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Role and Impact of Energy in the Business Cycle

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Role and Impact of Energy in the Business Cycle

by

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Abstract

Given the fundamental role of energy in the economy, the macroeconomic literature contains a large body of work on the impact of oil/energy on the business cycle, with much of the attention focusing on energy supply shocks, mostly modeled as exogenous oil/energy price increases. And yet, the oil price hikes pre-2008 suggest that other shocks to the energy market may be the source of such instance of price disturbances, so that their effects on the economy are no longer predicted by exogenous energy supply shocks. In such scenario, it is no longer valid to treat energy price disturbances as exogenous shocks to an economic model that seeks to study the impact of energy on the business cycle. The empirical works of Kilian (2008, 2009) affirm this point, showing that it is imperative not to view all oil/energy price increases as alike in terms of their impact on the economy, and that the underlying causes of the increases matter. There is thus a need to have a theoretical framework that helps disentangle the various sources of shocks to the energy market and understand the distinct mechanisms that may be at play.

This dissertation advances the study of the role of energy in the business cycle. In terms of theoretical modeling it extends the usual RBC framework with oil/energy to include an endogenous energy sector with convex energy production costs, as well as the explicit production and consumption of energy-dependent and non-energy- dependent goods. The former extension enables the investigation of demand shocks to the energy market, by producing low price elasticity of energy supply, as observed empirically, and meaningful energy price responses to changing energy demand. The latter establishes the theoretical link between the degree of energy dependence of a good and energy price disturbances. These features form the theoretical backbone for the analyses in all three chapters in this dissertation. Chapter 1 uses a closed-economy RBC model to demonstrate the distinct impacts of different energy supply and demand shocks on the macroeconomy, highlighting the different channels through which the shocks are transmitted. Chapter 2 extends this one-country framework to a two-country model with trade to study the general equilibrium effects of energy price shocks on external balances of energy-exporting and energy-importing countries. Finally chapter 3 revisits the question of the conduct of monetary policy in the events of these supply and demand shocks, prescribing the desirable monetary responses to minimize the shocks' impact and comparing the obtained results with those from previous literature.

Acknowledgement

My immense gratitude goes out to my Advisor, Sungbae An for his invaluable guidance and advice. I also need to thank Hian Teck Hoon, Haiping Zhang, and Anthony Tay for their much appreciated advice and input during the course of my research. I have also benefited greatly from my exchanges with my fellow Ph.D. candidates, Vishrut Rana, Shew Fan Liu and Zoe Chen Ye, and I am grateful for their support.

Contents

1. Introduction

There is an increasing recognition in the literature that the price of oil and other forms of energy is endogenous with respect to macroeconomic aggregates, and that the much-used premise of exogenous oil prices has to be re-examined (Barsky and Kilian 2002; Kilian 2008; Kilian and Vega 2011). Kilian (2009) finds a smaller role for oil supply shocks and a larger role for oil demand in driving oil price fluctuations (also see, e.g., Kilian and Murphy 2012, 2013; Baumeister and Peersman 2013a,b). This body of work highlights the need to distinguish between a range of different oil demand and oil supply shocks in empirical work as well as in dynamic stochastic general equilibrium (DSGE) modeling (see also Kilian and Lewis 2011). These models help in understanding, for example, how persistent oil price increases may coexist with economic growth, as was the case in the United States between 2003 and 2008. As Kilian (2008) concludes, "it is critical to account for the endogeneity of energy prices and to differentiate between the effects of demand and supply shocks in energy markets" in answering questions about the impact of energy price increases on the economy. On a related note, Kilian and Vigfusson (2011a, 2011b) find little evidence of asymmetry in the impact of oil prices, and renew support for linearized oil/energy DSGE models with no built-in asymmetry. However, Elder and Serletis (2011) and Rahman and Serletis (2011) find that the negative relationship between oil price volatility and output provides evidence supporting the hypothesis of an asymmetric impact of oil/energy price on economic activity.

Early DSGE models of oil price shocks, including Kim and Loungani (1992), Rotemberg and Woodford (1996) and Finn (2000) among others, treat the real price of oil as exogenously given and made no distinction between alternative sources of oil price fluctuations. More recently, Dhawan and Jeske (2008) studied the role of durables consumption in energy price shocks, again assuming the exogeneity of energy price. In light of the empirical evidence mentioned above, this traditional framework of exogenous oil/energy prices can no longer serve as the theoretical benchmark, as it cannot predict the behaviors of the economy in response to any shocks other than the oil/energy supply shock. The first theoretical effort towards endogenizing oil price is Backus and Crucini (2000), using a three-country framework to look at trade patterns in the event of oil shocks. Bodenstein et al. (2011) and Bodenstein and Guerrieri (2011) also studied the impact of oil shocks in the international context using a feature of oil price endogeneity. Nakov and Pescatori (2010), Bodenstein et al. (2008) and Bodenstein et al. (2012) looked at the question of optimal monetary conduct in response to oil price shocks, while Arora and Gomis-Porqueras (2011) showed that endogenous oil price helps a theoretical model to better match oil-related business cycle features in the data.

Chapter 2 seeks to complement these theoretical efforts with a multi-sector model of the U.S. economy with an energy sector and convex costs in energy production. The aim is to investigate the transmission mechanisms and characteristics of different sources of energy price shocks in terms of their impact on the business cycle. We explicitly model the consumption of durables and non-durables in the household utility function, following Dhawan and Jeske (2008), to add another dimension to the household's decisions. Usage of durables is energy-dependent, while consumption of non-durables is not. On the production side, capital use needs energy. However, energy does not enter directly into the household's utility, or the production functions of the various sectors. In this respect the model employs the setup used in Finn (2000), but also goes beyond Finn (2000) by implementing this method for the household. This implements the intuitive notion that capital and durables usage has a very high degree of complementarity with energy[1]. This produces for our model

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[1] Berndt and Wood (1975) estimated the elasticity of substitution between energy and capital to be -3.2

low price elasticities of energy consumption[2]. Additionally, convex costs in energy production allow for a fully specified energy sector and create a mechanism that replicates the observed fact that energy price is a lot more volatile than energy production (Kim and Loungani 1992). Furthermore, in employing separate production functions for durables and non-durables, we aim to theoretically demonstrate and analyze any heterogeneity in the impact of energy price increases across sectors whose goods differ in their energy dependence.

Our model differs from the aforementioned works of endogenous oil/energy price in a few important dimensions. Arora and Gomis-Porqueras (2011) and Nakov and Pescatori (2010) do not employ the consumption of energy/oil in the household, so the direct income-effect channel from energy price to the household is absent. In Bodenstein et al. (2008) and Bodenstein et al. (2012) oil price is endogenized but the oil supply is modeled as an exogenous endowment (similarly for Bodenstein and Guerrieri 2011, and Bodenstein et al. 2011). Backus and Crucini (2000) also employs an exogenous process for OPEC oil production. None of these frameworks thus employ a form of convex costs in energy production to bring about a small positive price elasticity of energy production, or the modeling of durables and non-durables consumption and production. Our work also differs from these slightly in scope, as we are not looking at the effects of energy price shocks in terms of trade or monetary policy. The scope of our Chapter comes close to Bodenstein and Guerrieri (2011), which quantifies the impact of different sources of oil price shocks on the U.S. economy. However, our model abstracts from an open economy setting with a fully specified global economy, as we choose to focus on the main implications of energy price endogeneity without the additional transmission mechanism through trade. In addition, while we are aware of the implications of the findings of Elder and Serletis (2011) and Rahman and Serletis (2011) on the modeling of oil price asymmetry in DSGE models, in this Chapter we

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[2] Lee and Lee (2010), Krichene (2005) and Maddala et al. (1997).

are mostly concerned with energy price increases and their different sources. As such, the consideration of an asymmetric relationship between oil/energy price and output is beyond the scope of the dissertation, and oil/energy price volatility is thus not considered in the setup of this model.

The model is calibrated to match broadly several aspects of U.S. macro data using first and second moments of the main macro variables. It does a good job at describing the cyclical properties of the U.S. economy. The endogenous energy production with convex costs creates energy price dynamics that come quite close to the empirical counterpart. The convex costs also produce a fairly low price elasticity of energy supply (of the order of 0.1) and help to improve the predictions of the model in the event of demand shocks to the energy market in terms of energy supply and energy price responses. The model also returns a considerably lower hours-wage correlation than the conventional value predicted by the standard RBC framework. The presence of multiple sectors and a separate productivity process for the energy sector play a key role in delivering this reduction in hours-wage correlation, moving it closer to empirical evidence.

We investigate three main kinds of shocks to the energy market, similar to Kilian (2008, 2009): an adverse energy supply shock; an aggregate shock to energy demand in the form of a positive TFP shock to the non-energy sectors; and energy market-specific demand shocks. The specific demand shocks come from shocks to the energy intensities of durables and capital, and are similar in nature to the oil intensity shock described in Bodenstein and Guerrieri (2011). Our setup, however, delineates the distinction between the specific demand shocks coming from the household and from the producers. This is important as our analyses show that they carry different transmission dynamics. In the case of the energy supply shock, we obtain an energy price-output elasticity of -0.1, which is double the response obtained by the earlier framework of Dhawan and Jeske (2008). Considering that this framework does not employ imperfect competition as in Rotemberg and Woodford (1996) or variable utilization of capital as in Finn (2000), we show thus that the presence of an energy sector deepens the role of energy in the business cycle. We also obtain energy price elasticities for household consumptions and investments, which fall within reasonable agreement with the empirical estimates reported in Edelstein and Kilian (2009) as well as Kilian (2008).

The analysis of different sources of energy price shocks delivers some key results. Indeed, not all energy price increases are the same, as Kilian (2009) stressed, because they do not all have the same effects on the business cycle. Each shock might carry additional mechanisms that go beyond the effects of energy price alone. The specific demand shocks cause more severe contractions in the business cycle than the energy supply shock. They also differ in that each has an amplification mechanism that acts on a different side of the economy and causes a correspondingly greater impact on that side. In the case of the positive TFP shock, the aggregate effects of an expanding business cycle mostly nullify the growth-retarding effects of an energy price increase. Overall, the time paths of energy price increases and energy production display fairly distinct dynamics, and the nature of each shock is captured in the energy price elasticities and relative movements of the macro variables. These observable behaviors could provide us with useful guidance on the underlying causes of energy price shocks. Additionally, the interaction in a general equilibrium environment between energy price and the prices of energy-dependent and non-energy-dependent goods in response to different kinds of energy price shocks has not been analyzed in previous studies, while our framework allows for this investigation. The results show that energy price shocks hit the non-energy-dependent goods sector harder on its supply side, while the impact is relatively stronger on the demand side for the energy-dependent goods sector.

Moving on to the international literature, Kilian et al. (2009) re-affirmed the call for endogenous energy prices with a comprehensive empirical investigation of the responses of the oil and non-oil trade balances of oil-exporting and oil-importing countries to various oil price shocks. That paper demonstrated the distinct effects on external balances of the different shocks considered and the crucial role played by the non-oil trade balance in determining the overall effect on the trade balance. Theoretically, however, this body of literature has not moved towards endogenous energy production to explain different sources of energy price increases. There have been several important studies on the impact of oil price shocks on external balances, such as Backus and Crucini (2000) and Bodenstein et al. (2011). Yet, in Bodenstein et al. (2011), the oil supply is an exogenous endowment, which represents the extreme case of a perfectly inelastic oil supply and does not capture the dynamics of energy production (similarly observed in Bodenstein and Guerrieri 2011; Bodenstein et al. 2012). Backus and Crucini (2000) also employed an exogenous process for OPEC oil production. Moreover, Backus and Crucini (2000) has no restriction on the endogenous component of the oil supply, which allows oil production to expand freely. This feature does not capture the inelastic nature of energy supply[3]. Therefore, for demand-driven energy price disturbances, these frameworks might not provide satisfactory descriptions of energy price and production dynamics, and thus, of energy and non-energy trade balances. Furthermore, little attention has been paid to the decomposition of the non-energy trade balance. An understanding of how goods with varying degrees of energy dependence influence trade patterns might provide additional policy tools to address energy price shocks.

Chapter 3 attempts to fill the gap with a richer setup of multiple sectors and a more generalized specification of energy production. The contribution is two-fold. First, we disentangle and establish the theoretical underpinnings of

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[3] Krichene (2005) provided a range of estimates for the short-run price elasticity of the oil and natural gas supplies and found them to be highly inelastic, with the highest estimate not exceeding 0.1. Estimates from Baumeister and Peersman (2013b) show that, since the late eighties, the median value of the short-run oil supply elasticities falls between 0.02 and 0.25. Kim and Loungani (1992) calculated the relative volatility of energy price to output at 6.02 using U.S. annual data from 1949 to 1987.

how different sources of energy price shocks impact external balances, which Kilian et al. (2009) have established empirically. The analysis considers to a wider set of shocks than either Backus and Crucini (2000) or Bodenstein et al. (2011), mirroring those analyzed in Kilian et al. (2009). An additional motivation is the prospect that the U.S. will become a net energy exporter over the next 15 to 20 years thanks to its shale gas boom. Within this framework, it is possible to make predictions about how this shift might impact the U.S. economy. Second, we look deeper into the composition of the non-energy trade balance to investigate the dynamics of goods with varying degrees of energy dependence, an angle not yet explored in previous research.

Our setup consists of two large economies, Home and Foreign, each with three production sectors: durables, nondurables and energy. These two countries can freely trade all three types of goods with each other. Energy is considered a homogeneous good worldwide, while some degree of differentiation is assumed between the two countries' durables (and non-durables). Energy is needed for durables and capital usage. By modeling the consumption and production of goods with different degrees of energy dependence, this model introduces a new dimension to the household consumption decision and creates heterogeneity in the way energy price increases impact these different sectors[4]. Energy production itself is energy-consuming and is subject to convex costs. The convex costs of energy production reduce the energy price elasticity of energy supply and bring it closer to the data. This feature makes the analysis of demand shocks to the energy market more meaningful. The model can also be flexibly calibrated to reflect varying degrees of energy dependence for the Home country, reflecting not only the U.S. but also a range of large economies with different levels of energy importation.

We calibrate the Home country to broadly match the U.S. using its readily available macro data. Home thus plays the role of a major energy importer,

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[4] Dhawan and Jeske (2008) considered consumption of durables and non-durables but not in an international context.

while the Foreign country plays the role of the rest of the world (an energy exporter). We investigate the dynamics of the two countries' external balances in response to a number of supply and demand shocks. We examine the standard case of an adverse energy supply shock to the rest of the world. We then look at a shock to the overall demand for energy resulting from expansions in the business cycle. A demand shock that is specific to the energy market is also analyzed. This shock is given a specific interpretation in our model and is implemented differently than in Bodenstein et al. (2011). These three shocks broadly correspond to the three supply and demand shocks analyzed in Kilian et al. (2009). In addition, we introduce a new type of demand shock: a preference shock coming from households' increased taste for durables. This shock has direct relevance for the case of a large growing economy whose citizens increasingly consume durables. Finally, we pose the question of what would happen if the energy importing country became a more productive energy producer.

Our results confirm the empirical findings of Kilian et al. (2009) that the responses of external balances vary in response to different energy price shocks, principally due to the diverse responses of the non-energy trade balance. The distinction of a broad, indirect shock to energy demand is especially pertinent, while the specific demand shocks exacerbate the usual impact of high energy prices. Our analysis connects these differences to the sources of the energy price increases and distinguishes the roles played by goods with different degrees of energy dependence. We show that the time path of the energy price increases is not the only factor influencing the trade responses of the Home country, as different shocks affect the Foreign economy differently and thus have different impacts on Home exports. Another main result of our analysis is that the response of trade in durables is highly volatile and is the determining component in the diverse responses of the non-energy trade balance. This result implies a more immediate channel through which energy price influences the non-energy trade balance: the energy dependent nature of durables. This channel leads to movements in the non-energy trade balance beyond the usual influence of the terms of trade. As such, each shock's impact on external balances is mostly determined by how it affects durables trade in both countries. Finally, our model also predicts beneficial effects to the energy importing country if it becomes more productive in energy. Cheaper, more readily available energy leads to an increase in Home output, expansion in its durables sector and improvement in its energy trade balance.

A large body of this literature focuses on the role of monetary policy in times of such shocks, firstly on whether and how much monetary policy exacerbates the negative effects of an oil price increase, and secondly on the prescriptions for an optimal policy reaction. On this latter question, results from a number of theoretical investigations involving New Keynesian DSGE models have produced diverse answers, and the debate is far from settled. For instance, Leduc and Sill (2004) prescribes price stability as the policy of choice in dealing with energy (oil) supply shock, while the results from Bodenstein et al (2008) argue against this policy, opting instead for more output stabilization. More recently, there is growing justification to go beyond oil supply shocks, towards looking at the possible different sources of energy price increases. As Kilian (2009) has pointed out, it is of crucial and practical importance to disentangle the different kinds of supply and demand shocks that could affect the energy markets and to distinguish their impacts, because not all energy price increases have the same underlying cause or should be treated equally (also see, e.g., Kilian and Murphy 2012, 2013; Baumeister and Peersman 2013a,b). Viewed against these developments, the literature on monetary policy has not concerned itself with energy price increases resulted from shocks other than energy supply shock, thus leaving still unexplored other possible sources of energy price disturbances and whether one optimal monetary prescription may or should be applicable to them all.

The aim of Chapter 4 is to address the lack of consensus regarding the case of energy supply shock and the question of how monetary policy should respond to a wider set of energy price increases. It joins the literature on monetary policy in the context of energy/oil supply shock, in which the works of Bernanke, Gertler and Watson (1997), Hamilton and Herrera (2004), Leduc and Sill (2004) and Kormilitsina (2011) have made major impact, bringing together the diverse conclusions on the desirable monetary conduct in response to oil/energy supply shock and see whether our results put us along this inflation-output divide. Second, we use the framework to extend the question of desirable monetary responses to other kinds of shocks to the energy markets. The endogenous energy production feature brings a completeness to a theoretical model with energy at its core and allows energy production and energy prices to fully respond to economic conditions. The introduction of convex costs of energy production helps create more realistic dynamics of energy price and energy supply in response to demand shocks to the energy market. The third contribution by this Chapter lies in the multi-sector feature of the theoretical setup. In introducing sectoral price stickiness, allied with goods with different degrees of energy dependency (in terms of their consumptions), we set out to investigate whether the relative price rigidity between the two sectors plays an important role in determining the response of the economy to energy price shocks and to monetary policy reactions.

We make use of the RBC model in Chapter 2, which comprises a fully endogenous energy sector with convex costs in production, as well as durables and non-durables sectors. New Keynesian features are introduced, in the form of monopolistic competition and price rigidity for the durables and non-durables sectors (energy price is assumed to be flexible), distortionary taxes and fiscal and monetary authorities. Sectoral price rigidity follows Monacelli (2009), but our framework is novel in both its setup and approach, in that it is augmented by the incorporation of energy production and consumption, and it is used for looking at energy-related issues. In the strand of related theoretical models, the works of Leduc and Sill (2004), Kormilitsina (2011), Bodenstein et al (2008) and Nakov and Pescatori (2010) provide the background and motivation for our analysis. However, our framework departs from previous efforts in a number of important dimensions. Leduc and Sill (2004), Kormilitsina (2011) and Nakov and Pescatori (2010) do not have oil/energy consumption in the household, thereby missing out on an important channel in terms of the direct income effect through which energy makes its impact on the demand side of the economy. Both Leduc and Sill (2004) and Kormilitsina (2011) also assumed an exogenous oil price process. In this kind of setup, all instances of energy related shocks are represented by an exogenous oil price increase, and are therefore considered to be the same in terms of their effects on the economy. In such setup it is therefore not possible to go beyond the case of energy supply shock. Bodenstein et al (2008) and Nakov and Pescatori (2010) incorporated features of endogenous energy production, but in Bodenstein et al (2008) there was no actual energy (oil) production, and Nakov and Pescatori (2010) employed a different structure of organization of the oil industry. Thus in Bodenstein et al (2008), while energy price can be considered endogenous, energy supply is not, and represents the extreme case of a perfectly inelastic energy source. Energy supply in Nakov and Pescatori (2010), while endogenous, has a too high price elasticity in the short run. Our setup is therefore strongly distinguished by the feature of convex costs for the energy producer. This feature ensures a highly inelastic energy supply to changes in energy price, as empirically observed[5], and endogenously creates energy price dynamics that come close to data[6].

In the context of monetary analysis with energy price shocks, our model

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[5] Krichene (2005) gave a range of estimates for the short-run price elasticity of oil supply and natural gas supply and found them to be highly inelastic, with the highest estimate not exceeding 0.1.

[6] Kim and Loungani (1992) calculated the relative volatility of energy price to output at 6.02 using US annual data from 1949 to 1987. Huynh (2014), with convex costs in energy production calibrated to give a price elasticity of energy supply at around 0.1, returns this ratio at 7.1.

also differs from these frameworks by explicitly modeling the consumptions and productions of goods with different degrees of energy-dependence[7]. This introduces additional dynamics into the household's consumption behaviors in response to energy price increases and creates heterogeneity in the way these shocks impact the different goods sectors. Our approach at analyzing the impact of monetary policy in events of energy price shocks also differs from Bodenstein et al (2008), Nakov and Pescatori (2010) and Kormilitsina (2011). We followed the approach of Leduc and Sill (2004) in that we compared the relative effectiveness of different monetary regimes with one another in terms of their impact on the business cycles, mainly output and consumption. The four shocks studied in this Chapter are: productivity shock to the energy sector, representing the usual energy supply shock, TFP shock to the non-energy sectors, which is a kind of aggregate shock to energy demand, and two energy-market specific demand shocks coming from the household and the producers respectively.

Regarding the energy supply shock, our results differ from those before in several aspects, and find agreement in others. We do not find that price stability is the best in terms of minimizing the shock's impact on output and consumption, in contrast to Leduc and Sill (2004). Our findings are more in line with Bodenstein et al (2008), as we lean towards output stabilization, even though we add to this with a caution against going too much towards output without a corresponding focus on inflation. The conclusions drawn from Nakov and Pescatori (2010) also differ from ours. While they did propose a certain degree of focus on output stabilization as an optimal form of monetary policy, their favorable view of strict price and aggressive inflation fighting policies are in contrast to what we obtained from our analyses.

Extending the analysis to other kinds of energy price shocks, we found that in the event of a positive TFP shock to non-energy producers, which increases

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[7] Dhawan and Jeske (2008) employed consumptions of durables and non-durables but not in a monetary policy context.

the aggregate demand for energy, a strong focus on inflation is best in terms of ensuring the strongest expansion in output and consumption. We showed that this instance of energy price shock is very distinct from the one before, not just in terms of the responses of the economy to it but also in terms of the relative performance of alternative monetary regimes. The two specific demand shocks to the energy market, however, require actions qualitatively similar to the case of an energy supply shock. Even so, the effectiveness of the required policy on stabilizing output and consumption varies between these two shocks, compared to the case of energy supply shock. This is due to the quantitatively distinct impact of each shock, especially on the durables sector.

We also showed that the price rigidity of the more energy-consuming goods plays a greater role in the propagation of energy price shocks. Output and consumption and many other macro variables show higher sensitivity to varying price stickiness of durables goods. Different degrees of durables' price rigidity also influence the non-durables sector's behavior more than vice versa. This is a consequence of the fact that the more energy-dependent goods sector always shows more volatile responses when energy price changes. Also it is due to the interplay between the substitution effect and the income effect that causes consumption of durables to vary little when the price of non-durables changes, but not vice versa.

2. Macroeconomic Effects of Energy Price Shocks on the Business Cycle

2.1 Introduction

The model in this Chapter is calibrated to match broadly several aspects of U.S. macro data using first and second moments of the main macro variables. It does a good job at describing the cyclical properties of the U.S. economy. The endogenous energy production with convex costs creates energy price dynamics that come quite close to the empirical counterpart. The convex costs also produce a fairly low price elasticity of energy supply (of the order of 0.1) and help to improve the predictions of the model in the event of demand shocks to the energy market in terms of energy supply and energy price responses. The model also returns a considerably lower hours-wage correlation than the conventional value predicted by the standard RBC framework. The presence of multiple sectors and a separate productivity process for the energy sector play a key role in delivering this reduction in hours-wage correlation, moving it closer to empirical evidence.

We investigate three main kinds of shocks to the energy market, similar to Kilian (2008, 2009): an adverse energy supply shock; an aggregate shock to energy demand in the form of a positive TFP shock to the non-energy sectors; and energy market-specific demand shocks. The specific demand shocks come from shocks to the energy intensities of durables and capital, and are similar in nature to the oil intensity shock described in Bodenstein and Guerrieri (2011). Our setup, however, delineates the distinction between the specific demand shocks coming from the household and from the producers. This is important as our analyses show that they carry different transmission dynamics. In the case of the energy supply shock, we obtain an energy price-output elasticity of -0.1, which is double the response obtained by the earlier framework of Dhawan and Jeske (2008). Considering that this framework does not employ imperfect competition as in Rotemberg and Woodford (1996) or variable utilization of capital as in Finn (2000), we show thus that the presence of an energy sector deepens the role of energy in the business cycle. We also obtain energy price elasticities for household consumptions and investments, which fall within reasonable agreement with the empirical estimates reported in Edelstein and Kilian (2009) as well as Kilian (2008).

The analysis of different sources of energy price shocks delivers some key results. Indeed, not all energy price increases are the same, as Kilian (2009) stressed, because they do not all have the same effects on the business cycle. Each shock might carry additional mechanisms that go beyond the effects of energy price alone. The specific demand shocks cause more severe contractions in the business cycle than the energy supply shock. They also differ in that each has an amplification mechanism that acts on a different side of the economy and causes a correspondingly greater impact on that side. In the case of the positive TFP shock, the aggregate effects of an expanding business cycle mostly nullify the growth-retarding effects of an energy price increase. Overall, the time paths of energy price increases and energy production display fairly distinct dynamics, and the nature of each shock is captured in the energy price elasticities and relative movements of the macro variables. These observable behaviors could provide us with useful guidance on the underlying causes of energy price shocks. Additionally, the interaction in a general equilibrium environment between energy price and the prices of energy-dependent and non-energy-dependent goods in response to different kinds of energy price shocks has not been analyzed in previous studies, while our framework allows for this investigation. The results show that energy price shocks hit the non-energy-dependent goods sector harder on its supply side, while the impact is relatively stronger on the demand side for the energy-dependent goods sector.

2.2 Model

2.2.1 Households

Households consume a CES aggregation of durables and non-durables according to

$$c_t = [\alpha^{1-\rho}(u_t d_t)^{\rho} + (1-\alpha)^{1-\rho} {n_t}^{\rho}]^{1/\rho}$$

where n_t is the household's consumption of non-durables in period t, d_t the stock of durables and u_t the utilization rate of this durables stock. The elasticity of substitution between durables and non-durables is represented by $\frac{1}{1-\rho}$, while α represents the share of durables usage in the household's consumption bundle. Together, $u_t d_t$ defines the service that the household derives from its existing stock of durables in period t.

Households' use of energy

Households' use of durables needs energy, the amount of which ($e_{h,t}$) is variable in each period and directly dependent on the utilization rate and the stock of durables. Energy consumption does not enter the utility function directly; instead, its cost enters into a household's budget constraint. In this specification, the model makes use of the specification in Finn (2000) and extends it to the household. Households' use of energy in each period can be thought of as a function of the multiple of the stock of durables and its utilization rate: $e_{h,t} = f(u_t d_t)$. In all analyses carried out in this Chapter, the amount of energy needed to sustain a utilization rate u_t of a stock of durables d_t is assumed to be linearly dependent on their product $u_t d_t$, that is $e_{h,t} = a u_t d_t$, where a is a constant to be calibrated. This linear relationship carries the assumption that durables in the aggregate have constant energy intensity.

The representative household's problem is to maximize its expected lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t (\varphi \log c_t + (1-\varphi) \log(1-h_t)) \tag{2.1}$$

subject to the following budget constraint

$$p_{e,t} a u_t d_t + p_{n,t} n_t + i_{d,t} + i_{k,t} = w_t h_t + r_t k_t \tag{2.2}$$

where $i_{d,t}$ and $i_{k,t}$ denote investments in durables and capital respectively, r_t the return on capital and w_t the wage. $p_{e,t}$ and $p_{n,t}$ are the prices of energy and non-durables, while the prices of durables and capital are normalized to 1. The household earns its income from the rental of its capital stock to firms and its labor service. The investments in capital and durables have the following adjustment costs:

$$i_{d,t} = d_{t+1} - (1-\delta_{d,t}) d_t + \frac{\omega_{d1}}{1+\omega_{d2}} \left(\frac{d_{t+1} - d_t}{d_t} \right)^{1+\omega_{d2}} \tag{2.3}$$

$$i_{k,t} = k_{t+1} - (1-\delta_k) k_t + \frac{\omega_{k1}}{1+\omega_{k2}} \left(\frac{k_{t+1} - k_t}{k_t} \right)^{1+\omega_{k2}} \tag{2.4}$$

where $\delta_{d,t}$ and δ_k denote the depreciation rates of durables and of capital respectively, and ω_{d1}, ω_{d2}, ω_{k1}, ω_{k2} the parameters of the cost functions. The rate of depreciation of durables is variable and varies positively with utilization rate. Here we use a power-function form for the depreciation rate, following Finn (2000):

$$\delta_{d,t} = \frac{a_1}{a_2+1} {u_t}^{a_2+1} \tag{2.5}$$

The household's choice of $\{n_t, u_t, h_t, d_{t+1}, k_{t+1}\}$ to maximize (1) subject to (2), (3), (4) and (5) results in the usual first order conditions, which are detailed in Appendix C.

2.2.2 Producers

There are three sectors in the model: durables, non-durables, and energy sectors. The energy sector provides energy to the other two sectors (and to itself) and to the household.

Energy use in production

This framework assumes that each sector's use of energy is a function of its use of capital, i.e. $e_{f,t} = g(k_t)$. Similarly to the household's case, g is calibrated to be a simple linear function; that is, a sector's energy consumption is given by $e_{f,t} = bk_t$, where b is a constant. This parameter b can thus be interpreted as the energy intensity of capital. For the overall analysis in this Chapter, it suffices to assume that b is the same for all three sectors. One implication of this setup is that the energy sector itself also needs energy for the production of its goods. In other words, energy is needed to produce energy. This brings into the energy sector's production plan a consideration about the opportunity cost of energy. When energy price increases, it also raises the cost of producing energy. Again, it should be noted that energy does not enter the production functions directly; its cost shows up in the first-order conditions of the three producers, where it adds to the cost of capital. The relationship $e_{f,t} = bk_t$ implies a very high degree of complementarity between capital and energy, and with this simple specification we emphasize the fundamental importance of energy in the operation of capital.

Energy producer

The model implements an energy production with convex costs, to produce a low price elasticity of energy supply. The production function of the energy sector takes the form

$$y_{e,t} = \exp(A_{e,t})(1 - \sigma_{e,t})k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e} \tag{2.6}$$

with $y_{e,t}$, $h_{e,t}$ and $k_{e,t}$ denoting output, labor and capital for the sector, respectively, and

$$\sigma_{e,t} = \frac{\omega_{e1}}{(1+\omega_{e2})}(k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}} \tag{2.7}$$

representing the fraction of energy output that is lost. This functional form for $\sigma_{e,t}$ implies that the higher the output of energy production, an increasingly higher fraction of that is lost, through wastage or inefficiencies in the production process. This implementation creates a mechanism whereby when a demand shock hits the energy market, the energy sector cannot simply expand its output by a large percentage quickly. This makes energy price more volatile to shocks, while energy supply itself is relatively less responsive. The calibration section explains the calibration of ω_{e1} and ω_{e2}.

Non-energy producers

The durables and non-durables sectors are assumed to have Cobb-Douglas production functions, but with different capital share parameters. They also share the same productivity process. The two sectors' production functions are given as

$$y_{i,t} = \exp(A_t) k_{i,t}^{\gamma_i} h_{i,t}^{1-\gamma_i} \tag{2.8}$$

with $y_{i,t}$, $k_{i,t}$, and $h_{i,t}$ denote output, capital and labor of sector i, where $i = d, n$.

Each sector solves the following profit-maximization problem

$$\max_{\{k_{j,t}, h_{j,t}\}} \{p_{j,t} y_{j,t} - w_t h_{j,t} - r_t k_{j,t} - p_{e,t} b k_{j,t}\} \tag{2.9}$$

where $j = d, n, e$. Wage and return of capital are assumed to be equal across the sectors.

2.2.3 Aggregation and equilibrium

It is assumed that all energy produced in each period is consumed (not an unreasonable assumption, when one thinks, for example, of electricity), non-durables produced are used wholly for consumption, and durables output is used for investments in capital and durables. The capital and labor market, as usual, also clear in every period. The market clearing conditions are thus:

$$k_t = k_{d,t} + k_{n,t} + k_{e,t} \tag{2.10}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t} \tag{2.11}$$

$$y_{d,t} = i_{d,t} + i_{k,t} \tag{2.12}$$

$$y_{n,t} = n_t \tag{2.13}$$

The energy market is automatically cleared given the budget constraint.

