# THE ROLE OF ENERGY IN REAL BUSINESS CYCLE MODELS

In-Moo Kim and Prakash Loungani

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# The Role of Energy in Real Business Cycle Models*

In-Moo Kim
University of Florida, Gainesville, FL 32611

Prakash Loungani
Federal Reserve Bank of Chicago, Chicago, IL 60604

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Abstract

This paper modifies Hansen's (1985) analysis of a real business cycle model with indivisible labor by explicitly including energy as a productive input and modelling the relative price of energy as an exogenous random process. One goal is to determine the extent to which the introduction of energy price shocks reduces the reliance of the real business cycle model on unobserved technology shocks. The other goal, following Christiano and Eichenbaum (1991), is to compare the correlation between real wages and hours predicted by the energy-inclusive model to that predicted by Hansen's model.

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## 1. Introduction

In recent years macroeconomists have pursued a line of inquiry which views business cycles as arising from variations in the rate of change of technology. Kydland and Prescott (1982) show that if the neoclassical growth model [Solow (1956)] is modified to include a stochastic shock to technology, the model is capable of replicating many of the features of modern business cycles. The real business cycle (RBC) model of Kydland-Prescott has been extended in several directions. An important extension is the introduction of labor indivisibilities into the model [Hansen (1985)]. Other RBC models allow for home production [Benhabib, Rogerson and Wright (1990)], inventory fluctuations [Christiano (1988)] and preference shocks [Benzivinga (1988)]. Cooley and Hansen (1989) incorporate money into the model using a cash-in-advance constraint. The basic model has also been extended to the study of open economies [Stockman (1990)]. King, Plosser and Rebelo (1988a, 1988b) elaborate upon the dynamics of the RBC model in response to technology shocks and outline several additional extensions of the model.

The assumption in the Kydland-Prescott-Hansen models that business cycles are driven largely by stochastic shocks to technology is controversial. A common criticism is that Solow residuals, which are used as the measure of technology in these models, reflect labor hoarding and other "off the production function" behavior rather than the state of technology [Summers (1986), Mankiw (1989)]. In a recent survey, McCallum (1989) points out that "the literature that followed Solow's 1957 contribution indicated that the magnitude of technical changes would be strongly overstated by the Solow procedure unless steps were taken to correct for certain neglected effects" such as adjustment costs and aggregation errors. McCallum also argues that reflection on the nature of technological change would lead one to the view that the variability of the economy-wide technology shock is fairly small.[1]

To summarize, there seems to be some skepticism among economists both on the issue of whether Solow residuals truly reflect the state of technology and also on whether the variance of the aggregate technology shocks can be as large as assumed in the Kydland-Prescott-Hansen models.

One of the goals of this paper is to see how important technology shocks are to the basic real business cycle model, once the model is extended to allow for the possibility of other real shocks. In particular, we consider the role of energy price shocks, the very shocks that triggered the resurgence of interest in real factors as causes of business cycles. The potential importance of

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[1] McCallum writes: "... the point is that highly distinctive technologies involving entirely different types of machines (and other sorts of capital) are used in different industries -- and for different products within the same industry. Accordingly, any specific technological discovery can impact on the production function for only a few products. According to this perspective, RBC models should be formulated so as to recognize that there are many different productive sectors whose technology shocks should presumably be nearly independent. Averaging across industries, then, the economy-wide technology shock would have a variance that is small in relation to the variance for each industry, much as the mean of a random sample of size n has a variance that is only 1/n times the variance of each observation."

these shocks in causing U.S. business fluctuations became apparent in the 1970's and early 1980's. Furthermore, Hamilton (1983) has shown that energy prices have Granger-caused output and unemployment even in the pre-OPEC period 1947 to 1973. Hamilton also presents evidence on the exogeneity of energy price movements over this period. These findings have to a large extent been corroborated in subsequent statistical analyses by Burbidge and Harrison (1984), Santini (1985), and Gisser and Goodwin (1986).

The case for incorporating energy price shocks into the real business cycle models has been made persuasively by McCallum (1989):

> "There is one prominent type of "supply-side" disturbance that has effects across a very wide category of industries, namely, a change in the real price that must be paid for imported raw materials - especially, energy. The oil price shocks of 1974, 1979 and 1986 clearly have had significant impact on the U.S. economy at the aggregate level. And since the Kydland-Prescott and Hansen models have no foreign sector, such effects are treated by their analyses as "residuals" -- shifts in the production function. Such a treatment is, however, avoidable since these price changes are observed and are documented in basic aggregate data sources. It is also analytically undesirable: to lump input price changes together with production function shifts is to blur an important distinction. Presumably future RBC studies will explicitly model these terms-of-trade effects and thereby reduce their reliance on unobserved technology shocks."

A second motivation for looking at shocks other than technology is provided by the recent work of Christiano and Eichenbaum (1991). They state that "the single most salient shortcoming" of existing RBC models is that they predict the correlation between real wages and hours to be in excess of 0.9 whereas the correlation in the data is essentially zero. Christiano and Eichenbaum suggest that one way to bring the theory closer to the data is "to find measurable economic impulses that shift the labor supply function." They find that incorporating shocks to government spending performs this function by substantially reducing the correlation between real wages and hours predicted by the model. We show below that incorporating an exogenous shock to oil prices, which leads to shifts in both labor demand and labor supply, also reduces the predicted correlation between real wages and hours. Furthermore, the magnitude of the reduction is comparable to that achieved by introducing government spending shocks.

