

# Energy, the Stock Market and the Putty-Clay Investment Model

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(Preliminary, comments welcome)

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## Abstract

Real energy prices jumped by 80% from 1973 to 1974. At the same time, the market value of firms plunged by 40%. Is the energy crisis responsible for the dramatic decline in the stock market? Many economists, starting with Baily (1981), have concluded that higher energy prices resulted in the effective scrapping of a substantial fraction of the capital stock. The fall in the stock market reflected the fall in the value of firms' assets, in this view. Because capital is never scrapped in a neoclassical model of capital, I build a model based on the putty-clay specification, where different vintages of capital are imperfect substitutes. I distinguish three factors: capital, energy, and labor. I take the production technology *ex ante* to be Cobb-Douglas with constant returns to scale, but for capital goods already installed, production possibilities take the Leontief form: there is no substitutability of capital, energy, and labor *ex post*. I use the model to evaluate the impact of the energy price shock on the securities market in 1974.

As a preliminary to the analysis based on the model, I calculate an upper bound on the effect of the energy price shock in a partial equilibrium putty-clay model, holding the real wage fixed. An 80% increase in real energy prices leads to a 10% decline in the market value of installed machines. Even this small effect exceeds what I find in the general equilibrium model. There, the energy price shock causes a decrease in the real wage, sufficient to offset the adverse impact of the increase in the energy cost on the value of capital. An 80% increase in the real energy prices causes the market value to decrease by only 2.2%. The theoretical analysis is supported by the observed decline in the real wage in 1974 of a magnitude comparable to that predicted by the model.

Finally, I conduct a cross-industry event study that shows that the energy share of production costs cannot explain the cross-sectional patterns of the decline of stock prices from 1972 to 1974.

The theoretical analysis and empirical evidence indicate that a broader set of forces was at work in causing the market downfall in 1974 than those effects of energy prices captured in the putty-clay model that appears to inform the thinking of most economists on this question.

# 1 Introduction

The energy crisis of 1973 – 74 coincided with a dramatic decline in the U.S. stock market capitalization. Real energy prices jumped by 80% from 1973 to 1974. At the same time, the market value of non-farm, non-financial corporations plunged by 40%. Because the timing of the two events coincides closely, the energy price hike is often considered a crucial factor in understanding the dramatic decline in the stock market in 1974. One of the leading advocates of the hypothesis of a causal link, Baily (1981), holds that the jump in energy prices made a substantial fraction of the capital stock obsolete. The value of existing capital decreased because it was not technologically suited to new economic conditions. This link between rising energy prices and capital obsolescence would be recognized by efficient financial markets and may constitute an explanation of the low level of stock market prices during that period. Sakellaris (1997) examines this hypothesis by focusing on firms in energy-intensive sectors. He shows that the firms which invested heavily when energy was relatively cheap were hit harder in their market value in 1974. In contrast, Hobijn and Jovanovic (2000, henceforth HJ) argue that oil constituted too small a fraction of costs to have much effect on market capitalization. To support the claim, they run a cross-sector regression of the decrease in the market capitalization from 1972 to 1974 on the 1972 energy intensity of each sector. The coefficient associated with the oil share of production costs was not significant.

I will use a dynamic general equilibrium model with production and capital accumulation to examine the magnitude of the energy-price effect. This will allow me to evaluate conflicting ideas using the general equilibrium principle. A vast literature examines the relationship between the energy price shock and macroeconomic performance, including Hamilton (1983, 1985, 1999). The question of how the market value of capital responds to energy price shocks has been much less explored. Greenwood and Yorukoglu (1997) used a dynamic general equilibrium model to explain the productivity slowdown after 1974, and Sakellaris (1997) developed a partial equilibrium illustration of the impact of the energy price shock on the drop in market value, no author has presented a modern general equilibrium explanation of how and to what extent the energy price shock was responsible

for the dramatic drop in the value of the stock market. This paper aims to fill the gap.

A natural framework for studying the effects of the energy price shock on stock prices and capital formation is a general equilibrium model with putty-clay production technology. The neoclassical production function describes a putty-putty investment technology, in that it allows for smooth substitutability between factors after installation and conversion of capital to consumption goods at little cost. By contrast, in the Leontief technology the productive factors are used in fixed proportions. Johansen (1959) proposed a synthesis of these extremes in which “any increment in production can be obtained by different combinations of increments in labor and capital inputs, whereas any piece of capital which is already installed will continue to be operated by a constant amount of labor throughout its life span”. This is the putty-clay technology. Because the technology is embodied in the capital stock in a putty-clay framework, changes in factor prices cause capital obsolescence and a decline in the value of capital. As a result, the putty-clay model is particularly suitable for studying the hypothesis put forward by Baily (1981). Fuss (1977) provides empirical evidence supporting the notion that capital and energy are complementary in the short run and substitutable in the long run.

This paper adapts the putty-clay model developed by Gilchrist and Williams (2000) into a three-factor model, in which the capital and energy intensities are embodied in the capital stock at the time of installation. The asset market implications are derived from optimal consumption and investment decisions. The energy price shock affects the market value of firms through three channels. The first channel is the effect of the energy price shock on investment; the second channel is the endogenous depreciation of the old vintage machines from both the decreases in the capacity utilization of the old machines and the drop in the expected profits of the machines in operation; and the third channel is the effect of the energy price shock on the interest rate. The direction and the magnitude of the impact of the fundamental shocks on the stock market depend on the resulting movement of price variables, such as the wage and the interest rate, which in turn depend upon the preference and production specifications, the characteristics of the energy price process, and the distribution of productivity and energy efficiency of capital before the energy price shock. Only a full general equilibrium model can sort out all of their interactions.

I start by calculating a simple upper bound on the impact of the en-

ergy price shock within a putty-clay structure. I derive such a measure in a partial equilibrium setting, where the real wage and interest rate are fixed exogenously. Extreme assumptions, including the inability to shut down unprofitable machines, are imposed to bound the impact of an energy price shock. In such a setting, an 80% permanent increase in the real energy price leads to a 10% decline in the market value of previously installed machines. The putty-clay structure, by capturing frictions in factor adjustment, allows the energy price shock to have a limited but noticeable impact on the securities market. In a general equilibrium putty-clay model, where the real wage and interest rate respond endogenously to the energy price shock, the impact of the energy price shock is even smaller. An 80% increase in the real energy price causes the stock market value to decline by only 2.2%. This is because the energy price increase causes the real wage to decline in general equilibrium. The real wage decrease is large enough to reverse the upward pressure on variable cost. The real wage falls 3.9% below the steady state in response to an 80% energy price increase. The decline in the real wage removes most of the increase in cost that depressed the value of capital in the bound calculation.

One might suppose that the model was unrealistic because wages are more rigid in the real world than in the model. But in fact the U.S. real wage dropped 3.4% below trend in 1974.

The evidence from the solutions of a general equilibrium model points to a small direct effect of energy cost increases on the securities market. It suggests that a broader set of forces was at work in causing the market downfall in 1974, than the effect of energy prices alone.

The cross-sectional patterns of decline in securities values across industries from 1972 to 1974 provide additional information on the role of the energy price shock. If the energy cost increase was indeed the dominant cause for the decline in the securities market in 1974, we should observe the energy-intensive industries suffering larger declines. I run a cross-industry regression of the changes in the market value from 1972 to 1974 on the energy share of production costs per industry. The empirical test is in the same spirit as HJ's (2000), but improves on theirs in several aspects. I measure the market value of a firm as the claims to the underlying real stock of capital, which is equal to the sum of the market value of outstanding equities, the constructed market value of long-term debt adjusted for its age structure, the constructed market value of the preferred stock and the short-term debt, less the short-term financial assets. This measure of market value is more

accurate than the one used in HJ (2000), which is a sum of the market value of equity plus the book value of debt. I construct the energy share of costs as the direct and indirect expenses on crude petroleum, natural gas, coal, and anthracite, whereas HJ (2000) restrict the energy costs to those of the first two items. Given that the coal price rose markedly from 1973 to 1974, it is important to treat substitutable energy sources as a whole. Despite the 80% increase in the real energy price, the empirical results indicate that the energy-intensive industries were not the ones that suffered the greatest declines in the market value in 1974.

Apart from the interpretation of the historical episode of 1974, the model and the solution technique have an independent interest. Asset pricing is traditionally studied in an endowment economy. In a seminal paper, Lucas (1978) sets forth the principles of market valuation of claims on endowments. Since there is no investment in the endowment economy, the amount of capital stock is fixed and shocks are absorbed entirely by changes in asset prices. With notable exceptions, for example, Cochrane (1991, 1996) and Abel (1999), financial economics has not considered the implications of capital accumulation for the evolution of securities values.

In this paper, I augment the traditional paradigm with a nontrivial production sector, and establish a structural relation between consumption and investment decisions and the market value of the securities. The rationale for explaining the market value of firms with the real economy model is as follows: On the assumption that the ownership of the capital stock is equivalent to the ownership of the firm, the stock market measures the value of a firm's capital, which is the product of the price of installed capital and its quantity. In a general equilibrium model with endogenous investment, capital accumulation and stock market valuations are determined jointly. This linkage between the fundamentals and the stock market has been exploited by Baily (1981) and Hall (2000).

It is a computational challenge to solve a general equilibrium putty-clay model, because the cross-vintage distributions of capital and energy intensities are the state variables in the model. Although the putty-clay production technology has strong theoretical appeal and empirical support, the "curse of dimensionality" of working with heterogeneous capital has hindered its application in general equilibrium models. Since the energy price shock is large in magnitude, the conventional method of log-linearization is unable to generate accurate results. I combine the multi-dimensional perturbation and the Fair-Taylor methods to compute the response of the economy to an 80%

increase in the real energy price. The nonlinear dynamics of the model are pronounced in the case of large energy price shocks.

This paper is organized as follows. Section 2 presents the financial and macroeconomic data in the periods following the energy price shock in 1973. In section 3, a simple partial equilibrium putty-clay model is used to provide an upper bound on the impact of the energy price shock on the stock market. Section 4 describes the general equilibrium version of the putty-clay model and derives its asset pricing implications. Section 5 describes the equilibrium dynamics of asset prices under a benchmark calibration. Section 6 conducts a cross-industry event study. Section 7 concludes.

## 2 Historical Facts

This section presents the historical background of the energy crisis of 1973 – 74 and summarizes the financial and macroeconomic data following 1973. Panel A in Figure 1 plots the real energy price<sup>2</sup> in billions of 1992 dollars. The real energy price was fairly stable from 1959 to 1972. This pattern is explained by the specific regulatory structure of the U.S. oil industry over the period 1948 – 72. Each month the Texas Railroad Commission (TRC), and other state regulatory agencies, would forecast demand for petroleum for the subsequent month and would set allowable production levels for wells in the state to meet this demand at the target price. As a consequence, much of the cyclically endogenous component of petroleum demand showed up as a regulatory shift in quantities, not prices. In March 1971, the Texas Railroad Commission set proration at one hundred percent for the first time. This means that Texas producers were no longer limited in the amount of oil that they produced. More importantly, it meant that the power to control crude oil prices shifted from the United States to the outside supplier, OPEC. In October 1973, OPEC imposed the oil embargo on the United States and cut production. The real energy price jumped by 80% from 1973 to 1974.

During the same period, the market value of non-farm, non-financial corporations dropped by 40%. This is shown in Panel B in Figure 1. I follow Hall (2000) in computing the market value of the securities of non-farm, non-financial corporations. The value of the financial securities is measured as

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<sup>2</sup>I construct a composite energy price measure which is a weighted sum of the prices of domestic and imported crude oil, natural gas and coal. A full explanation of the sources and methods used in my data construction is given in the appendix.

the market value of outstanding equities plus the constructed market value of financial liabilities less financial assets, all divided by the implicit deflator for private fixed nonresidential investment.

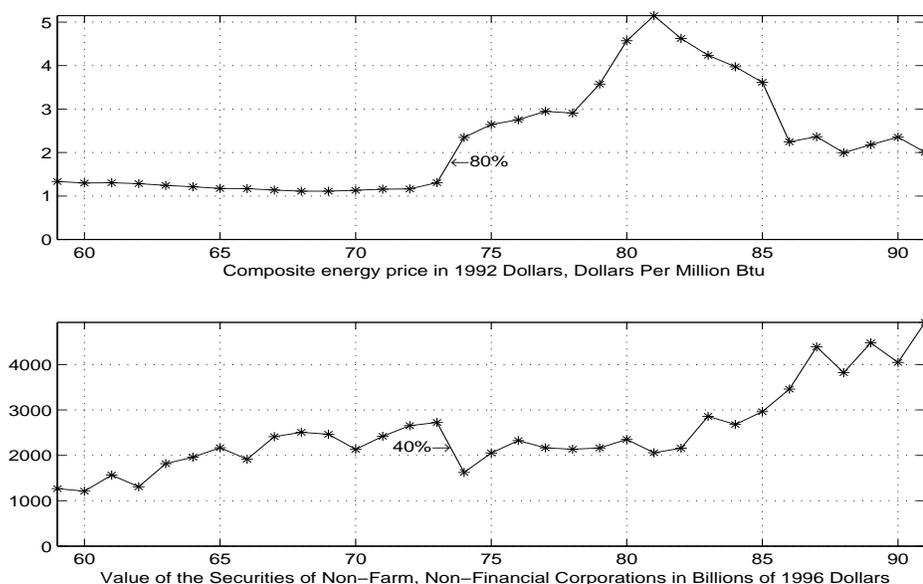


Figure 1: Energy Price versus Market Value

Table 1 presents the data on real wage, real consumption of non-durables and services, and real investment. All variables are measured relative to their trend-adjusted 1973 level<sup>3</sup>. Real consumption and investment are divided by the adult (16 and over) population. The variables are deflated by the personal consumption expenditure implicit price deflator. There are three patterns in these data from 1974 to 1976.