The aggregate price p_t (or CPI index) is given by

$$p_t = \left[\alpha\left(1 + ap_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha)p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}} \tag{2.14}$$

Aggregate output y_t (value added) is defined (excluding energy used in production) as

$$p_t y_t = y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t \tag{2.15}$$

2.2.4 Exogenous driving processes

The basic model is driven by two main shocks: the conventional TFP shock ($\epsilon_{u,t}$) that is common to both the durables and non-durables sectors, and a productivity shock that affects the energy sector alone (ϵ_t). A simple extension of the model will also have shocks to the household's energy consumption (shock to the parameter a, $\epsilon_{a,t}$), and to the producers' energy need (shock to parameter b, $\epsilon_{b,t}$). These shocks model energy market-specific demand shocks.

2.3 Model calibration and solution

2.3.1 Structural parameters

Certain parameters are calibrated following the standard literature. The discount factor β is set at 0.99; the share of consumption in the household utility function φ is set at 0.34; and the share of durables α in consumption is set at 0.2. Empirical research puts the elasticity of substitution between durables and non-durables close to 1. In our model it is set at 0.99 for the main analyses, and the CES parameter of the household's utility function ρ is therefore $1 - (1/0.99)$, which is negative and indicates that durables and non-durables are somewhat complementary. Other parameters are calibrated to produce theoretical moments of model aggregates that reproduce as best possible the empirical moments calculated from aggregate U.S. data (Table 2.1). Quarterly capital depreciation is calibrated at 1.5%, while the parameters of the durables depreciation function are chosen so as to produce a steady-state quarterly depreciation rate of 6.1% and utilization rate of 60% for durables; hence, $a_1 = 0.145$, $a_2 = 0.165$. The calibration of the parameters a and b, the energy intensity of durables and capital respectively, is based directly on the empirical ratios E_h/Y and E_f/Y. The resulting calibration yields $a = 0.085$ and $b = 0.0086$.

The functional forms of capital and durables adjustments costs are given in the form of a general power function, governed by two parameters ω_1 and ω_2. In this Chapter we assume a quadratic form for both stocks, thus $\omega_2 = 1$. The remaining choice of ω_1 does not affect the steady state of the model, so it has to be chosen using the volatilities of capital and durables in the data as a guide. We use the following calibration, $\omega_{k1} = 0.05$, $\omega_{k2} = 1$, $\omega_{d1} = 0.4$, $\omega_{d2} = 1$. The parameters of the three sectors' production functions are also calibrated using the ratios in Table 2.1 as a guide, plus additional ratios such as the ratio of durables consumption to total real personal consumption. The capital share of the energy sector is also calibrated to be higher than the average value of 0.36 usually found in the literature, meaning that the energy sector is more capital-intensive. Additionally the calibration of these parameters depends to a great extent on the equilibrium dynamics of the system. The parameters are thus chosen so that the model produces a stable equilibrium. The resulting parameters of production for the three sectors are given as $\gamma_d = 0.34$, $\gamma_n = 0.38$, $\gamma_e = 0.552$.

The parameters for the convex cost function of the energy sector are calibrated to bring about a low price elasticity of energy supply. However, choices are constrained by the volatility of various energy-related variables such as household and producer energy consumptions and energy output, and by the equilibrium dynamics of the model. Parameter values that give very low price elasticity of energy supply result in excess volatility of these variables and often cause the model to have no stable equilibrium. Here, we chose a cubic power function form for the convex cost, so $\omega_{e2} = 2$. A value for ω_{e1} is then chosen to be 9.36, to give a price elasticity of energy supply of around 0.13, while ensuring that the volatility of energy supply is as close to that in the data as possible and that the model has a stable equilibrium around the steady state.

2.3.2 Technology Processes

We assume that both the non-energy (TFP) and the energy productivities follow an exogenous AR(1) process:

$$A_t = \rho_a A_{t-1} + \epsilon_{u,t}, \epsilon_{u,t} \sim^{i.i.d} N(0, \sigma_u^2) \tag{2.16}$$

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_t, \epsilon_t \sim^{i.i.d} N(0, \sigma_e^2) \tag{2.17}$$

The model is calibrated with $\epsilon_{u,t}$ and ϵ_t active. We use the volatilities of various aggregates calculated from data as a guide to calibrating these shocks. The resulting calibration, with $\rho_a = 0.95$, $\rho_e = 0.95$, $\sigma_u = 0.00245$ and $\sigma_e =$

0.0075, produces theoretical volatilities that come closest to matching their empirical counterparts.

The model is solved for its steady state using a nonlinear solver, and an approximate solution to the model is found by linearizing the equilibrium conditions around the steady state using the perturbation method.

2.4 General equilibrium effects of energy price shocks

2.4.1 Adverse energy supply shock

A negative productivity shock to the energy sector in this framework acts as an energy supply crunch and causes energy price to increase. This energy price increase is also the closest thing to a traditional exogenous oil price increase. Note that this is a decline in the productivity of the energy sector only, and not a broad productivity decline. The shock is calibrated to cause a 10% increase in energy price. From the impulse responses it can be seen that a 10% energy price increase leads to a 0.97% decrease in value added (Fig. 2.1a), whose subsequent recovery is dependent on the persistence of the shock. The impact on value added is therefore significant. While falling short of the 2 - 2.5% decrease predicted by Rotemberg and Woodford (1996) and Finn (2000), this output response is twice as large as that in Dhawan and Jeske's model (around 0.5% for a 10% increase in energy price). In relation to Dhawan and Jeske (2008), therefore, the presence of endogenous energy production deepens the impact of an energy supply shock. Figure 2.1a also shows that in order to have a 10% increase in energy price, the energy supply must shrink by around 0.9%, illustrating the inelastic nature of energy demand.

Other aggregates also indicate a contracting business cycle. Overall employment, rental rate of capital and wage all fall (Fig. 2.1b). Both kinds of investment fall (Fig. 2.1c), but investment in durables less so than capital. The utilized durables (Fig. 2.1a), which represents the representative household's control of its energy consumption, fall by more than 2%. Consumption of non-durables also drops, albeit by a small amount (0.2%). The responses of these consumption/investment variables in response to an energy price increase compare favorably to empirical estimates of energy price elasticities in Kilian (2008). The 3% fall in durables investment in the model (representing durables consumption) approaches the -0.47 estimated elasticity of durables consumption in the study, while the 4.5% decline in capital investment is higher in magnitude than the estimated elasticity of total non-residential investment (-0.16), but is also not too far from the estimated elasticity for equipment investment (-0.30). Regarding household energy consumption, represented by the utilized durables ud (since a is constant), the sensitivity in this model (-0.23) is about half the estimated elasticity of -0.45 in Kilian (2008) for consumer total energy consumption. The elasticity of non-durables is also higher (in magnitude) in the data than in the model (-0.11 versus -0.02).

The large impact of an energy price increase on output results from endogenous energy production and the high complementarity of durables and capital with energy, with the durables sector contributing most to this decline. For the household, energy price makes its impact through both the expense and the income sides of its budget constraint. When energy price increases, the household suffers a large negative income effect: lower income due to lower factor prices (as shown in Fig. 2.1b) and reduced effective budget due to higher cost of energy consumption. All consumption is cut, but the small drop in non-durables consumption illustrates its role as an ‘anchor’ in energy crises, as the household substitutes durables utilization/investment with non-durables. Since investments in both capital and durables are cut by higher percentages than non-durables consumption and durables utilization, this means that a higher energy price affects the household predominantly through the intertemporal channel. The volatile responses of durables and capital investments demonstrate their energy dependence compared with non-durables, and those responses contribute strongly to contraction in the business cycle.

For the producers, their marginal costs of capital rise when energy price rises. As capital usage is highly complementary to energy, this puts a very large downward pressure on the return on capital. However, the impact of higher energy price is not homogeneous across the sectors. The durables sector is the hardest hit (4% drop in its output versus 0.2% drop in non-durables output; figure not shown) because of its double link with energy. Its capital needs energy to be operated, and its output needs energy to be consumed, and so it is badly impacted on both its demand and supply sides. The non-durables sector, in contrast, does not see its demand affected to such an extent, as its goods benefit from the substitution effect. This differential impact on the sectors points to the influence of energy price beyond the direct input-cost effect when it comes to durables purchases, as discussed in Edelstein and Kilian (2009). Lower productivity in the energy sector also contributes to the fall in output. Then, as recession kicks in, depressed energy demand delays the energy sector's recovery. Figure 2.1a shows this point clearly: the fall in energy production is rather prolonged. This dynamics of energy production demonstrates a clear feedback from energy demand to energy production. Inter-sectoral movements in capital and labor also show how the presence of an energy sector deepens the impact of the shock. The durables sector experiences a large squeeze on capital and labor, as these resources, already reduced, are relocated to the energy sector. Figure 2.1d shows the sectoral movements in labor; movements in capital follow this pattern.

2.4.2 Productivity boom: demand-driven energy price increase

In this section we investigate the effects of an aggregate shock to energy demand, corresponding to the aggregate demand shock analyzed by Kilian (2008, 2009). This is useful for understanding actual economic periods that throw doubts on the supply-side effects of energy prices, such as the boom period in 2003-2008. As is well known, that period saw good economic growth coexist with sky-high oil prices. To replicate this theoretically, we cause a positive shock to the productivity of the durables and non-durables sectors. This provides a supply-led boom to the economy. The endogenous production of energy will then allow a link to be established from the users of energy to the energy producer. Higher productivity lowers the non-energy producers' marginal costs and shifts up their supply. Factor prices rise, and the household benefits from higher income. As the household and the producers use more durables and capital, the overall demand for energy is pushed up, and energy price rises as a result. The IRFs returned by the model demonstrate clearly this expanding business cycle. Figure 2.2a shows that this boom is represented by a rise in output, accompanied by increases in employment and factor prices (Fig. 2.2b). More importantly, it also causes energy price to rise. A 1.1% increase in output is matched by an initial increase in energy price of almost 1% (Fig. 2.2d), very close to a 1-for-1 relationship, though energy price continues to rise thereafter and only peaks near the 15th quarter. Though we are not overly concerned with replicating the boom quantitatively, Kilian (2008) does give us a reference on the relationship between GDP growth and energy price increases. The VAR estimations in the study show that in response to an aggregate demand shock, U.S. real GDP increases by a maximum 1.5%, while real oil price increases by 2.5% and gas price by 1.5%. This relationship comes quite close to the relationship between output and energy price indicated by our model. This also means that the impact on the business cycle of this shock replicates the main features of the aggregate demand shock in Kilian (2008, 2009).

With regard to other aspects of this economic expansion, consumption of non-durables and capital investment both increase: non-durables slightly at 0.2%, capital investment quite significantly at more than 6% (Fig. 2.2c). Higher energy price, however, discourages the household initially in its durables investment decision. In contrast to Section 2.4.1, a higher return on capital here makes durables a lot less attractive than capital. As a result the household devotes more of its investment portfolio towards capital investment, causing its durables investment to be crowded out. The household also reduces its energy consumption because of higher energy price, as the amount of utilized durables falls gradually before recovering near the 10th quarter (Fig. 2.2a). However, the shape of the response differs from Section 2.4.1; it also has a much lower (in magnitude) energy price elasticity. This shows that the usual channel of higher energy price is countered by the aggregate effects of the expanding business cycle. While in Section 2.4.1 the income effects on both sides of the household's budget constraint work in the same direction and so reinforce each other, here the income effect coming from the income side of the budget is positive, partially offsetting the negative income effect from the expense side. The different relative price movements between energy and factors of production thus demonstrate the distinct nature of this energy price shock. The dynamics of energy production and energy price responses also reinforce this point. Figure 2.2d shows that energy price here does not decay as fast as it does in Section 2.4.1. In fact, it has a humped shape, reaching its peak around the 15th quarter. Hence the persistence of the energy price increase is a lot stronger for this shock, outlasting the persistence of the underlying shock by a large degree. Conversely, in Section 2.4.1, energy price actually decays faster than the underlying energy sector's productivity (represented by the solid line, scaled and inverted). This determination of energy price dynamics comes from the persistence of the underlying shock and the feedback from energy demand. When the energy price hike comes from the energy sector's productivity shrink, as in Section 2.4.1, falling energy demand and the decaying shock act in the same direction to pull energy price back down more quickly than the restoration of the energy sector's productivity. Here, conversely, energy demand works in the opposite direction to the tendency of the underlying shock; accumulated capital maintains a more persistently high energy consumption than the shock itself, and as a result sustains the energy price increase for longer. A higher energy price also stimulates the energy sector, and its increased output contributes to overall expansion. Again, the presence of the energy sector delivers energy price and production dynamics that can shed light on the underlying causes of energy price increases. This energy price increase results from a booming economy, and is demand led. If we take this energy price increase in isolation, the elasticities of the consumption and investment variables with respect to it would not tally with those reported in Section 2.4.1.

2.4.3 Energy market-specific demand shocks

2.4.3.1 Shock to the energy intensity of durables

We analyze a third kind of energy price shock, namely a demand shock that is specific to the energy market. We attempt here to provide a corresponding structural shock in the context of this model to the oil-market specific shock investigated by Kilian (2008, 2009), and establish a theoretical analysis of the impact of this shock on the business cycle. The parameter a governs the amount of energy needed to utilize a unit of durables, namely the energy intensity of durables. Thus a change in the value of a represents a demand shock that is specific to the energy market, coming from the household.

We effect a sudden 10% increase in a and look at how the macro variables respond. Energy price shoots up by almost 14%, and energy production rises by almost 2% (Figs. 2.3a and b). The household sees this shock as an energy price increase and reduces its durables usage correspondingly. Its utilized durables drop by almost 5.5% (Fig. 2.3a), a stronger response (in elasticity) than in Section 2.4.1. There is an amplifying effect here in this shock: the effective increase in energy cost is higher than just the energy price increase itself, because the 10% increase in the energy intensity of durables has to be taken into account. The high complementarity between durables and energy ensures that the utilized durables do not drop enough to offset the increase in the durables' energy intensity, and the household's use of energy still ends up increasing. The high complementarity between capital and energy also means that producers' energy consumption does not decrease enough to prevent a rise in overall energy consumption. At the same time, the convex costs in energy production prevent the energy sector from freely expanding its output. The inelastic nature of energy demand and energy supply thus ensures that energy production rises by just 2%, and the corresponding energy price increase is larger.

This shock has a qualitatively similar impact on the business cycle to Section 2.4.1. Beyond that, though, there are important differences. This shock has a slightly more severe impact on output than Section 2.4.1, with an energy price elasticity of around -0.11. The responses are also consistent with Kilian (2008) in the sense that output shows a persistent decline and energy price shows sharp increases. The greater energy price-output elasticity observed here is explained by a greater leftward shift in aggregate demand, due to the amplifying effect through a, mentioned above, which is absent in Section 2.4.1. The nature of the shock further manifests itself through the way the household readjusts its portfolio differently from what occurs in Section 2.4.1. It reduces durables consumption by a much larger percentage than capital investment (Fig. 2.3c), and a lot more than in Section 2.4.1. As the utilized durables drop by a greater percentage (in terms of elasticity), the depreciation rate of durables also drops more steeply, and the household needs to invest correspondingly less in durables. Thus the higher energy intensity of durables turns out to have a larger (negative) effect on the forward-looking behavior of the household in terms of durables investment than the mere increase in energy cost suggests. This much larger reduction in durables investment relative to capital investment also comes from the fact that durables become a lot less attractive than capital for the household, as the increase in a causes the effective cost of durables to move up significantly against the fall in the return on capital. Effectively, the demand for durables is shifted not just by the increase in energy price but by the entire increase in the energy cost of durables usage. The substitution effect then ensures that the household reduces its capital investment to a lesser extent than in Section 2.4.1. This also means that even though the household is hit with a reduced effective budget and lower income, the income effect through the expense side of its budget dominates.

For the producers, this shock is transmitted to them through shifting demand for their goods and through higher energy price pushing up their costs. The results again are lower wage, lower interest rate, and reduced employment, similarly to Section 2.4.1. But the shock does not affect the producers in the same way as it does in Section 2.4.1. The non-energy producers suffer from lower demand because the household cuts its durables and non-durables consumptions, but the energy sector benefits from higher demand. The durables sector again suffers most from this shock, in terms of output as well as employment (not shown). Furthermore, while in Section 2.4.1 the durables sector is already impacted more than the non-durables sector on its demand side, this demand shock has an even greater effect on the durables sector's demand because of the amplification mechanism explained above.

As we have seen, the increase in a creates an additional mechanism that amplifies the shock's impact on the demand side of the economy beyond the usual channel of energy price. By comparing the responses of the household and the producers to Section 2.4.1, we can discern that the initial severity of the shock on the two sides of the economy is very different. The impact of higher energy costs is disproportionately larger on the household, compared to Section 2.4.1, as its responses in the consumption and usage of durables are disproportionately more volatile than the producers' responses. The readjustment between the two kinds of investments, from durables to capital, is also apparent.

2.4.3.2 Shock to the energy intensity of capital

The parameter b represents the energy intensity of capital, i.e. the amount of energy needed to utilize a unit of capital. A change to b can also be interpreted as a demand shock specific to the energy market, but in this case coming from the producers. We analyze the effects on the business cycle of a sudden 10% increase in the value of b. Given the roughly equal amounts of energy consumed by the household and by the producers, we expect a similar energy price increase to Section 2.4.3.1, but this is not the case. Energy price shoots up by close to 28% (Fig. 2.3e), and energy supply responds with a 3.5% increase (Fig. 2.3d). Again, convex costs in energy production help produce more realistic responses of energy price and energy production. In terms of elasticity, this shock causes a larger decline in value added (-0.126) than in either Section 2.4.3.1 or 2.4.1.

The relative severity of the shock on the two sides of the economy now runs in the opposite direction to Section 2.4.3.1. To the producers, the input-cost effect does not comes from energy price alone. Recall that the marginal cost of capital for the producers is equal to the rental rate of capital plus the term bp_e. So, when there is an increase in the value of b, coupled with an energy price shock, the increase in the term bp_e is huge. Consequently, to the producers a higher energy intensity of capital means a far higher rise in energy cost than indicated by just energy price. The shift in demand for capital coming from the producers is larger, and the downward pressure on the rental rate of capital is higher. The result is a reduction in capital stock that is four times in magnitude the reduction that occurs in Section 2.4.3.1 in terms of energy price elasticity. The greater energy cost also means that there is a greater shift in aggregate supply than caused by higher energy price alone and explains the greater energy price-output elasticity observed for this shock. Given that this shock leads to an expansion in energy output and yet produces a more severe contraction in value added compared with Section 2.4.1 (where there is shrinkage in the energy sector), we can clearly see how an increase in the energy intensity of capital amplifies the impact on the supply side of the economy beyond what energy price demonstrates in 2.4.1.

The impact of this shock on the household is also different. The household readjusts its portfolio by reducing its capital investment much more than its durables investment (in percentage terms; Fig. 2.3f), compared with both Sections 2.4.1 and 2.4.3.1. The sensitivity of durables investment to energy price is roughly the same as in 2.4.1, while the elasticity of capital investment is higher in magnitude. The greater downward pressure on the rental rate of capital means the income effect now comes chiefly from the income side of the budget constraint, and the contraction in household income is more severe. It also means that durables have become more attractive to the household in relation to capital, relative to 2.4.3.1 and 2.4.1. Therefore, it is capital's turn to be on the losing end of the substitution effect. The combined income and substitution effects thus cause the household to drastically reduce its capital holding. However, the energy price elasticity of capital in this shock is still very much lower in magnitude than the energy price elasticity of utilized durables in Section 2.4.3.1. So even if both a and b increase by 10%, the increase in the producers' use of energy here still outstrips the rise in the household's use of energy in Section 2.4.3.1. This means that the shift in energy demand here is greater than in 2.4.3.1, which explains the greater increases in energy price and output. The durables sector again suffers much more than the non-durables sector, due to the energy-dependent nature of its goods, with its demand pronouncedly affected.

These two energy market-specific demand shocks display key differences in terms of impact and transmission compared with the energy supply shock in Section 2.4.1. The two demand shocks raise energy output in the economy, yet cause greater contractions in value added. They cause the household to readjust its investment portfolio differently, and produce an amplification mechanism beyond energy price. Where the two demand shocks principally differ from each other is that each shock is amplified on a different side of the economy. An increase in the energy intensity of durables amplifies the impact on aggregate demand, while a positive shock to the energy intensity of capital magnifies the effects of energy price increase on aggregate supply. This distinction leads to quantitatively distinct energy price elasticities of various aggregate variables and diverse movements in relative prices. The implication is that a hike in the energy intensity of capital is potentially most harmful to the economy, but it also demonstrates the potentially huge benefits brought about by a *decrease* in the energy intensity of capital.

2.5 Conclusion

We investigate the general equilibrium effects of energy price shocks with different underlying causes using a three-sector model with endogenous energy production. We model durables as energy-intensive goods and non-durables as non-energy-dependent goods, as in Dhawan and Jeske (2008); but we implement a high complementarity between energy and durables/capital and extend the framework by introducing an energy sector. We also incorporate convex costs in energy production to achieve a low price elasticity of energy supply. The calibrated model has business cycle properties that describe reasonably well the macro properties of the U.S. economy. It also produces energy price dynamics that come close to data, as well as energy production dynamics that satisfy the low price elasticity characteristics of actual energy supply. It also makes an important improvement by significantly lowering the correlation between hours and wage, bringing it closer to the virtually zero correlation observed empirically.

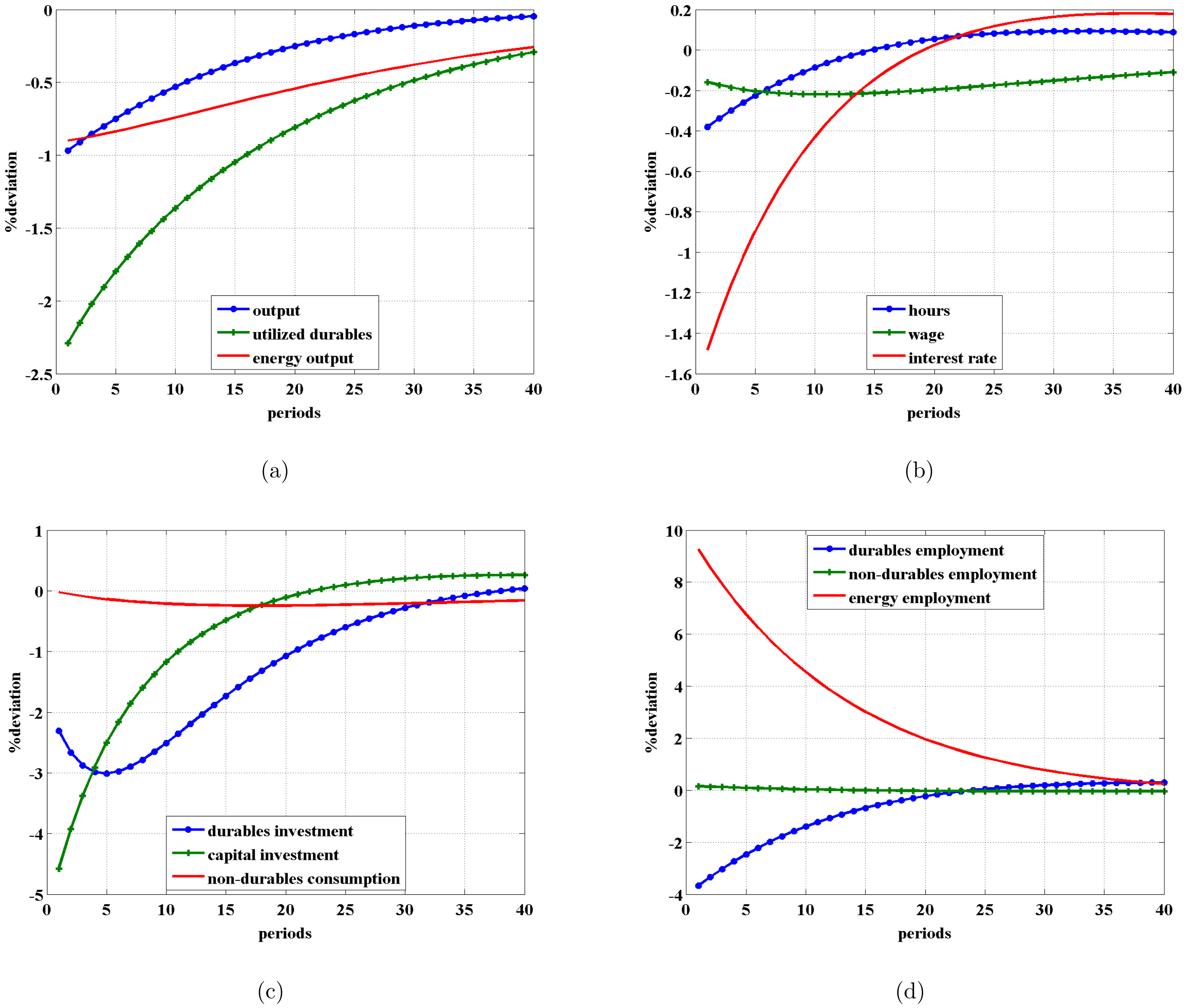
We provide a theoretical framework to demonstrate that energy price increases could have distinguishably diverse effects on the business cycle, and that their underlying causes matter. An energy supply shock sees the model return an energy price-output elasticity of -0.1, lower than that shown in Dhawan and Jeske (2008), which demonstrates the deepened impact of energy supply shock with endogenous energy production. An energy price shock caused by a productivity expansion sees the growth-retarding effects of high energy prices offset by the aggregate effects of the expanding business cycle, bringing this case of energy price increase into stark contrast with the energy supply shock in terms of the overall effects on the economy. The two demand shocks specific to the energy market cause more severe contractions in the business cycle, and leave their own distinctive mark on the economy. The demand shock coming from the household has a disproportionately greater impact on aggregate demand, while the demand shock from the producers very much transforms itself into a supply-side shock. Each shock sees its impact amplified beyond the usual channel of energy price on a different side of the economy. We show how these instances of energy price increase cause various macro variables to display varying energy price elasticities and engender diverse relative price movements, and make the connections between these observable behaviors and the underlying causes of the energy price increases. We also demonstrate clearly the differential effects that energy price increases have on goods with different degrees of energy dependence. For the non-energy-dependent goods sector (non-durables), the impact of energy price increases is mostly on its supply side, and the substitution effect from the household shields it to a certain extent. The energy-dependent goods sector (durables), in contrast, suffers more on its demand side, as the substitution effect works against the consumption of its goods.

Tables and Figures

Moments	**Values**
E_h/Y	0.0456
I_d/Y	0.0932
D/Y	1.3668
E_f/Y	0.0517
K/Y	12.000
H	0.3000

Table 2.1: Targeted Ratios

The aggregates present in the ratios are real GDP (Y), household's and production energy usages (E_h and E_f respectively), durables consumption (I_d), durables and capital stock (D and K), and labour (H). They each have a broadly corresponding theoretical counterpart in the model of Dhawan and Jeske (2008). Since in these variables our model matches the model of Dhawan and Jeske (2008) quite closely, these ratios provide good empirical bases with which to calibrate the theoretical moments of these variables in our model.



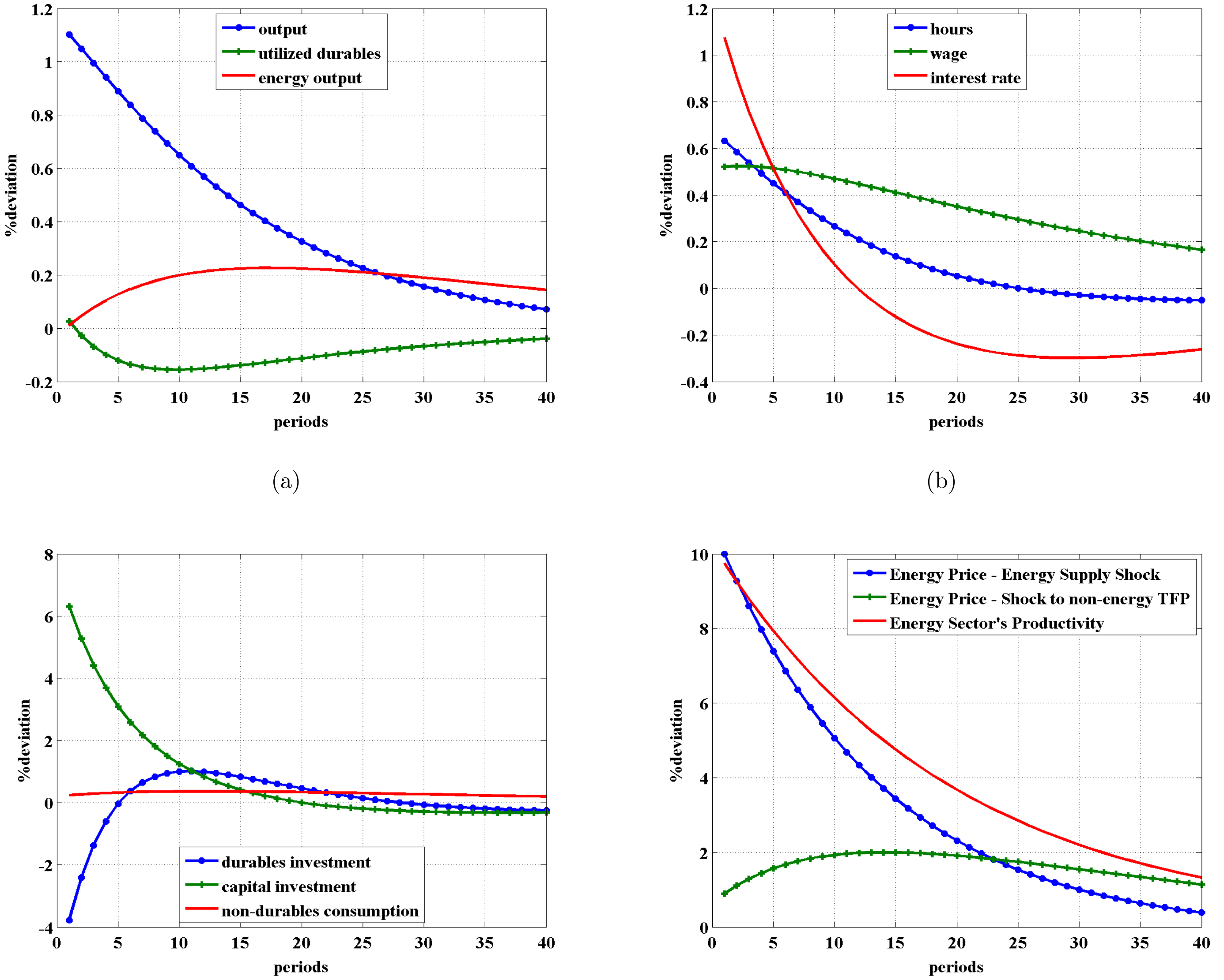
(a)

(b)

(c)

(d)

Figure 2.1: Impulse responses to a negative shock to the energy sector's productivity, scaled to produce a 10% increase in energy price.