The remainder of this paper is organized as follows. Section 2 presents the properties of the data that the model will attempt to replicate. Section 3 extends the basic RBC model and discusses the choice of parameter values. In Section 4, the model is simulated under the assumption that there are stochastic shocks to technology and also to the relative price of energy. An additional experiment that we carry out is to see how much of the volatility of output can be explained by the energy price shocks alone.

## 2. Cyclical Properties of the Data

Table 1 summarizes the statistical properties of U.S. business cycles using annual data for the period 1949 to 1987. In addition to the usual variables, the table introduces two additional series. The first is energy use, which is measured as the BTU consumption of fossil fuels (that is, petroleum, coal and natural gas). Our use of annual data was motivated by the fact the energy use series was available only on an annual basis. The energy price variable is the dollar price of fossil fuels per BTU divided by the GNP deflator.

The first column of the table gives the standard deviations ("volatility") of several macroeconomic variables, measured as deviations from trend, and the second column gives the correlation between each variable and output. Before the statistics were calculated, all the data were logged and detrended using the Hodrick-Prescott filter.[2] Columns (3) and (4) provide the same information for the data set used in Hansen (1985). The major qualitative discrepancy that emerges is in the volatility of hours relative to productivity. For our data set, productivity and hours are about equally volatile. On the other hand, the higher volatility of hours relative to productivity is considered to be a "stylized fact" of business cycles in previous RBC studies.[3]

With regard to the energy variables, the key properties are:
(1) Energy use is slightly more volatile than output.
(2) Energy prices are highly volatile; energy prices and output are negatively correlated with a point estimate of -0.44.

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[2] Since our timing interval is annual, we follow Costello (1989) in setting the smoothing parameter in the Hodrick-Prescott filter equal to 400.

[3] Appendix A examines the reasons for this discrepancy.

Table 1
Properties of Detrended U.S. Data: 1949-1987

| Variable | Annual Data 1949 to 1987 Std. (1) | Corr. (2) | Quarterly Data 1955:3 to 1984:1 Std. (3) | Corr. (4) |
|---|---|---|---|---|
| Output | 2.95 | 1.00 | 2.95 | 1.00 |
| Consumption | 1.83 | 0.77 | 2.16 | 0.85 |
| Investment | 6.53 | 0.82 | 14.41 | 0.92 |
| Capital | 1.00 | 0.19 | 1.06 | 0.04 |
| Hours | 1.80 | 0.85 | 2.78 | 0.76 |
| Productivity | 1.88 | 0.79 | 1.98 | 0.42 |
| Energy Use | 3.64 | 0.72 | . | . |
| Energy Price | 17.76 | -0.44 | . | . |
| Corr(h,w) | 0.28 | | -0.20 | |

**Key**: (1) Percent standard deviation, annual data
(2) Correlation with output, annual data
(3) Percent standard deviation, quarterly data
[Figures reported in Hansen (1985) are scaled up by 1.676]
(4) Correlation with output, quarterly data [Hansen (1985)]

**Notes**: All data are logged and detrended using the Hodrick-Prescott filter.
Corr(h,w) = correlation between hours and real wages (productivity).

**Data Sources**:
Output: Real GNP, Table C-2 in Economic Report of the President (ERP), 1990;
Consumption: Real personal consumption expenditures, Table C-2, ERP;
Investment: Real nonresidential fixed private investment, Table C-2, ERP;

Capital: Real gross stock of nonresidential fixed private capital, 1949-84 from Survey of Current Business (SCB), January 1986, 1985-87 from SCB, August 1989.
Hours: Manhours of employed labor force, household data, Citibase label LHOURS;
Productivity: Output divided by hours;

Energy Use: Consumption of fossil fuels measured in BTU, Table 3, in Annual Energy Review (AEnR), 1989, Energy Information Administration.
Energy Price: Fossil fuel price divided by GNP deflator, Table 27, AEnR.

Corr(h,w): annual correlation uses Hours and Productivity series described above; quarterly correlation is from Christiano and Eichenbaum (1991, Table 4a)

## 3. The Kydland-Prescott-Hansen Economy with Energy Price Shocks

A. The Model Economy

The model to be described in this section is an extension of Hansen's (1985) indivisible labor economy. The production technology of firms is described by a nested CES function with constant returns to scale:

$$y = \tau h^{\theta}[(1-a)k^{-v} + ae^{-v}]^{-(1-\theta)/v} \tag{1}$$

In addition to the usual inputs, labor (h) and capital (k), production is assumed to require the use of energy (e). The parameter v is equal to (1-s)/s, where s is the elasticity of substitution between capital and energy. Labor's distributive share is given by the parameter $\theta$. This functional form allows us, potentially, to relax the assumption of unitary elasticity of substitution between capital and energy that would be imposed by a Cobb-Douglas function.

