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ICT and Energy Use: Patterns of Substitutability and Complementarity in Production

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Abstract

In this project we investigate the relationship between ICT capital, energy use and economic growth. We first formulate and estimate e production model which embodies rational expectations and dynamic optimization in the presence of efficiency gains and adjustment costs. We investigate the role of price increases, though price elasticities, and how technical efficiency levels affect inputs and especially energy. The results suggest that efficiency gains from energy improvements or new energy inputs are not offset by their adjustment costs. They have though lower efficiency when compared to the other inputs. The elasticities suggest that energy is complement with ICT and non-ICT capital, skilled and unskilled labor; and a substitute to material inputs.

Keywords: ICT capital, energy, substitutability, complementarity, efficiency gains, adjustment costs.

1. Introduction

In this project we investigate the relationship between Information and Communication Technology (ICT), energy use and economic growth.

To do so, we first formulate and estimate econometrically a production model based on the work of Bernstein et al. (2004), which embodies rational expectations and dynamic optimisation in the presence of efficiency gains and adjustment costs. A model specification, such as this, provides the appropriate framework to assess the effect of energy prices on sectoral production costs and input demand, because it accounts for the fact that energy is closely tied to energy-using technology. Hence investments in new capital, e.g. in energy-saving technology, do not simply lead to efficiency gains; they also involve adjustment costs in the short run. In contrast to other modelling approaches, we do not distinguish

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between fixed and variable production factors: in our specification, whether each production factor is variable or not is tested empirically. To our knowledge, this is the first energy-related study that uses this modelling framework for energy along with both labor inputs (skilled and unskilled) as well as ICT capital.

We investigate the role of price increases in our empirically estimated model and how technical efficiency levels affect energy inputs, ICT and non-ICT capital and materials. With respect to energy inputs we estimate the efficiency gains from energy input improvements or new energy inputs and examine to what extent these are offset by adjustment costs from incorporating these inputs into the production process. Notably, these adjustment cost can be large due to the movement in renewable energy. Based on the empirical results obtained from our empirical analysis, we construct the price elasticities to see whether energy inputs behave as complements or substitutes to both types of capital (ICT and non-ICT capital) and both types of labour (skilled and unskilled). This is consistent with the NEUJOBS framework, which evaluates the impact of the socio-ecological transition on the labor marker, or employment and also ICT.

The socio-ecological transition (SET) is considered a transition between different societal energy regimes. The economies face the "historical" transition, into the fossil fuel energy regime and the "new" transition, away from fossils and towards solar and other low carbon energy sources. In an SET what is changing is not just the source of energy and technologies but many other features of society as well, due to the rice of energy prices. One of the main aspects of the NEUJOB project is to anticipate some of these changes, and in particular with respect to labor. Here, we will contribute to that purpose firstly by obtaining the technical efficiency levels from energy inputs and see if those are offset by the high costs of adjustment from incorporating new energy inputs (or improvements of old energy inputs) into the production process, and secondly by the evaluating complementarity/substitutability relations among of energy and other inputs. Specifically we are interested in this relationship with labor inputs and ICT capital which is the main purpose of the NEUJOB project. This will direct us to what will happen to the demands of these inputs when energy prices change.

With respect to energy, the empirical results suggest that efficiency gains from energy input improvements or new energy inputs are not offset by their adjustment costs. Energy inputs seem to have though the lowest technical efficiency level, when compared to the other inputs. It seems that the adjustment costs of energy changes are higher than those associated with changes in other inputs. Possibly, the improvement of energy inputs (moving towards renewable energy) is still at an early stage and their adjustments costs are still high. The total average elasticities suggest that energy is a complement with both types of capital and both types of labour as well; and a substitute to material inputs. This indicates that if energy prices increase, the demand for both types of capital and labor will decrease.

2. Literature review

In recent years, economists have observed a rapid diffusion of information technology and its related equipment, specifically computers, in world economies. Some economists suggest that this fact is a direct consequence of the dramatic decline in the price of computer related equipment, which has led to substitution of ICT equipment for other forms of capital and labour. Based on that, they suggested that this substitution has generated substantial returns for agents who undertake ICT investment and, also, had a very significant impact on economic growth.

Most of the early evidence, based on aggregate data, suggests that information technology and especially computers have no effect on productivity or growth (e.g. Berndt and Morrison, 1995; Jorgenson and Sitroh, 1999; Gordon, 2000). Most of these studies, however, are based on the aggregate production function; they assume constant returns to scale and competitive markets; and factor shares are often used as proxy for output elasticities. These limitations can impact on the estimated relationship between information technology and productivity/growth.

Research has recently moved to studies using disaggregated data at industry or sectoral level. They suggest that these data enable one to use more adequate methods of estimation suggesting that firms and industries that produce ICT assets have attracted considerable resources and benefited from extraordinary technological progress that enabled them to improve the performance of ICT goods. This is reflected in rapid total factor productivity (TFP) growth in the ICT industries (Siegel, 1997; Barua and Lee, 1997; Stiroh, 1998, 2002; Jorgenson, Stiroh and Ho, 2002; Jorgenson, 2001, 2004; Hendel, 1999; Oliner and Sichel, 2000). Most of the studies in the literature were based on the U.S. economy. With regard to non-US studies, most conclude that there is a significant positive relationship between ICT capital and economic growth (Biscourp et.al, 2002; Matteucci et.al. 2005; Basu et.al 2003; Hoon, 2003).

Some studies add new parameters in the ICT literature supporting the hypothesis that there is a significant positive relationship between ICT investment and productivity growth. For example, ICT investment is found to depend on adjustment costs, so that it takes time for productivity gains to be realised (Ahn, 1999; Amato and Amato, 2000; Bessen, 2002; Mun, 2002). Another issue highlighted is the existence of ICT spillovers that have a significant impact to an industry's productivity growth (Nadiri and Mun, 2002; Chun and Nadiri, 2002). Recently, nonlinearities have also become an issue in the ICT and growth literature. Parametric estimates assume a unique response coefficient for the variables of interest, i.e. ICT in growth regressions. Some works, however, have indicated that this assumption is not warranted. The results in this area indicate that there exists a nonlinear relationship between ICT and productivity, suggesting that the effect of ICT capital varies among units and time (Ketteni et.al. 2007, 2009).