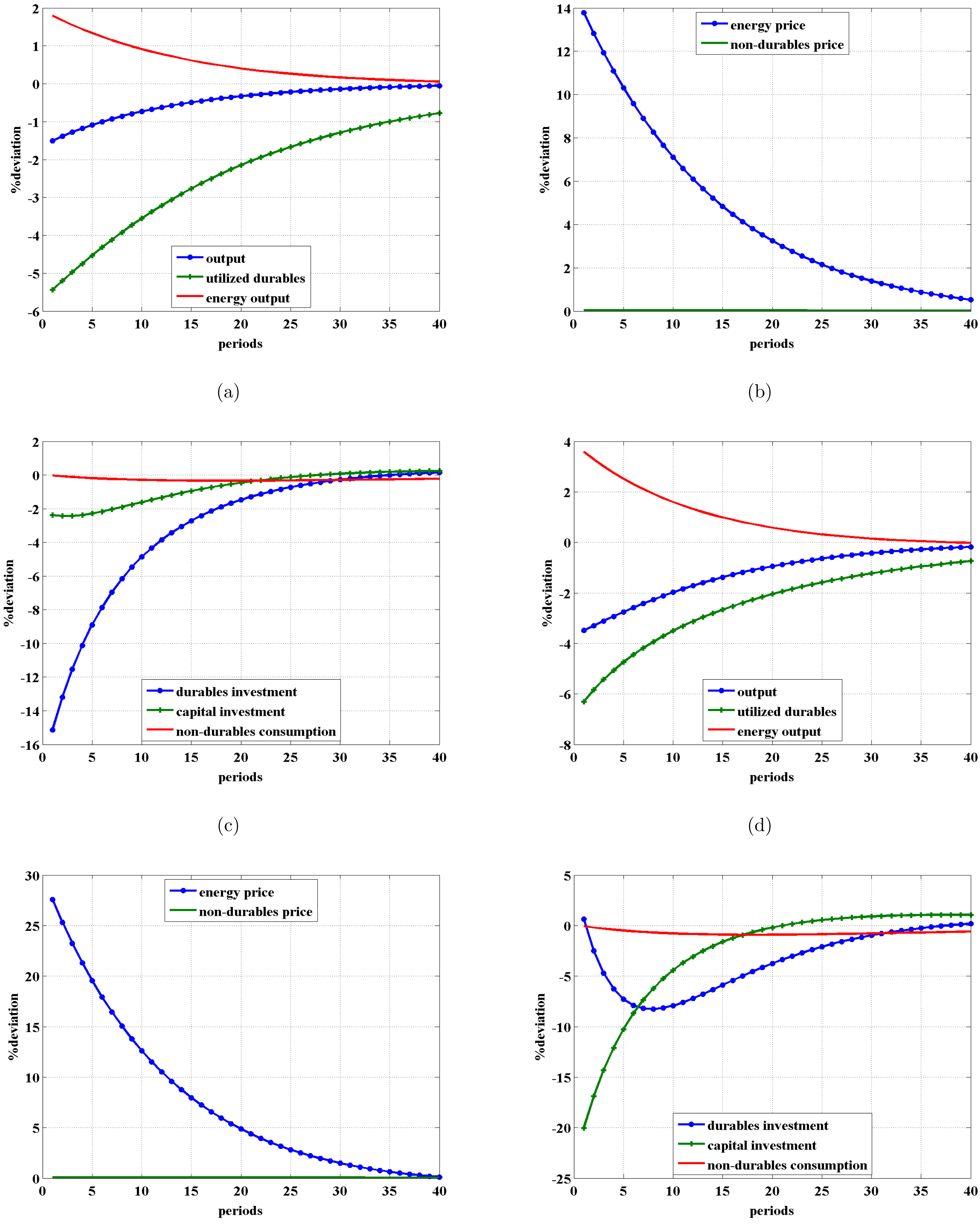
(a)

(b)

(c)

(d) Responses of energy price to the energy supply shock
) and to an increase in the non-energy producers' producti
(-+-). The solid line shows the productivity of the energy p
ducer in the case of energy supply shock, scaled and inver
to provide a better visual comparison. It can also represent
non-energy producers' TFP after a positive innovation.

Figure 2.2: Impulse responses to a positive innovation to the non-energy producers' productivity.



(a) (b)

(c) (d)

(e) (f)

Figure 2.3: Impulse responses to energy-market specific demand shocks: (a), (b), (c) to a 10% innovation to the energy intensity of durables; (d), (e), (f) to a 10% innovation to the energy intensity of capital.

3. Energy Price Shocks and External Balances

3.1 Introduction

For the analyses in this Chapter, we calibrate the Home country to broadly match the U.S. using its readily available macro data. Home thus plays the role of a major energy importer, while the Foreign country plays the role of the rest of the world (an energy exporter). We investigate the dynamics of the two countries' external balances in response to a number of supply and demand shocks. We examine the standard case of an adverse energy supply shock to the rest of the world. We then look at a shock to the overall demand for energy resulting from expansions in the business cycle. A demand shock that is specific to the energy market is also analyzed. This shock is given a specific interpretation in our model and is implemented differently than in Bodenstein et al. (2011). These three shocks broadly correspond to the three supply and demand shocks analyzed in Kilian et al. (2009). In addition, we introduce a new type of demand shock: a preference shock coming from households' increased taste for durables. This shock has direct relevance for the case of a large growing economy whose citizens increasingly consume durables. Finally, we pose the question of what would happen if the energy importing country became a more productive energy producer.

Our results confirm the empirical findings of Kilian et al. (2009) that the responses of external balances vary in response to different energy price shocks, principally due to the diverse responses of the non-energy trade balance. The distinction of a broad, indirect shock to energy demand is especially pertinent, while the specific demand shocks exacerbate the usual impact of high energy prices. Our analysis connects these differences to the sources of the energy price increases and distinguishes the roles played by goods with different degrees of energy dependence. We show that the time path of the energy price increases is not the only factor influencing the trade responses of the Home country, as different shocks affect the Foreign economy differently and thus have different impacts on Home exports. Another main result of our analysis is that the response of trade in durables is highly volatile and is the determining component in the diverse responses of the non-energy trade balance. This result implies a more immediate channel through which energy price influences the non-energy trade balance: the energy dependent nature of durables. This channel leads to movements in the non-energy trade balance beyond the usual influence of the terms of trade. As such, each shock's impact on external balances is mostly determined by how it affects durables trade in both countries. Finally, our model also predicts beneficial effects to the energy importing country if it becomes more productive in energy. Cheaper, more readily available energy leads to an increase in Home output, expansion in its durables sector and improvement in its energy trade balance.

3.2 Model

This model comprises two large, symmetrical economies representative of the U.S. and the rest of the world. Each country has three sectors, durables, non-durables and energy. Additionally, they trade all three goods freely. The consumer in each country is a representative household, and both households consume a bundle of durables and non-durables, which are composites of the relevant domestically and foreign produced goods. The manner in which energy is consumed is identical in both countries; the representative household needs energy to use its stock of durables, and all sectors need energy to operate their capital stocks. For the sake of brevity, only the setup of the home country is described here as the foreign country has a symmetric setup.

3.2.1 Household

The household consumes a CES aggregation of durables and non-durables as follows

$$c_t = [\alpha^{1-\rho}(u_t d_t)^{\rho} + (1-\alpha)^{1-\rho} n_t{}^{\rho}]^{1/\rho}$$

where n_t is household consumption of non-durables, d_t is the stock of durables and u_t the utilization rate of this durables stock. The elasticity of substitution between durables and non-durables is represented by $\frac{1}{1-\rho}$, while α represents the share of durables usage in the household's consumption bundle. Together, $u_t d_t$ defines the service the household derives from its existing stock of durables during period t.

The representative household's problem is to maximize its expected lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t (\varphi \log c_t + (1-\varphi)\log(1-h_t)) \tag{3.1}$$

subject to the following budget constraint:

$$p_{e,t} e_{h,t} + p_{n,t} n_t + p_{d,t} i_{d,t} + p_{d,t} i_{k,t} + i_{B,t} = w_t h_t + r_t k_t + r_B B_t \tag{3.2}$$

where $i_{d,t}$, $i_{k,t}$ and $i_{B,t}$ denote investments in durables, capital and foreign bonds, respectively, r_t is the return on capital, w_t the wage and r_B the return on foreign bonds. k_t and B_t are the household's capital stock and foreign bond holdings, respectively, and h_t the hours worked. $e_{h,t}$ denotes the energy needed by the household to utilize its durables stock. $p_{e,t}$ and $p_{n,t}$ are the prices of energy and non-durables, respectively, while the price of durables and capital is $p_{d,t}$. The household earns its income from the rental of its capital stock to firms, its labor service and returns on its foreign bonds. The investments in capital and durables have the following adjustment costs:

$$i_{d,t} = d_{t+1} - (1-\delta_{d,t})d_t + \frac{\omega_{d1}}{1+\omega_{d2}} \left(\frac{d_{t+1} - d_t}{d_t} \right)^{1+\omega_{d2}} \tag{3.3}$$

$$i_{k,t} = k_{t+1} - (1-\delta_k)k_t + \frac{\omega_{k1}}{1+\omega_{k2}} \left(\frac{k_{t+1} - k_t}{k_t} \right)^{1+\omega_{k2}} \tag{3.4}$$

where $\delta_{d,t}$ and δ_k denote the depreciation rates of durables and of capital, respectively, and ω_{d1}, ω_{d2}, ω_{k1}, and ω_{k2} represent the parameters of the cost functions. The rate of durables depreciation varies positively with the utilization rate. Here, we use the following power function form for the depreciation rate following Finn (2000):

$$\delta_{d,t} = \frac{a_1}{a_2+1} {u_t}^{a_2+1} \tag{3.5}$$

To render the model stationary, the household's foreign bond holdings are subject to a portfolio adjustment cost (PAC) following Schmitt-Grohe and Uribe (2002). This is a technical solution to the problem encountered by a Small Open Economy (SOE) with incomplete asset markets. Investment in foreign bonds during each period by the home country's household is given by:

$$i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B1}}{1+\omega_{B2}} \left(B_{t+1} - \bar{B} \right)^{1+\omega_{B2}} \tag{3.6}$$

The household's choice of $\{n_t, u_t, h_t, d_{t+1}, k_{t+1}, B_{t+1}\}$ to maximize (1) subject to (2), (3), (4), (5), and (6) results in the usual first order conditions detailed in appendix A.

Household energy use

Household use of durables requires a variable amount of energy ($e_{h,t}$) each period that is directly dependent on the utilization rate and stock of durables. Energy consumption does not enter the utility function directly. Instead, its cost enters into the household budget constraint. In this specification, the model makes use of the specification in Finn (2000) and extends it to the household. Household use of energy during each period can be described as a function of the stock of durables multiplied by its utilization rate $e_{h,t} = f(u_t d_t)$. In all analyses conducted in this Chapter, the amount of energy needed to sustain a utilization rate u_t of a stock of durables d_t is assumed to be linearly dependent on their product $u_t d_t$, that is, $e_{h,t} = a u_t d_t$, where a is a constant to be calibrated. This linear relationship assumes that aggregate durables have constant energy intensity.

In addition, to model an energy market specific demand shock originating from the household, we add the following exogenous shock to the household energy demand function:

$$e_{h,t} = \mu_{a,t} a u_t d_t \tag{3.7}$$

where $\mu_{a,t}$ is an AR(1) process with mean 1 and subject to i.i.d innovations

$$\mu_{a,t} - 1 = \rho_a(\mu_{a,t-1} - 1) + \epsilon_{a,t}, \epsilon_{a,t} \sim^{i.i.d} N(0, \sigma_{e,a}^2) \tag{3.8}$$

3.2.2 Producers

Each country has three sectors: durables, non-durables, and energy. The energy sector provides energy to these sectors (including itself) and to the household.

Energy Usage in Production

This framework assumes that each sector j's use of energy is tied directly to its use of capital, i.e. $e_{j,t} = g(k_{j,t})$, where g is a function to be determined. Similarly to the household case, g is calibrated to be a simple linear function; that is, a sector j's energy consumption is given by $e_{j,t} = b k_{j,t}$, where b is a constant. The parameter b can thus be interpreted as the energy intensity of capital. For the overall analysis in this Chapter, it suffices to assume that b is the same for all three sectors. One implication of this setup is that the energy sector also needs energy for its own production. In other words, energy is needed to produce energy. This factor introduces to the energy sector's production plan considerations about the opportunity cost of energy. When energy price increases, it also raises the cost of producing energy. Again, it should be noted that energy does not enter the production function directly. Its cost shows up in the first-order conditions of the three producers, where it adds to the cost of capital. The relationship $e_{j,t} = bk_{j,t}$ implies a very high degree of complementarity between capital and energy. With this specification, we emphasize the fundamental importance of energy in the operation of capital.

Again, we can model an energy market specific demand shock originating from the producers by introducing an exogenous shock to the producers' energy demand function such that for each producer

$$e_{j,t} = \mu_{b,t} b k_{j,t} \tag{3.9}$$

where $\mu_{b,t}$ is an AR(1) process with mean 1 and subject to i.i.d innovations

$$\mu_{b,t} - 1 = \rho_b(\mu_{b,t-1} - 1) + \epsilon_{b,t}, \epsilon_{b,t} \sim^{i.i.d} N(0, \sigma_{e,b}^2) \tag{3.10}$$

Energy Producer

The model implements energy production with convex costs to produce a low price elasticity of energy supply. The production function of the energy sector takes the following form:

$$y_{e,t} = \exp(A_{e,t})(1 - \lambda_{e,t}) k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e} \tag{3.11}$$

where $y_{e,t}$, $h_{e,t}$ and $k_{e,t}$ denote output, labor and capital of the sector, respectively, and

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_t, \epsilon_t \sim^{i.i.d} N(0, \sigma_e^2) \tag{3.12}$$

$\lambda_{e,t}$ represents the fraction of energy output that is lost, and has the following power function form:

$$\lambda_{e,t} = \frac{\omega_{e1}}{(1 + \omega_{e2})} (k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}} \tag{3.13}$$

This functional form for $\lambda_{e,t}$ implies that with higher outputs of energy production, an increasingly higher fraction of that is lost through waste or inefficiency in the production process. This implementation creates a mechanism whereby when a demand shock hits the energy market, the energy sector cannot simply expand its output by a large percentage quickly. This constraint makes energy price more volatile, while energy supply itself is relatively less responsive to shocks.

Non-energy Producers

The durables and non-durables sectors are assumed to have Cobb-Douglas production functions but with different capital share parameters. They also share the same productivity process. The two sectors' production functions are given as:

$$y_{i,t} = \exp(A_t) k_{i,t}^{\gamma_i} h_{i,t}^{1-\gamma_i} \tag{3.14}$$

where $y_{i,t}$, $k_{i,t}$, and $h_{i,t}$ denote output, capital and labor, respectively, of sector i, where $i = d, n$, and

$$A_t = \rho_A A_{t-1} + \epsilon_{u,t}, \epsilon_{u,t} \sim^{i.i.d} N(0, \sigma_u^2) \tag{3.15}$$

Each sector solves the following profit-maximization problem:

$$\max_{\{k_{j,t}, h_{j,t}\}} \{p_{j,t} y_{j,t} - w_t h_{j,t} - r_t k_{j,t} - p_{e,t} e_{j,t}\} \tag{3.16}$$

where $j = d, n, e$. Wages and returns of capital are assumed equal across sectors.

3.2.3 External Sector

This model assumes that energy is a homogenous good across countries and can be traded without friction. Durables and non-durables, although also traded without friction, are differentiated across the two countries. The household in each country therefore consumes durables/non-durables that are a composite of domestically produced and foreign produced durables/non-durables. For each country, there exists a packager who assembles domestic and foreign goods into composites for consumption within that country. For durables, the assembled supply for use in the country comes from the domestically produced durables and the imported durables defined as follows:

$$I_{D,t} = \left[\alpha_d^{1-\rho_d} I_{DD,t}^{\rho_d} + (1-\alpha_d)^{1-\rho_d} I_{DM,t}^{\rho_d}\right]^{1/\rho_d} \tag{3.17}$$

where α_d denotes the share of domestic durables in the durables bundle, and $\rho_d = 1 - 1/\epsilon_d$ where ϵ_d is the elasticity of substitution between domestic and foreign durables. The resulting quantity $I_{D,t}$ is used for investments in durables and capital

$$I_{D,t} = i_{d,t} + i_{k,t} \tag{3.18}$$

Similarly, for nondurables,

$$N_t = \left[\alpha_n^{1-\rho_n} N_{D,t}^{\rho_n} + (1-\alpha_n)^{1-\rho_n} N_{M,t}^{\rho_n}\right]^{1/\rho_n} \tag{3.19}$$

$$N_t = n_t \tag{3.20}$$

3.2.4 Prices

With the assumption that the packager minimizes production costs and enjoys zero profits, we arrive at the following prices for durables and non-durables in the home country:

$$p_{d,t} = \left[\alpha_d \left(p_{d,d,t}\right)^{\frac{\rho_d}{\rho_d-1}} + (1-\alpha_d)(ER_t p^*_{d,d,t})^{\frac{\rho_d}{\rho_d-1}}\right]^{\frac{\rho_d-1}{\rho_d}} \tag{3.21}$$

$$p_{n,t} = \left[\alpha_n \left(p_{n,d,t}\right)^{\frac{\rho_n}{\rho_n-1}} + (1-\alpha_n)(ER_t p^*_{n,d,t})^{\frac{\rho_n}{\rho_n-1}}\right]^{\frac{\rho_n-1}{\rho_n}} \tag{3.22}$$

where $p_{d,d,t}$ and $p_{n,d,t}$ are the prices of domestically produced durables and nondurables, respectively, and $p^*_{d,d,t}$ and $p^*_{n,d,t}$ their foreign counterparts, while ER_t is the real exchange rate. The CPI index for the home country is defined as follows:

$$p_t = \left[\alpha\left(p_{d,t} + ap_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha)p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}} \tag{3.23}$$

The real exchange rate is defined as the price (CPI index) of the foreign bundle of goods relative to the price (CPI index) of the goods bundle at home as follows:

$$ER_t = \frac{p^*_t}{p_t} \tag{3.24}$$

The terms of trade for the home country are defined as the relative price of its exports and its imports, where the price of exports is defined as the CPI index of wholly domestically produced goods and the price of imports is defined as the CPI index of wholly foreign produced goods.

3.2.5 Aggregation and Equilibrium

In this model, it is assumed that all energy produced worldwide is completely consumed during each period. The market clearing condition for energy is global and is automatically satisfied by both countries' household budget constraints and the market clearing conditions of the other two goods. Home's durable and nondurable outputs are used for domestic consumption, investments and exports

$$y_{d,t} = I_{DD,t} + I^*_{DM,t} \tag{3.25}$$

$$y_{n,t} = N_{D,t} + N^*_{M,t} \tag{3.26}$$

The factor markets also clear as follows:

$$k_t = k_{d,t} + k_{n,t} + k_{e,t} \tag{3.27}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t} \tag{3.28}$$

Aggregate output y_t (value added) is defined as follows (excluding energy used in production):

$$p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t \tag{3.29}$$

3.2.6 Exogenous driving processes

The model is driven by four main shocks: a conventional TFP shock ($\epsilon_{u,t}$) that is common to both the durables and non-durables sectors, a productivity shock that affects the energy sector alone (ϵ_t), a shock to household energy consumption ($\epsilon_{a,t}$), and a shock to producer energy needs ($\epsilon_{b,t}$).

3.3 Model Calibration and Solution

Certain parameters are calibrated following conventions in the literature and Dhawan and Jeske (2008). The discount factor β is set at 0.99; the share of consumption in the household utility function φ is set at 0.34. The share of durables α in consumption is set at 0.2. Empirical research estimates the elasticity of substitution between durables and non-durables to be close to 1. In our model, the elasticity is set at 0.99 for the main analyses, and the CES parameter of the household utility function ρ is therefore $1 - 1/0.99$, which is negative and indicates that durables and non-durables are somewhat complementary. Other parameters are calibrated to produce theoretical moments of model aggregates that reproduce in the best possible way the empirical moments calculated from aggregate U.S. data (Table 2.1). Quarterly capital depreciation is calibrated at 2.5%, while the parameters of the durables depreciation function, a_1 and a_2, are chosen to produce a steady-state quarterly depreciation rate of 3.37% and a utilization rate of 78% for durables. The calibration of the parameters a and b, representing the energy intensities of durables and capital, respectively, is based directly on the empirical ratios E_h/Y and E_f/Y in Table 2.1.

The functional forms of capital and durables adjustment costs are given in the form of a general power function governed by two parameters, ω_1 and ω_2. In this Chapter, we assume a quadratic form for both stocks, thus $\omega_2 = 1$. The remaining choice of ω_1 does not affect the steady state of the model; therefore, it must be chosen using the volatilities of capital and durables in the data as a guide. The parameters of the three sectors' production functions are also calibrated using the ratios in Table 2.1 as a guide as well as additional ratios, such as the ratio of durables consumption to total real personal consumption. Based on NIPA tables of real GDP and real personal consumption expenditures, these parameters are calibrated for the Home country to give household durables consumption of 14% of total household consumption expenditures and 10% of Home's output. The capital share of the energy sector is also calibrated to be higher than the average value of 0.36 usually found in the literature, meaning that the energy sector is more capital intensive. Additionally, the calibration of these parameters depends to a great extent on the equilibrium dynamics of the system, and they are chosen so that the model produces a stable equilibrium.

The parameters for the convex cost function of the energy sector, ω_{e1} and ω_{e2}, are calibrated to produce low price elasticities of energy supply for both Home and Foreign. However, their choices are constrained by the volatility of various energy-related variables, such as household and producer energy consumption and energy output, and by the equilibrium dynamics of the model. Parameter values that yield a very low price elasticity of energy supply result in excess volatility of these variables and often cause the model to have no stable equilibrium. We choose a quadratic function for the convex cost, where $\omega_{e2} = 1$ for both Home and Foreign, and $\omega_{e1} = 23$ for Home and 2.8 for Foreign.

The elasticity of substitution between domestic and imported goods (for both durables and non-durables, $\frac{1}{1-\rho_{d/n}}$) is set at 1.5, following Bodenstein et al. (2011) and standard literature, and is identical for both Home and Foreign countries. The shares of domestic goods in the composite durables (α_d) and non-durables (α_n) are set to produce an export share of approximately 14% of output, an import share of 17 - 18% of output, and an overall trade deficit of 3 - 4% of output for the Home country (following U.S. trade data obtained from the U.S. Census Bureau, Foreign Trade Division). The Home country is also calibrated to produce half of its total energy consumption, which corresponds to the current energy situation of the U.S.

The model is solved for its steady-state, and an approximate solution to the model is found by linearizing the equilibrium conditions around the steady-state using the first-order perturbation method of Schmitt-Grohe and Uribe (2004).

3.4 Cyclical Properties

Table 3.1 compares the relative volatility of various aggregates to output of the model and U.S. data. The empirical ratios were calculated from Dhawan and Jeske (2008), which was also used initially for reference and calibration, except for the trade ratio, which was taken from Backus and Crucini (2000).

Variables	**Model**	**U.S. data**
Output	1	1
Consumption	0.66	0.80
Nondurables consumption	0.56	0.52
Investment	3.13	3.06
Hours	0.50	0.96
Household's energy consumption	1.36	1.34
Trade ratio	4.48	3.96

Table 3.1: The relative volatility of aggregates to output.

These relative volatilities illustrate the cyclical properties of the model that broadly reflect the cyclical patterns of the U.S. economy. Both consumption and consumption of non-durables are less volatile than output, though consumption is slightly less volatile in the model than in the data. Household energy consumption and investment are more volatile than output, and these come close to matching their empirical values. The model does less well reflecting hours worked, as the relative volatility of hours worked in the model is substantially lower. A possible source of this low volatility concerns the frictionless movement of labor among the three sectors in the model. By making the relocation of labor more difficulty/costly, labor movements might be made more realistic, which might help bring up the volatility of total labor. The model also captures a trade aspect of the business cycle in that the trade ratio (value of exports over imports) is more volatile than output, even though in the model this ratio is slightly more volatile than in the data.

The presence of an energy sector produces an energy price that is endogenous, and the model produces energy price dynamics that come quite close to that found in the data. Table 3.2 shows the relative volatility of energy price to output and energy price-output correlation. For comparison, we present the same quantities calculated from Kim and Loungani (1992) in column 3. From the data it is found that energy price is highly volatile, its percent standard deviation is several times that of output, and that its correlation with output is negative. We can see that the model captures reasonably well these features of energy price dynamics. Kim and Loungani (1992) calculated the ratio of percent standard deviation of energy price to that of output to be 6, and their correlation to be -0.44 using annual data. This model puts these two values at 6.76 and -0.48, respectively, calibrated at quarterly frequency.

	Model	**Kim and Loungani (1992)**
Energy price-output	6.76	6.02
Energy Price-Output Corr	-0.48	-0.44

Table 3.2: Energy Price Dynamics: row 1 shows the relative standard deviation of energy price to output, row 2 displays the correlation between energy price and output.

3.5 Shocks to the Energy Market and External Balances

3.5.1 Adverse Foreign Energy Supply Shock

While this shock has been mostly modeled as a direct shock to energy/oil price, here we can model a more realistic energy supply shock with a negative shock to the productivity of the Foreign energy sector, scaled to induce a 10% increase in energy price.

This shock has a recessionary impact on Home. The increase in energy price causes an input cost shock to the producers and a negative income effect on the household, leading to a contraction in the business cycle. Though the figures are not shown here, Home's output shrinks by 1%, consumptions, investments, and factor prices all decrease. Because energy is needed to consume durables, a higher energy price pushes up the effective price of durables, causing demand for durables to decline more than that for non-durables. Home's durables sector is thus the hardest hit among the three sectors.

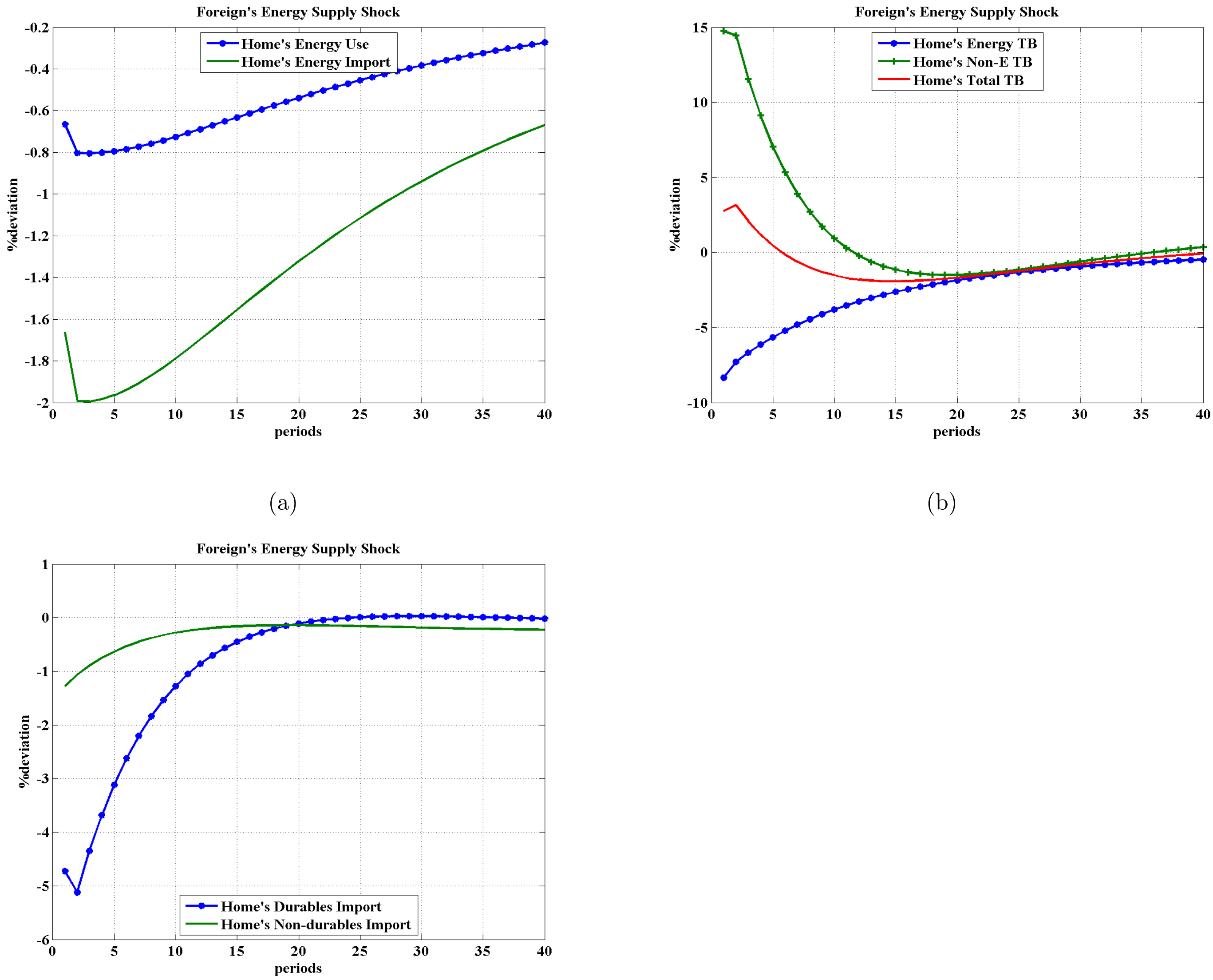
As energy is highly complementary with durables/capital, Home's energy use is very price inelastic. As a result, the higher energy price leads to only a small decline in Home's energy use (0.8%, figure 3.1a), similarly to Bodenstein et al. (2011) in the near Leontief case (0.6%). Home's energy import declines more than twice as much as energy use in percentage terms (2%), because Home's energy supply is also very price inelastic (Home's energy output increases by just 0.3%) and Home's energy import is half of its energy demand.

Concerning the external sector, given the price inelasticity of Home's energy import, Home's energy trade balance deteriorates by approximately 8% (figure 3.1b), which translates to 1% of output for a 50% increase in energy price, which is a similar result to that observed in Bodenstein et al. (2011). However, in contrast to Bodenstein et al. (2011), the non-energy trade balance improves by nearly 15%, causing the overall trade balance to improve by nearly 3%. Translating to a 50% price increase, this means an improvement in the overall trade balance of close to 0.16% of GDP, while Bodenstein et al. (2011) observe a significant overall trade balance deterioration of over 1.5% of GDP. However, it can be observed that the deterioration in the energy trade balance is more persistent than the non-energy trade balance, which deteriorates after 10 quarters. This causes the gain in the total trade balance to last only for the first 5 quarters. The responses are in line with those in Kilian et al. (2009), which reported a small and short-lived oil trade deficit and a non-oil trade surplus. Even though the responses are either small or not significant in Kilian et al. (2009), it should be noted that the estimated oil supply shock in the study is small and leads to a smaller oil price increase, while in this Chapter, we induce a 10% increase in energy price.

The large non-energy trade surplus is spurred in part by a decline in Home's terms of trade, which makes Home's imports more costly. Even though this also causes a decrease in the value of Home's exports, the decline in Home's imports more than compensates. In Bodenstein et al. (2011), a 50% increase in energy prices leads to a 6% deterioration in Home's terms of trade under the Leontief case, while in our framework, Home's terms of trade deteriorate by 3% following the same price increase. The contrast with Bodenstein et al. (2011) in terms of the response of the non-energy trade balance is due to the fact that in Bodenstein et al. (2011), the Home country's non-oil trade responds much more slowly to the declining terms of trade due to the presence of adjustment costs that cause non-oil goods demand to respond gradually to changes in the relative price of imports.

The composition of Home's non-energy trades further explains the improvement in Home's non-energy trade balance. Figure 3.1c shows that the response of Home's durables imports is a lot more volatile than that of Home's non-durables imports: Home's durables imports decrease by more than 5% in the 2nd quarter, while non-durables imports decline by a little more than 1%. Much of the improvement in Home's non-energy trade balance, therefore, comes from this sharp fall in durables imports. And yet, because the relative price of durables imports increases by approximately the same percentage as the relative price of non-durables imports (figure not shown), the increasing price of foreign durables cannot explain the sharp decrease in Home's durables imports. The decline in Home's terms of trade thus does not adequately explain the response of Home's non-energy trade balance. Rather, the explanation lies in the energy dependent nature of durables and direct influence of energy price. A higher energy price causes a greater contraction in Home's durables demand, and this, rather than the declining terms of trade, leads to a large decrease in Home's durables imports. Consequently, energy price plays a significant role in influencing the flow of durables trade, and the impact of this energy price shock on Home's non-energy trade balance extends beyond the usual channel of the terms of trade.

For the Foreign country, as it is the energy exporter, the responses of its external balances mirror those of the Home country.



(a)

(b)

(c)

Figure 3.1: Impulse responses to a negative shock to the Foreign's energy productivity, scaled to produce a 10% increase in energy price.

3.5.2 Productivity Booms

We now turn to the case where an energy price increase is demand-driven. As Kilian (2008) has noted, demand shocks to the energy market might have very different effects from energy supply shocks as they might affect the economy through channels other than energy price alone. The time paths of energy price increases might exhibit different characteristics from the case of a simple supply shock. In an example cited by Kilian et al. (2009), a rise in global demand for commodities brought about by a productivity shock might have a stimulating effect on the energy importing country even though the shock also raises the price of energy. In this case, the negative income effects produced by higher energy prices might be considerably or entirely offset by the underlying expanding business cycle. Our framework allows for this type of energy price shock to be investigated by causing a positive innovation to the productivity of the non-energy sectors. Through this productivity boom, the world economy goes through an expansion and the demand for energy rises. This shock can thus be compared to the case of an aggregate demand shock, such as in Kilian et al. (2009), in terms of external balances.

Here we compared two cases: a productivity boom in the Home country, and a boom of similar magnitude in the Foreign country. In both cases, energy price increases, but the overall effects of these shocks on the two economies are very different from the case of an energy supply shock. Focusing on Home, the effects are beneficial despite the higher energy price: output, consumption, investments, and factor prices increase. Higher energy prices here are a response to higher demand for energy throughout the economy. Producers employ more capital for their production, and the household utilizes and consumes more durables. This result is clearly observed in Figure 3.2a for the Home productivity boom, where Home's energy use rises by 0.4% and Home's energy import increases by nearly 1% at its peak during the 10th quarter. The case of a Foreign productivity expansion displays slightly different dynamics for Home's energy use (and energy import). The initial impact of the higher energy price causes Home's energy use to decrease. However, as the positive spillovers from the Foreign expansion take hold, Home's energy use eventually rises above its steady-state value after the 10th quarter. Energy import follows the pattern of energy use and displays a stronger response in percentage terms.

