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Abstract

This paper proposes a framework of endogenous energy production with convex costs to investigate the general equilibrium effects of energy price shocks on the business cycle. This framework explicitly models the consumption of durables and nondurables and implements a high complementarity between energy and the usage of durables and capital. The model predicts energy price elasticities of various consumption variables that fall within reasonable agreement with empirical estimates. Convex costs in energy production produce energy price and energy supply dynamics that tallies well with empirical behavior. Our analysis confirms in a theoretical setting recent observations that not all energy price shocks are the same. They can be distinct in terms of energy price dynamics and impact on the business cycle, as well as energy price elasticities of various macro variables that can be useful indicators for their underlying causes.

Keywords: Energy, Energy Price Shock, Business Cycle

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1. INTRODUCTION

There is 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 reexamined [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, 2014); Baumeister and Peersman (2013)]. 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, treated the real price of oil as exogenously given and made no distinctions 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 prices. In light of the empirical evidence mentioned previously, this traditional framework of exogenous oil/energy prices can no longer serve as a theoretical benchmark, as it cannot predict the behavior of the economy in response to any shocks other than the oil/energy supply shock. The first theoretical effort toward endogenizing oil price is that of Backus and Crucini (2000), who use 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 study the impact of oil shocks in the international context, using a feature of oil price endogeneity. Bodenstein et al. (2008, 2012) and Nakov and Pescatori (2010) look at the question of optimal monetary conduct in response to oil price shocks, whereas Arora and Gomis-Porqueras (2011) show that endogenous oil price helps a theoretical model to better match oil-related business cycle features in the data.

In this paper we complement these theoretical efforts with a multisector 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 nondurables 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, whereas consumption of nondurables 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 low price elasticities of energy consumption.[2] Additionally, convex costs in energy production allow 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 nondurables, 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 mentioned works of endogenous oil/energy price in a few important dimensions. Nakov and Pescatori (2010) and Arora and Gomis-Porqueras (2011) 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, 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 employ 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 nondurables 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 paper comes close to that of 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, although 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 paper we are mostly concerned with energy price increases and their different sources. The consideration of an asymmetric relationship between oil/energy price and output is beyond the scope of the paper, 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. Endogenous energy production with convex costs creates energy price dynamics that comes quite close to the empirical counterpart. The convex costs also produce a fairly low price elasticity of energy supply (on 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 an hours–wage correlation considerably lower 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, similarly 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 in 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 consumption and investment, which fall within reasonable agreement with the empirical estimates reported in Edelstein and Kilian (2009), as well as by 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, whereas our framework allows this investigation. The results show that energy price shocks hit the non-energy-dependent goods sector harder on its supply side, whereas the impact is relatively stronger on the demand side for the energy-dependent goods sector.

2. MODEL

2.1. Households

Households consume a CES aggregation of durables and nondurables 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 nondurables 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 nondurables is represented by $1/1-\rho$, whereas 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 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. 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 paper, 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,

$$E_0 \sum_{t=0}^{\infty} \beta^t [\varphi \log c_t + (1-\varphi)\log(1-h_t)], \qquad \textbf{(1)}$$

subject to the budget constraint

$$E_0 \sum_{t=0}^{\infty} \beta^t [\varphi \log c_t + (1-\varphi)\log(1-h_t)], \qquad \textbf{(1)}$$

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 nondurables, whereas 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:

$$i_{d,t} = d_{t+1} - (1 - \delta_{d,t})d_t + \frac{\omega_{d1}}{1 + \omega_{d2}} \left(\frac{d_{t+1} - d_t}{d_t} \right)^{1+\omega_{d2}}, \qquad \textbf{(3)}$$

$$i_{k,t} = k_{t+1} - (1 - \delta_k)k_t + \frac{\omega_{k1}}{1 + \omega_{k2}} \left(\frac{k_{t+1} - k_t}{k_t} \right)^{1+\omega_{k2}}, \qquad \textbf{(4)}$$

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} are 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):

$$\delta_{d,t} = \frac{a_1}{a_2 + 1} u_t^{a_2+1}. \qquad \textbf{(5)}$$

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 Online Appendix C.