The law of motion of the stochastic technology shock, $\tau$, is assumed to be:

$$\tau_t = \alpha_0 + \alpha_1\tau_{t-1} + \varepsilon_t \tag{2}$$

where the $\varepsilon$'s are i.i.d with standard deviation $\sigma$. The relative price of all energy used in the economy, p, is given exogenously and follows the process,

$$p_t = \gamma_0 + \gamma_1 p_{t-1} + \Phi_t + \eta\Phi_{t-1} \tag{3}$$

with an error variance of $\sigma_p$. The reason for picking this particular process is discussed later in the paper.

Capital accumulates according to the law of motion:

$$k_t = (1-\delta)k_{t-1} + i_t \tag{4}$$

where $0 < \delta < 1$ is the depreciation rate and $i_t$ is period t investment. The economy's resource constraint for period t is given by

$$c + i + pe \leq y \tag{5}$$

where c is consumption.

Households in the economy are infinitely-lived and have preferences defined over consumption and leisure. Each household's endowment of time is normalized to 1 so that leisure is equal to 1-h. In the RBC literature, two alternate assumptions are made about the sources of variation in aggregate hours worked. In the first economy - the divisible labor economy - all variations in aggregate hours come from changes in the hours worked per household (the intensive margin). In this case, the period t utility function is given by:

$$U(c,h) = \log c + A\log(1-h) \tag{6}$$

In the second economy--the indivisible labor economy--it is assumed that individuals can work either full time, $h_0$, or not at all. Hence all variations in aggregate hours come from changes in the number of people employed (the extensive margin). In this economy, the household's period t expected utility is given by

$$U(c,\pi) = \log c + A\pi\log(1-h_0) \tag{7}$$

where $\pi$ is the probability of working. Rogerson (1984, 1988) and Hansen (1985) discuss the properties of this economy in greater detail.

The indivisible and the divisible labor economies represent polar cases. In the real economy, about 75% of the aggregate labor fluctuation is due to changes in employment and the remainder due to changes in hours per person [Cho and Cooley (1988)]. In the interest of brevity we present simulation results for the indivisible labor economy only.

B. Model Calibration

Following Kydland and Prescott's approach, we calibrate the model based on microeconomic evidence and also on long-run considerations, i.e., we require that values for the parameters are chosen such that the model steady state values are close to average values for the U.S. economy over the data period being studied. For this purpose, we compute the steady state for the model. The first-order conditions for firms' profit maximization imply that the marginal products of the three inputs are set equal to their respective prices:

$$y_k = (1-a)(1-\theta)y/[...]k^{-v-1} = r+\delta \tag{8}$$

$$y_e = a(1-\theta)y/[...]e^{-v-1} = p \tag{9}$$

$$y_h = \theta y/h = w \tag{10}$$

The expression [...] is equal to $[(1-a)k^{-v} + ae^{-v}]$. The first-order condition for households' utility maximization gives:

$$c/w = (1-h)/A \tag{11}$$

Finally, in steady state, there is no net investment:

$$c = y - \delta k - pe \tag{12}$$

Using equations (8) to (12), the steady state values of y, c, k, e, and h can be obtained as:

$$y^* = b_4\tau^{1/\theta}h^* \tag{13}$$

$$c^* = (b_4-\delta b_3-pb_1b_3)\tau^{1/\theta}h^* \tag{14}$$

$$k^* = b_3\tau^{1/\theta}h^* \tag{15}$$

$$e^* = b_1b_3\tau^{1/\theta}h^* \tag{16}$$

$$h^* = \theta/(\theta+Ab_5) \tag{17}$$

The b's are functions of p and of the underlying parameters of the model:

$$b_1 = \{[(r+\delta)/p].[a/(1-a)]\}^{1/v+1} \tag{18}$$

$$b_2 = 1-a+ab_1^{-v} \tag{19}$$

$$b_3 = \{[(1-\theta)(1-a)/(r+\delta)].b_2^{-(1-\theta-v)/v}\}^{1/\theta} \tag{20}$$

$$b_4 = b_2^{-(1-\theta)/v}/b_3^{(1-\theta)} \tag{21}$$

$$b_5 = (b_4-\delta b_3-pb_1b_3)/b_4 \tag{22}$$

We begin by discussing the procedure used to pick a range of values for v and a. Equations (15) and (16) imply that the steady state energy/capital ratio, $e^*/k^*$, is $b_1$. The average energy/capital ratio for the U.S. economy over the sample period is 0.02. We use this as an estimate of $b_1$. Then, from equation (18), it is clear that for every choice of v, there is a corresponding value of a that satisfies that equation, given the values of the other parameters and the expected value of p.[4] We then restrict this set of combinations of v and a by using existing microeconomic evidence on possible values of v. This evidence is summarized in Table 2.[5]

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[4] From equation (3) above, the expected value is $\gamma_0/(1-\gamma_1)$. As discussed later in the paper, we set $\gamma_0$=0.143 and $\gamma_1$=0.896.

