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Technological change and energy demand in Europe

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Abstract:

The aim of this paper is the econometric analysis of embodied and induced technological change that reduces energy input and CO_2 emissions in production. For this purpose, a model of unit costs and factor demand for 35 industries in 23 EU countries has been set up, based on the WIOD database. The deterministic trend usually applied for describing the factor bias for energy is replaced by a mixed term of energy efficiency of physical production capacity and a trend in three energy intensive industries. This new variable for energy saving technological change is linked to the vintage structure of installed capital. By this link technological change becomes induced, if capital and energy are substitutes. If energy and capital are complements, this technological change can only be enforced by measures that accelerate the path of renovating the capital stock. Within the three energy intensive industries we identify one, where induced technological change is energy saving, but energy and capital are complements (pulp and paper), one where energy and capital are very weak substitutes, but technological change is energy using (non-metallic minerals) and one, where energy and capital are substitutes and technological change is energy saving (basic metals). Only in this latter case, price induced technological change can contribute significantly to fossil energy and emission reduction.

Key words: embodied and induced technological change, vintage models, emission mitigation policies

JEl codes: Q41, Q55, C54

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1. Introduction

Technological change is the main factor in the debate about economic impacts and macroeconomic costs of climate policies, based on carbon pricing. The last decade has seen the emergence of models for impact assessment of climate policy that integrate features of endogenous or induced technological change (two prominent examples are: the WITCH model by Bosetti, et al., 2006, or a CGE model by Otto, Löschel and Reilly, 2008). Notwithstanding, as Pizer and Popp (2008) have shown, there is still a gap between empirical research on the magnitude of this type of technological change and the application of these effects in macroeconomic impact assessment models. In both lines of the literature one can detect an emphasis on energy saving R&D and learning by doing for carbon free types of energy, based on the pioneer work of Popp (2002). Pizer and Popp (2008) identify a list of under-researched issues in the existing literature. Especially, from their point of view, a sound empirical base for different channels of induced technological change in various industries for CGE models is missing and has been put by them on a future research agenda.

Additionally, there are numerous examples of simulation exercises in climate policy design and evaluation that show that by higher diffusion of existing and mature technologies significant reductions in energy demand and emissions could be achieved. The most prominent example for this view is Pacala and Socolow (2004). This observation raises the question about the rationality of firms and households or possible market inefficiencies in the process of diffusion of energy saving and therefore also cost saving technologies. One route of the literature explains this slow diffusion phenomenon as a rational act, if features like adjustment costs, learning by using and returns to diversity effects are present. Mulder, de

Groot and Hofkes (2003) embody these features in a theoretical vintage model with two different sectors, namely a capital producer and a final goods producer.

In this paper this line of research is taken up and empirically applied to the WIOD data, combining them to ODYSSEE data for energy efficiency in 23 EU countries. Unfortunately, the full data set that would be necessary for empirically testing a vintage model for all WIOD industries is not available. The main issue of this paper is the endogenous diffusion of energy saving technologies (Jaffe, et al., 2003) in different industries in a consistent K,L,E,M model of unit costs and factor demand. The theoretical base for this work is the conviction, that endogenous or induced features of technological change must be embedded into a model that in a clear analytical way distinguishes between: (i) substitution effects in production, (ii) factor-saving or factor-using technological change, and (iii) other sources of technical change (e.g. total factor productivity growth, learning by doing). In such a consistent framework, as Sue Wing (2006) has noted, energy saving technological change can be seen as extending the set of substitution possibilities between fossil fuels and other inputs in production.

The paper contributes to the literature by applying a new specification for modeling the factor bias for energy in a Translog model. The first generation of K,L,E,M Translog models dealt with total factor productivity (TFP) and the bias in technical change (Jorgenson and Fraumeni, 1981, Jorgenson, 1984), based on the concept of factor-bias in technical change (Binswanger and Ruttan, 1978). This approach treats energy saving technological progress as exogenous, incorporated in AEEI (autonomous energy efficiency improvement) that can be built into long-term models. Another new approach of modeling the rate and the factor bias of technological change has been put forward by Jin and Jorgenson (2010). It replaces the deterministic trend for describing technological change by latent variables which are identified by applying the Kalman filter to the econometric model and thereby identifying price induced technological change.