With respect to energy, the mainstream growth models do not include energy as a factor that could constraint or enable economic growth, though macroeconomics pays a significant role to the impact of oil prices on the economic activity in the short run. Resource economists have developed models that incorporate the role of resources, including energy in the growth process, but these ideas remain isolated in the resource economics field. Ecological economists, on the other hand, often ascribe to energy the central role in economic growth (Stern, 2011; Ockwell, 2008).

Empirical studies in the literature mostly examine the causality between energy and growth using either Granger causality or cointegration tests. A general observation from these studies is that they provide conflicting results and there is no consensus neither on the existence nor the direction of causality between energy consumption and economic growth (Stern, 2011). According to Ozturk (2010) these diverse results arise due to differences in datasets, econometric techniques and country characteristics; and the causal relationship between energy consumption and economic growth could be categorised into the following four types, each having its own energy policy implications:

- No causality between energy consumption and GDP, implying that neither conservative nor expansive policies in relation to energy consumption would have any effect on economic growth.
- The unidirectional causality running from economic growth to energy consumption. In this case an increase in real GDP causes an increase in energy consumption and therefore any policy of conserving energy consumption may be implemented with little or no adverse effect on growth.
- The unidirectional causality running from energy to economic growth. This suggests that energy consumption plays an important role in economic growth both directly and indirectly in the production process and serves as a complement to labour and

capital. It implies that restrictions on the use of energy may adversely affect economic growth, while increases in energy may contribute to economic growth.

- Bidirectional causality between energy and economic growth, implying that energy consumption and economic growth affect each other (i.e. they are jointly determined).

Not knowing which of the above holds true in a particular situation it is difficult to reach a conclusion on the causal relationship between energy consumption and economic growth.

Based on the literature, Stern (2011) argues that the relationship between energy and an aggregate of output (GDP) can also be affected by:

- substitution between energy and other inputs, with the literature providing varying conclusions;
- technological change, and the rebound effect;
- shifts in the composition of the energy input (energy quality or energy mix), and also the transition of the economy to renewable energy regime; and
- shifts in the composition of output (different industries have different energy intensities).

Energy extraction and processing inevitably involves some forms of environmental disruption resulting to pollution and other negative environmental impacts, such as noise in transportation, land use in road construction etc. As nearly all human activities require energy, impacts on the environment could be seen as consequences of energy use. Disruption of nature can never be eliminated entirely (Stern, 1993, 1994, 2000, 2010 2003). However, not all impacts of energy use are equally harmful to the environment. A shift from lower to higher quality energy sources not only reduces the total energy required to produce a unit of GDP but can also reduce the environmental impact of the remaining energy use (Kaufmann, 1992, 1994; Stern, 2003; Stern and Cleveland, 2004).

The promotion of renewable energy has become an important strategy and a new topic in the literature. Studies suggest that investment in renewable energy technologies can result in an increase in GDP (Chien and Hu, 2008; Nakicenovic and Swart, 2000). This is due to the increase in macroeconomic efficiency through business expansion and increased employment opportunities as a result of developing renewable energy industries (Domac et.al. 2005). At the same time, however, it has been suggested that renewable energy can be detrimental to economic growth (Chiou-Wei et.al. 2009; Yang et.al. 2002).

There is clearly scope for further research to clarify the prospects of decoupling energy use and economic growth; and for understanding the role of energy on growth, especially through empirical investigation. This can be done by building on the important insights which are provided by Berndt and Wood (1987) and Berndt (1978, 1990) on the special relationship between energy and capital inputs and indicate that indirect impacts involving energy-capital interactions could change measures of multifactor productivity. Their argument is that a model that takes into account indirect effects permits energy price increases to have a much larger impact on productivity than that implied by considering only the energy cost shares, because energy price increases spill over to real capital use.

In analysing the economic effects of energy price changes, it should be kept in mind that the impact of energy on productivity and economic growth has always been a controversial subject. Some studies conclude that an increase in the price of electricity stimulates technical change, while others find that increases in the relative price of energy result in reduced productivity growth (Berndt and Hesse 1986; Berndt et.al. 1993). As regards the substitutability between energy and other factors of production, most authors find that energy and capital are complements – at least in the short run – and therefore increases in energy prices would result in lower growth (Apostolakis 1990; Berndt and Wood, 1979 Frondel and Schmidt 2002; Koetse et al. 2008). Morrison (1992, 1993) argues that the true impact of energy price changes is difficult to identify without fully modelling the production decisions and performance of firms in an appropriate framework capturing the full impact of energy prices.

The effect of technological progress on energy efficiency is also important in this respect. Judson et al. (1999) estimated time effects that show rising energy consumption by households over time but flat to declining effects in industry and construction. This suggests that technical innovations tend to encourage more energy-using appliances in households and energy-saving techniques in industry. Technology may also affect total factor productivity (TFP). For example, Jorgenson (1984) found that technical change was biased and tending towards energy-using, thereby, lowering energy prices and accelerating TFP growth; and vice versa.

Summarising the findings of empirical research on the existence and direction of causality between energy use and economic growth, Stern (2011) notes that the relationship between energy use and aggregate GDP is not simple to identify as it can be affected by other factors such as the substitution between energy and other inputs, technological change, shifts in the composition of energy inputs, shifts in the composition of output as well as environmental implications from the production and use of energy.

