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Perfect Competition and the Effects of Energy Price Increases on Economic Activity

Rotemberg and Woodford (1996) present new striking facts concerning the effects of energy price increases on economic activity. They advance a theory of imperfect competition to successfully address these facts—suggesting that imperfect competition is a necessary ingredient for success. The present study shows that a theory of perfect competition rises to the challenge of explaining the Rotemberg-Woodford evidence.

POPULAR DISCUSSION often refers to energy price increases as shocks, shocks that are in some sense equivalent to adverse technology shocks and, thus, induce significant contractions in economic activity. In fact, using U.S. data (1953–1984), Hall (1988, 1990) finds that a standard measure of technology, the Solow residual, systematically tends to fall whenever energy prices rise. Furthermore, a substantial amount of evidence more directly links energy price increases to the onset of recessions [for example, see Hamilton's (1983, 1996) studies of the postwar U.S. economy].

Economic theory has long struggled in attempting to explain the energy price–macroeconomy relationship. The puzzling issue for theory is how to explain the significant effects of energy price shocks in a manner that is consistent with the observed low energy share of output—on average about 4 percent for the United States. Recently, progress on this issue has been made. Rotemberg and Woodford (1996) (which will be abbreviated to RW) advance a new theory, a theory of imperfect competition, that successfully tackles the puzzle while simultaneously noting that a more traditional theory, a theory of perfect competition, spectacularly fails to solve the puzzle. In particular, RW begin by revealing new striking facts on the depth and persistency of the declines in U.S. output and real wages sparked by energy price increases. They go on to show that their imperfectly competitive theory can well explain this evidence and that their perfectly competitive theory cannot.

The author thanks Julio Rotemberg for discussion and for generously providing empirical data from his work with Michael Woodford. Also, the author is grateful to the Wharton School for its hospitality during the time she wrote this paper. Finally, thanks go to Peter Ireland and two anonymous referees for their extremely constructive comments and suggestions.

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Journal of Money, Credit, and Banking, Vol. 32, No. 3 (August 2000, Part 1)

The purpose of the present paper is not to challenge either the new evidence or new theory developed by RW. Instead, the goal here is to demonstrate that the idea of perfect competition per se does not prevent explanation of the RW evidence. This task is achieved by showing that a theory maintaining perfect competition also well explains the RW facts. The upshot is that the dramatic RW evidence on the effects of energy price increases on economic activity does not provide a basis for sharply discriminating between the usefulness of the ideas of perfect and imperfect competition in economic theory.

The perfectly competitive theory presented below was first developed by Finn (1991, 1995). It crucially differs from more traditional perfectly competitive models such as Rasche and Tatom (1981) and RW's perfectly competitive theory by viewing capital utilization as the avenue through which energy enters into the model economy—energy is essential for the utilization of capital. As will be explained in the next section, this avenue creates an indirect channel, working through the capital stock, in addition to the usual direct production function channel, found in the earlier energy models, through which fluctuations in energy usage impact on the model economy. The present study's theory has some further attractive features, especially for dealing with questions involving energy. First, the theory captures the popular and intuitive idea that an increase in the price of energy works just like a negative technology shock to generate contraction in economic activity. Second, the theory is quantitatively consistent with the U.S. evidence on connections between the Solow residual and energy prices (see Finn 1991, 1995).

The rest of the paper is organized as follows. Section 1 outlines the model economy. Section 2 provides a qualitative discussion of how energy price increases affect the model economy. Section 3 describes the model calibration. Section 4 presents RW's facts and the model economy's corresponding predictions. Section 5 concludes the paper.

1. THE MODEL ECONOMY

The economy produces a final good from three factors of production: labor, capital, and energy. In doing so, the degree to which capital is utilized varies endogenously. Energy enters into the production process because it is essential to the utilization of capital. Capital is never fully utilized because of costs, consisting not only of energy costs but also of depreciation costs. The final good is consumed, invested, and used to purchase energy from abroad. All households are identical, as are firms. Firms are owned by households. Markets are perfectly competitive. Stochastic exogenous shocks to technology and to the relative price of energy are two possible sources of fluctuations in the economy. A more exact description of the economy's structure and competitive equilibrium follows.[1]

1. The model economy is closely related to those in Finn (1991, 1995, 1996).

1.1 Structure

Taking market prices as given, the representative firm maximizes profit from final goods production by optimally choosing labor and capital services. That is,

$$\max_{(l_t, k_t u_t)} \pi_t = y_t - w_t l_t - r_t k_t u_t \quad (1)$$

subject to the production function:

$$y_t = F(z_t l_t, k_t u_t) = (z_t l_t)^{\theta}(k_t u_t)^{(1-\theta)}, \ 0 < \theta < 1 \ . \quad (2)$$

In equation (1), π is profit, y is gross output of final goods, l is labor, ku are capital services, w is the wage rate, and r is the rental rate of capital services. Meanwhile in equation (2), z is the exogenous stationary technology variable and θ is labor's output share. Capital services ku are the product of the capital stock k, assumed in place at the beginning of the period, and the utilization rate of capital u during the period. The production function F displays standard properties and constant returns to scale with respect to labor and capital services. It differs from the usual neoclassical production function solely by including u, representing the number of hours per period that the capital stock operates. The manner in which u enters into equation (2) allows a direct relationship between u and labor's productivity.[2]

The infinitely lived representative household has preferences over consumption and labor that are defined in

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_t, l_t), \quad U(.) = \frac{\left[c_t^{\varphi}(1-l_t)^{(1-\varphi)}\right]^{(1-\alpha)} - 1}{(1-\alpha)}, \quad (3)$$

$$0 < \beta \, , \varphi < 1, \quad \alpha > 0$$

where c is consumption, β is the subjective discount factor, φ and α are other preference parameters. Available time each period is normalized at unity. The momentary utility function U exhibits standard features.