In this paper the diffusion of new technologies drives the energy efficiency of the production process and occurs with investment in new energy efficient vintages of capital that replace installed and less energy efficient capital stock. Technological change is therefore also embodied (Berndt, Kolstad and Lee, 1993) in our model. The interaction of installing new capital equipment and energy consumption per unit of output comprises different effects in our model. First, energy and capital can be substitutes and embodied technological change energy saving. This can be seen as the 'optimistic' case, as far as the costs of climate mitigation is concerned: carbon pricing alone leads to induced technological change via the installation of new equipment. This case is an example of price induced energy saving technological change. The other less favourable cases are characterized by the fact that either energy and capital are complements or technological change is energy using, or – in the worst case – a combination of both features. If embodied technological change is energy using it becomes clear that the installation of new equipment cannot contribute to emission reduction. If energy and capital are complements and embodied technological change is energy saving, as in the vintage model of Mulder, de Groot and Hofkes (2003), carbon pricing alone leads to lower production capacities (than in the baseline without carbon pricing) and thereby *ceteris paribus* to a decrease in energy efficiency. In this case the price induced impact of technological change is negative and emission reduction comes at higher cost of reducing output and capacity. Nevertheless, in this case the efficiency effect of new vintages can be induced by other climate policy measures, for example incentives for ‘scrappage shemes’, financed out of the revenues of auctioning CO_2 emission allowances. Three energy intensive industries in Europe have been identified in a number of studies as well as in the European Commission (2009) assessment as being at major risk for carbon leakage and would therefore fall under exemptions following the EU Emission Trading System directive (European Commission, 2008), namely Steel production, Cement production, and Pulp and paper production (see also: Droege and Cooper, 2011).

Within these three industries, we find that only the basic metals industry represents the ‘optimistic’ case of energy and capital being substitutes and embodied technological change being energy saving. The pulp and paper industry reveals energy/capital complementarity and energy saving embodied technological change. In the non-metallic mineral industry (including cement production) energy and capital are very weak substitutes, but embodied technological change is energy using.

The remainder of the paper is organized as follows: in section 2 the theoretical model is set up and in section 3 data issues are laid down together with the estimation methodology and the empirical results. In section 4 some preliminary conclusions are drawn.

2. The Translog model and technological change

The representative producers in each industry all face a unit cost function with constant returns to scale

$$\log p_Q = \alpha_0 + \frac{1}{2}\sum_i \gamma_{ii}\left(\log(p_i)\right)^2 + \sum_{i,j}\gamma_{ij}\log(p_i)\log(p_j) + \alpha_t t + \frac{1}{2}\alpha_{tt}t^2 + \sum_i \rho_{ti} t \log(p_i) \quad (1)$$

, where p_Q is the output price (unit cost), p_i, p_j are the input prices for input quantities x_i, x_j, and t is the deterministic time trend. Note that equation (1) comprises different components of technological change. Autonomous technical change can be found for all input factors (i.e. the factor biases ρ_{ti}). Another source of autonomous technical change that only influences unit costs is TFP, measured by α_t, and α_{tt}.

The Translog model is set up with inputs of capital (*K*), labor (*L*), energy (*E*), imported (M^m) and domestic non-energy materials (M^d), and their corresponding input prices p_K, p_L, p_E, p_M and p_D. As is well known, Shepard's Lemma yields the cost share equations in the Translog case, which in this case of five inputs can be written as:

$$v_K = \left[\alpha_K + \gamma_{KK}\log(p_K/p_D) + \gamma_{KL}\log(p_L/p_D) + \gamma_{KE}\log(p_E/p_D) + \gamma_{KM}\log(p_M/p_D) + \rho_{tK}t\right]$$

$$v_L = \left[\alpha_L + \gamma_{LL}\log(p_L/p_D) + \gamma_{KL}\log(p_K/p_D) + \gamma_{LE}\log(p_E/p_D) + \gamma_{LM}\log(p_M/p_D) + \rho_{tL}t\right]$$

$$v_E = \left[\alpha_E + \gamma_{EE}\log(p_E/p_D) + \gamma_{KE}\log(p_K/p_D) + \gamma_{LE}\log(p_L/p_D) + \gamma_{EM}\log(p_M/p_D) + \rho_{tE}t\right]$$

$$v_M = \left[\alpha_M + \gamma_{MM}\log(p_M/p_D) + \gamma_{KM}\log(p_K/p_D) + \gamma_{LM}\log(p_L/p_D) + \gamma_{EM}\log(p_E/p_D) + \rho_{tM}t\right] \quad (2)$$

The homogeneity restriction for the price parameters $\sum_i \gamma_{ij} = 0$, $\sum_j \gamma_{ij} = 0$ has already been imposed in (2), so that the terms for the price of domestic intermediates p_D have been omitted. The usual parameter restrictions of the Translog function imply in this case:

$$\sum_i \alpha_i = 1,\ \sum_i \gamma_{ij} = 0,\ \sum_j \gamma_{ij} = 0,\ \sum_i \rho_{ti} = 0\ .$$

with i,j = K, L, E, M^m and M^d.

