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A Real-Business-Cycle model with energy use: Lessons for Bulgaria (1999-2018)

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February 27, 2024

Abstract

We introduce energy as a productive input into a real-business-cycle model with government sector. We calibrate the model to Bulgarian data for the period following the introduction of the currency board arrangement (1999-2018). We investigate the quantitative importance of the presence of energy, and the potential relevance of energy price shocks as driving forces behind the observed business cycle fluctuations in Bulgaria. In particular, a positive shock to energy prices in the model works like a negative technological shock. Allowing for the presence of energy as a factor of production does not substantially improve the model performance against data, and is thus an unlikely driver of business cycle fluctuations in Bulgaria.

Keywords: Business fluctuations, energy use, energy prices, Bulgaria

JEL Classification Codes: E32, E22, E37

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1 Introduction and Motivation

Real-business-cycle (RBC) theory emphasizes stochastic technology shocks as a main driving force of business cycles. This was also the approach taken in Vasilev (2009) for Bulgaria in the period following the introduction of currency board (1997). The standard RBC setup, when calibrated to Bulgarian data, fails along the labor market dimension, and produces too pro-cyclical wages, and too little variability in employment, among other things.

In order to quantitatively address this issue, and gain a deeper understanding of the transmission mechanism responsible for economic fluctuations, we introduce energy as an additional production into an RBC model with government. We examine the quantitative importance of the presence of energy in the framework and its relevance to generate plausible cyclical movements in aggregate variables in Bulgaria in the period after the introduction of the currency board arrangement. The period of our investigation was chosen due to the fact that the introduction of the hard exchange-rate peg achieved macroeconomic stability in Bulgaria, and thus the time series have good statistical properties.

We also argue for the importance of the energy as a possible alternative to technological shocks, as a higher cost in terms of higher energy use will have a direct negative effect working through the production function, which in turn following from fact that energy is a factor of production. We then use this simulated economy as a laboratory in order to study the importance of energy price shocks on the main aggregate variables. In order to be able to draw plausible quantitative predictions, we calibrate the theoretical economy to approximate Bulgaria in the period 1999-2018. We find that a positive shock to energy prices is akin to a negative technological shock. Unexpected changes in world energy prices are potentially very important for an energy-intensive industrial production in Bulgaria; more specifically, Bulgaria imports most of its energy inputs (oil and natural gas in particular) from the Russian federation, and price hikes make domestic industry less competitive. Having energy as a productive input is a way to circumvent the absence of a trade sector, while still capturing the effect of important terms-of-trade shocks.

Next, from the perspective of the Bulgarian economy, the price of the aggregate energy

input is taken as given. This, the industry structure of the energy production is not of central importance and will be ignored in this paper. More specifically, it is of limited relevance for the transmission mechanism described in this paper.¹ What takes a central stage in the model setup is that energy prices directly affect the productivity and aggregate output. Overall, the model with energy performs better than earlier real-business-cycle models vis-a-vis data for Bulgaria. In particular, consistent with observed cyclical fluctuations in Bulgaria, total hours follow output movement. Nevertheless, as with the standard RBC model, the model with energy falls far short of generating wage variability as in data, and the wage rate in the model is still moderately pro-cyclical, while wages are acyclical in data.

The rest of the paper is organized as follows: Section 2 describes the model framework and describes the decentralized competitive equilibrium system, Section 3 discusses the calibration procedure, and Section 4 presents the steady-state model solution. Section 5 proceeds with the out-of-steady-state dynamics of model variables, and compared the simulated second moments of theoretical variables against their empirical counterparts. Section 6 concludes the paper.

2 Model Description

There is a representative households which derives utility out of consumption and leisure. The time available to households can be spent working or enjoyed as leisure. The government taxes consumption spending and levies a common tax on all income, in order to finance its expenditure. On the production side, there is a representative firm, which hires labor and physical capital to produce a homogenous final good, which could be used for consumption, investment, government purchases, or energy consumption.

¹In another line of research, Rotemberg and Woodford (1996) emphasize the role of imperfect competition in the oil market to explain business cycle fluctuations in the US economy. Hamilton (1983, 1985, 1996) studies the effect of oil price on real output in the US.