Each period the household invests some of the economy's final good to form capital according to the law of motion:

2. Many other studies model endogenous capital utilization—for example, Lucas (1970), Taubman and Wilkinson (1970), Greenwood, Hercowitz and Huffman (1988), Kydland and Prescott (1988), Finn (1991, 1995, 1996), Bils and Cho (1994), Burnside and Eichenbaum (1996), and Greenwood, Hercowitz, and Krussel (1998). These studies show that capital utilization, by allowing an additional margin along which production can respond, enhances the model economy's response to technology and/or government spending shocks. The present study as well as Finn 1991, 1995, and 1996 expand the role of capital utilization further by making capital utilization the avenue through which energy usage enters into the model economy (see subsection 2.1 of the text). Thus, here and in Finn 1991, 1995, and 1996 capital utilization plays an essential role in the transmission of energy price shocks.

$$k_{t+1} = (1-\delta(u_t))k_t + i_t, \quad \delta(u_t) = \frac{\omega_0 u_t^{\omega_1}}{\omega_1}, \tag{4}$$

$$0 < \delta(.) < 1, \omega_0 > 0, \omega_1 > 1 ,$$

where i is gross investment and ω_0, ω_1 are parameters. This capital accumulation equation is standard except for the variable depreciation rate. Depreciation δ is an increasing convex function of u, as first formulated in Taubman and Wilkinson (1970) and Greenwood, Hercowitz, and Huffman (1988). This depreciation function captures Keynes's notion of the user cost of capital—higher utilization causes faster depreciation, at an increasing rate, because of wear and tear on the captial stock.

Capital utilization requires energy. Specifically, energy complements the service flow from capital in accordance with:

$$\frac{e_t}{k_t} = a(u_t), \quad a(u_t) = \frac{\upsilon_0 u_t^{\upsilon_1}}{\upsilon_1}, \quad \upsilon_0 > 0, \upsilon_1 > 1 \tag{5}$$

where e is energy usage and υ_0, υ_1 are parameters. The technical relationship a, the same as those developed by Finn (1991, 1995, 1996), states that energy is essential to the utilization of capital, with increases in utilization requiring more energy usage per unit of capital, at an increasing rate.[3] Therefore, when the household supplies capital services to the firm, it must also supply energy. Moreover, the household's decision on capital's utilization rate takes account of the two costs of utilization that are now evident: depreciation and energy costs, either of which would keep capital from being fully utilized.

Both the energy and depreciation cost margins of the capital utilization decision play a crucial role in the model. Absent the energy cost margin, energy usage (and energy prices) would not even enter into the present model economy. If the depreciation cost margin was absent or, in other words, if the depreciation rate was constant, then the entire production structure simplifies to allowing just one channel, a direct production function channel, for fluctuations in energy usage to affect the economy. To see this last point more clearly, rewrite the energy relationship, equation (5), as follows:

$$u_t = \left(\frac{e_t}{k_t}\right)^{\frac{1}{\upsilon_1}} \left(\frac{\upsilon_1}{\upsilon_0}\right)^{\frac{1}{\upsilon_1}} \tag{6}$$

and substitute equation (6) into the production function, equation (2), to get

3. Jorgenson and Griliches (1967) advanced a similar idea: electricity and utilized capital complement one another in production.

$$y_t = (z_t l_t)^{\theta} \left[k_t^{\left(1-\frac{1}{\upsilon_1}\right)} e_t^{\frac{1}{\upsilon_1}} \left(\frac{\upsilon_1}{\upsilon_0} \right)^{\frac{1}{\upsilon_1}} \right]^{(1-\theta)} . \tag{7}$$

Equation (7) specifies output as a function of labor, capital, and energy, showing energy's direct production function channel—the direct effect of energy on output. If the depreciation rate was constant, then the transmission of energy fluctuations is confined to this one direct production function channel, just as it is in the standard perfectly competitive models (for example, Rasche and Tatom 1981) and RW's perfectly competitive theory. But, as in the present model, when depreciation depends on utilization [see equation (4)] and through it on energy use [see equation (6)], then energy has an additional indirect transmission channel—the indirect effect of energy on output working through the capital stock [see equations (6), (4) and (7)]. Thus, endogenizing the capital utilization decision, with its energy and depreciation costs, leads to an important difference between the present and previous energy theories.

The remaining restriction on the household's activities is the budget constraint, setting total income equal to total spending each period:

$$w_t l_t + r_t k_t u_t = c_t + i_t + p_t e_t \tag{8}$$

where p is the exogenous relative price of energy in terms of the final good. p follows a stationary positively autocorrelated process, estimated by RW using U.S. data (1947:2–1980:3). In equation (8), income consists of wage and rental income from labor and capital services respectively; spending is on consumption, investment, and energy purchases. One way of interpreting pe is that it represents the present economy's (that is, the domestic economy's) energy purchases from the rest of the world. Correspondingly, the exogeneity of p may be viewed as signifying p's determination on a world market that is not influenced by the domestic economy.[4]

The household's problem may now be stated. It is to maximize lifetime utility in equation (3) by optimally choosing c_t, l_t, k_{t+1}, u_t (and therefore i_t and e_t) subject to the constraints in equations (4), (5), and (8) and to given market prices.