In this model, energy demand reacts to changes in the prices of all inputs and changes in time due to the factor bias that can be energy saving or energy using. The immediate reaction to price changes is given by the own and cross price elasticities. The own price elasticity of energy ε_{EE} demand can be written as:

$$\varepsilon_{EE} = \frac{\partial \log E}{\partial \log p_E} = \frac{v_E^2 - v_E + \gamma_{EE}}{v_E} \tag{3}$$

The cross price elasticity between energy and any other factor i is given with:

$$\varepsilon_{Ei} = \frac{\partial \log E}{\partial \log p_i} = \frac{v_i v_E + \gamma_{Ei}}{v_E} \tag{4}$$

The technological change in this model is the factor bias and can be described by the annual change in the energy cost share, which is directly measured by the parameter ρ_{tE}.

2.1 Energy saving technological change

The basic idea for introducing induced technological change into this model is adding an explicit variable that contains some information about the technical energy efficiency of the capital stock. At the industry level the deterministic trend in equation (2) captures different potential effects on the energy intensity per unit of output. That comprises changes in the technical energy efficiency of the equipment stock as well as changes in the product mix of firms or structural changes in the firm structure of an industry. As these various effects besides the technical energy efficiency are relevant, especially given the industry aggregation level, they shall still be captured by a deterministic trend.

Additionally, the impact of new vintages on the energy efficiency of the equipment installed shall be considered. Starting point is the observation that the aggregate capital stock, which is determined by equation (2) is made up by an aggregate of different vintages (Mulder, de Groot and Hofkes, 2003):

$$K_t = \int_{t-T}^{t} K_{\tau,t} d\tau \qquad (5)$$

In (5) $K_{\tau,t}$ is the amount of capital vintage τ used in year t, and T is the number of vintages in use. In Mulder, de Groot and Hofkes (2003) equation (5) is formulated as a Constant Elasticity of Substitution (CES) function, and capital vintages can be substituted against each other. All this detailed information on the vintage structure of capital in different industries is not available for our country sample, so that this full model cannot be set up. Our starting point is the capital accumulation equation, given depreciation rates and an estimate of an initial capital stock (K_0):

$$K_t = K_{t-1}(1-\delta) + I_t \qquad (6)$$

Vintage effects shall be measured in this context by the rate of investment over total capital, I_t/K_t, which corresponds to the new part of the capital stock in equation (6). For a given level of capital demand from (2), the distribution between $K_{t-1}(1 - \delta)$ and I_t is given by the depreciation rate. In a fully formulated vintage model as in Mulder, de Groot and Hofkes

(2003), the depreciation rate is endogenous, as different vintages are substituted against each other, depending on their productivity. In our model the depreciation rate is treated as exogenous, but as a policy variable that can be influenced by scrappage schemes. These schemes haven been introduced in 2008/2009 in several European countries for private cars. The essence of a scrappage scheme (see: Sivak and Schoettle, 2009, for car scrappage scheme effects) for energy efficiency lies in the faster diffusion to a capital stock with higher energy efficiency by increasing the depreciation rate and subsidizing the change towards higher energy efficiency. Therefore, for any given demand for total capital, different investment rates I_t/K_t can be found, depending on the actual depreciation rate. Furthermore, the specific energy input of these stocks in t, measured as energy input E_t per unit of physical production X_t with the use of this stock, is different for different vintages. In this most simple case dealt with here, the total energy efficiency of the capital stock in t, defined as $\eta_t = X_t / E_t$, is determined by:

$$\eta_t = \frac{K_{t-1}(1-\delta)}{K_t}\eta_{t-1} + \frac{I_t}{K_t}\eta_I \tag{7}$$

The dynamics in the aggregate energy efficiency are driven by the difference in the energy efficiency of old vintages (η_{t-1}) and the efficiency of new vintages (η_I), weighted by the speed of renovation of the capital stock. To measure this effect, we estimate Autoregresssive-Distributed Lag (ADL) models (Banerjee, et al., 1990) for energy efficiency and the investment rate:

$$\log(\eta_t) = \alpha_0 + \alpha_1 \log(\eta_{t-1}) + \beta_0 \log\left(\frac{I_t}{K_t}\right) + \beta_1 \log\left(\frac{I_{t-1}}{K_{t-1}}\right) \tag{8}$$

The long run elasticity of the efficiency η to the investment rate *I*/*K* is given by the term $\frac{\beta_0 + \beta_1}{1-\alpha_1}$.

The energy efficiency is used as an additional variable to describe the factor bias, together with the deterministic trend. That yields for the energy cost share equation:

$$v_E = \left\lfloor \alpha_E + \gamma_{EE} \log(p_E / p_D) + \gamma_{KE} \log(p_K / p_D) + \gamma_{LE} \log(p_L / p_D) + \gamma_{EM} \log(p_M / p_D) + \rho_{tE,\eta} t\eta \right\rfloor \tag{9}$$

The same term $\rho_{tE,\eta} t\eta$ is also inserted into the unit cost function (1) and substitutes the original term for the factor bias $\rho_{tE} t$ there.