2.1 Households

There is a representative household, which maximizes its expected utility function as in Hansen (1985)

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \ln c_t - \gamma h_t \right\}, \quad (2.1)$$

where E_0 denotes household's expectations as of period 0, c_t denotes household's private consumption in period t , h_t are hours worked in period t , $0 < \beta < 1$ is the discount factor, $0 < \gamma < 1$ is the relative weight that the household attaches to leisure.

The household starts with an initial stock of physical capital $k_0 > 0$, and has to decide how much to add to it in the form of new investment. The law of motion for physical capital is

$$k_{t+1} = i_t + (1 - \delta)k_t \quad (2.2)$$

and $0 < \delta < 1$ is the depreciation rate. Next, the real interest rate is r_t , hence the before-tax capital income of the household in period t equals $r_t k_t$. In addition to capital income, the household can generate labor income. Hours supplied to the representative firm are rewarded at the hourly wage rate of w_t , so pre-tax labor income equals $w_t h_t$. Lastly, the household owns the firm in the economy and has a legal claim on all the firm's profit, π_t .

Next, the household's problem can be now simplified to

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \ln c_t - \gamma h_t \right\} \quad (2.3)$$

s.t.

$$(1 + \tau^c)c_t + k_{t+1} - (1 - \delta)k_t + p_t e_t = (1 - \tau^y)[r_t k_t + \pi_t + w_t h_t] + g_t^t \quad (2.4)$$

where τ^c is the tax on consumption, τ^y is the proportional income tax rate on labor and capital ($0 < \tau^c, \tau^y < 1$), g_t^t denotes government transfers, and $p_t e_t$ is spending on energy. The household takes the tax rates $\{\tau^c, \tau^y\}_{t=0}^{\infty}$, government spending, $\{g_t^t\}_{t=0}^{\infty}$, profit $\{\pi_t\}_{t=0}^{\infty}$, the realized process for energy prices $\{p_t\}_{t=0}^{\infty}$, prices $\{w_t, r_t\}_{t=0}^{\infty}$, and chooses $\{c_t, h_t, k_{t+1}\}_{t=0}^{\infty}$ to

maximize its utility subject to the budget constraint.² The first-order optimality conditions as follows:

$$c_t : \frac{1}{c_t} = \lambda_t(1 + \tau^c) \quad (2.5)$$

$$h_t : \gamma = \lambda_t(1 - \tau^y)w_t \quad (2.6)$$

$$k_{t+1} : \lambda_t = \beta E_t \lambda_{t+1} \left[1 + [1 - \tau^y]r_{t+1} - \delta \right] \quad (2.7)$$

$$TVC : \lim_{t \rightarrow \infty} \beta^t \lambda_t k_{t+1} = 0 \quad (2.8)$$

where λ_t is the Lagrangean multiplier of the household's period- t budget constraint. The first-order conditions above are summarized as follows: the first one states that the marginal utility of consumption equals the marginal utility of wealth, corrected for the consumption tax rate. The second equation states that when choosing labor supply optimally, at the margin, each hour spent by the household working for the firm should balance the benefit and costs from doing so. The third equation describes how the household chooses to allocate physical capital over time. The last condition, "transversality condition" (TVC), states that at the end of the optimization horizon, the value of physical capital should be zero.

2.2 Firm problem

There is a representative firm in the economy, which produces a homogeneous product. The price of output is normalized to unity. As in Kim and Loungari (1992), the production technology is constant elasticity of substitution (CES) between capital and energy and uses physical capital, k_t , energy e_t and labor hours, h_t , to maximize static profit³

$$\Pi_t = A_t[(1 - b)k_t^{-v} + be^{-v}]^{-\alpha/v} h_t^{1-\alpha} - r_t k_t - w_t h_t - p_t e_t, \quad (2.9)$$

where A_t denotes the level of technology in period t . Since the firm rents the capital from households, the problem of the firm is a sequence of static profit maximizing problems. In equilibrium, there are no profits, and each input is priced according to its marginal product,

²Note that by choosing k_{t+1} the household is implicitly setting investment i_t optimally.