1.2 Competitive Equilibrium

Competitive equilibrium obtains when the firm and household solve their optimization problems and all markets clear. The equilibrium is implicitly determined by the law of motion for capital [equation (4)], the energy relationship [equation (5)] and the following equations.

$$w_t = F_1(z_t l_t, k_t u_t) z_t . \tag{9}$$

$$r_t = F_2(z_t l_t, k_t u_t) . \tag{10}$$

4. Empirical justification for treating p as exogenous with respect to developments in the U.S. economy is provided by Hamilton (1983, 1985).

$$-U_2(c_t,l_t) = U_1(c_t,l_t)w_t . \tag{11}$$

$$\delta'(u_t)k_t + p_t a'(u_t)k_t = r_t k_t . \tag{12}$$

$$U_1(c_t,l_t) = \beta E_t U_1(c_{t+1},l_{t+1})[r_{t+1}u_{t+1} + (1 - \delta(u_{t+1})) - p_{t+1}a(u_{t+1})] . \tag{13}$$

$$y_t = F(z_t l_t, k_t u_t) = c_t + i_t + p_t e_t . \tag{14}$$

Equations (9) and (10) equate wages and rent to the respective marginal productivities. The intratemporal efficiency condition governing labor supply is equation (11). Marginal depreciation and energy costs of utilization sum to equal the marginal return to utilization in equation (12), thereby determining the efficient value of u.[5] Equation (13) is the intertemporal efficiency condition governing capital accumulation. Notice that the total return to investment is the sum of capital's marginal return ru and the undepreciated component $(1 - \delta(u))$ *less* capital's marginal energy cost $pa(u)$. The economy's resource constraint is equation (14), obtained by substituting equations (9) and (10) into equation (8) while noting the properties of the production function. It shows that the output of final goods y is completely absorbed by consumption, investment, and energy purchases, $c + i + pe$.

The term pe in equation (14) may be interpreted as value added to the production of gross final output y by the rest-of-the-world's energy good. Thus, y-pe is the value added of the domestic economy. In this interpretation, the domestic economy exports final goods to and imports energy goods from the rest of the world. International trade balances each period—the value of exports equals the value of imports, which is pe.[6]

2. QUALITATIVE WORKINGS OF ENERGY PRICE SHOCKS

To provide intuition on how energy price shocks impact on the model economy, particularly on output and real wages, this section discusses the key qualitative effects of a one-time positive innovation leading to a persistent rise in p.

By raising the cost of energy, the p increase engenders sharp simultaneous decreases in e and u [see equations (12) and (5)]. Operating through the production function [see equation (7)], the decline in e directly reduces y and labor's marginal productivity. The fall in labor's marginal productivity induces a reduction in w [see

5. Equation (12) may be rearranged to show p equals the marginal product *less* the marginal depreciation cost of energy usage. Consequently, energy's share of output pe/y is not constant but instead varies inversely with both the depreciation rate δ and capital-output ratio k/y. An interesting implication is that by reducing both δ and k/y, an increase in p causes a *rise* in pe/y. This implication is consistent with the empirical evidence cited in RW.

6. Alternatively, pe may be interpreted as value added by an exogenous domestic energy production sector. But, the intuition is the same as that outlined above.

equation (9)], which in turn works to decrease l [see equation (11)]. e's direct effects on both y and the marginal productivity of labor, coming through the production function, show the sense in which a positive energy price shock translates into a negative technology shock.

Since the rise in p is persistent, the lower levels of e, u, and l propagate into the future, and working through the production function, reduce capital's future marginal productivity. The decline in capital's future marginal productivity causes a fall in capital's future marginal return, ru [see equation (10)], inducing a decrease in the total return to investment, and, thus, decreases in i and k, too [see equation (13)]. All of e's effects mentioned so far involve the direct production channel and, therefore, are quite standard. What is novel to the present model, as discussed earlier, is energy's indirect transmission channel. Energy's indirect transmission channel is integrally related to capital's marginal energy cost, $pa(u)$—part of the return to investment [see equation (13)].[7] This indirect channel manifests itself now because the persistent rise in p also causes a rise in capital's future marginal energy cost, prompting even further reductions in the total return to investment, i and k [see equation (13)].

In short, an increase in p has contractionary effects on economic activity. p's effects, including those on w and y, are potentially significant—even if energy's output share is low. The power of p's force on the economy stems from the energy relationship [equation (5)]—energy is indispensable in obtaining the service flow from capital. Viewing energy in this way creates an indirect channel, working through the stock of capital, in addition to the usual direct production function channel through which movements in energy exert economic effects. Moreover, p's effects are potentially long-lived. The positive autocorrelation of p and k's contraction work together to ensure long-lasting effects from p increases. The remaining question is: how well in practice does the theory explain the effects of energy price shocks? To find the answer, a quantitative investigation of the model economy is next undertaken.

3. CALIBRATION

Before examining the model's ability to explain the empirical evidence, model calibration is necessary. The calibration procedure, advanced by Kydland and

7. To see how energy's indirect channel is integrally related to capital's marginal energy cost, consider the following (dropping time subscripts for simplicity). First, using the energy relationship, equation (5), and the factor-pricing equation, equation (10), rewrite the total return to investment in equation (13) as $(1-\theta)y/k + (1-\delta(u)) - pe/k$—where $(1-\theta)y/k$ is capital's marginal product holding u constant [see equation (2)], $(1-\delta(u))$ is the undepreciated component of capital, and pe/k is capital's marginal energy cost. Second, again using equations (5) and (10), the first-order condition for u, equation (12), may be rearranged to show that energy's output share is $pe/y = (1-\theta)/\upsilon_1 - \delta'(u)uk/(y\upsilon_1)$. Third, substituting pe/y into the investment-return expression above gives an alternative statement of the total return to investment: $(1-\theta)(1-1/\upsilon_1)y/k + (1-\delta(u)) + \delta'(u)u/\upsilon_1$—where the first term is capital's marginal product holding e constant [see equation (7)] and the last term involves the first-order *derivative* of the depreciation function. Comparing the two investment return expressions, notice that pe/k is closely related to the term $\delta'(u)u/\upsilon_1$. But, energy's indirect transmission channel, explained in section 1 is entirely due to the *dependence of depreciation on utilization*. Thus, capital's marginal energy cost is centrally related to energy's indirect transmission channel.

Prescott (1982), assigns values to the model's parameters, variables at their steady state, and p process.[8] Some of these values are drawn from other studies of the U.S. economy. The remaining values are those implied by the model's steady-state relationships. The model's time period is defined as one quarter and the calibration is consistent with this definition.