2.2 Factor prices and indirect costs

Factor prices are exogenous for the derivation of factor demand in (2), but are endogenous in the system of supply and demand. This holds true for all factor prices, also for the price of labour, p_L, which is determined together with mechanisms in the labour market. Furthermore, some factor prices are directly linked to the output prices p_Q which are determined in the same system. That refers to the price of capital, p_K, the price of domestic, p_D and imported intermediates, p_M.

The price of domestic intermediates, p_D for an industry is directly linked to the output prices p_Q via the market shares matrix and the structure of domestic intermediate demand. Both matrices can be derived from the supply and use tables in the WIOD database. The same holds true for the price of imported intermediates, p_M, which is the weighted sum of the output prices p_Q of the sending countries in the international supply and use tables in the WIOD database (including international transport costs). The weights are given by the structure of the international supply and use tables.

The price of capital is based on the user cost of capital: $u_K = p_I(r+\delta)$ with p_I as the price of investment goods an industry is buying, r as the deflated benchmark interest rate and δ as the aggregate depreciation rate of the capital stock K. The investment goods price p_I can be defined as a function of the domestic commodity prices and import prices, given the input structures for investment, derived from a capital formation matrix (investment by industry * investment by commodity).

It is important to note that by these input-output loops in the model, indirect effects or feedback effects of prices occur. Policies that introduce carbon pricing with the impact of changing the effective price of energy also change prices of domestic and imported intermediates in all regions, which has important feedbacks on the production structures and on factor demand.

3. Data, estimation method and results

The empirical application of the K,L,E,M^m,M^d model outlined above is based on a detailed data set comprising all nominal values of inputs as well as their corresponding prices.

In general, the Socio Economic Accounts (SEA) of the WIOD database have been used, which contain aggregate nominal values as well as prices for the following variables from 1995 to 2009 for the EU 27:

$p_Q Q$ Nominal gross output (in millios of local currency)
M Intermediate material and service inputs at current purchasers' prices (in millions of local currency)
$p_L L$ Labour compensation (in millions of local currency)
$p_K K$ Capital compensation (in millions of local currency)

The Environmental Accounts of the WIOD database contain detailed data on energy consumption in energy units (TJ) by energy carrier (E) that have been combined with data from the OECD "Energy Prices and Taxes" to derive energy inputs in values from 1995 to 2009:

$P_E E$ Energy input in values (in millions of local currency)

By subtracting $P_E E$ from M, the total non-energy intermediates have been derived. These had to be split up into domestic and imported intermediates in a next step with the use of the International Supply and Use Tables (SUT) of the WIOD database. The column sum of all intermediate deliveries less the deliveries from domestic sources yields total imported intermediates and the column sum of the domestic deliveries yields total domestic intermediates by industry:

$p_M M^m$ Imported intermediate material and service inputs at current purchasers' prices (in US $, converted to millions of local currency)
$p_D M^d$ Domestic intermediate material and service inputs at current purchasers' prices (in US $, converted to millions of local currency)

Prices are either directly taken from the WIOD database or calculated from nominal values and quantity data. Directly from the SEA we take:

p_Q Deflator of gross output, 1995 = 1
p_I Deflator of gross fixed capital formation by industry, 1995 = 1

The prices p_L and p_E have been calculated by combining the nominal values with the quantity data (employment, energy in TJ). The prices of domestic intermediates, $p_{D,}$ have been taken from nominal and previous years prices from International SUT of the WIOD database. For prices of imported intermediates, p_M we do not use the previous years prices from International SUT of the WIOD database, but take a different deflation procedure carried out by IPTS (Iñaki Arto) and based on the regional input-output structure of the International SUT. The basic idea consists in using the domestic deflators of each country together with the regional input-output structure to calculate the price of inputs by receiving country.

The price of capital is based on the user price of capital, $u_K = p_I(r+\delta)$, where the following sources have been used:

δ Rate of depreciation of total capital stock, calculated from the structure of K and depreciation rate by asset

r Real rate of return, calculated by deflating the benchmark interest rate (treasury bills on the secondary market) with the deflator of GDP

p_K Index of $u_K = p_I(r+\delta)$, with 1995 = 1

Investment (gross fixed capital formation) in nominal values is also available from the SEA in the WIOD database. For calculating a time series of the capital stock in each industry, a starting value has been calculated by combining the relationship $p_K K/p_K$ with some benchmark values of capital per output from the capital files in the EUKLEMS database.