In this paper we first formulate and estimate econometrically a production model based on the work of Bernstein et al. (2004), which embodies rational expectations and dynamic optimisation in the presence of efficiency gains and adjustment costs. As will be explained in Section III, such a model specification provides the appropriate framework to assess the effect of energy prices on sectoral production costs and input demand, because it accounts for the fact that energy is closely tied to energy-using technology. Hence investments in new capital, e.g. in energy-saving technology, do not simply lead to efficiency gains; they also involve adjustment costs in the short run. In contrast to other modelling approaches, we do not distinguish between fixed and variable production factors: in our specification, whether each production factor is variable or not is tested empirically. To our knowledge, this is the first energy-related study that uses this modelling framework and especially, along with the use of energy input, as well as with respect to skilled, unskilled labor and ICT capital.

We investigate the role of price increases in our empirically estimated model and how technical efficiency levels affect energy inputs, ICT and non-ICT capital and materials. With respect to energy inputs we estimate the efficiency gains from energy input improvements or new energy inputs and examine to what extent these are offset by adjustment costs from incorporating these inputs into the production process. Notably, these adjustment cost can be large due to the movement in renewable energy. This is considered an indication on how the socio-ecological transition (SET) will affect the production process of an economy. This energy efficiency parameter will show (when the gains from factor improvement or new energy inputs and costs of adjustment are taken into account) how energy will affect production. If the adjustment costs from energy are larger than the gains then there will be a negative effect from energy.

Based on the empirical results obtained from our empirical analysis, we construct the price elasticities (total, per country and by industry) to see whether energy inputs behave as complements or substitutes to both types of capital (ICT and non-ICT capital) and both types of labour (skilled and unskilled). This will indicate how a change in the price of energy will affect the demands for labor (both skilled and unskilled), capital (ICT and non-ICT) and materials. The impact of SET and energy on labor specifically is one of the main purposes of NEUJOBS.

The next section outlines the methodology; section IV describes the data and presents the empirical results; and section V summarises and concludes the paper.

3. Methodology

The quantification of substitutability and complementarity between energy, employment, and other inputs of production for European industries allows answering a range of important questions related to the impact of the socio-ecological transition on employment, output, and productivity growth. In particular, the measurement of the patterns of substitutability/complementarity between energy inputs and different types of labour inputs, helps towards the better understanding of the labour market dynamics (intertemporal demand for low/middle/ high skilled labour) as the various industries of the EU economy move towards energy savings and a greater use of greener energy inputs. While, the measurement of the patterns of substitutability/complementarity between energy inputs and new technologies, like Information and Communications Technology (ICT), allows a better understanding of the effects of these new technologies on energy use and vice-versa.

In order to examine how changes in prices and inputs affect investment behaviour, employment, and energy use it is essential to employ a dynamic model. The assumption of instantaneous adjustment of all inputs to price changes may not be very useful, for instance, under energy price shocks. When energy price shocks occur, utilisation rates of the various surviving vintages of capital (as well as other inputs) adapt, which also affects the flow of services per unit of capital. If, for example, energy and capital are at least short run complements, then increased energy prices will cause the marginal product of capital -- and thus capital utilisation -- to decline. Not only would this cause efficiency to be suppressed, it would also cause errors in standard measures of technical change. This in turn would cause diminished technical change through reduced incentives to invest in new equipment that embodies new technology. Thus, the impact of energy price changes is difficult to identify without an appropriate modelling framework of a firm's production decisions and performance.

Following Bernstein et al. (2004), a dynamic production model is specified. This framework is sufficiently general and hence enables to capture the effect of input prices on the demands of all inputs under consideration (therefore capturing own and cross price effects), and to allow efficiency gains in production to arise when new inputs generate an improvement in technical efficiency that is not fully offset by adjustment cost. This is the first time that the use of this framework includes energy along with both types of labor (skilled and unskilled), as well as ICT capital.

This framework forms the basis for the estimation model. To begin, consider a production function written as:

$$Y_t = F[(v_{1t-1} + h_1(v_{1t} - v_{1t-1}), \ldots, v_{nt-1} + h_n(v_{nt} - v_{nt-1}), t] \tag{1}$$

where y_t is output quantity in period t, F is the production function, v_{it} is the ith input quantity in period t, and t also represents the exogenous disembodied technology index.

Parameters h_i provide for changes in technical efficiency levels related to factor additions. These parameters reflect the variations in "net" efficiency by capturing the gains from factor improvements, and the losses associated with adjustment costs. This is referred as net efficiency since it includes not only the gains from new factor improvements but also the costs. The value of these parameter are always positive ($h_i > 0$, i = 1,2, …, n). If h_i =1 the marginal product of net additions of input i in the current period is the same as that of existing units of the input, and the standard production function emerges; in this case increased technical efficiency of net additions is just offset by costs of adjustment. If h_i >1, the marginal product of net additions of input i in the current period exceeds that of existing units of the input. Accordingly, the benefits from factor improvements dominate adjustment costs incurred through incorporating new inputs into the production process. Finally, when 0< h_i <1, the marginal product of net additions of input i in the current period is lower than that of existing units of the input. Adjustment costs dominate the benefits associated with factor improvements, and as a result factor additions are less productive than existing inputs.

Factor accumulation is presented by:

$$v_{it} = x_{it} + (1 - \delta_i)v_{it-1} \tag{2}$$

where x_{it} is the addition to the ith input quantity in period t, and $0 \leq \delta i \leq 1$ is the ith input depreciation rate.

Input demands are determined from minimising the expected present value of acquisition and hiring costs. The expected value is given by the following expression:

$$\sum_{s=0}^{\infty} \sum_{i=1}^{n} a(t, t+s) q_{it+s}^{e} x_{it+s} \tag{3}$$

where q_{it+s}^{e} is the expectation in the current period t of the ith factor acquisition or hiring price in period $t+s$ and $a(t, t+s)$ is the discount factor.

Let $p_{it+s}^{e} = q_{t+s}^{e} - aq_{it+s+1}^{e}(1-\delta_i)$ be the ith factor price in period t, but expected in period $t+s$, and $a = a(t, t+s+1)/a(t, t+s)$ is the constant discount factor.

