A Theory of Vintage Capital Investment and Energy Use*

Antonia Díaz[a] and Luis A. Puch[b†]

[a]Universidad Carlos III de Madrid
[b]Universidad Complutense and ICAE

January 2015

Abstract

In this paper we propose a theory of investment and energy use to study the response of macroeconomic aggregates to energy price shocks. In our theory this response depends on the interaction between the energy efficiency built in capital goods (which is irreversible throughout their lifetime) and the growth rate of Investment Specific Technological Change (ISTC hereafter). ISTC reduces the cost to produce investment goods and renders them more productive. Depending on which effect is stronger, higher ISTC is a complement or a substitute for energy efficiency and, thus, affects differently aggregate energy demand. Our theory provides a discipline to identify both effects since it predicts that the relative price of investment goods (not quality adjusted as well as quality adjusted) depends not only on the two ISTC shocks but also on the energy efficiency built into capital units. Thus, we can disentangle the effects of ISTC shocks from the effects of energy efficiency: a distinction that the literature on ISTC growth abstracts from. Our theory can account for the fall of energy use per unit of output observed during the 1990s, a period in which energy prices fell below trend. By increasing investment in the years of high ISTC growth, the economy was increasing the average efficiency of the economy (the capital-energy ratio), shielding the economy against the impact of the 2003-08 price shock.

Keywords: Energy use, vintage capital, energy price shocks, investment-specific technology shocks
JEL Classification: E22, E23

*This paper was previously entitled "A Theory of Energy Use". We thank Raouf Boucekkine for his comments to a first version of this paper. We also thank Fabrice Collard, Andrés Erosa, Cyril Monnet, Omar Licandro, Franck Portier and Jesús Ruiz for helpful comments, and Manuel García and Alberto Sánchez for excellent research assistance. Díaz, and Puch, thank respectively the Dirección General de Investigación, projects ECO2010-20614 and ECO2010-17943, for financial support, and the EUI for its support during part of this research. Puch also thanks Fundación FocusAbengoa and FEDEA. We are grateful to participants of conferences 2012 REDg, 2012 SED Meetings, 2011 Wien Macro Workshop, as well as workshop participants at EUI.

†Corresponding Author: Antonia Díaz, Department of Economics, Universidad Carlos III de Madrid, 28093 Madrid, Spain; E-mail: andiaz@eco.uc3m.es

1 Introduction

The two oil crises in the 1970s and a growing environmental awareness of societies and governments have prompted many macroeconomists to study the determinants of aggregate energy use and, therefore, the response of macroeconomic aggregates to changes in energy prices.[1] Early studies estimated a very low short run price elasticity of energy demand, which accounted for the large impact of the oil price shocks in the 1970s (see Berndt and Wood 1975, Griffin and Gregory 1976, and Pindyck 1979). The same authors also report that this elasticity is higher in the long run, as the economies reduce their energy consumption slowly. More recently, Newell et al. (1999), and Popp (2002) find that energy prices have a strong positive effect on energy-efficient technical innovations, suggesting that the difference between the short and long run price elasticities of energy demand is due to the ability of the economies to move to more energy-efficient technologies.[2] Lately, though, it has been pointed out that innovation in energy efficiency is affected, even delayed, by the level of Investment Specific Technical Change (ISTC hereafter); see, for instance Steinbuks and Neuhoff (2010), or Knittel (2011).[3] This evidence suggests three things: First, that energy demand is very much related to the efficiency of the technologies chosen; second, that the level of energy efficiency responds to changes in energy prices and, third, that the existence of Investment Specific Technical Change (ISTC hereafter) affects the magnitude of that response. Accounting for these empirical findings is key to the policy debate on the transition to a low carbon economy. With few exceptions, however, previous theoretical literature abstracts from the long-run relationship between energy efficiency and energy prices. For instance, Pindyck and Rotemberg (1983), Atkeson and Kehoe (1999), and Díaz et al. (2004) have studied the interaction of energy prices and the energy efficiency of capital but have ignored the channel of ISTC. This is why we propose a theory of vintage capital investment to investigate the importance of ISTC growth in shaping the response of energy demand (and use) and macroeconomic aggregates to energy price shocks.

In our model economy final output is produced with capital, labor and energy. Capital is irreversible and heterogeneous in two dimensions: its vintage and its energy-efficiency. As in Atkeson

[1] See Hamilton (2008) or Kilian (2008) for a survey of the significant literature.

[2] Newell et al. (1999) estimate that during the period 1958-1993 about half of the total change in energy efficiency of the models of room air conditioners, central air conditioners, and gas water heaters was prompted by the high price shocks experienced during the 1970s and early 1980s.

[3] Knittel (2011) estimates that if car quality would have not improved from 1980 to 2006, energy efficiency of both passenger cars and light trucks could have increased by nearly 60 percent from 1980 to 2006, instead of the observed meager 15 percent.

and Kehoe (1999), the energy efficiency of a unit of capital is given by the energy required for this capital to yield services so that the energy intensity of production is a putty-clay factor. Higher efficiency comes at the cost of less capital services and, therefore, less output. Unlike Atkeson and Kehoe (1999), we assume that there is ISTC growth as in Solow (1960). Hence, aggregate energy use per unit of output may fall because either new capital is more energy efficient or is more productive per unit of energy consumed, or both things at the same time. To focus our study in the determinants of energy use and efficiency, we assume that all energy is imported and that the energy price is exogenously given. Moreover, there is no rationing: the amount of energy demanded at any given price is always satisfied. This is a closed economy in any other respect.

We start by studying the properties of the efficient allocation. We show that we can decentralize it by opening a secondary market for capital goods. In our economy the market price of one unit of capital depends not only on its vintage but also on its energy efficiency. The existence of ISTC imply that real wages rise over time and older vintages of capital become too costly to operate given their energy requirement and they are eventually scrapped. Therefore, as in Gilchrist and Williams (2000), we have endogenous capital utilization at the extensive margin. Standard aggregation (i.e., representing aggregate value added as a function of aggregate capital and labor) is only possible in absence of uncertainty. This is so because the complementarity of capital and energy at the micro level implies that the energy share in aggregate gross output varies with the distribution of capital across vintages and efficiency levels. We can, however, establish conditions under which there is a representation for aggregate gross output as a function of aggregate labor, energy, capital, and the rate of utilization of aggregate capital. This representation is obtained by aggregating capital using prices in units of gross output that are, essentially, cost production prices. The utilization rate is the fraction of capital used for production, which depends on the measure of capital scrapped.

Notice that our procedure to aggregate capital is consistent with the method used by the Bureau of Economic Analysis (and other statistical agencies in different countries) to construct the aggregate stock of capital of the US economy. The aforementioned cost production prices depend on the vintage as well as the energy efficiency of capital. We also find aggregate capital adjusted by quality and its corresponding price. Consistently with the estimates by Gordon (1990) and Cummins and Violante (2002), this price falls with the level of ISTC, but it rises with the level of energy efficiency. That is, the relative price of capital goods falls less rapidly in periods in which the economy is investing more in energy efficiency, as it happened in the 1970s. Thus, we provide a theoretical foundation to the view expressed by Gordon (1996), who argued that changes in energy efficiency is one of the key determinants of the dynamics of the relative price of investment goods. Another virtue of our theory is that it nests previous theories of investment and energy use: Atkeson and Kehoe (1999) and Díaz et al. (2004) are special cases of our economy without ISTC growth.

The aggregate representation of our economy shows very starkly that the existence of ISTC has two effects of opposite sign on aggregate energy use. On the one hand, new investment is needed to rip the benefits of higher ISTC, which rises the absolute level of energy use. On the other hand, higher ISTC, *ceteris paribus*, rises capital productivity and output, which lowers the level of energy use per unit of output. Depending on which effect is higher, ISTC can be thought of as an energy-consuming or an energy-saving technical device. In the first case ISTC and energy efficiency are complements, in the second case they are substitutes. This complex interaction of ISTC and energy efficiency —which also depends on the behavior of energy prices— cannot be ascertained theoretically. This is why we resort to study the dynamics of aggregate energy use and energy efficiency in our model economy quantitatively.

We calibrate our model economy to match selected statistics of the US economy for the period 1960-2008. We assume that there are energy price shocks as well as two ISTC shocks. The two ISTC shocks affect the cost of producing capital goods and the level of technical progress embodied in new capital units. We disentangle these two shocks by exploiting the fact that the BEA adjusts for quality the price of some (but not all) investment goods. We abstract from neutral technical progress to isolate the effects of ISTC shocks on energy efficiency and use. We estimate the three processes so that the relative price of energy and the relative prices of investment—both the non quality-adjusted as well as the quality-adjusted price—in the model have the statistical properties of their counterparts in the data. The identification of the two ISTC shocks becomes a central issue in order to assess the quantitative properties of our model economy. It turns out that our theory gives us discipline to implement a novel way to identify both shocks, provided that only one of them is permanent. We can identify them because, according to our theory, the relative price of investment goods (not quality adjusted as well as quality adjusted) depends not only on the two ISTC shocks but also on the energy efficiency built into capital units. Hence, we can disentangle the effects of ISTC shocks from the effects of energy efficiency. It is interesting to note that the innovations in ISTC shocks are larger and highly correlated right after the oil price shocks during the early 1980s and during the late 1990s, right before the 2003-08 oil price shock. In order to assess the importance of ISTC we compare the evolution of energy use and aggregate energy efficiency in our simulated economy and a version of Atkeson and Kehoe (1999) (which is essentially our economy without ISTC) to the observed evolution of energy use and efficiency in the US economy for the aforementioned periods.

Our simulations show that investment in energy efficiency depends on the persistence of energy price shocks and the nature and persistence of ISTC shocks. If energy prices are high and ISTC in the quality of new investment is low, agents invest in energy efficient capital goods. This is the regime observed in the 1970s and 1980s, where energy use per unit of output and the average efficiency in the economy are negatively and positively correlated with energy prices, respectively. If energy prices are low and ISTC shocks to the quality of new investment are high and transitory, agents invest in less efficient capital goods. In this case the correlation of energy use per unit of output and average energy efficiency with energy prices is reversed. Thus, our model economy can explain the regime change experienced during the 1990s, period of accelerated ISTC growth. A model economy without ISTC growth, as Atkeson and Kehoe (1999), cannot explain this change of regime, since in that economy the level of energy efficiency is solely governed by energy prices. We should note that, although our model economy features scrapping and, therefore, endogenous utilization of capital, this channel is not quantitatively significant to account for fluctuations in energy use and the average energy efficiency of capital. This is due to the fact that long-run rate of economic growth is moderate and energy expenditure is a very small fraction of aggregate value added in the data. Finally, we show that the short run price elasticity of energy use per unit of value added is equal to the value of the energy share in value added. Thus, we can quantify the regime change experienced. For instance, at the peak years 1981 and 2008 the real relative price of energy was about the same, a bit higher in 2008. The energy share, though, was 8.89 percent and 6.66 percent of value added, respectively. Thus, according to our theory, energy use has been less responsive to changes in energy prices during the last oil price shock because energy efficiency is much higher than in previous decades. Thus, our theory offers an explanation about the apparent softened response of GDP to the 2003-08 oil price shock. See for instance, Kilian (2008), or Blanchard and Galí (2007).

We view ours as a theory of investment where we make explicit the determinants of energy use and energy-saving technical change. Thus, ours has a flavor of a theory of directed technical change, as Acemoglu (2002), and Acemoglu et al. (2012), although the former studies the determinants of skill biased technical change whereas the latter focus on the substitution from environmental damaging to friendly technologies. A related work to ours is that by Hassler et al. (2012), who build on the tradition of Pindyck and Rotemberg (1983) and use an aggregate production function to calibrate a measure of energy-saving technical change consistent with the US experience, although they ignore the existence of Investment Specific Technical Change.

The organization of the paper is as follows. Section 2 describes our model economy and defines a quasi-social planner problem whose solution is the efficient allocation of our economy. In Section 3 we discuss the role of investment specific technological change. In Section 4 we describe how we calibrate our economy and our procedure to identify investment specific technological shocks. Section 5 presents our main results about the time series properties of our model economy in connection with the evidence. Section 6 concludes.

2 The benchmark model economy

Here we present our benchmark model economy where investment specific technological change plays a central role.

2.1 Preferences

There is a continuum of households that seek to maximize expected discounted lifetime utility,

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \xi \log\left(\ell_t\right)\right), \ \beta \in (0,1) \ \ \xi > 0, \tag{2.1}$$

where c_t is consumption and ℓ_t is leisure t. Each household is endowed with $\hbar$ units of time and, therefore, works $\hbar - \ell_t$ hours every period.

2.2 Technology and the physical environment

Production of the unique final good is carried out at a continuum of autonomous plants. A plant is created by installing one unit of capital. Plants are indexed by the vintage of the unit of capital installed, denoted by z, and the energy efficiency with which that unit of capital must be operated, denoted by v. Output is produced combining labor and the services of the unit of capital installed according to the technology

$$y_t(z,v) = A_t\,\kappa_t(z,v)^{\alpha}\,h_t(z,v)^{1-\alpha}\,,\ z \leq t,\ v \in I\!R_{++}, \tag{2.2}$$

with $\alpha \in (0,1)$. A_t is the neutral technical change factor; whereas $\kappa_t(z,v)$ and $h_t(z,v)$ are, respectively, the amount of services provided by the unit of capital installed and the amount of labor services employed in the plant.

As we have already mentioned, capital is heterogeneous in two dimensions: Its vintage, z, and its energy efficiency, v. The vintage is given by the date at which the unit of capital was produced. Thus, $z \leq t$. The efficiency type v takes values in $I\!R_{++}$. In order to yield services the unit of capital needs to be combined with energy. The type v determines the amount of energy, $e_t(z,v)$, needed to produce the amount $\kappa_t(z,v)$ of capital services:

$$\kappa_t(z,v) = \Lambda_z\,\Gamma_z\,v^{1-\mu}\min\left\{e_t(z,v)\,,\Gamma_z^{-1}v^{\mu}\right\},\ z \leq t,\ v \in I\!R_{++}, \tag{2.3}$$

where $\mu > 1$. Λ_z and Γ_z refer to embodied investment specific technical change. As shown in Figure 1, energy efficiency type v and embodied investment specific technological change are meant to refer to different factors. We may think of type v as engine power of a car. When the car is used at optimal speed the energy consumed is $\Gamma_z^{-1}\,v^{\mu}$. In this case, the services yielded by the unit of capital are $\kappa_t(z,v) = \Lambda_z\,v$. Since $\mu > 1$, energy consumption at optimal speed is more than proportional to engine power. When the amount of energy consumed is less than the amount required to drive at optimal speed, the amount of services decreases with the efficiency type v, $\kappa_t(z,v) = \Lambda_z\,\Gamma_z\,v^{1-\mu}\,e_t(z,v)$, although it increases with energy consumption. This assumption implies that a SUV car may yield less services when driven in downtown, at suboptimal speed, than a smaller car equipped with less engine power. Λ_z refers to technological improvements that increase capital services which are not directed to save energy, whereas Γ_z refers to innovations that save energy directly. For instance, any improvement in the ergonomics of car seats, so that driving is less tiring, would be an increase in Λ_z, whereas improvements in the aerodynamics of the car would rise its energy efficiency, and should be considered as increases in Γ_z.[4] Thus, embodied technological progress has a dual nature in our theory: it augments productivity and lowers energy consumption

[4]See Knittel (2011) for particular examples of both types of embodied technical innovations.

given the engine power, v. Either factor, Λ_z, and Γ_z, may vary stochastically over time in a manner specified in Section 4. For simplicity, we will call a pair (z, v) a *technology class*, and $\kappa_t(z, v)$ will be the amount services yielded by a unit of capital of class (z, v) at period t. Likewise, $k_t(z, v)$ is the amount of capital of class (z, v) at time t.

Additionally, there is a technology that allows agents to transform final good of period t into Θ_t units of capital of vintage $t + 1$. Thus, as it is standard in the literature, we take the view that investment specific technological change not only brings higher quality but also the production of capital goods becomes increasingly efficient with the passage of time (see, for instance, Greenwood et al. 1997). Specifically, we will denote as $x_t(v)$ the amount of final good invested in capital of vintage $t+1$ that will be operated with efficiency type $v \in I\!R_{++}$ at period $t+1$. The factor Θ_t may vary stochastically over time. Thus, notice that changes in Λ_{t+1}, Γ_{t+1} or Θ_t shift the technological frontier whereas changes in v are movements along the technological frontier.

The number of plants of class (z, v) is equal to the amount of capital of that class, $k_t(z, v)$. Notice that while the vintage is given exogenously by the time at which the unit of capital was produced, the measure of classes respond to economic conditions. Once capital is installed in a plant, it is irreversible; that is, it cannot be converted into consumption goods or capital goods of a different class, and it has zero scrap value. Plants, though, can be left idle by not allocating either energy or labor. As in Gilchrist and Williams (2000), the utilization choice of the plant is purely atemporal. As we will see in Section 2.5, where we discuss the equilibrium allocation, the optimal utilization choice for each plant will be determined by the difference between the (labor) productivity of the unit of capital net of labor costs and the cost of energy required for the capital to produce services. If the difference is positive, the plant will be used in production; otherwise, it will not.

