Oil Crisis, Energy-Saving Technological Change and the Stock Market Crash of 1973-74

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Abstract

The market value of U.S. corporations was nearly halved following the oil crisis of October 1973. Real energy prices more than doubled by the end of the decade, increasing energy costs and spurring innovation in energy-saving technologies by corporations. This paper uses a neo-classical growth model to quantify the impact of the increase in energy prices on the market value of U.S. corporations. In the model, corporations adopt energy-saving technologies as a response to the energy price shock and the price of installed capital falls due to investment irreversibility. The model calibrated to match the subsequent decline in energy consumption in the U.S. generates a 24% decline in market valuation - accounting for nearly half of what is observed in the data.

1 Introduction

The market value of U.S. corporations, relative to the replacement cost of their tangible assets, was nearly *halved* during 1973-74 (See Figure 1).[1] This ratio, also known as the Tobin's (average) q, was around 1.06 over the 1962-72 period, fell sharply during 1973-74, and stagnated for the following decade. Over 1974-1984, Tobin's q for U.S. corporations averaged only 0.55, 48% less relative to the decade prior to 1973. Tobin's q did not recover until the late 90s.

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[1] See the data appendix for data sources and calculations underlying all figures.

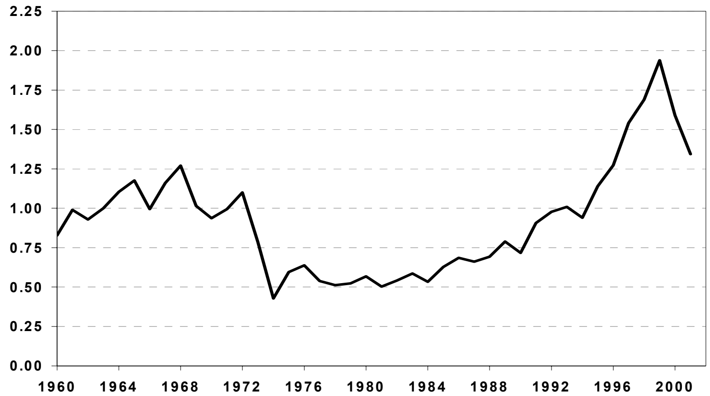

Figure 1: Tobin's average *q:* Market value relative to replacement value of tangible assets of U.S. corporations

This abrupt decline in corporate market valuations coincides exactly with the oil crisis initiated by the OPEC embargo announced in early October of 1973. The largest drop in market values occurred in the 4th quarter of 1973 and throughout 1974 (See Figure 2).

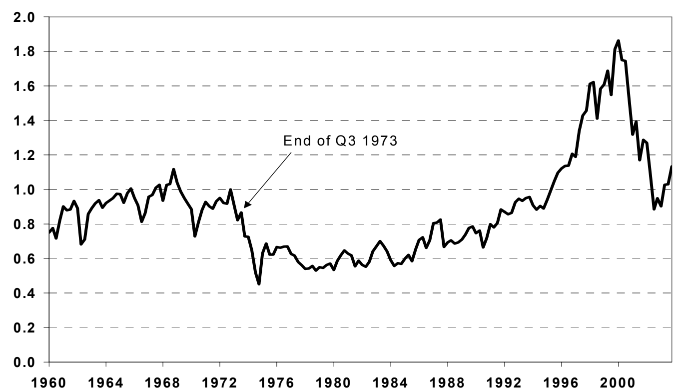

Figure 2: Market Value of U.S. corporations relative to GDP

The oil crisis translated into a 34% percent increase in real energy prices over 1973-74. Energy prices continued to rise for the rest of the decade, especially during 1979-81 due to the events in Iran (See Figure 3). By 1981, real energy prices were 2.1 times higher than what they were in 1972. Energy prices declined after 1982; however, they had yet to come back to their pre-1973 levels after 20 years.

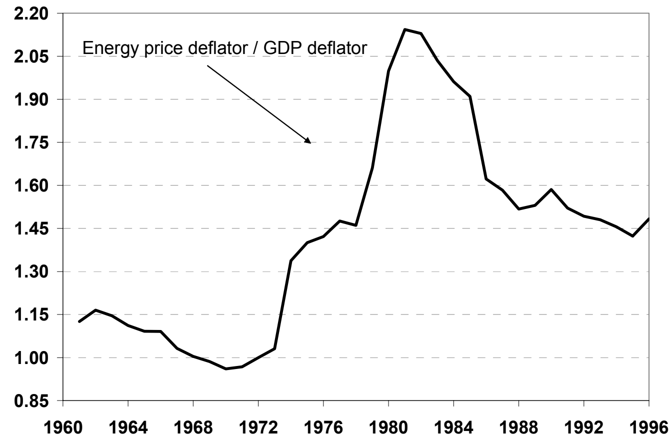

Figure 3: Energy prices relative to GDP deflator (1972 = 1)

The main objective of this paper is to determine how much of the decline in the market value of non-energy producing corporations can be accounted for by the observed changes in energy prices. To do so, we employ a dynamic general equilibrium model with technology-specific capital and investment irreversibility. These assumptions are standard in the literature (cf. Sargent [28], Dixit and Pyndick [10]), and allow for Tobin's q to fall below 1 as in the data. In the model economy firms develop and adopt energy-saving technologies as a response to the energy price shock and the price of installed capital falls due to investment irreversibility. Firms do not introduce these energy-saving technologies prior to the energy shock because it is costly for them to do so. The two costs involved in the process of developing and adopting a new type of capital are, first, a minimum size investment requirement similar to Boldrin and Levine [5] and, second, a learning curve associated with the use of the new technology.[2] With low energy prices, firms forego these costs. With sharp increases in energy prices, however, it pays for corporations to incur them. We calibrate the parameters of the model to match certain features of the U.S. economy; in particular we set the energy-efficiency of the new technologies to match the decline in real energy-output ratios. Our model suggests energy prices can account for almost half of the drop in Tobin's q, and partially for its stagnation throughout the 70s and 80s.

The links between the increase in energy prices and the fall in the market value of non-energy producing corporations, which are the focus of our analysis, are straightforward: First, the sharp and persistent increase in energy costs squeezed both current and expected future dividends causing a fall in market value. Second, as the increase in energy costs was highly persistent, corporations started adopting and investing in new technologies that were more energy-efficient. This spur in energy-saving technologies resulted in capital obsolescence for the old energy-inefficient technologies

[2]Bahk and Gort [4] gives empirical support to the existence of learning by doing in the context of a production function similar to the one in our model. The inclusion of learning by doing in aggregate quantitative studies like ours is common place in the literature. Recent contributions include Klenow [20] in the area of productivity analysis, Young [35] and Parente [23] in development, and Chang, et. al. [8] in business cycles.

driving their value down (cf. Baily [3]). Although these links are intuitive and the timing of the two events is suggestive, the energy explanation has had difficulties both empirically and theoretically and has led many authors to entertain other explanations for the stock market crash of 1973-74.

There are mainly two empirical criticisms regarding the energy explanation. The first is that there is not a high enough correlation between the drop in market values and the pre-1973 cost share of energy for corporations (cf. Wei [36], and Greenwood and Jovanovic [14]). We have computed the correlation between the percentage decline in market value from 1972 to 1974 and the ratio of energy expenditure to value added for all manufacturing industries (non-energy producing) at the 3-digit SIC code and found that this coefficient is actually negative.[3] Thus, we confirm previous results that energy-intensive industries did not suffer the largest drops in market value. The second empirical criticism is the absence of a stock market crash during the energy price shocks of 1979-1981. On the theoretical side, it has been difficult to construct models where energy prices have a quantitatively significant impact on corporate market values primarily because the share of energy in total costs is small. In particular, Wei [36] uses a putty-clay model that encompasses endogenous obsolescence of capital to find that energy price increases can account for only 2% of the decline in market valuation.