Bernstein et al (2004) show that if the expected value (defined by eq. (3)) is minimised subject to the production function and the factor accumulation equations, this problem is equivalent to the following one defined by the cost function:

$$C(w_{1t,}, \dots, w_{nt}, y_t, t) = \left\{ \min_{z_t} \sum_{i=1}^{n} w_{it} z_{it} : f(z_{1t}, \dots, z_{nt}, t) \gg y_t \right\} \tag{4}$$

where $w_{it} = h_i^{-1}\{p_{it} + \sum_{s=1}^{\infty} p_{it+s}^{e}[(a(1-h_i^{-1})]^s\}$ is the ith user cost in period t, and $z_{it} = h_i[v_{it} - (1-h_i^{-1})v_{it-1}]$ is the efficiency-adjusted ith input quantity. Note that because of the efficiency parameter h_i the user cost is more general than the traditional factor price. Producers take into account the effect of the efficiency change in current and all future efficiency adjusted marginal products of the inputs. To see this, assume that there is no efficiency change and set the efficiency parameters to unity. With $h_i = 1$ then $w_{it} = p_{it} = q_{it} - aq_{it+1}^{e}(1-\delta_i)$ which is the traditional factor price.

Using Shepard's Lemma it is possible to retrieve the efficiency-adjusted factor demands according to:

$$z_{it} = \frac{\partial C}{\partial w_i}, i = 1, \dots, n \tag{5}$$

The efficiency-adjusted factor demands, however, are not observable because the technical efficiency parameters are unknown. Using the definition of the efficiency-adjusted quantity, $z_{it} = h_i(v_{it} - (1-h_i^{-1})v_{it-1})$, the observable factor demands v_{it} can be obtained by

$$v_{it} = h_i^{-1}\frac{\partial C}{\partial w_{it}} + (1-h_i^{-1})v_{it-1\,,} i = 1, \dots, n \tag{6}$$

This set of equations forms the basis for the estimation model. They depend on user costs (and thereby depreciation and technical efficiency parameters, expected acquisition and hiring prices), output quantity, and technology indicator. Therefore, estimation of the above method requires the specification of two elements: the cost function and the price expectation-generating process for the acquisition and hiring prices.

The cost function is assumed to be the symmetric generalised McFadden functional form introduced by Diewert and Wales (1988). This functional form is attractive because it is flexible and retains its flexibility even under the imposition of concavity with respect to user costs,

$$c_t = \left(\sum_{i=1}^{n} \beta_i w_{it} + \frac{0.5 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} w_{it} w_{jt}}{B(w)} + \sum_{i=1}^{n} \beta_{it} w_{it} t + a_{tt} B(w) t^2 \right) y_t$$

$$+a_t B(w) t + \sum_{i=1}^{n} a_i \, w_{it} + a_{yy} B(w) y_t^2 \tag{7}$$

where $B(w) = \sum_{i=1}^{n} b_i w_{it}$ and the parameters are denoted by the $\alpha's$ and $\beta's$. The $n \times n$ matrix formed by parameters β_{ij} is symmetric, and must be negative semidefinite so that the function is concave in user costs. The $bi, i = 1, \ldots, n$ are nonnegative constants that are not all zero for some reference time period τ. For the reference time period, the cost function is homogenous of degree one in user costs if $\sum_{i=1}^{n} \beta_{ij} w_{i\tau} = 0$, and $\sum_{i=1}^{n} b_i w_{i\tau} \neq 0$. The expression $B(w) = \sum_{i=1}^{n} b_i w_{it}$ is an index of input prices, and the constants $bi, i = 1, \ldots, n$, are set equal to the input cost shares in the reference time period.

Based on the specified cost function (7), and dividing the observable factor demands (6) by output quantity, ith factor demand per unit of output becomes:

$$\frac{v_i}{y_t} = h_i^{-1} \left\{ \beta_i + \frac{\sum_{j=1}^{n} \beta_{ij} w_{jt}}{\sum_{i=1}^{n} b_i w_{it}} - \frac{.5 b_i \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} w_{it} w_{jt}}{\left(\sum_{i=1}^{n} b_i w_{it}\right)^2} + \frac{a_i}{y_t} + \frac{b_i a_t t}{y_t} + b_i a_{tt} t^2 \right.$$

$$\left. + \beta_{it} t + b_i a_{yy} y_t \right\} + \left(1 - h_i^{-1}\right) \frac{v_{it-1}}{y_t}, i = 1, \ldots, n \tag{8}$$

The next requirement for estimation involves the expectation generating processes for acquisition and hiring prices. It is assumed that price expectations follow a first order autoregressive process:

$$q_{it+1}^{e} = \varphi_i + \theta_i q_{it} + e_{it}, i = 1, \ldots, n \tag{9}$$

where q_{it+1}^{e} denotes $E_t(q_{it+1})$ and φ_i, θ_i are parameters that are known to the processors, but are unknown to the analyst and therefore must be measured in the estimation stage. The expected realised error is zero.

Equation (9) implies, in the current period t, that the ith expected acquisition or hiring price in period $t + s$ is,

$$q^e_{it+s} = \frac{\varphi_i(1-\theta_i^s)}{(1-\theta_i)} + \theta_i^s q_{it} \quad i = 1, \dots n \tag{10}$$

Equation set (10) shows the price expectations terms to be used in the user cost formulas. Substituting (10) into the user cost formula, expanding the geometric progression, and collecting terms, the user costs become[1]:

$$w_{it} = h_i^{-1}\left[q_{it}\frac{1-ad_i\theta_i}{1-a\mu_i\theta_i} + \frac{\varphi_i}{1-\theta_i}\left(\frac{1-ad_i}{1-a\mu_i} - \frac{1-ad_i\theta_i}{1-a\mu_i\theta_i}\right)\right], i = 1, \dots, n \tag{11}$$

With the cost function and price expectations processes specified, the estimation model becomes (8) and (9) - with (11) defining the user costs. We append errors to equation set (8), assuming these to be identically, and independently distributed over time with zero expected value[2]. This set of equations is estimated and the results are presented in the following section.