Finally, once production has taken place, the plant faces a positive probability of death, $\varpi \in [0, 1]$, which is i.i.d. across plants. This death implies the destruction of the unit of capital. This death probability plays the role of physical depreciation of capital. Therefore,

$$k_t(z, v) = (1 - \varpi)^{t-z}\, k_z(z, v),\ z \le t,\ v \in I\!R_{++}. \tag{2.4}$$

2.3 Energy consumption and energy prices

We will assume that energy is entirely bought in an international market at an exogenously given price ϱ_t. Therefore, from the point of view of the economic agents, the energy price follows a stochastic process. We assume that there is no international borrowing and lending. In absence of an international credit market we can think of the price of energy as given by nature. This implies that, under market completeness, the Second Welfare Theorem applies and, therefore, we can restrict our attention to efficient allocations.

2.4 Aggregate value added

The amount of aggregate labor used in the production of the final good satisfies

$$0 \leq \ell_t \leq \hbar - \sum_{z=-\infty}^{t} \int_0^{\infty} k_t(z,v)\, h_t(z,v)\, d\,v,\ 0 \leq h_t(z,v) \leq \hbar,\ z \leq t,\ v \in I\!R_{++}, \tag{2.5}$$

Aggregate value added, va_t, is aggregate production of the final good net of energy expenditures. The feasibility constraint is

$$c_t + \int_0^{\infty} x_t\,(v)\ d\,v \leq va_t \equiv \sum_{z=-\infty}^{t} \int_0^{\infty} k_t(z,v)\,[y_t(z,v) - \varrho_t\, e_t(z,v)]\, d\,v, \tag{2.6}$$

where c_t denotes consumption, and $\int_0^{\infty} x_t\,(v)\ d\,v$ is aggregate investment. Thus,

$$0 \leq k_{t+1}(t+1,v) \leq \Theta_t\, x_t\,(v)\,. \tag{2.7}$$

2.5 Properties of the efficient allocation

The efficient allocation is found by maximizing (2.1) subject to (2.2)-(2.7). The planning problem is fully specified in Appendix B. In Appendix C we show the decentralized version of our economy. There we show that we can price capital of all classes by opening a secondary market for plants. In what follows we are going to characterize the efficient allocation and provide conditions that guarantee that the economy can be aggregated.

Lemma 1. *Marginal productivity of labor is the same across all plants operated:*

$$(1-\alpha)\, A_t\, \kappa_t(z,v)^{\alpha} h_t(z,v)^{-\alpha} = \frac{u_\ell\,(c_t,\ell_t)}{u_c\,(c_t,\ell_t)}. \tag{2.8}$$

This is a direct consequence of labor being freely mobile across plants. In the decentralized version of our economy the price of one unit of labor services is $w_t \equiv \frac{u_\ell(c_t,\ell_t)}{u_c(c_t,\ell_t)}$. Thus, Lemma 1 implies that the labor share in gross output is the same in all plants. Now we turn to investigate which classes of capital are allocated energy.

Proposition 1. *If at time t a plant of class (z,v), $z \le t$, $v > 0$, is operated, $e_t(z,v) > 0$, then it is operated at the requirement level, $e_t(z,v) = \Gamma_z^{-1}\, v^{\mu}$ and $\kappa_t(z,v) = \Lambda_z\, v$.*

Proof. Consider the Lagrangian

$$\max_{e_t(z,v)} A_t \left(\Lambda_z\, \Gamma_z\, v^{1-\mu} e_t(z,v)\right)^{\alpha} h_t(z,v)^{1-\alpha} - \varrho_t\, e_t(z,v) + \Psi_t^{e_1}(z,v)\left(\Gamma_z^{-1} v^{\mu} - e_t(z,v)\right) + \Psi_t^{e_0}(z,v)\, e_t(z,v). \tag{2.9}$$

For any plant for which $h_t(z,v) > 0$, if $0 < e_t(z,v) < \Gamma_z^{-1}\, v^{\mu}$, then $\Psi_t^{e_0}(z,v) = 0$, and it must be the case that

$$\alpha\, A_t \left(\Lambda_z\, \Gamma_z\, v^{1-\mu}\right)^{\alpha} e_t(z,v)^{\alpha-1} h_t(z,v)^{1-\alpha} - \varrho_t = \Psi_t^{e_1}(z,v). \tag{2.10}$$

Using (2.3) and (2.8), expression (2.10) becomes

$$\alpha\, A_t^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_t}\right)^{\frac{1-\alpha}{\alpha}} \Lambda_z\, \Gamma_z\, v^{1-\mu} - \varrho_t = \Psi_t^{e_1}(z,v), \tag{2.11}$$

where $w_t \equiv \frac{u_\ell(c_t,\ell_t)}{u_c(c_t,\ell_t)}$. Notice that expression (2.11) does not depend on $e_t(z,v)$. Thus if $\Psi_t^{e_1}(z,v)$ is positive, then $e_t(z,v) = \Gamma_z^{-1}\, v^{\mu}$, and $\kappa_t(z,v) = \Lambda_z\, v$. □

Thus, it is never efficient to operate a plant using less energy than the requirement level. Proposition 1 and expressions (2.2) and (2.8) imply that production at the plant level, relative to production of the latest vintage, only depends on its class:

Corollary 1. *The amount of output produced and labor employed are proportional to the services yielded by the unit of capital installed in the plant:*

$$\frac{h_{t+i}\,(z, v_z)}{h_{t+i}\,(t, v_t)} = \frac{y_{t+i}\,(z, v_z)}{y_{t+i}\,(t, v_t)} = \frac{\Lambda_z}{\Lambda_t}\,\frac{v_z}{v_t},\ \textit{for all } i \geq 0. \tag{2.12}$$

This Corollary describes how labor is allocated across plants that are utilized. Labor is withdrawn gradually from older plants and placed in newer plants. Notice, though, that more efficient plants (those whose energy requirement, v^{μ}, is lower) require less labor than less efficient plants. Since energy is a fixed cost in the plant this Corollary implies that not all plants will be operated in equilibrium. The oldest class used is the one for which gross output net of labor cost is equal to the energy cost, as the following Corollary states:

Corollary 2. *For a plant of class (z, v) to be utilized in equilibrium it must be the case that*

$$\alpha\, A_t^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_t}\right)^{\frac{1-\alpha}{\alpha}} \Lambda_z\, v - \varrho_t\, \Gamma_z^{-1}\, v^{\mu} \geq 0, \tag{2.13}$$

where $w_t \equiv \frac{u_\ell(c_t,\ell_t)}{u_c(c_t,\ell_t)}$. For each efficiency level $v \in I\!R_+$ there exists a vintage $\underline{z}_{v\,t}$ for which (2.13) *holds with strict equality. The vintage $\underline{z}_{v\,t}$ increases with ϱ_t and v.*

In the decentralized version of this economy, expression (2.13)—which is the same that the first order condition shown in (2.11)—is the profit accrued in a plant of class (z, v). This expression says that for a plant to be utilized, profit has to be non-negative. This profit is equal to the return to capital net of energy expenditure, and it increases with the level of embodied technical change, Λ_z and Γ_z, and decreases with v. Notice that the profit decreases with the wage. This is so because the larger the wage, the higher must be labor productivity and, therefore, less labor should be hired and production is lower in an old plant.

Corollary 2 implies that, eventually, profit becomes negative due to the existence of ISTC, even if the energy price does not vary over time. Therefore, for any given energy efficiency, there is a threshold vintage so that plants older than the threshold will not be utilized in equilibrium. Plants will have a finite economic lifespan in our model economy. We are going to denote as $T(z, v)$. We restrict our analysis to economies in which plants are always used up to $T(z, v)$:

Assumption 1. *Profits are always positive along the economic lifespan of a plant: For all t such that $z < t \leq z + T(z, v)$, $v > 0$, $\pi_t(z, v) \geq 0$. For all $t > T(z, v)$, profits are negative, $\pi_t(z, v) < 0$.*

As we will see in Section 5, this Assumption restricts the type of stochastic processes that we can consider for the energy price. Intuitively, this assumption implies that fluctuations in the energy price cannot be too large. Thus, under Assumption 1, Corollary 2 says that the economic life of a plant is shorter the lower is its energy efficiency (higher v) and the faster ISTC is. The shorter the economic life of plants, the larger the measure of plants scrapped in equilibrium. This mechanism is equivalent to an endogenous variable utilization rate of aggregate capital. We can already advance that, as in Gilchrist and Williams (2000), this margin will not be quantitatively important in our model economy since long-run economic growth is not too high and energy expenditure is a very small fraction of aggregate value added in the data. Now we turn to analyze the investment decision and the characteristics of new plants.

Proposition 2. *All units of new capital are operated with the same level of energy efficiency, $v_{t+1} > 0$ with a finite expected economic lifespan $T(t+1) < +\infty$.*

Proof. The first order condition with respect to investment allocated to type v, $x_t(v)$, is

$$\Theta_t^{-1}\varphi_t - \Psi_t^k(v) = E_t \sum_{i=1}^{\infty} (1-\varpi)^{i-1} \varphi_{t+i} \max\{\alpha\, y_{t+i}(t+1, v) - \varrho_{t+i}\, e_{t+i}(t+1, v), 0\}, \qquad (2.14)$$

where φ_t is marginal utility of consumption at time t. Investment in type v is positive only if $\Psi_t^k(v) = 0$. This multiplier is non negative so zero is its minimum value. Thus, we have to show that $\Psi_t^k(v)$ has a unique minimum. Equivalently, present value of capital income, shown in the right hand side of (2.14), has a unique maximum. Using (2.8) and the result of Proposition 1 and plugging them in the expression of output at the plant level, (2.2), we can write (2.14) as

$$\Theta_t^{-1}\varphi_t - \Psi_t^k(v) = E_t \sum_{i=1}^{\infty} (1-\varpi)^{i-1} \varphi_{t+i} \max\left\{\alpha\, A_{t+i}^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_{t+i}}\right)^{\frac{1-\alpha}{\alpha}} \Lambda_{t+1}\, v - \varrho_{t+i}\, \Gamma_{t+1}^{-1}\, v^{\mu}, 0\right\}, \quad (2.15)$$

where $w_{t+i} \equiv \frac{u_\ell(c_{t+i}, \ell_{t+i})}{u_c(c_{t+i}, \ell_{t+i})}$. Let us denote as T the number of periods that a plant is allocated labor. Conditional on yielding non negative profits for that number of periods, there is a unique $v(T)$ that maximizes the present value of profits and its satisfies

$$\frac{\alpha}{\mu}\, E_t \sum_{i\in T}(1-\varpi)^{i-1}\varphi_{t+i}\, y_{t+i}\,(t+1, v_{t+1}(T)) = E_t \sum_{i\in T}(1-\varpi)^{i-1}\varphi_{t+i}\, \varrho_{t+i}\, \Gamma_{t+1}^{-1}\, v_{t+1}(T)^{\mu}, \quad (2.16)$$

that is, the present value of all future energy expenditures in a plant that uses a unit of capital of vintage $t+1$ is the fraction α/μ of the present value of future gross output produced by that plant. Hence the price of one unit of new capital, Θ_t^{-1}, must be equal to the fraction $\alpha(\mu-1)/\mu$ of the present value of future gross output. It is easy to check that for any $T_1 > T_2$, $v_{t+1}(T_1) \geq v_{t+1}(T_2)$ and it satisfies

$$v_{t+1}(T)^{\mu-1} = \Lambda_{t+1}\, \Gamma_{t+1}\, \frac{E_t \sum_{i\in T}(1-\varpi)^{i-1}\varphi_{t+i}\, \alpha\, A_{t+i}^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_{t+i}}\right)^{\frac{1-\alpha}{\alpha}}}{\mu\, E_t \sum_{i\in T}(1-\varpi)^{i-1}\varphi_{t+i}\, \varrho_{t+i}}. \quad (2.17)$$

Thus, the first order condition shown in (2.14) can be written as

$$\Theta_t^{-1}\varphi_t - \Psi_t^k(v_{t+1}(T)) = \frac{\alpha(\mu-1)}{\mu}\Lambda_{t+1} \left(\Lambda_{t+1}\, \Gamma_{t+1}\, \frac{\alpha}{\mu}\right)^{\frac{1}{\mu-1}} \frac{\left(E_t \sum_{i\in T}(1-\varpi)^{i-1}\varphi_{t+i}\, \alpha\, A_{t+i}^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_{t+i}}\right)^{\frac{1-\alpha}{\alpha}}\right)^{\frac{\mu-1}{\mu}}}{\left(E_t \sum_{i\in T}(1-\varpi)^{i-1}\varphi_{t+i}\, \varrho_{t+i}\right)^{\frac{1}{\mu}}}. \quad (2.18)$$

The last factor is strictly concave in T and it has a unique maximum for $T(t+1) < +\infty$. Thus, all investment takes place in only one efficiency type. □

2.6 Aggregation

We are going to represent aggregate gross output as a function of aggregate inputs. In order to aggregate capital we need to define appropriate relative prices for each class. It is easy to do so for the latest vintage produced, since its shadow price must be equal to the inverse of the productivity in the production of capital goods, Θ_t^{-1}, but we do not have an equivalent measure for the previous vintages. Therefore, we define a price for any class of capital in the following way:

Definition 1. *Let the cost of one unit of capital of class* (z, v), $z \leq t+1$, $v_z \in \mathbb{R}_{++}$, *in units of* *gross output at time t be defined as*

$$q_t\,(z, v_z) \equiv \Theta_t^{-1} \frac{\Lambda_z}{\Lambda_{t+1}} \frac{v_z}{v_{t+1}},\ z \leq t+1,\ v \in I\!R_{++}. \tag{2.19}$$

Notice that capital goods of the same vintage may have different prices, depending on their energy efficiency. This is consistent with Gordon (1990, 1996), who argued that not all changes in the relative price of capital goods are due to investment specific technical change but also to changes in energy efficiency (see Gordon 1996, p. 262).

We need to emphasize that the price defined above is not the market price of a unit of capital of class (z, v) at time t, since it does not measure the present value of the expected return to one unit of capital net of energy expenditures. Appendix C shows the decentralized version of this economy and that the market price of one unit of capital of class (z, v) at time $t \geq z$, $p_t(z, v)$, is bounded below by

$$\underline{p}_t\,(z, v_z) = \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}}\, \Theta_t^{-1} + \left(\frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}} - \frac{\Gamma_z^{-1}\, v_z^{\mu}}{\Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}} \right) \frac{\Theta_t^{-1}}{\mu - 1}, \tag{2.20}$$

and bounded above by

$$\overline{p}_t\,(z, v_z) = \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}}\, \frac{\mu}{\mu - 1}\, \Theta_t^{-1}. \tag{2.21}$$

The price shown in (2.19) is the cost of capital of class (z, v_z) in units of gross output at period t. It could be argued that we should find aggregate capital using market prices. We would do so if we could represent aggregate value added solely as a function of labor and capital, which we cannot do because of the complementarity of capital and energy at the plant level. This complementarity implies that factor shares in aggregate value added depend on the distribution of capital across vintages. As a consequence, we cannot write aggregate value added as a function of aggregate primary inputs. We can, however, find aggregate gross output since the share of labor in gross output is constant regardless of the capital vintage and energy efficiency.[5]

[5]See Sato (1976) for a more detailed discussion on the issue of aggregation.

2.6.1 Aggregate capital and its relative price

Let us define k_t as the aggregate volume of capital, in per capita terms, in units of the latest class. Thus,

$$k_t = \sum_{z=-\infty}^{t} \frac{q_t(z, v_z)}{q_t(t, v_t)} k_t(z, v_z) = \sum_{z=-\infty}^{t} \frac{\Lambda_z}{\Lambda_t} \frac{v_z}{v_t} k_t(z, v_z). \tag{2.22}$$

Taking into account that capital of class (z, v_z) is the investment of the previous period, we can express capital as

$$k_t = \sum_{z=-\infty}^{t} \frac{\Lambda_z}{\Lambda_t} \frac{v_z}{v_t} (1-\varpi)^{t-z} \Theta_{z-1} x_{z-1}. \tag{2.23}$$

The product $\frac{\Lambda_z}{\Lambda_t} \frac{v_z}{v_t} (1-\varpi)^{t-z}$ can be interpreted as the remaining value of the stock of class (z, v_z) (per unit of capital) once physical depreciation and obsolescence are taken into account. In other words, the average depreciation rate of capital class (z, v_z) at time t is

$$\delta_t(z, v_z) = 1 - (1-\varpi) \left(\frac{\Lambda_z}{\Lambda_t} \frac{v_z}{v_t} \right)^{\frac{1}{t-z}}. \tag{2.24}$$

The average relative price (cost) of capital in units of consumption good is, by definition of k_t, equal to the relative price of vintage t and type v_t.

$$q_t = \sum_{z=-\infty}^{t} q_t(z, v_z) \frac{k_t(z, v_z)}{k_t} = \frac{\Lambda_t}{\Lambda_{t+1}} \frac{v_t}{v_{t+1}} \Theta_t^{-1}. \tag{2.25}$$

We can also define the stock of capital adjusted by quality:

$$\kappa_t = \sum_{z=-\infty}^{t} \Lambda_z v_z k_t(z, v_z), \tag{2.26}$$

which, given the definition of capital, can be written as $\kappa_t = \Lambda_t v_t k_t$. Now we can define its cost in units of gross output:

Definition 2. *Let the cost of one unit of capital services of class (z, v_z), $z \leq t+1$, $v_z \in I\!R_{++}$, in* *units of gross output at time t be defined as*

$$q_t^{\kappa} \equiv \frac{q_t(z,v)}{\Lambda_z\, v_z},\ z \leq t+1,\ v \in I\!R_{++}. \tag{2.27}$$

This price is equal to $\Theta_t^{-1}\Lambda_{t+1}^{-1}v_{t+1}^{-1}$ for all classes of capital.