[5] We used the recent survey by Apostolakis (1990) to identify some of the important studies. We restricted our attention to studies that used U.S. data and that reported a value for the Allen elasticity of substitution between energy and capital. Some other studies are not referenced in Table 2 because they provided estimates that were similar to the ones cited in the table; for instance, Pindyck's (1979) estimates were similar to those of Griffin and Gregory (1976).

**Table 2: Model Calibration**

| Authors | (1) A.E.S. | (2) v | (3) $c^*/y^*$ | (4) $h^*$ | (5) $k^*/y^*$ |
|---|---|---|---|---|---|
| Berndt and Wood(1979) | -3.20 | -3.0* | 1.00 | 0.34 | 0.00 |
| Morrison and Berndt(1981) | -0.08 | 0.7 | 0.62 | 0.34 | 2.99 |
| Griffin and Gregory(1976) | 1.00 | 0.0# | 0.73 | 0.31 | 2.15 |
| Average, U.S. data | . | . | 0.61 | . | 1.80 |

Key: (1) Estimate of Allen elasticity of substitution
(2) Estimate of parameter "v" implied by (1)
(3) Value of $c^*/y^*$
(4) Value of $h^*$
(5) Value of $k^*/y^*$

Notes:
* Since v=-3 is outside the admissible range of parameter values, the value used to compute the steady state is v=-.99.

# Since the steady state cannot be computed if v is exactly zero, the value actually used is v=.001.

Column (1) shows the estimates of the Allen elasticity of substitution given in three representative empirical studies while column (2) provides the value of v implied by these estimates.[6] For each estimate of v we calculate, using equations (13) through (17) above, the steady state value of c/y, h and k/y. These are reported in columns (3) through (5), respectively, along with the average values of c/y and k/y for the U.S economy. It is evident that the negative value of v grossly violates estimates of other steady state relationships and hence we exclude it from consideration. We present results for the two other cases, v=0.001 and v=0.7.

[6] Sato (1967) shows that for the CES production used above, the Allen elasticity of substitution is equal to $1-[v/((1-\theta)(1+v))]$. Following Hogan (1979), we assume that the CES function is a reasonable approximation to the more flexible translog form used in the empirical studies and that the results for the manufacturing sector extend to the full economy.

The remaining parameters are chosen in conformity with earlier studies. The parameter $\theta$, labor's share in production, is set equal to 0.64, the depreciation rate is assumed to be 10% a year and the annual discount factor is set equal to 0.96. The parameter A in the utility function i set equal to 2.

## 4. Cyclical Properties of the Model

A. Specification of the Price and Technology Processes

To investigate the cyclical properties of the model, we have to specify the parameters of the technology and the energy price processes. To determine a suitable process for the relative price of energy, we fit several ARMA processes to the actual data on p for the period 1949 to 1987. The following model best fits the data:

$$p_t = \gamma_0 + \gamma_1 p_{t-1} + \Phi_t + \eta\Phi_{t-1}$$

The estimated coefficients of this model are $\gamma_0 = 0.143$, $\gamma_1 = 0.896$ and $\eta = 0.408$ with asymptotic standard errors of 0.103, .073 and 0.180 respectively.[7] The error variance, $\sigma_p$, is 0.15.

The parameter $\alpha_1$ in the technology process is set equal to the first-order serial correlation coefficient of Solow residuals, which are measured using actual data on output, capital, hours and

[7] Said and Dickey (1984) showed that the unit root estimator from an ARMA(1,1) process has the asymptotic distribution tabulated by Dickey-Fuller. Using an augmented Dickey-Fuller test, we *cannot*, at a 1% level of significance, reject the null hypothesis of a unit root in the price process. With only 39 observations, this test has very low power against an alternate hypothesis that the autoregressive parameter is, say, 0.4. Nevertheless it may be fruitful, in future research, to develop versions of our model which can accommodate nonstationarity in the price process.

energy. It should be noted that the Solow residuals series--and hence the estimate of $\alpha_1$--changes when the value of v is changed. In practice, the values of $\alpha_1$ were 0.939 and 0.955, corresponding to values of v equal to .7 and .001 respectively.[8]

B. Simulation Results

For the indivisible labor economy, the stochastic social planning problem can be written as:

$$\max \Sigma \beta^t U(c,\pi) \tag{23}$$

subject to (1)-(5). The state of the economy in period t is described by $k_t$, $\tau_t$, $p_t$ and $\Phi_t$. The decision variables are $h_t$, $i_t$, $e_t$ and $c_t$. Since the problem cannot be solved analytically to obtain the decision rules, we construct a linear quadratic approximation to the problem in the neighborhood of the deterministic steady state; this problem yields linear decision rules. Details on the linear-quadratic approximation procedure are given in Christiano (1990).

The approximate problem is simulated by feeding in realizations of the stochastic processes of $\tau_t$ and $p_t$. The artificial time series that are generated are then logged and detrended using the Hodrick-Prescott filter. Finally, we compute the standard deviations of the detrended series and their correlations with output. The simulation exercise is repeated 50

[8] The associated standard errors are .014 and .011 respectively. In both cases we *can*, at a 1% level of significance, reject the null hypothesis of a unit root in the technology process using a Dickey-Fuller test. However, using an augmented Dickey-Fuller test (i.e., including a time trend and lagged differences as explanatory variables), we *cannot* reject the null of a unit root.

times to obtain samples of artificially generated time series. Each sample has 39 periods--the same number of periods as the actual data period being studied. The numbers reported in the tables below are averages over the 50 simulations.