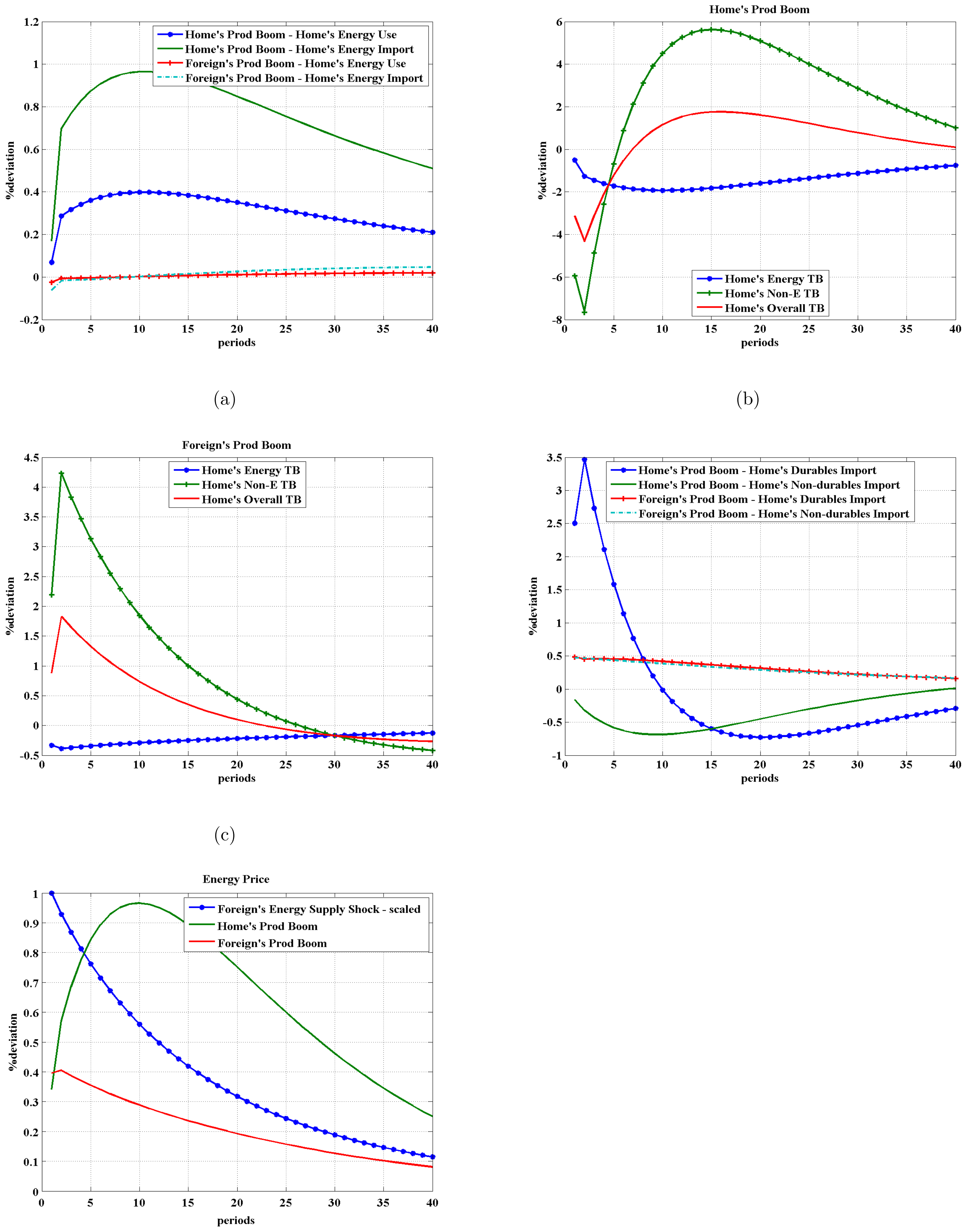
Figure 3.2e shows the contrast in the time paths of energy price responses for these two productivity booms and the energy supply shock described in Section 3.5.1. The energy supply shock in Section 3.5.1 produces an energy price increase that is less persistent than either energy price increase caused by the productivity booms in this section. This is because when there is an energy supply shock, the higher energy price and contraction in the business cycle reinforce each other and quickly depress energy demand thereby easing the pressure on energy price. Conversely, the productivity expansions in this section overcome the demand-slowing effect of higher energy prices not only causing energy demand to rise but also sustaining it. As a result, the increases in energy price display higher persistence in response to productivity-led expansions in the business cycle.

Turning to Home's external sector, the increases in energy price in response to these two productivity booms are more persistent, and Home experiences higher energy import. Therefore, the energy balance registers a larger (in terms of energy price elasticity) and more persistent deterioration than in the case of an energy supply shock (Figures 3.2b and c). In response to economy-wide productivity expansions, therefore, the behavior of the energy trade balance is rather different in both the magnitude and persistence of the deterioration compared to an energy supply shock.

The responses of Home's non-energy and total trade balances are also quite different from those described in Section 3.5.1. Home productivity boom causes a sharp, relatively short-lived deterioration in the total trade balance lasting approximately 6 - 7 quarters, while Foreign productivity expansion produces a large, persistent improvement. By comparison, Kilian et al. (2009) reported a marginally significant trade deficit. These differences are largely determined by the response of the non-energy trade balance. Home productivity expansion causes its non-energy trade balance to deteriorates by nearly 8% during the 2$^{\text{nd}}$ quarter. Foreign productivity expansion, however, causes Home's non-energy trade balance to improve by nearly 4.5% by the 2$^{\text{nd}}$ quarter.

Trade in durables and nondurables in turn provides insight into the responses of Home's non-energy trade balance. When productivity expands in the Home economy, even though it experiences a decline in the terms of trade, Home's durables imports still rise sharply (peaking at 3.5%) due to the higher demand for capital and durables investments (Figure 3.2d). Home's imports of non-durables decrease, but by a much smaller percentage, as do Home's exports (not shown). The result is that Home's durables imports dominate the non-energy trades and Home's non-energy trade balance deteriorates. When the productivity expansion occurs abroad, Home's terms of trade improve. This causes Home's imports to rise; however, Home also exports more durables because the Foreign economy demands more durables. This sharp increase in Home's durables exports dominates, and we see a large improvement in Home's non-energy trade balance.

The main distinction with Section 3.5.1 stems from the fact that with these two shocks, the direct channel of energy price is offset by the greater momentum of the expanding business cycle, so that the influence of energy price on durables trade is muted (shown by the increases in Home's durables imports despite the higher energy price). In Section 3.5.1, conversely, the larger increase in the price of energy relative to durables and non-durables indicates a much larger influence of energy price on both the durables trade and non-energy trade balance.



(a)

(b)

(c)

(e)

Figure 3.2: Impulse responses to Home's and Foreign's productivity boom.

3.5.3 Energy Market Specific Demand Shocks

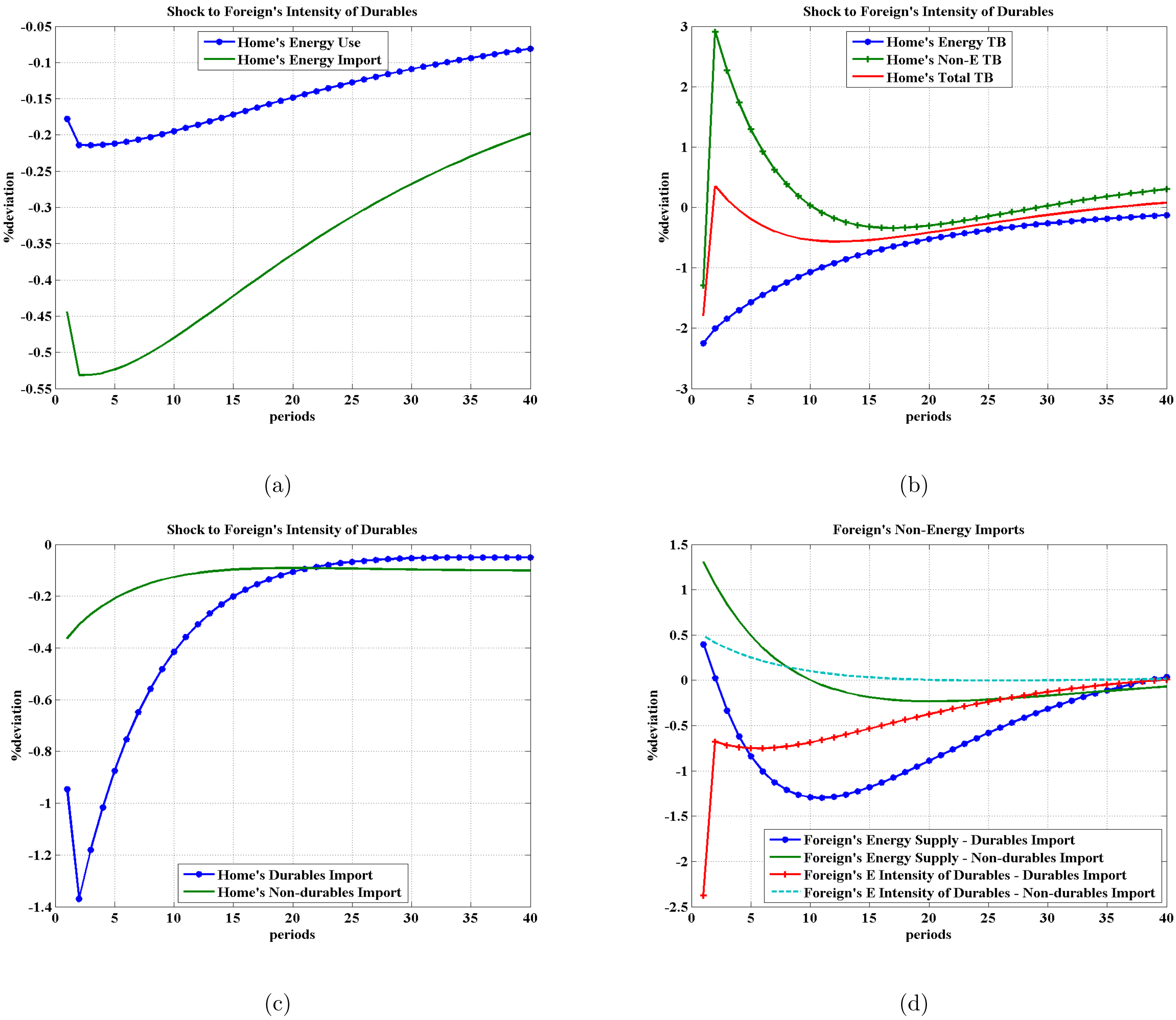
3.5.3.1 Shock to Foreign's energy intensity of durables

This section addresses a demand shock specific to the energy market, mirroring the oil-market specific demand shock analyzed in Kilian et al. (2009) and in Bodenstein et al. (2011). In Bodenstein et al. (2011), a preference shock increases the marginal productivity of oil in the Foreign household utility function, causing the Foreign household to need more oil. Here, we model this shock in the form of an exogenous shock to the Foreign household energy demand function (according to equation 7), which raises the effective energy intensity of durables for the Foreign household. This shock causes the Foreign household to need more energy for a given stock of durables thus representing a demand shock specific to the energy market.

This shock has a direct negative income effect on the Foreign household, because it is now more costly to operate its stock of durables. The immediate effect is that the Foreign household tries to reduce its durables stock as well as its durables utilization rate. However, given the inelastic nature of energy use, the reduction in utilized durables cannot offset the rise in the energy intensity of durables. The result is a higher demand for energy from the Foreign household and a higher energy price. For Home, this higher demand for energy from abroad has an adverse impact on its economy that is qualitatively similar to the energy supply shock considered in Section 3.5.1. The convex cost of energy production is important here as it ensures that Home cannot freely expand its energy sector to meet the higher demand. For a 20% increase in the Foreign household's energy demand, energy price rises by 2.7% and Home's output decreases by 0.28% (not shown). Compared to an energy supply shock, this demand shock has a similar effect on Home's output in terms of output-energy price elasticity. Home's energy use and import also decline, with similar elasticities to Section 3.5.1 (figure 3.3a).

The responses of Home's external balances show slight qualitative differences from the case of an energy supply shock (figure 3.3b). The energy trade balance still deteriorates with similar persistence and magnitude (in terms of energy price elasticity), but the non-energy trade balance does not improve upon impact, only reaching its peak in the 2^{nd} quarter. Moreover, peak improvement in the non-energy trade balance is only one and a half times the largest deterioration of the energy trade balance in percentage terms compared to almost two times in Section 3.5.1. This delayed and smaller response of the non-energy trade balance means that there is an initial sharp worsening of the total trade balance. Subsequently, during the 2^{nd} quarter, the overall trade situation for Home improves but it also quickly worsens for the rest of the 10-year horizon. Qualitatively, the results are similar to Kilian et al. (2009) and Bodenstein et al. (2011) in that an overall trade deficit was recorded, and the energy balance shows a similarly persistent and significant deficit. The model, however, gives a response of the non-energy trade balance that is closer to the estimated response in Kilian et al. (2009), which reported a statistically insignificant non-oil trade surplus, while Bodenstein et al. (2011) showed a non-oil trade deficit. Again, the non-oil deficit reported in Bodenstein et al. (2011) comes from the slower adjustment of non-oil trades to changes in the terms of trade.

The decomposition of Home's non-energy trades emphasizes the essential role of trade in durables in determining the response of the non-energy trade balance. From the perspective of Home, this shock's impact is similar to that of an energy supply shock, reflected in Home's similar responses in energy usage and import as well as non-energy imports (Figure 3.3a and c). However, this shock impacts the Foreign economy in different ways than an energy supply shock. It causes a greater increase in the effective energy cost of durables consumption for the Foreign household than the energy supply shock does. The explanation is as follows. An energy supply shock causes the energy cost of durables usage to increase by the amount of the resultant energy price increase alone. This shock, however, causes the energy cost of durables usage to increase by the combined amount of the energy price increase *and* the higher energy intensity of durables. Consequently, Foreign's durables demand is more severely affected by this shock in terms of energy price elasticity. The greater impact of this shock on Foreign's durables demand directly influences its non-energy trade response. Figure 3.3d, which compares Foreign's responses in non-energy imports between this shock and the energy supply shock, shows that Foreign's durables imports suffer a larger decrease in response to this shock (in terms of energy price elasticity) despite the fact that Home's terms of trade deteriorate more in response to this shock than to the energy supply shock (not shown). This pattern demonstrates the larger decrease in Foreign's demand for durables in response to this shock. Therefore, for Home, its exports suffer more, despite the fact that its goods are cheaper. The result is a smaller improvement in Home's non-energy trade balance than in the case of an energy supply shock.



(a) (b) (c) (d)

Figure 3.3: Impulse responses to a 20% innovation to Foreign's energy intensity of durables.

3.5.3.2 Preference Shock

Another interpretation of an energy market specific demand shock comes in the form of a preference shock to durables consumption. Whether this is strictly an energy market specific shock is debatable because this shock to energy demand comes from a shock to demand for energy-dependent goods. The example cited in Kilian et al. (2009) of a shift in Chinese tastes from bicycles to motorcycles and cars illustrates this debate, because clearly, the demand for more energy comes about as a result of a preference shift towards consumption of more durables or durables of higher value (cars vs. bicycles). Here, we consider what happens when the tastes of Foreign households shift towards durables through the following preference shock to the consumption of the Foreign household:

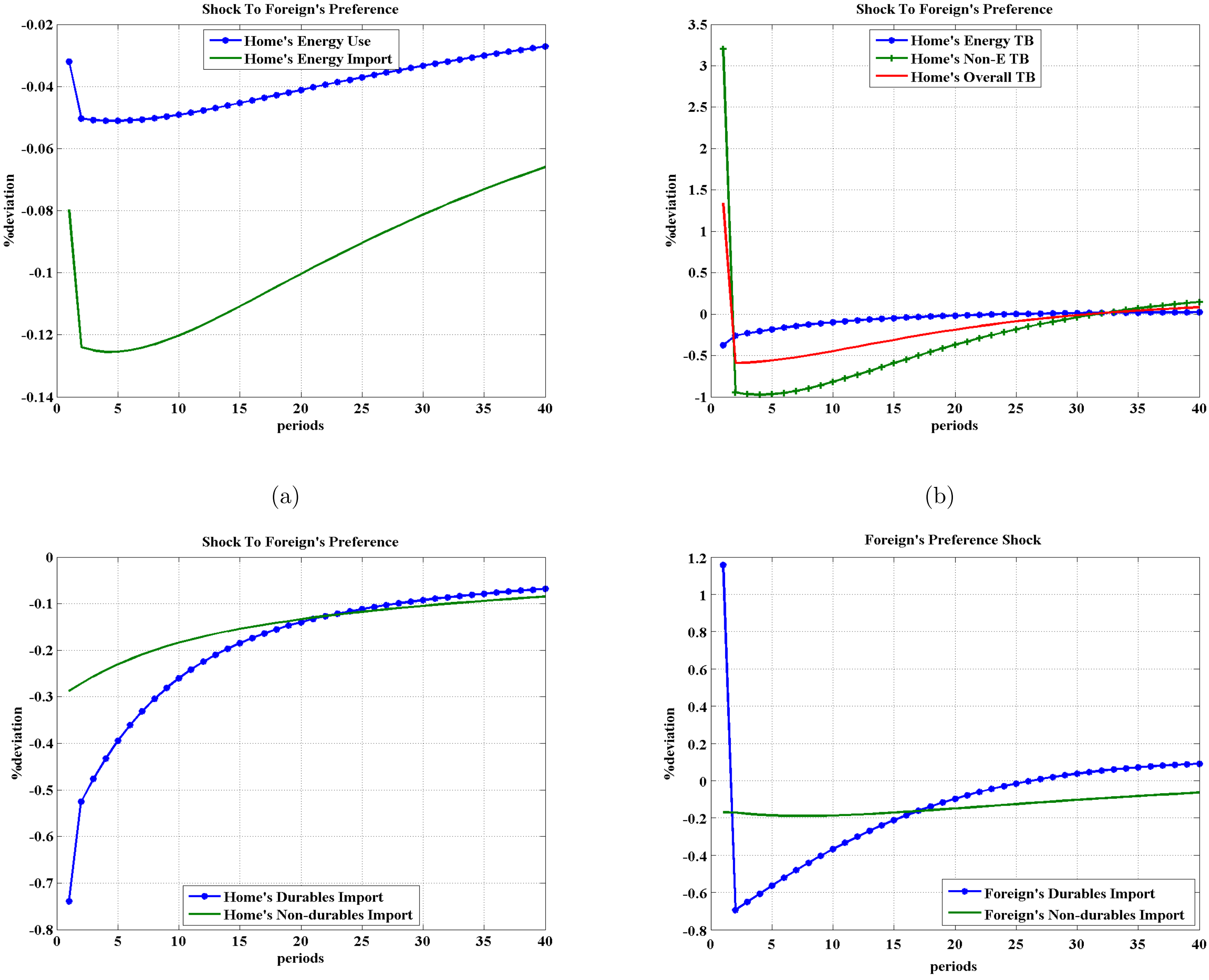
$$c_t = [\alpha^{1-\rho}(u_t \tfrac{d_t}{\mu_{p,t}})^{\rho} + (1-\alpha)^{1-\rho}{n_t}^{\rho}]^{1/\rho}$$

where $\mu_{p,t}$ is an AR(1) process with mean 1. When there is a positive innovation to $\mu_{p,t}$, this raises the marginal productivity of durables for the Foreign household such that Foreign's demand for durables increases.

Given the energy dependence of durables, this change represents a shock to energy demand. The price of energy increases due to higher demand for energy from the Foreign household but through a slightly different mechanism. This higher energy demand is coupled with a higher level of durables stock in the Foreign household. The Foreign household responds by reducing the utilization rate of its durables, but because the response is energy price inelastic, the result is still a higher utilized durables stock and higher household energy consumption. The main difference from the shock in Section 3.5.3.1 is the way the Foreign household rebalances its portfolio of capital and durables stocks: this preference shock causes the household to augment its durables stock while reducing its capital stock. The opposite pattern is observed in Section 3.5.3.1.

This preference shock has similarly adverse effects on Home as a shock to Foreign's energy intensity of durables: energy price rises, and Home's output drops. The higher energy price leads to lower energy usage and energy import, which again exhibits a larger decrease in percentage terms (Figure 3.4a). The responses of the trade balances also come close to Kilian et al. (2009) in this shock (Figure 3.4b). The energy trade balance registers a similarly persistent deterioration as in Section 3.5.3.1, and the total trade balance shows an overall deterioration. The distinction with Section 3.5.3.1 is determined by the response of the non-energy trade balance and originates in the more volatile response of trade in durables, as expected. In response to this preference shock, Foreign's non-energy prices increase more dramatically relative to Home's non-energy prices as the shift in Foreign's durables demand amplifies the increase in Foreign's durables prices. This has two effects. The first is a larger deterioration in Home's terms of trade (not shown). The second is that the income effect on the Foreign household is also more severe. The result is that, compared to the shock in Section 3.5.3.1, even though Home's imports decline more (Fig 3.4c), Foreign's durables imports also decline considerably more after the 1st quarter in terms of energy price elasticity (Fig 3.4d). Consequently, Home's non-energy trade balance registers a persistent deterioration after the 1st quarter.

The implication of the results of these two specific demand shocks is that even though these shocks cause energy price increases that are mostly identical to the increase caused by an energy supply shock, the non-energy trade balance for the Home country responds differently. The reason is that these shocks affect the Foreign country differently, especially in terms of durables demand, and have a different impact on Home's durables exports. We show thus that the time path of the energy price increase is not the only factor in determining the responses of the trade balances in contrast to the conclusion of Bodenstein et al. (2011) that only the time path of the energy price increase matters for the trade balances of the energy importing country. These two shocks also show again the more immediate influence of energy price on the non-energy trade balance, which is observed through the volatile nature of trade in durables. Energy price shocks are thus transmitted to non-energy trade responses by more than the usual terms of trade channel.



(a) (b)

(c) (d)

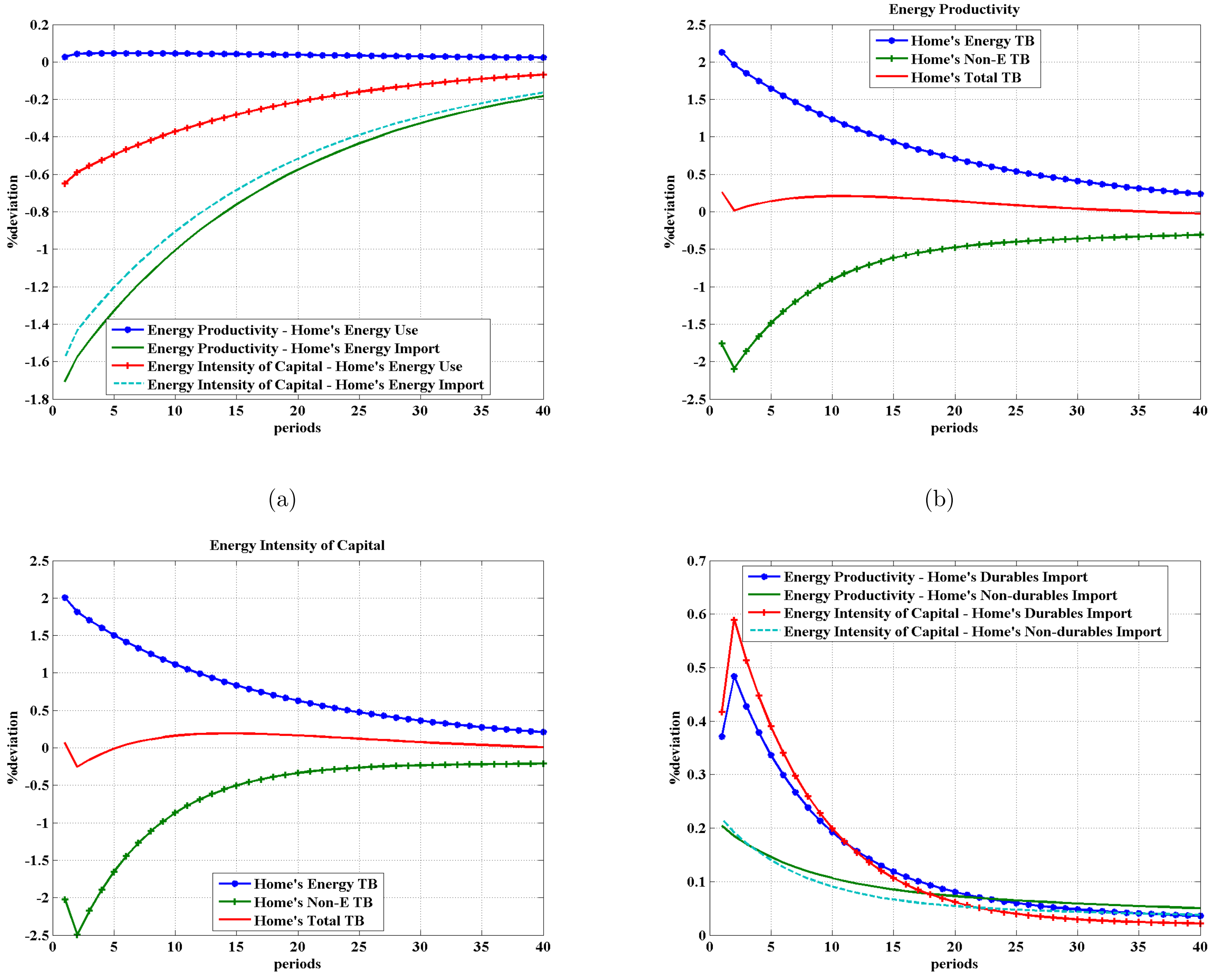
Figure 3.4: Impulse responses to a shock to Foreign's preference.

3.6 Energy Boom in the Home Country

The U.S. is widely anticipated to become a net energy exporter over the next 15 to 20 years thanks to its shale gas boom. What would the effects of progress in energy extracting or processing technology on the Home country be? In this framework, we could address this question by implementing a positive shock to Home's energy sector and analyzing its effects. There are two ways to model this shock: an exogenous increase in the productivity of Home's energy sector or an exogenous, persistent shock to the energy demand of Home's energy sector (according to equation 9). The former is a straightforward supply shock to energy output, while the latter is a demand shock to the energy market, but since it affects the effective energy intensity of capital in the energy sector, this shock could affect energy supply. We introduce an innovation to the energy demand function of Home's energy sector in one case (case 6.a), so that the effective energy intensity of capital in Home's energy sector decreases by 20%, and an increase in the productivity of Home's energy sector in the other (case 6.b). The increase in productivity of Home's energy sector is calibrated so that both cases produce a reduction in energy prices of the same magnitude. Both shocks are modeled as temporary but persistent shocks.

Though the nature of each shock differs somewhat, their impacts on Home's internal sector are similar. In both cases, a lower energy price stimulates Home's economy. Home's durables sector benefits from the lower energy price and expands. The lower energy price lowers the cost of using durables and capital, producing a positive income effect on the household and a lower total marginal cost of capital. This reduction stimulates investment in energy-dependent goods (durables and capital) and results in a higher utilization rate of the household's durables stock (figures not shown). The result is higher household energy usage and a higher stock of capital. The durables sector benefits the most from this shock, and contributes the most to Home's economic expansion as a lower energy price boosts the sector's supply as well as demand for its goods.

What we have then is a difference in how Home's energy usage is realized in response to the two shocks, as Figure 3.5a shows. In case 6.a, Home's energy usage decreases; the lower energy demand coming from the energy sector offsets the higher energy use from the household and the other sectors. In case 6.b, since there is no shift in energy demand from the energy sector, Home's overall energy demand rises. In both cases, a large decrease in Home's energy import occurs. What this means for Home's energy balance is that both cases produce a similar significant improvement (Figures 3.5b and c) due to both a lower energy price and a reduction in energy import. The non-energy balance deteriorates by a similar amount in both cases due to the large increase in durables imports (Figure 3.5d) as the lower energy price stimulates Home's durables demand to a greater extent than non-durables. This sensitivity of trade in durables to energy price again determines the behavior of the non-energy trade balance. The result is little movement in the total trade balance in either case.



(a) (b)

(c) (d)

Figure 3.5: Impulse responses to Home's energy boom.

Through a lower energy intensity of capital in the energy sector, we arrive at a lower energy price that stimulates the economy and at the same time achieve lower overall energy consumption thanks to the reduced energy demand of the energy sector itself. A more abundant energy supply, as interpreted in this framework, is also beneficial to the economy, but such expansion in energy output also means that more energy is consumed. These shocks are less beneficial to the Foreign economy, however. In either case, the decrease in energy price has an adverse effect on Foreign's energy sector, which is reduced in size. Though the lower energy price also benefits its household and its non-energy sectors, the effect on its energy sector is larger than the expansion in the other two sectors. The result is that Foreign's output shrinks, though by a rather small percentage.

3.7 Sensitivity Analysis

In this section, we examine the robustness of the model with respect to the calibration of a couple of important parameters. We investigate whether and how the dynamic properties of the model change when we adjust Home's elasticity of substitution between domestic and foreign goods ($\frac{1}{1-\rho_{d/n}}$). In addition, given the important role of durables in producing the results, we vary the elasticity of substitution between Home's durables and non-durables ($\frac{1}{1-\rho}$) and observe the impact on the dynamic responses of the model. Overall, this analysis demonstrates the robustness of the model with regard to these two parameters. The dynamic responses of the macro variables change quantitatively but not qualitatively when the values of the two parameters are varied, and the change occurs in the direction that is expected based on the roles of these two parameters in the model.

3.7.1 Home's foreign-domestic goods elasticity of substitution

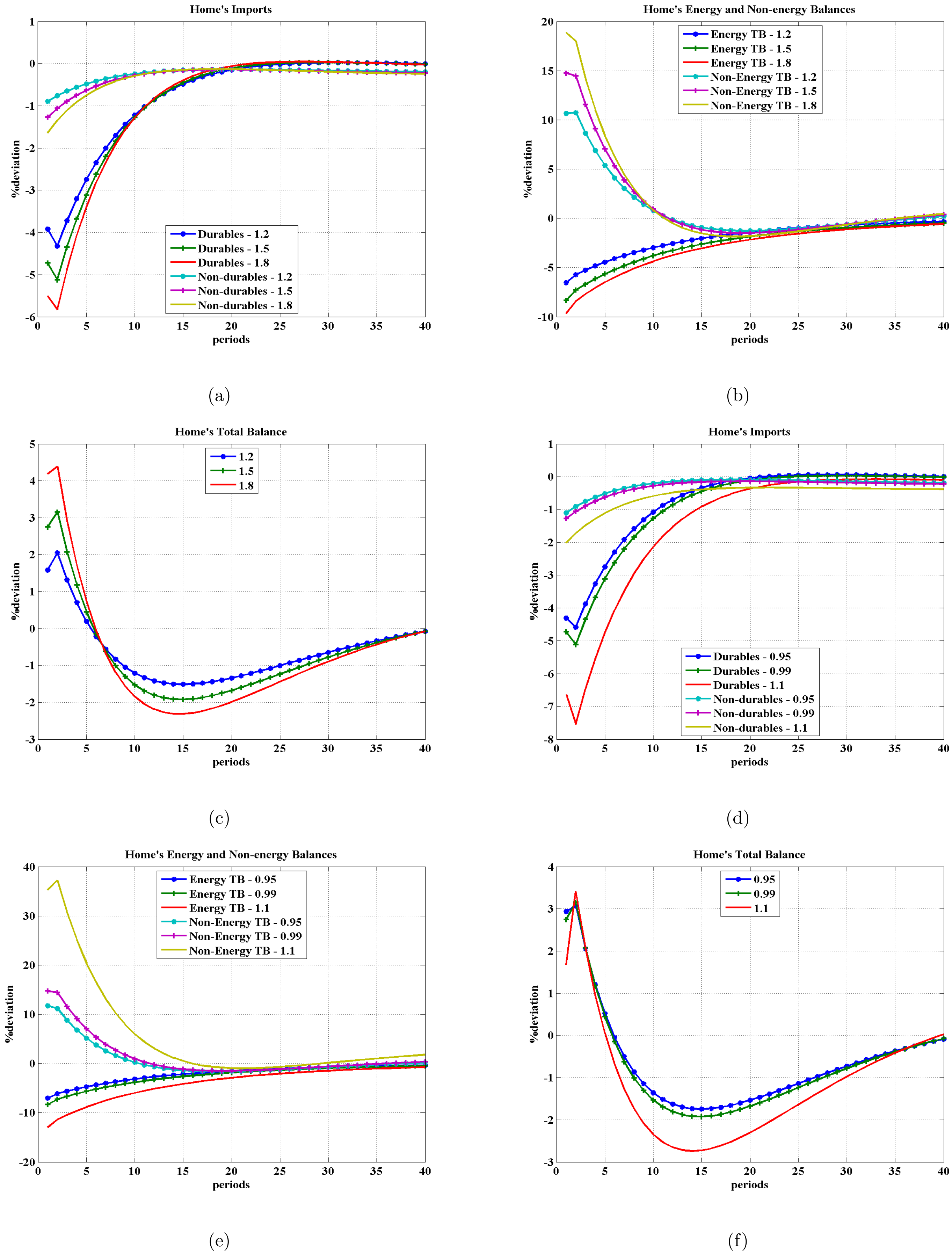
Figures 3.6a, b, and c show the responses of Home's trade balances to a Foreign energy supply shock at three values of this elasticity ($\frac{1}{1-\rho_{d/n}}$): 1.2, 1.5

(baseline), and 1.8 (other shocks show similar variations in the responses of Home's trade balances). A higher value of the elasticity means that the Home household is more willing to substitute for domestic goods when the prices of foreign goods rise (as in the case of Foreign adverse supply shock and specific demand shock), and accordingly Home's non-energy imports decrease further (Fig. 3.6a). The result is a larger improvement in the non-energy trade balance (Fig. 3.6b). Even though the energy trade balance deteriorates more at higher values of this elasticity, the effect on Home is a larger improvement in its total trade balance during the first 6 quarters (Fig. 3.6c). This movement in Home's total trade balance, as seen in Fig. 3.6c, occurs because the response of Home's total trade balance is sensitive to the relative proportions of its energy and non-energy trade balances, which can be changed by varying the elasticity. However, the distinct impact of this shock (and indeed of other shocks) is preserved in response to small changes in the value of the elasticity, such as the deterioration observed in the energy trade balance and the qualitative response of the non-energy trade balance.

