2.41	[1.63,3.26]
σ_{y^f}	1.50	1.06	[0.88,1.25]	1.50	1.49	[1.11,1.88]
σ_{π^f}	0.55	3.04	[2.58,3.48]	0.55	1.61	[0.99,2.18]
σ_g	0.25	0.19	[0.12,0.26]	0.25	0.25	[0.12,0.38]
σ_u	0.55	1.18	[0.76,1.61]	0.55	3.79	[2.4,5.15]
σ_q	1.00	0.45	[0.33,0.56]	1.00	1.77	[1.33,2.19]
σ_ν	0.25	12.39	[7.05,18.41]	0.25	16.59	[13.09,20]

Table 17: Posterior estimation results of the model with alternative inital k: Shock parameters. Posterior mean, lower and upper bound of 90 % HPD interval.