We present results for three model economies, the first of which is simply the Hansen indivisible labor economy augmented to include energy inputs. For this model, the standard deviation of the error term in the technology shock, $\sigma$, is picked to match the standard deviation of Solow residuals, measured using actual data on output, capital, hours and energy for the 1949-87 period. It is important to remember that the Solow residuals series--and hence the estimate of $\sigma$--changes when the value of v is changed. For convenience we refer to this economy as the basic RBC model.[9]

The other two economies allow for positive values of $\sigma_p$, the standard deviation of the error term in the relative price of energy process. In both models $\sigma_p$ is picked to match the actual volatility of energy prices over the 1949-87 period. The models differ in their assumptions about $\sigma$. Energy Model I allows for both technology and energy price shocks; in this model, $\sigma$ is picked to match the standard deviation of Solow residuals in the actual data. In Energy Model II, $\sigma$ is set equal to zero, i.e., the model abstracts completely from stochastic shocks to technology.

In evaluating the energy models, we focus our attention on the following two features. First, how much of the volatility of output

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[9] This model holds the relative price of energy constant at its expected value, determined from equation (3) to be equal to $\gamma_0/(1-\gamma_1)$. We set $\gamma_0$=0.143 and $\gamma_1$=0.896.

is explained by these models? As stated in the introduction to the paper, one motivation for introducing energy price shocks is to determine the extent to which they reduce the basic RBC model's reliance on unobserved technology shocks. If the energy-inclusive model, Energy Model I, leads to a substantial increase in the percentage of output volatility explained, then it could be argued that the technology shock measure used in RBC studies is largely a proxy for exogenous energy price shocks. Second, does the model reduce the predicted correlation between hours and real wages ? Christiano and Eichenbaum (1989) point to the basic RBC model's prediction of a strong positive correlation between hours and real wages as an important shortcoming of the model since the correlation in the data is fairly small.

As discussed in the section on model calibration, the two alternate values of v to be considered are .001 and 0.7. Table 3 presents the results for the first case, v=.001. This estimate of v implies that the elasticity of substitution between energy and capital (s) is nearly unitary and hence this case is fairly close to a Cobb-Douglas specification with three inputs. As is familiar from earlier work, the basic RBC model does a good job of replicating the broad features of the data. For example, investment is far more volatile than consumption and the correlation between output and capital predicted by the model is close to that observed in the data. However, the model substantially understates the volatility of hours. With regard to the features of interest, (i) stochastic variations in technology account for about 80% of the volatility of output and (ii) the correlation between hours and real wages predicted by the model is 0.8. Next, we consider the implications of adding an energy price shock to the basic model. The first important finding is that the percentage of output volatility explained rises from 80% to 90%. Second, the predicted correlation between hours and real wages drops from 0.8 to 0.66, a 17% reduction in the point estimate. To provide some assessment of the quantitative importance of this reduction, note that the introduction of government spending shocks lowers the point estimate of the correlation by about 20% [Christiano and Eichenbaum (1991), Table 4a].

Energy Model II abstracts completely from stochastic variations in technology. The results show that a model with energy price shocks alone explains about 35% of the volatility of output. Also, the correlation between hours and wages drops to about 0.3. We offer some conjectures on the mechanism whereby energy price shocks deliver a much lower correlation between hours and real wages than that delivered by technology shocks. Broadly speaking, technology shocks shift both labor demand and labor supply but the impact on labor demand is the dominant one. This leads to a strong positive correlation between hours and real wages in the basic RBC model. In Energy Model II, a change in energy prices, say an increase, also affects both labor demand and labor supply. Labor demand shifts to the left--assuming that the "income" or "scale" effect from the reduction in output outweighs the substitution effect--and labor supply shifts to the right because of the negative wealth effect from increased energy import costs. Hence, the impact on real wages is unambiguous but the impact on hours is not. In some simulations of this model the correlation between hours and real wages was negative, suggesting that the effect on labor supply was fairly strong; however, as noted above, the average correlation over the 50 simulations of the model is about 0.3.

To test these conjectures we investigated the impact on the hours/wages correlation of (counterfactually) lowering $\gamma_1$ and thereby reducing the persistence of the energy price shock. This should attenuate the wealth effect and raise the correlation. The evidence is supportive: We find that setting $\gamma_1$=0.5 raises the correlation to 0.65 (s.e .066) and setting $\gamma_1$=0.01 raises it further to 0.708 (s.e .076).

Table 4 presents the results for the case of v=0.7; this implies an elasticity of substitution (s) of about 0.6 and hence involves a substantial departure from the Cobb-Douglas assumption. We refer to this case as the "CES" case. Note that the predicted volatility of energy use is fairly close to that in the data, which was not the case when v was set equal to .001.