2.2. Producers

There are three sectors in the model: durables, nondurables, 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 paper, 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 of the opportunity cost of energy. When the 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 energy production with convex costs, to produce a low price elasticity of energy supply. The production function of the energy sector takes the form

$$y_{e,t} = \exp(A_{e,t})(1 - \sigma_{e,t})k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e}, \qquad \textbf{(6)}$$

with ye,t , he,t , and ke,t denoting output, labor, and capital for the sector, respectively, and

$$\sigma_{e,t} = \frac{\omega_{e1}}{(1 + \omega_{e2})} (k_{e,t}^{\gamma_e} h_{e,t}^{1-\gamma_e})^{1+\omega_{e2}} \qquad \textbf{(7)}$$

representing the fraction of energy output that is lost. This functional form for $\sigma_{e,t}$ implies that as the output of energy production becomes higher, an increasingly high 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, whereas energy supply itself is relatively less responsive. The calibration section explains the calibration of ω_{e1} and ω_{e2}.

Nonenergy producers. The durables and nondurables 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

$$y_{i,t} = \exp(A_t) k_{i,t}^{\gamma_i} h_{i,t}^{1-\gamma_i}, \qquad \textbf{(8)}$$

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

Each sector solves the profit-maximization problem

$$\max_{\{k_{j,t}, h_{j,t}\}} \{p_{j,t} y_{j,t} - w_t h_{j,t} - r_t k_{j,t} - p_{e,t} b k_{j,t}\}, \qquad \textbf{(9)}$$

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

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), nondurables produced are used wholly for consumption, and durables output is used for investments in capital and durables. The capital and labor markets, as usual, also clear in every period. The market clearing conditions are thus

$$k_t = k_{d,t} + k_{n,t} + k_{e,t}, \qquad \textbf{(10)}$$

$$h_t = h_{d,t} + h_{n,t} + h_{e,t}, \qquad \textbf{(11)}$$

$$y_{d,t} = i_{d,t} + i_{k,t}, \qquad \textbf{(12)}$$

$$y_{n,t} = n_t. \qquad \textbf{(13)}$$

The energy market is automatically cleared, given the budget constraint.

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

$$p_t = \left[\alpha \left(1 + a p_{e,t}\right)^{\frac{\rho}{\rho-1}} + (1-\alpha) p_{n,t}^{\frac{\rho}{\rho-1}}\right]^{\frac{\rho-1}{\rho}}. \qquad \textbf{(14)}$$

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

$$p_t y_t = y_{d,t} + p_{n,t} y_{n,t} + p_{e,t} a u_t d_t. \qquad \textbf{(15)}$$

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 nondurables 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 (shocks to the parameter a, $\epsilon_{a,t}$) and to the producers' energy need (shocks to the parameter b, $\epsilon_{b,t}$). These shocks model energy-market-specific demand shocks.

TABLE 1. Targeted ratios

Moment	Value
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

3. MODEL CALIBRATION AND SOLUTION

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 nondurables 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 nondurables are somewhat complementary.

Other parameters are calibrated to produce theoretical moments of model aggregates that reproduce as well as possible the empirical moments calculated from aggregate U.S. data [Table 1; Dhawan and Jeske (2008)]. The aggregates present in the ratios are real GDP (Y), household and production energy usage (E_h and E_f, respectively), durables consumption (I_d), durables and capital stock (D and K), and labor (H). They each have a broadly corresponding theoretical counterpart in the model of Dhawan and Jeske (2008). Because 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.

Using Table 1, quarterly capital depreciation is calibrated at 1.5%, whereas the parameters of the durables depreciation function are chosen to produce a steady-state quarterly depreciation rate of 6.1% and a 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 intensities 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 adjustment costs are given in the form of a general power function, governed by two parameters ω_1 and ω_2. In this paper we assume a quadratic form for both stocks; thus $\omega_2 = 1$. The remaining choice of $\omega 1$ 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 calibration $\omega_{k1} = 0.05$, $\omega_{k2} = 1$, $\omega_{d1} = 0.4$, $\omega_{d1} = 1$. The parameters of the three sectors' production functions are also calibrated using the ratios in Table 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 $\gamma_d = 0.34$, $\gamma_n = 0.38$, and $\gamma_e = 0.552$.

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 consumption 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 choose 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.