Table 1 presents most parameter values as well as the values of fundamental steady-state variables. Steady-state variables are denoted using the same notation as before except that time subscripts are omitted. Noting that the net real interest rate equals the rate of time preference in the steady state, Prescott's (1986) measure of the long-run average net real interest rate in the United States at 0.01 per quarter gives $\beta = 0.99$. Although the parameter of relative risk aversion, α, has proven difficult to pin down precisely in the empirical literature, here α is set equal to 2, which falls within the estimated confidence intervals of many empirical studies of the U.S. economy (see, for example, Hansen and Singleton 1983). Depending on how proprietors' income and consumer-durable-service flows are treated, measures of labor's output share, θ, from the U.S. national income accounts range from 0.64 (Prescott 1986) to 0.76 (Lucas 1990); here, the midpoint of this range, $\theta = 0.70$, is chosen. Finn (1998) estimates the quarterly depreciation rate of capital in the United States (1950–1994) from a constant-depreciation-rate version of equation (4); since u and, thus, δ are constant in the steady state, steady-state δ may be equated to the estimated value, $\delta = 0.025$. [Prescott (1986) and Kydland and Prescott (1991) also measure the value of δ to be 0.025.] l is set equal to 0.30, consistent with the time-allocation measurements of Ghez and Becker (1975) for the U.S. economy. The average value of capacity utilization in the United States (since 1953) gives 82 percent for u (see Finn 1996). pe/y is set equal to 4.3 percent, which is the average energy share of output in the U.S. economy (1960-1989) calculated by Finn (1995).[9]

TABLE 1

Parameter and Steady-State-Variable Values

Preferences	Production	Steady-State Variables
$\beta = 0.99$	$\theta = 0.70$	$y = 1.000$
$\alpha = 2.00$	$\omega_0 = 0.04$	$c = 0.774$
$\varphi = 0.32$	$\omega_1 = 1.25$	$i = 0.183$
	$\upsilon_0 = 0.01$	$e = 0.043$, $pe/y = 0.043$
	$\upsilon_1 = 1.66$	$p = 1.000$
		$z = 1.546$
		$l = 0.300$
		$k = 7.322$, $\delta = 0.025$
		$u = 0.820$

8. It is not necessary to calibrate the z process because the quantitative model analysis in Section 4 holds z constant at its steady-state value.

9. Finn (1995) measures energy usage as the sum of electricity, coal, natural gas, and petroleum usage; and output as gross domestic product *plus* energy usage. Both measures pertain to the private *nonenergy* production sector. Some advantages of these measures are that (1) they are *net* of energy production sec-

Given the aforementioned number settings, together with the normalization of y and p at unity, the model's steady-state relationships imply numerical solutions for φ, ω_0, ω_1, υ_0, υ_1 and all remaining steady-state variables reported in Table 1 (see subsection 3.1). p's stochastic process is calibrated so as to exactly match the relative price of energy process estimated by RW using U.S. data (1947:2–1980:3). See RW or subsection 3.2 for a more detailed description of the p process.

Finally, it is necessary to specify the theoretical variables that correspond as closely as possible to the empirical variables underlying the RW facts reported in the next section. In the U.S. data, RW measure output by private value added at constant prices, which unfortunately due to constraints on data availability includes value added by the energy production sector. Currently, the model's closest corresponding variable is value added of the domestic economy at constant energy prices—that is, $y_t - pe_t$, where energy prices are held constant at their steady-state value denoted by p. Because the model's value added consists of final *nonenergy* goods only, it does not closely correspond to the U.S. data's. However, following RW a better correspondence is obtained by adding a proxy for the value added of an energy production sector to the model economy. The proxy is a fraction of energy usage:

$$o_t = s_d e_t \tag{15}$$

where o is value added of the energy production sector and s_d is the share of energy usage that is domestically produced. s_d is set equal to 0.5, as in RW. Thus, the model's value added to be compared with the U.S. data's is

$$y_t - pe_t + po_t = y_t - (1 - s_d)pe_t\,. \tag{16}$$

RW measure real wages in the U.S. data as the nominal wage divided by the private value-added deflator, henceforth referred to as the value-added real wage. The model's real wage w is already implicitly deflated by the price of gross output rather than by the value-added deflator and, consequently, does not match the U.S. data's construct. Drawing on the foregoing analysis and again following RW, the model's value-added real wage may be derived as follows. First, define the relative price of value added in terms of gross output (p^v) as the ratio of value added at current energy prices to value added at constant energy prices:

$$p_t^v = \frac{y_t - (1 - s_d)p_t e_t}{y_t - (1 - s_d)pe_t}\,. \tag{17}$$

Second, divide w by p^v to get the value-added real wage (w^v):

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tor activities, consistent with the theory; (2) energy usage is comprehensive; and (3) by *adding* energy usage to gross domestic product, the output measure is consistent with the theory's gross output y (as opposed to value added $y - pe$).

$$w_t^v = \frac{w_t}{p_t^v}\,. \tag{18}$$

The model's value-added real wage will be compared with the U.S. data's.

3.1 Solving the Model's Steady-State Relationships

This subsection shows how the parameter and steady-state-variable value settings discussed on page 407 (in the second paragraph of section 3) are used together with the model's steady-state relationships to derive values for all remaining parameters and steady-state variables reported in Table 1. The model's key steady-state relationships follow.

$$y = F(zl,\, ku) = (zl)^{\theta}(ku)^{(1-\theta)} \tag{19}$$

$$U(c,\, l) = ([c^{\varphi}(1-l)^{(1-\varphi)}]^{(1-\alpha)} - 1)/(1-\alpha) \tag{20}$$

$$k = (1-\delta(u))k + i, \qquad \delta(u) = \omega_0\, u^{\omega 1}/\omega_1 \tag{21}$$

$$e/k = a(u), \qquad a(u) = \upsilon_0\, u^{\upsilon 1}/\upsilon_1 \tag{22}$$

$$-U_2(c,\, l) = U_1(c,\, l)F_1(zl,\, ku)z \tag{23}$$

$$\delta'(u)k + pa'(u)k = F_2(zl,\, ku)k \tag{24}$$

$$1 = \beta[F_2(zl,\, ku)u + (1-\delta(u)) - pa(u)] \tag{25}$$

$$y = c + i + pe \tag{26}$$

Solving for k. Noting the properties of the production function and substituting $e/k = a$ from equation (22) and $y = 1$, equation (25) gives

$$k = [(1-\theta) - pe/y\,]/[\,\beta^{-1} - (1-\delta)]\,. \tag{27}$$

Equation (27) together with the value settings on page 407 imply $k = 7.322$.