The addition of energy price shocks to the Hansen model raises the percentage of output volatility by a modest amount, from 69% to 72%. The predicted correlation between hours and wages drops from 0.75 to 0.68, a 11% reduction in the point estimate. Energy Model I now explains 16% of the volatility of output, and the hours-wages correlation falls further to 0.2.

**Table 3: Simulation Results**
**"Cobb-Douglas" case (v=.001)**
**["High" elasticity of substitution between energy and capital]**

| | U.S. Data | | Basic RBC | | Energy I | | Energy II | |
|---|---|---|---|---|---|---|---|---|
| | std. | corr. | std. | corr. | std. | corr. | std. | corr. |
| **Output** | **2.95** | **1.00** | **2.38** | **1.00** | **2.63** | **1.00** | **1.02** | **1.00** |
| | | | (.43) | (.00) | (.51) | (.00) | (.26) | (.00) |
| **Consumption** | **1.83** | **0.77** | **1.85** | **0.98** | **2.18** | **0.94** | **1.01** | **0.79** |
| | | | (.38) | (.01) | (.48) | (.03) | (.34) | (.08) |
| **Investment** | **6.53** | **0.82** | **4.51** | **0.97** | **5.42** | **0.94** | **2.95** | **0.92** |
| | | | (.81) | (.01) | (.99) | (.02) | (.48) | (.03) |
| **Capital** | **1.00** | **0.19** | **0.98** | **0.18** | **1.21** | **0.18** | **0.63** | **0.08** |
| | | | (.27) | (.12) | (.37) | (.17) | (.20) | (.19) |
| **Hours** | **1.80** | **0.85** | **0.91** | **0.92** | **1.15** | **0.87** | **0.69** | **0.86** |
| | | | (.16) | (.03) | (.20) | (.04) | (.10) | (.04) |
| **Productivity** | **1.88** | **0.79** | **1.59** | **0.97** | **1.72** | **0.94** | **0.56** | **0.72** |
| | | | (.32) | (.01) | (.37) | (.02) | (.17) | (.16) |
| **Energy Use** | **3.64** | **0.72** | **1.81** | **0.99** | **11.03** | **0.53** | **11.05** | **0.93** |
| | | | (.34) | (.00) | (2.98) | (.19) | (3.21) | (.03) |
| **Energy Price** | **17.76** | **-0.44** | . | . | **17.27** | **-0.36** | **17.27** | **-0.86** |
| | | | | | (7.81) | (.24) | (7.81) | (.06) |
| $\sigma$ | 0.0162 | | 0.0162 | | 0.0162 | | 0.0000 | |
| $\sigma p$ | 0.1500 | | 0.0000 | | 0.1500 | | 0.1500 | |
| **Corr(h,w)** | | | | | | | | |
| **Mean** | **0.282** | | **0.798** | | **0.659** | | **0.306** | |
| (std. dev.) | | | (0.057) | | (0.088) | | (0.217) | |

Key: $\sigma$ = standard deviation of Solow residuals series
$\sigma p$= standard deviation of energy price process
Corr(h,w) = correlation between hours and real wages

**Table 4: Simulation Results**
**"CES" case (v=0.7)**
**["Low" elasticity of substitution between energy and capital]**

| | U.S. Data std. | U.S. Data corr. | Basic RBC std. | Basic RBC corr. | Energy I std. | Energy I corr. | Energy II std. | Energy II corr. |
|---|---|---|---|---|---|---|---|---|
| **Output** | **2.95** | **1.00** | **2.05** (.38) | **1.00** (.00) | **2.13** (.40) | **1.00** (.00) | **0.48** (.12) | **1.00** (.00) |
| **Consumption** | **1.83** | **0.77** | **1.76** (.35) | **0.99** (.00) | **1.96** (.42) | **0.96** (.02) | **0.75** (.23) | **0.95** (.02) |
| **Investment** | **6.53** | **0.82** | **3.81** (.65) | **0.95** (.02) | **4.51** (.80) | **0.90** (.05) | **2.33** (.47) | **0.93** (.02) |
| **Capital** | **1.00** | **0.19** | **0.78** (.21) | **0.22** (.13) | **0.98** (.30) | **0.24** (.19) | **0.54** (.17) | **0.34** (.15) |
| **Hours** | **1.80** | **0.85** | **0.64** (.11) | **0.88** (.04) | **0.70** (.12) | **0.84** (.07) | **0.27** (.05) | **0.70** (.11) |
| **Productivity** | **1.88** | **0.79** | **1.53** (.31) | **0.98** (.00) | **1.60** (.35) | **0.97** (.01) | **0.36** (.12) | **0.83** (.05) |
| **Energy Use** | **3.64** | **0.72** | **0.94** (.20) | **0.96** (.01) | **5.19** (1.21) | **0.41** (.21) | **5.13** (1.21) | **0.99** (.00) |
| **Energy Price** | **17.76** | **-0.44** | . | . | **17.27** (7.81) | **-0.25** (.25) | **17.27** (7.81) | **-0.94** (.04) |
| **σ** | 0.0153 | | 0.0153 | | 0.0153 | | 0.0000 | |
| σp | 0.1500 | | 0.0000 | | 0.1500 | | 0.1500 | |
| **Corr(h,w)** **Mean** (std. dev.) | **0.282** | | **0.753** (0.067) | | **0.676** (0.119) | | **0.173** (0.161) | |