Major data gaps and problems have been encountered in Bulgaria, Cyprus, Estonia and Malta, so that a full time series could not have been constructed for these countries without the wide application of interpolation techniques. Minor data gaps, for example for depreciation rates, investment data, and energy price data, have been either bridged by interpolation techniques or by applying aggregate variables development or the development of the same variable in a country with a similar industry structure.

These economic data have been complemented by data on energy efficiency from the ODYSSEE database. This database contains energy efficiency indicators for different sectors of the economy, mainly measured by specific consumption or unit consumption per service or physical output. The ODYSSEE database contains unit energy consumption data for different processes in energy intensive industries. We take these as a proxy for the energy efficiency of the capital equipment installed in these industries. The original ODYSSEE data comprise:

- unit consumption of crude steel (in toe per ton)
- unit consumption of cement (in toe per ton)
- unit consumption of clinker (in toe per ton)
- unit consumption of glass production (in toe per ton)
- unit consumption of crude steel (in toe per ton)

The average development of the unit consumption of cement, clinker and the glass production has been taken to calculate the development of unit energy consumption in the non-metallic mineral industry. The other two unit consumption indices have been applied directly to the corresponding industries in the WIOD database. The inverse of the unit consumption is used as energy efficiency and is transformed into an efficiency index with 1995 = 1.

4. Estimation results

The econometric estimation is carried out for the system comprising the unit cost function (1) and the factor demand functions (2). The systems have been estimated applying the Seemingly Unrelated Regression (SUR) estimator for balanced panels in EViews 6.0 for each of the 35 industries in the WIOD database. The full dataset contains a balanced panel for 23 EU countries for the time series 1995 to 2009, which gives a total of 345 observations.

As a first result, we derive all parameter estimates of the model, which have been estimated under the restrictions of homogeneity and symmetry of the Translog model. We did not in general enforce concavity of the cost function, but only forced parameters to certain values, when in a first step concavity was violated and some positive mean values of own price elasticities appeared.

Table 2 shows selected parameter values for the factor bias in the case of the deterministic trend. About one half (65) out of the 128 parameters for technological change (Table 2) turn out to be insignificant (not even significant at the 10% level). Technological change assumed as a deterministic trend is energy saving (negative value of ρ_{tE}) in 22 out of 32 industries, though not always based on a significant parameter value. As far as energy intensive activities are concerned, technological change is energy using in the pulp and paper/printing industry, in electricity, gas and water supply, as well as in the air transport sector. In the other two out of the three energy intensive manufacturing sectors (non-metallic minerals; basic metals and fabricated metal) a deterministic trend for technological change shows energy saving impacts, though not based on significant parameter values. In any case, the technological change parameters for energy have rather small magnitude. Note that the parameter ρ_{tE} directly measures the annual decrease in the energy cost share, which is about - 0.1 percentage points in the non-metallic minerals industry and in the basic metals and fabricated metal industry. The average energy cost share in these two industries over countries and time is 7.3% and 5.9% respectively. Technological change is labour saving (negative value of ρ_{tL}) in almost all industries.

Table 3 compares the estimation of technological change specified as a deterministic trend with the specification as a mixed term of physical energy efficiency and a trend. In the specification of the mixed term the parameters are significant in two out of the three energy intensive industries (pulp and paper/printing; non-metallic minerals). The direction of technological change also changes for some industry when moving to this new specification. Technological change is energy saving in the pulp and paper/printing industry and energy using in the non-metallic minerals industry in the specification with energy efficiency. These two parameter values are significant in the new specification with energy efficiency, whereas the parameter stays insignificant in the basic metals industry.

A more comprehensive picture of the different impacts and channels of prices and technical change on factor demand can be concluded from the calculation of the elasticities. In Table 4 the mean values and corresponding standard errors for own and cross price elasticities of capital are shown. The own price elasticity of capital is below one in almost all industries and not very different across the manufacturing sectors. The cross price elasticity of capital wrt energy is positive in mining and quarrying; non-metallic minerals; basic metals and fabricated metal; transport equipment; manufacturing nec, recycling; electricity, gas and water supply; inland transport; and air transport. This group of industries comprises some of the most energy intensive sectors, but does not include the pulp and paper/printing industry. Therefore, an increase in the price of energy induces investment in new equipment in two out of the three energy intensive manufacturing industries, where energy and capital are substitutes. This effect is very small on average in the non-metallic minerals sector, where energy and capital are very weak substitutes. The additional investment in equipment, induced by an energy price rise, can in turn lead to higher energy efficiency. In that case we would identify price induced technological change. In the model presented, energy price induced technological change can only be expected, if both conditions are fulfilled: (i) energy and capital are substitutes, and (ii) embodied technological change is energy saving. Out of the three energy intensive manufacturing sectors, only the basic metals and fabricated metal industry fulfils both conditions. In the pulp and paper/printing industry, embodied technological change is energy saving, but energy and capital are complements. In the non-metallic minerals industry energy and capital are (weak) substitutes, but embodied technological change is energy using.