Consistently with Gordon (1990) and Cummins and Violante (2002), this price falls when ISTC rises, as measured by $\Theta_t\,\Lambda_{t+1}$, but it rises when energy efficiency rises; that is, when v_{t+1} falls. Thus, when agents invest in improving energy efficiency of new capital, the relative price of new capital rises, as it was suggested by Gordon (1996). Thus, our theory says that we cannot attribute all changes in the relative price of investment to ISTC but also to changes in energy efficiency.

The procedure that we have used to aggregate capital is consistent with the method used by the Bureau of Economic Analysis (and other statistical agencies in different countries) to measure the real value of the net stock of capital. The only difference is that the BEA defines the stock of capital in units of output; in our notation:

$$\tilde{k}_t = \sum_{z=-\infty}^{t} (1-\varpi)^{t-z} \frac{\Lambda_z}{\Lambda_t}\,\frac{v_z}{v_t}\,\frac{\Theta_{z-1}}{\Theta_{t-1}}\,x_{z-1} = \sum_{z=-\infty}^{t} (1-\varpi)^{t-z} \frac{q_{t-1}^{\kappa}}{q_{z-1}^{\kappa}}\,x_{z-1}. \tag{2.28}$$

Notice that $\tilde{k}_t$ is equal to our stock of quality-adjusted capital valued at prices at the beginning of the period, $\tilde{k}_t = q_{t-1}^{\kappa}\,\kappa_t$, which is equal to $\Theta_{t-1}^{-1}\,k_t$. The BEA depreciates investment realized at time $z-1$ by applying economic depreciation rates which include physical decay as well as obsolescence.[6] In terms of our theory, the obsolescence component of the depreciation rate must be given by the change in the quality-adjusted relative price of investment, $q_{t-1}^{\kappa}/q_{z-1}^{\kappa}$. As a matter of fact, this is the procedure followed by Cummins and Violante (2002) to calibrate the physical depreciation rate of capital. We add to their analysis by providing a theory of how the relative price of investment depends on energy efficiency and, therefore, energy prices.

[6] See Bureau of Economic Analysis (2003) for a detailed description of the perpetual inventory method used to construct the aggregate stock of capital measure.

2.6.2 Output, hours worked and energy use

Aggregate production, using (2.12), can be written as

$$y_t = \sum_{z=\underline{z}_t}^{t} \frac{\Lambda_z}{\Lambda_t} \frac{v_z}{v_t} k_t(z, v_z) \, y_t(t, v_t) = \frac{\kappa_t^*}{\Lambda_t \, v_t} y_t(t, v_t), \tag{2.29}$$

where $\underline{z}_t$ is the oldest vintage utilized at time t and κ_t^* is the amount of services yielded by the plants utilized in equilibrium:

$$\kappa_t^* = \sum_{z=\underline{z}_t}^{t} \Lambda_z \, v_z \, k_t(z, v_z). \tag{2.30}$$

We can write capital services as

$$\kappa_t^* = \kappa_t \, u_t^k. \tag{2.31}$$

where κ_t was defined in (2.26) as the stock of capital adjusted by quality. u_t^k can be thought of as the utilization rate of the capital stock, and is given by the expression

$$u_t^k = 1 - \left(1 - \delta_t\left(\underline{z}_t - 1, v_{\underline{z}_t - 1}\right)\right)^{t - \underline{z}_t + 1} \left(\frac{k_{\underline{z}_t - 1}}{k_t}\right). \tag{2.32}$$

Notice that $\delta_t\left(\underline{z}_t - 1, v_{\underline{z}_t - 1}\right)$ is the economic depreciation rate defined in (2.24). Expression (2.32) says that the stock of capital used at time t, $u_t^k \, k_t$, is the total stock, k_t, minus the undepreciated part of the capital stock already in place at time $\underline{z}_t - 1$. Thus, the existence of scrapping gives us a measure of utilization at the extensive margin as in Gilchrist and Williams (2000). In Section 5 we will return to this issue and estimate its quantitative importance.

Likewise, using (2.8) and (2.19) we can write aggregate labor as

$$h_t = \sum_{z=\underline{z}_t}^{t} \frac{\Lambda_z}{\Lambda_t} \frac{v_z}{v_t} k_t(z, v_z) \, h_t(t, v_t) = \frac{\kappa_t^*}{\Lambda_t \, v_t} h_t(t, v_t). \tag{2.33}$$

Aggregate gross output is

$$y_t = A_t \left(u_t^k \, \kappa_t\right)^{\alpha} h_t^{1-\alpha}. \tag{2.34}$$

Finally, aggregate energy consumption is

$$e_t^* = e_t\, u_t^e, \tag{2.35}$$

where e_t is the energy required for the entire stock of capital to produce services,

$$e_t = \sum_{z=-\infty}^{t} \Gamma_z^{-1}\, v_z^{\mu}\, k_t\left(z, v_z\right), \tag{2.36}$$

and u_t^e can be thought of as the rate of utilization of the amount of energy required to use all installed capital:

$$u_t^e = \left[1 - (1-\varpi)^{t-\underline{z}_t+1}\left(\frac{e_{(\underline{z}_t-1)}}{e_t}\right)\right]. \tag{2.37}$$

Now we can rewrite the condition that characterizes $\underline{z}_t$ in terms of aggregate variables:

Corollary 3. *The oldest vintage used in equilibrium, $\underline{z}_t$, satisfies*

$$\alpha\, \frac{y_t}{u_t^k\, \kappa_t}\, \Lambda_{\underline{z}_t}\, v_{\underline{z}_t} \geq \varrho_t\, \Gamma_{\underline{z}_t}^{-1}\, v_{\underline{z}_t}^{\mu}, \;\; \textit{for all } t. \tag{2.38}$$

Notice that the realized lifespan of a vintage does not necessarily equal its expected lifespan. It depends on the assumed fluctuations in the energy price and the innovations in ISTC factors. We will return to this issue later.

2.6.3 The aggregate economy

Now we can write the quasi-social planner's problem, in which we need to specify the utilization rule, given by equation (2.38):

$$
\begin{aligned}
\max_{\substack{c_t,\, x_t,\\ v_{t+1}}} \quad & E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \xi \log\left(\hbar - h_t\right)\right) \\
\text{s. t.} \quad & c_t + x_t \leq A_t \left(u_t^k\, \kappa_t\right)^{\alpha}\, h_t^{1-\alpha} - \varrho_t\, u_t^e\, e_t, \\
& e_{t+1} \geq \Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}\, \Theta_t\, x_t + (1-\varpi)\, e_t, \\
& 0 \leq \kappa_{t+1} \leq v_{t+1}\, \Lambda_{t+1}\, \Theta_t\, x_t + (1-\varpi)\, \kappa_t, \\
& \kappa_0 \text{ given},\ v_{t+1} \geq 0,\ x_t \geq 0.
\end{aligned}
\tag{2.39}
$$

Hence, by solving this planner's problem we can find the aggregates of our decentralized economy. This problem already shows the various channels through which the different sources of ISTC operate. Both types of embodied technical change, Γ and Λ are energy saving devices. The first one reduces directly the amount of energy required, whereas the second increases the services yielded by one unit of capital without rising energy use. The disembodied technical change factor, Θ, rises both capital services and energy use. We call Γ and Λ the "intensive margin" of ISTC, whereas Θ is the "extensive margin". Thus, improvements in the intensive margin of ISTC reduce energy use without investing in energy efficiency (i.e., lower type v), whereas any increase in Θ increases energy use without reducing energy efficiency. In other words, energy efficiency and embodied technical change are substitutes (in terms of energy use), whereas disembodied technical change and efficiency are complements. This will play a role when we study the quantitative properties of our theory.

3 The role of investment specific technological change

In this section we want to highlight the effect of investment specific technical change on the utilization decision and the choice of energy efficiency. Without loss of generality, assume that agents do not value leisure so that $h_t = \hbar$ every period.

3.1 The lifespan of capital

Let us turn to an economy with where capital is putty-clay but where there is no ISTC, as that proposed by Atkeson and Kehoe (1999). Their economy is essentially ours in absence of ISTC but, still, capital is irreversible and heterogeneous in its energy efficiency. We show in Appendix D.1 the mapping of their economy to our economy in detail. In this economy, profit for a plant of type v is:

$$\alpha \, A_t^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_t} \right)^{\frac{1-\alpha}{\alpha}} v - \varrho_t \, v^{\mu}. \tag{3.1}$$

This expression is the counterpart of expression (2.13) in absence of ISTC. At the balance growth path the wage and the neutral factor $A_t^{1/1-\alpha}$ grow at the same rate. Thus, if fluctuations in the energy price are not too high (conditional on the fact that energy expenditure is a small fraction of value added), all capital is always utilized and its lifespan is infinite. This is a key difference with our theory. In the presence of ISTC and irreversibility, utilization depends not only on the energy price but also on the growth rate of ISTC, which governs the obsolescence of installed capital.

3.2 Capital utilization and the choice of energy efficiency

Here we show that the existence of ISTC not only implies that new vintages are more efficient than older vintages but also that there is scrapping in equilibrium. To illustrate this result we focus on the non-stochastic balanced growth path of this economy. Let us assume that the energy price, ϱ_t, neutral progress factor, A_t, and ISTC factors, Θ_t, Λ_t, and Γ_t, all grow at a constant rate. Thus,

$$\varrho_t = (1+g_\varrho)^t, \; A_t = (1+g_a)^t, \; \Theta_t = (1+\theta)^t, \; \Lambda_t = (1+\lambda)^t, \text{ and } \Gamma_t = (1+g_\gamma)^t. \tag{3.2}$$

In the balanced growth path the expected lifespan of a vintage is exactly equal to its realized lifespan and constant over time. Thus, the utilization rate of capital and energy use must be constant. This implies that gross output and energy expenditure must grow at the same rate, g_y, which satisfy

$$1 + g_y = (1+g_a)\,(1+g_\kappa)^\alpha \,, \tag{3.3}$$

where g_κ is the growth rate of capital services. Using the expression for aggregate capital shown in (2.22) we can show that capital grows at a rate g_k that satisfies

$$1 + g_k = (1+\theta)(1+g_y), \tag{3.4}$$

whereas capital adjusted by quality grows at rate g_κ that is given by

$$1 + g_\kappa = (1+\lambda)(1+g_v)(1+g_k), \tag{3.5}$$

where g_v, the growth rate of v, is obtained using the law of motion of energy shown in problem (2.39):

$$\frac{\varrho_t}{\varrho_{t+1}}\,\varrho_{t+1}\,e_{t+1} = \varrho_t\,\Gamma_{t+1}^{-1}\,v_{t+1}^{\mu}\,\Theta_t\,x_t + (1-\varpi)\,\varrho_t\,e_t. \tag{3.6}$$

In the balanced growth path, the product $\varrho_t\,\Gamma_{t+1}^{-1}\,v_{t+1}^{\mu}\,\Theta_t$ must be constant since investment, x_t, and energy expenditure, $\varrho_t\,e_t$, must grow at the same rate. Thus, the energy efficiency type, v_{t+1} grows at a constant rate g_v that satisfies

$$1 + g_v = (1+g_\varrho)^{\frac{-1}{\mu}}\,(1+\gamma)^{\frac{1}{\mu}}\,(1+\theta)^{\frac{-1}{\mu}}\,. \tag{3.7}$$

Thus, depending on which factor grows faster, energy efficiency (i.e., the inverse of v_{t+1}) has a positive or a negative trend. Throughout this paper we are going to focus our attention on economies in which energy efficiency has a positive trend; i.e., v_{t+1} decreases over time.

Assumption 2. *We assume that* $(1+\gamma)^{\frac{1}{\mu}}\,(1+\theta)^{\frac{-1}{\mu}} < 1$.

In absence of ISTC, the trend in energy efficiency is given solely by the trend in the energy price. The extensive margin of ISTC implies that, over time, the economy becomes more capital intensive, which rises energy use. Thus, efficiency of new capital must grow over time to compensate for the augment in capital intensity.

The average depreciation rate of vintages shown in (2.24) is constant,

$$\delta_t\,(z, v_z) = 1 - \frac{(1-\varpi)}{(1+\lambda)\,(1+g_v)}. \tag{3.8}$$

The intensive margin of ISTC, together with the fix energy requirement, render old plants less and less profitable relative to new plants. Thus, older plants are scrapped. In the balanced growth path the economic lifespan of vintages is constant, $T = t - \underline{z}_t + 1$ as can be shown using (2.13). The utilization rate of capital is equal to

$$u^k = 1 - \left[\frac{(1-\varpi)}{(1+\lambda)(1+g_v)(1+g_k)}\right]^{t-\underline{z}_t+1}, \tag{3.9}$$

whereas the utilization rate of the energy requirement is

$$u^e = 1 - \left[\frac{(1-\varpi)(1+g_\varrho)}{(1+g_y)} \right]^{t-\underline{z}_t+1}. \tag{3.10}$$

Thus, the existence of ISTC implies that in the balanced growth path the economic lifespan of machines is finite and constant and energy efficiency rises steadily. This will not be the case when we add uncertainty. We can, however, advance that the quantitative importance of scrapping is negligible in our model economy.

4 Calibration and estimation

In this section we describe the procedure used to calibrate our economy and the estimation of the shocks. We briefly discuss the data that we use. We take the U.S. to be our reference economy. We construct series for the energy price and energy consumption as well as economic aggregates for the period 1960-2008. Since we assume that all energy is imported in our model economy, we need to construct measures of value added, investment and the capital stock excluding, respectively, output, investment, and capital of energy-producing sectors. Our measure of value added includes the imputed services of consumer durable goods and government capital. Capital and aggregate investment are defined accordingly. To obtain an aggregate series on energy consumption for the US economy, we construct a constant-price measure of the consumption of coal, petroleum, natural gas and electricity by end-use sectors. Correspondingly, our aggregate energy price is the ratio of energy use measured in current prices to energy use measured in constant prices. A full explanation of the sources and methods used in our data construction is given in Appendix A.

4.1 The energy price shock

Following Atkeson and Kehoe (1999), we estimate an ARMA(1,1) process for the aforementioned energy price deflator parameterized by

$$\log \varrho_{t+1} = (1-\rho)\log \overline{\varrho} + \rho \log \varrho_t + \phi \epsilon_t + \epsilon_{t+1}, \tag{4.1}$$

where $\epsilon \sim N\left(0, \sigma_\epsilon^2\right)$ and $\overline{\varrho}$ is the average energy price in the data. We find that $\rho \simeq 0.94$, $\phi \simeq 0.45$ for 1960-08.

4.2 The specification of the investment specific shocks

In this section we discuss the set of observations that we are going to use to specify a structure for the ISTC processes, Θ_t, Λ_t and Γ_t. First, we assume that Γ_t is constant. This is consistent with assuming that the energy price has no trend, in line with our estimated price shown in expression (4.1). Thus, we have left Θ_t, which affects the technology that transforms final good into investment goods, and Λ_t, which affects the amount of capital services yielded by one unit of new capital. The literature on growth or real business cycles that incorporates ISTC do not differentiate between its two sources—higher productivity in producing investment goods or higher quality of those goods. See for instance, Greenwood et al. (2000), or Fisher (2006), among others. This literature assumes that the quality adjusted relative price of capital goods falls due to ISTC and estimates a process to match the statistical properties of this price in the data. In our notation, this literature assumes a relative price equal to $\widetilde{q}_t = \Theta_t^{-1}\,\Lambda_{t+1}^{-1}$ since it abstracts from energy requirement. In that setting, the more traditional approach in Greenwood et al. (2000) consists of estimating a process for $\widetilde{q}_t$ that features a deterministic trend and transitory shocks. After Fisher (2006), however, it is common to estimate a process that features a stochastic trend.

Differently from the standard theory, we need to distinguish both ISTC sources. In order to do so, we need to select two model variables and two sets of observations. In our theory, the two ISTC shocks govern the evolution of the price of new investment, $q_t\left(t+1, v_{t+1}\right) = \Theta_t^{-1}$, and the quality-adjusted price of capital, $q_t^\kappa\left(t+1, v_{t+1}\right) = \Theta_t^{-1}\,\Lambda_{t+1}^{-1}\,v_{t+1}^{-1}$, as defined in (2.27). We chose as the data counterpart of q_t the inverse of the ratio of the chain weighted NIPA deflator for non durable consumption and services over that of durable consumption expenditures and private investment in structures, which we denote as Q_t. We proceed in this way because the prices of durable expenditures and investment in structures have significant quality bias in NIPA (see Gort et al. 1999). Next, we use as the data counterpart of $q_t^\kappa\left(t+1, v_{t+1}\right)$ the estimates of Gordon (1990) and Cummins and Violante (2002) (hereafter the GCV deflator) of the inverse of the quality-adjusted relative price of equipment and software, which we denote as Q_t^κ.[7]

[7] Rodríguez-López and Torres (2012) extend the GCV prices by using the methodology proposed by Cummins and Violante (2002). We use this update.