Key: σ = standard deviation of Solow residuals series
σp= standard deviation of energy price process
Corr(h,w) = correlation between hours and real wages

## 5. Conclusions

In the introduction to this paper we referred to McCallum's suggestion that real business cycle (RBC) models, of the type popularized by Kydland-Prescott and Hansen, should explicitly model exogenous energy price changes. In this paper we have implemented this suggestion in the simplest possible way: energy is included as an input in the production function and the relative price of energy is modelled as an exogenous stochastic process. The parameters of the model are chosen to be consistent with microeconomic evidence and with certain historical averages for the U.S. economy. We find that the inclusion of energy price shocks leads to only a modest reduction in the RBC model's reliance on unobserved technology shocks. The addition of energy price shocks raises the percentage of output volatility explained by the basic RBC model by about 13% (from 80% to 90%) in the Cobb-Douglas case (s=1) and by 4% in the CES case (s=0.6).

We also find that the inclusion of energy price shocks in the basic RBC model lowers the predicted correlation between hours and real wages by 11% in the CES case and 17% in the Cobb-Douglas case. The latter figure is comparable to the reduction achieved by Christiano and Eichenbaum (1991) through the introduction of government spending shocks.

A model with <u>only</u> energy price shocks accounts for 16% of output volatility in the CES case and 35% in the Cobb-Douglas case. While these are not trivial amounts, this model does not mimic other features of the data, such as the fact that consumption is much smoother than output, with the same success as the basic RBC model.

Our results do offer some support to the views of macroeconomists who downplay the impact of energy shocks on the economy. For instance, Tobin (1980, p.31-32) has argued that the share of energy in GNP is so small that it would require implausible parameter values to generate strong aggregate impacts from energy price shocks. Darby (1982) supports Tobin's view and suggests that the energy price-output correlation that other researchers have documented arises as a result of the monetary policy response to the shocks.

On the other hand, we should point out that our model abstracts from many of the channnels through which energy prices may affect the macroeconomy. First, many of the studies that derive strong impacts of energy on real variables do so by assuming some rigidity in the response of wages and (non-energy) prices to the energy price shock [e.g. Gordon (1975), Mork and Hall (1980) and Black (1985)]. Our model, of course, assumes that wages and prices are perfectly flexible.

Second, Bernanke (1983) has emphasized the impact of uncertainty on the economy when investment projects are irreversible. He discusses an example where there is uncertainty about the future long-run price of energy--arising from, say, the formation of a cartel. This increases the option value associated with delaying investment in all kinds of capital, including energy-efficient capital, and hence reduces the propensity to invest.

Finally, several writers [Davis (1985), Loungani (1986), Hamilton (1988) and Mork (1989)] have emphasized the "reallocative" effects of energy shocks. In a multi-sector economy with specialized inputs, energy price shocks can trigger costly reallocations of capital and labor across sectors and this may be an important channel through which energy prices affect the macroeconomy.

In short, this paper represents the first step in modelling energy price shocks in a RBC framework, not the final word.

REFERENCES

Apostolakis, Bobby, 1990, Energy-capital substitutability /complementarity, Energy Economics, January, 48-58.

Benhabib, Jess, Richard Rogerson and Randall Wright, 1990, Homework in macroeconomics, NBER Working Paper No. 3344, Parts I and II.

Benzivinga, Valerie, 1988, An econometric study of hours and output variation with preference shocks, University of Western Ontario Working Paper.

Bernanke, Ben, 1983, Irreversibility, uncertainty and cyclical investment, Quarterly Journal of Economics, 98, 85-106.

Berndt, Ernst and David Wood, 1979, Engineering and econometric interpretations of energy-capital complementarity, American Economic Review, 69, 342-354.

Black, Stanley, 1985, Learning from adversity: policy responses to two oil shocks, Essays in International Finance No. 160, Princeton University.

Burbidge, John and Alan Harrison, 1984, Testing for the effects of oil-price rises using vector autoregressions, International Economic Review, 25, 459-484.

Cho, Jang-Ok and Thomas Cooley, 1988, Employment and hours over the business cycle, RCER Working Paper No. 132.

Christiano, Lawrence, 1988, Why does inventory investment fluctuate so much ?, Journal of Monetary Economics, 21, 247-280.

Christiano, Lawrence, 1990, Linear-quadratic approximation and value-function iteration: a comparison, Journal of Business and Economic Statistics, 8, 99-113.

Christiano, Lawrence and Martin Eichenbaum, 1991, Current real business cycle theories and aggregate labor market fluctuations, forthcoming, American Economic Review.

Cooley, Thomas and Gary Hansen, 1989, The inflation tax and the business cycle, American Economic Review, 79, 733-748.

Costello, Donna, 1989, A cross-country, cross-industry comparison of the behavior of Solow residuals, University of Rochester working paper.

Darby, Micahel, 1982, The price of oil and world inflation and recession, American Economic Review, 72, 738-751.