3.7.2 Home household's durables-non-durables elasticity of substitution

Figures 3.6d, e and f show the responses of Home's trade balances to a Foreign energy supply shock at three values of this elasticity ($\frac{1}{1-\rho}$): 0.95, 0.99 (baseline), and 1.1 (again, the other shocks show similar variation in the responses of Home's trade balances). Intuitively, when this elasticity increases, we expect the impact of energy price fluctuations on the consumption and trade of durables to be more pronounced as the Home household is more willing to substitute for non-durables when the relative price of durables increases. This substitution should lead to a stronger decrease in Home's durables imports and a larger improvement in Home's non-energy trade balance, which are shown in Figure 3.6d and e. Figure 3.6e also shows that as the elasticity goes from

0.99 to 1.1 (so that ρ changes sign from negative to positive, meaning that durables and non-durables switch being complements to being substitutes), the response of the non-energy balance moves quite significantly. At the same time, Home's energy trade balance deteriorates more at higher values of this elasticity due to higher Home's energy use and import (not shown). The result is that Home's total trade balance shows greater deterioration (Fig. 3.6f). This deterioration is due mostly to the fact that as durables imports fall while energy import rises, the relative proportion of the non-energy trade balance in Home's total trade balance decreases. Thus, even though Home's non-energy trade balance improves by a greater percentage than does the energy trade balance, the overall effect is still an increase in the deficit of Home's total trade. The qualitative signature of the shock, however, remains. The same pattern applies to the other shocks analyzed in this Chapter.



(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.6: Sensitivity analysis: a b, c: changes in $\frac{1}{1-\rho_{d/n}}$; d, e, f: changes in $\frac{1}{1-\rho}$

3.8 Conclusion

This Chapter extends the analysis of energy price shocks on external balances to a number of supply and demand shocks to the energy market in a two-country model comprising multiple sectors and endogenous energy production with convex costs. Convex costs of energy production help produce a low energy price elasticity of energy supply, bringing energy price and production dynamics closer to the data. The explicit modeling of durables and non-durables allows insights into the composition of the non-energy trade balance in response to these diverse energy price shocks.

Our theoretical investigations show that, in line with Kilian et al. (2009), different shocks to the energy market trigger distinct responses of the external trade balances of the energy importing and energy exporting countries. The response of the non-energy trade balance plays a crucial role in determining the dynamics of the overall trade balance. We distinguish the different sources of the energy price increases by tracing their diverse responses back to the nature of the shocks. We show how the volatile nature of durables trade contributes most to differentiate these responses through the large impact of energy price on durables. Our results reinforce the need to look beyond energy price to the sources of energy price shocks, especially in the formulation of appropriate policy responses.

We also demonstrate and compare the two different ways that the energy importing countries could experience an energy boom and how they both could boost the domestic economy, expanding its output and its durables sector. The two cases demonstrate similar responses from the energy importer (Home). The Home economy receives a boost, especially in the durable sector, while its energy trade balance improves. The overall trade balance, however, moves little due to the deterioration of the non-energy trade balance.

4. Monetary Policy and Energy Price Shocks

4.1 Introduction

This Chapter follows the approach of Leduc and Sill (2004) in that we compared the relative effectiveness of different monetary regimes with one another in terms of their impact on the business cycles, mainly output and consumption. The four shocks studied in this Chapter are: productivity shock to the energy sector, representing the usual energy supply shock, TFP shock to the non-energy sectors, which is a kind of aggregate shock to energy demand, and two energy-market specific demand shocks coming from the household and the producers respectively.

Regarding the energy supply shock, our results differ from those before in several aspects, and find agreement in others. We do not find that price stability is the best in terms of minimizing the shock's impact on output and consumption, in contrast to Leduc and Sill (2004). Our findings are more in line with Bodenstein et al (2008), as we lean towards output stabilization, even though we add to this with a caution against going too much towards output without a corresponding focus on inflation. The conclusions drawn from Nakov and Pescatori (2010) also differ from ours. While they did propose a certain degree of focus on output stabilization as an optimal form of monetary policy, their favorable view of strict price and aggressive inflation fighting policies are in contrast to what we obtained from our analyses.

Extending the analysis to other kinds of energy price shocks, we found that in the event of a positive TFP shock to non-energy producers, which increases the aggregate demand for energy, a strong focus on inflation is best in terms of ensuring the strongest expansion in output and consumption. We showed that this instance of energy price shock is very distinct from the one before, not just in terms of the responses of the economy to it but also in terms of the relative performance of alternative monetary regimes. The two specific demand shocks to the energy market, however, require actions qualitatively similar to the case of an energy supply shock. Even so, the effectiveness of the required policy on stabilizing output and consumption varies between these two shocks, compared to the case of energy supply shock. This is due to the quantitatively distinct impact of each shock, especially on the durables sector.

We also showed that the price rigidity of the more energy-consuming goods plays a greater role in the propagation of energy price shocks. Output and consumption and many other macro variables show higher sensitivity to varying price stickiness of durables goods. Different degrees of durables' price rigidity also influence the non-durables sector's behavior more than vice versa. This is a consequence of the fact that the more energy-dependent goods sector always shows more volatile responses when energy price changes. Also it is due to the interplay between the substitution effect and the income effect that causes consumption of durables to vary little when the price of non-durables changes, but not vice versa.

4.2 Model Description

4.2.1 Households

The representative household consumes a CES aggregation of durables and non-durables of the following form

$$c_t = [\alpha^{1-\rho}(u_t d_t)^{\rho} + (1-\alpha)^{1-\rho} {n_t}^{\rho}]^{1/\rho}$$

where n_t is the household's consumption on non-durables, d_t is the household's stock of durables and u_t is the utilization rate of this durables stock. The elasticity of substitution between durables and non-durables is represented by $\frac{1}{1-\rho}$. Together, $u_t d_t$ defines the service the household derives from its existing stock of durables in period t.

Household's energy usage

Household' use of durables needs energy, the amount of which ($e_{h,t}$) is variable in each period and directly dependent on the utilization rate and the stock of durables. Energy consumption does not enter the utility function directly, instead its cost enters into the household's budget constraint. In this specification, the model makes use of the specification in Finn (2000) and extends it to the household. Households' use of energy in each period can be thought to be a function of the stock of durables times its utilization rate $e_{h,t} = f(u_t d_t)$. In all analyses carried out in this Chapter the amount of energy needed to sustain a utilization rate u_t of a stock of durables d_t is assumed to be linearly dependent on their product $u_t d_t$, that is $e_{h,t} = a u_t d_t$, where a is a constant to be calibrated. This linear relationship carries the assumption that durables in the aggregate have a constant energy intensity.

The representative household's problem is therefore to maximize its expected lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_t, h_t) \tag{4.1}$$

where

$$U_t = \varphi log c_t + (1 - \varphi) log(1 - h_t)$$

subject to the following budget constraint

$$\begin{aligned} &(1 + \tau_{e,c,t}) p_{e,t} a u_t d_t + (1 + \tau_{c,t}) p_{n,t} n_t + (1 + \tau_{c,t}) p_{d,t} i_{d,t} + p_{d,t} i_{k,t} + i_{B,t} \\ &= (1 - \tau_{i,t})(w_t h_t + r_t k_t) + R_t B_t \end{aligned} \tag{4.2}$$

where $i_{d,t}$, $i_{k,t}$ and $i_{B,t}$ denote investments in durables, capital and government risk-free bond respectively, r_t the return on capital, w_t the wage and R_t the return on government bond. The household earns its income from the rental of its capital stock to firms, its labor service and the return on its government bond. The taxes it has to pay are: an ad-valorem tax on its energy consumption, income tax on its wage and return on capital, and consumption tax on its durables and non-durables consumptions. Investments in capital and durables are subject to the following adjustment costs

$$i_{d,t} = d_{t+1} - (1 - \delta_{d,t})d_t + \frac{\omega_{d1}}{1 + \omega_{d2}} \left(\frac{d_{t+1} - d_t}{d_t} \right)^{1+\omega_{d2}} \tag{4.3}$$

$$i_{k,t} = k_{t+1} - (1 - \delta_k)k_t + \frac{\omega_{k1}}{1 + \omega_{k2}} \left(\frac{k_{t+1} - k_t}{k_t} \right)^{1+\omega_{k2}} \tag{4.4}$$

Investment in government bond is also subject to a portfolio adjustment cost and is given by

$$i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B1}}{1 + \omega_{B2}} \left(B_{t+1} - \bar{B} \right)^{1+\omega_{B2}} \tag{4.5}$$

With $\bar{B}$ calibrated it is then possible to solve for the aggregate price level in the economy. The rate of depreciation of durables is variable and varies positively with utilization rate. Here we use a power-function form for the depreciation rate following Finn (2000)

$$\delta_{d,t} = \frac{a_1}{a_2 + 1} {u_t}^{a_2+1} \tag{4.6}$$

The household's choice of $\{n_t, u_t, h_t, d_{t+1}, k_{t+1}, B_{t+1}\}$ to maximize (1) subject to (2), (3), (4), (5) and (6) results in the usual first order conditions, detailed in appendix A.

4.2.2 Energy Usage in Production

This framework assumes that each sector's energy use is tied directly to its use of capital, i.e. $e_{f,t} = g(k_t)$, with g a function to be determined. Similar to the household's case, g is calibrated to be a simple linear function, except for the energy sector; that is, a non-energy sector's energy consumption is given by $e_{f,t} = bk_t$, where b is a constant. For the overall analysis in this

Chapter, it suffices to assume that b is the same for the two non-energy sectors. This parameter b is thus a technological parameter that embodies the energy intensity of capital. The relationship $e_{f,t} = bk_t$ implies a very high degree of complementarity between capital and energy. With this specification we emphasize the fundamental importance of energy in production.

4.2.3 Energy Production

The energy sector operates in a perfectly competitive market, and energy price is assumed to be fully flexible. The model implements an energy production with convex cost to bring about low price elasticity of energy supply.

The production function of the energy sector takes the form

$$y_{e,t} = exp(A_{e,t}) k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e} \tag{4.7}$$

$A_{e,t}$ is the energy sector-specific productivity process

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_{e,t} \tag{4.8}$$

Energy needed to operate capital in energy production is dependent on the level of output at an increasing rate

$$b_{e,t} = \frac{\omega_{e1}}{(1+\omega_{e2})} (k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}} \tag{4.9}$$

This convex energy intensity of capital used in energy production creates a mechanism whereby when a demand shock hits the energy market the energy sector cannot simply expand its output by a large percentage quickly. The calibration section will explain in more details the process of calibrating this convex cost.

The firm's maximization is

$$\max_{\{p_{e,t},k_{e,t},h_{e,t}\}} \{p_{e,t}y_{e,t} - w_t h_{e,t} - r_t k_{e,t} - (1+\tau_{e,f,t})p_{e,t}b_{e,t}k_{e,t}\} \tag{4.10}$$

where $\tau_{e,f,t}$ is an ad-valorem tax on the firm's energy usage.

4.2.4 Durables and Non-durables Final Goods Producers

Each sector has a perfectly competitive final good producer who purchases the intermediate goods in that sector and assembles them into the final product according to the following production function

$$y_{i,t} = \left(\int_0^1 {y_{i,j,t}}^{\frac{\epsilon_i - 1}{\epsilon_i}} dj \right)^{\frac{\epsilon_i}{\epsilon_i - 1}} \tag{4.11}$$

where ϵ_i is the elasticity of substitution between the differentiated varieties in sector i $(i = d, n)$, $y_{i,j,t}$ the output of each firm j in sector i, and $y_{i,t}$ the output of the final good producer in sector i.

Profit maximization means that each firm j in sector i faces the following demand schedule for its good

$$y_{i,j,t} = \left(\frac{p_{i,j,t}}{p_{i,t}} \right)^{-\epsilon_i} y_{i,t} \tag{4.12}$$

where $p_{i,j,t}$ is the price of firm j's good in sector i, and $p_{i,t}$ the aggregate price index in sector i, given by

$$p_{i,t} = \left(\int_0^1 {p_{i,j,t}}^{1-\epsilon_i} dj \right)^{\frac{1}{1-\epsilon_i}} \tag{4.13}$$

4.2.5 Durables and Non-durables Intermediate Goods Producers

It is assumed that in each sector i there exists a continuum (with a mass index of 1) of firms, each producing a variety j of that sector's goods in a monopolistically competitive market. Each firm j in each sector has access to the same kind of production technology specific to that sector

$$y_{i,j,t} = exp(A_t)\,(k_{i,j,t})^{\gamma_i}\,(h_{i,j,t})^{1-\gamma_i} - \chi_i \tag{4.14}$$

where $i = d, n$ and χ_i denotes fixed costs of production for sector i.

A_t is a technology process that is common across the two sectors

$$A_t = \rho_A A_{t-1} + \epsilon_{A,t} \tag{4.15}$$

Since each firm has monopolistic power over its own variety, it can set prices to maximize its profit. However every time it does so, it incurs a Rotemberg-style quadratic cost proportional to final output in the following form

$$\frac{\vartheta_i}{2}\left(\frac{p_{i,j,t}}{p_{i,j,t-1}} - 1\right)^2 y_{i,t} \tag{4.16}$$

Each firm's objective is to choose a sequence of price, labor and capital $\{p_{i,j,t}, h_{i,j,t}, k_{i,j,t}\}$ to maximize its expected discounted nominal profits

$$E_0\{\sum_{t=0}^{\infty}\Lambda_{i,t}(p_{i,j,t}y_{i,j,t} - w_t h_{i,j,t} - (r_t + bp_{e,t}(1+\tau_{e,f,t}))k_{i,j,t} - \frac{\vartheta_i}{2}\left(\frac{p_{i,j,t}}{p_{i,j,t-1}} - 1\right)^2 p_{i,t}y_{i,t})\} \tag{4.17}$$

where $\Lambda_{i,t}$ is the stochastic discount factor.

By log-linearizing the resulting first-order condition of the above problem around a zero-inflation deterministic steady-state, a sectoral Phillips curve is obtained for each sector i

$$\hat{\pi}_{i,t} = \beta E_t[\hat{\pi}_{i,t+1}] + \frac{\epsilon_i - 1}{\vartheta_i} m\hat{c}_{i,t} \tag{4.18}$$

where $\hat{\pi}_{i,t}$ denotes log-deviation of sector i's inflation from its steady-state value, and $m\hat{c}_{i,t}$ log-deviation of sector i's real marginal cost from the steady state.

In a symmetric equilibrium, each sector i's real marginal cost is given by

$$mc_{i,t}exp(A_t)(1-\gamma_i)\left(\frac{k_{i,t}}{h_{i,t}}\right)^{\gamma_i} = \frac{w_t}{p_{i,t}} \tag{4.19}$$

together with sector i's first-order condition resulting from cost minimization

$$\frac{1-\gamma_i}{\gamma_i}\frac{k_{i,t}}{h_{i,t}} = \frac{w_t}{r_t + bp_{e,t}(1+\tau_{e,f,t})} \tag{4.20}$$

Wage and rate of return on capital are assumed to be equalized across all three sectors.

4.2.6 CPI Inflation

The CPI index for the economy is given by

$$p_t = \left[\alpha\left(p_{d,t} + ap_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha)p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}} \tag{4.21}$$

And gross CPI inflation is thus

$$\pi_t = \frac{p_t}{p_{t-1}} \tag{4.22}$$

4.2.7 Fiscal and Monetary Policies

On the fiscal side the government levies three kinds of taxes: ad-valorem tax on energy consumption on both the household and the producers, consumption tax on durables and non-durables consumption, and income tax on return on capital and wage. In addition it also issues risk-free bonds each period to the household. This revenue from taxes and bonds is used to finance its spending and payment on interest on the household's current bond holdings.

Its budget constraint is given by

$$\tau_{e,c,t}p_{e,t}au_td_t + \tau_{e,f,t}p_{e,t}(b(k_{d,t}+k_{n,t}) + b_{e,t}k_{e,t}) + \tau_{c,t}(p_{n,t}n_t + p_{d,t}i_{d,t}) + \tau_{i,t}(r_tk_t + w_th_t)$$

$$+i_{B,t} = p_tg_ty_t + R_tB_t \tag{4.23}$$

where g_t indicates government spending as a fraction of real output, and is given as an exogenous stochastic process.

Here we also assume that for its spending the government consumes a CES basket of durables and non-durables, similarly to the household, *sans* utilization rate for durables

$$g_ty_t = \left[\alpha^{1-\rho}g_{d,t}^{\rho} + (1-\alpha)^{1-\rho}g_{n,t}^{\rho}\right]^{1/\rho} \tag{4.24}$$

such that

$$p_tg_ty_t = p_{d,t}g_{d,t} + p_{n,t}g_{n,t} + p_{e,t}ag_{d,t} \tag{4.25}$$

The fiscal authority follows a passive fiscal regime, with the sole aim of debt stabilization. To do so, it sets tax rates for each period as a function of the outstanding bond balance at the beginning of the period[1]

$$log\left(\frac{\tau_{(),t}}{\bar{\tau}_{()}}\right) = \rho_{()}log\left(\frac{\tau_{(),t-1}}{\bar{\tau}_{()}}\right) + \phi_{()}log\left(\frac{B_t}{\bar{B}}\right) \tag{4.26}$$

where $\tau_{(),t}$ represents the general term for all four kinds of taxes in our model, with $() = (e,t), (e,f), c, i$, and $\bar{\tau}_{()}$ the corresponding steady-state rate for each tax. $\bar{B}$ is the steady-state value of nominal government debt.

The monetary authority sets the short-term nominal interest rate on risk-free bonds according to the following Taylor-type rule

$$R_t - R^* = \alpha_R(R_{t-1} - R^*) + \alpha_\pi(\pi_t - \pi^*) + \alpha_y(y_t - y_{t-1}) + \epsilon_{r,t} \tag{4.27}$$

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[1] These rules follow closely in form those of Forni, Monteforte and Sessa (2009).

where R^* is the interest rate target consistent with the steady-state nominal return on risk-free bond, and π^* is the inflation target, $\epsilon_{r,t}$ is an exogenous shock to the interest rate rule.

4.2.8 Aggregation and Equilibrium

Factor markets clear

$$k_t = k_{d,t} + k_{n,t} + k_{e,t} \tag{4.28}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t} \tag{4.29}$$

as well as goods markets

$$y_{d,t} = i_{d,t} + i_{k,t} + g_{d,t} + \frac{\vartheta_d}{2}(\pi_{d,t} - 1)^2 y_{d,t} \tag{4.30}$$

$$y_{n,t} = n_t + g_{n,t} + \frac{\vartheta_n}{2}(\pi_{n,t} - 1)^2 y_{n,t} \tag{4.31}$$

Aggregate output (value added) is defined as

$$p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t \tag{4.32}$$

4.2.9 Exogenous driving processes

The model is driven by four main shocks: the conventional TFP shock that is common to both the durables and non-durables sectors, a productivity shock that affects the energy sector alone, and shocks to the energy intensities of durables and of capital (shocks to a and to b respectively).

4.3 Model Calibration and Solution

The model is calibrated to the broad characteristics of U.S. economy at quarterly frequency. Table 2.1 displays the empirical ratios of main U.S. macro variables obtained from Dhawan and Jeske (2008)[2] for the purpose of calibrating our model.

Certain standard parameters are calibrated following standard literature. The discount factor β is set at 0.99, which translates to annual interest rate of around 4%. Following standard literature, the share of consumption in the household's utility function φ is set at 0.34, and the share of durables α in consumption is set at 0.2. Empirical research puts the elasticity of substitution between durables and non-durables close to 1. Here it is set at 0.99 for the main analyses, and the CES parameter of the household's utility function is therefore $\rho = 1 - 1/0.99$, which is negative and indicates that durables and non-durables are somewhat complementary. Other parameters are calibrated to produce theoretical moments of model aggregates that reproduce as best possible the empirical moments found in aggregate US data. Quarterly capital depreciation is calibrated at 1.5%, while the parameters of the durables depreciation function are chosen so as to produce a steady-state quarterly depreciation rate of 3.3% and utilization rate of around 80% for durables. Hence, $a_1 = 0.005, a_2 = 0.3$. The calibration of the parameters a and b , the dependence of the amount of energy used on durables and capital respectively, is based approximately on the empirical ratios E_h/Y and E_f/Y in Table 2.1. The resulting calibration is: $a = 0.06, b = 0.012$. The functional forms of capital and durables adjustments costs are given in the form of a general power function, governed by two parameters ω_1 and ω_2. In this Chapter we assume a quadratic form for both stocks, thus $\omega_{d2} = \omega_{k2} = 1$. The remaining choice of ω_1 does not affect the steady state of the model, so it has to be chosen using the volatilities of capital and durables in the data as a guide. We used the following calibration, $\omega_{k1} = 50, \omega_{k2} = 1, \omega_{d1} = 5, \omega_{d2} = 1$.

The parameters of the three sectors' production functions are also calibrated using the ratios in Table 2.1 as a guide, plus additional ratios such

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[2] Dhawan and Jeske (2008), Table 1.

that the ratio of durables consumption to total real personal consumption. The capital share of the energy sector is also calibrated to be higher than the average value of 0.36 usually found in the literature, meaning that the energy sector is more capital-intensive. Additionally the calibration of these parameters depends to a great extent on the equilibrium dynamics of the system, meaning they are also carefully chosen so that that the model produces a stable equilibrium.

The parameters for the convex cost function of the energy sector are calibrated to bring about low price elasticity of energy supply and energy price dynamics that reflect empirical facts. In addition, their choices are also constrained by the volatility of various energy-related variables such as household's and producers' energy consumptions and energy output, and, of no less importance, by the equilibrium dynamics of the model. Parameter values that give very low price elasticity of energy supply result in excess volatility of variables and often cause the model to have no stable equilibrium. Here we chose a cubic power function form for the convex cost, so $\omega_{e2} = 2$. ω_{e1} is then calibrated to be 3.77, to give a price elasticity of energy supply of around 0.1, keeping it as close to the range of empirical estimates as possible while ensuring that the model has a stable equilibrium around the steady state.

Both the durables and non-durables sectors have their elasticity of substitution between their own varieties, ϵ_d and ϵ_n, set at 5, a value frequently used in the literature, to give a steady-state flexible-price markup of 25%. The price adjustment cost parameters for durables and non-durables sectors, ϑ_d and ϑ_n , are calibrated following the method used in Monacelli (2009), which matches the coefficient on the deviation of real marginal cost in the new Keynesian Phillips curve obtained in this model with its counterpart in the Phillips curve obtained from Calvo-type price rigidity. In the usual framework of price rigidity using Calvo-style contracts, the fraction of firms that cannot change their price in any given quarter is set at 0.75 to obtain a price contract length of about 4 quarters, a standard calibration in the recent literature. The coefficient on the deviation of real marginal cost in such Phillips curve is given by $\frac{(1-\theta)(1-\theta\beta)}{\theta}$ with $\theta = 0.75$, while that in the Phillips curve derived here is $\frac{\epsilon_i - 1}{\vartheta_i}$. Equating these two thus gives us $\vartheta_d = \vartheta_n = 46$, meaning that for the baseline analysis the prices of two sectors are considered to be equally sticky.

Ad-valorem energy taxes are calibrated to be 10% at the steady-state, while income tax is 15%, and consumption tax 7%. Government spending is calibrated to be 18% of output at the steady-state. For the baseline Taylor-type monetary policy rule, we follow the estimates of Clarida, Gali, and Gertler (2000), also used in Leduc and Sill (2004), and set: $\alpha_R = 0.8$, $\alpha_\pi = 0.2$, and $\alpha_y = 0.09$. The parameters for the tax rules are calibrated to ensure a determinate equilibrium for the model and stable dynamics of government debt. They are chosen to be: $\rho_{e,c} = \rho_{e,f} = \rho_c = \rho_i = 0.8$, and $\phi_{e,c} = \phi_{e,f} = \phi_c = \phi_i = 0.12$.

The model is solved for its steady state using a non-linear solver, and the set of equilibrium conditions is approximated around the steady-state using the first-order perturbation method. The system's decision rules and transition functions are thus obtained.

4.4 Systematic Monetary Policy Response to Energy Price Shocks

4.4.1 Energy Supply Shock

One of the main areas of debate has been the role of monetary policy in the event of an adverse energy supply shock. In this, Kormilitsina (2011) and Leduc and Sill (2004) arrived at different conclusions on what the optimal monetary policy would be. Bodenstein et al (2008) and Nakov and Pescatori (2010) incorporated features of endogenous energy price into their frameworks and also arrived differently at the optimal monetary policy response to an energy price shock. We conducted our own analysis of this shock using our framework to see where our results sit in relation to these previous works and to shed light on the differences between our findings and their results. Our approach to evaluating the various monetary policies is similar to that of Leduc and Sill (2004), by focusing on the responses of the observable macro variables such as output and consumption. We calibrated the shock to the productivity of the energy sector so as to produce a 10% increase in energy price. This is a temporary shock that creates a half-life for the energy price increase of about 12 quarters. Figures 4.1 to 4.6 show on surface plots the responses of output, inflation and interest rate when the inflation coefficient of the Taylor rule is swept from 0 to 0.4 at two values of the output coefficient: 0 and 0.3.

One main observation jumps out when the monetary policy function pays no attention to variations in output. As more emphasis is placed on fighting inflation, the response of output gets progressively worse, even though the objective of obtaining smoother, less volatile response in inflation is achieved. The maximum drop in output goes from around -0.7% with an interest rate-peg regime (nominal interest rate is fixed at steady state value) to -1.1% with a maximum response on inflation. The aggravation of this regime is therefore very large, almost a 60% larger drop in output for a 10% increase in energy price. As more weight is put on output, the drop in output gets smaller, while inflation gets higher. However, at the higher value of output coefficients (0.3), as the inflation coefficient gets higher, inflation response does get smoother as well; the interest rate path also displays considerably less fluctuation. A larger weight on inflation helps manage expectations of inflation, and so keeps interest rate from changing too rapidly from one period to the next. Responding to output alone however doesn't seem to be effective either, by comparing the outer edge of each output surface plot (where inflation coefficient = 0). As the rule gets more aggressive at fighting output fluctuations, with no or little regard to inflation, it actually causes larger contraction and more volatile response in output.

The best response in terms of output is achieved when the monetary rule is aggressive at both responding to output fluctuations and managing inflation expectations. That happens when the weight on output is maximum at 0.3 and the weight on inflation is quite high at around 0.3 as well. The path of nominal interest rate shows that the monetary authority is required to bring it down gradually and keep it steady before slowly raising it back to steady state. Inflation is initially accommodated and is the highest at more than 0.15% at this point. The response of household's consumption and investments follows closely that of output; smaller drops in output lead to smaller drops in these variables as well. Figures 4.7 and 4.8 display the variances of output and inflation achieved under different monetary responses. With a strong focus in inflation, we achieve less volatility in inflation but have to trade that off with higher volatility in output. A policy that is aggressive in fighting with both inflation and output fluctuations seems to give us the best trade-off between the volatilities of the two variables. The path of the interest rate realized from this policy indicates an overall output stabilization stance. This means stimulating output by reducing the nominal interest rate. The harm to output and consumption is greatest when the nominal interest rate responds to the shock with an immediate jump, meaning the monetary policy following a strict price stability mandate. The drops in output and consumptions are also large when the nominal interest rate drops immediately after the shock, as in following strict output stabilization mandate. The best policy, therefore, occurs when the interest rate is adjusted gradually, making an initial accommodation for inflation, then as energy price starts its downward path the interest rate slowly drops to stimulate output. As energy price drops further and the pressure on inflation gets greater, the interest rate slowly tightens up again to reach back the steady state eventually.

The responses of the economy to this wide range of monetary regimes are understood by looking at the source of the energy price shocks. When energy price jumps due to a real decline in energy supply, the real price of energy relative to durables and non-durables surges, and real marginal costs of capital of the producers are pushed up. Aggregate supply shrinks as a consequence. The presence of nominal price rigidities means that the non-energy producers are even more sluggish to adjust their prices to keep up with the energy price increase, making the increase in real marginal costs worse than in the case of full price flexibility. Since the household is also affected by the negative income effect due to higher energy price, aggregate demand also shifts leftward. Thus this energy price hike is a result of both demand and supply shrinking. A strict price stability regime is forced to raise interest rate right after the shock hits. And yet, because a large part of this upward pressure on the marginal costs is due to the surge in the real price of energy, a desirable reduction in real marginal costs can only come about by engineering a real reduction in energy price relative to the other prices. This course of action turns out to be too broad and too aggressive. It tries to engender a reduction in the relative price of energy indirectly through deflating the non-energy goods by contracting aggregate demand to raise the producers' marginal products of capital and labor. But its effect on real energy price relative to the broad impact it has on aggregate demand (and output) is too small compared to what is needed for this scenario to be successful. So what happens instead is only slightly lower real price of energy, traded off with a large additional depression of output.

The answer is to push up aggregate demand already depressed by higher energy price. In doing so the producers are forced to operate at an even higher level of marginal costs, and inflation is pushed up further. But as demand is forced to shift back to the right, the drop in output and consumption is lessened. The trade-off between the impact on output and the impact on real energy price is precisely the opposite of a restrictive monetary stance. The real price of energy rises slightly higher, but the benefit on output and consumption outweighs that. Additionally, lower nominal interest rates stimulates investment in capital, allowing the economy to maintain a higher stock of capital that is beneficial over the longer run. Paying sole intention to variations in output, however, results in too large an immediate drop in interest rate, causing an excessive stimulus to aggregate demand. This may result in a smaller initial drop in output, but since the nominal interest rate is dropped too low too quickly, this causes an excessive building up of capital that pushes down the real return to capital. In the subsequent periods this sees the household's income squeezed further by the already low return on government bonds and the collapsing return on capital. The result is a further fall in output and consumption as aggregate demand shifts to the left even more. With a sole, strong focus on output, the monetary policy is forced to bring down the nominal interest rate further, aggravating the contraction in output and consumption. The inefficiency of boosting up output too much thus shows itself a few quarters later after the shock. The prerogative therefore is a balance between the initial impact and the subsequent influence on aggregate demand of the inter-temporal effects of changing interest rate.

Our results deviate from those of Leduc and Sill (2004), even though we both assess the performances of systematic monetary policy from the view of its impact on output. Leduc and Sill (2004) called for price stability as the weapon of choice against such shocks. They showed showed that increasing weights on output always amplifies the negative impact of the shock on output while increasing weights on inflation always does the opposite, regardless of the weight on the other coefficient. Our framework on the contrary shows that increasing weights on inflation does not lead to lower output contraction at every level of output weight, only in cases where the weight on output is sufficiently high, and that increasing weights on output does not always lead to more severe contraction in output at every value of the inflation coefficient. For us, consequentially, a hawkish stance on inflation should not be without strong focus on output. This main distinction between our findings and those of Leduc and Sill (2004) stems from the exogenous nature of oil price in their framework. An oil price increase in such a nominal environment does not necessarily reflect a real disturbance coming from a shrink in the oil supply. As Nakov and Pescatori (2010) stated, such shock is observationally equivalent to a negative TFP shock, and a ‘divine’ coincidence occurs for the monetary authority when it tries to stabilize prices.