4. Empirical analysis

4.1 Data

The data used for the estimation of the model described in the previous section are drawn from the EU KLEMS database financed by the European Commission. For our analysis we are using countries for which data for energy are available. These include Austria, Denmark, Belgium, Spain, Finland, France, Germany, Italy, Netherlands, Sweden, UK and the US.

The variables used are:

- gross output at current and constant prices,
- intermediate inputs at current and constant prices,
- intermediate energy inputs are current and constant prices,

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[1] Recall that the user cost formula is given by $w_{it} = h_i^{-1}\{p_{it} + \sum_{s=1}^{\infty} p^e_{it+s}[(a(1-h_i^{-1})]^s\}$and $p^e_{it+s} = q^e_{t+s} - aq^e_{it+s+1}(1-\delta_i)$.

[2] See Nadiri and Prucha (1998) for a justification of additive errors in the factor demand equations.

- intermediate material inputs at current and constant prices,
- number of employees and persons engaged,
- total hours worked,
- labour compensation, ICT capital compensation,
- non-ICT capital compensation,
- ICT and Non-ICT capital services at current and constant prices,
- high skilled labour compensation,
- medium skilled labour compensation,
- low skilled labour compensation, and
- hours worked by high, medium and low skilled person.

All series are in constant 1995 prices. Since one of the main interests of our analysis is the use of energy, energy inputs based on EU KLEMS are defined as all energy mining products, oil refining products, and electricity and gas products. ICT capital includes hardware, software and communication equipment.

The definitions of high, medium and low skilled labour are consistent over time for each country, but might differ across countries. The high-medium-low skill split is too restrictive, given the differences in educational systems throughout Europe. The EU KLEMS database assumes educational comparability only at the bachelor degree level, but not at other levels. Consequently, care should be taken in comparing shares of educational attainment across countries. What one can do is aggregate the two types (low and medium skilled) into one type of labour, in order to be consistent across countries; and, therefore, have two types of labour: high skilled and medium-low skilled.

For most of the countries of our analysis, high skilled labour are basically employees with tertiary education and higher university degree holders; medium skilled labour includes employees with secondary and further education; and low skilled labour are employees is primary and low education.

The industries are:

1. Agriculture, Hunting, Forestry and Fishing
2. Mining and Quarrying
3. Total Manufacturing
4. Electricity, Gas and Water Supply
5. Construction

6. Wholesale and Retail Trade
7. Hotels and Restaurants
8. Transport, Storage and Communication
9. Finance, Insurance, Real Estate and Business Services
10. Community Social and Personal Services

4.2 Results

The equation sets presented in Section II are jointly estimated by the Nonlinear Seemingly Unrelated Regression Estimator and the parameter estimates obtained are reported in Table 1, along with appropriate diagnostic tests (see Bernstein et al. 2004).

The method SUR was chosen due to the fact that it is a generalization of a linear (or nonlinear) regression model that consists of several regression equations, each having its own dependent variable and potentially different sets of exogenous explanatory variables, which is the case here. The model was proposed by Arnold Zellner in 1962. In this model, each equation is a valid linear/nonlinear regression on its own and can be estimated separately, which is why the system is called seemingly unrelated, although authors suggests that this term is not very valid since the error terms are assumed to be correlated across equations. The model can be estimated equation by equation using standard OLS. Such estimates even though they appear consistent, they are not as efficient as the SUR method. This method can be further generalized into a model where explanatory variables are allowed to be the endogenous variables as well.

There are six factors of production (skilled labour, unskilled labour, non-ICT capital, ICT capital, materials and energy); thus, the estimated model is a system of twelve equations – six input demand equations and six equations capturing price expectations. Concavity has been imposed using the Wiley, Schmidt and Bramble technique. Dummies are also included for each industry and country in all equations.

A chi-square test has been performed showing that the dummy variables are jointly significant and should be included in the system estimated. In addition the constant terms (φ_i) of the price expectation equations have been tested and found to be not jointly significant; thus, they are set equal to zero. The hypotheses of first and second order serial correlation, white heteroskedasticity and ARCH are all rejected. Constant returns to scale seem to exist in our data and also the trend appears to be significant.

TABLE 1

Parameter estimates

Parameter	Estimate	St. error	Parameter	Estimate	St. error
β_{UU}	-0.127	0.098	β_{UT}	-0.019	0.006
β_{UK}	0.046	0.031	β_{KT}	-0.012	0.039
β_{US}	0.055	0.041	β_{ST}	0.008	0.007
β_{UI}	-0.111	0.131	β_{ET}	-0.009	0.027
β_{UE}	0.027	0.064	β_{MT}	0.002	0.005
β_{KK}	-0.089	0.181	β_{IT}	-0.038	0.095
β_{KS}	-0.024	0.017	β_{M}	0.375	0.013
β_{KI}	0.063	0.008	β_{U}	0.650	0.104
β_{KE}	-0.066	0.065	β_{K}	0.104	0.035
β_{EE}	-0.108	0.014	h_E^{-1}	0.293	0.0038
β_{EI}	-0.064	0.013	h_I^{-1}	0.016	0.052
β_{ES}	0.043	0.011	h_K^{-1}	0.083	0.003
β_{SS}	-0.038	0.039	h_M^{-1}	0.233	0.011
β_{IS}	-0.029	0.030	θ_I	0.941	0.028
β_{II}	-0.057	0.031	θ_E	0.165	0.019
β_{S}	-0.038	0.025	θ_M	0.279	0.018
β_{I}	-1.004	0.045	θ_U	0.239	0.017
β_{E}	0.066	0.034	θ_K	0.944	0.005
			h_S^{-1}	0.214	0.022
			h_U^{-1}	0.246	0.058

Equation	St. Error	R^2
Unskilled Labor	0.171	0.685
Skilled Labor	0.043	0.759
Non-ICT Capital	0.012	0.994
ICT capital	0.066	0.949
Energy	0.020	0.964
Materials	0.048	0.907
Log of LF	34745.1	

All the efficiency parameters were tested against the null hypothesis that their true value is unity, i.e. $h_i = 1$ (see Table 2). When this hypothesis cannot be rejected, no efficiency gains can be associated with the use of the ith input. In contrast, rejection of the null hypothesis is taken to indicate that efficiency gains from the use of the input in question do exist. Moreover, as the case of $h_i = 1$ implies that efficiency does not change; the rate of efficiency growth for the ith input can be expressed as $h_i - 1$.