Davis, Steve J., 1985, Allocative disturbances and temporal asymmetry in labor market fluctuations, unpublished Ph.D thesis, Brown University.

Gisser, Micha and Thomas H. Goodwin, 1986, Crude oil and the macroeconomy: tests of some popular notions, Journal of Money Credit and Banking, 18, 95-103.

Gordon, Robert, 1975, Alternative responses to external supply shocks, Brookings Papers on Economic Activity, 1:183-206.

Griffin, James and Paul Gregory, 1976, An intercountry translog model of energy substitution responses, American Economic Review, 66, 845-57.

Hamilton, James D., 1983, Oil and the macroeconomy since World War II, Journal of Political Economy, 91, 228-48.

Hansen, Gary, 1985, Indivisible labor and the business cycle, Journal of Monetary Economics, 16, 309-27.

Hogan, William W., 1979, Capital-energy complementarity in aggregate energy-economic analysis, Resources and Energy, 2, 201-20.

King, Robert, Charles Plosser and Sergio Rebelo, 1988a, Production, growth and business cycles, I: the basic neoclassical model, Journal of Monetary Economics, 21, 195-232.

King, Robert, Charles Plosser and Sergio Rebelo, 1988b, Production, growth and business cycles, II: new directions, Journal of Monetary Economics, 21, 309-42.

Kydland, Finn and Edward Prescott, 1982, Time to build and aggregate fluctuations, Econometrica, 50, 1345-70.

Loungani, Prakash, 1986, Oil price shocks and the dispersion hypothesis, The Review of Economics and Statistics, 68, 536-39.

Mankiw, Gregory, 1989, Real business cycles: a new Keynesian perspective, The Journal of Economic Perspectives, Summer, 79-90.

McCallum, Bennett, 1989, Real business cycles, in: Robert Barro, ed., Modern business cycle theory (Cambridge: Harvard University Press).

Mork, Knut Anton, 1989, Oil and the macroeconomy when prices go up and down : an extension of Hamilton's results, Journal of Political Economy, 97, 740-744.

Mork, Knut Anton and Robert Hall, 1980, Energy prices, inflation and recession: 1974-75, Energy Journal, 1, 31-63.

Morrison, C.J. and Ernst Berndt, 1981, Short-run labor productivity in a dynamic model, Journal of Econometrics, 16, 339-65.

Pindyck, Robert, 1979, The Structure of World Energy Demand (Cambridge, Mass).

Rogerson, Richard, 1984, Topics in the theory of labor economics, unpublished Ph.D thesis, University of Minnesota.

Rogerson, Richard, 1988, Indivisible labor, lotteries and equilibrium, Journal of Monetary Economics, 21, 3-16.

Said, S.E. and D. A. Dickey, 1984, Testing for unit roots in autoregressive time series with a unit root, Biometrica, 71, 599-607.

Santini, Danilo J., 1985, The energy-squeeze model: energy price dynamics in U.S. business cycles, International Journal of Energy Systems, 5, 18-25.

Sato, K., A two-level constant-elasticity-of-substitution production function, Review of Economic Studies, 34, 201-18.

Solow, Robert, 1956, A contribution to the theory of economic growth, Quarterly Journal of Economics, 70, 65-94.

Solow, Robert, 1957, Technical change and the aggregate production function, The Review of Economics and Statistics, 39, 312-20.

Stockman, Alan, 1990, International transmission and real business cycle models, American Economic Review Papers and Proceedings, 80, 134-138.

Summers, Lawrence, 1986, Some skeptical observations on real business cycle theory, Federal Reserve Bank of Minneapolis Quarterly Review, Fall, 23-27.

Tobin, James, 1980, Stabilization policy ten years after, Brookings Papers on Economic Activity, 1:19-71.

## Appendix A

The hours series used in this paper is "manhours of employed labor force, household data" (Citibase label LHOURS) which differs from the series used by Hansen. For our data set, productivity and hours are about equally volatile [see column (4) in Table A1 below]. On the other hand, the higher volatility of hours relative to productivity is considered to be a "stylized fact" of business cycles in previous RBC studies such as Hansen [see column (1) below]. There are three potential explanations--which are not mutually exclusive--for this difference: the sample period is different or the timing interval is different or the hours series used is different. The evidence given below suggests that it is the sample period that accounts for the bulk of the discrepancy.

Table A1

| | Hansen | | Kim and Loungani | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Quarterly 1955:3-84:1 | | Quarterly 1955:3-87:4 | | Annual 1956-87 | | Annual 1949-87 | |
| | std. | corr. | std. | corr. | std. | corr. | std. | corr. |
| | (1) | | (2) | | (3) | | (4) | |
| Output | 1.76 | 1.00 | 1.75 | 1.00 | 2.48 | 1.00 | 2.95 | 1.00 |
| Hours | 1.66 | 0.76 | 1.51 | 0.71 | 1.91 | 0.86 | 1.80 | 0.85 |
| Produc. | 1.18 | 0.42 | 0.89 | 0.55 | 1.27 | 0.73 | 1.88 | 0.79 |
| Ratio# | 1.41 | | 1.70 | | 1.50 | | 0.96 | |

# Ratio = std(Hours)/std(Productivity)