- The real wage decreased by 3.43% in 1974 and continued to decline in the following years.
- Real consumption of non-durables and services dropped below the trend.
- Real gross private domestic fixed investment in nonresidential capital dropped by around 6% in 1974 and the sharp decline continued in the following years.

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<sup>3</sup>I detrend the variables by the average growth rate from 1959 to 1973.

Table 1: Percentage of Deviation Relative to the Trend-Adjusted 1973 Level

Year	1974	1975	1976
Real Wage	-3.43	-4.79	-4.52
Consumption	-3.49	-5.46	-5.38
Investment	-6.48	-18.04	-19.40

The energy price hike also affected the energy technology choice of individual manufacturing plants, which is documented in Doms (1993). The pattern of energy use in the U.S. changed substantially after the energy price shock. In 1972 the U.S. used 72.0 quadrillion BTU of primary energy input to sustain a real GNP of \$1171 billion in constant dollars of 1972. This corresponds to an energy-GNP ratio of 61.4 (million BTU per 1972 dollar). In 1976, GNP had increased to \$1275 billion in constant dollars but energy use had risen only to 73.7 quadrillion BTU, resulting in a significantly reduced energy-GNP ratio.

I will show that a general equilibrium putty-clay model captures the qualitative and quantitative features of the equilibrium dynamics of the price and quantity variables. In a partial equilibrium setting, the putty-clay feature in the production specification is capable of delivering a limited but noticeable impact of the energy shock on the securities market. I will illustrate this point in the next section.

### 3 A Back-of-the-Envelope Partial Equilibrium Calculation

This section provides a variant of Sakellaris's (1997) partial equilibrium model to derive analytically an upper bound for the impact of the energy price shock on the securities market. For notational clarity,  $\tilde{\cdot}$  is used to denote the quantity variables in this section to distinguish them from the variables in the general equilibrium model.

The theoretical framework in the partial equilibrium setting involves a forward-looking neoclassical firm facing adjustment costs. Capital, labor

and energy are used in production. The production technology is putty-clay. Capital stock of different vintages embodies the capital and energy intensity chosen at the time of installation. Investment is assumed to be irreversible. The economy is in a steady state before the energy price shock.

I make three strong assumptions to derive an upper bound for the impact of the energy price shock on the stock market. They are:

1. All machines are in full operation each period. They depreciate at an exogenous rate  $1 - \omega$ .
2. The real interest rate is assumed to be constant. It is exogenously given and known with certainty. The conditional expectation of the real wage is given by

$$E_s W_t = W_s, \quad \forall t \geq s. \tag{1}$$

3. The real wage does not respond to the energy price shock and remains at its pre-shock steady state level

If the machines can be shut down at no cost in response to an adverse shock, there exists a lower bound on the market value of machines, which is 0. By assumption 1, I prevent firms from adjusting capacity utilization. The machines which are unprofitable will remain in operation. The real wage and interest rate are assumed not to respond endogenously to an energy price shock. Given that the real wage actually decreases after an energy price increase, both in the general equilibrium model and in the data, fixing the real wage and interest rate delivers an upper bound on the impact of the energy price shock.

The above three assumptions constitute the key distinctions between the partial and the general equilibrium settings. In the general equilibrium model in the next section, both the real wage and the interest rate will respond endogenously to an energy price shock. I will also relax assumption 1 by allowing the adjustment of capacity utilization.

In addition to the above three key distinctions, I make two slightly different assumptions in the partial equilibrium setting for analytical convenience. First, I assume that the machine has an infinite life span. The partial equilibrium calculation would be almost the same in the case where the life span

of machines is finite. Second, the conditional expectation of the real energy price is given by

$$E_s P_t = P_s, \forall t \geq s, \quad (2)$$

which means that the expected real energy price in each future period is equal to the current realization. In the general equilibrium model, I assume that the real energy price follows a persistent process with mean reversion. The upper bound derived under this alternative assumption in a partial equilibrium setting is slightly smaller than the one obtained here.

In this section, the first subscript denotes the time period of observation, and the second subscript denotes the vintage of capital. The derivation of the market value of machines is straightforward. The production function is assumed to be separable across vintages. Each period the firm is faced with the following *ex ante* production function:

$$\tilde{Y}_{s,s} = \tilde{K}_s^{\alpha\lambda} \tilde{E}n_s^{\alpha(1-\lambda)} \tilde{L}_s^{1-\alpha}, \quad (3)$$

where  $\tilde{Y}_{s,s}$  is the output of vintage  $s$  machine at time  $s$ ,  $\tilde{K}_s$  is the amount of capital of vintage  $s$ ,  $\tilde{E}n_s$  is the amount of energy used, and  $\tilde{L}_s$  is the amount of labor employed.  $1 - \alpha$  is the labor share of income, and  $\alpha\lambda$  is the capital share of income.

In period  $t$ , the post-depreciation capital stock of vintage  $s$  is denoted by  $\tilde{K}_{t,s}$ , where

$$\tilde{K}_{t,s} = \omega^{t-s} \tilde{K}_s. \quad (4)$$

After the capital is installed, the firm is faced with a Leontief production function *ex post*. The amount of the variable factors of production that the firm hires depends on the optimal factor intensities *ex ante* and the remaining physical capacity of the vintage of capital. This implies that:

$$\tilde{L}_{t,s} = \omega^{t-s} \tilde{L}_s, \quad \tilde{E}n_{t,s} = \omega^{t-s} \tilde{E}n_s, \quad \tilde{Y}_{t,s} = \omega^{t-s} \tilde{Y}_{s,s}. \quad (5)$$

At each period  $s$ , the firm chooses the factor intensities to maximize the present value of the new vintage of capital:

$$\max_{(\tilde{K}_s, \tilde{L}_s, \tilde{E}n_s)} E_s \sum_{t=s}^{\infty} R^{t-s} (\tilde{Y}_{t,s} - W_t \tilde{L}_{t,s} - P_t \tilde{E}n_{t,s}) - g(\tilde{K}_s), \quad (6)$$

where the discount rate  $R$  is given, and  $g(\tilde{K}_s)$  is the cost of purchasing and installing the capital of vintage  $s$ .

Using (1) through (5), I can obtain the optimal use of variable factors as follows:

$$\tilde{L}_s^* = \frac{a(\omega, R, \tilde{K}_s) (1 - \alpha)}{W_s \alpha \lambda}, \quad (7)$$

$$\tilde{E}n_s^* = \frac{a(\omega, R, \tilde{K}_s) (1 - \lambda)}{P_s \lambda}, \quad (8)$$

$$\tilde{Y}_{s,s}^* = \frac{a(\omega, R, \tilde{K}_s)}{\alpha \lambda}, \quad (9)$$

where  $a(\omega, R, \tilde{K}_s)$  equals  $g'(\tilde{K}_s) \tilde{K}_s (1 - R\omega)$ .

Denote the market value of vintage  $s$  capital at time  $t$  as  $\tilde{V}_{t,s}$ . Simple manipulations yield:

$$\tilde{V}_{t,s} = E_t \sum_{j=0}^{\infty} R^j (\tilde{Y}_{t+j,s} - W_{t+j} \tilde{L}_{t+j,s} - P_{t+j} \tilde{E}n_{t+j,s}) \quad (10)$$

$$= b(t, s, \omega, \tilde{K}_s) \left( \frac{1}{\alpha \lambda} - \frac{(1 - \alpha) W_t}{\alpha \lambda W_s} - \frac{1 - \lambda P_t}{\lambda P_s} \right). \quad (11)$$

where  $b(t, s, \omega, \tilde{K}_s)$  is a function depending upon the initial capital installed at time  $s$ .

In the steady state,  $W_{t'} = W^*$ ,  $P_{t'} = P^*$ , for all  $t' \leq t$ . As a result, the steady state market valuation of vintage  $s$  capital at time  $t'$  is described as

$$\tilde{V}_{t',s} = b(t', s, \omega, \tilde{K}_s). \quad (12)$$

Suppose that at time  $t$  the real energy price suddenly jumps by 80%. Holding the real wage fixed, the percentage decline in the market value of

previously installed machines is<sup>4</sup>

$$\frac{\sum_{s<t} (\tilde{V}_{t,s}) - \sum_{s<t'} (\tilde{V}_{t',s})}{\sum_{s<t'} (\tilde{V}_{t',s})} = \frac{1-\lambda}{\lambda} \left( \frac{P_t}{P^*} - 1 \right). \quad (13)$$

Recall that  $\lambda\alpha$  is the capital share of income and  $(1-\lambda)\alpha$  is the energy share of income. The parameter  $\lambda$  is calibrated to equal 0.89, so that the labor share of income is 0.64 and the energy share of income is 0.04. Substituting these numbers into equation (13), I find that under a fixed real wage rate, the market value of previously installed capital drops by 10% in response to an 80% hike in the real energy price. In the data, the total market value of firms dropped by 40% in 1974. The simple computations show a noticeable impact of the energy price shock.

As is shown in (13), the effect of the energy price shock on the stock market depends upon  $\lambda$ . A smaller share of energy expenses in total production costs corresponds to a higher  $\lambda$ , and smaller impact of the energy price shock on the stock market. Despite the small share of energy expenditure in total production costs, in a partial equilibrium setting, the putty-clay feature of the production technology is capable of delivering a noticeable impact of the energy price shock on the securities market.

Another way to measure the upper bound is to compute the decline in the real wage rate required to counter the effect of the energy price increase. Simple manipulations of equation (11) yield the required magnitude of a real wage decrease at

$$\frac{\alpha(1-\lambda)}{1-\alpha} \left( \frac{P_t}{P^*} - 1 \right). \quad (14)$$

A 5% decrease in the real wage is sufficient to reverse the influence of an 80% energy price increase on the value of the capital stock.

In order to evaluate the impact of the energy shock, one needs a general equilibrium framework to study how and to what extent the wage and interest rate move in response to the energy price shock, and whether they amplify or diminish the effect of the energy price shock.

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<sup>4</sup>Strictly speaking, the market value of capital at the end of period  $t$  is equal to  $\sum_{s<t} (\tilde{V}_{t,s}) + \tilde{V}_{t,t}$ , where  $\tilde{V}_{t,t}$  is the market value of capital installed at time  $t$ . However, the determination of  $\tilde{V}_{t,t}$  involves specific assumptions on the functional forms of  $g(\cdot)$ . I choose to focus on the first item, the market value of previously installed capital instead.

## 4 The Model

The economy consists of many identical, infinitely lived households who derive utility from the consumption of goods and leisure. Firms own all of the initial physical capital stock and also make all future investments in capital. Households own all shares in firms. They receive their income from supplying labor services to firms, and from dividends on the shares they hold in the firms. There exists a securities market. The claims on the profit streams of firms are traded.

Three factors are used for production: capital, labor and energy. Energy is imported at an exogenous given price, and energy imports are paid for with exports of output, with trade balanced in every period<sup>5</sup>.

Other than labor and energy, there are  $M + 1$  types of goods. They are the consumption good and capital goods of  $M$  vintages. Capital goods require one period for initial installation and are productive for the next  $M$  ( $M \geq 1$ ) periods. Each vintage of capital goods is characterized by two identifying features: its capital intensity and its energy efficiency. The *ex ante* production technology is assumed to be Cobb-Douglas with constant returns to scale, but for capital goods already installed, production possibilities take the Leontief form: there is no *ex post* substitutability of capital, energy and labor. Investment is irreversible. Once installed, capital goods cannot be converted into consumption goods or capital goods with different embodied characteristics, and they have zero scrap value.

There exists idiosyncratic uncertainty regarding the productivity of individual machines within each vintage. The idiosyncratic productivity term is realized after each unit of new machines is installed and stays the same while the machine is in use. After its realization, further investment in existing machines is not allowed. Since the idiosyncratic uncertainty is resolved after the investment decisions on new capital have been made, the decisions on the capital intensity and energy efficiency of new machines only depend upon the aggregate state variables. The introduction of heterogeneity within vintages allows for a varying utilization rate in response to the cost variables in the model, smooths the aggregate allocation, and simplifies the computation of the equilibrium.

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<sup>5</sup>I interpret the putty-clay model as covering the private non-energy production sector of the economy.

## 4.1 Assumptions

The following assumptions are made with regard to the general economic environment:

1. There is no growth in the economy<sup>6</sup>.
2. The energy price shock is a once-and-for-all shock unanticipated by the agents in the model. Afterwards, there is no more aggregate uncertainty.
3. The economy starts at a steady state.