³As a robustness check, we tried the Cobb-Douglas case for the production function as well. The results did not change quantitatively.

i.e.:

$$k_t : \alpha \frac{y_t}{(1-b)k_t^{-v} + be^{-v}}(1-b)k_t^{-v-1} = r_t, \quad (2.10)$$

$$e_t : \alpha \frac{y_t}{(1-b)k_t^{-v} + be^{-v}}be_t^{-v-1} = p_t, \quad (2.11)$$

$$h_t : (1-\alpha)\frac{y_t}{h_t} = w_t. \quad (2.12)$$

In equilibrium, given that the inputs of production are paid their marginal products, $\pi_t = 0$, $\forall t$.

2.3 Government

In the model setup, the government is levying taxes on labor and capital income, as well as consumption, in order to finance spending on government purchases, and government transfers. The government budget constraint is as follows:

$$g_t^c + g_t^t = \tau^c c_t + \tau^y [w_t h_t + r_t k_t + \pi_t] \quad (2.13)$$

2.4 Dynamic Competitive Equilibrium (DCE)

For a given process followed by technology and energy prices $\{A_t, p_t\}_{t=0}^{\infty}$ tax schedules $\{\tau^c, \tau^y\}_{t=0}^{\infty}$, and initial capital stock $\{k_0\}$, the decentralized dynamic competitive equilibrium is a list of sequences $\{c_t, i_t, k_t, e_t, h_t\}_{t=0}^{\infty}$ for the household, a sequence of government purchases and transfers $\{g_t^c, g_t^t\}_{t=0}^{\infty}$, and input prices $\{w_t, r_t\}_{t=0}^{\infty}$ such that (i) the household maximizes its utility function subject to its budget constraint; (ii) the representative firm maximizes profit; (iii) government budget is balanced in each period; (iv) all markets clear, and $y_t = c_t + i_t + g_t^c + p_t e_t$.

3 Data and Model Calibration

To characterize business cycle fluctuations in Bulgaria, we will focus on the period following the introduction of the currency board (1999-2018). Quarterly data on output, consumption and investment was collected from National Statistical Institute (2020), while the real interest rate is taken from Bulgarian National Bank Statistical Database (2020). The calibration strategy described in this section follows a long-established tradition in modern

macroeconomics: first, as in Vasilev (2016), the discount factor, $\beta = 0.982$, is set to match the steady-state capital-to-output ratio in Bulgaria, $k/y = 13.964$, in the steady-state Euler equation. The labor share parameter, $1 - \alpha = 0.571$, is obtained as in Vasilev (2017d), and equals the average value of labor income in aggregate output over the period 1999-2018. Parameters b and v , which determine the complementarity and the curvature of the CES production function, were set to match the steady-state consumption-to-output ratio. Next, the average labor and capital income tax rate was set to the flat rate in data, or $\tau^y = 0.1$. Similarly, the average tax rate on consumption is set to its value over the period, $\tau^c = 0.2$.

Next, the relative weight attached to the utility out of leisure in the household's utility function, γ , is calibrated to match that in steady-state consumers would supply one-third of their time endowment to working. This is in line with the estimates for Bulgaria (Vasilev 2017a) as well over the period studied. Next, the steady-state depreciation rate of physical capital in Bulgaria, $\delta = 0.013$, was estimated as the average quarterly depreciation rate over the period 1999-2018. Finally, the processes followed by the TFP and energy price process, respectively, is estimated from the detrended series by running an AR(1) regression and saving the residuals. Table 1 below summarizes the values of all model parameters used in the paper.

4 Steady-State

Once the values of model parameters were obtained, the steady-state equilibrium system solved, the "big ratios" can be compared to their averages in Bulgarian data. The results are reported in Table 2 below. For computational ease, the steady-state level of output was normalized to unity; the model matches consumption-to-output and government purchases ratios by construction; the investment ratios are also closely approximated. The after-tax return, where $\bar{r} = (1 - \tau^y)r - \delta$ is also relatively well-captured by the model.