Solving for z, e, i, c, and φ. Equation (19) may be rearranged to show

$$z = y^{(1/\theta)}l^{(-1)}(ku)^{(\theta-1)/\theta}\,. \tag{28}$$

Substituting the values from page 407 and the solution for k into equation (28) implies $z = 1.546$. The values on page 407 directly give: $e = 0.043$. From equation (21) it's easy to see

$$i = \delta k\,. \tag{29}$$

Given the solution for k and δ's value on page 407, equation (29) implies $i = 0.183$. Solving equation (26) for c gives

$$c = y - i - pe \,. \tag{30}$$

Equation (30) together with the solutions for i and e and page 407's value settings imply $c = 0.774$. Noting the properties of the production and utility functions, equation (23) simplifies to give

$$\varphi = 1/[1 + \theta y(1-l)/(lc)] \,. \tag{31}$$

Plugging the solution for c and page 407's value settings into equation (31) gives $\varphi = 0.32$.

Solving for ω_0, ω_1, υ_0, *and* υ_1. There are two main steps to the solution here: (1) solve for ω_1 and υ_1 and (2) solve for ω_0 and υ_0.

Step (1): Noting the properties of the production, δ, and a functions, equation (24) may be more simply written as

$$\omega_1\delta + p\upsilon_1 a = (1-\theta)y/k \,. \tag{32}$$

For now, it is helpful to rewrite the δ function in equation (21) as

$$\delta = h^{\omega 1}/\omega_1 \tag{33}$$

and to rewrite the a function in equation (22) as

$$a = h^{\upsilon 1}/\upsilon_1 \tag{34}$$

where h is a scalar multiple (denoted by s) of u, that is, $h = su$. The value of a is determined from $a = e/k$ in equation (22) and the previous solutions for e and k. Once the solutions for a and k and page 407's value settings are subtituted into equations (32)–(34), one can see that those equations form a system of three nonlinear equations in the three unknowns: ω_1, υ_1, and h. Numerically solving this system gives $\omega_1 = 1.25$, $\upsilon_1 = 1.66$, and a value for h (not interesting to report).

Step (2): Recall from step (1) that: $h = su$ and

$$h^{\omega 1}/\omega_1 = \omega_0 u^{\omega 1}/\omega_1 \,, \tag{35}$$

$$h^{\upsilon 1}/\upsilon_1 = \upsilon_0 u^{\upsilon 1}/\upsilon_1 \,. \tag{36}$$

These last three equations may be solved to find

$$s = h/u \,; \qquad \omega_0 = s^{\omega 1} \,; \qquad \upsilon_0 = s^{\upsilon 1} \,. \tag{37}$$

By using step (1)'s solutions for h, ω_1, and υ_1 and page 407's value setting for u, the equations in (37) give $\omega_0 = 0.04$, $\upsilon_0 = 0.01$, and a value for s (not interesting to report).

3.2 Relative Price of Energy Process

This subsection briefly describes RW's estimated relative price of energy (p) process. When estimating the p process, RW simultaneously want to identify the exogenous component of energy price shocks—exogenous with respect to the U.S. economy. RW argue that this exogenous component is the innovation in *nominal* energy prices that is orthogonal to the innovation in *real* energy prices. To achieve their goals, RW estimate a bivariate vector autoregression for the two stationary series, the logarithm of the real price of energy ($\log p$) and the growth rate of nominal energy prices ($\Delta \log n$). The only current-period regressor in the bivariate autoregression is the current value of $\Delta \log n$ appearing in the equation for $\log p$—thereby rendering the innovations in the two equations orthogonal to each other and, thus, producing the exogenous energy price shock equal to the innovation in $\Delta \log n$. The estimated bivariate vector autoregression using U.S. data from 1947:2–1980:3 (taken directly from RW's Table 1) is

$$\Delta\log n_t = 1.51\Delta\log n_{t-1} + 0.15\Delta\log n_{t-2} - 1.22\log p_{t-1} + 1.19\log p_{t-2}\,; \tag{38}$$

$$\log p_t = 0.98\Delta\log n_t - 0.32\Delta\log n_{t-1} - 0.06\Delta\log n_{t-2} + 1.32\log p_{t-1} - 0.32\log p_{t-2} \tag{39}$$

where, for simplicity, constant terms and trend coefficients have been omitted.

4. EXPLAINING THE FACTS

Using quarterly data on the U.S. economy (1947:2–1980:3), RW estimate the effects of a one-time 1 percent exogenous innovation in nominal energy prices on the relative price of energy, private value added, and the value-added real wage. Their findings are summarized by the three impulse response profiles (together with confidence bands of plus or minus two standard errors) reproduced here in Figures 1–3.[10] The responses, up to ten quarters following the exogenous innovation, are percentage deviations of variables from their average values.

In Figure 1, U.S. real energy prices respond to the exogenous shock in a positive, highly persistent and hump-shaped fashion. Real energy prices increase by almost 1

10. See RW for a complete description of their estimation exercise. Julio Rotemberg kindly provided me with the data on the estimated impulse responses and confidence bands shown in Figures 1–3.