The estimates of the efficiency parameters suggest that technical efficiency levels increase with factor additions. Significant adjustment costs would occur if efficiency parameters were below 1, implying negative rates of efficiency growth. These rates, for our data, are estimated to be 52.5% for ICT capital, 11% for non-ICT capital, 2.4% for energy inputs, 3.7% for skilled labor, 3% for unskilled and 3.3% for materials.

TABLE 2

Hypothesis tests

	Test Statistic	$X^2_{0.05}$
1st order serial correlation	LM=12.5	124.34
2nd order s. correlation	LM=24	255
Heteroskedasticity-ARCH(2)	LM=30	31
Heteroskedasticity-white	LM=13	31
Constant Returns to scale	LR=0.3	14.07
No technical change	LR=190	14.07

These estimation results indicate that technical efficiency levels rise with new ICT inputs used in production. From the estimation we observe that ICT capital has the largest rate of efficiency growth among all inputs. Therefore, the efficiency gains from ICT input improvements or new ICT inputs are not offset by reductions in efficiency arising from their adjustment costs. The large efficiency effect of ICT relative to other inputs implies that every year the contribution of this input in production increases not only because of net editions, but also because those net additions have a higher marginal product than ICT inputs already in use.

Additionally, technical efficiency levels rise with new non-ICT capital, new skilled and unskilled labor and new material inputs. Similarly, energy inputs contribute to an increasing technical efficiency level. This suggests that efficiency gains from energy input improvements or new energy inputs are not offset by their adjustment costs. Energy inputs seem to have the lowest technical efficiency level, when compared to the other inputs. This can be taken to imply that the adjustment cost of the energy inputs is relatively higher. The improvement of energy inputs (moving towards renewable energy) is at an early stage and the costs are still high. It is encouraging though that efficiency gains do exist and they may rise in the future. So the SET may lead to high efficiency gains in production.

Table 3 reports the short-run own and cross price elasticities of input demand, i.e. the percentage change in demand for the ith input in response to a change in the price of the jth input. Note that a positive elasticity implies that the two inputs are substitutes, while a negative one points to a complementary relationship. In our model these elasticities are given by:

$$e_{ij} = \frac{\partial v_i}{\partial w_j}\frac{w_j}{v_i} = h_i^{-1}\left\{\frac{\partial Z_i}{\partial w_j}\frac{w_j}{v_i}\right\}$$

As expected, the own price effect of each input is negative. Therefore, each input price affects its own demand negatively. The total average elasticities shown in Table 2 suggest that energy is a complement to both ICT and non-ICT capital and both skilled and unskilled labour. It behaves, however, as a substitute to material inputs. The same results hold for all countries and industries. Therefore an increase in the price of energy will negatively affect the demands for skilled and unskilled labor, as well as the demands for ICT and non-ICT capital. It will have a positive effect on the demand for material inputs. This result is an indication of how the SET will impact the labor of an economy.

TABLE 3

Elasticities (average over the sample)

	Quantity					
Price	Unskilled	Non-ICT	Materials	Skilled	ICT	Energy
Unskilled	-0.0001	0.0016	0.0013	-0.0009	0.0071	-0.0045
Non-ICT	0.0001	-0.0029	0.0024	-0.0021	-0.0175	-0.0080
Materials	0.0004	0.0119	-0.0113	0.0150	0.0674	0.0420
Skilled	-0.0001	-0.0028	0.0034	-0.0078	-0.0254	-0.0137
ICT	0.0002	-0.0077	0.0066	-0.0125	-0.3567	-0.0291
Energy	-0.0001	-0.0033	0.0033	-0.0045	-0.0255	-0.0168

As regards ICT and non-ICT capital, there seem to be a complementary relationship between them; and between ICT capital and skilled labour. In contrast, ICT capital is a substitute of unskilled labour and materials. Non-ICT capital also is a complement to skilled labour and a substitute of unskilled labour and materials. Material inputs appear to be a substitute for all inputs. Finally, skilled labour seems to have a complementary relationship with all inputs except materials[3].

5. Conclusion

The aim of this study is to analyse the patterns of substitutability and complementarity between energy and ICT capital with employment, and other inputs of production for European countries and industries.

This paper considers the introduction of new technologies (and substitution and complementarity among inputs) and the model used takes into account the possible efficiency gains from new input additions to avoid understatement of input growth and, thereby, biased estimates of productivity growth. Furthermore, it considers that bias in the measurement of productivity growth can originate from output mismeasurement and aggregation. The aggregation bias arises from the fact that changes in efficiency through input additions alter efficiency-adjusted relative user costs. Also, cost minimisation requires that more efficient inputs be substituted for less efficient ones. Both the user cost and factor proportion changes cause efficiency-adjusted cost shares to differ from the measured cost shares used to estimate the contribution of each input to output growth; and, consequently, efficiency-adjusted contributions differ from measured contributions in the calculation of productivity growth rates.

In order to guard against these biases we use in our analysis a technical efficiency model allowing for the possibility that the efficiency of factor additions from physical and ICT capital accumulation, intermediate input purchases, energy inputs or labour hiring, differ from current efficiency levels. Technical efficiency (including adjustment costs) is parameterised directly into the production function, thus adding a dynamic dimension to the analysis. Efficiency gains in production arise when new inputs generate an improvement in technical efficiency that is not fully offset by

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[3] We have also calculated elasticities per country and per industry and long run elasticities. Notably, the rest of the relationships, are the same as the total price elasticities presented in Table 3.

costs of adjustment. An attractive feature of our model is the parsimonious treatment of these efficiency gains, as they can be captured by a single parameter for each input. This is the first study that uses this framework and includes energy along with skilled, unskilled labor and ICT capital.