Now we need to specify a stochastic structure for both ISTC processes. We build on Fisher (2006) and assume that the productivity in the production of capital goods, Θ_t, is non-stationary and its growth rate, θ, is subject to shocks, z_t^θ, whereas the quality level of new capital goods, Λ_{t+1}, exhibits deterministic growth at the rate λ and it is subject to transitory shocks, z_t^λ. Specifically:

$$\Theta_t = \Theta_{t-1}\, e^{\theta + z_t^\theta}, \tag{4.2}$$

$$\Lambda_{t+1} = (1+\lambda)^t e^{z_t^\lambda}. \tag{4.3}$$

There are two reasons why we choose Λ_{t+1} to be subject to transitory instead of permanent shocks. In this way, the empirical model used to estimate both processes, (4.2), and (4.3), is stationary in first differences, as we will show in Section 4.4. There is another reason and it has to do with the fact that the model variable used to identify Λ_{t+1}, the quality-adjusted relative price of capital, $q_t^\kappa\,(t+1, v_{t+1})$, depends also on one non-observable variable, the efficiency type, v_{t+1}. In our identification strategy shown in Section 4.4 we use the fact that Λ_{t+1} is only subject to transitory shocks.

We are not the first in assuming two different shocks affecting Investment Specific Technical Change. Justiniano et al. (2011) also specify two investment shocks to study business cycle fluctuations in a neokeynesian model economy. There are significant differences, however, between their approach and ours. As in Justiniano et al. (2011) we assume one of the shocks is permanent, and it is the one that affects the productivity in the production of investment goods. These authors use the NIPA deflators to estimate this process, but they check the robustness of their results to the use of their update of the GCV deflator. They also assume the other investment shock to be transitory but they interpret it in a different manner. They call it a shock to the marginal efficiency of investment (MEI hereafter) and estimate it using a proxy for the market value of firms. We could think of our transitory shock to quality of new capital goods as a sort of MEI shock, although making the mapping is difficult since Justiniano et al. (2011) abstract from energy requirements.

4.3 The stationary version of our model economy

It is convenient to obtain a stationary representation of our model economy by normalizing with respect to the state of technology. In our economy, output and capital grow at different rates, as we have learnt in Section 3. Moreover, since one of the ISTC shocks is permanent, our economy features a stochastic trend.

Proposition 3. *Assume that Assumption 1 holds, so that in equilibrium all installed capital has a finite lifespan, $T(t) < \infty$, for all t. Suppose that the energy price has no trend, that $\Gamma_t = 1$, for all t, and that Θ_t and Λ_t are given by (4.2) and (4.3), respectively. The efficiency type v_{t+1} has a stochastic trend given by*

$$G_t^v = \Theta_t^{\frac{-1}{\mu}}, \text{ for all } t. \tag{4.4}$$

Gross output, y_t, investment and consumption, x_t, c_t, and $\varrho_t\, e_t$, have a trend G_t^y which satisfies

$$G_t^y = A_{t-1}^{\frac{1}{1-\alpha}} \left[\Lambda_t\, \Theta_{t-1}\right]^{\frac{\alpha}{1-\alpha}} \Theta_{t-1}^{\frac{-\alpha}{\mu(1-\alpha)}}. \tag{4.5}$$

The trend of capital and capital services satisfy

$$G_{t-1}^k = G_t^y\, \Theta_{t-1}, \quad G_{t-1}^\kappa = \Lambda_t\, G_{t-1}^v\, G_{t-1}^k. \tag{4.6}$$

The trend of the relative price of capital and the trend of the relative price of capital services are, respectively:

$$G_t^q = \Theta_{t-1}^{-1}, \quad G_t^{q^\kappa} = G_t^q\, \Lambda_t^{-1}\, G_{t-1}^v. \tag{4.7}$$

The economic lifespan of vintages have no trend.

Proof. Taking into account (2.17) and that gross output and energy expenditure should grow at the same rate the result follows. □

It is interesting to note that changes in Λ_t do not affect the trend in energy efficiency, v_{t+1}. Its innovations, however, will affect the fluctuations in energy efficiency over time. Notice also that the trend in the relative price of capital is given by the permanent shock Θ_t, whereas the quality-adjusted price depends also on the trend of embodied technical change and that of energy efficiency.

Since the economic life span of capital goods have no trend, the utilization rate of capital and the energy requirement, u_t^k, and u_t^e, have no trend either. Thus, we are going to approximate the equilibrium allocation that is found by solving the problem shown in (2.39) by a quasi-planner's problem where we replace u_t^k and u_t^e by their counterparts in the balanced growth path shown by (3.9) and (3.10):

$$\begin{aligned}
\max_{\substack{c_t,\, x_t,\\ v_{t+1}}} \quad & E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \xi \log\left(\hbar - h_t\right)\right) \\
\text{s. t.} \quad & c_t + x_t \leq A_t \left(u^k \kappa_t\right)^{\alpha} h_t^{1-\alpha} - \varrho_t\, u^e\, e_t, \\
& e_{t+1} \geq v_{t+1}^{\mu}\, \Theta_t\, x_t + (1-\varpi)\, e_t, \\
& 0 \leq \kappa_{t+1} \leq v_{t+1}\, \Lambda_{t+1}\, \Theta_t\, x_t + (1-\varpi)\, \kappa_t, \\
& \kappa_0 \text{ given},\ v_{t+1} \geq 0,\ x_t \geq 0.
\end{aligned} \tag{4.8}$$

This problem assumes that the economic lifespan of capital is constant over time and not affected by uncertainty. Notice that the problem is written abstracting from the energy saving intensive margin of ISTC. In Section 5.3 we will discuss the quantitative implications of ignoring fluctuations in the utilization rate.

4.4 Empirical strategy

Figure 2(a) shows the NIPA deflator for private investment in structures and durable consumption expenditures (hereafter, St&D) and the GCV deflator for investment in equipment and software (hereafter E&S), over non-durable consumption and services. The former (NIPA St&D) is used as a proxy for the price of new investment goods in our model economy, $q_t = \Theta_t^{-1}$, whereas the latter (GCV E&S) proxies the relative price of capital services, $q_t^{\kappa} = \Theta_t^{-1}\, \Lambda_{t+1}^{-1}\, v_{t+1}^{-1}$. We use these two prices to estimate a joint process defined over Q_t and Q_t^{κ} as discussed in Section 4.2 above:

$$Q_t = Q_{t-1}\, e^{\theta + z_t^{\theta}}, \tag{4.9}$$

$$Q_t^{\kappa} = Q_t\, (1+\lambda)^t\, e^{z_t^{\tilde{\lambda}}}, \tag{4.10}$$

with $e^{z_t^{\tilde{\lambda}}} \equiv e^{z_t^{\lambda}}\, v_{t+1}$ since we cannot, a priori, disentangle the shocks in Λ_{t+1} from the endogenous response of energy efficiency v_{t+1}.

A stationary representation of the joint investment specific technical change processes can be described in a state space form according to

$$\xi_{t+1} = \quad \Gamma + F\xi_t + \varepsilon_{z_{t+1}}, \quad \text{state equation,} \tag{4.11}$$

$$y_t = \quad H\xi_t(+Ax_t) + \nu_t, \quad \text{observation equation.} \tag{4.12}$$

where $y_t = [\nabla \log Q_t^\kappa \quad \nabla \log Q_t]'$, $\varepsilon_{z_t^m} = (1-\rho_m L)z_t^m$, with $m = \widetilde{\lambda}, \theta$, and Γ, F, H, and A are matrices of parameters. The term $(+Ax_t) + e_t$ accounts for measurement error with exogenous variables x_t if necessary. The innovations ν_t are generated recursively using the Kalman filter, and they are used to form the sample log likelihood function for observables y_t. Parameters of interest are estimated by maximizing numerically this likelihood, and those estimates are used to identify the ISTC shocks. The investment specific transitory shock, $\varepsilon_{z^{\tilde{\lambda}}}$ is identified with the GCV E&S deflator, whereas the permanent shock ε_{z^θ} is identified with the NIPA St&D deflator. The unobservable process is $\tilde{\Lambda}_{t+1} \equiv \Lambda_{t+1} v_{t+1}$, and consequently $Q_t^\kappa = Q_t \tilde{\Lambda}_{t+1}$. With unit matrix H, the empirical model can be then written:

$$\begin{bmatrix} \nabla \log Q_t^\kappa - (\lambda+\theta) \\ \\ \nabla \log Q_t - \theta \end{bmatrix} = \begin{bmatrix} \rho_\lambda & \rho_\theta - \rho_\lambda \\ \\ 0 & \rho_\theta \end{bmatrix} \begin{bmatrix} \nabla \log Q_{t-1}^\kappa - (\lambda+\theta) \\ \\ \nabla \log Q_{t-1} - \theta \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \varepsilon_{z_t^{\tilde{\lambda}}} \\ \\ \varepsilon_{z_t^\theta} \end{bmatrix} \tag{4.13}$$

Thus, z_t^θ in (4.9) represents exactly the state $\nabla \log Q_t - \theta \equiv S_t$. However, combined states S_t and $S_t^\kappa \equiv \nabla \log Q_{t-1}^\kappa - (\lambda+\theta)$, represent $z_t^\theta + z_t^{\tilde{\lambda}} - z_{t-1}^{\tilde{\lambda}} \equiv \rho_\theta S_{t-1} + \varepsilon_{z_t^\theta} + \rho_\lambda S_{t-1}^\kappa + \varepsilon_{z_t^{\tilde{\lambda}}} - \rho_\lambda S_{t-1}$, where $z_t^{\tilde{\lambda}} \equiv z_t^\lambda + \log(v_{t+1})$ so we keep track of the bias in our estimation through the response of endogenous variable v_{t+1} to the shocks. To identify the embodied technological change shock, z_t^λ, we simulate our model economy solving the quasi-social planner's problem shown in (4.8) feeding to it the innovations z_t^θ and $z_t^{\tilde{\lambda}}$ (as well as the energy price innovations). Then we obtain a path for energy efficiency v_{t+1} and calculate the innovation $z_t^\lambda = z_t^{\tilde{\lambda}} - \log(v_{t+1})$. We simulate again our model economy feeding to it z_t^λ until the equilibrium price of quality-adjusted capital in the model converges. We proceed in this way because quality innovations z_t^λ only affect the fluctuations of energy efficiency, v_{t+1}, but not its trend, since we have assumed Λ_{t+1} to be subject only to transitory shocks. Consequently, the trend of the quality-adjusted price is not affected by quality innovations.

Table 2 in its lower rows reports the parameter estimates obtained by using annual data over both the benchmark sample period 1959-2009, and also 1947-2009. As a robustness check, we also compute the estimates corresponding to quarterly data from 1959QIV to 2009QI and from 1947QIV to 2009QI. It can be checked that all parameter estimates are in line with those reported in the literature (Fisher 2006 or Justiniano et al. 2011, among others). For instance, σ_θ is about 0.5% quarterly, and say, $\sigma_{\lambda\theta}$ is about 6%, whereas ρ_θ is about 0.2 and $\rho_{\lambda\theta}$ is about 0.7.

Figure 2(b) shows the correlation of the innovations z_t^θ and z_t^λ to the Q_t and Q_t^κ processes. To compute this correlation a window of 5 years (20 quarters, quarterly estimation) has been used. The vertical red lines correspond to years 1974, 1978 and 1992. The correlation lies above average (zero in the figure) right after the oil price shocks in the 1980s and the early 2000s, when the 2003-08 oil price shock first hits. On the contrary, the correlation lies below average during the late 1990s. This picture suggests that ISTC innovations seem to be related to energy price changes but during the 1990s.

Before showing our quantitative experiments we discuss the aggregate targets and the discipline imposed by our theory to calibrate the model.

4.5 Aggregate targets

The calibration of the model follows the methods discussed in Atkeson and Kehoe (1999) and Díaz et al. (2004). In this version of our benchmark economy we abstract from labor choice, and concentrate on the behavior of investment. Parameter values are calibrated so that selected statistics of the steady state of our economy match their counterparts in the data. Table 1 shows the values of the calibrated parameters. In our data, the share of labor income over Value Added is about 60 percent. This implies a value for $\alpha = 0.4406$. Taking α from the data implies obtaining β to match a capital-gross output ratio of about 2.66. Investment is 28.41 percent of gross output in the data, which implies a depreciation rate $\varpi = 0.0521$.

We have two other technological parameters to calibrate: the stationary value for energy intensity, $\widetilde{v}_{t+1}^\mu \equiv v_{t+1}^\mu/\Theta_t$, which determines the capital-energy ratio at the steady state, and μ, which governs the dynamic response of energy use to shocks. The reason why we need to set the steady state ratio $\widetilde{v}_{t+1}$ is because of the complementarity of capital and energy at the plant level. Our theory accounts for the dynamics of such complementarity, but we need to set its steady state level. Hence, the ratio v_{t+1}^μ/Θ_t is set so that the aggregate share of energy in our economy, in absence of shocks, is constant and equal to the mean of the considered period. Finally, we have left to calibrate

μ. As we show in Appendix E, the share of energy in gross output for the latest vintage is equal to $\frac{\alpha}{\mu}\,\Omega$, where Ω is a function of parameters. In Appendix E we show that the share of any vintage can be written as

$$\frac{\varrho_t\, e_t\,(z, v_z)}{y_t\,(z, v_z)} = \frac{\alpha}{\mu}\,\frac{\Lambda_t\,\Gamma_t\,v_t^{1-\mu}}{\Lambda_z\,\Gamma_z\,v_z^{1-\mu}}\,\Omega, \text{ for all } z \leq t. \tag{4.14}$$

Thus we can use our theory to find an appropriate value for μ consistent with the aggregate share of energy being constant and equal to its counterpart in the data. This value is $\mu = 20.9988$.

5 Quantitative experiments

In this section we show the main experiments conducted. To study the dynamics of aggregate energy use and energy efficiency in our model economy we proceed in the following way: we feed into the model the energy price and the two ISTC shocks, estimated in section 4.4, consistent with the fact that the model delivers, endogenously, the path for the two relative prices of capital (the price of structures and durable goods and the GCV relative price) observed in the US economy for the period 1990-2008. In this way we can measure the contribution of energy efficiency versus ISTC in the dynamics of all macroeconomic aggregates. We also analyze the quantitative importance of scrapping for our vintage economy.

5.1 The target data

We need to select the particular statistics that describe the dynamics of energy use and efficiency appropriately in the data to compare them with their counterparts in our model economy. In Figure 3(a), we plot the logarithm of the share of energy, $p\,E/VA$, the relative price of energy, p, and energy use, E/VA, for the US economy over the period 1960-2010.[8] The share of energy has a very high volatility, in spite of being small on average, 4.75 percent of our measure of gross output for the whole period 1960-2010, peaking 8.89 percent in 1981 and reaching a minimum of 3.18 percent in 1998.[9] Let us turn to inspect our measure of energy price, p. The first thing that we notice is that

[8] All aggregates have also been deflated using the implicit price deflator of non durable consumption goods and services.

[9] It may be thought that the evolution of this share hides significant differences in prices for the different energy sources considered. This is not the case; as pointed out by Kilian (2008), the pattern of fluctuations in the share of energy primarily reflects changes in the price of crude oil rather than shifts in energy consumption.

the price tracks very closely the evolution of the energy share. The second thing is the size of the shocks experienced in the years 1974, 1979-81, and 2003-08 that dwarf other price shocks.[10]

Let us turn to inspect the evolution of energy use, the ratio E/VA. As we can see, this ratio is falling since the early 1970s. This behavior, though, is a composite effect of changes in energy consumption, E, and value added, VA. Figure 3(c) shows that energy consumption responds belatedly to changes in energy prices but it has had a different behavior since the 1990s. In particular, it fell during the late 1970s, when value added was stagnant and has grown at a slower pace than value added since 1990. Thus, the ratio E/VA was more or less constant during the late 1980s and fell during the 1990s, in spite of the falling energy prices during that decade, and kept doing so during the 2000s when we witnessed the last upsurge in the energy price.[11]

Now we turn to inspect Figure 3(b), where we show the capital to value added ratio, K/VA, and the capital to energy ratio, K/E. Capital is measured in units of value added. Notice that the ratio of both figures, $(K/VA)/(K/E)$, is equal to energy use, E/VA. The capital to value added ratio measures capital intensity and the capital to energy ratio is our aggregate measure of energy efficiency. Notice that the capital to value added ratio fluctuated less than the capital to energy ratio. This implies that the observed changes in energy use were mostly due to changes in aggregate energy efficiency, as measured by K/E. This ratio responds with some sluggishness to energy prices. When the price increases, the capital to energy ratio falls. This was the case for all years but for the 1990s, where the ratio decreased in spite of the falling energy price. It is also interesting to note that the capital to value added ratio decreased whereas the capital to energy ratio increased during the 1990s. This suggests that capital was becoming more productive and more efficient at the same time during that decade.