3.2. Technology Processes

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

$$A_t = \rho_a A_{t-1} + \epsilon_{u,t}, \epsilon_{u,t} \sim^{\text{i.i.d.}} N(0, \sigma_u^2), \quad \textbf{(16)}$$

$$A_{e,t} = \rho_e A_{e,t-1} + \epsilon_t, \epsilon_t \sim^{\text{i.i.d.}} N(0, \sigma_e^2). \quad \textbf{(17)}$$

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.

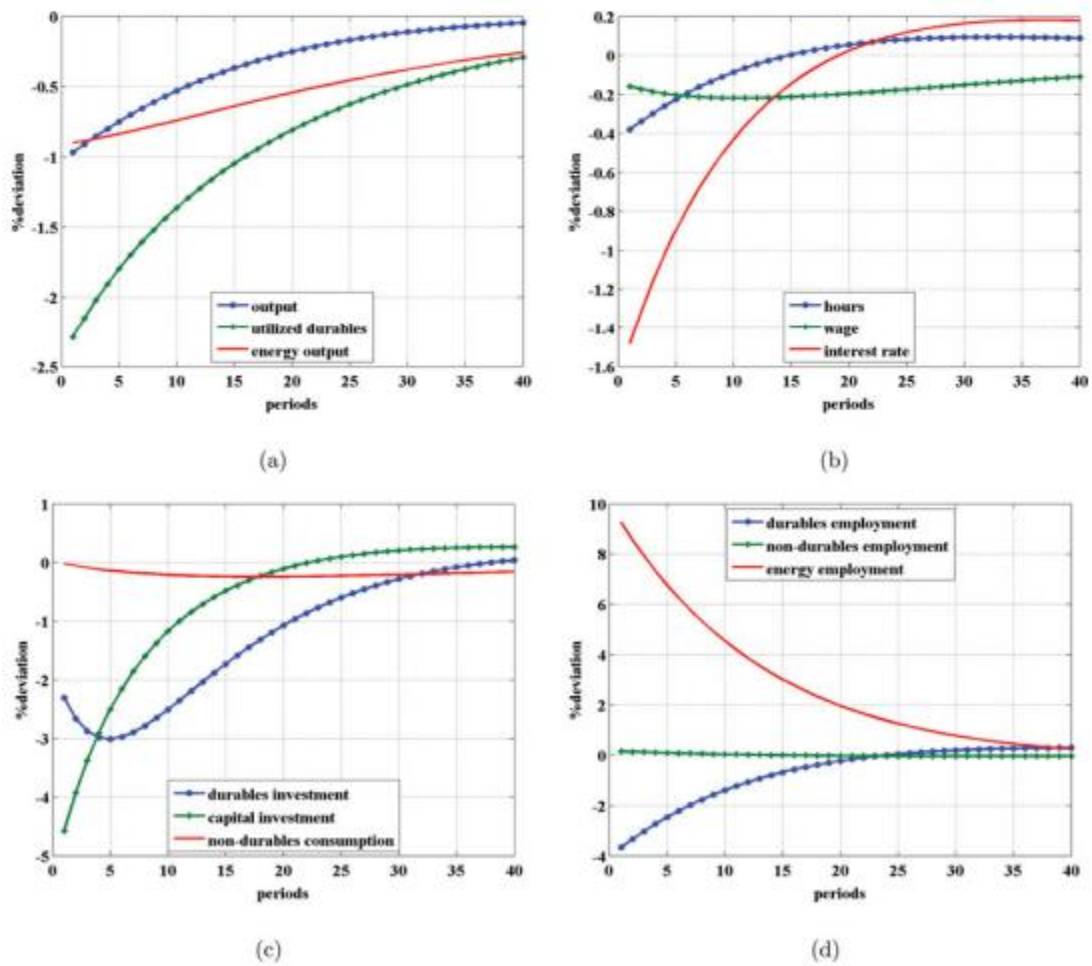
The model is solved for its steady state using a nonlinear solver, and an approximate solution to the model is found by linearizing the equilibrium conditions around the steady state using the perturbation method. The cyclical properties and energy price dynamics of the model are described in Online Appendices A and B.