The second assumption is justified by the widely accepted belief that the 1973 energy shock came as a surprise, given that the energy price had remained stable for a long time.

## 4.2 Firms

Firms combine capital of various vintages with labor and energy to produce a single good, which can be used for consumption and investment in new “projects”. Each period a set of new investment “projects” becomes available. Ex-ante constant returns to scale implies an indeterminacy of scale at the level of projects. Without loss of generality, all projects can be normalized to employ one unit of labor at full capacity. These projects are referred to as “machines”. Labor employed per machine is subject to the capacity constraint of 1.

Machines are heterogeneous and are characterized by four attributes: vintage, capital-energy ratio and energy-labor ratio chosen at the time of installation, and the value of the idiosyncratic productivity term. A fraction  $\delta_j$  of machines fail exogenously  $j$  periods after installation.

The idiosyncratic productivity of machine  $i$  installed at time  $t-j$ , denoted as  $\theta_{i,t-j}$ , is a log-normally distributed random variable. Namely,

$$\log \theta_{i,t-j} \sim N\left(-\frac{1}{2}\sigma^2, \sigma^2\right), \quad (15)$$

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<sup>6</sup>The assumption of zero growth simplifies the exposition in the paper. The mechanism of the real wage decrease remains at work when the exogenous growth in the embodied technology and labor endowment is incorporated. Wei (2001) examines the putty-clay model in an economy with growth.

where  $\sigma^2$  is the variance. The mean correction term  $-\frac{1}{2}\sigma^2$  implies that the mean of the idiosyncratic productivity,  $\theta_{i,t-j}$ , equals 1.

Subject to the constraint that the labor employed,  $L_{i,t,j}$ , is nonnegative, and less than or equal to unity (capacity), final output produced in period  $t$  by machine  $i$  of vintage  $t - j$ <sup>7</sup> is

$$Y_{i,t,j} = \theta_{i,t-j} k_{i,t-j}^{\lambda\alpha} e_{i,t-j}^\alpha L_{i,t,j}, \quad (16)$$

where  $k_{i,t-j}$  is the capital-energy ratio,  $e_{i,t-j}$  is the energy-labor ratio,  $\lambda\alpha$  is the capital share of income, and  $1 - \alpha$  is the labor share of income. Both  $k_{i,t-j}$  and  $e_{i,t-j}$  are chosen at period  $t - j$ , the time of installation.

The labor productivity of machine  $i$  of vintage  $t - j$  is denoted by

$$X_{i,t-j} \equiv \theta_{i,t-j} k_{i,t-j}^{\lambda\alpha} e_{i,t-j}^\alpha \quad (17)$$

Since  $k_{i,t-j}$  and  $e_{i,t-j}$  are chosen before the idiosyncratic shock term is revealed, all machines of vintage  $t - j$  share the same capital-energy ratio  $k_{t-j}$ , and energy intensity  $e_{t-j}$ . Accordingly, the average productivity of the entire stock of vintage  $t - j$  capital is denoted by

$$X_{t-j} = k_{t-j}^{\lambda\alpha} e_{t-j}^\alpha \quad (18)$$

The firms' decisions consist of the atemporal decision of capacity utilization at each period, and the intertemporal investment decision.

#### 4.2.1 Capacity Utilization Decision

At each period, the only variable cost to operate one unit of vintage  $t - j$  machines is the labor cost  $W_t$  and energy expenses  $P_t e_{t-j}$ . There are no costs for taking machines or workers on- or off-line. Thus the capacity utilization choice is purely atemporal. The net income from running machine  $i$  of vintage  $t - j$  at time  $t$  is

$$\pi_{i,t,j} = Y_{i,t,j} - W_t L_{i,t,j} - P_t e_{i,t-j} L_{i,t,j}, \quad (19)$$

where  $W_t$  is the real wage and  $P_t$  is the price of energy in terms of the consumption good.

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<sup>7</sup>For notational convenience, vintage  $t - j$  machines mean the machines installed at period  $t - j$ .

The net income of running each machine is linear in labor employed. There exists a cutoff value for the minimum productivity level of machines used in production: those with productivity  $X_{i,t-j} \geq W_t + P_t e_{t-j}$  are run at full capacity at period  $t$ , while those less productive are left idle.

Given that the idiosyncratic shock  $\theta_{i,t-j}$  is log-normally distributed, the proportion of machines of vintage  $t - j$  in use at time  $t$  can be summarized as

$$\Pr [X_{i,t-j} > (P_t e_{t-j} + W_t) | W_t, P_t] = 1 - \Phi(z_t^{t-j}), \quad (20)$$

where  $\Phi(\cdot)$  is the cumulative distribution function of the standard normal random variable. Using  $X_{i,t-j} = \theta_{i,t-j} X_{t-j}$ , we can get

$$z_t^{t-j} = \frac{1}{\sigma} \left[ \log(P_t e_{t-j} + W_t) - \log X_{t-j} + \frac{1}{2} \sigma^2 \right] \quad (21)$$

Capacity utilization for machines of vintage  $t - j$  at time  $t$  is defined to be the ratio of actual output produced from the capital of a given vintage to the level of output that could be produced at full capital utilization. Let  $F(\cdot)$  denote the cumulative distribution function of  $X_{i,t-j}$ . Capacity utilization is defined as:<sup>8</sup>

$$\frac{\int_{P_t e_{t-j} + W_t}^{\infty} X_{i,t-j} dF(X_{i,t-j})}{\int_0^{\infty} X_{i,t-j} dF(X_{i,t-j})} = 1 - \Phi(z_t^{t-j} - \sigma) \quad (22)$$

Taking the real wage as given, the firms make optimal capacity utilization decisions on individual machines. We can aggregate the machines across vintages to obtain the aggregate labor demand, energy use and output of the firms.

#### 4.2.2 Aggregation

Aggregation is a two-step process. First, labor input, energy input and output of machines in each vintage are aggregated into vintage totals. Second, inputs and outputs from the  $M$  productive vintages are summed to yield aggregate values.

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<sup>8</sup>The derivation makes use of the lognormal distribution of idiosyncratic shock. Proofs are in the appendix.

Total labor employment,  $L_t$ , is

$$L_t = \sum_{j=1}^M \{[1 - \Phi(z_t^{t-j})](1 - \delta_j)Q_{t-j}\}, \quad (23)$$

where  $Q_{t-j}$  is the quantity of new machines started in period  $t - j$ ,  $\Phi(z_t^{t-j})$  is the idle rate of those machines in period  $t$ , and  $\delta_j$  reflects the fact that a subset of machines has failed completely. The summation of labor inputs makes use of the fact that in equilibrium each machine employs one unit of labor at full capacity.

Total inputs of energy,  $En_t$ , is

$$En_t = \sum_{j=1}^M \{[1 - \Phi(z_t^{t-j})](1 - \delta_j)Q_{t-j}e_{t-j}\}, \quad (24)$$

noting that  $e_{t-j}$  is the energy-labor ratio of vintage  $t - j$  machines.

Aggregate final output,  $Y_t$ , is

$$Y_t = \sum_{j=1}^M \{[1 - \Phi(z_t^{t-j} - \sigma)](1 - \delta_j)Q_{t-j}X_{t-j}\}. \quad (25)$$

Recalling that from equation (22),  $1 - \Phi(z_t^{t-j} - \sigma)$  is the ratio of actual output produced from vintage  $t - j$  capital to the level of output that could be produced at full capacity utilization, which is  $(1 - \delta_j)Q_{t-j}X_{t-j}$ .

Aggregate cash flow from all machines in operation,  $D_t$ , is the residual of the value of the output produced after the factor payments to labor and energy have been made and investment has been financed:

$$D_t = Y_t - W_tL_t - P_tEn_t - Q_tk_t e_t. \quad (26)$$

Since  $Q_t$  is the quantity of machines with each machine hiring one unit of labor, and  $e_t k_t$  is the capital-labor ratio for newly installed machines,  $e_t k_t Q_t$  is the gross investment in the new capital.

### 4.2.3 The Firm's Problem

At the beginning of period  $t$ , there are  $M$  vintages of capital in existence. Each vintage of capital is identified by the capital-energy ratio,  $k_{t-j}$ ; the

energy-labor ratio,  $e_{t-j}$ ; and the quantity of machines installed per vintage,  $Q_{t-j}$ ,  $j = 1, \dots, M$ . All these attributes have been chosen at the time of installation. The control variables chosen by the representative firm at each period are: the quantity of new machines,  $Q_t$ ; the capital-energy ratio for the new machines,  $k_t$ ; the energy-labor ratio for the new machines,  $e_t$ ; and the cutoff value of utilization for machines of vintage  $t-j$ ,  $z_t^{t-j}$ ,  $j = 1, \dots, M$ . Once the capacity utilization is determined, the employment, energy use and output at time  $t$  are determined from equations (23), (24) and (25). Given that the choices on  $Q_t$ ,  $k_t$ , and  $e_t$  will be embodied in the newly installed capital, the decisions on the new investment are intertemporal.

The firm takes the owners' (representative households) marginal rate of substitution,  $\{m_{t,t+s}\}_{s=0}^{\infty}$ , the real energy price  $\{P_{t+s}\}_{s=0}^{\infty}$ , and the real wage rate,  $\{W_{t+s}\}_{s=0}^{\infty}$ , as given. It chooses  $\{Q_{t+s}, k_{t+s}, e_{t+s}\}_{s=0}^{\infty}$  and  $\{z_{t+s}^{t+s-j}, j = 1, \dots, M\}_{s=0}^{\infty}$  to maximize its net present value, which is equal to the present discounted value of all current and future cash flows:

$$\sum_{s=0}^{\infty} [m_{t,t+s} (Y_{t+s} - W_{t+s}L_{t+s} - P_{t+s}En_{t+s} - Q_{t+s}k_{t+s}e_{t+s})], \quad (27)$$

subject to equations (23), (24), (25) and

$$P' = 1 + \rho(P - 1), \quad (28)$$

where  $\rho$  is the persistence parameter of the energy price process. In solving the above maximization problem, the firms also take the initial condition  $\{Q_{t-j}, k_{t-j}, e_{t-j}\}_{j=1}^M$  as given.

The first order condition with respect to  $Q_t$  is:

$$k_t e_t = \sum_{s=1}^M m_{t,t+s} d_{t+s}^t, \quad (29)$$

where  $d_{t+s}^t$  is the average net income from one unit of vintage  $t$  machines at period  $t+s$ :

$$d_{t+s}^t = [1 - \Phi(z_{t+s}^t - \sigma)](1 - \delta_s)X_t - (P_{t+s}e_t + W_{t+s})[1 - \Phi(z_{t+s}^t)](1 - \delta_s),$$

and  $z_{t+s}^t$  is defined according to equation (21).

The first-order conditions with respect to  $k_t$  and  $e_t$  are:

$$e_t = \sum_{s=1}^M m_{t,t+s} \{ \lambda \alpha [1 - \Phi(z_{t+s}^t - \sigma)] (1 - \delta_s) k_t^{\lambda \alpha - 1} e_t^\alpha \},$$

$$k_t = \sum_{s=1}^M m_{t,t+s} \{ \alpha [1 - \Phi(z_{t+s}^t - \sigma)] (1 - \delta_s) k_t^\lambda e_t^{\alpha - 1} - P_{t+s} [1 - \Phi(z_{t+s}^t)] (1 - \delta_s) \}.$$

The left-hand sides of the above two equations are respectively the marginal costs of increasing the capital-energy ratio and energy-labor ratio of the newly installed machines. The right-hand sides are the discounted marginal benefits brought by the marginal increases in  $k_t$  and  $e_t$ .

The first-order conditions with respect to  $\{z_t^{t-j}\}$  are the same as in equation (21).

The above equations involve  $M$  leads and lags of  $\{Q_t, k_t, e_t\}$ . Given the current vintage structure of the machines, the firm has to be forward looking in determining the capital and energy efficiency of the new machines.

### 4.3 The Household's Problem

The representative household maximizes the lifetime utility of consumption and leisure subject to a sequential budget constraint:

$$\max \sum_{s=0}^{\infty} \beta^s U(C_{t+s}, L_{t+s}), \quad 0 < \beta < 1, \quad (30)$$

subject to

$$C_t + A_{t+1} \cdot q_t^A = W_t L_t + A_t \cdot (q_t^A + D_t^A), \quad \forall t \quad (31)$$

Here  $A_t$  is a vector of financial assets held in the current period and chosen in the previous period, an  $q_t^A$  and  $D_t^A$  are vectors of asset prices and current period payouts. The asset vector  $A_t$  contains claims to machines of the representative firm and possibly other assets. In addition, the representative

household faces a normalized time constraint. The time spent on leisure equals  $1 - L_t$ , where  $L_t$  is labor supply.

The one-period utility function for period  $t$  is

$$U(C_t, L_t) = \frac{1}{1 - \gamma} [C_t (1 - L_t)^\varphi]^{1 - \gamma}, \quad \varphi > 0, \gamma > 0, \quad (32)$$

where  $\gamma$  is the coefficient of relative risk aversion and  $\varphi$  indexes the consumer's preferences for leisure.