Table 1: Model Parameters

Parameter	Value	Description	Method
β	0.982	Discount factor	Calibrated
$1 - \alpha$	0.571	Labor Share	Data average
b	0.200	capital-energy complementarity	Calibrated
v	0.700	CES parameter, production function	Calibrated
γ	0.873	Relative weight attached to leisure	Calibrated
δ	0.013	Depreciation rate on physical capital	Data average
τ^y	0.100	Average tax rate on income	Data average
τ^c	0.200	VAT/consumption tax rate	Data average
p	1.000	Steady-state energy price level	Calibrated
ρ_a	0.701	AR(1) persistence coefficient, TFP process	Estimated
ρ_p	0.980	AR(1) persistence coefficient, energy price process	Estimated
σ_a	0.044	st. error, TFP process	Estimated
σ_p	0.013	st. error, energy price	Estimated

Table 2: Data Averages and Long-run Solution

Variable	Description	Data	Model
y	Steady-state output	N/A	1.000
c/y	(non-energy) Consumption-to-output ratio	0.574	0.0574
i/y	Investment-to-output ratio	0.201	0.175
pe/y	Energy consumption-to-output ratio	0.050	0.050
g^c/y	Government purchases-to-output ratio	0.151	0.151
h	Share of time spent working	0.333	0.333
\bar{r}	After-tax net return on capital	0.014	0.016

5 Out of steady-state model dynamics

Since the model does not have an analytical solution for the equilibrium behavior of variables outside their steady-state values, we need to solve the model numerically. This is done by log-linearizing the original equilibrium (non-linear) system of equations around the steady-state.

This transformation produces a first-order system of stochastic difference equations. First, we study the dynamic behavior of model variables to an isolated shock to the total factor productivity process, and energy price, respectively. Then we proceed to fully simulate the model to compare how the second moments of the model perform when compared against their empirical counterparts.

5.1 Impulse Response Analysis

This subsection documents the impulse responses of model variables to a 1% surprise innovation to technology, as well as an unexpected one-percent change in energy prices.⁴ The impulse response functions (IRFs) are presented in Fig. 1 and Fig.2 on the next page.

5.1.1 Impulse Responses to Technology Shocks

As a result of the one-time unexpected positive shock to total factor productivity, output increases upon impact. This expands the availability of resources in the economy, so used of output - consumption, investment, energy use and government consumption also increase contemporaneously. At the same time, the increase in productivity increases the after-tax return on the two factors of production, labor and capital. The representative households then respond to the incentives contained in prices and start accumulating capital, and supplies more hours worked. In turn, the increase in capital input feeds back in output through the production function and that further adds to the positive effect of the technology shock. In the labor market, the wage rate increases, and the household increases its hours worked. In turn, the increase in total hours further increases output, again indirectly.

Over time, as capital is being accumulated, its after-tax marginal product starts to decrease, which lowers the households' incentives to save. As a result, physical capital stock eventually returns to its steady-state, and exhibits a hump-shaped dynamics over its transition path. The rest of the model variables return to their old steady-states in a monotone fashion as the effect of the one-time surprise innovation in technology dies out.

⁴This price is to be interpreted as an aggregate category, comprising electricity, coal, natural gas, and petroleum.