Our findings are more in line with Bodenstein et al (2008), which found that an aggressive inflation-targeting regime is not helpful in terms of welfare and that a balanced, ’dual-mandate’ regime performs well relative to the optimal policy. Our results, like theirs, lean towards output stabilization. However, our findings do not advocate moving away from a balanced approach towards too much output stabilization. As explained above, this leads to excessive stimulus and amplifies the subsequent responses of most of the macro variables. Indeed the variation in the response of the business cycles can be quite considerable when we move across different weights on output stabilization. Nakov and Pescatori (2010), though also using welfare as the criterion for evaluation of alternative monetary regimes, did not come to similar conclusions to Bodenstein et all (2008). They did stress that a strict price stability regime deviates from an optimal policy, but did not go as far towards output stabilization. Their distinction with our results also rests on several points about the relative merits of alternative policies. In Nakov and Pescatori (2010) a baseline Taylor rule performs worse than a more aggressive inflation-fighting policy or a strict inflation targeting policy. They also found that an interest rate peg regime is the worse of the lot, not just in terms of welfare but also in terms of inflation and output contraction and volatility. Our analyses in terms of drops in output, consumption and welfare simply say the opposite on both of these points. Furthermore according to their results the best policy in the class of Taylor rules using observed instruments is one that responds positively to oil prices. However, that would mean raising interest rate as if fighting inflation, a stance that our results do not advocate.

With regard to Kormilitsina (2011), our results agree only in the response of inflation, that it should be let to rise. However the reasons behind this are very different between our results and those of Kormilitsina (2011). In her framework, the nominal interest rate has to rise to accommodate a rise in the real interest rate, considered optimal in the point of view of the Ramsey planner. For us, high inflation is achieved because of a lowering of interest rate by the monetary authority, to accommodate inflation and boost output. This difference is traced back to the response of real interest rate to energy price increase. In the RBC version of her model, the real interest rate rises, but the results from our RBC version (where the return rate of capital represents the real interest rate) indicate that it must drop due to the downward pressure of high energy price on the marginal cost of capital. Therefore, in our New Keynesian framework, it is in fact more desirable for the real return rate of capital to drop as well. Furthermore, Kormilitsina (2011)'s prescription of higher nominal interest rate leaves it without much detail on the more precise nature of a desirable simple targeting or Taylor-based rule. Our results thus go further by indicating a primary focus on output, initial inflation accommodation and a balanced attention on inflation.

4.4.2 TPF shock to non-energy producers

The picture is different for the case of positive productivity shock to the non-energy sectors. A supply shock in this manner could cause energy price to increase even though it would lead to a drop in non-energy prices and the general price level. This reflects a broad, indirect demand shock to the energy market as the household consumes and invests more in durables and the producers uses more capital in production. Figures 4.9 to 4.14 display the surface plots of output, inflation and nominal interest rate for two weights of output (0 and 0.3) as the weight of inflation goes from 0 to 0.4. For this shock, aggressively responding to inflation/deflation seems to be the most effective way to accommodate the expanding business cycles, in ensuring highest rise in output and consumption. As more weight is put on output, output expansion is curbed right after the shock and rises to a lower peak. Also, in this scenario, an interest rate-peg regime does just as well as a regime designed to respond aggressively to both inflation and output. Again, responding solely to output results in higher volatility in output, inflation and interest rate.

The main distinction from the case of energy supply shock comes from the comovements between output and energy price and between inflation and energy price. The economy benefits from a rightward shift in aggregate supply. Therefore an effective way to respond is to slowly bring aggregate demand up to catch up. An inflation-focused monetary objective in this case serves that purpose. This causes energy price to rise higher. But since an expansionary monetary stance engineers a reverse co-movement between inflation and the real price of energy, what we end up with as we fight deflation more aggressively is a smaller degree of deflation to accompany a slightly higher nominal energy price. The negative effects of a real energy price increase are therefore not much greater. Focusing only on output means a rise in interest rate to put a brake on the expansion. It has the immediate effect of dampening consumption and investment. This is shown in the deeper drops in real marginal costs, as the producers have to balance increased productivity with a slower-growing demand. But this also means that the household is transferring its current consumption to the future as the household seeks to transfer their consumption to bonds. This comes at a time when higher productivity is putting pressure on output, and consequently household's income, to grow. This pressure is instead transferred into excess bond holdings. After the inter-temporal effects of increasing interest rate have been in play for a few quarters, they start to bring higher income to the household. So as the momentum of a supply increase slows down, demand starts its own upward momentum. We can see that at higher weights on output, deflation is reversed into inflation near the

4th quarter mark. However, the effects of higher interest rate also include lower investment in capital. This means that in the initial period of the supply expansion, capital build-up is slower; a smaller proportion of the expanding output is transferred into capital for future production. Figure 4.15 makes this clear, as it compares the capital stock between a strong price stability regime and a strong output stabilization regime. As a consequence, even though output continues to rise until after the 5th quarter, its peak is of a smaller magnitude compared to when the focus is put instead on inflation. Thus, higher weights on output cause larger dampening of demand at the start but greater demand momentum later that result in high volatility in output and inflation, but they also mean that a chunk of potential output growth is taken away because of an inefficient build-up of capital. The response of consumption very much follows the behavior of output. Responding strongly to inflation and output at the same time is better than a sole focus on output in the sense that the response of the economy is less volatile, but output growth is also curbed, because interest rate rises back up too quickly with the monetary authority overly concerned with stabilizing output.

A prescription for the monetary policy thus calls for a strong take on inflation. This has the immediate effect of releasing most of the deflationary pressure as it allows demand to shift quickly to meet the increase in supply. What we have consequentially is smoother responses for all the macro variables. Output rises fully to its maximum and declines as the productivity shock wears off. Interest rate is kept slightly lower than steady state for a long period to sustain the productivity increase, and prices are thus allowed to slowly decline over the period of higher productivity.

The results of 4.4.1 and 4.4.2 can be distilled further into the observation that in both cases, there is no question of responding positively to energy price increase in terms of monetary policy, whether energy price is a good indicator for inflation or output in each case. They also highlight the crucial consideration that is a common theme in dealing with instances of energy price shocks: the trade-off between engineering a reduction in the relative price of energy and minimizing the impact on output and consumption. Viewed in another way, it also means a balance between the immediate effect on aggregate demand of a monetary response and its longer-term, inter-temporal impact, especially on capital. Though the main guiding principles are the same, each shock merits a clear, thorough look at its nature, and each instance of energy price increase needs to be looked at for its underlying cause, so as to arrive at the right trade-off point.

4.4.3 Energy-market Specific Demand Shocks

The endogenous energy production and convex costs allow us to analyze the impact of demand shocks to the energy market on the economy, as they create a mechanism for large energy price responses and much less responsive energy supply, a stylized fact about energy observed in data. The two energy-market specific demand shocks analyzed here are: a shock to the household's energy intensity of durables, represented by the parameter a, and a shock to the producers' energy intensity of capital, represented by the parameter b. Any increase in the value of either of these two parameters means in surge in demand for energy for a given stock of durables or capital, but one comes from the household's side while the other comes from the production side.

Figures 4.16 to 4.19 display the surface plots of output in response to the two shocks for two weights of output (0 and 0.3) as the weight of inflation goes from 0 to 0.4. Qualitatively these two shocks call for similar policy response to the case of energy supply shock. Even though they are technically demand shocks, their overall effect on aggregate demand is actually contractionary due to the large negative income effect that higher energy prices have on durables and non-durables consumption (supply shifts to the left as always due to energy being an input into production). So with both demand and supply contracting the situation is similar to the case of an energy supply shock. Energy price and output again have a negative relationship, and real energy price and inflation move together. In such cases, the call again is for a strong focus on output to stimulate demand, to let inflation rise at the start, while at the same time having a tight rein on inflation to avoid excess stimulation and high volatility in the responses of the aggregates.

What distinguishes these two shocks from the usual case of energy supply crunch is the greater elasticity (in magnitude) of output (value added) to energy price. The relative extent of the impact of energy price increase on demand and supply varies strongly between these two shocks. It is thus expected that, quantitatively at least, there would be varying degrees in the influence of monetary policy on the business cycles in response to these shocks, especially from the demand side. The surface plots of output show clearly that within the same range of values for the weights on output and inflation, the monetary policy response does not bring the same benefits (or cause the same extent of damage) to output (and also consumption) in these two shocks. The negative effect of focusing solely on price stability is worse for the case of an increase in a. Inflation caused by an interest rate-peg regime in the case of the shock to a is lower, but ironically the effectiveness of a strong inflation-fighting regime is also lower. The fact that a strong inflation-focus monetary objective causes output to drop relatively more but inflation to drop relatively less in the case of an increase in a tells us that aggregate output is more adversely affected by this high interest rate regime when it is used in response to the energy demand shock coming from the household. The rationale is as follows. For both shocks, inflation occurs when both supply and demand have shrunk, the inflationary cost-push effect overcoming the deflationary income effect. But since the demand shock coming from the increase in household's energy intensity of durables has a disproportionately larger impact on aggregate demand, this means the increase in a has already shifted aggregate demand by a relatively larger extent than the increase in b. This is evidenced by the greater elasticities (in magnitude) of durables investment and overall consumption to energy price in the case of the shock to a. A strong inflation-fighting monetary response would shift demand further to the left. But in the case of demand shock coming from a, the household's consumption has moved to a point of very high marginal cost for any further marginal reduction in durables investment, and so the substitution effect ensures that the household doesn't reduce its durables stock much further when the nominal interest rate gets higher, but turns to cutting more of its capital stock. This would mean that there is immediately a disproportionately tighter squeeze on capital for production in this case compared to the shock to b. The consequence is that, for the case when the demand shock to the energy market comes from the household, supply is adversely impacted by a larger extent, causing a stronger inflationary pressure on prices, and so a strong inflation-fighting monetary response is comparatively less successful at bring down inflation.

It is of no surprise too then that the benefit of aggressively fighting both inflation and output is smaller for the demand shock coming from a. As Figures 4.20 and 4.21 show, at maximum values for both inflation and output coefficients, the aggressive dual-mandate monetary regime achieves a 16.7% reduction in initial drop of output for the case of increase in a vs. a 40% reduction for the case of increase in b, relative to an interest rate-peg regime. The improvement in terms of maximum output contraction is better for the case of b as well, in percentage terms. A similarly aggressive regime also delivers better improvement in both of these measures for the case of energy supply shock. The reason is the presence of an amplification mechanism from the demand side for the case of energy demand shock through a. When the household's durable stock is more energy-intensive, the impact of the demand shock goes beyond energy price itself, as the increased cost of durables investment and utilization is reflected by more than just energy price. The elasticities of household's consumption and investment (with the exception of capital investment) to energy price in this case are greater in magnitude than both the cases of energy supply shock and demand shock through b. This greater pressure on durables consumption causes the expansionary monetary regime to be less effective at bringing up demand to minimize the contraction in output. The demand shock coming from higher energy-intensity of capital on the other hand causes a much greater elasticity (in magnitude) of capital investment to energy price, since the increase in energy cost for producers is by more than just the energy price increase. The shock thus has a disproportionately greater impact on the supply side of the economy. A strong inflation-regime triggers the substitution effect from the household in precisely the opposite direction between capital and durables investments. An output-stabilization regime is therefore able to stimulate demand to a greater extent, since the amplification mechanism of higher energy demand from the household is absent.

The two demand shocks to the energy market show important quantitative differences in their impact on the business cycles as well as in their interactions with monetary responses. These distinctions come from the different degrees of impact on the demand and supply sides of the economy and the diverse relocations of resources in accordance with the sources of the shocks. The effectiveness of monetary intervention definitely varies between the two shocks, and the need here is to be mindful of this fact so as to not go too little or too far in devising the appropriate responses.

4.5 The role of Sectoral Price Rigidities

In the baseline calibration of the model, both sectors have the same degree of price rigidity. Given the different degrees of energy dependency between the consumption of durables and non-durables, it is natural to pose the question as to whether there is a difference in the sensitivity of the business cycles to each of these price rigidities in events of energy price shocks. For analysis we ran the model along a two-dimensional grid containing values of price rigidities of the durables and non-durables sector. Throughout this exercise the monetary policy function is kept at the baseline Taylor-type specification. Figures 4.22 and 4.24 display the output responses to the energy supply shock and the TFP shock to the non-energy producers at three degrees of non-durables price rigidity relative to durables: more flexible ($\vartheta_n = 1$), as sticky ($\vartheta_n = 46$), and more sticky ($\vartheta_n = 86$), while Figures 4.23 to 4.25 show the output responses to these two shocks at three degrees of durables price rigidity relative to non-durables: more flexible ($\vartheta_d = 1$), as sticky ($\vartheta_d = 46$), and more sticky ($\vartheta_d = 86$).

From the graphs it is clear that the price rigidity of the durables sector plays a greater role in determining the responses of the economy. Output (value added) has a higher sensitivity to variation in this price rigidity. The main reason is again that in energy price shocks, especially the adverse ones, the durables sector's response is always more volatile due to the bigger impact of the shocks on its demand. The nondurables become like a kind of 'anchor' goods in these adverse times, and so its consumption shows a lot lower sensitivity than durables (and capital) consumption to energy price. Another reason is that the behavior of the non-durables sector shows higher sensitivity to variations in the durables' price rigidity than vice versa. Thus, as non-durables prices get more flexible, the contraction in nondurables output gets more severe. But this contraction is already of quite small a magnitude, in the order of 0.3 to 0.4% for a 10% increase in energy price. At the same time, the fall in durables output is in fact smaller, but this change is negligible. The result is that the variation in the response of value added is very small. Conversely, as durables prices get more flexible, the contraction in durables output gets worse, and the variation can be up to the order of 1%. Non-durables output displays noticeable sensitivity too. Its output drop lessens at more flexible durables prices, but this is of a small magnitude and does little to alleviate the considerable worsening in durables output contraction. As a consequence, value added displays noticeably higher variation within the same range of durables price rigidity.

This asymmetry in how price rigidity in one sector affects consumption/output of the other sector's goods is a direct consequence of the different degrees of energy-dependency among these goods. As energy price gets higher, it triggers a substitution effect that moves the household from more energy-dependent goods towards less energy-dependent goods, balanced of course by the income effect. Consumption of durables moves much more strongly than the consumption of non-durables. So upon the impact of energy price shocks, the household moves to a point of consumption where the marginal utility of durables consumption is already a lot higher than that of non-durables consumption. When prices of more energy-dependent goods are more flexible, meaning the initial surge in their prices is higher, this reinforces the move towards less energy-consuming goods, but this also requires the household to acquire a relatively large quantity of non-durables for a small marginal reduction in durables consumption. Non-durables consumption is therefore highly sensitive to the price stickiness of durables. And conversely, when prices of non-durables are more flexible, the move back towards durables consumption simply doesn't happen with the same magnitude, because the household is willing to give up a large margin of non-durables for a relatively smaller marginal gain in durables consumption. Hence durables consumption and output simply do not exhibit the same sensitivity to nondurables' price rigidity.

4.6 Conclusion

This Chapter employs a New Keynesian model with endogenous energy production to extend the analysis on the role of monetary policies in the event of shocks to the energy market. The framework makes use of convex costs in energy production to create dynamics of energy supply and energy price that come close to empirical observations. This convex cost feature and the presence of multiple sectors represent a marked departure from previous theoretical works on the subject.

Our findings show a number of distinctions and also come to some agreements with results from previous works on the case of energy supply shock. We lean towards output stabilization, as did Bodenstein et al (2008), with an appropriate degree of price stability to avoid excessive volatility in output and prices. Our results run counter to Leduc and Sill (2004), and Nakov and Pescatori (2010), who found strong inflation fighting regimes more desirable. With Kormilitsina (2011), we are in the agreement that inflation should be accommodated, but as her conclusion left it quite inconclusive on the degree of output stimulation to pursue, our results went further in prescribing the policy that should accompany this inflation-accommodation stance.

We also shed light on the impact of alternative monetary regimes in the events of other kinds of energy price shocks, such as a TFP shock and demand shocks specific to the energy markets. A more aggregate shock to the energy market such as the TFP shock requires a wholly distinct policy reaction. In this case, it favors price stability. The two energy market specific demand shocks need policy intervention that is qualitatively similar to the case of energy supply shock, but they do highlight important quantitative differences that cause the impact/effectiveness of various monetary regimes to vary between them. In none of these shocks however does a desirable monetary response entail responding positively to energy price movements, if minimizing the impact of high energy prices on output and consumption is the goal.

The explicit modeling of goods with different degree of energy dependency allowed us to gain important insights into the inter-sectoral dynamics. When the shock is more confined to the energy market, the surge in the relative price of energy to the other goods can be very large, and the energy price shock hits the energy-dependent goods and the non-energy-dependent goods quite differently. The durables sector suffers comparatively more on its demand side than the non-durables sector, which is affected primarily through its supply side. Our analysis on sectoral price rigidities indicate that the degree of price stickiness of the more energy-dependent goods plays a greater role at amplifying or dampening the impact of energy price shocks in the presence of monetary response, as the behavior of the less energy-dependent goods sector is more sensitive to this price rigidity than vice versa.

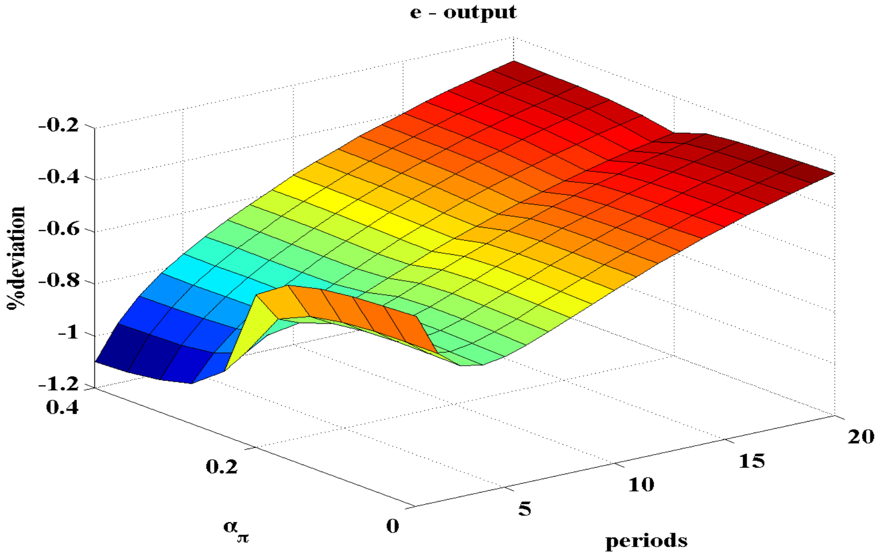

Figure 4.1: response of output to energy supply shock, with output weight at 0 and inflation weight going from 0 to 0.4

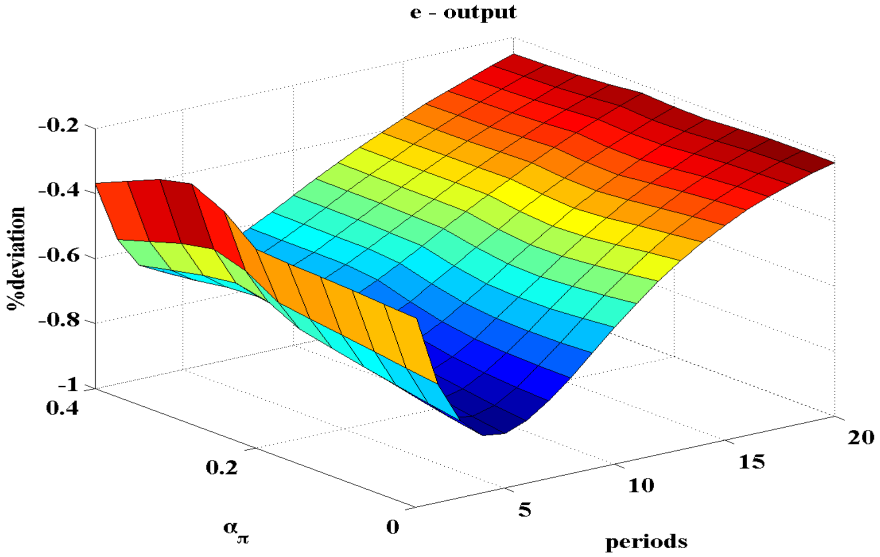

Figure 4.2: response of output to energy supply shock, with output weight at 0.3 and inflation weight going from 0 to 0.4

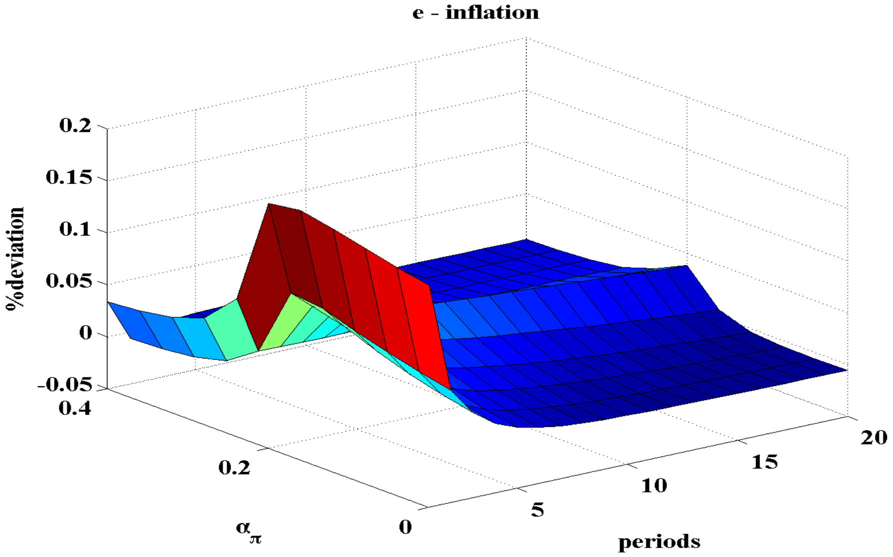

Figure 4.3: response of inflation to energy supply shock, with output weight at 0 and inflation weight going from 0 to 0.4

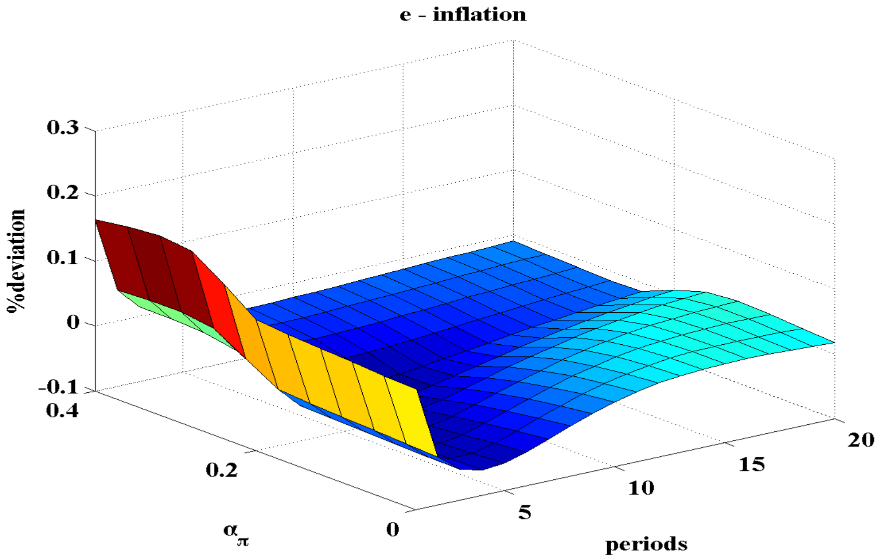

Figure 4.4: response of inflation to energy supply shock, with output weight at 0.3 and inflation weight going from 0 to 0.4

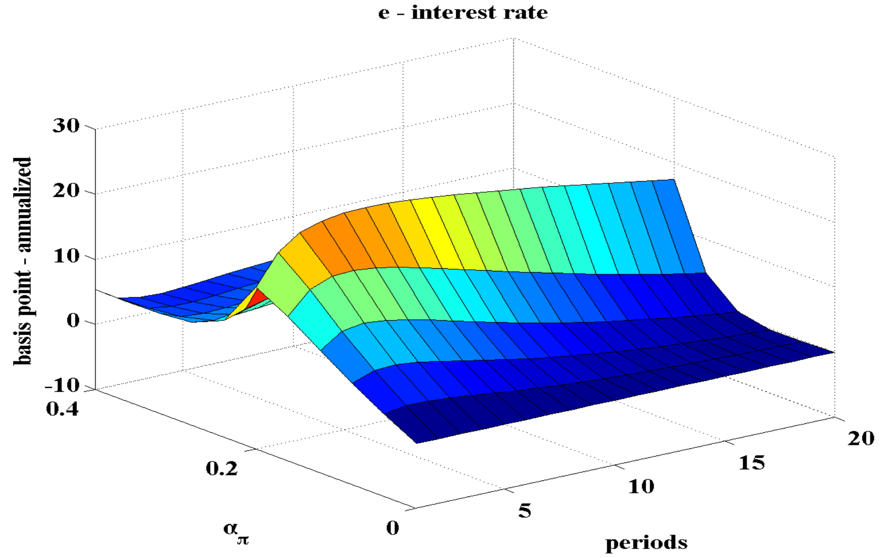

Figure 4.5: response of interest rate to energy supply shock, with output weight at 0 and inflation weight going from 0 to 0.4

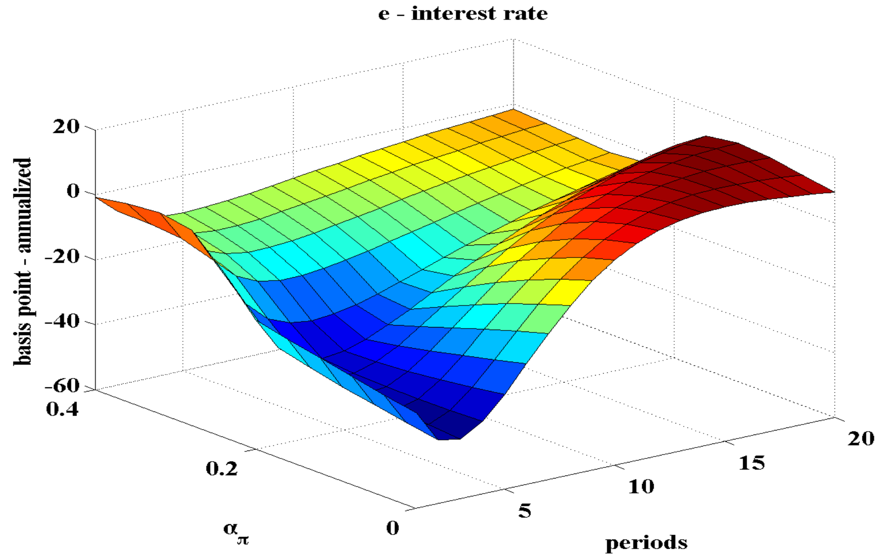

Figure 4.6: response of interest rate to energy supply shock, with output weight at 0.3 and inflation weight going from 0 to 0.4

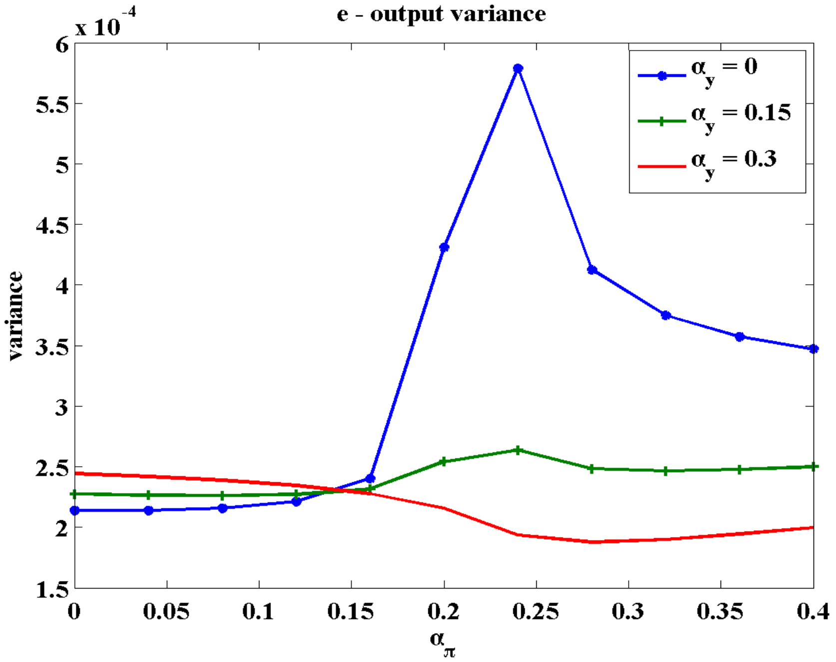

Figure 4.7: variance of output at output weights = 0 (-*-), 0.15 (-+-) and 0.3 (-), with inflation weight going from 0 to 0.4

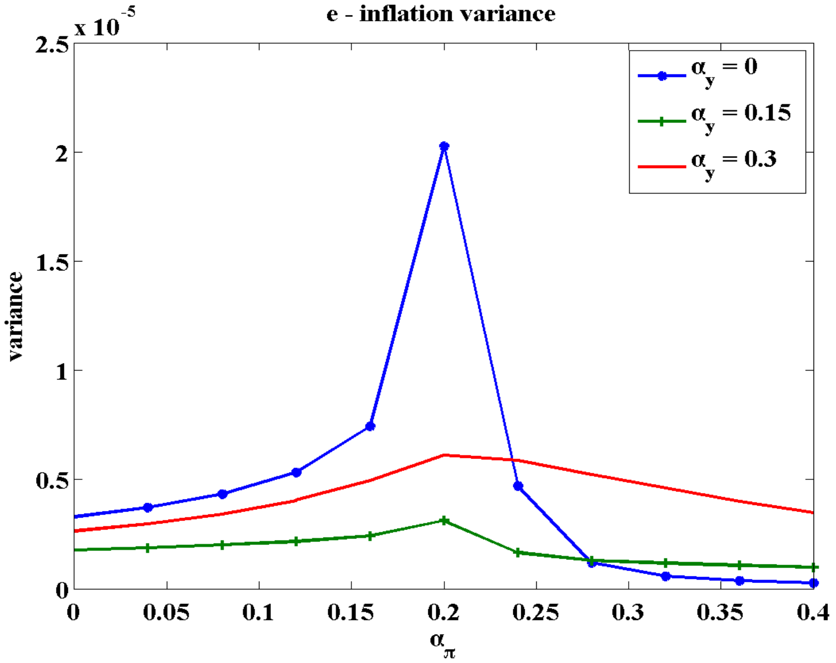

Figure 4.8: variance of inflation at output weights = 0 (-*-), 0.15 (-+-) and 0.3 (-), with inflation weight going from 0 to 0.4

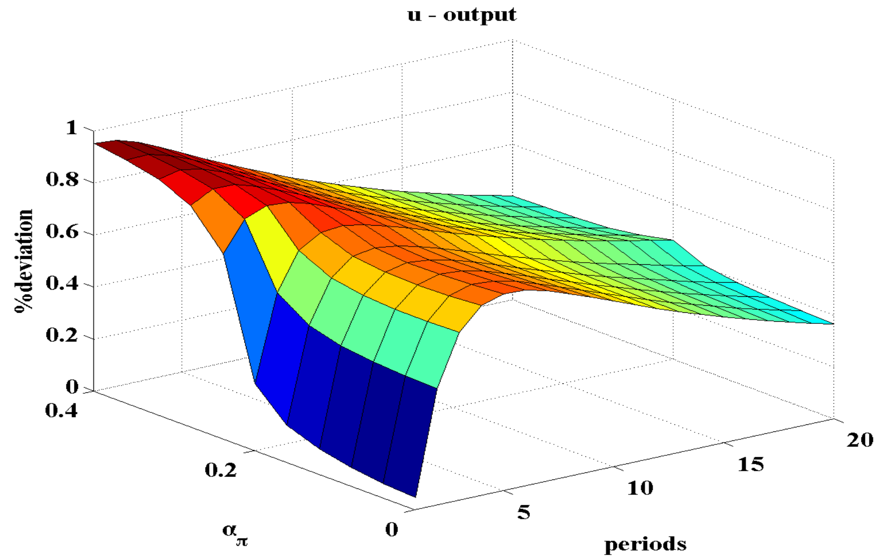

Figure 4.9: response of output to a positive TFP shock to non-energy producers, with output weight at 0 and inflation weight going from 0 to 0.4