The first-order conditions with respect to the labor supply  $L_t$  and consumption  $C_t$  are

$$W_t = \varphi \frac{C_t}{1 - L_t}, \quad (33)$$

$$m_{t,t+1} (1 + r_{t+1}^A) = \mathbf{1}, \quad (34)$$

where  $(1 + r_{t+1}^A)$  is the vector of the gross rate of return to all assets held from time  $t$  to  $t + 1$ , and  $m_{t,t+1}$  is the marginal rate of substitution:

$$m_{t,t+1} = \beta \frac{U_1(C_{t+1}, L_{t+1})}{U_1(C_t, L_t)}. \quad (35)$$

#### 4.4 Market Equilibrium

The perfect foresight competitive equilibrium is a set of prices  $\{W_{t+s}, P_{t+s}, q_{t+s}^A, m_{t,t+s}\}_{s=0}^\infty$ , an allocation  $\{Q_{t+s}, k_{t+s}, e_{t+s}\}_{s=0}^\infty$  and  $\{z_{t+s}^{t+s-j}, j = 1, \dots, M\}_{s=0}^\infty$  for the representative firm, and an allocation  $\{L_{t+s}, A_{t+s}\}_{s=0}^\infty$  for the representative household, such that

- For all periods  $t + s$ , each household and firm solves its maximization problem as described above, taking prices and the vintage structure  $\{Q_{t+s-j}, k_{t+s-j}, e_{t+s-j}\}_{j=1}^M$  as given;
- All markets are clear, including:
  - All produced goods are either consumed, invested or paid for energy expenses:

$$Y_t = C_t + e_t k_t Q_t + P_t E n_t, \quad \forall t \quad (36)$$

- Labor supply equals labor demand;
- Households hold all outstanding equity shares. All other assets are in zero net supply.

## 4.5 Asset Pricing Implications

In this section, the market value of the firm and vintage machines will be derived from the equilibrium prices and quantities. I define the market value of the firm at time  $t$  as the value of the firm after the current period payout is distributed and investment is made. The market value of the firm, defined as  $V_t$ , is

$$\begin{aligned}
V_t &= \sum_{s=1}^{\infty} [m_{t,t+s} (Y_{t+s} - W_{t+s}L_{t+s} - P_{t+s}En_{t+s} - Q_{t+s}k_{t+s}e_{t+s})] \\
&= \sum_{s=1}^{\infty} \sum_{j=1}^M (m_{t,t+s}Q_{t+s-j}d_{t+s}^{t+s-j}) - \sum_{s=1}^{\infty} (m_{t,t+s}Q_{t+s}k_{t+s}e_{t+s}) \\
&= \sum_{j=0}^M \left[ Q_{t-j} \left( \sum_{s=1}^{M-j} m_{t,t+s}d_{t+s}^{t-j} \right) \right] \tag{37}
\end{aligned}$$

where  $d_{t+s}^{t-j}$  is the net income from one unit of vintage  $t-j$  machines at period  $t+s$ :

$$\begin{aligned}
d_{t+s}^{t-j} &= [1 - \Phi(z_{t+s}^{t-j} - \sigma)] (1 - \delta_{j+s})X_{t-j} \\
&\quad - (P_{t+s}e_{t-j} + W_{t+s}) [1 - \Phi(z_{t+s}^{t-j})] (1 - \delta_{j+s}).
\end{aligned}$$

The first term of the above equation multiplied by  $Q_{t-j}$  is the output produced by vintage  $t-j$  machines, which can be verified by referring back to equation (25). The second term represents the average cost of operating one unit of vintage  $t-j$  machines.

The last equality in equation (37) is obtained using equation (29), which states that future investments have zero economic rent—the present discounted value of their expected returns is equal to their costs. As a result, the market value of the firm is equal to the market value of the capital already installed.

Equation (37) can be further simplified if we define

$$q_t^{t-j} = \sum_{s=1}^{M-j} m_{t,t+s} d_{t+s}^{t-j}, \quad j = 0, \dots, M \quad (38)$$

Using standard pricing formulas, we can recognize that  $q_t^{t-j}$  is the average price of one unit of vintage  $t-j$  machines at time  $t$ . Even though the vintage  $t-j$  machines with different  $\theta_{i,t-j}$  have different market prices, it is proven in the appendix that the aggregated values of vintage  $t-j$  machines are equal to the total amount of vintage  $t-j$  machines,  $Q_{t-j}$ , multiplied by the average price of vintage  $t-j$  machines at time  $t$ , which is  $q_t^{t-j}$ . This simplification is possible given that  $\theta_{i,t-j}$  is idiosyncratic across vintage  $t-j$  machines.

The market value of the firm  $V_t$ , which is also the value of the installed capital of the firm, can now be written as

$$V_t = Q_t k_t e_t + \sum_{j=1}^{M-1} Q_{t-j} q_t^{t-j}. \quad (39)$$

Here  $Q_t k_t e_t$  is the investment made at time  $t$ . From equation (29), we can see that the price of one unit of machines installed at time  $t$ ,  $q_t^t$ , is equal to  $k_t e_t$ . Note that the depreciation is accounted for in the average price of vintage  $t-j$  machines,  $q_t^{t-j}$ , so the total value of the vintage  $t-j$  machines, equals  $Q_{t-j} q_t^{t-j}$ .

The rate of return to all assets held from time  $t$  to  $t+1$  is

$$r_{t+1} = \frac{1}{m_{t,t+1}} - 1 \quad (40)$$

## 5 Asset Market Dynamics

### 5.1 Calibration

Table 2 summarizes the preference and technology parameter values which constitute what I will refer to as the benchmark calibration.

A time period is taken to be one year. The coefficient of the relative risk aversion  $\gamma$  is 1.5. The discount rate  $\beta$  equals 0.97 and the leisure parameter  $\varphi$  is set to be 3. The leisure parameter  $\varphi$  is chosen so that households work about 23% of their time in the competitive steady state.

Table 2: Benchmark calibration

<i>Preferences</i>	<i>Production</i>	<i>Transition Process</i>
$\gamma = 1.5$ $\beta = 0.97$ $\varphi = 3$	$\lambda = 0.89$ $\alpha = 0.36$ $\delta = 0.084$ $\sigma = 0.25$ $M = 15$	$\rho = 0.95$

The steady state values of the quantity and price variables are independent of  $\gamma$ . Together with  $\varphi$ , the parameter  $\gamma$  governs the intertemporal substitution of consumption and labor supply across time. Holding  $\varphi$  fixed, a higher  $\gamma$  implies a lower intertemporal elasticity of substitution.

On the production side,  $\lambda$  is set to 0.89 and  $\alpha$  is set to 0.36. Together they imply a labor share of income of 0.64, and an energy share of income of 0.04, which are close to their data counterpart in the 1970s. The depreciation rate  $\delta$  is 0.084. I define

$$1 - \delta_j = (1 - \delta)^{j-1}, \quad j = 1, \dots, M. \quad (41)$$

The number of vintages,  $M$ , is set to be 15. The average life span of equipment is around 14 or 15 years in the 1970s<sup>9</sup>.

Table 3: Steady State Values for Benchmark Calibration

	<i>C/Y</i>	<i>WL/Y</i>	<i>PE<sub>n</sub>/Y</i>	<i>L</i>
<i>Benchmark</i>	0.69	0.64	0.04	0.23
	<i>Q</i>	<i>k</i>	<i>e</i>	$1 - \Phi(z)$
<i>Benchmark</i>	0.03	51.65	0.05	0.89

<sup>9</sup>Brainard, Shoven and Weiss (1980) find that the average life span for equipment for their sample of firms is 14.5 years.

There is no prior estimate for the standard deviation of the idiosyncratic uncertainty,  $\sigma$ . For the benchmark case,  $\sigma$  is set to 0.25. The benchmark calibration of  $\sigma$  implies that 89% of machines are in operation in the steady state, close to a utilization ratio of 88% among major industries in 1973<sup>10</sup>.

The persistence of the energy price shock,  $\rho$ , is set to 0.95. This persistence parameter is close to what Kim and Loungani (1992) obtained from the auto-regression of the real energy price for the period from 1949 to 1987. Assuming the energy price to be a unit root process slightly magnifies the adverse impact of the energy shock on the securities market, without changing the main conclusion<sup>11</sup>. The mean of the energy price is set to be 1.

Varying the initial distribution of the capital and energy efficiency in the economy has the potential of delivering a slightly larger impact of the energy price shock. However, since the energy share of total costs had remained stable before 1973, this factor will impose an upper limit on the impact of the energy price shock, even in the case where the economy is not in the steady state to begin with.

In Table 3, I summarize the steady state values of the benchmark case. The steady state consumption-output ratio is 69%. Since we start from the steady state, machines of all vintages share the same capital intensity and energy efficiency, which correspond to an energy-capital ratio of 0.02 and energy-labor ratio of 0.05. Both are within the acceptable region of their counterpart in the data.

## 5.2 Asset Market Dynamics

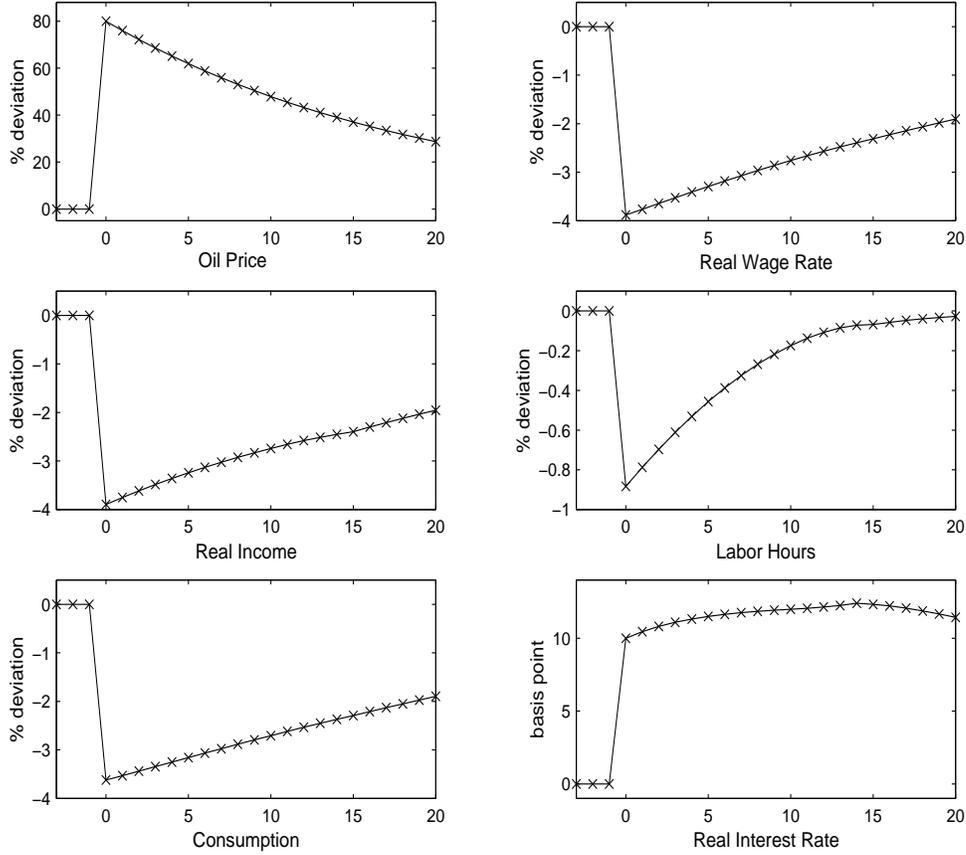
Assume that the energy price shock arrives in period  $t$  in the sense that the energy price increases by 80% in that period. Afterwards, the energy price follows the process specified in equation (28). In all of the figures, I assume that the period  $t$  is 1974.

Figure 2 shows the equilibrium paths of the quantity and price variables following the energy price shock. The real income,  $Y_t - P_t E n_t$ , decreases by 3.9% at the period of the energy price shock, mostly due to the increase in the energy expenditure. Real consumption decreases by 3.6% in the first period and stays low in the following years.

<sup>10</sup>See Table B – 52 in *Economic Report of the President*, February 2000.

<sup>11</sup>One might also assume that the expected energy prices held by agents are the actual prices observed after 1974. I have looked into this alternative specification. The mechanism described in the paper remains robust as long as the energy price process is persistent.

Figure 2: Equilibrium Paths Following the Energy Price Shock(%)



The x-axis is the number of years after the energy price shock.

On impact the real wage rate decreases by 3.9%, a magnitude comparable to that observed in the data<sup>12</sup>. The reason for the real wage decrease is intuitive. The rising energy price pushes up the variable cost of operating the existing machines. The relatively inefficient machines face the prospect of being shut down. With ex post Leontief technology, labor cannot be re-allocated to relatively efficient machines. An energy price increase shifts the labor demand curve to the left. In the meantime, the negative wealth effect from higher energy expenditure leads households to work more at a given

<sup>12</sup>A real wage decrease of 3.9% is slightly larger than the 3.4% decrease observed in 1974. However, this small discrepancy makes at most 1% difference in the eventual impact of the energy price shock on the securities market.

wage. The real wage has to decline to clear the labor market. Since the labor demand is determined by the capacity utilization of previously installed machines, the labor demand remains low while the previously installed machines are still in operation. As a result, the real wage stays persistently below the steady state after the energy price shock, as observed in the data. The persistence of the real wage indicates that its decrease has nontrivial effects on the market value of capital.