5.2 The dynamics of energy use and the capital-energy ratio

Figures 4(a) and 4(b) show, respectively, the evolution of energy use and the energy share, and the evolution of our aggregate measure of efficiency: the capital to energy ratio, where capital is

[10] More than 50 percent of all energy included in our measure E is petroleum-based for the entire period 1960-2010. That is, the important source of fluctuations in our measure of the energy price is the price of oil and its importance in our price index has not changed significantly during the period considered.

[11] It may be argued that the behavior of our measure of energy use is affected by the choice of base year prices. For instance, Metcalf (2008) measures energy consumption as the ratio of the amount of BTUs yielded by various energy sources to measured GDP. The behavior of his measure of energy use is fairly similar to the evolution of our measure.

measured in units of value added in the model as well as in the data. Figure 4(a) shows that our theory accounts remarkably well for the evolution of energy use in the US throughout the period 1960-2008. This is also why the energy share mimics so well its counterpart in the data. As we can see, energy use falls in our benchmark model economy as in the data since 1990 to the early 2000s, a period in which energy prices fell below trend. Correspondingly, the capital to energy ratio increases in our model economy as in the data for the same period, as shown in Figure 4(b).

Recall that in our vintage economy capital goods are scrapped at a finite time. To quantify the importance of scrapping we simulate what we think is a worst case scenario: an economy with high intensive margin of ISTC and low energy price at the time when the capital was installed. The efficiency of this new machine will be below trend and at its lowest optimal level. We assume that the growth rate of the wage is that of balanced growth. Then we compute the time at which the plant yield negative profit at the highest possible energy price. In this way we find the shortest economic lifespan of a machine. This lifespan is 48 years. The average depreciation rate is $\delta_t(z, v_z) = 0.083$, which implies that after 48 years remains 1.56 percent of the stock of that age. This implies an utilization rate $u_t^k = 0.999$ of the aggregate stock of capital.

To assess how embodied ISTC and the energy price interact in determining the lifespan of capital we have also conducted the opposite exercise. Assume that embodied ISTC was below trend and the energy price was the highest possible at the time the unit of capital was installed. The economic lifespan of this unit of capital is 66 years and, given the average depreciation rate, the fraction of the stock of capital installed 66 years ago that remains is 0.3 percent. Thus, the utilization rate of aggregate capital is even higher.

We interpret these findings as suggesting that a fix energy requirement is not a key driver of the scrapping activity, at least at the aggregate level, and in what follows we approximate our benchmark economy with an economy in which the lifespan of machines is infinite.

5.3 The role of ISTC shocks

In order to assess the importance of ISTC shocks in our theory of investment and energy use we strip our economy from them. This alternative economy is essentially the putty-clay economy studied by Atkeson and Kehoe (1999) calibrated to reproduce the aggregate targets shown in Table 1. We should note that there is no steady state growth in the Atkeson and Kehoe (1999) economy, whereas our economy features stochastic growth. Moreover, capital is always fully utilized in their case. We compare the detrended version of our economy with theirs. In this way we compare one economy (putty-clay –PC economy hereafter) where there are energy price shocks and the relative price of investment is always one and another economy with energy price shocks and shocks to the relative price of capital services: our benchmark economy with vintage capital structure.

The simulated evolution of energy use in the putty-clay (PC) economy is shown in Figure 4(c). In the PC economy, energy use reacts to prices more than in the benchmark economy. Moreover, it rises since the mid 1980s until the energy price starts rising again in the 2000s, missing completely the change of regime observed during the 1990s. As for the capital to energy ratio, shown in Figure 4(d), two features of this ratio stand out: first, its evolution is flatter than the evolution of its counterparts in the data and in our benchmark economy [cf. Fig. 4(b)], and second, it also misses the change of regime during the 1990s.

To understand further the role of ISTC shocks we need to recall that we abstract here from labor supply decisions. Thus, after receiving a shock, both economies respond by changing the level of investment and the energy efficiency built into that investment. Figure 4(e) shows the evolution of the capital to value added ratio in both economies. As we can see, this ratio is more responsive to energy price shocks in our benchmark vintage economy. This is so because investment is more volatile in the presence of ISTC shocks. The putty-clay (PC) economy also misses the fall in this ratio observed since the mid 1980s until the 1990s, which is captured by our benchmark economy. Let us turn to inspect Figure 4(f) which compares the level of efficiency built into new capital goods in our benchmark economy (red line) and the PC economy (blue line). We are plotting here the detrended value of v_{t+1}^{-1} (multiplied by $\Theta_t^{\frac{1}{\mu}}$) with its counterpart in the PC economy. Notice that energy efficiency is also less volatile in the PC economy than in our benchmark economy. During the 1970s and early 1980s, our benchmark economy invests in more efficient machines than the PC economy. This is so because ISTC growth is only realized by investing, which rises the energy demand of the economy. If expected prices are high, the only way to reduce the future energy bill is by investing in efficient machines. On the contrary, during the 1990s, a period of high embodied ISTC growth and low energy prices, our benchmark economy invest less in efficiency than the PC economy and produces an investment boom. This is so because agents try to materialize all the benefits of transitory embodied ISTC shocks. In spite of the fall in efficiency during the 1990s, energy use in our benchmark economy falls because the accelerated ISTC embodied in new capital goods renders them more productive without rising energy consumption.

5.4 Permanent versus transitory ISTC shocks

We have distinguished between a permanent shock to the production of investment goods, Θ_t, and a transitory shock to the technical level embodied in the new capital good, Λ_t. Thus, we have specified that ISTC allows to produce not only more machines but also better machines at the same cost in units of final good. Typically, the literature on ISTC growth abstracts from such a distinction. In our case, this decomposition is important because the two shocks have different effects on the demand of energy and, therefore, in the level of efficiency built into new capital goods. In this section we would like to assess the contribution of each shock separately.

We start by shutting down the transitory shock and simulate again our economy. Basically, the permanent ISTC shock is needed to capture the trend in energy use and the capital to energy ratio observed in the data, as shown in Figure 5(c), particularly after the 1990s. Permanent shocks alone, however, cannot capture the fluctuations in the capital to energy ratio. This is mirrored by the lower volatility of efficiency of new capital goods, as shown in Figure 5(e). Now we shut the permanent shock and leave the transitory shock only. This economy cannot capture the change of regime observed in 1990s; as we can see in Figure 5(b), energy use has no trend after 1990s, whereas it has a negative trend in the data. The implication of this behavior of energy use is that the capital to energy ratio has no trend either, as shown in Figure 5(d).

Summarizing, permanent shocks are needed to capture the trends observed in energy use and the capital to energy ratio, whereas the transitory shocks are mostly needed to capture the fluctuations in the capital to energy ratio. Fluctuations in energy efficiency are affected by both permanent and transitory ISTC shocks. Figures 5(e) and 5(f), however, confirm our guess: embodied technical change along the intensive margin (the one we have assumed to be transitory) is indeed a sort of energy saving technical change. In particular, during the 1990s investment in efficiency would have been higher had embodied technical change not accelerated (Fig. 5(e)). It is interesting to note, though, that the evolution of the capital to value added ratio is very similar in both economies (when capital is measured in units of output), as shown in Figures 5(g) and 5(h). This implies that in order to disentangle permanent from transitory ISTC shocks we need further information that the one provided by the capital to value added ratio. Hence, our theory of investment and energy use gives us guidance about how to identify both ISTC shocks.

5.5 The short run price elasticity of energy use

Finally, it has been argued that the relationship between energy prices and the macroeconomy seems to have changed in the last two decades, since the response of GDP to the 2003-08 oil-price shock has been much softer than in the 1970s and 1980s (see, for instance, Kilian 2008, or Blanchard and Galí 2007). On this respect, Baumeister and Peersman (2012) find evidence of a decrease in the short run price elasticity of aggregate energy demand. This is corroborated by microeconomic evidence that suggests that the short run price elasticity of energy demand to energy prices may have changed and, in fact, decreased and that this change is due to the fact that capital has become more energy efficient over time; see Edelstein and Kilian (2007), Metcalf (2008), or Steinbuks and Neuhoff (2010).

Our theory tells us that these findings are related and key to understand the effects of the 2003-08 oil price shock. In our model economy, right after an unexpected price shock energy consumption, e_t, does not change since all capital installed is utilized in equilibrium. Value added, though, falls and, therefore, so does energy use (energy consumption per unit of value added, $e_t/\left(y_t - \varrho_t e_t\right)$). Appendix F shows that the value of the short run elasticity of energy use with respect to the price is equal to the share of energy in value added,

$$\varepsilon_{eu_t} = \frac{\varrho_t \, e_t}{y_t - \varrho_t \, e_t}. \tag{5.1}$$

Hence, according to our theory, by increasing investment in the years of high ISTC the economy was increasing the average efficiency of capital and lowering the response of energy use (and value added) to energy price shocks. This implication of our theory is shown in Figure 3(a), which depicts energy use and the energy share in the data. The energy price level in the peak years 1981 and 2008 is around 60 percent above the mean of the entire period. Yet, the energy share is significantly lower in 2008; 6.66 percent versus 8.89 in 1981. Thus, according to our theory, energy use has been less responsive to changes in energy prices during the last oil price shock because energy efficiency is much higher than in previous decades.

6 Concluding remarks

In this paper we propose a theory to study how technology shapes the response of energy demand to energy price changes. In our theory, aggregate demand of energy depends on the complementarity of capital and energy at the plant level and the state of investment specific technical change (ISTC). The complementarity is modeled as an energy requirement built into irreversible capital, whereas ISTC implies that capital of different vintages differ in productivity due to technical progress. Thus, capital is heterogenous in two dimensions: its vintage and its energy requirement. A lower energy requirement (higher efficiency) comes at the cost of less capital services.

In our model, energy prices and the nature of investment specific technical change affect the choice of energy requirement built into new capital units. If ISTC reduces the cost of producing new capital goods, higher investment rises the exposure to energy price risk, which will entice investing in energy efficient, less productive, capital. If ISTC brings higher quality in capital, higher investment becomes more productive without providing an energy burden, which reduces the incentives to invest in energy efficiency. The complementarity of capital and energy at the plant level implies that the energy share in aggregate gross output varies with the distribution of capital across vintages and efficiency levels. Moreover, we have shown that there is scrapping of capital in equilibrium. We can, however, establish conditions under which there is a representation for aggregate gross output by aggregating capital using cost production prices.

Nevertheless, the complex interaction of ISTC and energy efficiency cannot be ascertained theoretically. This is why we study the dynamic properties of our theory quantitatively. To do so, we calibrate our model economy to match selected statistics of the US economy. Then, we focus on three shocks: one governing the energy price and two other governing the extensive and intensive margins of ISTC. The identification of these shocks relies on observables: the relative price of energy and the relative price of investment goods, not quality adjusted as well as quality adjusted. One of the points that we make in this paper is that the identification of ISTC shocks in existing literature reduces the scope of factors that influence the efficiency of producing investment goods relative to consumption goods. According to our theory, however, the relative price of investment goods depends not only on the two ISTC shocks but also on the energy efficiency built into capital units. Thus, the model imposes a novel discipline to disentangle the effects of ISTC shocks from the effects of energy efficiency. This discipline can be interpreted as a theoretical foundation to the view expressed by Gordon (1996), who argued that changes in energy efficiency is one of the key determinants of the dynamics of the relative price of investment goods. Our theory also gives us a discipline for aggregating output and capital in a way that is consistent with National Accounts.

Our model with ISTC accounts for the fall of energy use per unit of output observed during the 1990s, a period in which energy prices fell below trend. This pattern of the data cannot be accounted for by previous theories of energy demand, which abstract from ISTC and assume that all technical change is neutral. According to previous theories, the fall in the energy price during the 1990s should have induced higher investment in less efficient capital and a rise in energy use per unit of output. According to our theory, the 1990s were a period of accelerated ISTC that raised quality of capital substantially. This rise in productivity allowed to lower energy efficiency of new capital goods and, at the same time, reduced energy use per unit of output at the aggregate level. Finally, scrapping of capital is not a significant source of aggregate fluctuations in our quantitative theory.

We have abstracted from the determinants of energy supply as well as from either environmental concerns or exhaustible energy. Although we have focused our analysis on annual fluctuations, we think that this theory can be used to address more longer term questions as climate change. We have also abstracted from taxes and the related issue of giving subsidies to using renewable energies. We leave these issues for further research.

Appendix

A The data

In this Appendix we document the construction of the data series we use in the empirical part of the paper. We obtain data from two sources: the Annual Energy Review (2000) and National Income and Product Accounts. The data we use can be accessed in the addresses: http://www.eia.gov/ and http://www.bea.gov. From now on we will refer to each source as AER, and NIPA, respectively. Our data set is available upon request.

A.1 Output, consumption, investment, and the capital stock

We follow the method described by Cooley and Prescott (1995) to construct broad measures of output, consumption, investment, and the capital stock. Specifically, our measure of capital includes private stock of capital, the stock of inventories, the stock of consumer durable goods and the government stock. Consequently, the measured value of GDP is augmented with the imputed flow of services from the stock of durable goods and the government stock. We subtract from each of the series of output, investment and capital the corresponding series for the energy producing sectors: oil and gas extraction, electricity and gas services, petroleum and coal production, and pipeline transportation, as our theory cannot account for the behavior of the energy-producing sectors. We have information on the three variables for the last two sectors but about the first two sectors we only have information about the net stock of capital, and we use it to impute estimates of output and investment. Gross output is the sum of value added and the final expenditure on energy. Real variables are obtained by dividing the nominal variables by the implicit price deflator of non durable consumption goods and services.

A.2 Energy price, use, and expenditures series

Our energy data covers the primary energy consumption of end-users and is obtained from the Annual Energy Review (AER, hereafter). We consider four forms of energy: coal, petroleum, natural gas and electricity. AER (Table 2.1a) gives data on total energy consumption by end users measured in British termal units (BTUs) disaggregated into the four forms of energy considered. We denote these data on energy consumption for each type of energy by Q_{it}, where the index i denotes the form of energy.

This measure Q_{it} is already net of energy consumption of the electricity sector. We subtract from total primary energy consumption of the industrial sector that of four energy sectors: oil and gas extraction, electricity and gas services, petroleum and coal production, and pipeline transportation. The BEA gives information on the net stock of Fixed Assets by industry and we assume that the amount of BTUs consumed by those four sectors, as a proportion of BTUs consumed by the industrial sector, is the same that the amount of capital in those sectors as a proportion of assets in the industrial sector.

We construct a constant-price measure of energy consumption. We choose the base year to be 2005 and define total energy use to be $E_t = \sum_i Q_{it} P_{i0}$, where P_{i0} is the price in dollars per BTUs of energy type in 2005 from AER, divided by the implicit price deflator of non durable consumption goods and services in NIPA (which is constructed as a weighted average of the two implicit price deflators). For coal, natural gas and petroleum we use the production price series (AER, Table 3.1). For electricity, we use the retail price of electricity sold by electric utilities (see AER, Table 8.10). In Table 8.10 the price for electricity is in cents per kilowatt-hour. We use AER Table A.6 to convert the price to cents per BTUs. All prices are in real terms; i.e., divided by the implicit price deflator of non durable consumption goods and services. We construct the energy price deflator as

$$p_t = \frac{\sum_i Q_{it} P_{it}}{\sum_i Q_{it} P_{i0}}. \tag{A.1}$$

Finally, energy expenditure is $p_t \cdot E_t = \sum_i Q_{it} P_{it}$.

B The quasi-social planner's problem

The efficient allocation for this economy can be found as the solution to the following planning problem:

$$\begin{aligned}
\max_{\substack{c_t, x_t(t+1,v),\\ \ell_t, k_{t+1}(t+1,v)}} \quad & E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \xi \log\left(\ell_t\right)\right) \\
\text{s. t.} \quad & c_t + \int_0^{\infty} x_t(v)\, d\, v \leq \sum_{z=-\infty}^{t} \int_0^{\infty} (1-\varpi)^{t-z} k_z(z,v) \left[y_t(z,v) - \varrho_t\, e_t(z,v)\right] d\, v, \\
& 0 \leq y_t(z,v) \leq A_t\, \kappa_t\left(z,v\right)^{\alpha} h_t\left(z,v\right)^{1-\alpha}, \\
& 0 \leq \kappa_t(z,v) \leq \Lambda_z \Gamma_z v^{1-\mu} e_t\left(z,v\right), \\
& 0 \leq e_t(z,v) \leq \Gamma_z^{-1}\, v^{\mu}, \\
& 0 \leq \ell_t \leq \hbar - \sum_{z=-\infty}^{t} \int_0^{\infty} (1-\varpi)^{t-z} k_z(z,v)\, h_t(z,v) d\, v, \\
& 0 \leq h_t(z,v) \leq \hbar, \\
& 0 \leq k_{t+1}(t+1,v) \leq \Theta_t\, x_t(v),\ t \geq 0, \\
& k_z(z,v) \text{ given}, \quad z \leq t,\ v \geq 0.
\end{aligned} \tag{B.1}$$

C Decentralization of the efficient allocation

Here we show how to decentralize the economy described in Section 2.

C.1 Market arrangements

We assume that households are the owners of the plants and, therefore, of the capital installed. There is a market for plants that opens at the end of the period, once profits have been realized. Notice, though, that capital is not traded since it is already installed in a plant and it cannot be reallocated. Since there is a one to one correspondence between plants and units of capital, the price of a plant is also equal to the price of the unit of capital installed, $p_t(z,v)$, where $p_t(z,v)$ is the price of one unit of capital of vintage z and type v at the end of period t in units of consumption good at time t. We further assume that all households start out with the same amount of shares of the plants installed. Additionally, we assume that households trade a one risk free bond which is in zero net supply.