Table 5 and 7 contain the price elasticities for labour and imported intermediates. Table 6 shows the price elasticities of energy. Concerning the cross price elasticity of energy wrt capital, Table 6 presents the symmetric view to the corresponding elasticity in Table 4. Note that the elasticities, which are combinations of parameters and cost shares according to (4) are not symmetric, though the parameters γ_{ij} are symmetric. Table 6 shows the same pattern as Table 4 with respect to the capital/energy substitutability of the three energy intensive manufacturing sectors, namely that the pulp and paper/printing industry is the only one that exhibits complementarity between energy and capital.

The own price elasticities of energy are almost all below one and differ slightly across industries. In general, there is some indication that the own price elasticities of energy are larger in the energy intensive industries, where the cost share of energy is larger. The only exception of that is the basic metals and fabricated metal industry, where the own price elasticity of energy is only -0.2.

Table 8 shows the parameter values, as well as the short and long run reaction of the energy efficiency variable to the renovation rate of the capital stock. The ADL equations described in (8) have been estimated for the same balanced panel as the Translog functions (23 EU countries, 1995 to 2009). The single equations for efficiency in the three industries have been estimated applying the Generalised Method of Moments (GMM) estimator for balanced panels in EViews 6.0.

The long run elasticity of energy efficiency to the capital stock differs considerably across these three industries and is biggest in the basic metal industry. The long run elasticity only partially relies on significant parameter estimates in these three industries. The reaction of energy efficiency to the renovation rate of the capital stock only creates energy saving technological change in the basic metal industry, as well as in the pulp and paper/printing industry. In the basic metal industry, this technological change is induced by the energy price effect alone. In the pulp and paper/printing industry the technological change had to be induced by other policy measures aiming at a higher renovation rate of the capital stock. If these measures were part of a climate policy program that also covers carbon pricing, then the technological change impact could partially compensate the negative effect on investment, stemming from capital/energy complementarity in the pulp and paper/printing industry.

4. Conclusions

In this paper the role of embodied and induced technical change for the energy demand of 35 industries in 23 EU countries has been explored. The basic idea was to set up a modelling framework, where different sources of technological change can be separated in a clear analytical way from short-term substitution effects. The approach chosen was a Translog model, where substitution effects between capital (K), labour (L), energy (E), imported (M^m) and domestic (M^d) materials, total factor productivity and the factor bias of technological change are differentiated.

Our main finding concerns the interaction between (i) the substitution process between energy and capital, and (ii) the direction and realisation of embodied technological change. When capital and energy are substitutes, carbon pricing leads to higher investment and potentially to lower costs of emission reduction than in a case where energy and capital are complements and capacity output has to be reduced.

The deterministic trend usually applied to measure the factor bias of technological change is in our model replaced by a combined term of physical energy efficiency and a trend term. In a separate econometric model, the development of energy efficiency has then been linked to the vintage structure of the capital stock, measured by the renovation rate of the stock. This methodology allows for differentiating between energy saving or energy using technological change, that is embodied in the vintages of capital.

One case identified is an industry, where energy and capital are complements and technological change embodied in capital is energy saving. This case is represented in our study by the pulp and paper/printing industry. Carbon pricing leads to lower capital demand and investment in that case, with corresponding negative impacts on energy efficiency. That had to be compensated by measures leading to a higher renovation rate of the capital stock.

Another case is the non-metallic mineral industry, where technological change is energy using, though energy and capital are substitutes. In that case, mainly substitution effects can contribute to emission reduction and these effects will be counteracted by lower energy efficiency due to induced technological change.

Finally, the basic metals and fabricated metal industry is characterized by energy saving technological change as well as by substitutability between energy and capital. Price induced technological change is sufficient in that case to amplify the pure substitution effect on emissions.