With the decrease in the real wage, machines which otherwise would be shut down are now able to remain in operation. Capacity utilization of previously installed machines decreases slightly in response to the energy price shock. As a result, labor hours drop in the initial periods, but to a lesser degree.

The real interest rate rises above its steady state level by 10 basis points and remains stable around this level. In response to the energy price shock, the real interest rate increases so that the agent consumes less in the current relative to the next period.

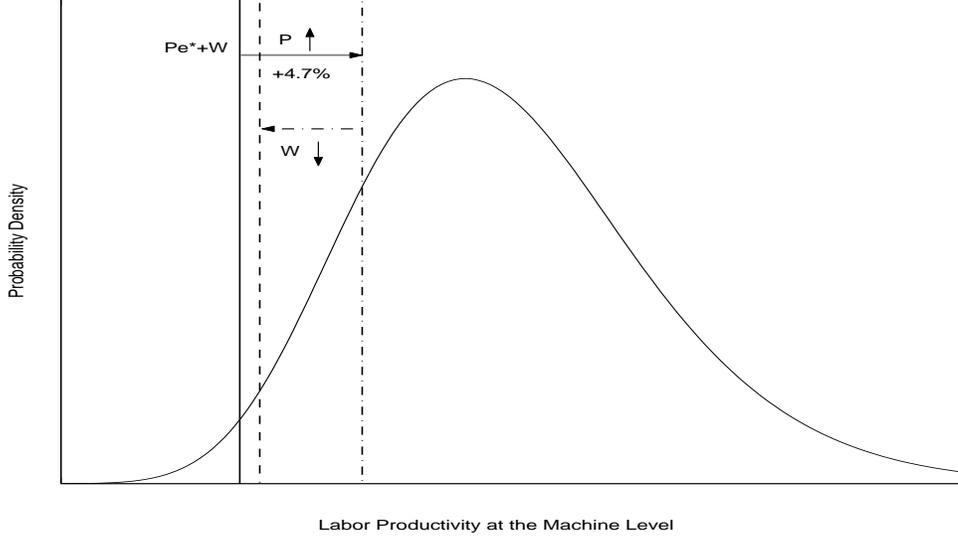
Now I turn to the dynamics of the asset prices. Equation (39) states that the market value of firms is equal to the value of installed capital. Both the investment in the new machines and the prices of old vintage machines change in response to the energy price shock. The next two subsections describe separately the changes in the market value of machines installed before and at period  $t$ .

### **5.2.1 The Market Value of Machines Installed Before Period $t$**

The machines installed before period  $t$  are embodied with the technological choices made earlier. Their market value depends upon the variable cost of operation over their remaining life span. The rise in the energy price induces a persistent decrease in the real wage rate. If the decrease in the wage rate does not fully offset the increase in the energy cost, a fraction of the energy inefficient machines will be shut down. For the machines still in operation, the expected profit decreases because of the higher variable costs. Since the wage is endogenously determined in the model, the cross price elasticity of the labor and energy is important in assessing the direction and magnitude of the effects of energy price shocks on the market value of the machines.

Figure 3 illustrates how the decrease in the real wage offsets the adverse

Figure 3: The Cutoff Point

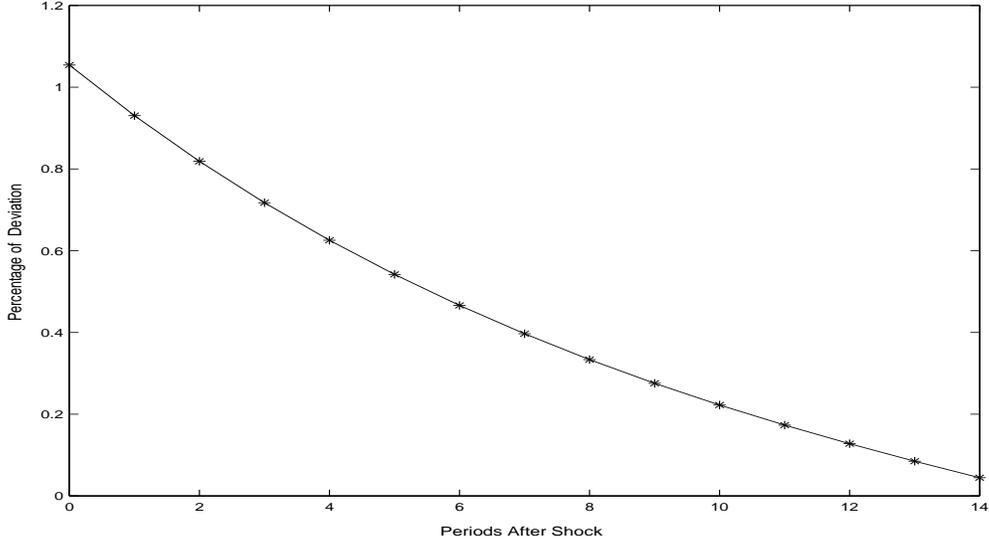


impact of the energy cost increase on the market value of capital<sup>13</sup>. This figure plots the probability density of the labor productivity,  $X_{i,t-j}$ , at the machine level. The cutoff point for the capacity utilization is shown as a solid vertical line. All machines with labor productivity higher than  $Pe^* + W$  are fully utilized in the steady state, where  $e^*$  is the steady state energy-labor ratio. Holding the real wage fixed, an 80% increase in the energy price  $P$  pushes the cutoff point to the right by 4.7%. This implies that around 4% of machines will be shut down if the real wage does not adjust. The decrease in the real wage of 3.9% eventually shifts the cutoff line back. The increase in the variable cost ends up to be very small, due to the mitigating effects of the real wage decrease.

Figure 4 traces the variable costs of operating the machines installed before period  $t$  along their life span. The variable cost of running one unit of vintage  $t - j$  machines is  $P_{t+i}e_{t-j} + W_{t+i}$ , where  $i$  takes the value from 0 to  $M - j$ .  $M - j$  is the remaining life span of the machines. In this figure, the x-axis is the number of periods after  $t$ , the y-axis is the percentage of deviation in the wage and energy costs associated with these machines along their life paths, relative to what would have been spent without the energy shock.

<sup>13</sup>Figure 3 uses arbitrary units for illustration purposes.

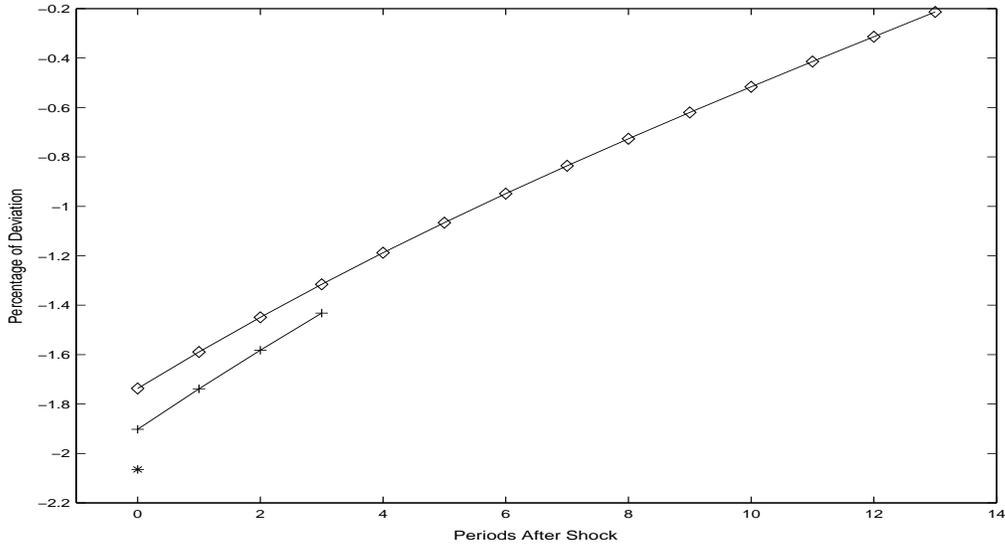
Figure 4: Percentage of Deviation in Variable Costs



Given the assumption that the economy is in the steady state before the energy price shock, all machines installed before period  $t$  are embodied with the same energy efficiency  $e^*$  and cost the same while in use. As displayed in Figure 4, despite the 80% energy price hike, the variable cost of operating one machine rises by less than 1.2%, owing to the decrease in the real wage.

Variable cost returns to the steady state at a speed faster than the energy price itself because the real wage is decreasing over time. This pattern is reflected in Figure 5 in that the machines which are installed earlier lose more value than those installed more recently, except for those installed at period  $t$ . In Figure 5, the x-axis is the number of periods after  $t$ , the y-axis is the percentage of deviation in the price of the vintage  $t - j$  machines,  $q_{t+i}^{t-j}$ , relative to the steady state price of machines of the same age. Here  $i$  takes the value from 0 to  $M - j$  as in the previous figure. The cross-vintage pattern of the declines in the market value comes from the fact that, for the more recently installed machines, the current losses from the higher energy price can be compensated with future savings in the variable cost due to the real wage decrease. At time  $t$ , the machines installed  $M - 1$  periods ago have only one period of production ahead. The variable cost facing this vintage of machines in the next period is 1.1% above the steady state. As a result, the market value of this vintage of machines decreases by 2.1%. Under a certain

Figure 5: Percentage of Deviation in Prices of Vintage  $t - j$  Machines



The symbol  $*$  denotes the percentage of deviation in the price of the machines installed at period  $t - (M - 1)$ . The symbol  $+$  denotes the percentage of deviation in the price of the machines installed at period  $t - (M - 4)$ . The symbol  $\diamond$  denotes the percentage of deviation in the price of the machines installed at period  $t - (M - 14)$ .

parameterization, the machines installed just before the energy price shock even experience slight appreciation in their market value if the real wage decrease over the machines' life span over-compensates the increase in the energy cost.

The rise in the interest rate depresses the value of capital stock, with a larger impact on younger machines. The rise in the interest rate accounts for one-twentieth of the 2.1% decrease in the vintage  $t - (M - 1)$  machines, versus one-third of the 1.7% decrease in the vintage  $t - 1$  machines. Summing across different vintages of the capital stock, the market value of machines installed before the energy price shock decreases by only 1.8% on impact.

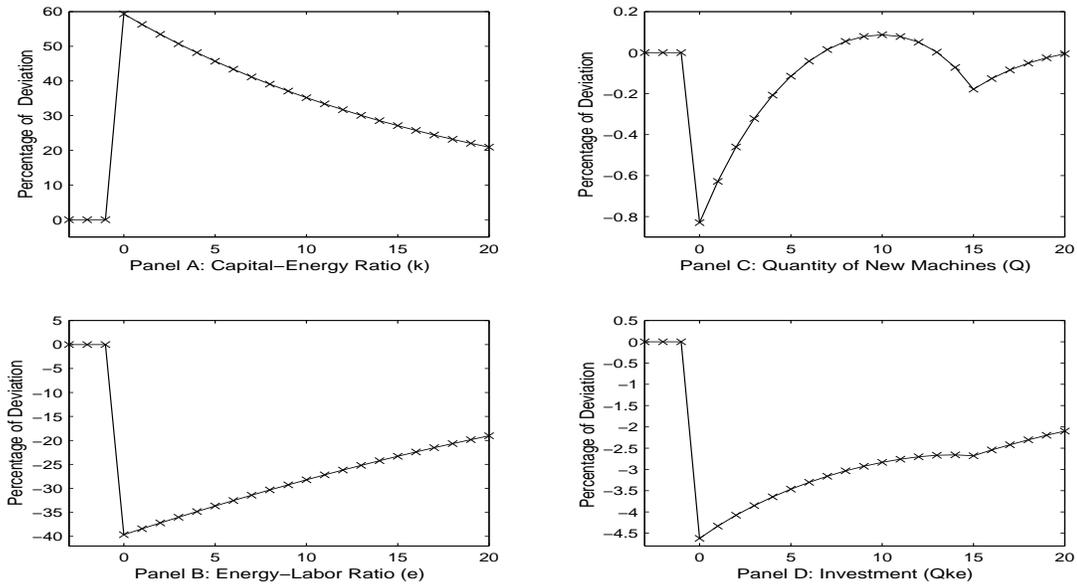
### 5.2.2 The Market Value of Machines Installed at Period $t$

In this section, the machines installed at time  $t$ , the period of the energy price shock, are called new machines. The energy price shock affects the configurations of new machines and the real wage and interest rate over

their life span. The capital intensity,  $k$ , and energy efficiency,  $e$ , of machines installed at and after time  $t$  are determined so that all investments have zero economic rent in equilibrium.