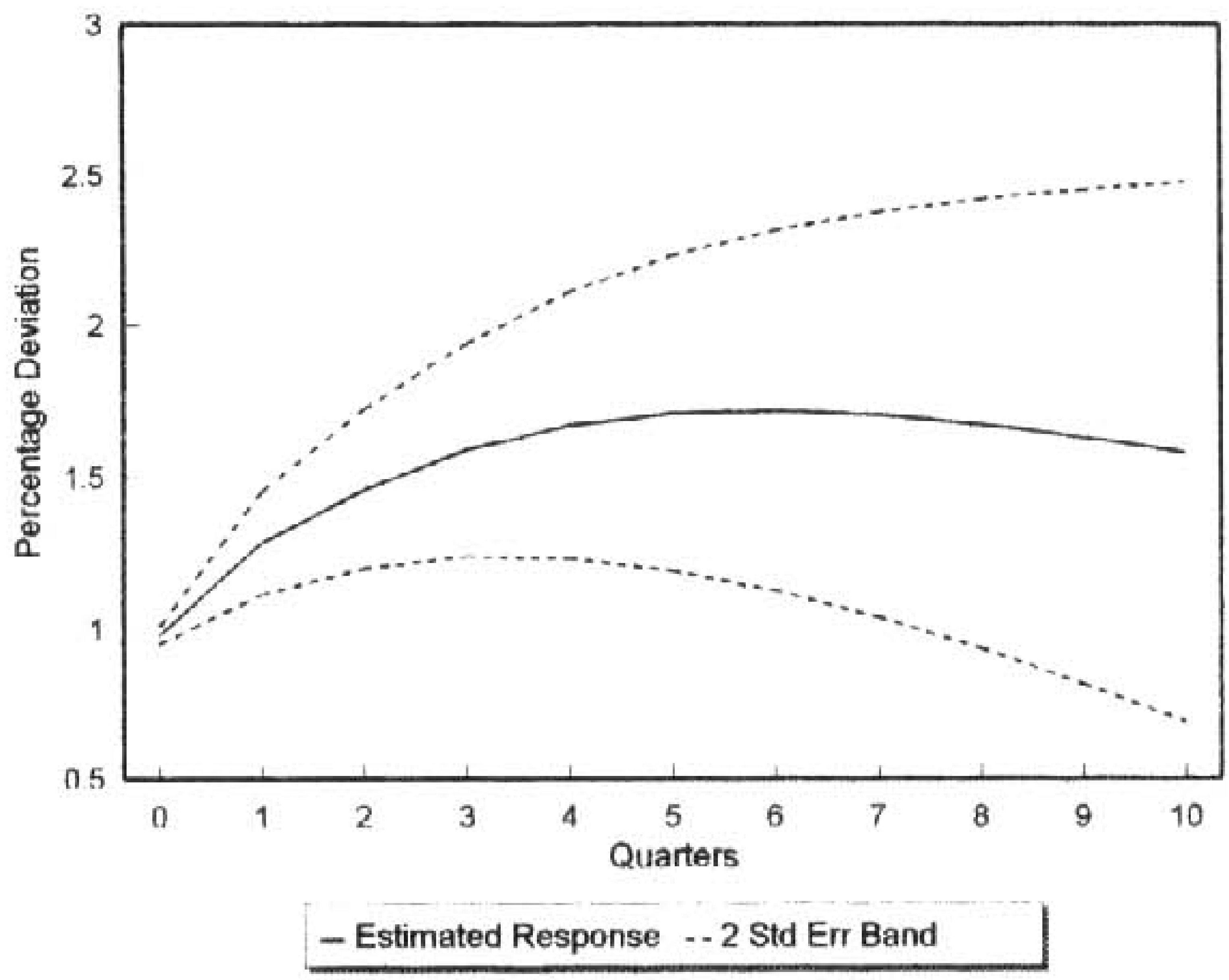

FIG. 1. Estimated Real Energy Price Response

percent on impact; peak at 1.6 percent five to six quarters later and then begin gradually returning to their original value. The response of U.S. private value added to the exogenous innovation, graphed in Figure 2, is a contractionary, long-lasting, and near U-shaped one. At first value added declines by 0.04 percent. Interestingly, as emphasized by RW, the sharpest fall in value added, equaling 0.25 percent, occurs about five to six quarters later—coinciding with the peak of real energy prices. Having reached its minimum, value added begins a slow recovery. Figure 3 shows that the exogenous shock induces a qualitatively similar response in the U.S. value-added real wage to that of U.S. private value added. The impact fall in value-added real wages is 0.03 percent while the severest decline is 0.09 percent five to six quarters after the exogenous shock.

The key questions now are these: Can the perfectly competitive theory with endogenous capital utilization explain the empirical responses manifested in the U.S. data ? Does this new theory better explain the evidence than the standard theory ? Earlier in the paper, the novelty of the new theory is seen to stem from endogenous capital utilization, with the new theory specializing to become the standard theory by holding depreciation constant. Thus, to answer the posed questions, both the perfectly competitive theory with endogenous capital utilization (alternatively referred to as the capital utilization model) and its special case with constant depreciation (alternatively referred to as the constant depreciation model) are simulated. More specifically, both model economies' predictions for the effects of a one-time 1 percent exogenous innovation to nominal energy prices on value added and the value-added real wage are derived. This shock and its effect on real energy prices are