The aforementioned empirical criticisms would be especially strong if rising energy costs were the only channel through which energy affected market values and Tobin's q. However, this is not necessarily the case. In fact, there is no reason to expect a drop in Tobin's q due to an increase in energy prices as long as the price of installed capital does not deviate from potential replacements. In Section 3, we show that as long as investment in the old technologies does not stop, Tobin's q will remain constant regardless of the cost share of energy. In this respect, the introduction of new energy-efficient technologies and the obsolescence of old technologies appears to be a better explanation for the drop in Tobin's q. The latter transmission mechanism has the implication that the drop in Tobin's q should be correlated with the *drop* in the energy consumption to corporate GDP ratio (rather than the pre-crisis *level* of energy cost share). This implication of our model is largely supported by the data as the industries that suffered larger drops in market value also experienced large declines in their cost share of energy. Using energy expenditure data (at the 3-digit SIC level) from the Annual Survey of Manufactures, together with market value trends by SIC from Standard and Poor's Compustat, we found that the correlation between the drop in energy cost share between 1972 and 1994 and the percent decline in market values in 1973-74 is 0.276.[4] Another implication of the transmission mechanism we propose is that further price shocks would not necessarily impact Tobin's q, as long as newly introduced capital after the initial price shock does not become obsolete after further price shocks; as for instance the absence of a fall in market

[3] Market value by SIC is taken from the Standard and Poor's COMPUSTAT quarterly data base. We only consider the market value of firms listed in COMPUSTAT before 1972, which controls for the effects of entry. Energy expenditure and value added by SIC is taken from the Annual Survey of Manufactures.

[4] We only considered manufacturing industries as comprehensive data on energy expenditure at 3-digit SIC do not exist for all sectors. Notice also that we used energy expenditure as a proxy for energy consumption given that no data on energy consumption at 3-digit SIC sector is available for our sample period.

value during 1979-1981.

On the theoretical side, the putty-clay model can deliver only a small decline in market values as a result of the energy crisis. The energy crisis translates, through a general equilibrium effect, into a decline of wages that almost completely counteracts the negative impact on dividends of higher energy costs. Thus, in a putty-clay framework the energy crisis translates into a small decline in the present value of dividends (cf. Wei [36]). The drop in the wage rate required for the labor market to clear after the energy shock is relatively smaller in our model because labor can be freely adjusted in both the new *and* the old technology unlike the putty-clay model where the only adjustment takes place for the new technologies. This is translated into a bigger drop in market values in our model relative to the putty-clay model.[5] Moreover, the standard putty-clay model delivers predictions for energy consumption that are not consistent with the U.S. data. In particular, under perfect foresight for energy prices, a putty-clay model would predict an increasing real energy to value added ratio during the 1980s and 1990s, a period where energy prices substantially declined. This prediction is at odds with what is observed in the data. As Figure 4 below illustrates, real energy use (as a share of business GDP) declined monotonically after 1973-74. The monotone decline in energy is, however, consistent with the introduction of a new technology characterized by a lower energy requirement per unit of production (i.e. energy-saving technological change), which is one of the main features of our model.

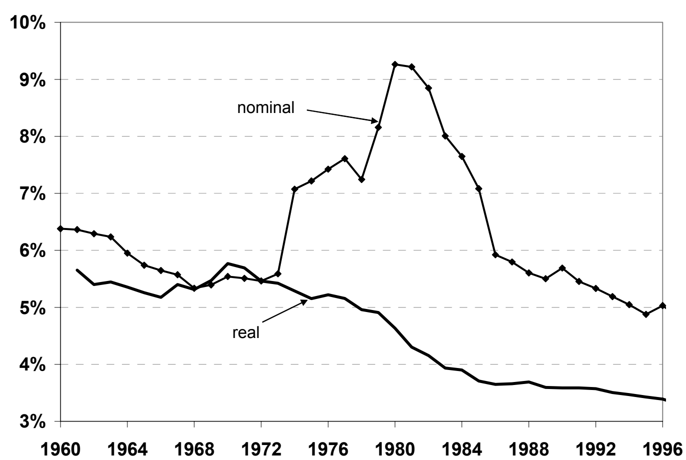

Figure 4: Energy expenditure (nominal) and energy use (real) of the business sector as a share of business GDP

Our paper focuses on the 1974-1994 period which Hall [15] refers to as the "single hardest [equity market] episode to understand"; a period where the market value of U.S. corporations was much lower than the replacement cost of their tangible assets.[6] Other explanations put forward for the stock market crash of 1973-74 are the IT revolution (cf. Greenwood & Jovanovic [14], and

[5] A more detailed discussion of these issues are provided in Sections 3 and 5.

[6] We do not try to account for the boom and subsequent crash in equity prices during 1994-2004.

Laitner and Stolyarov [21]) and investment subsidies provided by the government to businesses in this period (cf. McGrattan & Prescott [22]). The IT explanation is similar to ours in spirit, whereby the innovation of information technologies drives down the price of installed capital. Peralta-Alva [24] uses a neoclassical growth model with capital accumulation to test this idea and finds that the quality of new technologies that will generate the observed drop in Tobin's q would also generate a two-fold increase in investment, sharply in contrast with the data. McGrattan & Prescott [22] argue that the investment subsidies drive a wedge between the price of installed capital and replacement capital and can account for one third of the decline in market valuations observed in the 70s. Our model is not inconsistent with this explanation, since investment subsidies were given partly to encourage firms to adopt energy-efficient technologies. We, nevertheless, abstract from subsidies in our model, and study the effects of the oil crisis and energy-saving technological change in isolation from the government response.

The rest of our paper is structured as follows: Section 2 provides some empirical evidence in support of the price induced innovation hypothesis. Section 3 lays out the model. Calibration of model parameters are given in Section 4 and findings are discussed in Section 5. Section 6 concludes.

2 Energy-Saving Technological change after 1974

Our model connects the decline in the energy requirements per unit of output observed in the U.S. aggregate data to the endogenous introduction of energy-saving technologies. A fundamental assumption in our analysis is that capital embodies a particular technology as in Solow [31]. Our hypothesis is that the observed increase in energy prices provided the right incentives for firms to develop and adopt a new type of capital. The introduction of this new type of capital, in turn, resulted in a new aggregate production function characterized by its energy-saving properties. In what follows, we elaborate on the existing empirical support for our key hypotheses and assumptions. First, we evaluate the main alternative explanation for the observed decline in the U.S. aggregate energy consumed per unit of output, which attributes this decline to changes in the sectoral composition of the U.S. GDP. We find that this alternative explanation falls short of accounting for the data. Secondly, we give some key examples of energy-saving technologies introduced during the mid-70s as a result of the energy crisis of 1973-74.

The observed decline in the energy to GDP ratio might have been caused by changes in the level and structure of sectoral activity. As it is well known, the sectoral composition of the U.S. GDP has changed quite dramatically over the last 40 years. In particular, the value added of the manufacturing sector (which is energy intensive) has declined relative to GDP. At the same time, the value added of service sectors, which are less energy intensive, have increased relative to GDP. To test whether changes in sectoral composition can account for the observed decline in the energy to GDP ratio, we performed the following experiment: First, we obtain from Jorgenson's KLEM data set the average 1960-72 real energy to value added ratio for each economic sector at the 2 digit SIC classification level.[7] Then we compute, from the sectoral GDP-by-industry accounts of the BEA, the change in the fraction of the GDP produced by each of these sectors. Finally, we assume that the energy to value added ratio of all sectors remained constant across time and compute the implied energy output ratio at the aggregate level. We find that sectoral activity can account for less than a fifth of the total decline of the energy output ratio (a drop of 7% in the overall energy to output ratio). This result is consistent with the findings of Schiper [29] and with those of the International Energy Agency [17], which document that most of the decline in energy intensity of the U.S. economy can be attributed to improved energy efficiency and not to the change in sectoral composition.