Panels *A* to *C* in Figure 6 plot the responses of the capital intensity, energy efficiency, quantities of machines installed after the energy price shock. In this figure, the x-axis is the time period after the energy price shock, and the y-axis represents the above attributes embodied in the machines installed in the corresponding time period. Panels *A* and *B* reflect the substitution of the factor inputs in the production technology embodied in the new generations of machines. After the energy price shock, the capital-energy ratio increases and the energy-labor ratio drops, showing a substitution of capital and labor away from energy. As a result, the labor productivity of new generations of machines,  $k^{\lambda\alpha}e^{\alpha}$ , declines.

Figure 6: Equilibrium Responses to the Energy Price Shock(%)



The kinks in panel *C* and *D* reflect the replacement echo due to the finite life span of machines.

The investment decreases in response to the energy price shock and stays below the steady state during the subsequent years. This pattern is due

to the following reasons. First, the real income declines because of the rise in the energy expenditure. Less resources are available for the investment. Second, only a very small fraction of machines becomes obsolete as a result of the real wage decrease. The demand for replacing the obsolete capital is weak. Third, the persistently low real wage rate encourages the substitution of labor away from capital. As a result, the price of new machines,  $ke$ , which is also the capital-labor ratio, decreases by 3.8% at the period of the energy price shock.

The energy price shock generates a 4.6% decline in investment at the period of the energy price shock, close to the 6% decline observed in 1974. The market value of the firm is equal to the market value of machines installed at and before the energy price shock. Owing to the decrease in the real wage, an 80% increase in the energy price causes the market value of firms to decline by only 2.2%. The direct effect of the energy price shock on market capitalization is very small.

I have conducted a sensitivity analysis with a wide range of parameters. Raising the dispersion of the idiosyncratic productivity,  $\sigma$ , to 0.28, while holding other parameters fixed, leads to a decrease in the real wage of around 4%, and a decrease in the market value of 2.1%. Alternatively, changing the coefficient of the relative risk aversion  $\gamma$  to 3 results in a real wage decrease of 3.8%, and a decrease in the market value of 2.3%. The results reported in this paper are not sensitive to reasonable variations in these parameters<sup>14</sup>.

### 5.3 Findings from the Quantitative Analysis

The general equilibrium putty-clay model predicts a drop in the market value in response to the energy price shock. However, the direct effect of the energy cost increase turns out to be small. As stated in Section 1, the energy price shock affects the market value of firms through its effect on the investment, earnings of previously installed machines and the real interest rate. The effects through the three channels in the benchmark case are summarized below:

- The 80% energy price increase leads to a 4.6% decline in investment, comparable to a 6% drop observed in 1974.

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<sup>14</sup>The details of the comparative dynamics are available from the author.

- For the machines already installed, the decrease in the real wage offsets the adverse impact of the energy cost increase on the capacity utilization and the expected earnings. As a result, an 80% increase in real energy prices leads to only a 1.8% decrease in the value of previously installed machines.
- The rise in the interest rate depresses the value of capital stock. Of the three channels through which the energy price shock exerts its influence on the securities market, the interest rate channel is the weakest.

The theoretical analysis is supported by the observed decline in the real wage in 1974 of a magnitude comparable to that predicted by the model. The energy price increase by itself is not sufficient to account for the dramatic decline in the securities market in 1974.

## 6 Cross-Industry Event Study

In this section, a cross-industry event study is conducted to examine the cross-sectional patterns of capital depreciation from 1972 to 1974. As stated before, if the energy price shock was the major cause for the market downfall, the energy intensive industries should suffer larger declines.

The initial sample includes all publicly-traded non-farm firms (except coal mining (12), oil and gas extraction (13), electric, gas and sanitary services (49)<sup>15</sup>) in the historical COMPUSTAT database that are incorporated in the U.S. and have data on the variables used to compute the market value of firms for the years between 1972 and 1974.

I aggregate the firms up to the industry classification in the 1972 input-output table. After excluding those industries on the basis of natural resources and measurement problems, I have 34 observations<sup>16</sup>.

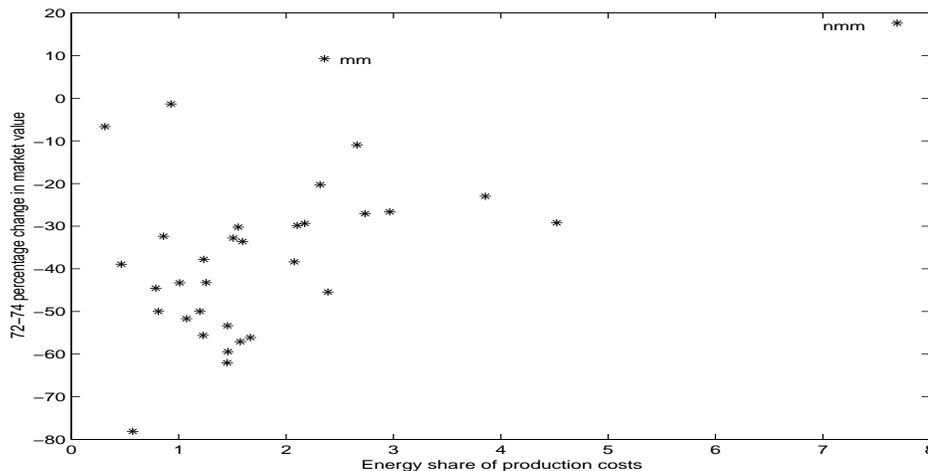
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<sup>15</sup>I exclude the coal mining and oil and gas extraction industry because energy reserves make up more than 10% of the book value of assets for these two industries. The electric, gas and sanitary services industry (industry 49) is excluded because of the measurement problem. In this industry, the number of firms with full observations is 25 in 1972, and 210 in 1974. The measurement problem heavily contaminates the computation of the change in the market value in this industry.

<sup>16</sup>In contrast, HJ (2000) have 52 observations in their cross-industry regression. The industry classification in the input-output table is different from the standard industrial classification. In some cases, several 2-digit industries in the SIC system correspond to

The empirical estimation takes a linear form. The dependent variable is the percentage of deviation in the market value of firms per industry from the end of 1972 to the end of 1974. The regressors are constant and the energy share of production costs per industry. It is reasonable to assume the 1972 energy share of production costs to be exogenous.

Figure 7: Scatter Plot (without industry 29)



mm: metal mining; nmm: non-metallic mining

Initial examination of the constructed data shows that industry 29, the petroleum refining and related industries, is clearly special. It may even be termed an “outlier” in the language of robust statistics. Its energy share of production cost was as high as 52%, while its market value declined by only 19%. This single observation exhibits a large influence on the fittings of the regression model. The influence of this observation can be formally described by its “leverage”, which is the corresponding diagonal element of the orthogonal projector matrix onto the model space (i.e. on the regressors)<sup>17</sup>. The

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one industry in the input-output table. In this case, HJ (2000) assigns the same energy share of production costs to all the 2-digit industries corresponding to the *one* industry in the I-O table. This appears to move their empirical results toward finding an insignificant effect of an oil price increase. Here I aggregate the firms in COMPUSTAT up to the industry classification in the I-O table. That is why I have fewer observations.

<sup>17</sup>See, for example, Venables and Ripley (1999).

leverage of industry 29 is indeed exceedingly high. This formally warrants the intuitive exclusion of industry 29 from my regression.

Figure 7 shows the scatter plot of the percentage of deviation in the market value versus the energy share of production costs. Each observation represents one industry. Table 4 shows that the coefficient for the energy intensity variable has a significantly positive sign, which says that the energy intensive industries were faring better in terms of the market value than others.

Considering that there were material shortages in 1972, the industries with significant reserves of natural resources might have behaved differently from other industries. I conduct the above empirical regression with an extra independent variable, a dummy variable which equals 1 when the share of natural resources of the total book value of assets of the industry is higher than 10%. Metal mining (10) and the mining and quarrying of non-metallic minerals industry (14) have the dummy equal to 1. Table 4 shows the results with the dummy variable incorporated. Durable goods are more cyclical than others. To control for this factor, I include the dummy variable which is one for durable goods producing sectors (Construction, Furniture, Industrial Machinery, Electronic and Electric equipment, Motor Vehicles, Transportation equipment, Instruments). The coefficient for the durable goods dummy is not significant.

The empirical results strongly reject a negative correlation between the energy share of production costs and the change in the market value across industries. It indicates that factors other than the energy price shock were mainly responsible for the securities market decline. As a result, the cross-sectional patterns can not be explained by the energy intensity of industries.

Despite the 80% increase in the energy price, the empirical results show that the energy intensive industries were not those which suffered the most<sup>18</sup>. The finding is even more surprising if we look at the monthly equal-weighted stock return (excluding dividends) constructed from CRSP. The market value of equity declined by more than 17% from October to November 1973! Yet October 1973 was exactly the month in which Arab oil embargo started.

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<sup>18</sup>I have run similar regressions using the changes in the market value of equity constructed from CRSP. The results show that the energy intensive industries did not endure larger declines in terms of the equity value.

Table 4: Least Square Regression

Independent Variables	Dependent Variable (33 Observations)	
	1972 – 1974 Percentage Change in the Market Value	
	Regression 1	Regression 2
Constant	–50.53 (5.50)	–45.67 (5.78)
Energy Share of Production Costs	8.02 (1.80)	4.20 (2.13)
Dummy for Natural Resources		37.98 (7.99)
<i>P</i> -value for the Energy Share Coefficient	0.00	0.03
<i>R</i> -squared	0.29	0.42
Adjusted <i>R</i> -squared	0.27	0.38

The standard errors (White heteroskedasticity-constant) of the estimates are in parentheses.

## 7 Conclusion

There are continuing debates on the causes of the massive market decline from 1973 to 1974. This paper focuses on the prime suspect by conventional wisdom: the energy price crisis of 1973 – 74. A putty-clay model is used to evaluate the direct effect of energy cost increases on the securities market. The energy price shock causes a large decrease in the real wage, which is sufficient to offset the adverse impact of the increase in the energy cost. An 80% increase in the real energy prices causes the market value to decrease by only 2.2%. Given that the market value of firms plunged by 40% in 1974, the direct impact of the energy cost increase on the securities market is small. A broader set of forces was responsible for the market downfall.

In the general equilibrium model, the energy price shock has generated the movements of the real wage, income and consumption of the right direction and reasonable magnitude. The real wage falls 3.9% below the steady state in response to an 80% energy price increase, whereas in the data, the real

wage dropped to 3.4% below the trend in 1974. The decrease in the real wage is persistent, both in the model and in the data. Recall that in the partial equilibrium computation of section 3, a permanent decrease in the wage rate of 5% is sufficient to reverse the upward pressure on the variable cost brought by the energy price increase. The real wage declines implied by the model and observed in the data are large enough to counter the adverse effect of the increase in the energy cost.

In the partial equilibrium setting where the real wage and interest rate are held fixed, an 80% increase in the real energy price leads to a 10% decline in the market value of previously installed machines. The small share of energy cost per se does not necessarily imply that the energy price shock plays an unimportant role in explaining the securities market. It is the general equilibrium dynamics of the real wage that dampens the effect of the energy shock. The smaller the energy share of production costs, the less will be the decrease in the real wage required to offset the impact of the increase in energy prices, as shown in equation (14).

The model solutions are obtained under a neoclassical model with putty-clay production technology. The mechanism of the real wage decrease is neoclassical in nature. The increase in the energy costs pushes for a reduction in labor demand. The real wage has to decline to clear the labor market. As a result, the compensation for labor bears the brunt of the energy price shock. The capacity utilization of machines declines only slightly; so does the market value of capital.

To keep the analysis simple, I abstract from the unemployment problem. This issue is the focus of Hamilton (1988) in studying the real economy consequences of energy shocks. Hamilton (1988) shows that small disruptions in the energy supply can cause high unemployment in a two-sector neoclassical model. Two key assumptions are made: (a) energy is a complementary input used along with labor in one sector; (b) the marginal utility of leisure is fixed. Workers must endure one period of unemployment before switching to another sector. The model provides a theoretical possibility of the multiplier effect on employment. However, its quantitative relevance in interpreting the events in 1974 is subject to two caveats. First, the magnitude of the effect depends upon the employed workers' outside options in 1974. Second, given that energy is highly complementary with labor in producing one of the two goods, a "small" disruption in the energy supply may not be small in magnitude if we consider the implied change in the shadow price of energy instead.

A better understanding of the labor market phenomena, including the cause and duration of unemployment, is important for studying the asset market anomaly in 1974. The logical next step is to quantify the role of labor market frictions in a model calibrated to the economic environment in 1974. More elaborate modeling of the labor market, including the relation between labor contracting and asset prices, is left for future research.

It is interesting to go beyond the episode of the energy price crisis of 1973–74 and study whether the energy price shocks affected the stock market in other historical events involving radical energy price changes. These events are: the second oil price crisis caused by the Iran revolution in 1979, the oil price decline in 1986 caused by the collapse of the oil cartel, the 1990 oil price crisis triggered by the invasion of Kuwait and the ongoing 1999 – 2000 energy price hike. A cross-industry event study on all these incidents is the focus of a companion empirical paper. The dynamic interactions among oil prices, the real wage and cross-industry stock returns are also being studied in my ongoing empirical work.