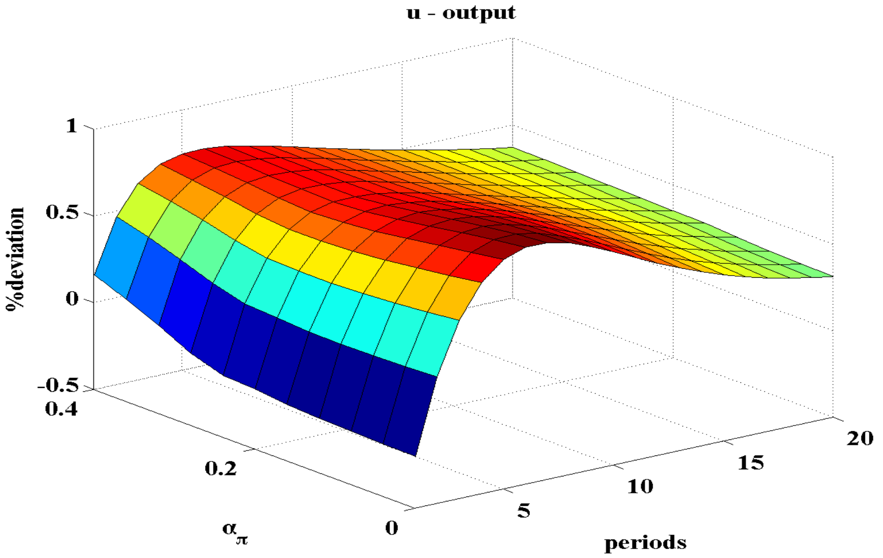

Figure 4.10: response of output to a positive TFP shock to non-energy producers, with output weight at 0.3 and inflation weight going from 0 to 0.4

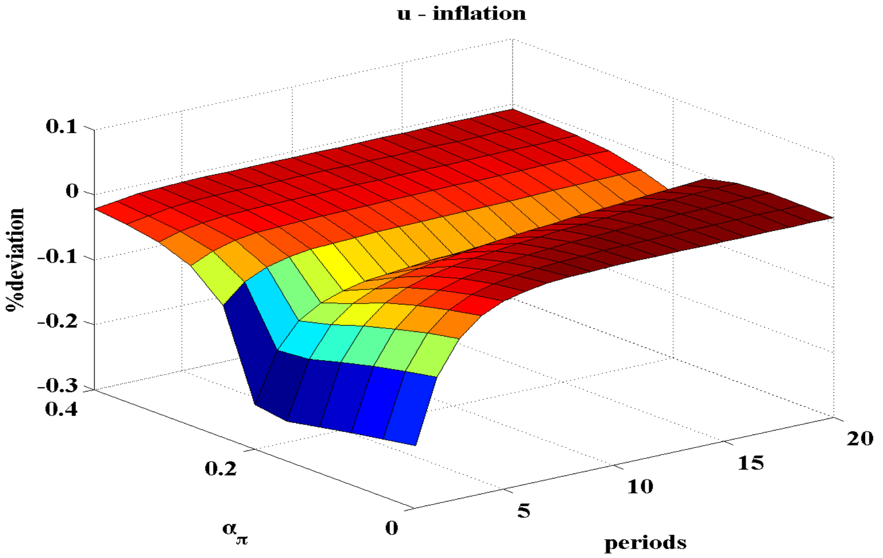

Figure 4.11: response of inflation to a positive TFP shock to non-energy producers, with output weight at 0 and inflation weight going from 0 to 0.4

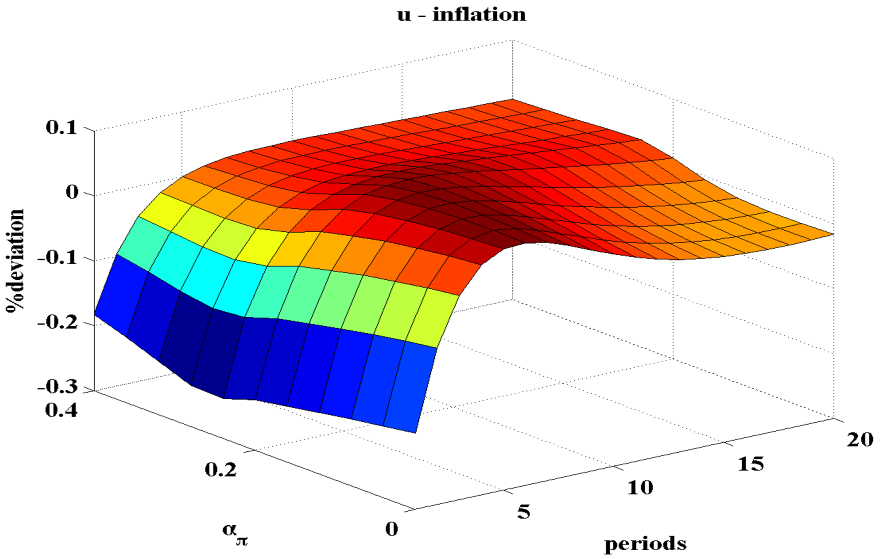

Figure 4.12: response of inflation to a positive TFP shock to non-energy producers, with output weight at 0.3 and inflation weight going from 0 to 0.4

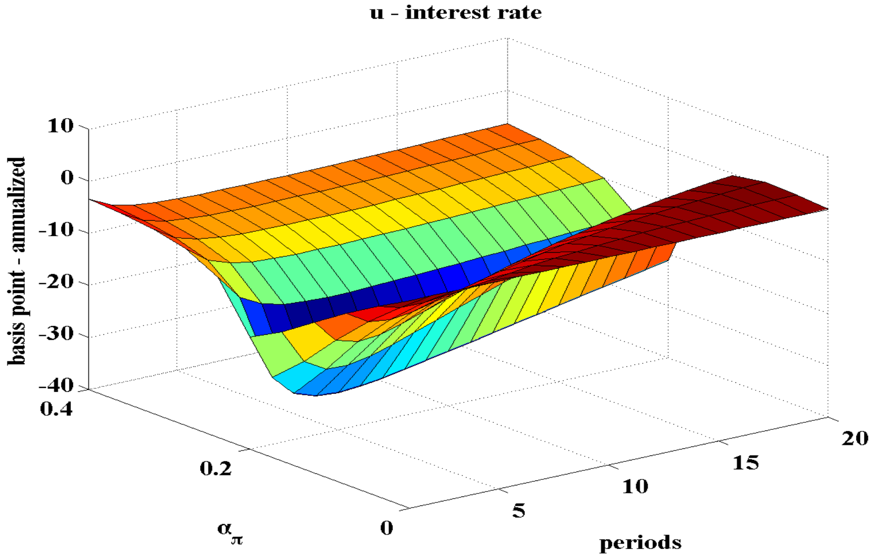

Figure 4.13: response of interest rate to a positive TFP shock to non-energy producers, with output weight at 0 and inflation weight going from 0 to 0.4

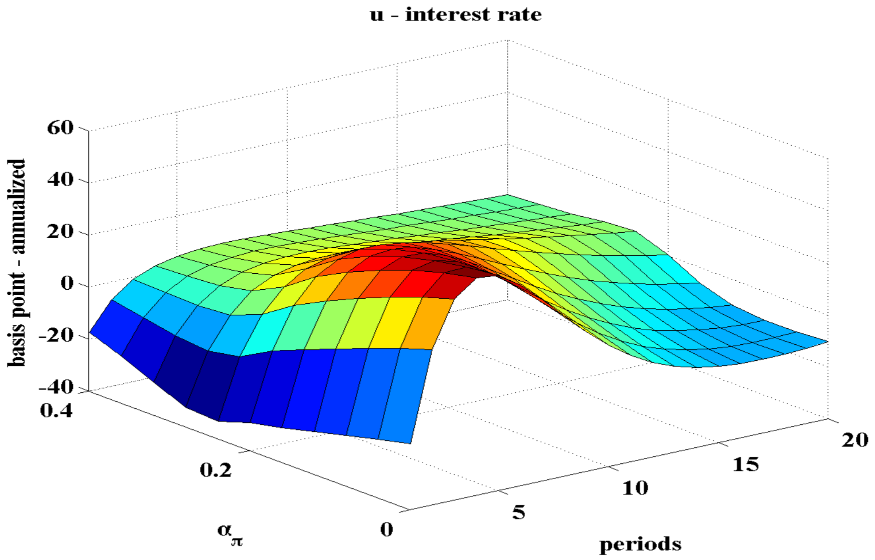

Figure 4.14: response of interest rate to a positive TFP shock to non-energy producers, with output weight at 0.3 and inflation weight going from 0 to 0.4

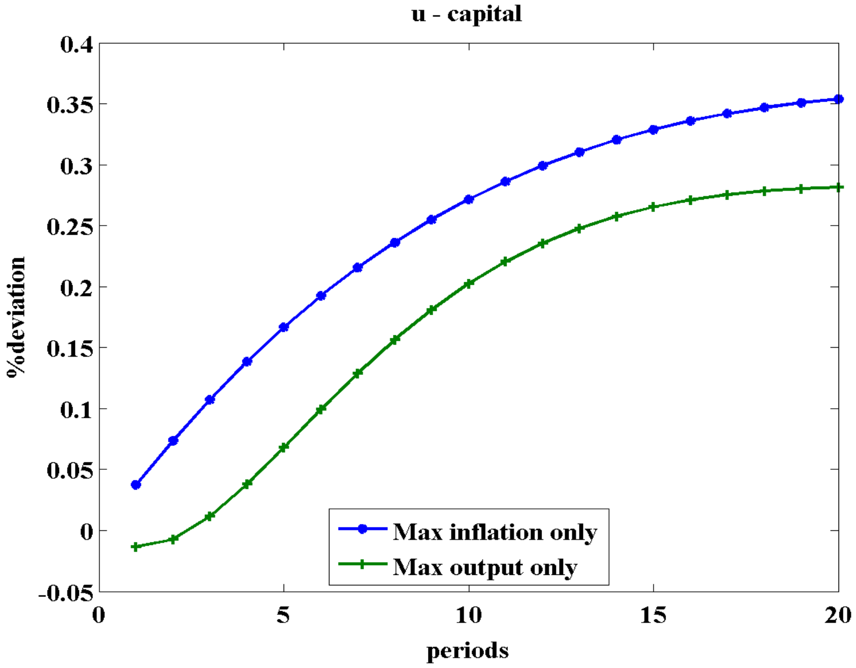

Figure 4.15: response of capital stock to a positive TFP shock to non-energy producers under strong inflation-only focus (-*) and under strong output-only focus (-+-)

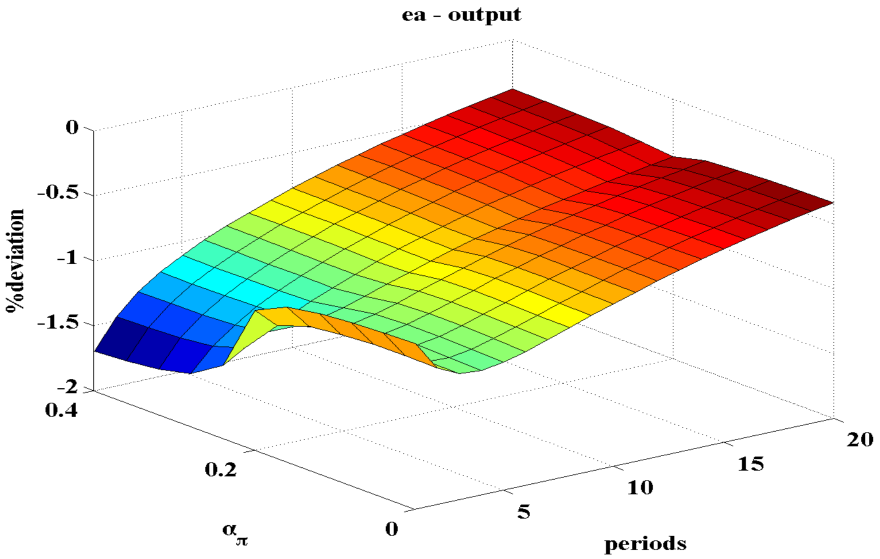

Figure 4.16: response of output to a positive shock to household energy demand, with output weight at 0 and inflation weight going from 0 to 0.4

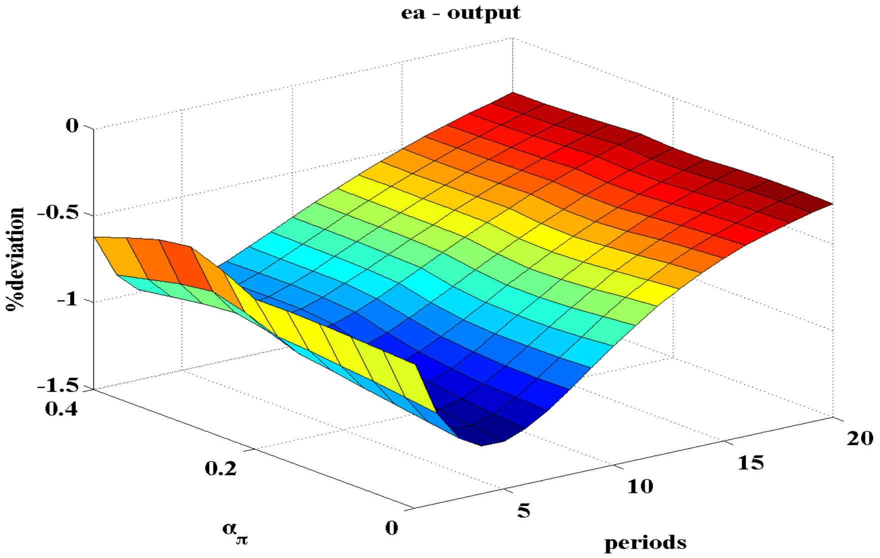

Figure 4.17: response of output to a positive shock to household energy demand, with output weight at 0.3 and inflation weight going from 0 to 0.4

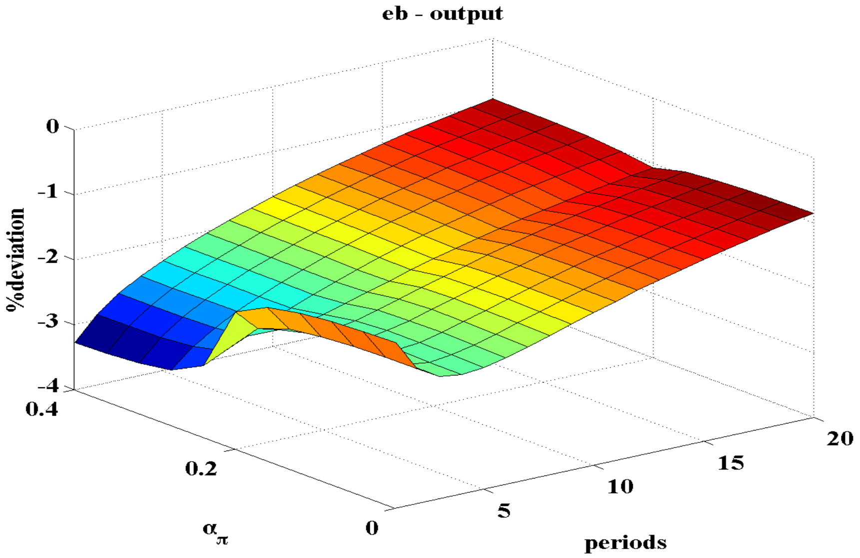

Figure 4.18: response of output to a positive shock to producers' energy demand, with output weight at 0 and inflation weight going from 0 to 0.4

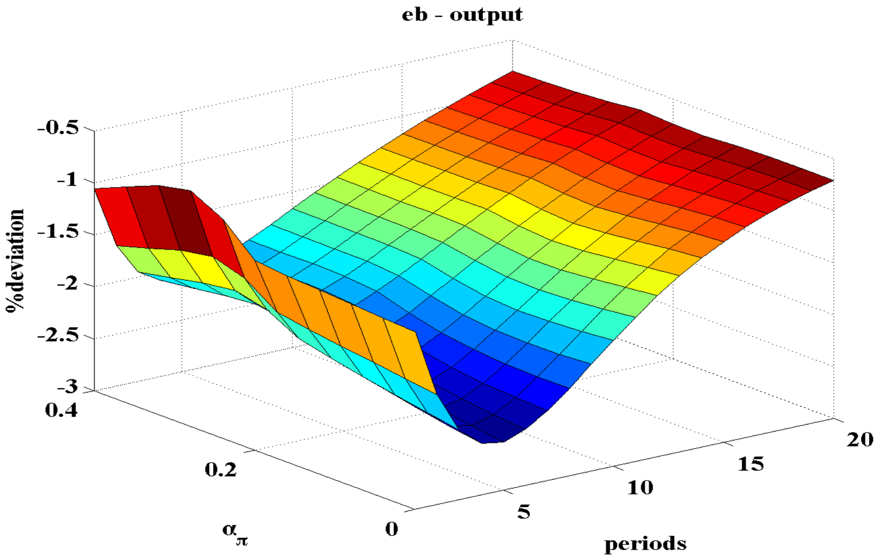

Figure 4.19: response of output to a positive shock to producers' energy demand, with output weight at 0.3 and inflation weight going from 0 to 0.4

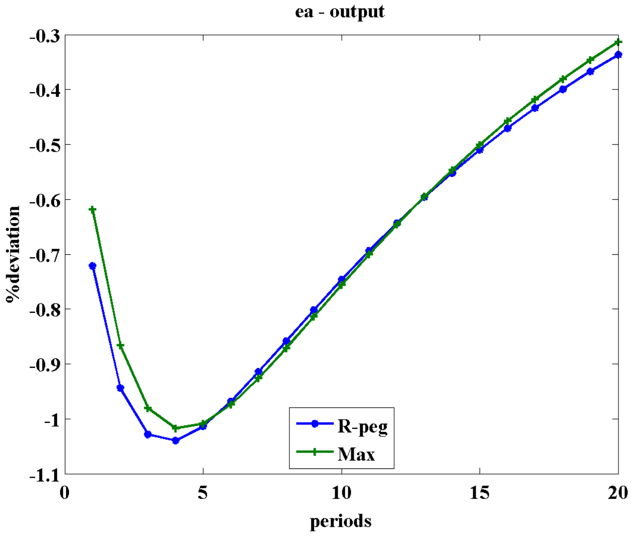

Figure 4.20: response of output to a positive shock to household energy demand under strong dual mandate (-+-) and under the interest rate peg (-*-)

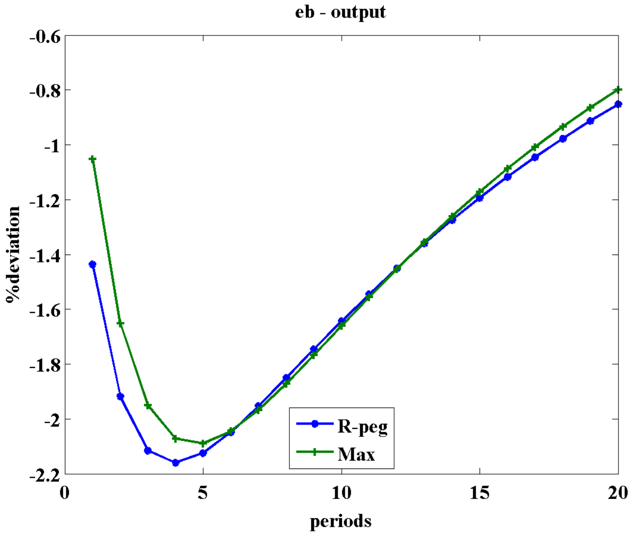

Figure 4.21: response of output to a positive shock to producers' energy demand under strong dual mandate (-+-) and under the interest rate peg (-*-)

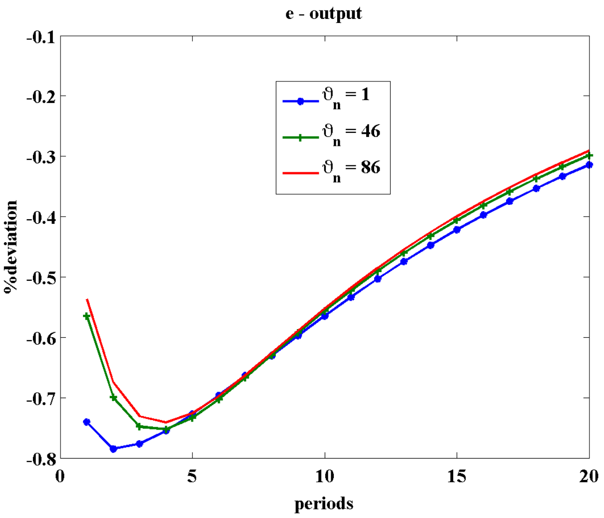

Figure 4.22: response of output to energy supply shock at three degrees of non-durables price rigidity under baseline Taylor rule

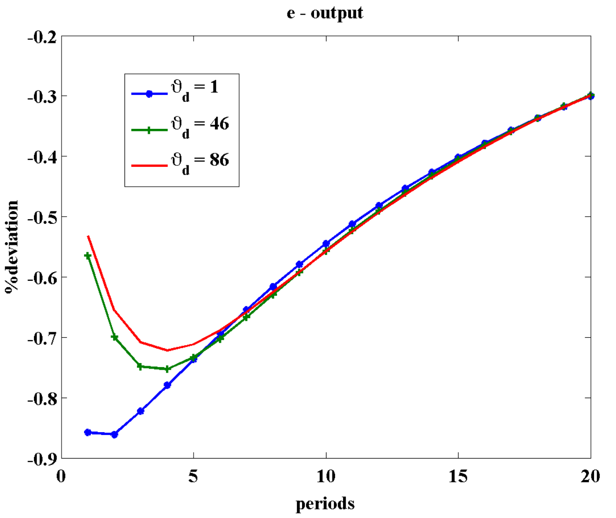

Figure 4.23: response of output to energy supply shock at three deg of durables price rigidity under baseline Taylor rule

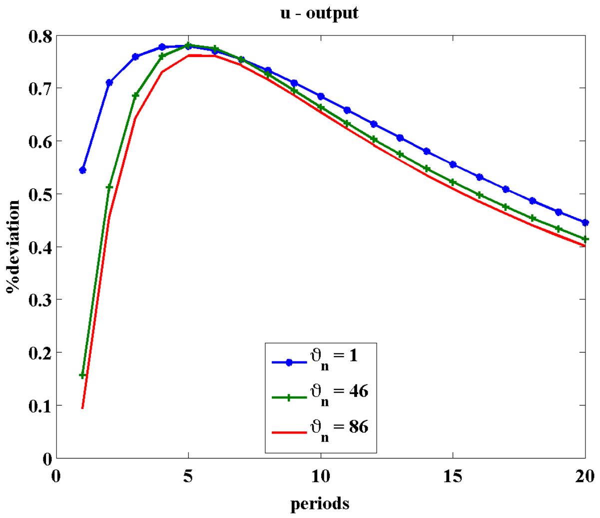

Figure 4.24: response of output to a positive TFP shock to non-energy producers at three degrees of non-durables price rigidity under baseline Taylor rule

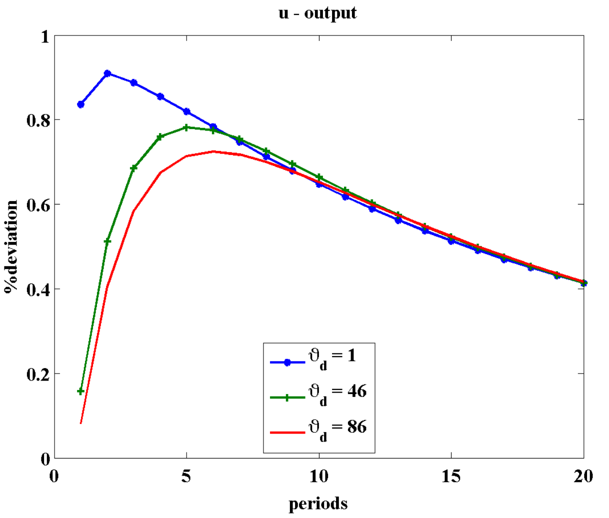

Figure 4.25: response of output to a positive TFP shock to non-ene producers at three degrees of durables price rigidity under baseline Ta rule

5. Conclusion

This dissertation investigates the general equilibrium effects of energy price shocks with different underlying causes using a three-sector model with endogenous energy production. We model durables as energy-intensive goods and non-durables as non-energy-dependent goods, as in Dhawan and Jeske (2008); but we implement a high complementarity between energy and durables/capital and extend the framework by introducing an energy sector. We also incorporate convex costs in energy production to achieve a low price elasticity of energy supply. The calibrated model has business cycle properties that describe reasonably well the macro properties of the U.S. economy. It also produces energy price dynamics that come close to data, as well as energy production dynamics that satisfy the low price elasticity characteristics of actual energy supply.

Chapter 1 demonstrates that energy price increases could have distinguishably diverse effects on the business cycle, and that their underlying causes matter. An energy supply shock sees the model return an energy price-output elasticity of -0.1, lower than that shown in Dhawan and Jeske (2008), which demonstrates the deepened impact of energy supply shock with endogenous energy production. An energy price shock caused by a productivity expansion sees the growth-retarding effects of high energy prices offset by the aggregate effects of the expanding business cycle, bringing this case of energy price increase into stark contrast with the energy supply shock in terms of the overall effects on the economy. The two demand shocks specific to the energy market cause more severe contractions in the business cycle, and leave their own distinctive mark on the economy. The demand shock coming from the household has a disproportionately greater impact on aggregate demand, while the demand shock from the producers very much transforms itself into a supply-side shock. Each shock sees its impact amplified beyond the usual channel of energy price on a different side of the economy. We show how these instances of energy price increase cause various macro variables to display varying energy price elasticities and engender diverse relative price movements, and make the connections between these observable behaviors and the underlying causes of the energy price increases. We also demonstrate clearly the differential effects that energy price increases have on goods with different degrees of energy dependence. For the non-energy-dependent goods sector (non-durables), the impact of energy price increases is mostly on its supply side, and the substitution effect from the household shields it to a certain extent. The energy-dependent goods sector (durables), in contrast, suffers more on its demand side, as the substitution effect works against the consumption of its goods.

Chapter 2 extends the analysis of energy price shocks on external balances to a number of supply and demand shocks to the energy market in a two-country model comprising multiple sectors and endogenous energy production with convex costs. Convex costs of energy production help produce a low energy price elasticity of energy supply, bringing energy price and production dynamics closer to the data. The explicit modeling of durables and non-durables allows insights into the composition of the non-energy trade balance in response to these diverse energy price shocks. Our theoretical investigations show that, in line with Kilian et al. (2009), different shocks to the energy market trigger distinct responses of the external trade balances of the energy importing and energy exporting countries. The response of the non-energy trade balance plays a crucial role in determining the dynamics of the overall trade balance. We distinguish the different sources of the energy price increases by tracing their diverse responses back to the nature of the shocks. We show how the volatile nature of durables trade contributes most to differentiate these responses through the large impact of energy price on durables. Our results reinforce the need to look beyond energy price to the sources of energy price shocks, especially in the formulation of appropriate policy responses.

We also demonstrate and compare the two different ways that the energy importing countries could experience an energy boom and how they both could boost the domestic economy, expanding its output and its durables sector. The two cases demonstrate similar responses from the energy importer (Home). The Home economy receives a boost, especially in the durable sector, while its energy trade balance improves. The overall trade balance, however, moves little due to the deterioration of the non-energy trade balance.

Chapter 3 employs a New Keynesian model with endogenous energy production to extend the analysis on the role of monetary policies in the event of shocks to the energy market. Our findings show a number of distinctions and also come to some agreements with results from previous works on the case of energy supply shock. We lean towards output stabilization, as did Bodenstein et al (2008), with an appropriate degree of price stability to avoid excessive volatility in output and prices. Our results run counter to Leduc and Sill (2004), and Nakov and Pescatori (2010), who found strong inflation fighting regimes more desirable. With Kormilitsina (2011), we are in the agreement that inflation should be accommodated, but as her conclusion left it quite inconclusive on the degree of output stimulation to pursue, our results went further in prescribing the policy that should accompany this inflation-accommodation stance.

We also shed light on the impact of alternative monetary regimes in the events of other kinds of energy price shocks, such as a TFP shock and demand shocks specific to the energy markets. A more aggregate shock to the energy market such as the TFP shock requires a wholly distinct policy reaction. In this case, it favors price stability. The two energy market specific demand shocks need policy intervention that is qualitatively similar to the case of energy supply shock, but they do highlight important quantitative differences that cause the impact/effectiveness of various monetary regimes to vary between them. In none of these shocks however does a desirable monetary response entail responding positively to energy price movements, if minimizing the impact of high energy prices on output and consumption is the goal.

The explicit modeling of goods with different degree of energy dependency allowed us to gain important insights into the inter-sectoral dynamics. When the shock is more confined to the energy market, the surge in the relative price of energy to the other goods can be very large, and the energy price shock hits the energy-dependent goods and the non-energy-dependent goods quite differently. The durables sector suffers comparatively more on its demand side than the non-durables sector, which is affected primarily through its supply side. Our analysis on sectoral price rigidities indicate that the degree of price stickiness of the more energy-dependent goods plays a greater role at amplifying or dampening the impact of energy price shocks in the presence of monetary response, as the behavior of the less energy-dependent goods sector is more sensitive to this price rigidity than vice versa.

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Appendix

A. Cyclical Properties

To facilitate comparisons with data and Dhawan and Jeske (2008), in this section the model was run with just two shocks active: the TFP shock and energy productivity shock.

A.1 Aggregates

Table A.1 compares the percentage standard deviation of the aggregates across US data, out model and the model of Dhawan and Jeske (2008), with the two productivity shocks calibrated as in Section 2.3.

Variables	**Model**	**US data**	**Dhawan and Jeske**
Output	1.54	1.57	1.41
Non-durables	0.90	0.82	0.43
Durables	4.56	4.55	4.55
Fixed Investment	5.35	5.37	5.37
Hours	0.65	1.51	0.72
Household's energy	2.72	2.10	2.10

Table A.1: Each variable's value is calculated as the ratio of its standard deviation to its mean in percentage.

The simulated economy returns a percent standard deviation for output that is in line with that in US data. The value for non-durables also comes close to the empirical value, while that in Dhawan and Jeske (2008) stays quite well below. It is also notable that the percentage standard deviation of hours worked reported in the model is quite below that in the data, though it is close to Dhawan and Jeske (2008). The model also returns household's use of energy that is slightly more volatile. Clearly along the dimension of labor the model falls short of describing the dynamics in the data. A possible source of this low volatility concerns the frictionless movement of labor among the three sectors in the model. By making relocation of labor more difficulty/costly, labor movements might be made more realistic, which might help bring up the volatility of overall labor. Regarding the excess volatility of energy usage, it is connected to the energy price and production dynamics, and thus is dependent on the calibration of the convex costs in energy production. A lower cost schedule, e.g. by reducing the scale parameter of the cost function, brings down energy price volatility and energy use volatility at the same time. The elasticity of energy supply will then also become higher. Clearly there is potential for improvement in this area, as a more precise guidance on the elasticity of energy supply from empirical estimates would help the calibration of the convex cost function achieve a better trade-off point between the volatilities of these energy-related variables.

A.2 Hours-wage correlation

The model does report an hour-wage correlation that is lower than the figure usually obtained in conventional RBC models (Table A.2).

	Model	**US data**	**RBC**
Hours-wage corr	0.51	0	0.8-0.9

Table A.2: Hours-wage Correlation

This lower correlation seems to come from the presence of three different sectors in the model and a separate productivity process for the energy sector. When the model is run with just one productivity process common to all three sectors, with a standard error of 0.007 for the Solow residuals, the model returns a correlation of 0.6015 between hours and wage, a significant improvement in itself. It seems that the presence of three sectors with equalized wage helps bring down this value. This is mostly due to the heterogeneity in the impact of energy price shocks across the three sectors. The energy sector itself has a different relationship with energy price than the other two sectors, while the durables sector is more highly exposed to energy price fluctuations than the non-durables sector due to the energy-dependent nature of its goods. So when there is an energy price shock, its uneven effects on these sectors cause a relocation of labor to occur across them, reducing the co-movement of labor with wage. The addition of a separate productivity process for the energy sector helps to bring the correlation down further, because a productivity shock to the energy sector tends to cause a reversed tendency to the energy sector relative to the other sectors in terms of employment. When the energy sector encounters a productivity shrink, the resultant energy price increase reduces overall employment (with huge decrease in hours worked for the durables sector), but this overall reduction is tempered by the increase in the energy sector's labor.