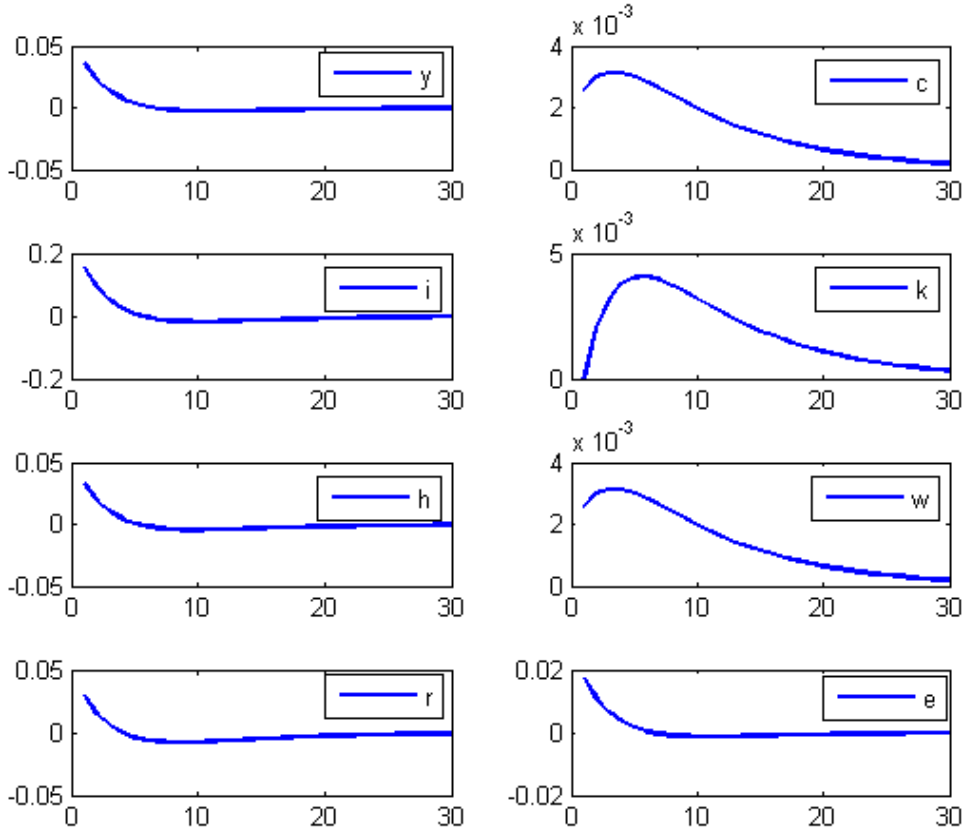


Figure 1: Impulse Responses to a 1% surprise innovation in technology

5.1.2 Impulse Responses to Unanticipated Energy Prices

As a result of an unexpected one-time increase in the price of the aggregate energy input, illustrated in Fig. 2 below, the effect is similar to a negative technology shock. In particular, consumption of both energy, and the non-energy private consumption, decreases. In turn, capital accumulation, and investment decrease. As a result of the lower capital availability, real interest rate goes up. Due to the substitutability between hours and capital-energy mix, hours go up, but the effect is small, and aggregate output also goes down. Alternatively, the increase in energy prices can be regarded as a negative wealth effect, akin to an increase in government consumption, which is a drain on resources, and makes the household poorer; thus, it tries to compensate for that effect by working more. This compensation is unsuccessful, as overall income decreases, due to the fall in both capital income, and the wage rate.

Over time, all variables return to their steady-state; despite causing a prolonged adjustment, the quantitative effect of energy price shocks on the economy is rather small.