Examples for the introduction of energy-saving technologies during the mid-70's abound. One of the most important changes in the manufacturing sector during the 1975-1995 period was the increased use of Advanced Manufacturing Technologies (AMTs). AMTs include computer aided design and manufacturing, numerically-controlled machines, and information networks. These improvements constitute a form of embodied technological change. Doms and Dunne [12] use establishment-level data to determine changes in energy intensity arising from differences in plant characteristics and energy prices. The first of their two main findings is that plants that utilize higher numbers of AMTs are less energy intensive. Their second finding is that plants constructed during the period of high energy prices, 1973-1983, are generally more energy efficient than plants built during other periods. Another development that lowered the energy intensity of all sectors was the introduction of energy-efficient buildings. U.S. residential and commercial buildings consume 40% of all U.S. energy and are therefore key to understand the trends in energy intensity. Rosenfeld [26] finds that most of the efficiency gains in the heating and cooling of buildings took place during the period of 1973-1983. During those years, technological improvements in the heating, lighting and cooling systems allowed for a decrease of 1.2 million barrels of oil consumption per day despite the fact that 20 million new homes were built, and commercial floor space increased by 40 percent. Another sector that experienced dramatic energy-saving changes after 1973 was the plastics industry. Joyce [19] documents that the Union Carbide Unipol Process, introduced in the mid-70s, required a much smaller plant, produced twice as much product, and lowered the energy efficiency of polyethylene production from 8400 BTUs per pound to 1500 BTUs.[8]

Other authors have suggested a causal link between the energy crisis and the introduction of energy-saving technologies. For example, Schurr [30] finds that the energy intensity of the U.S. economy started its long-run decline by the end of World War I and stabilized (actually increased slightly) during 1950-1973. He finds that energy intensity declined at a faster speed between 1973-1983 than any other period in the 20th century. He concludes that the introduction of energy-saving technologies resulting from the oil crisis is the main culprit for this faster decline. Popp [25] uses patent data to analyze the impact of energy prices on energy-saving innovation. He finds that the

[7] The KLEM data set is available online at http://post.economics.harvard.edu/faculty/jorgenson/data/35klem.html.

[8] Many more examples of energy-saving technologies introduced during the mid 1970s can be found in Tester, Wood and Ferrari [32].

number of successful patent applications of energy-saving technologies increased dramatically during the mid-70s. The main conclusion of the author, based on econometric analysis, is that energy prices have a strong, positive impact on the number of energy-saving technologies.

3 Model economy

In this section, we present a general equilibrium asset pricing model with capital accumulation and an explicit causal link between energy prices and the introduction of energy-saving technologies. Production is undertaken by corporations which are in turn owned by infinitely-lived households. Energy, an input in production, is imported from abroad and there is trade balance each period. There are two types of production technologies which differ in their energy requirements. Capital is technology specific and investment decisions are irreversible. Prior to 1974, agents assume that energy prices are going to stay at their pre-crisis level forever. The energy crisis takes place in the beginning of 1974 and takes the agents in the model by surprise. After 1974, the model is deterministic and all economic agents have perfect foresight on energy prices. In particular, agents learn after 1974 about the actual sequence of energy prices, as reported in Figure 4. Available evidence (see Section 5.2) suggests energy price expectations during the mid 1970s pointed towards continuously high (and possibly increasing) energy prices in both the short-run and the long-run. Hence, our analysis derives a lower bound for the magnitude of the drop in market value that can be explained by the energy crisis.

Stand-in household

The population in period t is denoted by N_t and it grows with factor η, so $N_{t+1} = \eta N_t$. The stand-in household's preferences are described by the following utility function

$$\sum_{t=0}^{\infty} \beta^t u(c_t) N_t,$$

where c is per-capita consumption, and $u(\cdot)$ is given by

$$u(c) = \begin{cases} \frac{c^{1-\sigma}}{1-\sigma} \text{ for } \sigma > 0,\ \sigma \neq 1 \\ \log(c) \text{ for } \sigma = 1 \end{cases}$$

which implies an intertemporal elasticity of substitution equal to $1/\sigma$. Each member of the household is endowed with a unit of time each period, which is supplied inelastically to the labor market. The household participates in a market for shares of the corporations. Owning a fraction s_t of the perfectly divisible share entitles the shareholder to the same fraction of the dividends paid by the firm. The household's problem is to choose sequences of consumption $\{c_t\}$ and shares of equity $\{s_t\}$ that maximize utility subject to the following budget constraint:

$$\sum_{t=0}^{\infty} p_t [N_t c_t + V_t (s_{t+1} - s_t)] = \sum_{t=0}^{\infty} p_t [w_t N_t + d_t s_t]$$

where V denotes the price of an equity share (after dividend payments from period t have occurred), w is the wage rate, and d is dividends per share. The Arrow-Debreu price, denoted by p_t, is the date-0 value of one unit of consumption in period t.

Representative firm

The representative firm produces the output good y, using a constant returns to scale technology. Production utilizes two technology-specific types of capital, k_1 and k_2, labor, n_1 and n_2, energy, e_1 and e_2, and is summarized by:

$$\begin{aligned} y &= y_1 + y_2 \\ y_1 &= \left[\gamma k_1^\rho + (1-\gamma)(\xi_1 e_1)^\rho\right]^{\frac{\alpha}{\rho}} (A_1 n_1)^{1-\alpha} \\ y_2 &= \left[\gamma k_2^\rho + (1-\gamma)(\xi_2 e_2)^\rho\right]^{\frac{\alpha}{\rho}} (A_2 n_2)^{1-\alpha}. \end{aligned}$$

All other factors held equal, technology one requires more energy per unit of output than technology two and thus $\xi_1 < \xi_2$. The parameter $\rho < 0$ determines the degree of complementarity between capital and energy. The labor share of total income is given by $1-\alpha$. The sequences of total factor productivities, A_1 and A_2 are exogenously given and deterministic. Every period A_1 grows by a factor of γ_{A1}.[9]

As initial conditions for our analysis, we assume $k_{1,0} > 0$ and $k_{2,0} = 0$. Thus, the energy-intensive technology 1 is active and the associated capital stock follows the law of motion

$$\begin{aligned} k_{1,t+1} &= x_{1,t} + (1-\delta)k_{1,t} \\ x_{1,t} &\geq 0, \text{ for all } t \geq 0. \end{aligned} \tag{1}$$

The firm may also choose to pay the development and adoption costs of a new, energy-saving, type of capital, k_2. However, a one-shot minimum investment of $C > 0$ units of output must be spent in order to obtain the first ψC units of k_2, where $0 \leq \psi \leq 1$. D_t denotes the amount of resources the firm chooses to spend on the adoption and development of the energy-saving technology, and $\hat{t}$ is the period when the firm chooses to incur such costs. Adoption costs must be paid only once and thus $D_t = 0$ for all $t > \hat{t}$. Clearly, when $\psi < 1$, the firm would set $D_{\hat{t}} = C$. These assumptions are standard in the literature that studies endogenous innovation in perfectly competitive settings like ours. Detailed analysis on existence, uniqueness and general properties of equilibria for this type of models can be found in a series of papers by Boldrin and Levine [5], [6] and [7]. These authors also provide a careful discussion on the economic incentives and mechanisms that make innovation possible in a world with perfect competition.

After the minimum size requirement for capital of type two is satisfied for the first time, its law

[9] The behavior of A_2 will be described below.

of accumulation is standard and is given by

$$\begin{aligned} k_{2,t+1} &= x_{2,t} + (1-\delta)k_{2,t} \\ x_{2,t} &\geq 0 \text{ for all } t > \hat{t}. \end{aligned} \tag{2}$$

The level of productivity for technology 2 is initially lower than technology one and is subject to a learning curve described by

$$A_{2,t} = (\Lambda - (1-\Phi)\lambda^{-(t-\hat{t})})A_{1,t} \text{ for all } 0 \leq t - \hat{t} \leq 5,$$
$$A_{2,t} = A_{1,t} \text{ for all } t - \hat{t} \geq 5$$
$$\Lambda > 0,\ 0 \leq \Phi \leq 1, \text{ and } \lambda > 1.$$

where the parameters on the learning curve determine how much lower the initial level of A_2 is relative to A_1 and how fast it catches up to the level of A_1.

The firm hires labor services and imports energy from abroad. It owns the capital stock and in turn pays dividends d to its shareholders, who are the residual claimants of the income of the firm. The output of the firm is subject to a time invariant tax at a rate of τ_y.[10] Dividends equal firm after-tax income less payments for wages, energy purchased at an exogenously given price p^e, and new investments, i.e.

$$d = (1-\tau_y)y - D - \sum_{i=1}^{2} \{wn_i + x_i + p^e e_i\}.$$

The objective of the firm is to maximize shareholder's value,

$$\sum_{t=0}^{\infty} p_t d_t$$

taking prices as given.

Competitive equilibrium

A *competitive equilibrium* for this economy is a sequence of prices $\{p_t^e, p_t, V_t, w_t\}$ and allocations for consumption, asset holdings, investment, energy, labor, and development costs $\{c_t, s_t, x_{1,t}, x_{2,t}, e_{1,t}, e_{2,t}, n_{1,t}, n_{2,t}, D_t\}$ such that

1. Given prices, $\{c_t, s_t\}$ are a solution to the household's problem

2. Given prices, $\{x_{1,t}, x_{2,t}, e_{1,t}, e_{2,t}, n_{1,t}, n_{2,t}, D_t\}$ are a solution to the problem of the firm

[10] The tax on output is used to match the appropriate interest rate in the calibration presented in Section 4 and is kept constant throughout our analysis. All tax revenue is assumed to be wasted by the government.