The timing is the following: At the end of period $t-1$ any prospective plant must install one unit of capital before the energy price is known. After this decision has been made, at the beginning of period t the uncertainty is resolved: agents learn the productivity of the investment technology Θ_t and the quality of new capital goods, Λ_{t+1}. The energy price is realized. Then, they decide the amount of energy to be consumed, $e_t(z,v)$, and the number of workers hired, $h_t(z,v)$. Households consume and save. A fraction ϖ of plants die.

C.1.1 The household's problem

Plants of any vintage and type can be traded at the individual level. New investment, however, comes in new vintage—it is a technological restriction, as in the one sector model TFP grows exogenously, we cannot help to be more productive. Agents can, though, choose the type of the new capital units to be installed. The household's problem can be written in the following way:

$$
\begin{aligned}
\max \quad & E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \xi \log\left(\ell_t\right)\right) \\
\text{s. t.} \quad & c_t + \int_0^{\infty} x_t(v)\, d\,v + \sum_{z=-\infty}^{t+1} \int_0^{\infty} p_t(z,v)\, m_{t+1}(z,v)\, d\,v + b_{t+1} \le w_t\left(\hbar - \ell_t\right) + \left(1 + r_t^b\right) b_t + \\
& \int_0^{\infty} p_t(t+1,v)\, k_{t+1}(t+1,v)\, d\,v + \sum_{z=-\infty}^{t} \int_0^{\infty} \left[\left(1-\varpi\right) p_t(z,v) + \pi_t\left(z,v\right)\right] m_t(z,v)\, d\,v, \qquad \text{(C.1)} \\
& k_{t+1}(t+1,v) \le \Theta_t\, x_t(v),\ v > 0, \\
& x_t \ge 0,\ m_{t+1}(z,v) \ge 0,\ k_{t+1}(t+1,v) \ge 0,\ \text{for all } z \le t+1,\ v > 0, \\
& b_{t+1} \ge \underline{b}, \\
& m_0(z,v),\ b_0,\ \text{ and energy prices given.}
\end{aligned}
$$

The constraint $k_{t+1}(t+1,v) \le \Theta_t\, x_t(v)$ implies that the amount of new capital that agents can sell in the market cannot be higher that the amount of good needed to create them.

C.1.2 The plant's problem

$$
\begin{aligned}
\max_{\substack{y_t(z,v)\ge 0,\, h_t(z,v)\ge 0,\\ e_t(z,s)\ge 0}} \quad & \pi_t(z,v) = y_t(z,v) - w_t h_t(z,v) - \varrho_t\, e_t(z,v) \\
\text{s. t.} \quad & y_t(z,v) \le A_t\, \kappa_t\left(z,v\right)^{\alpha} h_t\left(z,v\right)^{1-\alpha}, \qquad \text{(C.2)} \\
& \kappa_t\left(z,v\right) \le \Lambda_z\, \Gamma_z\, v^{1-\mu} \min\left\{e_t\left(z,v\right), \Gamma_z^{-1}\, v^{\mu}\right\}.
\end{aligned}
$$

C.1.3 Definition of equilibrium

An equilibrium for this economy, given the sequence of energy prices, $\{\varrho_t\}_{t=0}^{\infty}$, is a sequence of prices $\left\{\{p_t(z,v)\}_{z=-\infty}^{t+1}, w_t, r_t^b\right\}_{t=0}^{\infty}$, an allocation $\left\{c_t, \ell_t, \{m_t(z,v)\}_{z=-\infty}^{t+1}, x_t(v), k_{t+1}(t+1,v), b_{t+1}\right\}$

for each consumer, and an allocation for each plant of variety (z,v), $\{y_t(z,v), h_t(z,v), \kappa_t(z,v), e_t(z,v)\}_{z=-\infty}^{t}$, $v \in \mathbf{R}_{++}$, such that:

1. $\left\{c_t, \ell_t, \{m_t(z,.)\}_{z=-\infty}^{t+1}, x_t(v), b_{t+1}\right\}$ solves the household's problem shown in (C.1) given the sequence of prices,
2. $\{y_t(z,v), h_t(z,v), e_t(z,v)\}_{z=-\infty}^{t}$, $v \in \mathbf{R}_{++}$, solves the plant's problem given the sequence of prices,
3. the relative price of the latest vintage is $p_t(t+1,v) = \Theta_t^{-1}$, for any v,
4. markets clear,
   (a) the bond is in zero net supply, $b_{t+1} = 0$,
   (b) the amount of plants of class (z,v) must be equal to the amount of capital of that class, $m_t(z,v) = k_t(z,v)$, for all $z \leq t$, $v > 0$,
   (c) the labor market clears, $\hbar - \ell_t = \sum_{z=-\infty}^{t} \int_0^\infty m_t(z,v)\, h_t(z,v)\, d\, v$,
   (d) the final good market satisfies $c_t + x_t = \sum_{z=-\infty}^{t} \int_0^\infty m_t(z,v)\, y_t(z,v)\, d\, v$,
5. and the law of motion of capital of class (z,v) is $k_t(z,v) = (1-\omega)^{t-z}\Theta_{z-1}x_{z-1}(v)$, for all $t \geq z$, $v \in I\!R_+$, for all t.

C.1.4 Some properties of equilibrium

We have shown in Section 2.5 some properties of the efficient allocation. In this economy, given the energy prices, the Welfare Theorems hold; thus, in equilibrium Propositions 1 to 2, as well as Corollary 2, hold. Thus, we keep Assumption 1. Clearly, as shown in Proposition 2, the price of a new plant, $p_t\,(t+1, v_{t+1})$, is equal to the cost of producing the unit of capital installed in that plant, which was defined as $q_t\,(t+1, v_{t+1}) = \Theta_t^{-1}$. Moreover, we know, using Proposition 2 that agents only invest in one type of capital, that for which the present value of all future profits is maximized. The price of an old plant is equal to the present value of profits that the plant will accrue in the future:

$$p_t\,(z, v_z) = E_t \sum_{i=1}^{T(z)} (1-\varpi)^{i-1} \frac{\varphi_{t+i}}{\varphi_t} \left[\alpha\, y_{t+i}\,(z, v_z) - \varrho_{t+i}\, \Gamma_z^{-1}\, v_z^{\mu}\right], \tag{C.3}$$

It is not easy to characterize this price in the presence of uncertainty. We know, however that is bounded above and below. Notice that

$$p_t\,(z, v_z) = E_t \sum_{i=1}^{T(z)} (1-\varpi)^{i-1} \frac{\varphi_{t+i}}{\varphi_t} \left[\alpha\, y_{t+i}\,(t+1, v_{t+1})\, \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}} - \frac{\Gamma_z^{-1}\, v_z^{\mu}}{\Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}}\, \varrho_{t+i}\, \Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}\right], \tag{C.4}$$

and we know that $p_t\,(z, v_z) > \underline{p}\,(z, v_z)$, where $\underline{p}\,(z, v_z)$ is defined as

$$\underline{p}_t\,(z, v_z) = E_t \sum_{i=1}^{T(t+1)} (1-\varpi)^{i-1} \frac{\varphi_{t+i}}{\varphi_t} \left[\alpha\, y_{t+i}\,(t+1, v_{t+1})\, \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}} - \frac{\Gamma_z^{-1}\, v_z^{\mu}}{\Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}}\, \varrho_{t+i}\, \Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}\right],$$

(C.5)

Using (2.12) we can write (C.5) as

$$\underline{p}_t\,(z, v_z) = \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}}\, p_t\,(t+1, v_{t+1}) + \left(\frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}} - \frac{\Gamma_z^{-1}\, v_z^{\mu}}{\Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}} \right) E_t \sum_{i=1}^{T(t+1)} (1-\varpi)^{i-1} \frac{\varphi_{t+i}}{\varphi_t}\, \varrho_{t+i}\, \Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}. \tag{C.6}$$

Since for the latest class of capital the present value of all energy expenditures is equal to the fraction α/μ of expected gross output, using (2.16) we find that

$$\underline{p}_t\,(z, v_z) = \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}}\, \Theta_t^{-1} + \left(\frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}} - \frac{\Gamma_z^{-1}\, v_z^{\mu}}{\Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}} \right) \frac{\Theta_t^{-1}}{\mu - 1}. \tag{C.7}$$

Likewise, it is easy to check that the price has an upper bound which is proportional to the cost of of unit of capital installed, as defined in Definition 1,

$$p_t\,(z, v_z) < \overline{p}_t\,(z, v_z) = E_t \sum_{i=1}^{T(t+1)} (1-\varpi)^{i-1} \frac{\varphi_{t+i}}{\varphi_t} \left[\alpha\, y_{t+i}\,(t+1, v_{t+1})\, \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}} \right]. \tag{C.8}$$

It is easy to check that

$$\overline{p}_t\,(z, v_z) = \frac{\Lambda_z\, v_z}{\Lambda_{t+1}\, v_{t+1}}\, \frac{\mu}{\mu - 1}\, \Theta_t^{-1}. \tag{C.9}$$

As a matter of fact, if the energy to capital services ratio is the same in the two classes of capital, $\frac{\Gamma_z^{-1}\, v_z^{\mu}}{\Lambda_z\, v_z} = \frac{\Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}}{\Lambda_{t+1}\, v_{t+1}}$, the lower bound collapses to $q_t\,(z, v_z)$.

D The cost of saving energy in a putty-clay model economy

D.1 Putty-clay at the micro level

Atkeson and Kehoe (1999) abstract from investment specific technological progress but retain the assumption about efficiency types and capital irreversibility. In particular, the amount of capital services, $\kappa_t\,(u)$, depends on the amount of energy used in the plant, $e_t\,(u) \geq 0$, according to the technology

$$\kappa_t\,(u) = f(u) \min \left\{ e_t\,(u)\,, \frac{1}{u} \right\}, \tag{D.1}$$

where $f(u)$ is a strictly increasing function of v, where $f'(u) \geq 0$, and $f''(u) < 0$. In this economy, the efficiency type u plays the same role that v^{-1} in our model economy. The production of one new unit of capital always takes one unit of output, which is equivalent to assuming in our framework that $\Theta_t = 1$, for all t.

The firms optimally choose $e_t(u) = u^{-1}$ and $\kappa_t(u) = f(u)/u$. By denoting $v = f(u)/u$, it is easy to show that $e_t(v)$ is an increasing and convex function of v. Thus, the social planner's problem in this case is exactly the one shown in expression (2.39). In this economy, the capital-energy ratio is solely governed by changes in capital type, v, which respond to changes in energy prices.

D.2 Putty-clay at the macro level

Here we show that a model economy where capital is putty-putty but there are investment costs at the aggregate level, as Díaz, Puch, and Guilló (2004), is observationally equivalent to a model economy with a putty-clay technology at the micro level.

D.2.1 Preferences

There is a continuum of households that seek to maximize expected discounted lifetime utility,

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \xi \log\left(\ell_t\right)\right), \ \beta \in (0,1)\,, \ \xi > 0, \tag{D.2}$$

where c_t is consumption and ℓ_t is leisure t. Each household is endowed with $\hbar$ units of time and, therefore, works $\hbar - \ell_t$ hours every period.

D.2.2 Technology

Production of the unique final good is carried out at a continuum of autonomous plants which are indexed by the amount of energy-saving capital used, v. In each plant output is produced with labor, energy and the unit of working capital installed, according to the technology

$$y_t\left(v\right) = A_t\, \kappa_t\left(v\right)^{\alpha} h_t\left(v\right)^{1-\alpha}, \tag{D.3}$$

with $0 < \alpha < 1$, where A_t is the growth factor of the disembodied technological knowledge, $\kappa_t\left(v\right)$ is the amount of services provided by the unit of working capital installed, whereas $h_t\left(v\right)$ is the amount of labor services employed in the plant. The amount of services yielded by the unit of working capital, $\kappa_t\left(v\right)$, depends on the amount of energy used in the plant, $e_t\left(v\right)$, and the amount of energy-saving capital installed, v, according to the technology

$$\kappa_t\left(v\right) = v \ \min\left\{e_t\left(v\right), \frac{\zeta}{v}\right\}. \tag{D.4}$$

Each period households save and have the possibility of transforming final good into new units of working capital or new units of energy-saving capital. Investing in energy-saving capital, though, is subject to adjustment costs, which imply that working capital cannot be transformed on a one-to-one basis into energy-saving capital, and vice versa. Households rent out energy-saving capital to plants in period $t-1$ to be used in period t. Plants can be scrapped at no cost. Finally, at the end of the period, once production has taken place, the unit of working capital installed has a positive probability of death, $\varpi \in [0,1]$, which is i.i.d. across types and plants. This death probability plays the role of physical depreciation of working capital. To simplify the exposition of the model, energy-saving capital depreciates at the same rate $\varpi \in [0,1]$.

D.2.3 Planner's problem

Notice that since plants can be scrapped at no cost, and the amount of energy-saving capital can be changed every period, all plants are ex-ante identical at all periods. Moreover, the total number of plants is always equal to the amount of working capital, k_t. Thus, the problem of a household is

$$
\begin{aligned}
\max_{\substack{c_t, x_t(v),\\ \ell, k_{t+1}(v)}} \quad & E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(c_t\right) + \varphi \log\left(\ell_t\right)\right) \\
\text{s. t.} \quad & c_t + x_t \leq \int_0^{\infty} k_t(v) \left[y_t(v) - \varrho_t \, e_t(v)\right] d\, v, \\
& 0 \leq y_t(v) \leq A_t \, \kappa_t\left(v\right)^{\alpha} h_t\left(v\right)^{1-\alpha}, \\
& 0 \leq \kappa_t(v) \leq v \, e_t\left(v\right), \\
& 0 \leq e_t(v) \leq \tfrac{\zeta}{v}, \\
& 0 \leq \ell_t \leq 1 - \int_0^{\infty} k_t(v) \, h_t(v) d\, v, \\
& 0 \leq h_t(v) \leq 1, \\
& k_{t+1} + \mathbf{v}_{t+1} - \left(1 - \varpi\right)\left(k_t + \mathbf{v}_t\right) + \psi\left(\mathbf{v}_{t+1}, \mathbf{v}_t\right) \leq x_t, \\
& k_{t+1}(v) \geq 0, \\
& \int_0^{\infty} k_{t+1}(v) \, d\, v \leq k_{t+1}, \\
& \mathbf{v}_{t+1} \geq \int_0^{\infty} v \, k_{t+1}(v) \, d\, v, \\
& k_0(v) \text{ given}, \;\; v \geq 0.
\end{aligned}
\tag{D.5}
$$

D.2.4 Properties of the efficient allocation

Proposition App. 1. *The ratio labor to working capital services is the same across all classes of working capital used:*

$$
\left(1 - \alpha\right) A_t \, \kappa_t(v)^{\alpha} h_t(v)^{-\alpha} = \frac{u_{\ell}\left(c_t, \ell_t\right)}{u_c\left(c_t, \ell_t\right)}. \tag{D.6}
$$

Now we turn to investigate which classes are allocated energy.

Proposition App. 2. *If a time t the type $v > 0$, is allocated energy, $e_t(v) > 0$, then it must be the case that $e_t(v) = \zeta \, v^{-1}$ and $\kappa_t(v) = \zeta$.*

The previous Proposition implies a rule for the utilization of capital.

Corollary App. 1. *Only installed working capital of types $v \geq \underline{v}_t$ are utilized in equilibrium, where $\underline{v}_t$ is defined as*

$$
\alpha \, A_t^{\frac{1}{\alpha}} \left(\frac{1 - \alpha}{w_t}\right)^{\frac{1-\alpha}{\alpha}} v = \varrho_t, \tag{D.7}
$$

and $w_t \equiv \frac{u_{\ell}(c_t, \ell_t)}{u_c(c_t, \ell_t)}$. The type $\underline{v}_t$ increases with ϱ_t.

Let us turn now to analyze the investment decision and the characteristics of the new plants.