4. GENERAL EQUILIBRIUM EFFECTS OF ENERGY PRICE SHOCKS

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 (Figure 1a), whose subsequent recovery is dependent on the persistence of the shock. The impact on value added is therefore significant. Although 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 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.

FIGURE 1. Impulse responses to a negative shock to the energy sector's productivity, scaled to produce a 10% increase in energy price



Other aggregates also indicate a contracting business cycle. Overall employment, rental rate of capital, and wage all fall (Figure 1b). Both kinds of investment fall (Figure 1c), but investment in durables less so than capital. The utilized durables (Figure 1a), which represents the representative household's control of its energy consumption, fall by more than 2%. Consumption of nondurables 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, whereas the 4.5% decline in capital investment is higher in magnitude than the estimated elasticity of total nonresidential 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 u_d (because 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 nondurables is also higher (in magnitude) in the data than in the model (−0.11 versus −0.02).

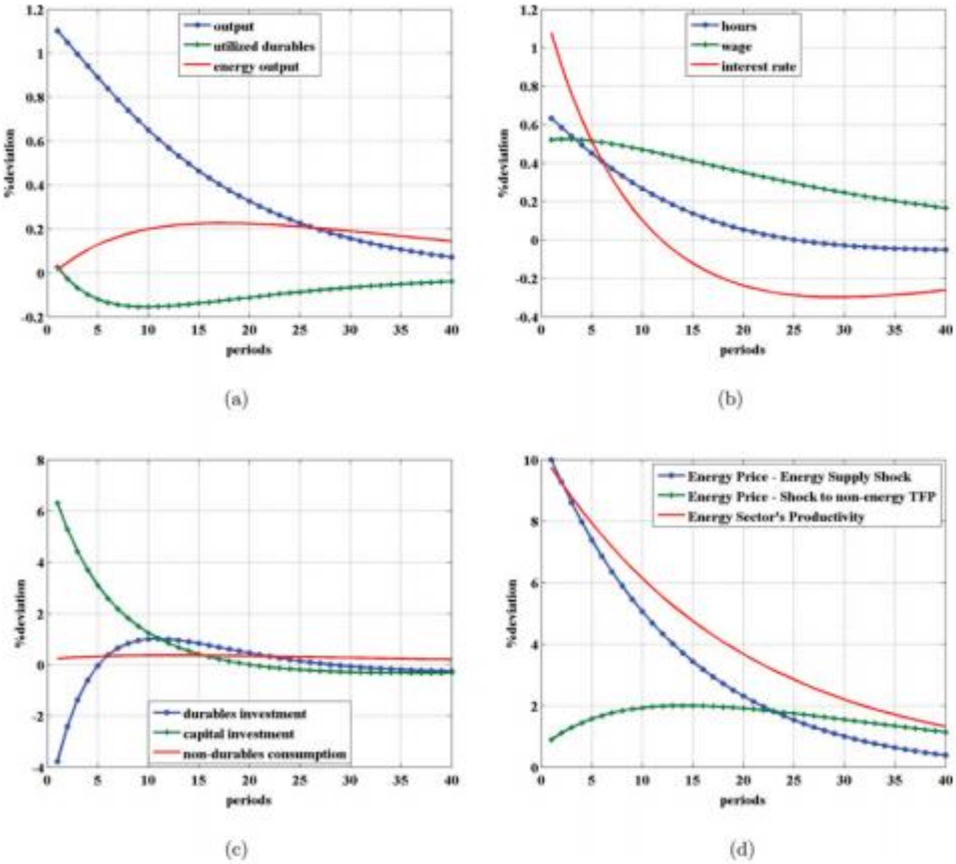
The high impact of an energy price increase on output results from endogenous energy production and the high complementarity of durables and capital with energy, with the durables sector contributing most to this decline. For the household, energy price makes its impact through both the expense and the 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 Figure 1b) and reduced effective budget due to higher cost of energy consumption. All consumption is cut, but the small drop in nondurables consumption illustrates its role as an “anchor” in energy crises, as the household substitutes nondurables for durables utilization/investment. Because investments in both capital and durables are cut by higher percentages than nondurables 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 nondurables, and those responses contribute strongly to contraction in the business cycle.

For the producers, 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 nondurables 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 nondurables 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 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. Intersectoral 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 1d shows the sectoral movements in labor; movements in capital follow this pattern.