3. Markets clear, and aggregate feasibility is satisfied at all times, namely for all t:

$$s_t = 1$$
$$n_{1,t} + n_{2,t} = N_t$$
$$N_t c_t + x_{1,t} + x_{2,t} + p_t^e \left(e_{1,t} + e_{2,t}\right) + D_t = (1 - \tau_y) y_t \tag{3}$$

3.1 Analysis of the model

First note that in any equilibrium, the replacement cost of a unit of existing capital is equal to one unit of period t consumption good. This follows as a consequence of the aggregate resource constraint (3), and of the laws of motion of capital. The model's replacement cost of existing capital at the beginning of period $t+1$ is then given by $k_{1,t+1} + k_{2,t+1}$, which constitutes the denominator of Tobin's q. Market capitalization in the model as of the end of period t equals V_t, which is the numerator of Tobin's q. Therefore the model's measure of Tobin's average q is given by

$$q_t = \frac{V_t}{k_{1,t+1} + k_{2,t+1}}.$$

The equilibrium behavior of asset prices for the model economy is characterized by the following proposition[11]:

Proposition 1 *In any equilibrium*

$$V_t = \frac{1}{p_t} \sum_{\tau=t+1}^{\infty} p_\tau d_\tau. \tag{4}$$

Moreover, in any equilibrium where the two types of capital are available

$$V_t = \left(1 - \frac{\mu_{1,t}}{p_t}\right) k_{1,t+1} + \left(1 - \frac{\mu_{2,t}}{p_t}\right) k_{2,t+1}, \tag{5}$$

where μ_1 and μ_2 are the multipliers on the irreversibility constraints (1) and (2).

Proof. *The consumer's first order conditions with respect to s_{t+1} and c_t imply*

$$p_t V_t = p_{t+1} \left(d_{t+1} + V_{t+1}\right). \tag{6}$$

[11] Development costs do not appear in asset pricing equation (5) because of the unexpected nature of the energy price shock we consider. In general, the value of the firm equals the value of its capital, plus a term including the discounted present value of adoption costs. However, we depart from a case where agents expect energy prices to continue at their 1960s level and no firm finds it optimal to adopt the new technology. Moreover, we measure market value as the present value of future dividends. When energy prices increase unexpectedly adoption costs are immediately paid and current, but not future, dividends are affected. Thus, the relevant asset pricing equation for our quantitative analysis is indeed (5).

Without loss of generality set $p_0 = 1$. *The recursive application of equation (6) delivers* $p_t V_t = \lim_{T\to\infty}\left\{\sum_{\tau=t+1}^{T} p_\tau d_\tau + p_T V_T\right\}$, *which paired with the transversality condition* $\lim_{T\to\infty} p_T V_T = 0$ *delivers the first result,* $V_t = \frac{1}{p_t}\sum_{\tau=t+1}^{\infty} p_\tau d_\tau$. *To derive the second part of the proposition, consider an equilibrium where capital of type two has been already introduced. The first order conditions with respect to capital and investment imply*

$$p_t - \mu_{i,t} = p_{t+1}\left[(1-\delta) + (1-\tau_y)\frac{\partial y_{i,t+1}}{\partial k_{i,t+1}}\right] - \mu_{i,t+1}(1-\delta), \text{ for } i = 1,2. \tag{7}$$

Multiply both sides of equation (7) by $k_{i,t+1}$. *Adding the two sides of these equalities yields*

$$\begin{aligned}\left(p_t - \mu_{1,t}\right)k_{1,t+1} + \left(p_t - \mu_{2,t}\right)k_{2,t+1} &= \{\left(p_{t+1} - \mu_{1,t+1}\right)k_{1,t+1} + \\ &\quad \left(p_{t+1} - \mu_{2,t+1}\right)k_{2,t+1}\}(1-\delta) + \\ &\quad + p_{t+1}\left(1-\tau_y\right)\left(\frac{\partial y_{1,t+1}}{\partial k_{1,t+1}}k_{1,t+1} + \frac{\partial y_{2,t+1}}{\partial k_{2,t+1}}k_{2,t+1}\right).\end{aligned}$$

Using the fact that competitive prices equal marginal products, the homogeneity of the production function, and the definition of dividends, we get

$$d_{t+1} = (1-\tau_y)\left(\frac{\partial y_{1,t+1}}{\partial k_{1,t+1}}k_{1,t+1} + \frac{\partial y_{2,t+1}}{\partial k_{2,t+1}}k_{2,t+1}\right) - x_{1,t+1} - x_{2,t+1}. \tag{8}$$

Solve for $(1-\tau_y)\left(\frac{\partial y_{1,t+1}}{\partial k_{1,t+1}}k_{1,t+1} + \frac{\partial y_{2,t+1}}{\partial k_{2,t+1}}k_{2,t+1}\right)$ *in (8) and substitute the resulting term in (7). Finally, the law of motion for capital can be used to obtain*

$$\begin{aligned}\left(p_t - \mu_{1,t}\right)k_{1,t+1} + (p_t - \mu_{2,t})k_{2,t+1} = (p_{t+1} - \mu_{1,t+1})k_{1,t+2} + \\ (p_{t+1} - \mu_{2,t+1})k_{2,t+2} + p_{t+1}d_{t+1}.\end{aligned} \tag{9}$$

The recursive application of equation (9) together with the firm's transversality conditions for capital accumulation deliver the desired result since

$$V_t = \frac{1}{p_t}\sum_{\tau=t+1}^{\infty} p_\tau d_\tau = k_{1,t+1}\left(1 - \frac{\mu_{1,t}}{p_t}\right) + k_{2,t+1}\left(1 - \frac{\mu_{2,t}}{p_t}\right)$$

■

Note that the model delivers the standard result where the market value of the firm is equal to the expected present value of its dividend flows. The above proposition also illustrates the mechanism through which the market value of a firm can go below the replacement cost of its assets. In a world where investment decisions are *reversible,* if agents have too much capital, they can consume a portion of it and bring capital back to its optimal level. In a world where investment is *irreversible,* it is impossible to resort to this mechanism. When agents have a stock of capital larger than the optimal one, irreversibility binds and the price of capital falls below one.

If there was no structural break in the behavior of energy prices of this economy, no over accumulation of any given type of capital would occur and irreversibility would never bind, forcing Tobin's q to equal one at all periods.[12] Hence, the role that a sudden, unexpected, change in the behavior of energy prices plays with respect to market value is that it may imply a sudden change in the optimal composition of capital, causing the irreversibility constraint to bind. Finally, observe that value of the irreversibility constraint multiplier is directly related to the magnitude of the drop in the market value of capital. Thus, the larger is the benefit of switching to a new technology, the larger will be the drop in the value of existing capital.

Before deriving the quantitative implications of this model, it is useful to compare the transmission mechanism we are proposing to that in the standard putty clay model. The market value of existing capital is equal to the present discounted value of the dividend flows it generates. This fundamental asset pricing principle is valid for both the putty-clay model and ours. Higher energy prices translate into higher energy costs and lower dividends. The energy crisis also has general equilibrium implications for the interest rate and wages. The increase in energy prices makes energy saving technologies attractive, pushing the investment demand up. In equilibrium, increased investment demand translates into higher interest rates, which ultimately depress asset prices. Our quantitative analysis below illustrates, nevertheless, that the interest rate channel is not the main reason why Tobin's q goes down more in our model than in the standard putty-clay framework after the structural break in energy prices. There are, however, important differences on the general equilibrium implications for wages between the putty-clay model and ours. Some putty clay models assume the capital labor ratio must be constant for all installed capital. This ex-post fixity in the labor market requires a strong decline in real wages for the labor market to clear after the energy crisis. As Wei ([36]) illustrates, this decline in wages may almost completely counteract the drop in market value that results from increased energy costs. The drop in the wage rate required for the labor market to clear after the energy shock is relatively smaller in our model because labor can be freely adjusted in both, the new and the old technology. Labor in our model is distributed across the two technologies until marginal productivities are equated. Hence, the endogenous introduction of energy saving technologies counteracts the negative impact of energy prices on labor productivity and the wage rate.