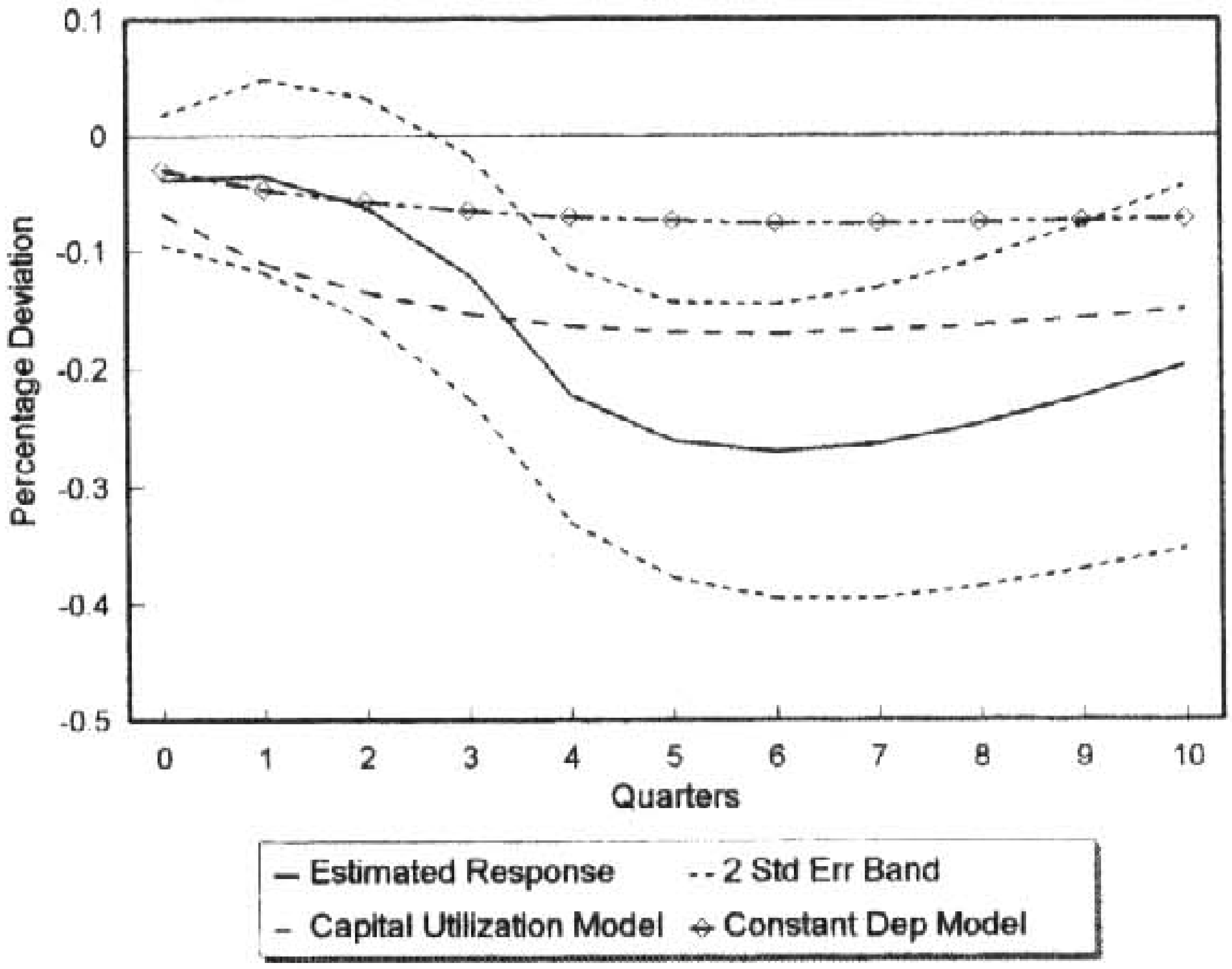

FIG. 2. Estimated and Simulated Value Added Responses

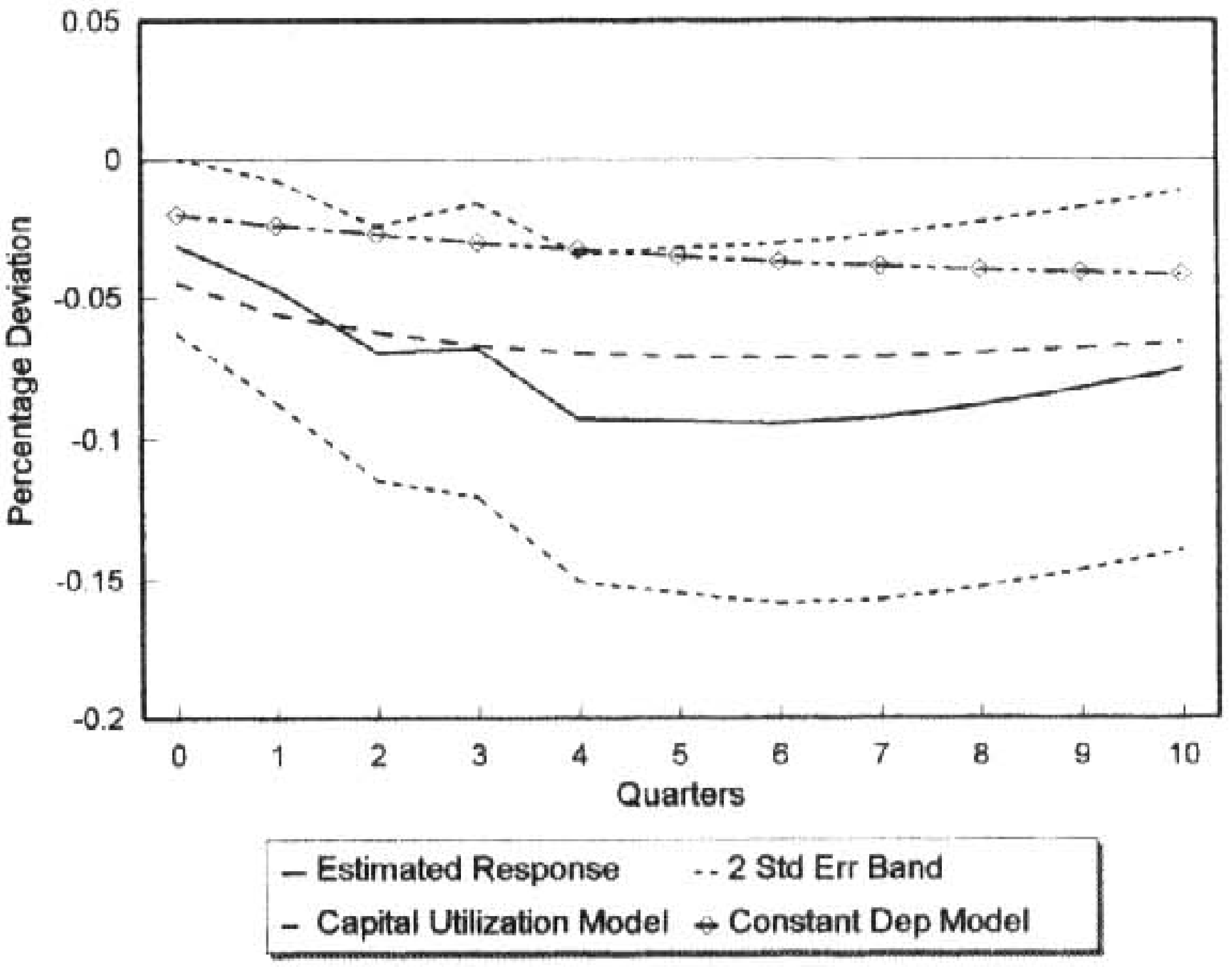

FIG. 3. Estimated and Simulated Real Wage Responses

identical in the model economies and in the U.S. data analysis. The two models' impulse response profiles for value added and the value-added real wage are graphed along with the corresponding U.S. impulse responses in Figures 2 and 3.[11, 12] Responses in the model economies, like those in the U.S. economy, are up to ten quarters following the innovation and are measured in terms of percentage deviations of variables from their average (that is, steady-state) values.

First consider the capital utilization model. Figure 2 shows that the capital utilization model's value added response to the exogenous shock tracks the empirical response quite well. Just like in the U.S. economy, a persistent and almost U-shaped contraction in value added takes place in the model economy.[13] Intuitively, value-added's decline reflects the contractionary effects of the energy price increase on the factors of production. Quantitatively, the model's impact 0.06 percent fall in value added and maximum 0.17 percent decline in value added occurring five to six quarters after the shock well capture U.S. value-added behavior. The capital utilization model predicts the empirical response of the value-added real wage to the exogenous innovation even better, as can be seen from Figure 3. Again just like in the U.S. economy, the value-added real wage's reduction is long-lasting and approximately U-shaped in the model economy. Intuitively, the value-added real wage's fall is due to the declining marginal productivity of labor set in motion by rising energy prices. The model's value-added real wage initially decreases by 0.04 percent and experiences its biggest fall of 0.07 percent five to six quarters later, thereby closely matching the quantitative response of U.S. value-added real wages. The persistency and U-shape of the declines in the model's value added and the value-added real wage seen in Figures 2 and 3 primarily stem from the shape of the energy price shock shown in Figure 1.

Now consider the constant depreciation model. Figures 2 and 3 reveal that the constant depreciation model generally cannot capture the depth of the recession occurring in the U.S. economy. The model's contractions in value added and value-added real wages are mostly significantly smaller than the corresponding U.S. economy's contractions—especially during quarters five to six when the U.S. recession is at its worst.

11. The derivation of each model's impulse responses is described as follows. First, the model economy is log linearized around its steady state and solved using standard methods for systems of dynamic linear equations. Second, it is assumed that the only innovation disturbing the economy is a one-time 1 percent exogenous innovation to nominal energy prices, occurring at date zero. Third, using p's law of motion and the model's solution, the responses of value added and the value-added real wage, up to ten quarters following the innovation, are computed.