Table1 : WIOD industries and definition by NACE

WIOD industries	NACE
AGRICULTURE, HUNTING, FORESTRY AND FISHING	AtB
MINING AND QUARRYING	C
FOOD , BEVERAGES AND TOBACCO	15t16
Textiles and textile	17t18
Leather, leather and footwear	19
WOOD AND OF WOOD AND CORK	20
PULP, PAPER, PAPER , PRINTING AND PUBLISHING	21t22
Coke, refined petroleum and nuclear fuel	23
Chemicals and chemical products	24
Rubber and plastics	25
OTHER NON-METALLIC MINERAL	26
BASIC METALS AND FABRICATED METAL	27t28
MACHINERY, NEC	29
ELECTRICAL AND OPTICAL EQUIPMENT	30t33
TRANSPORT EQUIPMENT	34t35
MANUFACTURING NEC; RECYCLING	36t37
ELECTRICITY, GAS AND WATER SUPPLY	E
CONSTRUCTION	F
Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel	50
Wholesale trade and commission trade, except of motor vehicles and motorcycles	51
Retail trade, except of motor vehicles and motorcycles; repair of household goods	52
HOTELS AND RESTAURANTS	H
Inland transport	60
Water transport	61
Air transport	62
Supporting and auxiliary transport activities; activities of travel agencies	63
POST AND TELECOMMUNICATIONS	64
FINANCIAL INTERMEDIATION	J
Real estate activities	70
Renting of m&eq and other business activities	71t74
PUBLIC ADMIN AND DEFENCE; COMPULSORY SOCIAL SECURITY	L
EDUCATION	M
HEALTH AND SOCIAL WORK	N
OTHER COMMUNITY, SOCIAL AND PERSONAL SERVICES	O
PRIVATE HOUSEHOLDS WITH EMPLOYED PERSONS	P

Table 2: Selected parameter estimates: technological change

	ρ_{tK}		S.E	ρ_{tL}		S.E	ρ_{tE}		S.E	ρ_{tM}		S.E
AtB	-0.0123	***	0.0035	0.0029		0.0035	0.0020	**	0.0009	0.0039	***	0.0009
C	0.0111	***	0.0027	-0.0112	***	0.0017	-0.0002		0.0010	0.0010		0.0010
15t16	-0.0006		0.0009	-0.0011		0.0008	-0.0015	**	0.0007	0.0016	*	0.0009
17t18	-0.0004		0.0011	-0.0047	***	0.0011	-0.0017		0.0011	0.0016		0.0012
19	0.0023	*	0.0012	-0.0029	**	0.0012	-0.0005		0.0013	0.0022	**	0.0011
20	0.0019	*	0.0010	-0.0017	**	0.0009	-0.0012	*	0.0007	0.0044	***	0.0015
21t22	-0.0026	**	0.0010	-0.0019	*	0.0011	0.0010	*	0.0006	0.0013		0.0013
24	0.0006		0.0015	-0.0044	***	0.0010	-0.0024		0.0015	0.0066	***	0.0015
25	-0.0010		0.0009	-0.0007		0.0010	-0.0002		0.0007	0.0010		0.0011
26	-0.0011		0.0009	-0.0016	*	0.0009	-0.0007		0.0008	0.0014		0.0009
27t28	-0.0020	***	0.0008	-0.0019	**	0.0008	-0.0010		0.0009	0.0033	***	0.0013
29	0.0027	**	0.0013	-0.0040	***	0.0011	-0.0017		0.0011	0.0026	**	0.0011
30t33	0.0000		0.0013	-0.0036	***	0.0011	-0.0018	**	0.0008	0.0050	***	0.0013
34t35	0.0012		0.0013	-0.0023	*	0.0013	-0.0007		0.0006	0.0050	***	0.0014
36t37	-0.0009		0.0011	0.0012		0.0013	0.0003		0.0008	0.0005		0.0011
E	-0.0006		0.0018	-0.0016		0.0012	0.0020		0.0016	0.0024	**	0.0011
F	-0.0004		0.0015	-0.0027	***	0.0010	-0.0011	**	0.0005	0.0008		0.0010
50	-0.0009		0.0011	0.0012		0.0013	0.0003		0.0008	0.0005		0.0011
51	-0.0010		0.0015	-0.0028	**	0.0013	-0.0017		0.0011	0.0017	**	0.0008
52	-0.0033	***	0.0012	0.0016		0.0017	-0.0012		0.0007	-0.0011	***	0.0009
H	-0.0016		0.0015	0.0008		0.0011	-0.0020	***	0.0006	-0.0004	***	0.0009
60	-0.0031	*	0.0018	-0.0029	**	0.0015	-0.0009		0.0010	0.0015	***	0.0012
62	-0.0036	**	0.0017	-0.0020		0.0014	0.0071	***	0.0012	0.0015		0.0013
63	-0.0076	***	0.0017	0.0025	*	0.0014	-0.0001		0.0006	0.0018	*	0.0009
64	-0.0028	**	0.0014	-0.0084	***	0.0009	-0.0018	**	0.0008	0.0021	**	0.0008
J	-0.0002		0.0015	-0.0052	***	0.0013	0.0004		0.0009	-0.0004		0.0015
70	-0.0027		0.0017	0.0007		0.0006	0.0004		0.0007	0.0015	**	0.0006
71t74	-0.0024		0.0017	-0.0005		0.0013	-0.0033	***	0.0008	0.0005		0.0008
L	0.0011		0.0009	0.0001		0.0013	0.0001		0.0006	-0.0001		0.0007
M	0.0034	***	0.0009	-0.0046	***	0.0013	0.0003		0.0006	0.0005		0.0005
N	0.0034	***	0.0011	-0.0045	***	0.0011	-0.0010		0.0007	0.0008		0.0007
O	0.0010		0.0014	-0.0018		0.0012	-0.0036	**	0.0015	-0.0005		0.0009

S.E. is the standard error, *, **, and *** represent 10%, 5%, and 1% of significance, respectively.