4 Calibration

To calibrate the parameters of the model, we follow Cooley and Prescott [9] and match certain aggregate features of the U.S. economy in the pre-crisis period of 1962-1972 to the balanced growth path of the model. We set η equal to 1.01 to match the 1% average growth rate of population, and γ_{A1}, the growth factor of labor-augmenting efficiency for technology 1, equal to 1.02 to match the average per capita growth rate of U.S. corporate GDP which is 2%.

[12] Notice also that constant returns to scale, $A_{1,t} = A_{2,t}$, and $\xi_1 < \xi_2$, imply that the firm will never invest a positive amount of resources in both types of technologies at the same time.

Estimates of the intertemporal elasticity of substitution found in the literature imply values for σ within the interval [1,2]. We pick $\sigma = 1.5$ and perform sensitivity analysis on this parameter. The depreciation rate δ is set equal to 5.8% and the proportional tax on output, τ, to 30% to match the investment-corporate GDP and the capital-corporate GDP ratios of non-energy producing corporations (0.15 and 1.7, respectively). We set the discount factor β to 0.98 to match a steady state real interest rate of 5.15%.

The observed average labor share of income in the corporate sector is matched by the model by setting α equal to 0.33. γ is calibrated to 0.77 so that the model's initial steady-state energy-corporate GDP ratio (prior to the energy shock) matches the 1962-72 U.S. average (5.5%). ξ_1 is set equal to 30.9 to match the pre-crisis capital-energy ratio and ξ_2 is set equal to 53 so as to match a new steady-state energy-corporate GDP ratio of 3.3%. ρ is set equal to -20 to match the model's transition of energy-use to corporate GDP ratio from the old to the new steady-state as close to the data as possible.

Parameters C and ψ are jointly determined. We set the minimum investment size parameter C equal to 0.19 (9% of the capital stock), which is the minimum value such that corporations do not adopt the energy-saving capital before 1974 but choose to adopt after the energy shock. The percentage of the initial minimum size which is actually in operation, ψ, is set to 94% so that the model's equilibrium investment matches the data one year after the shock.

Bahk and Gort [4] document that the higher growth in the productivity of a new technology fades away, on average, after the fifth year it was introduced. Jovanovic and Nyarko [18] document "progress ratios", i.e. ratios of peak to initial productivity, from a dozen of empirical studies of learning by doing. The range is 1.14-2.9. We pick a value of 2 for our benchmark experiments and perform several sensitivity tests to the values of this parameter. All of the aforementioned empirical studies coincide in that most of the learning takes place within the first two years that follow the introduction of any given new technology. Thus, we assume that one half of the total productivity gains associated with learning by doing are achieved by the second year of the introduction of the energy-saving capital. Based on these observations, we set the parameters of the learning curve ($\Lambda = 1.392, , \Phi = 0.108$ and $\lambda = 1.787$) such that: i) $A_{2,\hat{t}} = \frac{A_{1,\hat{t}}}{2}$ ii) $A_{2,\hat{t}+2} = \frac{3}{4} A_{1,t+2}$ and iii)$A_{2,\hat{t}+5} = A_{1,\hat{t}+5}$.[13]

5 Results

In this section, we derive the quantitative implications of the oil crisis for equity prices and other macroeconomic aggregates. In all of our quantitative experiments, we assume that the U.S. economy was in a *balanced growth path equilibrium* (i.e. a competitive equilibrium where all variables grow

[13] Note that having only one type of adoption cost does not yield satisfactory aggregate series. For example, with only learning by doing, but no minimum size requirement, firms would invest a very small amount of technology 2 and then wait for 5 years for the level of productivity to catch up. With only minimum size, but no learning-by-doing, the mimimum size required for endogenous adoption is very high and therefore the aggregate series (for example investment) are unrealistic.

at a constant rate) during 1960-72.[14] Households and firms assume that technological constraints and energy prices will remain unchanged over the infinite future.

Our analysis starts with simple versions of our model where we can illustrate clearly the role of the different channels linking energy prices to market valuations implicit in the theory. Finally, we present the full-fledged version of the model where the introduction of energy-saving technologies results as an optimal choice after the energy price goes up, and where new technologies face a standard learning by doing curve.

Consider a version of the model where energy saving technologies arrive exogenously, for free, and paired with the energy price shock. In particular, we start off from a balanced growth path equilibrium where C equals infinity and agents expect energy prices to remain at their average 1960-73 level. On 1974, we change energy price expectations to match the time series data from 1974 up to 2000. On 1974, energy-saving capital becomes available, and C is set equal to zero. The results for this economy where the new technology arrives exogenously and is as productive as the old one are summarized by Figure 5 below.

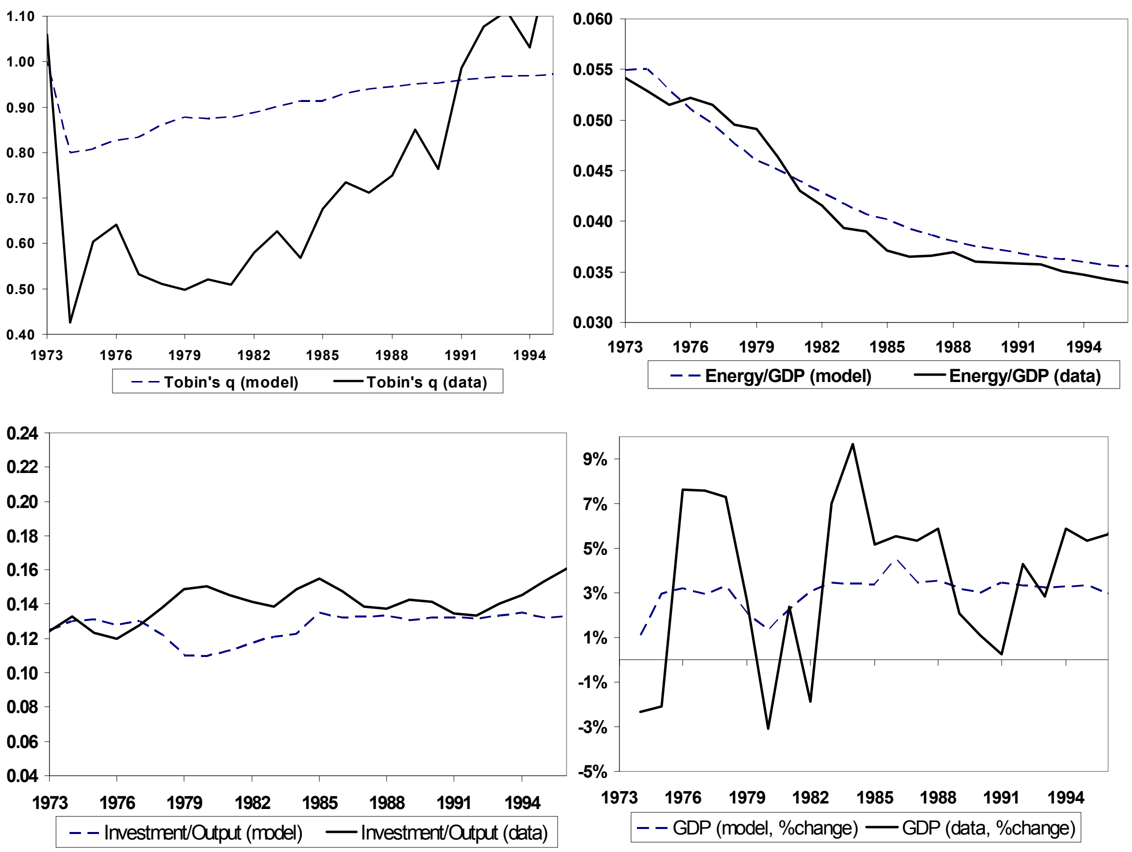

Figure 5: Unexpected arrival of energy-saving technologies

The exogenous arrival of energy-saving technologies can account for a 20% drop in Tobin's q. Energy-saving capital enters gradually into the economy and market values recover in a smooth fashion.

[14] The computational appendix describes the numerical method employed to solve for equilibrium.