12. Sensitivity analysis shows that the two models' impulse responses are robust to small variations in the parameters: relative risk aversion, α, and labor's output share, θ.

13. The U-shaped response of value added to the positive energy price shock in the present model possibly brings to mind the hump-shaped response of output to positive technology or government spending shocks in the Burnside and Eichenbaum (1996) model. Because capital utilization plays an important role in the two models' transmission processes, one may be tempted to think that capital utilization drives the nonlinear output responses in each case. However, the mechanism responsible for the nonlinearity differs across the two models. Predetermined employment generates the hump-shaped output response in Burnside and Eichenbaum (1996) (see Cogley and Nason 1995) while the hump-shaped real energy price process (see Figure 1) causes the U-shaped value-added response in the present model.

The perfectly competitive theory with endogenous capital utilization well explains the RW facts. It is considerably more successful in explaining these facts than is the standard theory.

5. CONCLUSION

Historically, energy price increases appear to cause substantial and persistent recessions in economic activity. For instance, Rotemberg and Woodford (1996) estimate that a 1 percent innovation in energy prices engenders declines in U.S. output of 0.25 percent and in U.S. real wages of 0.09 percent about five to six quarters later. Rotemberg and Woodford (1996) advance a theory of imperfect competition to explain these facts. The present study shows that a theory of perfect competition explains this evidence, too. Therefore, Rotemberg and Woodford's (1996) evidence on the effects of energy price increases on U.S. economic activity does not in and of itself provide a basis for discriminating between the usefulness of the ideas of perfect and imperfect competition.

At the heart of the perfectly competitive theory in this paper is the popular and intuitive idea that an increase in the price of energy works much like an adverse technology shock to induce contraction in economic activity. But the power and persistency of the force exerted by energy price shocks derives from the novel relationship between energy usage and capital services—energy is essential to obtaining the service flow from capital, and capital services play an important role in the economy.

Of course, many questions concerning the effects of energy price shocks remain to be tackled. In particular, questions involving the apparent asymmetry in the relationship between energy prices and the economy, as Mork (1989) documents. Addressing these remaining questions may clearly identify a winner amongst perfectly competitive versus imperfectly competitive theories. For now, this task is left to future research.

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