Estimation of the above model requires the specification of two elements: a cost function; and a price expectation-generating process for the acquisition and hiring prices. The cost function specified is assumed to be the symmetric generalised McFadden functional form, which has the advantage of being flexible even under the imposition of concavity with respect to user costs. The expectation generating processes for acquisition and hiring prices is assumed to follow a first order autoregressive process. With the cost function and price expectations processes specified, the resulting estimation model consists of the factor demand per unit of output equations and the price expectation equations. Furthermore, from the estimated parameters of the model price elasticities of input demands can be calculated to establish the relationship (complementarity or substitutability) between the inputs under investigation.

The empirical analysis described in the previous paragraph is accomplished using the EU KLEMS database. For our analysis we are using countries for which data for energy are available (i.e. Austria, Denmark, Belgium, Spain, Finland, France, Germany, Italy, Netherlands, Sweden, UK and the US) and cover the industries: Agriculture, Hunting, Forestry and Fishing, Mining and Quarrying, Total Manufacturing, Electricity, Gas and Water Supply, Construction, Wholesale and Retail Trade, Hotels and Restaurants, Transport, Storage and Communication, Finance, Insurance, Real Estate and Business Services and Community Social and Personal Services.

One of the main aspects of the NEUJOB project is to anticipate some of the changes from SET, and in particular with respect to labor. Here, we will contribute to that purpose firstly by obtaining the technical efficiency levels from energy inputs and see if those are offset by the high costs of adjustment from incorporating new energy inputs (or improvements of old energy inputs) into the production process, and secondly by the evaluating complementarity/substitutability relations among of energy and other inputs. Specifically we are interested in this relationship with labor inputs and ICT capital which is the main purpose of the NEUJOB project. This will direct us to what will happen to the demands of these inputs when energy prices change.

The empirical results, and specifically the new insights from this analysis, suggest that technical efficiency levels increase with all factor additions. The most important insight is that energy inputs have an increasing technical efficiency level. This suggests that efficiency gains from energy input improvements or new energy inputs are not offset by their adjustment costs. Energy inputs seem to have the lowest technical efficiency level, when compared to the other inputs. It seems that the adjustment costs of energy changes are higher than those associated with changes in other inputs. Possibly, the improvement of energy inputs (moving towards renewable energy) is still at an early stage and their adjustments costs are still high. The total average elasticities suggest that energy is a complement with both types of capital and both types of labour as well; and a substitute to material inputs, so an increase in the price of energy will reduce the demands for both types of labor and capital and increase the demand for materials.

References

Ahn, S., (1999) ´Technology upgrading with learning cost: A solution for two productivity puzzles´, OECD, Economics Department, Working Paper No. 220.

Amato, L. H., and Amato, C. H., (2000) ´The impact of high tech production techniques on productivity and profitability in selected US manufacturing industries´, *Review of Industrial Organization* 16: 327-42.

Apostolakis, B. E., (1990) ´Energy-capital substitutability/complementarity: the dichotomy´, *Energy Economics* 12: 48–58.

Barua, A., and Lee, B., (1997) ´The information technology productivity paradox revisited: A theoretical and empirical investigation in the manufacturing sector´, *The International Journal of Flexible Manufacturing Systems* 9: 145-66.

Basu, S., Fernald, J. G., Oulton, N., and Srinivasan, S., (2003) ´The case of the missing productivity growth, or does information technology explain why productivity accelerated in the United States but not in the United Kingdom?´, NBER Working Paper No. 10010.

Berndt, E. R., (1978) ´Aggregate energy, efficiency, and productivity measurement´, *Annual Review of Energy* 3: 225-73.

Berndt, E. R., and Wood, D. O., (1987) ´Technology prices and the derived demand for energy´, *Review of Economics and Statistics* 57: 259-68.

Berndt, E. R., and Wood, D. O., (1979) ´Engineering and econometric interpretations of energy-capital complementarity´, *American Economic Review* 69: 342–54.

Berndt, E. R., (1990) ´Energy use, technical progress and productivity growth: a survey of economic issues´, *The Journal of Productivity Analysis* 2: 67-83.

Berndt, E., and Hesse, D., (1986) ´Measuring and assessing capacity utilization in the manufacturing sectors of nine OECD countries´, *European Economic Review* 30: 961- 89.

Berndt, E. R., and Morrison, C. J., (1995) ´High-tech capital formation and economic performance in US manufacturing industries. An exploratory analysis´, *Journal of Econometrics* 65: 9-43.

Berndt, E.R., Kolstad, C., and Lee, J. K., (1993) ´Measuring the energy efficiency and productivity impacts of embodied technical change´, *Energy Journal* 14: 33-55.

Bernstein, J., Mamuneas, T. P., and Pashardes, P., (2004) ´Technical efficiency and U.S. manufacturing productivity growth´, *Review of Economics and Statistics* 86(1): 402-12.

Bessen, J., (2002) ´Technology adoption costs and productivity growth: The transition to information technology´, *Economic Dynamics* 5: 443-69.

Biscourp, P., Crepon, B., Heckel, T., and Riedinger, N., (2002) ´How do firms respond to cheaper computers? Microeconomic evidence for France based on production function approach´, *Economie et Statistique* 8: 355-6.

Chien, T., and Hu, J. L., (2008) ´Renewable energy: an efficient mechanism to improve GDP´, *Energy Policy* 36(8): 3035–42.

Chiou-Wei, S. Z., Ching-Fu, C., and Zhu, Z., (2008) ´Economic growth and energy consumption revisited—evidence from linear and non linear Granger causality´, *Energy Economics* 30(6): 3063–76.

Domac, J., Richards, K., and Risovic, S., (2005) ´Socio-economic drivers in implementing bioenergy projects´, *Biomass and Bioenergy* 28: 97–106.

Frondel, M., and Schmidt, C. M., (2002) ´The capital-energy controversy: an artifact of cost shares?´, *Energy Journal* 23: 53–79.