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 doubt 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 nondurables sectors. This provides a supply-led boom in 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 2a shows that this boom is represented by a rise in output, accompanied by increases in employment and factor prices (Figure 2b). More importantly, it also causes the energy price to rise. A 1.1% increase in output is matched by an initial increase in energy price of almost 1% (Figure 2d), very close to a one-for-one 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 of 1.5%, whereas real oil price increases by 2.5% and gasoline 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).

FIGURE 2. Impulse responses to a positive innovation to the non-energy producers' productivity. Panel d shows responses of energy price to the energy supply shock (*) and to an increase in the non-energy producers' productivity (+). The solid line shows the productivity of the energy producer in the case of energy supply shock, scaled and inverted to provide a better visual comparison. It can also represent the non-energy producers' TFP after a positive innovation.



With regard to other aspects of this economic expansion, consumption of nondurables and capital investment both increase: nondurables slightly at 0.2%, capital investment quite significantly at more than 6% (Figure 2c). Higher energy price, however, discourages the household initially in its durables investment decision. In contrast to Section 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 toward 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 (Figure 2a). However, the shape of the response differs from Section 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. Whereas in Section 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 2d shows that energy price here does not decay as fast as it does in Section 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 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 4.1, falling energy demand and the decaying shock act in the same direction to pull energy prices 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 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 took 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 4.1.

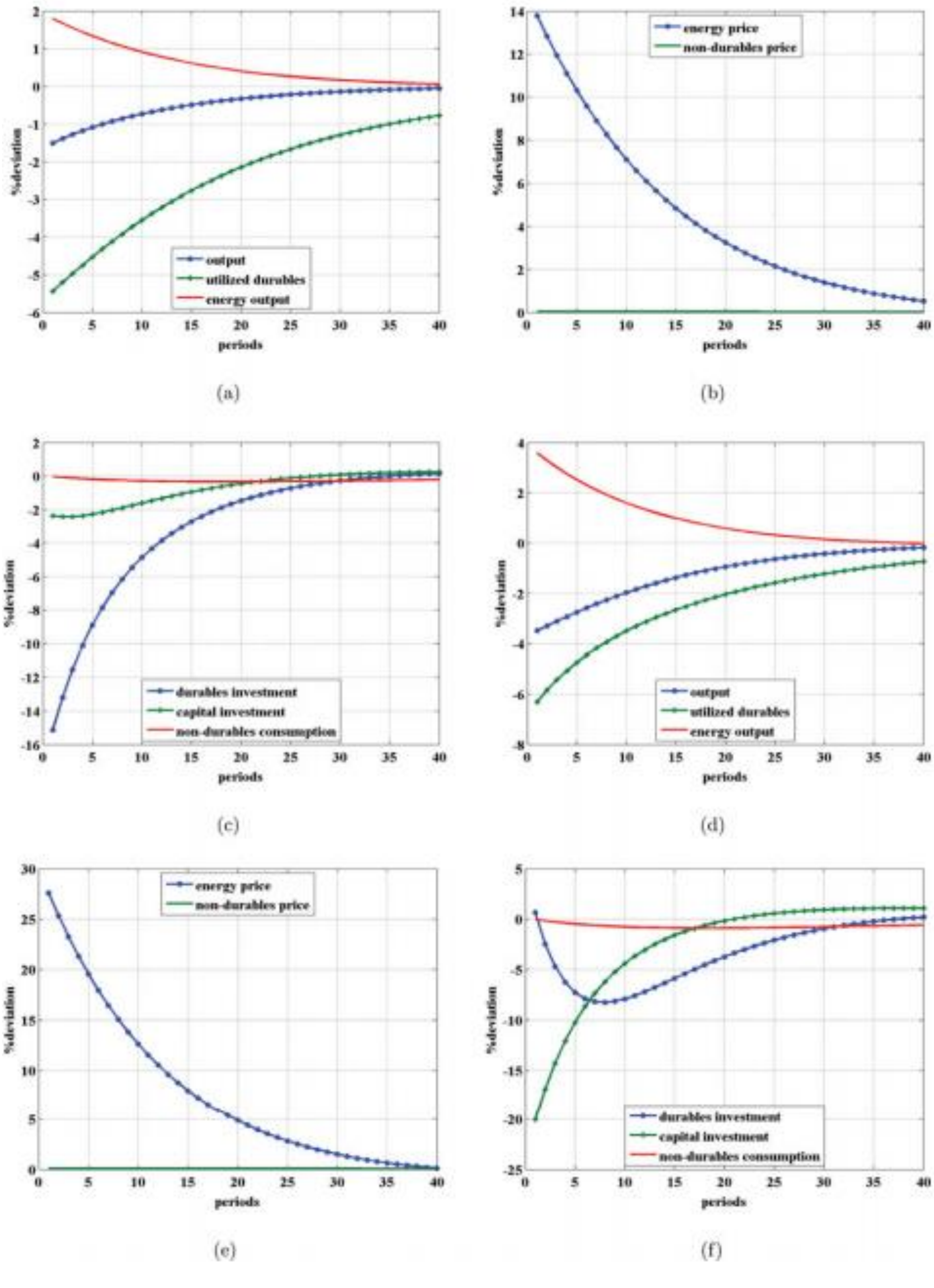
4.3. Energy-Market-Specific Demand Shocks