The recovery takes almost 20 years, which is consistent with the U.S. data. The model has been calibrated so that its energy to corporate GDP ratio delivers the best fit possible to the average trends of its U.S. counterpart. In this benchmark case, the energy crisis translates into an economic recession much less pronounced than what is observed in the U.S. data. Notice, however, that we have abstracted from business cycle movements in total factor productivity.[15]

To understand what drives the large drop in market valuation generated by our theory, relative to previous analyses, observe that, given the high complementarity of capital and energy, higher energy prices result in higher energy costs and lower dividends. According to U.S. corporate data, corporate GDP before the energy crisis was distributed in the following way: Energy costs represented 5.5% of corporate GDP, labor costs 47%, investment 12%, taxes 30%, and the residual 5.5% of corporate GDP corresponded to shareholders income. If the firm had not changed its productive inputs nor its investment level after the 50% average increase in energy prices observed in the data, then shareholders income would have declined to 2.75% of corporate GDP. Equity prices would then have suffered a permanent decline of 50% (equal to the drop in the fraction of income that accrues to shareholders).

Of course, firms in our model do change productive inputs and investment plans optimally after the energy shock. Moreover, firm and household reactions have general equilibrium implications on interest rates and wage rates that interact with dividend flows, and thus market valuations. A counterfactual experiment that illustrates the aforementioned mechanisms consists of simulating an economy where the only available technology is energy-intensive (capital of type one) and energy prices change as in the data. The resulting equilibrium behavior of some key variables of such a model is reported in Figure 6 below.

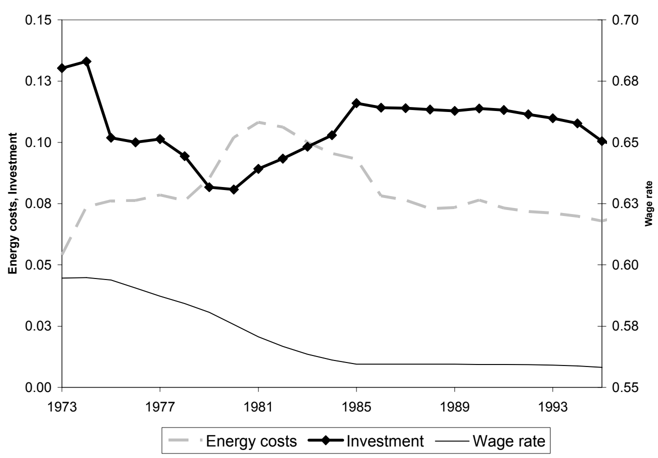

Figure 6: Distribution of value added after the energy crisis, no energy saving technology available.

[15] Note that in the model economy the investment output ratio falls in contrast with the U.S. data. The increase in investment observed in the data is most likely due to investment subsidies (the investment tax credit) that peaked during the late 1970s. Our paper focuses on the impact of technical change on the stock market and abstracts from investment subsidies. Nevertheless, if investment subsidies were introduced, the drop in market values predicted by our model would be even larger (cf. McGrattan and Prescott [22]).

Proposition 1 implies that the energy crisis under the aforementioned conditions generates no drop in Tobin's average q as investment remains strictly positive through the whole sample period. We also find that equity prices are not significantly affected by the energy crisis. The reason for this puzzling asset price behavior resides on the general equilibrium implications of the energy crisis. Observe that energy costs double after the crisis but investments and the wage rate also suffer substantial declines. The resulting general equilibrium movements of wages and investment are just enough to compensate for the increase in energy costs and market values are not affected by higher energy prices. These results are similar in spirit to those found in Wei [36].

In contrast to the previous trends, we report in Figure 7 the behavior of energy costs, investment and the wage rate for our first benchmark experiment where energy saving technologies become available at the same time that the energy price shock hits.

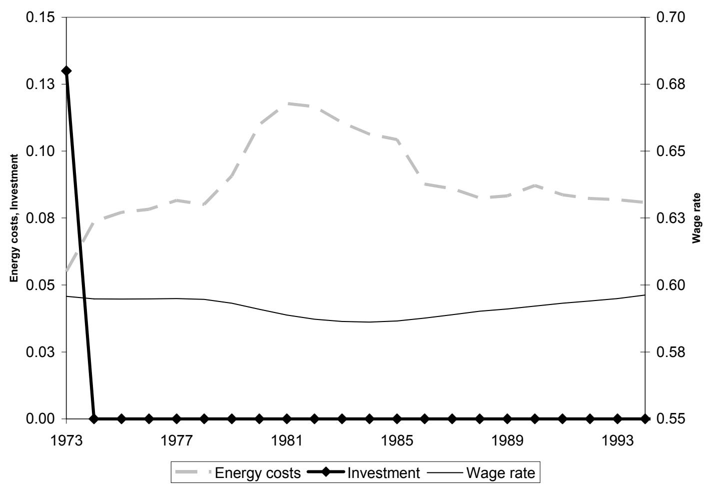

Figure 7: Distribution of value added from old technology, exogenous arrival of new technology

Observe first that irreversibility binds and, according to Proposition 1, that must imply a drop in Tobin's average q. In sharp contrast to the case where no energy saving technology is ever available, wages move down only slightly after the second energy price shock but remain high through the whole sample period. The wage bill captures the largest fraction of corporate GDP. Thus, the higher equilibrium wages generated by our model do not compensate for the increase in energy costs associated to the energy crisis.[16]

Finally, Figure 8 below illustrates the equilibrium behavior of dividend flows (relative to trend) from the energy intensive technology under the two different scenarios we have considered.

[16] Regarding wage behavior, the U.S. data shows a slowdown in wage growth right around 1974. As our analysis focus on long-run analysis, our model has abstracted from cyclical movements in total factor productivity. Notice, however, that the observed decline in real wages of the U.S. data could easily be rationalized by a model that incorporates an exogenous slowdown in total factor productivity compatible with what was observed for the U.S. economy.

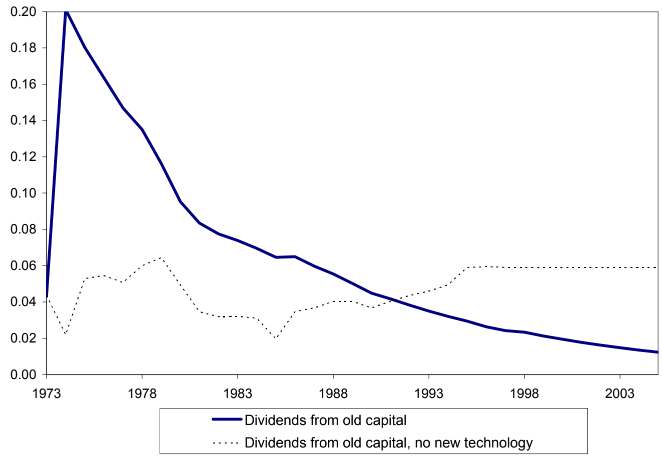

Figure 8: Time series behavior of dividend flows relative to a 2% trend.

These time series reveal an important transmission mechanism embedded in our theory. Observe that, before the energy crisis, existing capital was priced under the assumption that it would generate an infinite stream of dividends. However, if energy saving technologies arrive at the time of the energy crisis investment in old technologies completely stops. Dividends in the model, where energy saving technologies become available are, for some years, higher than the case where no energy saving technology arrives. However, as a result of the arrival of the better technology, the old technology is gradually abandoned and its dividends slowly decay. The overall impact on market valuation of relatively higher wages and shorter life span for old capital results in a 20% decline in Tobin's average q.

It is also important to mention that the present value of the above dividend flows assuming no change in interest rates after the energy crisis was only 2% higher than what results with flexible interest rates. Thus, general equilibrium movements in the interest rate are not quantitatively relevant for understanding equity price movements in our model.

5.1 Price induced innovation in Energy-saving technologies

We now examine the full fledged version of our model in a situation where energy prices and energy-cost shares in 1973 correspond to the 1962-72 average for the U.S. economy and are expected to continue at that level for the infinite future. Energy-saving technologies can be adopted after incurring a fixed cost and are subject to a learning curve. The model economy departs from a balanced growth path in which, given energy price expectations and adoption costs, energy-saving technologies are not adopted by the representative firm. We associate this equilibrium with the average behavior of the U.S. economy during 1962-72. On 1974, energy prices rise unexpectedly and energy price expectations match the U.S. data from 1974 to 2000. Our objective is to determine the quantitative implications of the energy crisis for the market value of U.S. corporations. The equilibrium time series from the model economy after the energy price shock hits are summarized in Figure 9.