This paper studies the impact of the energy price shock in isolation. It is possible that the energy price shock, combined with other shocks might have had a different effect on the securities market in 1974. There are also other possible explanations for the market decline in 1974. Among them are the tightening of the monetary policy, the arrival of information technology, the rise in uncertainty, etc. The quantitative relevance of these explanations in a general equilibrium environment remains to be judged in a calibrated model, as has been done here. More work is under way to uncover the mysteries behind the massive market decline in 1974.

## References

- [1] Abel, Andrew, 1999, "The Effects of a Baby Boom on Stock Prices and Capital Accumulation in the Presence of Social Security," Wharton School, unpublished, October.
- [2] Annual Energy Review, Energy Information Administration. Washington, DC: U.S. Department of Energy,
- [3] Atkeson, Andrew and Patrick Kehoe, 1994, "Putty-Clay Capital and Energy," *NBER Working Paper* 4833.
- [4] Atkeson, Andrew and Patrick Kehoe, 1999, "Models of Energy Use: Putty-Putty Versus Putty-Clay," *American Economic Review*, September.
- [5] Baily, Martin, 1981, "Productivity and the Service of Capital and Labor", *Brookings Papers on Economic Activity* No. 1. 1-50.
- [6] Barsky, Robert and Lutz Kilian, 2000, "A Monetary Explanation of the Great Stagflation of the 1970s," mimeo.
- [7] Bernanke, Ben, 1983, "Irreversibility, Uncertainty, and Cyclical Investment," *Quarterly Journal of Economics*, 98, 85-106.
- [8] Berndt Ernst and Barry Field, 1981, *Modeling and Measuring Natural Resource Substitution*, The MIT Press.
- [9] Brainard, William, John Shoven and Laurence Weiss, 1980, "The Financial Valuation of the Return to Capital," *Brookings Papers on Economic Activity*, P 453-502.
- [10] Bresnahan, Timothy and Valerie Ramey, 1993, "Segment Shifts and Capacity Utilization in the U.S. Automobile Industry," *American Economic Review*, Volume 83, Issues 2, 213-218.
- [11] Boldrin, Michele, Lawrence Christiano and Jonas Fisher, 1999, "Habit Persistence, Asset Returns and the Business Cycle," *Federal Reserve Bank of Chicago Research Department*, Working Paper.
- [12] Chen, Naifu, Richard Noll and Stephen Ross, 1986, "Economic Forces and the Stock Market," *Journal of Business*, Vol 59, Issue 3, 383-403.

- [13] Cochrane, John, 1991, "Production-Based Asset Pricing and the Link Between Stock Returns and Economic Fluctuations," *Journal of Finance*, 209-237.
- [14] Cochrane, John, 1994, "Shocks," *Carnegie-Rochester Conference Series on Public Policy* 41, 295-364.
- [15] Cochrane, John, 1996, "A Cross-Sectional Test of an Investment-Based Asset Pricing Model," *Journal of Political Economy*, 104: 572-621.
- [16] Cochrane, John, 1997, "Where is the Market Going? Uncertain Facts and Novel Theories," *Federal Reserve Bank of Chicago Economic Perspectives*, Nov/Dec, 3-37.
- [17] Cochrane, John and Lars Hansen, 1992, 'Asset Pricing Explorations for Macroeconomics,' *NBER Macroeconomics Annual*, 115-165.
- [18] Compustat, Standard and Poor's Compustat data.
- [19] CRSP, Center for Research in Securities Prices, Graduate School of Business, University of Chicago.
- [20] Davis, Steven and John Haltiwanger, 1999, "Sectoral Job Creation and Destruction Responses to Oil Price Changes," *NBER Working Paper* 7095.
- [21] Dixit, Avinash and Robert Pindyck, 1994, *Investment Under Uncertainty*, Princeton University Press.
- [22] Doms, M.E. 1993, "Inter Fuel Substitution and Energy Technology Heterogeneity in U.S. Manufacturing," *CES Discussion Paper* 93-5, U.S. Bureau of the Census.
- [23] DRI/McGraw-Hill Historical Data.
- [24] Epstein, Larry and Stanley Zin, 1989, "Substitution, Risk Aversion, and the Temporal Behavior of Consumption and Asset Returns: A Theoretical Framework," *Econometrica* 57, 937-969.
- [25] Epstein, Larry and Stanley Zin, 1991, "Substitution, Risk Aversion, and the Temporal Behavior of Consumption and Asset Returns: An Empirical Analysis," *Journal of Political Economy*, 99, 263-286

- [26] Fair, R. and J. Taylor, 1983, "Solution and Maximum Likelihood Estimation of Dynamic Nonlinear Rational Expectation Models," *Econometrica*, 51, 1169-85.
- [27] Fama, Eugene and Kenneth French, 1997, "The Corporate Cost of Capital and the Return on Corporate Investment," mimeo.
- [28] Finn, Mary, 1995, "Variance Properties of Solow's Productivity Residual and Their Cyclical Implications," *Journal of Economic Dynamics and Control*, July-September 1995, 19(5-7), 1249-81.
- [29] Fuss, Melvyn, 1977, "The Structure of Technology Over Time: A Model for Testing the 'Putty-Clay' Hypothesis," *Econometrica*, Vol 45, Issue 8, 1797-1821.
- [30] Gilchrist Simon and John Williams, 2000, "Putty-Clay and Investment: A Business Cycle Analysis," *Journal of Political Economy*, Vol 108, No.5.
- [31] Greenwood, Jeremy and Mehmet Yorukoglu, 1997, "1974," *Carnegie-Rochester Conference Series on Public Policy*, Vol 46, 49-96
- [32] Hall, Brownyn, 1990, "The Manufacturing Sector Master File: 1959-1987," *NBER Working Paper* 3366.
- [33] Hall, Robert, 1999, "The Stock Market and Capital Accumulation," *NBER Working Paper* 7180.
- [34] Hamilton, James, 1983, "Oil and the Macroeconomy since World War II", *Journal of Political Economy*, Vol 91, Issue 2, 228-248.
- [35] Hamilton, James, 1985, "Historical Causes of Postwar Oil Shocks and Recessions," *Energy Journal*, 6, 97-116.
- [36] Hamilton, James, 1988, "A Neoclassical Model of Unemployment and the Business Cycle," *Journal of Political Economy*, 96: (3) 593-617.
- [37] Hamilton, James, 1999, "What is an Oil Shock?," *NBER Working Paper* 7755.
- [38] Hickman Bert, Hillard Huntington and James Sweeney, 1987, *Macroeconomic Impacts of Energy Shocks*, Elsevier Science Publishers B.V.

- [39] Hobijn, Bart and Boyan Jovanovic, 1999, "The Information Technology Revolution and the Stock Market: Preliminary Evidence," mimeo.
- [40] Hudson, Edward and Dale Jorgensen, "Energy Prices and the U.S. Economy, 1972-1976," *Natural Resources Journal*, Vol. 18 (October 1978) 877-97.
- [41] Hulten, Charles, 1990, *Productivity Growth in Japan and the United States*, The University of Chicago Press.
- [42] Jermann, Urban, 1998, "Asset Pricing in Production Economy," *Journal of Monetary Economics*, 41 257-275.
- [43] Johansen, Leif, 1959, "Substitution versus Fixed Production Coefficients in the Theory of Economic Growth: A synthesis," *Econometrica*, 27, 157-176.
- [44] Jones, Charles and Gautam Kaul, 1996, "Oil and the Stock Markets," *Journal of Finance*, Vol 51, Issue 2.
- [45] Judd, Kenneth, 1998, *Numerical Methods in Economics*, Cambridge, MA.: MIT Press.
- [46] Kim, In-Moo and Prakash Loungani, 1992, "The Role of Energy in Real Business Cycle Models," *Journal of Monetary Economics*,
- [47] Kling, John, 1985, "Oil Price Shocks and Stock Market Behavior," *Journal of Portfolio Management*, 12: (1) 34-39.
- [48] Kogan, Leonid, 1999, "Asset Prices and Irreversible Real Investment," mimeo.
- [49] Lucas, Robert, 1978, "Asset Prices in an Exchange Economy," *Econometrica*, 46: 1429-1445, November.
- [50] Mehra, Rajnish and Edward Prescott, 1985, "The Equity Premium: A Puzzle," *Journal of Monetary Economics*, 15, 145-161.
- [51] Mork, Knut and Robert Hall, 1980, "Energy Prices, Inflation, and Recession, 1974-1975," *Energy Journal*, Vol 1, No. 3, 31-63.

- [52] Pindyck, Robert and Julio Rotemberg, 1983, "Dynamic Factor Demands and the Effects of Energy Price Shocks," *American Economic Review*, December, 73(5), 1066-79.
- [53] Rotemberg, Julio and Michael Woodford, 1996, "Imperfect Competition and the Effects of Energy Price Increases on Economic Activity," *Journal of Money, Credit and Banking*, November, 28(4), 549-77.
- [54] Rouwenhorst, Geert, 1995, "Asset Pricing Implications of Equilibrium Business Cycle Models," in Thomas Cooley, editor, *Frontiers of Business Cycle Analysis*, Princeton University Press.
- [55] Sakellaris, Plutarchos, 1997, "Irreversible Capital and the Stock Market Response to Shocks in Profitability," *International Economic Review*, Vol 38, No. 2.
- [56] Sadorsky, Perry, 1999, "Oil Price Shocks and Stock Market Activity," *Energy Economics*, 21, 449-469.
- [57] Sato, k, 1967, "A Two-level Constant-Elasticity-of-Substitution Production Function," *Review of Economic Studies* 34, 201-218.
- [58] *Survey of Current Business*, United States Department of Commerce. Washington, DC: Bureau of Economic Analysis, February, April 1979. "The Input-Output Structure of the U.S. Economy, 1972".
- [59] Venables, W and Ripley, B, 1999, *Modern Applied Statistics with S-PLUS*, Springer
- [60] Wei, Chao, 1999, "Non-Expected Utility in a Production Economy", mimeo.
- [61] Wei, Chao, 2000, "Do Oil Price Shocks Affect the Stock Market: Empirical Evidence", mimeo.
- [62] Wei, Chao, 2001, "Energy, the Stock Market and the Putty-Clay Investment Model," Stanford University, Ph.D. Dissertation.

# Appendix

## A Description of the Planner's Problem

The planner's problem is as follows:

At the beginning of each period, the energy price  $P$  is observed. The energy price and the attributes of the  $M$  vintages of capital in existence characterize the state of the economy. Each vintage of capital is identified by the capital-energy ratio,  $k_{-j}$ ,  $j = 1, \dots, M$ ; the energy-labor ratio,  $e_{-j}$ ,  $j = 1, \dots, M$ ; and the quantity of machines installed per vintage,  $Q_{-j}$ ,  $j = 1, \dots, M$ . All these attributes have been chosen at the time of installation. Thus the model consists of  $3M + 1$  state variables. The control variables are: the quantity of new machines,  $Q$ ; the capital-energy ratio for the new machines,  $k$ ; the energy-labor ratio for the new machines,  $e$ ; the cutoff value of utilization for machines of vintage  $j$ ,  $z_{-j}$ ,  $j = 1, \dots, M$ . Once the  $3 + M$  control variables are chosen, the employment, output and consumption are determined from equations (23), (25) and (36).

The value function for the planner's problem in this model is:

$$V(\mathbf{Q}, \mathbf{k}, \mathbf{e}, P) =$$

$$\max_{Q, k, e, \{z_{-j}\}} U(C, L) + \beta V(\mathbf{Q}', \mathbf{k}', \mathbf{e}', P'),$$

subject to equations (23), (36) and

$$P' = 1 - \rho + \rho P. \tag{42}$$

The variables  $\mathbf{Q}$  denotes  $\{Q_{-1}, Q_{-2}, \dots, Q_{-M}\}$ . Accordingly,  $\mathbf{Q}'$  denotes  $\{Q, Q_{-1}, \dots, Q_{-(M-1)}\}$ . Other variables such as  $\mathbf{k}, \mathbf{e}$  and etc. are defined in the similar fashion.

It is straightforward to verify that the decentralized economy shares the same equilibrium allocations as the planner's economy.

## B Technical Appendix

### B.1 Derive the capacity utilization formula<sup>19</sup>

$$\frac{\int_{P_{t+j}e_t+W_{t+j}}^{\infty} X_{i,t}dF(X_{i,t})}{\int_0^{\infty} X_{i,t}dF(X_{i,t})} = 1 - \Phi(z_{t+j}^t - \sigma) \quad (43)$$

**Proof:**

The derivation uses the density of a truncated random variable  $\chi$ :

$$f(\chi|\chi > a) = \frac{f(\chi)}{\text{prob}(\chi > a)}. \quad (44)$$

Denote the left hand side of the equation (43) as *LHS*, we have

$$\begin{aligned} LHS &= \frac{\left[ \int_{P_{t+j}e_t+W_{t+j}}^{\infty} X_{i,t}f(X_{i,t}|X_{i,t} > P_{t+j}e_t + W_{t+j})dX_{i,t} \right] \text{prob}(X_{i,t} > P_{t+j}e_t + W_{t+j})}{\int_0^{\infty} X_{i,t}dF(X_{i,t})} \\ &= \frac{E(X_{i,t}|X_{i,t} > P_{t+j}e_t + W_{t+j})\text{prob}(X_{i,t} > P_{t+j}e_t + W_{t+j})}{E(X_{i,t})} \\ &= 1 - \Phi(z_{t+j}^t - \sigma). \end{aligned} \quad (45)$$

The last equality makes use of the lognormal distribution of the idiosyncratic shock. If  $\ln(\mu) \sim N(\zeta, \varepsilon^2)$ , then  $E(\mu|\mu > \nu) = \frac{(1-\Phi(\kappa-\varepsilon))}{(1-\Phi(\kappa))}E(\mu)$ , where  $\kappa = (\ln \nu - \zeta)/\varepsilon$ . (Johnson, Kotz and Balakrishnan 1994).