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 structural shock in the context of this model corresponding 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% (Figures 3a and 3b). The household sees this shock as an energy price increase and reduces its durables usage correspondingly. Its utilized durables drop by almost 5.5% (Figure 3a), a stronger response (in elasticity) than in Section 4.1. There is an amplifying effect here in this shock: the effective increase in energy cost is greater 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 an impact on the business cycle qualitatively similar to that in Section 4.1. Beyond that, though, there are important differences. This shock has a slightly more severe impact on output than that in Section 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 previously, which is absent in Section 4.1. The nature of the shock manifests itself further through the way the household readjusts its portfolio differently from what occurs in Section 4.1. It reduces durables consumption by a much higher percentage than capital investment (Figure 3c), and a lot more than in Section 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 also 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 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.

FIGURE 3. Impulse responses to energy-market specific demand shocks: (a), (b), (c) to a 10% innovation in the energy intensity of durables; (d), (e), (f) to a 10% innovation in the energy intensity of capital.



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 wages, lower interest rates, and reduced employment, similarly to Section 4.1. But the shock does not affect the producers in the same way as it does in Section 4.1. The non-energy producers suffer from lower demand because the household cuts its durables and nondurables 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, whereas in Section 4.1 the durables sector is already impacted more than the nondurables 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 previously.

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 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 that in Section 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.

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 an energy price increase similar to that for a shock to the energy intensity of durables, but this is not the case. Energy price shoots up by close to 28% (Figure 3e), and energy supply responds with a 3.5% increase (Figure 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 either for a shock to the energy intensity of durables or for a negative productivity shock to the energy sector (Section 4.1).

The relative severity of the shock on the two sides of the economy now runs in the opposite direction to that for a shock to the energy intensity of durables. 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 b_{pe}. So, when there is an increase in the value of b, coupled with an energy price shock, the increase in the term b_{pe} 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 for a shock to the energy intensity of durables in terms of energy price elasticity. The greater energy cost also means that there is a greater shift in aggregate supply than that 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 that in Section 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 that of energy price in Section 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; Figure 3f), compared with both for a shock to the energy intensity of durables and a negative productivity shock to the energy sector. The sensitivity of durables investment to energy price is roughly the same as in Section 4.1, whereas 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 the other scenarios. 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 reduce its capital holding drastically. However, the energy price elasticity of capital for this shock is still very much lower in magnitude than the energy price elasticity of utilized durables for a shock to the energy intensity of durables. 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 that case. This means that the shift in energy demand here is greater, which explains the greater increases in energy price and output. The durables sector again suffers much more than the nondurables sector, because of 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 from the energy supply shock in Section 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, whereas 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.

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 nondurables 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 into 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 comes close to data, as well as energy production dynamics that satisfies the low price elasticity characteristics of actual energy supply. It also makes an important improvement by significantly lowering the correlation between hours and wages, 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, whereas 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, 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 (nondurables), 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.

NOTES

1. Berndt and Wood (1975) estimated the elasticity of substitution between energy and capital to be −3.2.

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

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