A.3 Energy price dynamics

The presence of an energy sector means an energy price that is endogenous, and the model produces energy price dynamics that comes quite close to that found in the data. Table A.3 reports the percent standard deviation of energy price, its ratio to the percent standard deviation of output, and energy price-output correlation. For comparison we have the values calculated from Kim and Loungani (1992) in column 3. We can see that the model captures reasonably well the main features of energy price dynamics. From the data it is found that energy price is highly volatile, its percent standard deviation is several times that of output, and that its correlation with output is negative. Kim and Loungani (1992) calculated the ratio of percent standard deviation of energy price to that of output at 6, and their correlation at -0.44 using annual data. This model puts those two values at 7 and -0.43 respectively, calibrated at quarterly frequency.

	Model	**Kim and Loungani (1992)**
Energy Price	10.96	17.76
Energy price-output	7.10	6.02
Energy Price-Output Corr	-0.4278	-0.44

Table A.3: Energy Price Dynamics: row 1 displays the percentage standard deviation of energy price, row 2 shows the ratio of this percentage standard deviation to the percentage standard deviation of output, row 3 displays the correlation between energy price and output.

A.4 Contribution of energy shock

Table A.5 shows the contributions of TFP shock and energy productivity shock to the variability of the aggregates in terms of percentage. In this calibration output is explained by energy productivity shock by a significant percentage. Energy price, predictably, is mostly explained by this shock. As is energy output. A little more than one-third of labor's variability is explained by the energy-related shock. Overall, the decomposition for energy price and hour, and to a certain extent output, matches quite well Blanchard and Gali (2010). Thus an economy with a productivity shock for the energy sector helps explain reasonably well the percentage of the variability in the business cycle that is attributed to energy-related disturbances.

	u_t	e_t
p_e	13.02	86.98
δ_d	22.48	77.52
n	63.77	36.23
i_k	57.69	42.31
i_d	20.42	79.58
h	69.31	30.69
y	54.42	45.58
y_d	33.04	66.96
y_n	63.77	36.23
y_e	29.60	70.40
u	22.48	77.52

Table A.4: Variance decomposition in percentage

B. Dynamics of price responses

We make a comparison here of the dynamics of price increases across the four different shocks analyzed so far. Figures B.1 and B.2 display the responses of energy price and non-durables price respectively. The clearest qualitative difference occurs for the case of productivity boom of 2.4.2 versus the rest of the shocks. The increase in energy price relative to non-durables price increase is the smallest, reflecting the fact that the shock makes its initial impact on a wider part of the economy and not just the energy market. After an initial rise the price of non-durables drops even as energy price continues to rise. Durables become more valuable than non-durables even as the cost of its usage gets higher, as the positive income effect coming the expanding business cycle starts to dominate the negative effects of higher energy price.

Regarding the other three adverse shocks, the extent of non-durables price increase is greater when there is a greater shock to energy price, as it is expected that the energy price increase affects the non-durables sector more on its supply, also that non-durables would become more valuable compared to durables. One key observation is that the increase in non-durables' price has a much higher persistence than the energy price increase as well as the persistence of the underlying shocks. As we have explained before, even though non-durables consumption also drops cross all these shocks, it does benefit from the substitution effect as the household moves away from durables consumption and usage. Non-durables become very much like a kind of 'anchor' goods for the household in these energy price crises. As the non-durables sector sees its output get depressed due to higher energy cost while benefiting at the same time from a sustained demand for its goods due to deep fall in investments in durables and capital in the early quarters after the shock, this combined effect keeps non-durables price higher for much longer than the duration of the shocks. Energy price increase, by contrast, decays quickly as this steep contraction in investments works precisely in the opposite direction on energy demand. These price increase dynamics very much reveal the differential impact of energy price shocks on sectors whose goods differ in their energy dependency. The sustained high price of non-durables points to energy price increases making its main impact on the sector's supply, while the quickly collapsing price of energy indicates a larger impact on the durables sector's demand (since energy demand in our framework can very much be viewed as a proxy for durables and capital demand).

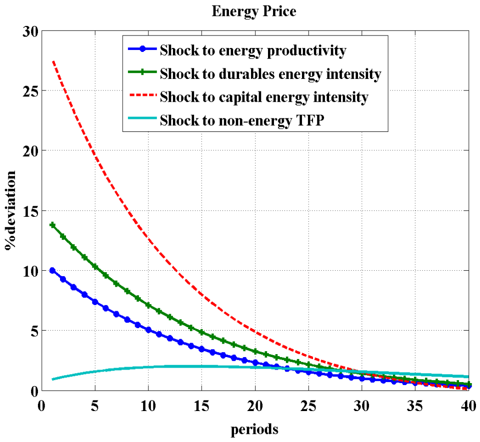

Figure B.1: Response of energy price to energy supply shock (-*-), shocks to energy intensity of durables (-+-) and capital (- -), and positive TFP shock to non-energy producers (–)

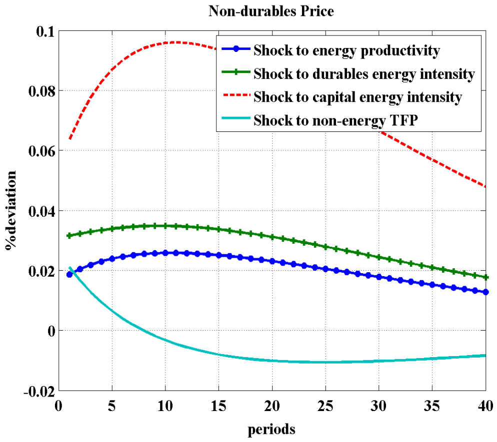

Figure B.2: Response of Non-durables price to energy supply shock (-*-), shocks to energy intensity of durables (-+-) and capital (- -), and positive TFP shock to non-energy producers (–)

C. Sensitivity analysis

To check on the robustness of the model we ran it with a number of different calibrations, employing different values for the elasticity of substitution between durables and non-durables. For the main analyses we already employed a value of 0.9 for the elasticity (translating to $\rho = 0.111$). Here we ran the model with different values of 0.5, 0.7 and 1.2. We found that this is the range in which the model is stable with all other calibrations unchanged. A value lower than 0.5 would necessitate a re-calibration of the capital share parameters of the three production functions. We ran the model through a negative shock to the productivity of the energy sector. Qualitatively the model behaves pretty similarly for these values of elasticity. The differences are quantitative, both in the steady state and the dynamic responses of the model. For illustration we only consider here the responses of the model under energy productivity shock. Concerning the steady state properties of the model, higher values of the elasticity bring about higher steady-state values of output; the output share of the durables sector however declines while those of the non-durables and energy sectors rise. The stock of durables and utilized durables increase substantially with increasing elasticity, while non-durables consumption decreases. Table C.1 gives a summary.

Steady-state	**Elasticity=0.5**	**Elasticity=0.7**	**Elasticity=1.2**
y	1.0082	1.0555	1.2336
y_d	0.7608	0.7267	0.6055
y_n	0.2280	0.2467	0.313
y_e	0.1688	0.1826	0.2319
ud	1.3265	1.7031	3.0393
d	1.5812	2.0301	3.6230
n	0.6528	0.6311	0.5543

Table C.1: Model's steady state properties

The impact of higher values of the elasticity is clearly observed in the following graphs, which show the responses of output (y, Fig. C.1) and utilized durables (ud, Fig. C.2) to a negative shock in energy productivity, corresponding with various values of elasticity. The impact of a shock to energy productivity is more severe the higher the value of elasticity. When it goes from a value of 0.5 to a value of 1.2, the drop in output gets larger from less than 0.5% to more than 1.4%, while the fall in utilized durables goes from 1.5% to more than 2.5%. Clearly, the elasticity of substitution between durables and non-durables plays a crucial role in determining the household's response, thus the economy's, to an adverse shock to energy prices. Higher elasticity makes it easier for household to substitute non-durables for durables, but ironically this leads to sharper contractions in output of the durables sector (and total output) and makes the effects of higher energy prices more pronounced. The impact of increasing elasticity on non-durables consumption reinforces this observation (Fig. C.2). Higher values of elasticity lead to smaller declines in the consumption of non-durables; in fact at the value of 1.2 the non-durables consumption increases upon impact of the shock. This means that the higher the elasticity, the more readily the household moves away from durables usage and consumption and towards non-durables in its portfolio, because it is easier to do so. At a value of 1.2 the household re-balances its portfolio so much that its consumption of non-durables increases despite the adverse conditions.

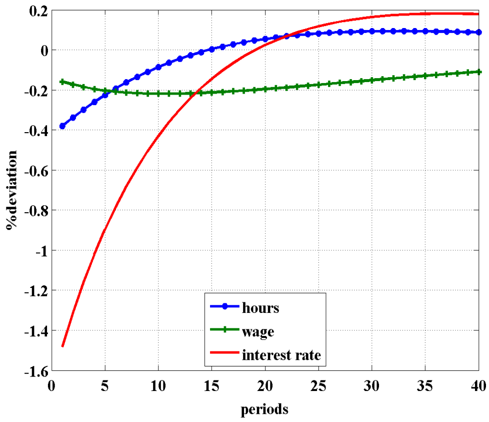

Figure C.1: response of inflation to a positive shock to household energy demand under strong inflation-only focus (-+-) and under the interest rate peg (-*-)

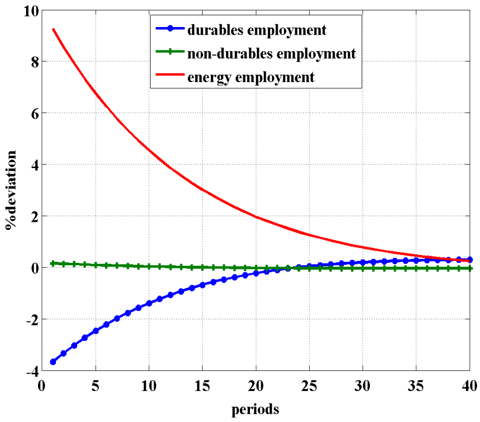

Figure C.2: response of inflation to a positive shock to producers' energy demand under strong inflation-only focus (-+-) and under the interest rate peg (-*-)

D. Equilibrium Conditions for Chapter 2

Household's first order conditions

Euler equation for durables

$$(1-\alpha)^{1-\rho}\tfrac{c_t{}^{-\rho}n_t^{\rho-1}}{p_{n,t}}\left(1+\tfrac{\omega_{d1}}{d_t}\left(\tfrac{d_{t+1}-d_t}{d_t}\right)^{\omega_{d2}}\right)=\beta E\alpha^{1-\rho}c_{t+1}^{-\rho}(u_{t+1}d_{t+1})^{\rho-1}u_{t+1}$$

$$+\beta E\tfrac{(1-\alpha)^{1-\rho}}{p_{n,t+1}}c_{t+1}^{-\rho}n_{t+1}^{\rho-1}[-ap_{e,t+1}u_{t+1}+1-\delta_{d,t+1}+\tfrac{\omega_{d1}d_{t+2}}{d_{t+1}^2}\left(\tfrac{d_{t+2}-d_{t+1}}{d_{t+1}}\right)^{\omega_{d2}}]$$

Euler equation for capital

$$\frac{c_t^{-\rho}n_t^{\rho-1}}{p_{n,t}}\left(1+\frac{\omega_{k1}}{k_t}\left(\frac{k_{t+1}-d_t}{k_t}\right)^{\omega_{k2}}\right)=\beta E\frac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{p_{n,t+1}}[r_{t+1}+1-\delta_k+\frac{\omega_{k1}k_{t+2}}{k_{t+1}^2}\left(\frac{k_{t+2}-k_{t+1}}{k_{t+1}}\right)^{\omega_{k2}}]$$

Intra-temporal non-durables-labor

$$(1-\alpha)^{1-\rho}\frac{\varphi}{1-\varphi}(1-h_t)c_t{}^{-\rho}n_t^{\rho-1}=\frac{p_{n,t}}{w_t}$$

Intra-temporal non-durables-utilization

$$\frac{(1-\alpha)^{1-\rho}}{\alpha^{1-\rho}}\frac{n_t^{\rho-1}}{(u_td_t)^{\rho-1}}=\frac{p_{n,t}}{ap_{e,t}+\delta'_{d,t}}$$

with

$$c_t=[\alpha^{1-\rho}(u_td_t)^{\rho}+(1-\alpha)^{1-\rho}{n_t}^{\rho}]^{1/\rho}$$

Budget constraint

$$p_{e,t}au_td_t+p_{n,t}n_t+i_{d,t}+i_{k,t}=w_th_t+r_tk_t$$

Investment adjustment costs and variable depreciation

$$i_{d,t}=d_{t+1}-(1-\delta_{d,t})d_t+\frac{\omega_{d1}}{1+\omega_{d2}}\left(\frac{d_{t+1}-d_t}{d_t}\right)^{1+\omega_{d2}}$$

$$i_{k,t} = k_{t+1} - (1-\delta_k)k_t + \frac{\omega_{k1}}{1+\omega_{k2}}\left(\frac{k_{t+1}-k_t}{k_t}\right)^{1+\omega_{k2}}$$

$$\delta_{d,t} = \frac{a_1}{a_2+1}{u_t}^{a_2+1}$$

Firms' production functions

$$y_{e,t} = \exp(A_{e,t})(1-\sigma_{e,t})k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e}$$

$$\omega_{e,t} = \frac{\omega_{e1}}{(1+\omega_{e2})}(k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}}$$

$$y_{i,t} = \exp(A_t)\left(k_{i,t}\right)^{\gamma_i}\left(h_{i,t}\right)^{1-\gamma_i}$$

with $i = d, n$

Firms' first order conditions

$$w_t = (1-\gamma_i)\exp(A_t)\left(k_{i,t}\right)^{\gamma_i}\left(h_{i,t}\right)^{-\gamma_i}$$

$$r_t + bp_{e,t} = \gamma_i \exp(A_t)\left(k_{i,t}\right)^{\gamma_i-1}\left(h_{i,t}\right)^{1-\gamma_i}$$

with $i = d, n$

$$w_t = p_{e,t}\exp(A_{e,t})\left((1-\gamma_e)(1-\sigma_{e,t})\left(\frac{k_{e,t}}{h_{e,t}}\right)^{\gamma_e} - \sigma'_{e,t}k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e}\right)$$

$$r_t + b_{e,t}p_{e,t} = p_{e,t}\exp(A_{e,t})\left(\gamma_e(1-\sigma_{e,t})\left(\frac{k_{e,t}}{h_{e,t}}\right)^{\gamma_e-1} - \sigma'_{e,t}k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e}\right)$$

Market clearing

$$k_t = k_{d,t} + k_{n,t} + k_{e,t}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t}$$

$$y_{d,t} = i_{d,t} + i_{k,t}$$

$$y_{n,t} = n_t$$

Aggregate price and aggregate value add

$$p_t = \left[\alpha \left(1 + ap_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha) p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}$$

$$p_t y_t = y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t$$

Exogenous shock process

$$A_t = \rho_A A_{t-1} + u_t$$

$$A_{e,t} = \rho_e A_{e,t-1} + e_t$$

E. Equilibrium Conditions for Chapter 3

textitHousehold's first order conditions

Euler equation for durables

$$(1-\alpha)^{1-\rho}\tfrac{p_{d,t}}{p_{n,t}}{c_t}^{-\rho}n_t^{\rho-1}\left(1+\tfrac{\omega_{d1}}{d_t}\left(\tfrac{d_{t+1}-d_t}{d_t}\right)^{\omega_{d2}}\right)=\beta E\alpha^{1-\rho}c_{t+1}^{-\rho}(u_{t+1}d_{t+1})^{\rho-1}u_{t+1}$$

$$+\beta E\tfrac{(1-\alpha)^{1-\rho}}{p_{n,t+1}}c_{t+1}^{-\rho}n_{t+1}^{\rho-1}[-ap_{e,t+1}u_{t+1}+p_{d,t+1}\left(1-\delta_{d,t+1}+\tfrac{\omega_{d1}d_{t+2}}{d_{t+1}^2}\left(\tfrac{d_{t+2}-d_{t+1}}{d_{t+1}}\right)^{\omega_{d2}}\right)]$$

Euler equation for capital

$$\tfrac{p_{d,t}}{p_{n,t}}{c_t}^{-\rho}n_t^{\rho-1}\left(1+\tfrac{\omega_{k1}}{k_t}\left(\tfrac{k_{t+1}-d_t}{k_t}\right)^{\omega_{k2}}\right)=$$

$$\beta E\tfrac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{p_{n,t+1}}[r_{t+1}+p_{d,t+1}\left(1-\delta_k+\tfrac{\omega_{k1}k_{t+2}}{k_{t+1}^2}\left(\tfrac{k_{t+2}-k_{t+1}}{k_{t+1}}\right)^{\omega_{k2}}\right)]$$

Euler equation for foreign bond

$$\frac{{c_t}^{-\rho}n_t^{\rho-1}}{p_{n,t}}\left(1+\omega_{B1}\left(B_{t+1}-\bar{B}\right)^{\omega_{B2}}\right)=\beta E\frac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{p_{n,t+1}}[1+r_B]$$

Intra-temporal nondurables-labor

$$(1-\alpha)^{1-\rho}\frac{\varphi}{1-\varphi}(1-h_t){c_t}^{-\rho}n_t^{\rho-1}=\frac{p_{n,t}}{w_t}$$

Intra-temporal nondurables-utilization

$$\frac{(1-\alpha)^{1-\rho}}{\alpha^{1-\rho}}\frac{n_t^{\rho-1}}{(u_td_t)^{\rho-1}}=\frac{p_{n,t}}{ap_{e,t}+p_{d,t}\delta_{d,t}^{'}}$$

with

$$c_t=[\alpha^{1-\rho}(u_td_t)^{\rho}+(1-\alpha)^{1-\rho}{n_t}^{\rho}]^{1/\rho}$$

Budget constraint

$$p_{e,t}au_td_t + p_{n,t}n_t + p_{d,t}i_{d,t} + p_{d,t}i_{k,t} + i_{B,t} = w_th_t + r_tk_t + r_BB_t$$

Investment adjustment costs and variable depreciation

$$i_{d,t} = d_{t+1} - (1-\delta_{d,t})d_t + \frac{\omega_{d1}}{1+\omega_{d2}}\left(\frac{d_{t+1}-d_t}{d_t}\right)^{1+\omega_{d2}}$$

$$i_{k,t} = k_{t+1} - (1-\delta_k)k_t + \frac{\omega_{k1}}{1+\omega_{k2}}\left(\frac{k_{t+1}-k_t}{k_t}\right)^{1+\omega_{k2}}$$

$$i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B1}}{1+\omega_{B2}}\left(B_{t+1}-\bar{B}\right)^{1+\omega_{B2}}$$

$$\delta_{d,t} = \frac{a_1}{a_2+1}{u_t}^{a_2+1}$$

Firms' production functions

$$y_{e,t} = \exp(A_{e,t})(1-\lambda_{e,t})k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e}$$

$$\lambda_{e,t} = \frac{\omega_{e1}}{(1+\omega_{e2})}(k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}}$$

$$y_{i,t} = \exp(A_t)\left(k_{i,t}\right)^{\gamma_i}\left(h_{i,t}\right)^{1-\gamma_i}$$

with $i = d, n$

Firms' first order conditions

$$w_t = (1-\gamma_i)\exp(A_t)\left(k_{i,t}\right)^{\gamma_i}\left(h_{i,t}\right)^{-\gamma_i}$$

$$r_t + bp_{e,t} = \gamma_i\exp(A_t)\left(k_{i,t}\right)^{\gamma_i-1}\left(h_{i,t}\right)^{1-\gamma_i}$$

with $i = d, n$

$$w_t = p_{e,t} \exp(A_{e,t}) \left((1-\gamma_e)(1-\lambda_{e,t}) \left(\frac{k_{e,t}}{h_{e,t}} \right)^{\gamma_e} - \lambda'_{e,t} k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e} \right)$$

$$r_t + b_{e,t} p_{e,t} = p_{e,t} \exp(A_{e,t}) \left(\gamma_e (1-\lambda_{e,t}) \left(\frac{k_{e,t}}{h_{e,t}} \right)^{\gamma_e - 1} - \lambda'_{e,t} k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e} \right)$$

Market clearing

$$k_t = k_{d,t} + k_{n,t} + k_{e,t}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t}$$

$$y_{d,t} = I_{DD,t} + I^*_{DM,t}$$

$$y_{n,t} = N_{D,t} + N^*_{M,t}$$

Aggregation

$$I_{D,t} = \left[\alpha_d^{1-\rho_d} I_{DD,t}^{\rho_d} + (1-\alpha_d)^{1-\rho_d} I_{DM,t}^{\rho_d} \right]^{1/\rho_d}$$

$$I_{D,t} = i_{d,t} + i_{k,t}$$

$$N_t = \left[\alpha_n^{1-\rho_n} N_{D,t}^{\rho_n} + (1-\alpha_n)^{1-\rho_n} N_{M,t}^{\rho_n} \right]^{1/\rho_n}$$

$$N_t = n_t$$

Prices

$$p_{d,t} = \left[\alpha_d \left(p_{d,d,t} \right)^{\frac{\rho_d}{\rho_d - 1}} + (1-\alpha_d)(ER_t p^*_{d,d,t})^{\frac{\rho_d}{\rho_d - 1}} \right]^{\frac{\rho_d - 1}{\rho_d}}$$

$$p_{n,t} = \left[\alpha_n \left(p_{n,d,t} \right)^{\frac{\rho_n}{\rho_n - 1}} + (1-\alpha_n)(ER_t p^*_{n,d,t})^{\frac{\rho_n}{\rho_n - 1}} \right]^{\frac{\rho_n - 1}{\rho_n}}$$

$$p_t = \left[\alpha \left(p_{d,t} + a p_{e,t} \right)^{\frac{\rho}{\rho - 1}} + (1-\alpha) p_{n,t}^{\frac{\rho}{\rho-1}} \right]^{\frac{\rho - 1}{\rho}}$$

$$ER_t = \frac{p^*_t}{p_t}$$

Aggregate value added

$$p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t$$

Exogenous shock process

$$A_t = \rho_A A_{t-1} + \epsilon_{u,t}$$

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_t$$

F. Calibrated Parameters for Chapter 3

Parameter	Value	Description
		Home
β_1	0.99	Time preference
φ_1	0.34	Share of consumption in household's utility
α_1	0.2	Share of durables in household's consumption
ρ_1	1 - 1/0.99	Durables-nondurables CES parameter
δ_k	0.025	Capital depreciation rate
a_1	0.06	Param1 of durables depreciation function
a_2	0.3	Param2 of durables depreciation function
γ_{e1}	0.59	Capital share of energy production function
γ_{d1}	0.366	Capital share of durables production function
γ_{n1}	0.336	Capital share of nondurables production function
α_{d1}	0.845	Share of domestic durables in Home's composite durables
ρ_{d1}	1 - 1/1.5	CES parameter between Home's domestic and imported durables
α_{n1}	0.875	Share of domestic nondurables in Home's composite nondurables
ρ_{n1}	1 - 1/1.5	CES parameter between Home's domestic and imported nondurable
ρ_{A1}	0.95	Persistence of non-energy sectors' productivity process
ρ_{e1}	0.95	Persistence of energy sector's productivity process
ω_{k1}	100	Param1 of capital adj. cost function
ω_{k2}	1.2	Param2 of capital adj. cost function
ω_{d1}	100	Param1 of durables adj. cost function
ω_{d2}	1.2	Param2 of durables adj. cost function
ω_{B1}	0.1	Param1 of portfolio adj. cost function
ω_{B2}	1	Param2 of portfolio adj. cost function
ω_{e1}	23	Param1 of energy convex cost function
ω_{e2}	1	Param2 of energy convex cost function

Parameter	Value	Description
$\bar{B}$	2	Bond target in PAC function
r_B	0.01	World interest rate
a	0.02	Energy-intensity of durables
b	0.006	Energy-intensity of capital
		Foreign
γ_{e2}	0.49	Capital share of energy production function
γ_{d2}	0.378	Capital share of durables production function
γ_{n2}	0.368	Capital share of nondurables production function
α_{d2}	0.822	Share of domestic durables in Foreign's composite durables
ρ_{d2}	1 - 1/1.5	CES parameter between Foreign's domestic and imported durables
α_{n2}	0.822	Share of domestic nondurables in Foreign's composite nondurables
ρ_{n2}	1 - 1/1.5	CES parameter between Foreign's domestic and imported nondurab
ω_{e1}	2.8	Param1 of energy convex cost function
ω_{e2}	1	Param2 of energy convex cost function

Table F.1: Calibrated Parameters

G. Equilibrium Conditions for Chapter 4

Household's first order conditions

Euler equation for durables

$$(1-\alpha)^{1-\rho}\tfrac{p_{d,t}}{p_{n,t}}c_t^{-\rho}n_t^{\rho-1}\left(1+\tfrac{\omega_{d1}}{d_t}\left(\tfrac{d_{t+1}-d_t}{d_t}\right)^{\omega_{d2}}\right)=\beta E\alpha^{1-\rho}c_{t+1}^{-\rho}(u_{t+1}d_{t+1})^{\rho-1}u_{t+1}$$

$$+\beta E\tfrac{(1-\alpha)^{1-\rho}}{(1+\tau_{c,t+1})p_{n,t+1}}c_{t+1}^{-\rho}n_{t+1}^{\rho-1}[-ap_{e,t+1}(1+\tau_{e,c,t+1})u_{t+1}$$

$$+(1+\tau_{c,t+1})p_{d,t+1}\left(1-\delta_{d,t+1}+\tfrac{\omega_{d1}d_{t+2}}{d_{t+1}^2}\left(\tfrac{d_{t+2}-d_{t+1}}{d_{t+1}}\right)^{\omega_{d2}}\right)]$$

Euler equation for capital

$$\tfrac{p_{d,t}}{(1+\tau_{c,t})p_{n,t}}c_t^{-\rho}n_t^{\rho-1}\left(1+\tfrac{\omega_{k1}}{k_t}\left(\tfrac{k_{t+1}-d_t}{k_t}\right)^{\omega_{k2}}\right)=$$

$$\beta E\tfrac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{(1+\tau_{c,t+1})p_{n,t+1}}[(1-\tau_{i,t+1})r_{t+1}+p_{d,t+1}\left(1-\delta_k+\tfrac{\omega_{k1}k_{t+2}}{k_{t+1}^2}\left(\tfrac{k_{t+2}-k_{t+1}}{k_{t+1}}\right)^{\omega_{k2}}\right)]$$

Euler equation for bond

$$\frac{c_t^{-\rho}n_t^{\rho-1}}{(1+\tau_{c,t})p_{n,t}}\left(1+\omega_{B1}\left(B_{t+1}-\bar{B}\right)^{\omega_{B2}}\right)=\beta E(1+R_{t+1})\frac{c_{t+1}^{-\rho}n_{t+1}^{\rho-1}}{(1+\tau_{c,t+1})p_{n,t+1}}$$

Intra-temporal nondurables-labor

$$(1-\alpha)^{1-\rho}\frac{\varphi}{1-\varphi}(1-h_t)c_t^{-\rho}n_t^{\rho-1}=\frac{(1+\tau_{c,t})p_{n,t}}{(1-\tau_{i,t})w_t}$$

Intra-temporal nondurables-utilization

$$\frac{(1-\alpha)^{1-\rho}}{\alpha^{1-\rho}}\frac{n_t^{\rho-1}}{(u_td_t)^{\rho-1}}=\frac{(1+\tau_{c,t})p_{n,t}}{a(1+\tau_{e,c,t})p_{e,t}+(1+\tau_{c,t})p_{d,t}\delta_{d,t}^{'}}$$

with

$$c_t=[\alpha^{1-\rho}(u_td_t)^{\rho}+(1-\alpha)^{1-\rho}{n_t}^{\rho}]^{1/\rho}$$

Budget constraint

$$(1+\tau_{e,c,t})p_{e,t}au_t d_t + (1+\tau_{c,t})p_{n,t}n_t + (1+\tau_{c,t})p_{d,t}i_{d,t} + p_{d,t}i_{k,t} + i_{B,t}$$

$$= (1-\tau_{i,t})(w_t h_t + r_t k_t) + R_t B_t$$

Investment adjustment costs and variable depreciation

$$i_{d,t} = d_{t+1} - (1-\delta_{d,t})d_t + \frac{\omega_{d1}}{1+\omega_{d2}}\left(\frac{d_{t+1}-d_t}{d_t}\right)^{1+\omega_{d2}}$$

$$i_{k,t} = k_{t+1} - (1-\delta_k)k_t + \frac{\omega_{k1}}{1+\omega_{k2}}\left(\frac{k_{t+1}-k_t}{k_t}\right)^{1+\omega_{k2}}$$

$$i_{B,t} = B_{t+1} - B_t + \frac{\omega_{B1}}{1+\omega_{B2}}\left(B_{t+1}-\bar{B}\right)^{1+\omega_{B2}}$$

$$\delta_{d,t} = \frac{a_1}{a_2+1}{u_t}^{a_2+1}$$

Sectors' aggregate outputs

$$y_{e,t} = exp(A_{e,t})k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e}$$

$$b_{e,t} = \frac{\omega_{e1}}{(1+\omega_{e2})}(k_{e,t}^{\gamma_e}h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}}$$

$$y_{i,t} = exp(A_t)\left(k_{i,t}\right)^{\gamma_i}\left(h_{i,t}\right)^{1-\gamma_i} - \chi_i$$

with $i = d, n$

Firms' first order conditions

$$mc_{i,t}exp(A_t)(1-\gamma_i)\left(\frac{k_{i,t}}{h_{i,t}}\right)^{\gamma_i} = \frac{w_t}{p_{i,t}}$$

$$\frac{1-\gamma_i}{\gamma_i}\frac{k_{i,t}}{h_{i,t}} = \frac{w_t}{r_t + bp_{e,t}(1+\tau_{e,f,t})}$$

$$p_{e,t}exp(A_{e,t})\gamma_e\left(\frac{k_{e,t}}{h_{e,t}}\right)^{\gamma_e-1} = r_t+b_{e,t}p_{e,t}(1+\tau_{e,f,t})+k_{e,t}p_{e,t}(1+\tau_{e,f,t})b'_{e,t}h_{e,t}^{1-\gamma_e}\gamma_e k_{e,t}^{\gamma_e-1}$$

$$p_{e,t}exp(A_{e,t})(1-\gamma_e)\left(\frac{k_{e,t}}{h_{e,t}}\right)^{\gamma_e} = w_t + k_{e,t}p_{e,t}(1+\tau_{e,f,t})b'_{e,t}h_{e,t}^{-\gamma_e}(1-\gamma_e)k_{e,t}^{\gamma_e}$$

Sectoral Phillips curves

$$\hat{\pi}_{i,t} = \beta E_t[\hat{\pi}_{i,t+1}] + \frac{\epsilon_i - 1}{\vartheta_i}m\hat{c}_{it}$$

with $i = d, n$

Fiscal and monetary policies

Government budget constraint

$$\tau_{e,c,t}p_{e,t}au_td_t + \tau_{e,f,t}p_{e,t}(b(k_{d,t}+k_{n,t})+b_{e,t}k_{e,t}) + \tau_{c,t}(p_{n,t}n_t + p_{d,t}i_{d,t}) + \tau_{i,t}(r_tk_t + w_th_t)$$

$$+i_{B,t} = p_tg_ty_t + R_tB_t$$

Tax rules

$$log\left(\frac{\tau_{(),t}}{\bar{\tau}_{()}}\right) = \rho_{()}log\left(\frac{\tau_{(),t-1}}{\bar{\tau}_{()}}\right) + \phi_{()}log\left(\frac{B_t}{\bar{B}}\right) \tag{G.1}$$

with $() = (e,c), (e,f), c, i$

Monetary policy function

$$R_t - R^* = \alpha_R(R_{t-1} - R^*) + \alpha_\pi(\pi_t - \pi^*) + \alpha_y(y_t - y_{t-1}) + \epsilon_{r,t}$$

Market clearing

$$k_t = k_{d,t} + k_{n,t} + k_{e,t}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t}$$

$$y_{d,t} = i_{d,t} + i_{k,t} + g_{d,t} + \frac{\vartheta_d}{2}(\pi_{d,t} - 1)^2 y_{d,t}$$

$$y_{n,t} = n_t + g_{n,t} + \frac{\vartheta_n}{2}(\pi_{n,t} - 1)^2 y_{n,t}$$

$$g_t y_t = \left[\alpha^{1-\rho} g_{d,t}^{\rho} + (1-\alpha)^{1-\rho} g_{n,t}^{\rho}\right]^{1/\rho}$$

$$p_t g_t y_t = p_{d,t} g_{d,t} + p_{n,t} g_{n,t} + p_{e,t} a g_{d,t}$$

Aggregate price and aggregate value added

$$p_t = \left[\alpha \left(p_{d,t} + a p_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha) p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}$$

$$p_t y_t = p_{d,t} y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t$$

Exogenous shock process

$$A_t = \rho_A A_{t-1} + \epsilon_{A,t}$$

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_{e,t}$$

$$g_t = \rho_g g_{t-1} + \epsilon_{g,t}$$