Proposition App. 3. *Working capital is installed to one efficiency type $v_{t+1} > 0$, $k_{t+1}(v_{t+1}) > 0$.*

Proof. The first order condition with respect to $k_{t+1}(v)$ is

$$\Psi_t^k + v\,\Psi_t^{\mathbf{v}} = E_t \lambda_{t+1}\left[\alpha\, y_{t+1}(v) - \varrho_{t+1} e_{t+1}(v)\right] + \Psi_t^{k_0}(v), \tag{D.8}$$

where Ψ_t^k is the first order condition with respect the aggregate k_{t+1}, $\Psi_t^{\mathbf{v}}$ is the first order condition with respect to $\mathbf{v}_{t+1}$, $\Psi_t^{k_0}(v)$ is the multiplier associated to the non-negativity constraint on $k_{t+1}(v)$, and λ_{t+1} is marginal utility of consumption at time $t+1$. Using Proposition App. 2 we can write the previous expression as

$$\Psi_t^k + v\,\Psi_t^{\mathbf{v}} = E_t \lambda_{t+1}\left[\alpha\, A_{t+1}^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{w_{t+1}}\right)^{\frac{1-\alpha}{\alpha}} \zeta - \varrho_{t+1}\,\zeta\, v^{-1}\right] + \Psi_t^{k_0}(v), \tag{D.9}$$

If $k_{t+1}(v) > 0$, then $\Psi_t^{k_0}(v) = 0$. Continuity of both sides of (D.9) with respect to v imply that only one type is used in equilibrium. Since working capital can be reallocated across types, only a particular type v_{t+1} is used. □

D.2.5 Aggregation

In this economy, at any period t only one efficiency type is used at every period. Thus, all plants are alike and aggregate output is $y_t = y_t(v_t)\, k_t$; likewise happens to labor. Moreover, services of working capital are just $\kappa_t = \zeta\, k_t$. The total amount of capital is $k_t + \mathbf{v}_t = (1+v_t)\, k_t$. The amount of energy used every period is $e_t = \zeta\, k_t / v_t$. Thus, we can write the planner's problem as

$$\begin{array}{ll} \max & E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(c_t) + \xi \log(\ell_t)\right) \\ \text{s. t.} & c_t + x_t \le A_t\, \zeta^\alpha\, k_t^\alpha\, h_t^{1-\alpha} - \varrho_t e_t, \\ & c_t \ge 0,\ \ell_t \le 1 - h_t, \\ & e_{t+1} \ge \frac{\zeta\,(x_t - \psi(v_{t+1}k_{t+1}, v_t k_t))}{v_{t+1}(1+v_{t+1})}\, x_t + (1-\varpi)\frac{v_t(1+v_t)}{v_{t+1}(1+v_{t+1})}\, e_t, \\ & 0 \le k_{t+1} \le \frac{1}{1+v_{t+1}}\, x_t - \frac{\psi(v_{t+1}k_{t+1}, v_t k_t)}{1+v_{t+1}} + (1-\varpi)\frac{1+v_t}{1+v_{t+1}}\, k_t, \\ & k0,\ v_0, \text{ and energy prices given, } t \ge 0. \end{array} \tag{D.10}$$

E Calibration

Let us write the quasi-planner's problem shown in (4.8) where we abstract from the labor decision:

$$\begin{aligned}
\max \quad & E_0 \sum_{t=0}^{\infty} \beta^t \log(c_t) \\
\text{s. t.} \quad & c_t + x_t \leq A_t \left(u^k\, \Theta_{t-1}\, \Lambda_t\, v_t\, \tilde{\kappa}_t\right)^{\alpha}\, h_t^{1-\alpha} - \varrho_t\, u^e\, e_t, \\
& e_{t+1} \geq \Gamma_{t+1}^{-1}\, v_{t+1}^{\mu}\, \Theta_t\, x_t + (1-\varpi)\, e_t, \\
& 0 \leq \tilde{\kappa}_{t+1} \leq x_t + (1-\varpi)\, \tfrac{v_t\, \Lambda_t\, \Theta_{t-1}}{v_{t+1}\, \Lambda_{t+1}\, \Theta_t}\, \tilde{\kappa}_t, \\
& \tilde{\kappa}_0 \text{ given},\ x_t \geq 0.
\end{aligned} \tag{E.1}$$

$\tilde{\kappa}_t$ is the amount of capital services in units of gross output (i.e., multiplied by $q_{t-1}\kappa$). We calibrate α so that labor share in aggregate value added matches its corresponding counterpart in the data. Let us now turn to the law of motion of capital. Since capital is expressed in units of gross output, the ratio must be constant at the steady state,

$$\frac{y_{t+1}}{y_t}\, \frac{\tilde{\kappa}_{t+1}}{y_{t+1}} = \frac{x_t}{y_t} + (1-\varpi)\, \frac{v_t\, \Lambda_t\, \Theta_{t-1}}{v_{t+1}\, \Lambda_{t+1}\, \Theta_t}\, \frac{\tilde{\kappa}_t}{y_t}. \tag{E.2}$$

Matching the capital-output ratio and the investment ratio yields

$$1 - \tilde{\varpi} \equiv (1-\varpi)\, \frac{v_t\, \Lambda_t\, \Theta_{t-1}}{v_{t+1}\, \Lambda_{t+1}\, \Theta_t}, \tag{E.3}$$

where $q_t^{\kappa} = \Theta_t^{-1}\, \Lambda_{t+1}^{-1}\, v_{t+1}^{-1}$. At the steady state, the share of energy, $\varrho_t\, e_t/y_t$, must be constant, as c_t/y_t and the investment ratio. Now we can rewrite the law of motion of energy as

$$\frac{\varrho_t}{\varrho_{t+1}}\, \frac{y_{t+1}}{y_t}\, \frac{\varrho_{t+1}\, e_{t+1}}{y_{t+1}} = \left(\frac{\Gamma_{t+1}}{\varrho_t}\right)^{-1} v_{t+1}^{\mu}\, \Theta_t\, \frac{x_t}{y_t} + (1-\varpi)\, \frac{\varrho_t\, e_t}{y_t}. \tag{E.4}$$

Thus, matching the energy share determines the stationary value of $\tilde{v}_t^{\mu}$,

$$\tilde{v}_t^{\mu} = \left(\frac{\Gamma_{t+1}}{\varrho_t}\right)^{-1} v_{t+1}^{\mu}\, \Theta_t. \tag{E.5}$$

We have left obtaining μ. Unless we assume that there is no neutral progress, we cannot use the gross output growth rate to calibrate μ. For the same reason, we cannot use q_t^{κ}. We know that for any new vintage installed, energy expenditures are the share α/μ of gross output. If, at the steady state, the energy price is constant, $\varrho_t = \overline{\varrho}$, for all t, by using (2.16) it is easy to show that

$$\frac{\varrho_t\, e_t\,(t, v_t)}{y_t\,(t, v_t)} = \frac{\alpha}{\mu}\, \Omega, \text{ for all } t, \tag{E.6}$$

where Ω is equal to

$$\Omega = \frac{\sum_{i=1}^{T} \left[(1-\varpi)\, \beta\, (1+g_y)^{\frac{1}{\alpha}} \right]^{i-1}}{\sum_{i=1}^{T} \left[(1-\varpi)\, \beta\, (1+g_y) \right]^{i-1}}, \tag{E.7}$$

where T is the lifespan of vintages at the balanced growth path. Likewise,

$$\frac{\varrho_t\, e_t\,(z, v_z)}{y_t\,(z, v_z)} = \frac{\alpha}{\mu}\, \frac{\Lambda_t\, \Gamma_t\, v_t^{1-\mu}}{\Lambda_z\, \Gamma_z\, v_z^{1-\mu}}\, \Omega, \text{ for all } z \leq t. \tag{E.8}$$

The energy share on aggregate gross output is

$$\frac{\varrho_t\, e_t}{y_t} = \sum_{z=\underline{z}_t}^{t} \frac{\varrho_t\, e_t\,(z, v_z)}{y_t\,(z, v_z)}\, \frac{y_t\,(z, v_z)\, (1-\varpi)^{t-z}\, \Theta_{z-1}\, x_{z-1}}{y_t}. \tag{E.9}$$

Now, using our aggregation strategy and the fact the economy is at a steady state, we find that

$$\frac{\varrho_t\, e_t}{y_t} = \frac{\alpha}{\mu}\, \frac{\sum_{z=\underline{z}_t}^{t} \left(\frac{1-\varpi}{1+g_y} \right)^{t-z}}{\sum_{z=\underline{z}_t}^{t} \left(\frac{1-\varpi}{1+g_\kappa(\mu)} \right)^{t-z}}\, \Omega. \tag{E.10}$$

Calling α^e to the share of energy in gross output in the data,

$$\alpha^e = \frac{\alpha}{\mu}\, \frac{\sum_{z=\underline{z}_t}^{t} \left(\frac{1-\varpi}{1+g_y} \right)^{t-z}}{\sum_{z=\underline{z}_t}^{t} \left(\frac{1-\varpi}{1+g_\kappa(\mu)} \right)^{t-z}}\, \Omega. \tag{E.11}$$

This is a non-linear equation in μ, since it affects the growth rate of capital services, $g_\kappa(\mu)$. It must be that α^e is greater than α/μ, since older vintages operate with higher energy requirements that the new one. This is a key difference with Atkeson and Kehoe (1999). Notice that the calibrated value of μ, the estimated values of λ and θ (ISTC growth), jointly with the observed growth rate of gross output in the data, $g_y = 1.5$ percent, imply a growth rate of neutral progress equal to $g_a = -1.1$ percent.

F The short run elasticity of energy use

In our notation, energy use is

$$eu_t = \frac{e_t}{y_t - \varrho_t\, e_t}. \tag{F.1}$$

Differentiating both sides with respect to ϱ_t, and multiplying by ϱ_t / eu_t we find

$$\frac{\partial \, eu_t}{\partial \, \varrho_t} \frac{\varrho_t}{eu_t} = \frac{\partial \, e_t}{\partial \, \varrho_t} \frac{\varrho_t}{e_t} + s_t^e - \frac{1-\alpha}{1-s_t^e} \frac{\partial \, h_t}{\partial \, \varrho_t} \frac{\varrho_t}{h_t}. \tag{F.2}$$

s_t^e is the share of energy in value added. In our model economy energy consumption does not change after a price shock given our Assumption 1. Moreover, labor is inelastically supplied. Thus, the elasticity of energy use is

$$\varepsilon_{eu_t} = s_t^e. \tag{F.3}$$

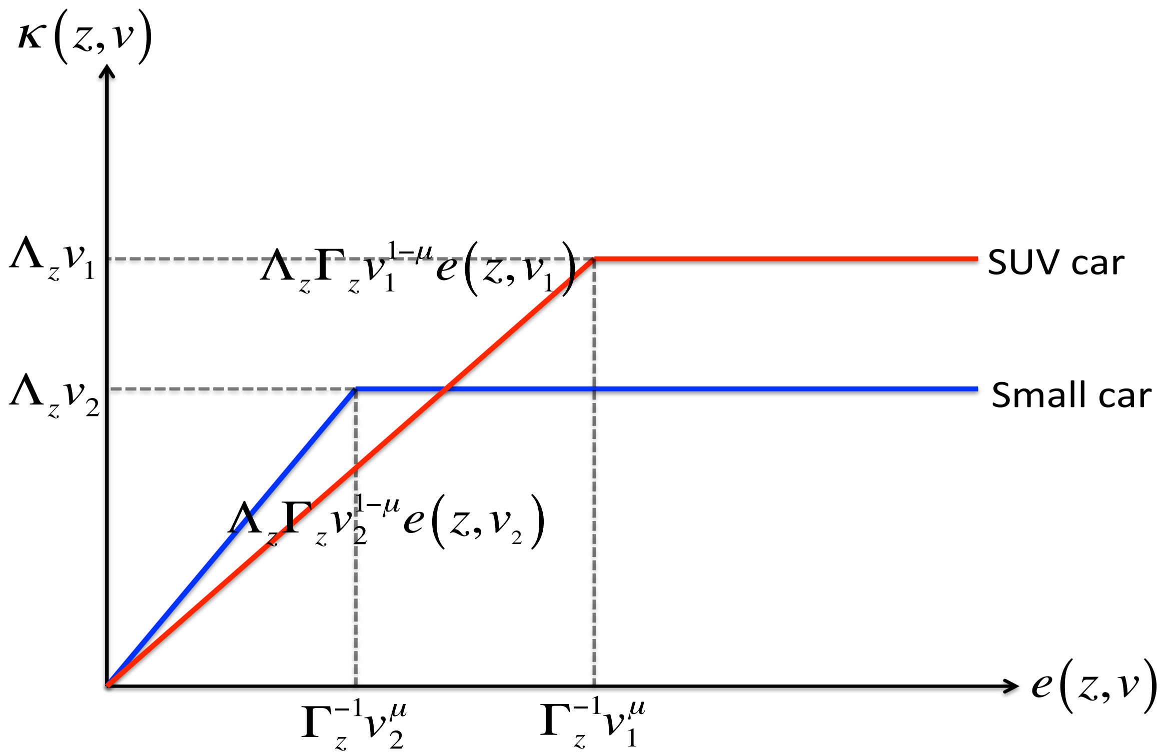
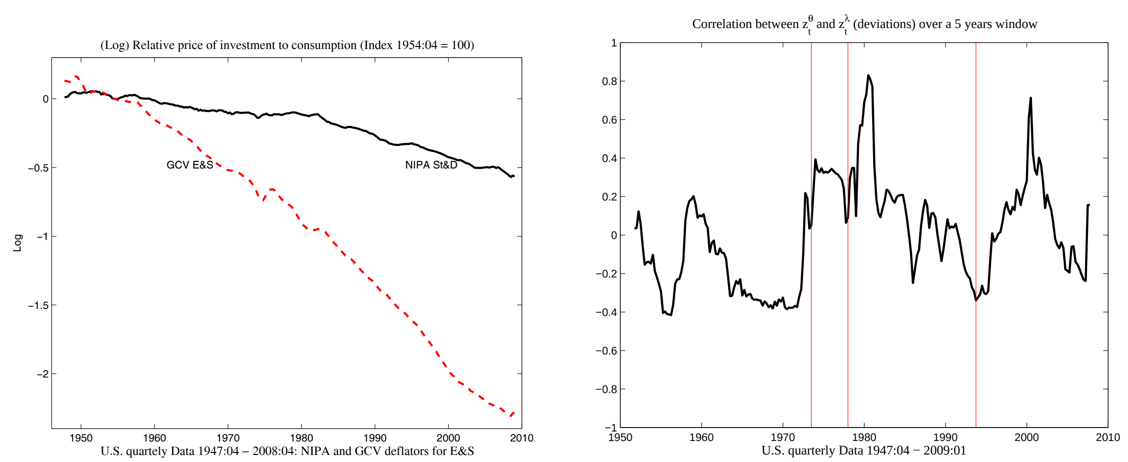


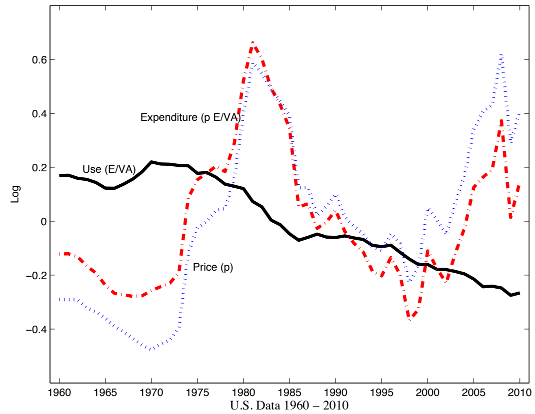
Figure 1: Energy requirement.



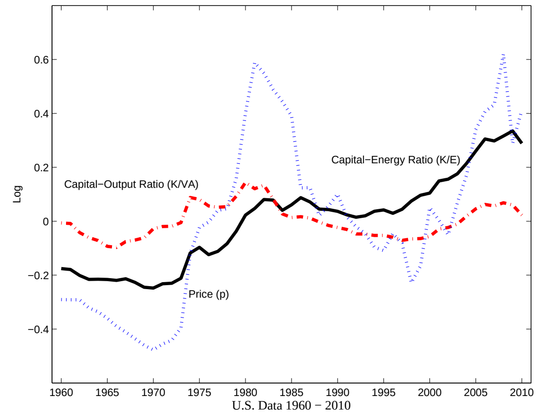
(a) Alternative measures of the relative price of investment. NIPA St&D is based on the National Income and Product Accounts deflators for structures and durables. GCV E&S uses the Gordon-Cummins-Violante deflator for equipment and software.

(b) A measurement of the joint evolution of the innovations to investment specific disturbances.

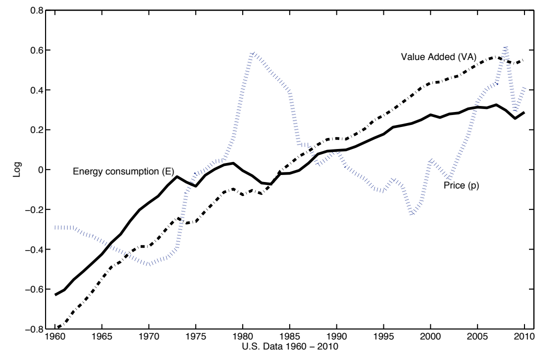
Figure 2: Investment prices and correlation of innovations.



(a) Energy use, E/VA, energy expenditure, $p\,E/VA$, and the price of energy, p.

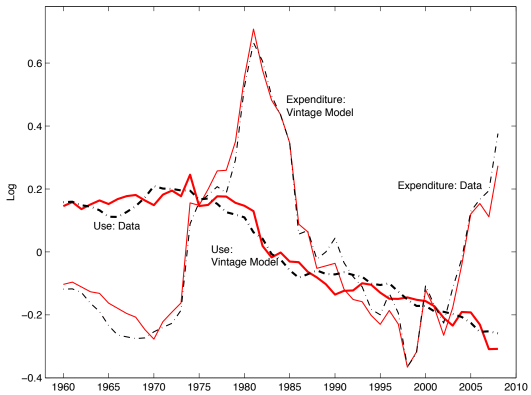


(b) Capital-energy ratio and capital-value added ratio

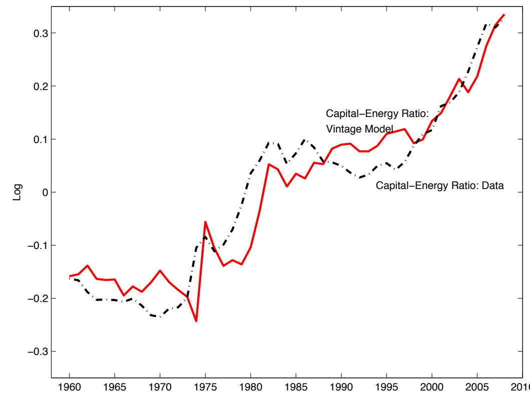


(c) Energy use, E, Value Added, VA, and the price of energy, p, for the US economy.