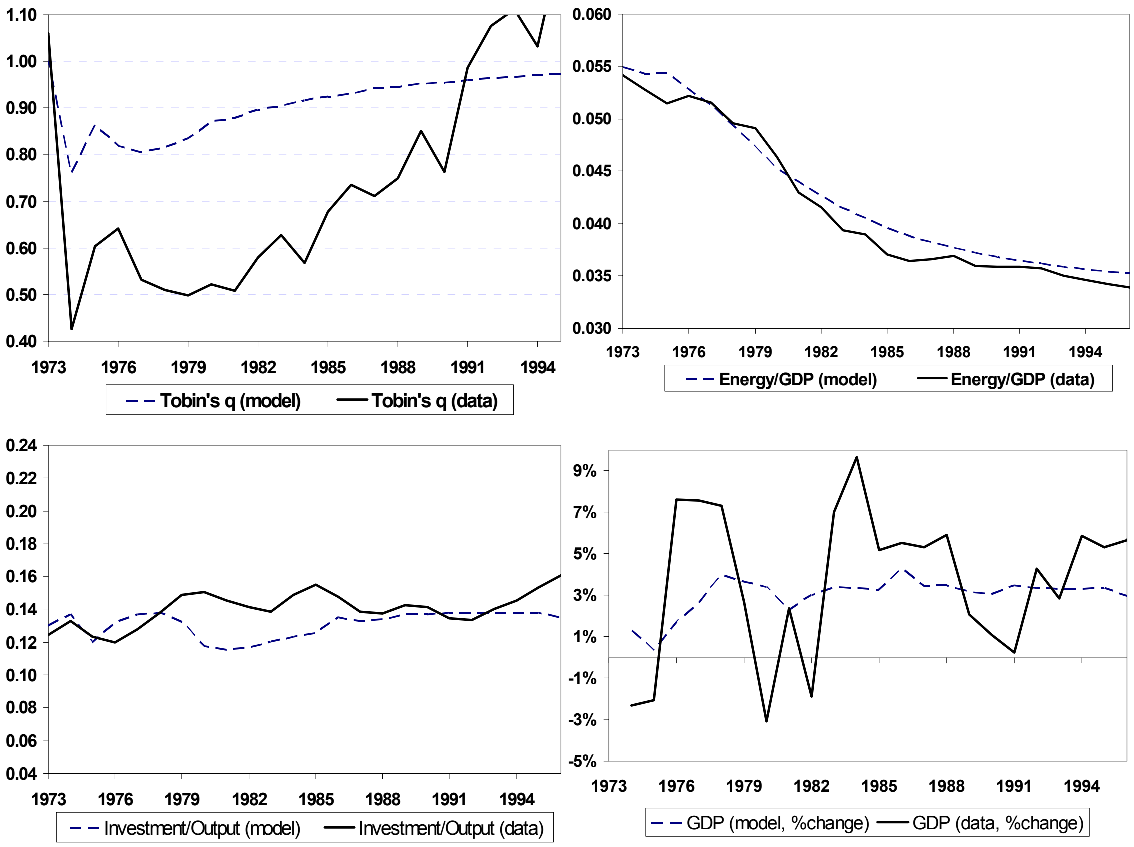

Figure 9: Price induced innovation in energy saving technologies

The behavior of energy prices from 1974 to 2000 gives firms enough incentives to pay the fixed costs associated with the development and adoption of energy-saving technologies. Thus, the energy crisis gives rise to the endogenous obsolescence of existing capital and a decline in market value by 24%. The learning curve makes this drop in market value persistent. Tobin's q is 20% below its 1973 level up to 1978. Energy saving technologies gradually replace the old production methods and, after the total factor productivity of the new technology catches up with the old one, market values recover in a smooth fashion. As in the exogenous case, the trends in the energy to corporate GDP ratio from the model are consistent with those in the U.S. data. Investment on the year of the energy crisis matches the data by construction. From 1975 to 1979, the model's investment-corporate GDP ratio tracks the movements in its data counterpart fairly well given we have not introduced investment subsidies into our analysis. The behavior of corporate GDP in the model is also qualitatively consistent with the observed trends in the U.S. data.

5.2 Energy price expectations during the mid 1970s

The development and adoption of a new aggregate production technology is costly. With the low energy prices that prevailed during 1960-72 it was not economically optimal to incur these costs. Higher energy prices may have provided the incentives to do so, but only if this increase in energy prices was perceived as persistent. In what follows we provide some evidence suggesting that was indeed the case.

The main source of our analysis is the Energy Information Administration (EIA) which, after the energy crisis, was required by Congress to report short and long-run forecasts for energy prices, energy production and consumption. To do so, the EIA developed the Project Independence Evaluation System (PIES). The PIES models energy demand and supply independently. Energy demand for the different types of energy are assumed to depend on its price, and on the price of substitutes; demand is also assumed to depend on the level of economic activity, and on the ability of consumers and capital stocks to adjust to these factors. Energy supply is estimated separately for oil, natural gas and coal. For each region and fuel type, reserve estimates are combined with the technologies and costs of finding and producing these fuels to estimate the costs of increasing supply. The PIES then attempts to match these energy demands as a function of fuel, sector and price with the available supply in the regions which can supply these needs at the lowest price to find a balance of equilibrium. If supply is not available to satisfy the specific demands in an area, the prices are allowed to vary until supply and demand are brought into balance.[17]

According to the EIA, energy prices were expected to remain at their 1976 level through 1985 as the following quote illustrates[18] "...there is no significant likelihood of a considerable lower price for OPEC oil in this period ... Most of the analytical emphasis is placed on a continuation of current prices (in 1975 dollars)." One year later the forecasts were even more pessimistic. The 1977 Annual Report to Congress of the EIA states: "Prices for all energy fuels are forecast to increase in real terms through 1990." The 1977 energy price forecast of the EIA is summarized in Figure 10 below:

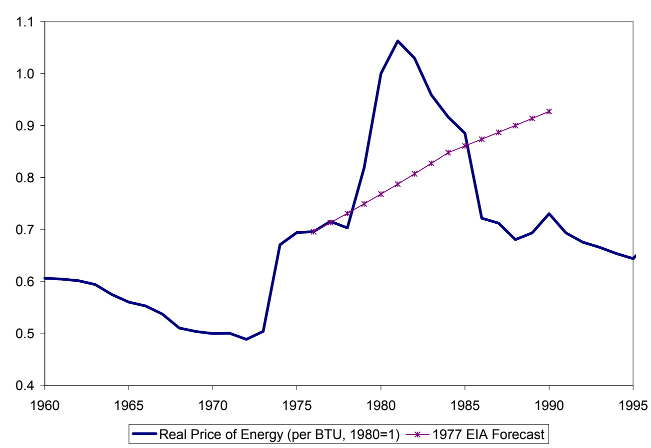

Figure 10: Real price of energy and 1977 EIA forecast

In its 1977 volume, the EIA reports a survey of the "principal, most recent, long-term energy price projections". The purpose of the survey was to collate the prevailing long-term views projected by "prominent authorities." None of these forecasts predicted any decline in real energy prices through

[17] The details about the PIES model can be found at Appendixes A-E of the 1976 National Energy Outlook.

[18] 1976 National Energy Outlook. Pages 14 and 15.

1985 and all but one predicted that real energy prices in 1985-2000 would be significantly (27% on average) higher than during 1975-85.[19]

Figure 11 below illustrates that energy price forecasts produced by the EIA were not able to predict the large drop in energy prices that occurred during the late 1980s even after energy prices had started declining.

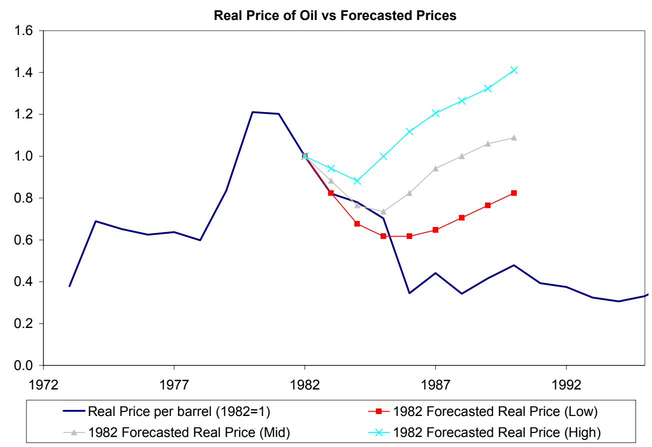

Figure 11: Real price of oil and 1982 forecasts

In summary, energy price forecasts after the crisis of 1973-74 predicted either constant or increasing trends in the medium term, and most of them expected prices to go up in the long run. Furthermore, energy price forecasts could not foresee the huge decline that started around 1982 even when the decline had started. Hence, there is evidence that suggests that energy price expectations during the mid 1970s and early 1980s pointed to a more pessimistic energy price behavior than what actually occurred. Hence, the drop in market values generated in Section 4 should be considered as a lower bound of the impact of the energy crisis of the mid 1970s.