### B.2 Derive the average price $q_t^{t-j}$

$$\int_0^{\infty} [q_t(t-j, \theta_{i,t-j}) f(\theta_{i,t-j})] d\theta_{i,t-j} = q_t^{t-j}, \quad (46)$$

where  $q_t(t-j, \theta_{i,t-j})$  is the price of the vintage  $t-j$  machine with the realized idiosyncratic productivity,  $\theta_{i,t-j}$ , at time  $t$ , and  $f(\theta_{i,t-j})$  is the probability density function of  $\theta_{i,t-j}$ . The average price  $q_t^{t-j}$  is defined in equation (38).

**Proof:**

Denote  $A = \left\{ \theta_{i,t-j} | \theta_{i,t-j} > \frac{P_{t+n}e_{t-j}+W_{t+n}}{X_{t-j}} \right\}$ . Define  $d_t(t-j, \theta_{i,t-j})$  to be the dividend generated at time  $t$  by the vintage  $t-j$  machine with the

<sup>19</sup>This proof is adapted from Gilchrist and Williams (2000).

realized idiosyncratic productivity  $\theta_{i,t-j}$ . From the Euler equations in the decentralized equilibrium, we can get

$$q_t(t-j, \theta_{i,t-j}) = \sum_{n=1}^{M-j} [m_{t,t+n} d_{t+n}(t-j, \theta_{i,t-j})], \quad j = 0, \dots, M-1 \quad (47)$$

where

$$\begin{aligned} d_{t+n}(t-j, \theta_{i,t-j}) &= \mathbf{1}_{\theta_{i,t-j} \in A} (1 - \delta_{j+n}) \theta_{i,t-j} X_{t-j} \\ &\quad - \mathbf{1}_{\theta_{i,t-j} \in A} (P_{t+n} e_{t-j} + W_{t+n}) (1 - \delta_{j+n}), \quad j = 0, \dots, M-1. \end{aligned}$$

Denote *LHS* as the left hand side of the equation (46), we can derive the following from equation (47):

$$LHS = \sum_{n=1}^{M-j} [m_{t,t+n} (G1 - G2)] \quad (48)$$

where

$$G1 = \int_0^\infty [\mathbf{1}_{\theta_{i,t-j} \in A} (1 - \delta_{j+n}) \theta_{i,t-j} X_{t-j}] f(\theta_{i,t-j}) d\theta_{i,t-j} \quad (49)$$

$$G2 = \int_0^\infty [\mathbf{1}_{\theta_{i,t-j} \in A} (P_{t+n} e_{t-j} + W_{t+n}) (1 - \delta_{j+n})] f(\theta_{i,t-j}) d\theta_{i,t-j} \quad (50)$$

$$j = 0, \dots, M-1$$

Define

$$\eta_{i,t-j} = \frac{1}{\sigma} \left[ \log(\theta_{i,t-j}) + \frac{1}{2} \sigma^2 \right]. \quad (51)$$

From equation (15), we can see that  $\eta_{i,t-j}$  is a random variable with a standard normal distribution.

After simple manipulations, we have

$$\begin{aligned} G1 &= \int_{z_{t+n}^{t-j}}^\infty \left[ \exp\left(\eta_{i,t-j} \sigma - \frac{\sigma^2}{2}\right) \exp\left(-\frac{\eta_{i,t-j}^2}{2}\right) (1 - \delta_{j+n}) X_{t-j} \right] d\eta_{i,t-j} \\ &= \int_{z_{t+n}^{t-j}}^\infty \left\{ \exp\left[-\left(\frac{\eta_{i,t-j} - \sigma}{2}\right)^2\right] (1 - \delta_{j+n}) X_{t-j} \right\} d\eta_{i,t-j} \\ &= [1 - \Phi(z_{t+n}^{t-j} - \sigma)] (1 - \delta_{j+n}) X_{t-j}. \end{aligned} \quad (52)$$

Accordingly, we can get

$$\begin{aligned}
G2 &= \int_{z_{t+n}^{t-j}}^{\infty} \left[ (P_{t+n}e_{t-j} + W_{t+n}) \exp\left(-\frac{\eta_{i,t-j}^2}{2}\right) (1 - \delta_{j+n}) \right] d\eta_{i,t-j} \\
&= [1 - \Phi(z_{t+n}^{t-j})] (1 - \delta_{j+n})(P_{t+n}e_{t-j} + W_{t+n})
\end{aligned} \tag{53}$$

Summing these two terms up establishes the result.

## C Data Appendix

### C.1 Construct the Energy Share of Production Costs

The energy share of production costs for each industry is constructed from the 1972 input-output table<sup>20</sup>. The table of “Commodity-by Commodity Total Requirements” contains the data on the direct and indirect costs required of one commodity for each dollar of delivery to final demand of another commodity at producers’ prices. I sum up the cost shares of crude petroleum, natural gas, coal and anthracite for each industry of final demand.

The table of “The Make of Commodities by Industries” contains the data on the total output of each industry. The energy share of production costs can be computed from these two tables.

The matching table of the industry classification of the input-output table and the standard industrial classification is available from *Survey of Current Business* (1979, February and April).

### C.2 Construct the market value of a firm

COMPUSTAT contains the book value of assets, liabilities and net worth of a firm. The book value of short-term financial assets and liabilities can be safely assumed to be equal to their market value. Such assumptions do not apply to the long-term debt, which by definition has the maturity of more than one year.

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<sup>20</sup>I thank Bart Hobijn for providing me his programs of constructing the oil share of production costs.

### C.2.1 The Market Value of Long-Term Debt

Following Brainard, Shoven and Weiss (1980, henceforth BSW), I make the following assumptions to compute the market value of long-term debt (I will call it bonds for short):

1. New bonds are issued at par and have a maturity of 20 years.
2. Bonds have identical default characteristics represented by a Baa rating of Moody's.
3. No new debt is issued unless total long-term debt in  $t$  is greater than long-term debt in  $t - 1$  minus estimated matured issuances of debt. Under these conditions, new debt issued by industry  $i$  in period  $t$ ,  $N_{i,t}$ , for  $t > t_0$  is calculated by

$$N_{i,t} = LTD_{i,t} - LTD_{i,t-1} + L_{i,t-19}^{t-1}, \quad (54)$$

if

$$LTD_{i,t} > LTD_{i,t-1} - L_{i,t-19}^{t-1}, \quad (55)$$

where  $LTD_{i,t}$  is the book value of long-term debt (data9 in COMPU-STAT) for industry  $i$  at time  $t$ ,  $L_{i,t-j}^t$  is the time  $t$  book value of debt issued by industry  $i$  at  $t - j$ , and  $t_0$  is the starting year. If the above condition is satisfied at time  $t$ , we have

$$L_{i,t-j}^t = L_{i,t-j}^{t-1}, \quad j = 1, \dots, 19, \quad (56)$$

which means that the book value of long-term debt for each maturity is the same as that of previous period. By definition,

$$L_{i,t}^t = N_{i,t}. \quad (57)$$

If the condition in equation (55) is not satisfied, then

$$N_{i,t} = 0, \quad (58)$$

and

$$L_{i,t-j}^t = \frac{LTD_t}{LTD_{i,t-1} - L_{i,t-19}^{t-1}} L_{i,t-j}^{t-1}, \quad j = 1, \dots, 19, \quad (59)$$

that is, early retirements are proportional to existing issuance of debt for each maturity. This method of construction guarantees that

$$N_{i,t} \geq 0, \quad (60)$$

and

$$N_{i,t} + \sum_{j=1}^{19} L_{i,t-j}^t = LTD_{i,t}. \quad (61)$$

4. I use 1958 as the starting year and assume that the maturity distribution of bonds for each industry in 1958, is proportional to the maturity distribution of aggregate outstanding issues. I choose 1958 as the starting year for two reasons. First, the aggregate maturity distribution is readily available this year from BSW (1980). Second, given that I am interested in the years from 1972 to 1974, an earlier starting year allows me to capture the distinct paths of changing debt structure of each industry from 1958 to 1972.

Given the derived maturities and associated coupon rates, the market value of long-term debt for each industry from 1972 to 1974 can be computed. Specifically, the coupon rate of the long-term debt is determined at the time of issuance, while the coupon and principal are discounted by the yield to maturity at the time of observation. As might be expected in a period of accelerating inflation and rising interest rates, most bonds have sold at a discount from book value.

To emphasize, I compute the above maturity distribution treating each industry as one unit, the long-term debt of an industry is equal to the sum of all firms in that industry. It is possible that the condition in equation (55) is satisfied for the industry as a whole, but not for the individual firm. This introduces the measurement error which is likely to bias the maturity distribution toward the previously issued debt. However, if we derive the debt structure on the firm basis, our sample will have to be restricted to those firms with observations for the entire period from 1958 to 1972.

### C.2.2 The Market Value of Preferred Stock

The market value of preferred stock is computed by dividing the firm's total reported preferred dividends (data19) by Moody's preferred stock yield index for medium risk companies.

### C.2.3 Sum Up the Components

Now we have the market value of a firm, denoted by  $MV$ ,

$$MV = MVEQUITY + MVPRE + MVLTD + CULIB - (CUAST - BKINV), \quad (62)$$

where  $MVEQUITY$  is the market value of equity (data24+data25),  $MVPRE$  is the market value of preferred stock derived above,  $CULIB$  is the total current liabilities (data5),  $CUAST$  is the total current assets (data4), including inventories, which is denoted by  $BKINV$ . Since inventories are part of physical capital, I add the book value of inventories back to the market value of the firm.

## C.3 Construct the Real Energy Price

The series used to construct the real energy price are taken from *Annual Energy Review* 1999, Energy Information Administration. The data are downloaded from the website <http://www.eia.doe.gov/emeu/aer/contents.html>.

Energy Prices (dollar prices per million Btus in chained 1992 dollars, calculated by using personal consumption expenditure implicit price deflators):

pdomoil: domestic first purchase price of crude oil, series in Table 3.1.

pimpoil: imported cost of crude oil, dollars per barrel, series in Table 5.19, converted into Btu units using the thermal conversion factors in Table 13.2.

pnatgs: domestic price of natural gas, series in Table 3.1.

pcoal: domestic price of coal, series in Table 3.1.

The Btu content of the above energy sources are obtained from Table 1.2, 5.2, 5.3 and 5.5. The domestic price of crude oil is weighted by the share of Btu content of the domestically produced crude oil minus the export. All other prices are weighted by their respective shares in total Btu content. The weighted energy price is the composite real energy price plotted in Figure 1.

Using 1987 as base year, the energy price deflator can be constructed from the composite real energy price. The percentage change in the energy price deflator from 1973 to 1974 is also around 80%.

## C.4 Other Data

Real Wage (Table 1): *DRI*, *LBCPU7*, real compensation per hour, non-farm business (1982=100, SA, quarterly).

Real Consumption (Table 1): real consumption of nondurable goods and services : *National Income and Products Accounts*.

Real Investment (Table 1): gross private domestic fixed investment in non-residential capital excluding the purchase of the structures in the petroleum and natural gas sectors (*GANMG*), *National Income and Products Accounts*.

Adult (16 and over) Population (Table 1): Department of Commerce, Bureau of the Census

## D Computational Method

I exploit the second welfare theorem and find the equilibrium allocations by solving the relevant planner's problem. It is shown in Appendix A that the equilibrium allocations in the decentralized economy are the same as those in the planner's economy.

The model consists of  $3M + 1$  state variables and  $3 + M$  control variables. I use a combination of the multi-dimensional perturbation method and Fair-Taylor method to obtain an accurate solution to the multi-dimensional system involving large deviations from the steady state. The advantage of regular perturbation methods based on an implicit function formulation is that one directly computes the Taylor expansions in terms of whatever variables one wants to use, and that expansion is the best possible asymptotically. In my model, the first order coefficients of the Taylor series approximation are computed using the implicit function theorem and generalized Schur decomposition. The 1st order Taylor coefficients computed using the perturbation method provides a close approximation in the neighborhood of the steady state and serves as a good initial guess for the Fair-Taylor algorithm. The Fair-Taylor method then iterates on the future paths of the expected endogenous variables till the convergence is obtained.

A combination of the perturbation and Fair-Taylor methods produce very precise results, compared to the conventional log-linearization approach. The accuracy of the results is checked by substituting the solutions back into

the Euler equations of the original problem and compute the relative Euler equation errors. The maximum absolute relative Euler equation error is  $1.4 \times 10^{-11}$ .