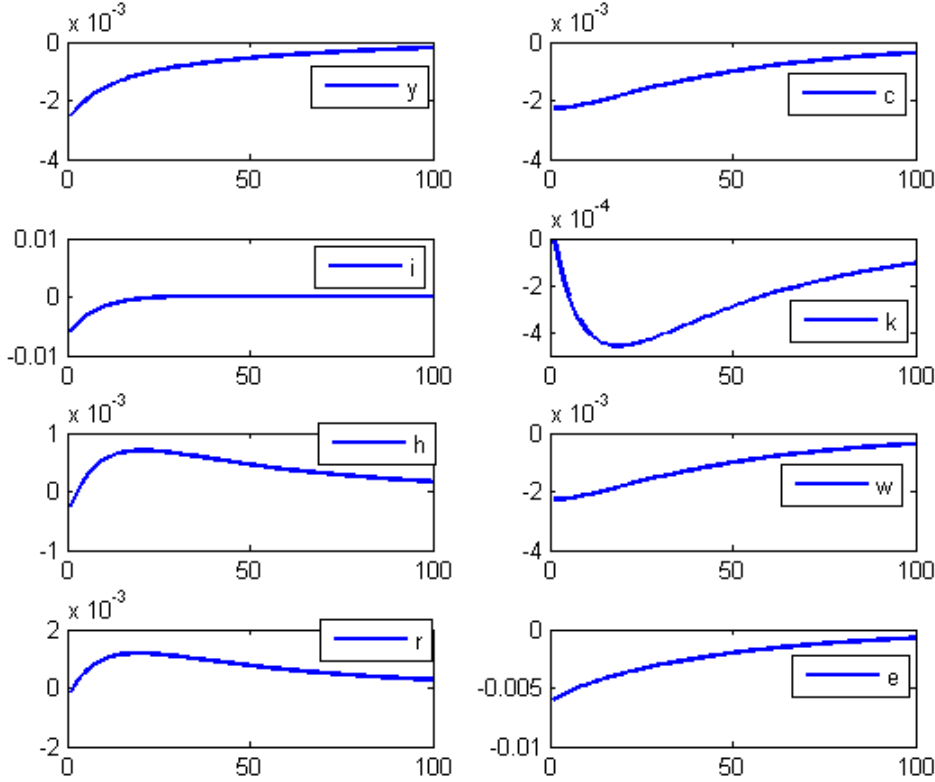


Figure 2: Impulse Responses to a 1% surprise innovation in energy price

5.2 Simulation and moment-matching

As in Vasilev (2017b), we will now simulate the model 10,000 times for the length of the data horizon. Both empirical and model simulated data is detrended using the Hodrick-Prescott (1980) filter. Table 3 on the next page summarizes the second moments of data (relative volatilities to output, and contemporaneous correlations with output) versus the same moments computed from the model-simulated data at quarterly frequency. We present three specifications: with both shocks at work, and then with each of them working in isolation. As it turns out, the additional value of energy presence is rather small, while energy price shock on its own, in the absence of technology shocks, is not able to produce business cy-

cles of the magnitude observed in data. Thus, in what follows, we will focus on the setup with the two stochastic processes at work. As in Vasilev (2016, 2017b, 2017c), the model with energy matches quite well the absolute volatility of output and investment. However, the setup underestimates non-energy consumption volatility, due to the presence of energy consumption, which acts as a substitute. Still, the model is qualitatively consistent with the stylized fact that consumption generally varies less than output, while investment is more variable than output.

Table 3: Business Cycle Moments

	Data	Model (Both shocks)	Model (Tech. shocks only)	Model (energy price shocks only)
σ_y	0.05	0.05	0.05	0.05
σ_c/σ_y	0.55	0.40	0.39	1.33
σ_i/σ_y	1.77	4.05	4.07	1.54
σ_g/σ_y	1.21	1.00	1.00	1.00
σ_h/σ_y	0.63	0.87	0.87	0.34
σ_w/σ_y	0.83	0.40	0.39	1.33
$corr(c, y)$	0.85	0.49	0.47	0.96
$corr(i, y)$	0.61	0.95	0.96	0.75
$corr(g, y)$	0.31	1.00	1.00	1.00
$corr(h, y)$	0.49	0.91	0.91	-0.55
$corr(w, y)$	-0.01	0.49	0.47	0.95

With respect to the labor market variables, the variability of employment predicted by the model is significantly higher than that in data, while the variability of wages in the model is much lower than that in data. This is yet another confirmation that the perfectly-competitive assumption, e.g. Vasilev (2009), does not describe very well the dynamics of labor market variables. Next, in terms of contemporaneous correlations, the model systematically overpredicts the pro-cyclicality of the main aggregate variables - consumption, investment, government consumption, employment and wages. The model predicts moderate cyclicalities of wages, while wages in data are acyclical. Still, the current model is still better than the

standard setup without energy, which produced almost perfect positive correlation between wages and utput.

In the next subsection, as in Vasilev (2016), we investigate the dynamic correlation between labor market variables at different leads and lags, thus evaluating how well the model matches the phase dynamics among variables. In addition, the autocorrelation functions (ACFs) of empirical data, obtained from an unrestricted VAR(1) are put under scrutiny and compared and contrasted to the simulated counterparts generated from the model.

5.3 Auto- and cross-correlation

This subsection discusses the auto-(ACFs) and cross-correlation functions (CCFs) of the major model variables. The coefficients empirical ACFs and CCFs at different leads and lags are presented in Table 4 below against the averaged simulated AFCs and CCFs.