6 Conclusion

This paper employs a calibrated dynamic general equilibrium model to evaluate how much of the stock market crash of 1973-74 can be accounted for by changes in energy prices and adoption of energy-saving technologies. In a world where capital is technology specific, and investment decisions are irreversible, we find that the observed changes in energy prices, together with the energy-saving technologies derived from the energy use series data, translate into a 24% drop in Tobin's average q. This corresponds to almost half of the observed drop in q of the mid-70's. Our analysis indicates that changes in energy prices should be part of any theory of the stock market collapse of 1973-74.

[19] See Table 2.11 of the 1977 EIA Annual Report to Congress, Volume II, page 35.

7 Data Appendix

Here we outline how the major series used in the figures were constructed.

Figures 1 and 2. Ratio of Market Value to Replacement Cost of Tangible Assets for Corporations and to GDP

Market value of corporations was constructed using data from the *Flow of Funds Accounts of the United States* (FOF) issued by the Board of Governors of the Federal Reserve System (FRB).[20] In the FOF, domestic corporations are divided into nonfinancial and financial corporate business. Financial corporations are further divided to the following categories as listed in Table F.213: Commercial banking, life insurance companies, other insurance companies, closed-end funds, exchange-traded funds, real estate investment trusts (REITs) and brokers and dealers.

Our measure of market value reflects both equity value and debt of all domestic corporations, and all direct or indirect (through mutual funds) intercorporate holdings of corporate equity and debt has been netted out. To that effect market value of domestic corporations (MV) has been constructed as follows:

MV = Corporate equity issued by nonfinancial and financial corporate businesses + Net financial liabilities (i.e. Total liabilities - total financial assets) of nonfarm nonfinancial corporate businesses,commercial banks, life insurance companies, other insurance companies, closed-end funds, exchange-traded funds, REITs, and security brokers and dealers.

We construct the market value for energy-producing industries (the sum of coal mining, oil and gas extraction, petroleum, electric services and gas services) and subtract this from total MV to arrive at the market value of non-energy producing corporations.

Replacement cost of tangible assets of corporations was constructed using data from the *Fixed Assets Tables* (FA) reported by the Bureau of Economic Analysis (BEA)[21] and also from the FOF. Our measure of tangible assets include all nonresidential and residential fixed assets, plus inventories. Corporate fixed assets are the sum of corporate nonresidential fixed assets and corporate residential fixed assets. Stock of inventories held by nonfarm nonfinancial corporations is from the FOF. We assume financial corporations hold no inventories as their inventory investment is zero in the product account, and we neglect inventories held by farm corporations since they are negligibly small.

We subtract the capital stock of energy-producing corporations (coal mining, oil and gas extraction, petroleum, electric services and gas services) from the total. This data was obtained from the BEA Table 5KCU.

Figure 3. Energy Prices relative to the GDP Deflator

We follow the methodology outlined in Atkeson & Kehoe [2] and construct an energy price deflator from a weighted average of coal, natural gas, petroleum and electricity consumed in the commercial, industrial and the transportations sectors. This excludes residential consumption as we focus only on the business sector and also energy consumed by the electric power sector as in

[20] This data can be downloaded from the FRB website at http://www.federalreserve.gov/releases/z1/current/data.htm.

[21] This data can be downloaded from the BEA website at http://www.bea.doc.gov/bea/dn/faweb/AllFATables.asp.

our model all energy is imported. We assume 60% of petroleum used in the transportation sector is not business related and subtract this from total energy-consumption. We also exclude energy consumption of energy-producing sectors since production in our model refers only to non-energy production. To do this, we assume that energy-consumption in these sectors are proportional to their value added and subtract the resultant from the total industrial energy consumption.

We use quantity and price data reported in the Annual Energy Review (AER) 2001.[22] The quantity of each type of energy (measured in units of BTUs) consumed in the commercial, industrial and the transportation sectors are from Tables 2.1c, 2.1d, 2.1e respectively. For prices we use consumer price estimates of energy (as businesses are consumers of energy) reported in Table 3.3 and we label the price of energy for each type as P_i. For each type of energy i, we add the consumption of that energy type in all sectors and call that Q_i. Then, total energy expenditure is simply $\sum_i Q_{it}P_{it}$. We calculate real energy use using 1972 prices as the base year. Hence real energy use equals to $\sum_i Q_{it}P_{i1972}$. The energy price deflator P_t is simply the ratio of the total energy expenditure to total energy use:

$$P_t = \frac{\sum_i Q_{it}P_{it}}{\sum_i Q_{it}P_{i1972}}$$

The GDP deflator is constructed in the usual way from nominal and real GDP series reported in BEA's NIPA Tables 1.1 and 1.2.

Figure 4. Energy Expenditure and use in the Business Sector

Total energy expenditures of the non-energy producing business sector was calculated as in Figure 3.3 and then was divided by the nominal GDP of the non-energy producing business sector (from NIPA). The total real energy use of the business sector (expenditure using 1972 prices) was calculated as explained for Figure 3.3. This number was divided by the real GDP of the business sector in 1972 prices. Real GDP of the business sector data is from BEA's NIPA Table 1.8. We subtract the value-added of the energy-producing sectors. These numbers are reported in 1996 dollars. We first construct a price deflator using nominal and real GDP of the business sector, readjust the level of the deflator such that 1972 = 1 rather than 1996. Then we multiply this number with nominal GDP of business to get real GDP of business in 1972 dollars.

8 Computational appendix

Notice that, after the energy-saving technology has been introduced, the production set is convex. Hence, the life-time utility associated to a competitive equilibrium where technology 2 is already available can be obtained as a solution to the dynamic programming problem

$$\begin{aligned} v(k_1, k_2, p^e) &= \max_{x_1,x_2,e_1,e_2} u(c) + \beta v(k_1', k_2', p^{e\prime}) \qquad (10) \\ & s.t. \end{aligned}$$

[22] This data can be downloaded from the EIA website at http://www.eia.doe.gov/emeu/aer/contents.html.

$$
\begin{aligned}
c + x_1 + x_2 + p^e (e_1 + e_2) &= (1 - \tau_y) y \\
x_i &\geq 0, \text{ for } i = 1, 2,
\end{aligned}
$$

where the laws of motion of energy prices and total factor productivity are as described in Section 3. Notice that energy prices and TFP growth are time invariant after a finite number of periods, which allows us to solve for function v by backwards induction. To obtain an approximated solution to the dynamic programming problem (10) we employ the value function iteration algorithm with spline interpolation described in Santos [27].

The initial conditions of our problem imply that capital of type two is not available. Moreover, a minimum size investment must be incurred before the energy-saving technology becomes available. This minimum size constraint introduces a non-convexity into the analysis. Hence, we must solve directly for the recursive competitive equilibrium of this economy, which is characterized by:

1. The firm's problem:

$$
W(k_1, p^e) = \max_{e_1, x_1, n_1, D} \{(1 - \tau_y) y - w n_1 - p^e e_1 - x_1 - D\} +
$$

$$
\begin{aligned}
\beta v(k_1', k_2', p^{e'}) \text{ if } D &\geq C \\
\beta W(k_1', p^{e\prime}) \text{ if } D &< C
\end{aligned}
$$

2. The Household's problem:

$$
\begin{aligned}
H(s, p^e) &= \max_{s', c} u(c) + \beta H(s', p^{e\prime}) \\
& s.t. \\
c + V(s' - s) &= wN + ds \\
s' &\geq 0.
\end{aligned}
$$

3. Feasibility and market clearing constraints:

$$
\begin{aligned}
c + x_1 + p^e e_1 + D &= (1 - \tau_y) y \\
n_1 &= N \\
s &= 1.
\end{aligned}
$$

We obtain a numerical approximation to each of the above value functions using the value function iteration algorithm, for each given set of prices. Finally, we solve for the set of prices that makes the household's and firm's choices compatible with market clearing and feasibility.

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