Gordon, R. J., (2000) ´Does the 'new economy' measure up to the great inventions of the past´, *Journal of Economic Perspectives* 14(4): 49-74.

Hendel, I., (1999) ´Estimating multiple-discrete choice models: An application to computerization returns´, *The Review of Economic Studies* 66(2): 423-46.

Hoon, Y-S., (2003) ´Does information technology contributed to economic growth in developing countries? A cross-country analysis´, *Applied Economics Letters* 10 (11): 679-82.

Jorgenson, D. W., (1984) ´The role of energy in productivity growth´, *American Economic Review* 74 (2): 22-30.

Jorgenson, D. W., and Stiroh, K. J., (1999) 'Information technology and growth', *American Economic Review* 89(2): 109-15.

Jorgenson, D. W., (2001) 'Information technology and the US economy', *American Economic Review* 91(1): 1-32.

Jorgenson, D. W., (2004) 'Accounting for growth in the information age', Forthcoming in Aghion, P., and Durlauf, S., (eds.) *Handbook of Economic Growth*, Amsterdam: North Holland.

Jorgenson, D. W., Stiroh, K. J., and Ho, M. S., (2002) ´Information technology, education and the sources of economic growth across US industries´, Mimeo, April.

Jorgenson, D. W., and Motohashi, K., (2005) ´Information technology and the Japanese economy´, NBER Working Paper No. 11801.

Judson, R. A., Schmalensee, R., and Stoker, T. M., (1999) ´Economic development and the structure of demand for commercial energy´, *The Energy Journal* 20(2): 29-57.

Kaufmann, R. K., (1992) ´A biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change´, *Ecological Economics* 6: 35-56.

Kaufmann, R. K., (1994) ´The relation between marginal product and price in US energy markets: implications for climate change policy´, *Energy Economics* 16(2): 145-58.

Ketteni, E., Mamuneas, T., and Stengos, T., (2007) ´Nonlinearities in economic growth: A semiparametric approach applied to information technology data´, *Journal of Macroeconomics* 29(3): 555-568.

Ketteni, E., (2009) ´Information technology and economic performance in US industries´, *Canadian Journal of Economics*: 42(3): 844-65

Koetse, M. J., de Groot H., and Florax, R., (2008) ´Capital-energy substitution and shifts in factor demand: a meta-analysis´, *Energy Economics* 30: 2236–51.

Matteucci, N., Mahony, O., Robinson, M., and Zwick, T., (2005) ´Productivity, workplace performance and ICT: Industry and firm-level evidence for Europe and the US´, *Scottish Journal of Political Economy* 52 (3): 359-86.

Morrison, C. J., (1992) ´Investment in capital assets and markup behaviour: The U.S. chemicals and primary metals industries in transition´, *Journal of Business and Economic Statistics* 11 (1): 45–60.

Morrison, C. J., (1993) ´Energy and capital: Further exploration of E-K interactions and economic performance´, *Energy Journal* 14 (1): 217-43.

Mun, S-B., (2002) ´Computer adjustment costs: Is quality improvement important?´, Mimeo.

Nadiri, M. I., and Prucha, I. R., (1989) ´Dynamic factor demand models, productivity measurement and rates of return: Theory and empirical application to the U.S. Bell System´, NBER Working Paper No. 3041.

Nadiri, M. I., and Mun, S-B., (2002) ´Information technology externalities: Empirical evidence from 42 US industries´, NBER Working Paper No. 9272.

Nakicenovic, N., and Swart, R., (2000) *Emissions Scenarios,* IPCC, WGIII, Cambridge University Press.

Ockwell, D.G., (2008) ´Energy and economic growth: Grounding our understanding in physical reality´, *Energy Policy* 36: 4600-04.

Oliner, S. D., and Sichel, D. E., (2000) ´The resurgence of growth in the late 1990s: Is information technology the story?´, *Journal of Economic Perspectives* 14(4): 3-22.

Ozturk, I., (2010) ´A literature survey on the energy-growth nexus´, *Energy Policy* 38: 340–49.

Siegel, D., (1997) ´The impact of computers on manufacturing productivity growth: A multiple indicators-multiple causes approach´, *The Review of Economics and Statistics* 79(1): 68-78.

Stern, D. I., (1993) ´Energy use and economic growth in the USA, A multivariate approach´, *Energy Economics* 15: 137-50.

Stern, D. I., (1994) ´Natural resources as factors of production: Three empirical studies´, Ph.D. Dissertation, Department of Geography, Boston University, Boston MA.

Stern, D. I., (2000) ´A multivariate cointegration analysis of the role of energy in the U.S. macroeconomy´, *Energy Economics* 22: 267-83.

Stern, D. I., (2003) ´Modeling stochastic technological change in economy and environment using structural time series models´, in Dovers S., Stern, D. I., and Young, M. D., (eds.) *New Dimensions in Ecological Economics: Integrative Approaches to People and Nature*, Edward Elgar, Cheltenham, pp. 146-75

Stern, D. I., (2010) ´Energy quality´, *Ecological Economics* 69: 1471–8.

Stern, D. I., (2011) ´The role of energy in economic growth´, *Annals of the New York Academy of Sciences* 1219: 26-51.

Stern, D. I., and Cleveland, C. J., (2004) ´Energy and economic growth´, Rensselaer Polytechnic Institute, Department of Economics, Working Paper in Economics No. 0410.

Stiroh, K. J., (1998) ´Computers, productivity and input substitution´, *Economic Inquiry* 36(2): 175-91.

Stiroh, K. J., (2002) ´Information technology and the US productivity revival: What do the industry data say?´, *American Economic Review* 92(5): 1559-76.

Yang, C. W., Hwang, M. J., and Huang, B. N., (2002) ´Analysis of factors affecting price volatility of the US oil market´, *Energy Economics* 24: 107–19.

Zellner, A., (1962) ´An efficient method of estimating seemingly unrelated regression equations and tests for aggregation bias´, *Journal of the American Statistical Association* 57: 348–68.