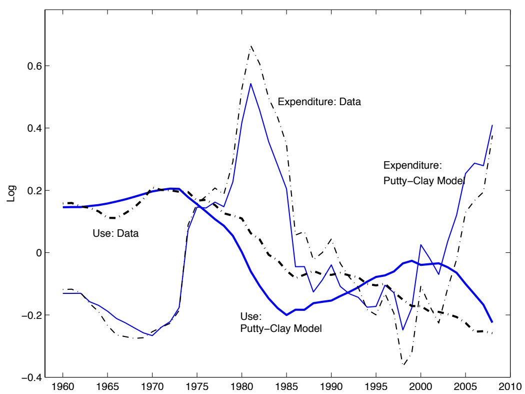
Figure 3: Energy use and energy efficiency in the US economy.



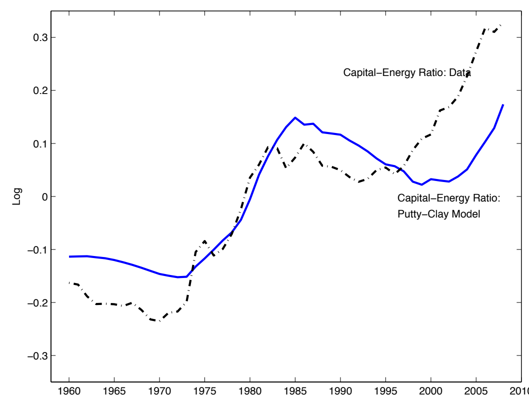
(a) Energy use and energy expenditure



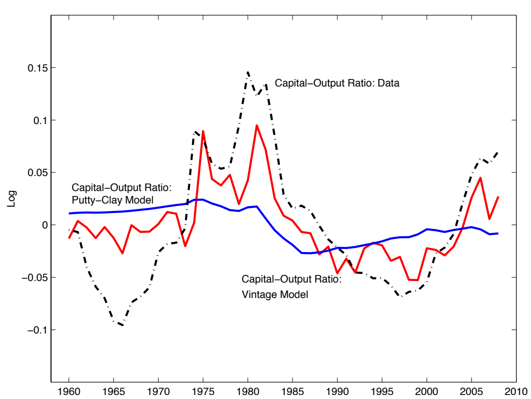
(b) Capital to energy ratio



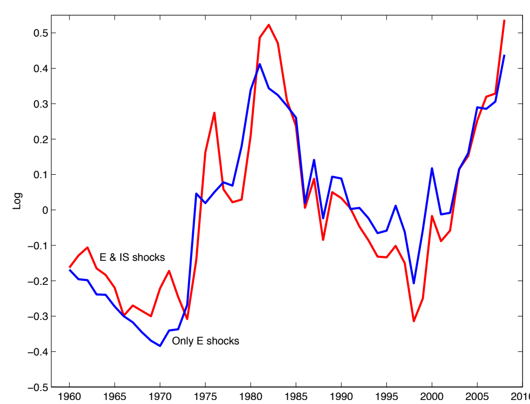
(c) Energy use and energy expenditure



(d) Capital to energy ratio

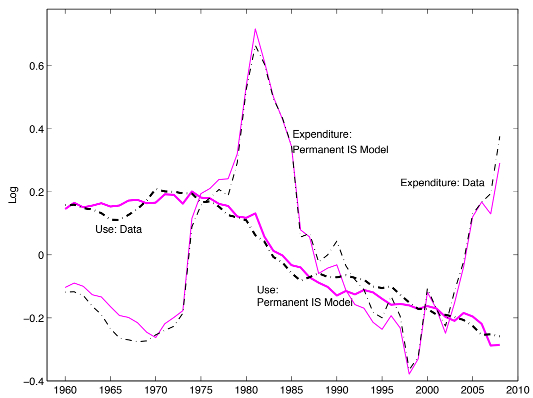


(e) Capital to value added ratio

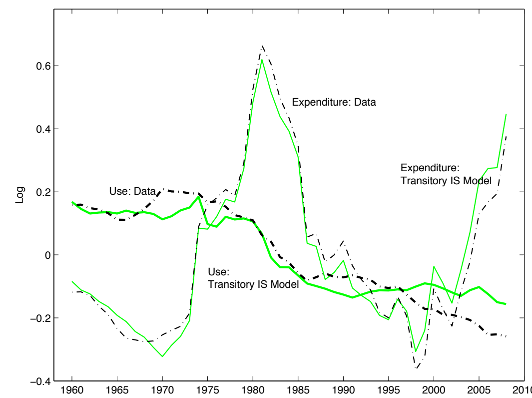


(f) Efficiency of the new capital goods, v_{t+1}^{-1}

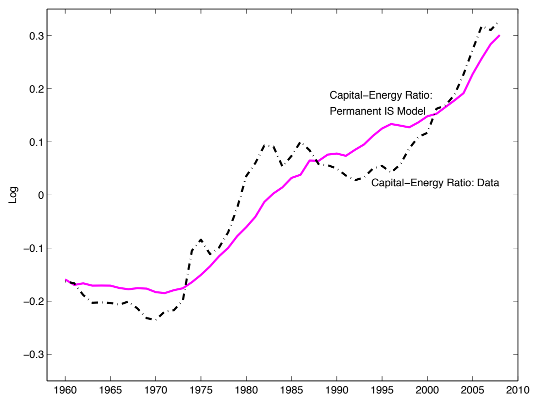
Figure 4: The benchmark economy (red line), the economy without ISTC shocks (blue line), and the data (black line).



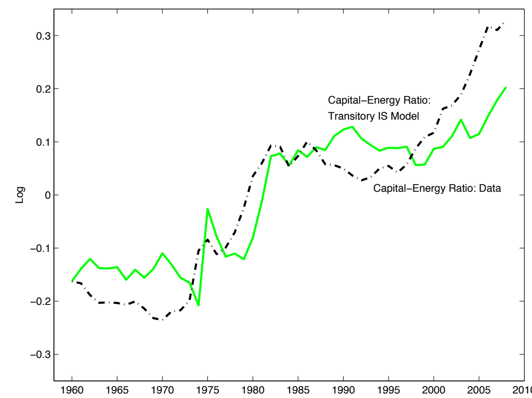
(a) Energy use and energy expenditure



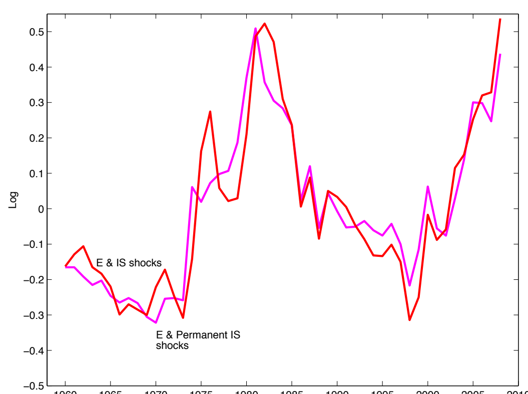
(b) Energy use and energy expenditure



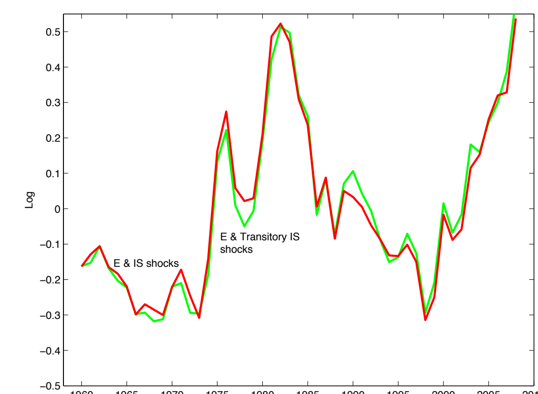
(c) Capital to energy ratio



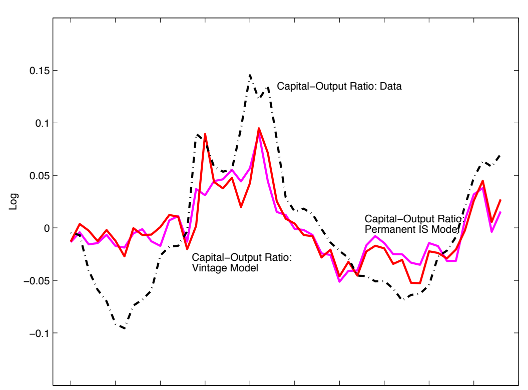
(d) Capital to energy ratio



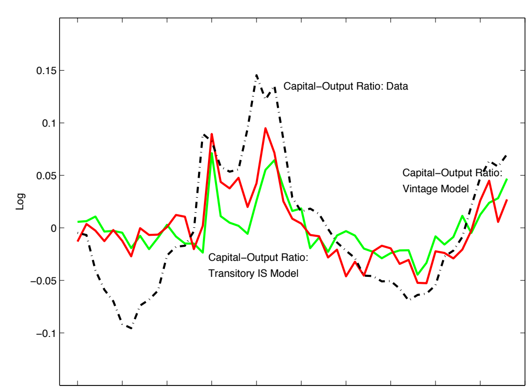
(e) Efficiency of the new capital goods, v_{t+1}^{-1}



(f) Efficiency of the new capital goods, v_{t+1}^{-1}



(g) Capital to value added ratio



(h) Capital to value added ratio

Figure 5: Permanent (pink line) versus transitory shocks (green line).

Table 1: Aggregate targets

Param.	Observation		Value
	Preferences		
β	$K/(VA+p\,E)$	$= 2.66$	0.9545
	Technology		
α	$w\,L/(VA+p\,E)$	$= 55.94\%$	0.4406
ϖ	$I/(VA+p\,E)$	$= 28.41\%$	0.0521
$\tilde{\upsilon}^{\mu}$	$p\,E/(VA+p\,E)$	$= 4.51\%$	0.0106
μ	energy share in vintage t	$= \alpha/\mu$	20.9988

Notes: Average for period 1960-2008. $u(c) = \ln c$, VA = measured GDP + services of consumer durables + services of public capital − VA of energy producing sectors.

Table 2: State space representation of embodied and disembodied technical progress. Full sample: 1947-2009, and restricted sample: 1959-2009, in annual and quarterly frequency.

	λ	θ	ρ_λ	ρ_θ	σ_λ	σ_θ
Quarterly Data	0.0073	0.0023	0.6622	0.2856	0.0063	0.0052
47:04 - 09:01	(0.0010)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0001)
Quarterly Data	0.0078	0.0028	0.7223	0.2633	0.0054	0.0049
59:04 - 09:01	(0.0006)	(0.0001)	(0.0004)	(0.0002)	(0.0001)	(0.0001)
Annual Data	0.0303	0.0092	0.0368	0.2336	0.0282	0.0139
1947 - 2009	(0.0079)	(0.0005)	(0.0137)	(0.0020)	(0.0026)	(0.0004)
Annual Data	0.0323	0.0112	0.1444	0.1463	0.0272	0.0125
1959 - 2009	(0.0119)	(0.0007)	(0.0114)	(0.0021)	(0.0053)	(0.0006)
Observations	(1) 246	(2) 198	(3)	(4) 61	(5) 49	(6)
LL	(1) -1831	(2) -1522	(3)	(4) -306	(5) -253	(6)
Prob>F	0.000	0.000		0.000	0.000	

Notes: Standard errors in parentheses. All estimates are significant at 1%. F-test for joint significance.

References

Acemoglu, D. (2002). Directed technical change. *Review of Economic Studies 9*(4), 781–809.

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012, February). The environment and directed technical change. *American Economic Review 102*(1), 131–66.

Atkeson, A. and P. J. Kehoe (1999). Models of energy use: Putty-putty versus putty-clay. *American Economic Review 89*(4), 1028–43.

Baumeister, C. and G. Peersman (2012). The role of time-varying price elasticities in accounting for volatility changes in the crude oil market. *Journal of Applied Econometrics 27*(4).

Berndt, E. R. and D. O. Wood (1975). Technology, prices and the derived demand for energy. *Review of Economics and Statistics 57*(3), 259–68.

Blanchard, O. J. and J. Galí (2007, January). The macroeconomic effects of oil price shocks: Why are the 2000s so different from the 1970s? In *International Dimensions of Monetary Policy*, NBER Chapters, pp. 373–421. National Bureau of Economic Research, Inc.

Bureau of Economic Analysis (2003). Fixed assets and consumer durable goods in the United States, 1925-97. http://www.bea.gov.

Cooley, T. F. and E. C. Prescott (1995). Economic growth and business cycles. In T. F. Cooley (Ed.), *Frontiers of Business Cycle Research*, Chapter 1, pp. 1–38. Princeton: Princeton University Press.

Cummins, J. G. and G. L. Violante (2002). Investment-Specific Technical Change in the US (1947-2000): Measurement and macroeconomic consequences. *Review of Economic Dynamics 5*(2), 243–284.

Díaz, A., L. A. Puch, and M. D. Guilló (2004). Costly capital reallocation and energy use. *Review of Economic Dynamics 7*(2), 494–518.

Edelstein, P. and L. Kilian (2007). The response of business fixed investment to changes in energy prices: A test of some hypotheses about the transmission of energy price shocks. *The B.E. Journal of Macroeconomics 7*(1), 35.

Fisher, J. D. M. (2006, June). The dynamic effects of neutral and investment-specific technology shocks. *Journal of Political Economy 114*(3), 413–451.

Gilchrist, S. and J. C. Williams (2000, October). Putty-Clay and Investment: A Business Cycle Analysis. *Journal of Political Economy 108*(5), 928–960.

Gordon, R. J. (1990). *The Measurement of Durable Goods Prices*. Chicago: University of Chicago Press: National Bureau of Economic Research Monograph Series.

Gordon, R. J. (1996). *NBER Macroeconomics Annual*, Volume 11, Chapter Can Technology Improvements Cause Productivity Slowdowns?: Comment, pp. 259–267. The University of Chicago Press.

Gort, M., J. Greenwood, and P. Rupert (1999, January). Measuring the rate of technological progress in structures. *Review of Economic Dynamics 2*(1), 207–230.

Greenwood, J., Z. Hercowitz, and P. Krusell (1997). Long-run implications of investment-specific technological change. *American Economic Review 87*(3), 342–62.

Greenwood, J., Z. Hercowitz, and P. Krusell (2000, January). The role of investment-specific technological change in the business cycle. *European Economic Review 44*(1), 91–115.

Griffin, J. M. and P. R. Gregory (1976). An intercountry translog model of energy substitution responses. *American Economic Review 66*(5), 845–57.

Hamilton, J. D. (2008). *The New Palgrave Dictionary of Economics*, Chapter Oil and the Macroeconomy. Houndsmills, U.K. and New York: Palgrave Macmillan.

Hassler, J., P. Krusell, and C. Olovsson (2012, October). Energy-saving technical change. Working Paper 18456, National Bureau of Economic Research.

Justiniano, A., G. Primiceri, and A. Tambalotti (2011). Investment shocks and the relative price of investment. *Review of Economic Dynamics 14*(1), 101–121.

Kilian, L. (2008, December). The economic effects of energy price shocks. *Journal of Economic Literature 46*(4), 871–909.

Knittel, C. R. (2011). Automobiles on steroids: Product attribute trade-offs and technological progress in the automobile sector. *American Economic Review 101*(7), 3368–99.

Metcalf, G. E. (2008). An empirical analysis of energy intensity and its determinants at the state level. *The Energy Journal 29*(3), 1–26.

Newell, R. G., A. B. Jaffe, and R. N. Stavins (1999). The induced innovation hypothesis and energy-saving technological change. *The Quarterly Journal of Economics 114*(3), 941–975.

Pindyck, R. S. (1979). Interfuel substitution and the industrial demand for energy: An international comparison. *Review of Economics and Statistics 29*(2), 173–89.

Pindyck, R. S. and J. J. Rotemberg (1983). Dynamic factor demands and the effects of energy price shocks. *American Economic Review 73*(5), 1066–79.

Popp, D. (2002). Induced innovation and energy prices. *American Economic Review 92*(1), 160–180.

Rodríguez-López, J. and J. L. Torres (2012, February). Technological sources of productivity growth In Germany, Japan, and the United States. *Macroeconomic Dynamics 16*(01), 133–150.

Sato, K. (1976). The meaning and measurement of the real value added index. *The Review of Economics and Statistics 58*(4), 434–442.

Solow, R. M. (1960). *Mathematical Methods in Social Sciences, 1959: Proceedings of the First Stanford Symposium*, Chapter Investment and technological progress, pp. 89–104. Stanford University Press.

Steinbuks, J. and K. Neuhoff (2010). Operational and investment response to energy prices in the OECD manufacturing sector. Cambridge Working Papers in Economics 1015, Faculty of Economics, University of Cambridge.