Table 4: Autocorrelations for Bulgarian data and the model economy

		k			
Method	Statistic	0	1	2	3
Data	$corr(n_t, n_{t-k})$	1.000	0.484	0.009	0.352
Model	$corr(n_t, n_{t-k})$	1.000	0.951	0.880	0.818
	(s.e.)	(0.000)	(0.030)	(0.057)	(0.082)
Data	$corr(y_t, y_{t-k})$	1.000	0.810	0.663	0.479
Model	$corr(y_t, y_{t-k})$	1.000	0.952	0.893	0.824
	(s.e.)	(0.000)	(0.029)	(0.055)	(0.079)
Data	$corr(a_t, a_{t-k})$	1.000	0.702	0.449	0.277
Model	$corr(a_t, a_{t-k})$	1.000	0.955	0.900	0.837
	(s.e.)	(0.000)	(0.027)	(0.052)	(0.076)
Data	$corr(c_t, c_{t-k})$	1.000	0.971	0.952	0.913
Model	$corr(c_t, c_{t-k})$	1.000	0.958	0.909	0.854
	(s.e.)	(0.000)	(0.024)	(0.047)	(0.068)
Data	$corr(i_t, i_{t-k})$	1.000	0.810	0.722	0.594
Model	$corr(i_t, i_{t-k})$	1.000	0.951	0.890	0.819
	(s.e.)	(0.000)	(0.029)	(0.056)	(0.081)
Data	$corr(w_t, w_{t-k})$	1.000	0.760	0.783	0.554
Model	$corr(w_t, w_{t-k})$	1.000	0.958	0.909	0.853
	(s.e.)	(0.000)	(0.024)	(0.047)	(0.068)

As seen from Table 4 on the previous page, the model compares relatively well vis-a-vis data. Empirical ACFs for output and investment are slightly outside the confidence band predicted by the model, while the ACFs for total factor productivity and household consumption are well-approximated by the model. The persistence of labor market variables are also relatively well-described by the model dynamics. Next, as seen from Table 5 below, over the business cycle, in data labor productivity leads employment. The model, however, cannot account for this pattern.

Table 5: Dynamic correlations for Bulgarian data and the model economy

Method	Statistic	k						
		-3	-2	-1	0	1	2	3
Data	$corr(n_t, (y/n)_{t-k})$	-0.342	-0.363	-0.187	-0.144	0.475	0.470	0.346
Model	$corr(n_t, (y/n)_{t-k})$	0.099	0.097	0.088	0.128	-0.037	-0.064	-0.079
	(s.e.)	(0.331)	(0.289)	(0.242)	(0.349)	(0.204)	(0.241)	(0.275)
Data	$corr(n_t, w_{t-k})$	0.355	0.452	0.447	0.328	-0.040	-0.390	-0.57
Model	$corr(n_t, w_{t-k})$	0.099	0.097	0.088	0.128	-0.037	-0.064	-0.079
	(s.e.)	(0.331)	(0.289)	(0.242)	(0.349)	(0.204)	(0.241)	(0.275)

6 Conclusions

We introduce energy as a productive input into a real-business-cycle model with government sector. We calibrate the model to Bulgarian data for the period following the introduction of the currency board arrangement (1999-2018). We investigate the quantitative importance of the presence of energy, and the potential relevance of energy price shocks as driving forces behind the observed business cycle fluctuations in Bulgaria. In particular, a positive shock to energy prices in the model works like a negative technological shock. Allowing for the presence of energy as a factor of production does not substantially improves the model performance against data, and is thus an unlikely driver of business cycle fluctuations in Bulgaria. .

In addition, the failure of the model along the labor market dimension - the too high variability in hours in the model, the moderate pro-cyclicality of wages, and the too low wage variability versus that observed in data both suggest that the setup should depart from the perfectly-competitive paradigm. As a suggestion for future research, the model should focus on the important frictions in the labor market, which forms almost two-thirds of total income (and much quantitatively much more important than the share of capital and energy), and extend the model along the lines of Vasilev (2016, 2017b, 2017c).

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