Table 3: Selected parameter estimates in energy intensive industries: specifications of technological change

	ρ_{tE}		$\rho_{tE,\,\eta}$	
21t22	0.0010	*	-0.0002	***
26	-0.0007		0.0008	*
27t28	-0.0010		-0.0004	

*, **, and *** represent 10%, 5%, and 1% of significance, respectively.

Table 4: Own and cross price and elasticities of K

K	K	S.E.	L	S.E.	E	S.E.	M^m	S.E.
AtB	-0.052	5.29	-0.050	2.90	-0.104	0.86	0.016	0.47
C	-0.655	1.33	0.225	0.39	0.059	0.28	0.073	0.36
15t16	-0.615	0.00	0.015	0.00	-0.038	0.00	-0.061	0.00
17t18	-0.339	0.01	-0.166	0.01	-0.256	0.01	0.103	0.00
19	-0.352	0.02	0.125	0.01	-0.088	0.01	0.122	0.01
20	-0.139	0.01	-0.183	0.01	-0.277	0.01	0.066	0.00
21t22	-0.968	0.00	0.090	0.00	-0.018	0.00	0.171	0.00
24	-0.928	0.00	0.016	0.00	-0.007	0.00	0.488	0.00
25	-0.903	0.00	0.310	0.00	-0.036	0.00	0.207	0.00
26	-0.655	0.00	0.206	0.00	0.005	0.00	0.083	0.00
27t28	-0.940	0.00	0.140	0.00	0.396	0.00	0.018	0.01
29	-0.181	0.01	-0.030	0.00	-0.174	0.00	0.082	0.00
30t33	-0.770	0.00	0.103	0.00	-0.185	0.00	0.186	0.00
34t35	-0.605	0.01	-0.093	0.01	0.046	0.00	0.373	0.00
36t37	-0.595	0.00	0.169	0.00	0.076	0.00	-0.153	0.01
E	-0.829	0.01	0.184	0.00	0.244	0.00	0.072	0.00
F	-0.206	0.03	-0.404	0.02	-0.018	0.00	-0.353	0.01
50	-0.184	0.02	-0.473	0.03	-0.027	0.00	0.064	0.00
51	-0.804	0.00	0.107	0.00	-0.144	0.00	0.030	0.00
52	-0.392	0.07	0.796	0.06	-0.228	0.04	-0.430	0.08
H	-0.548	1.04	0.046	1.01	-0.165	0.62	-0.118	0.62
60	-0.822	0.01	0.031	0.02	0.208	0.00	-0.348	0.02
62	-0.935	0.02	0.126	0.08	0.204	0.08	0.137	0.04
63	-1.311	0.02	0.493	0.01	0.057	0.00	-0.022	0.00
64	-0.676	0.00	0.216	0.00	-0.001	0.00	0.058	0.00
J	-0.538	0.00	0.197	0.00	0.080	0.00	-0.064	0.00
70	-0.356	0.01	0.090	0.00	0.033	0.00	0.036	0.00
71t74	-0.402	0.04	-0.085	0.04	-0.249	0.02	0.010	0.01
L	-0.692	0.03	0.538	0.01	0.041	0.01	0.003	0.01
M	-1.174	0.97	0.959	0.92	-0.028	0.21	0.018	0.03
N	-0.178	0.04	-0.001	0.03	0.029	0.00	0.054	0.00
O	-0.417	0.01	0.161	0.00	-0.222	0.01	-0.042	0.00

S.E. is the standard error, based on *ex post* forecast values of cost shares

Table 5: Own and cross price and elasticities of L

L	K	S.E.	L	S.E.	E	S.E.	M^m	S.E.
AtB	0.356	0.01	-0.706	0.01	-0.044	0.00	0.049	0.00
C	0.093	0.02	-0.543	0.03	-0.054	0.02	-0.012	0.01
15t16	0.016	0.00	-0.987	0.00	0.037	0.00	0.080	0.00
17t18	-0.033	0.00	-0.367	0.00	0.055	0.00	0.026	0.00
19	0.053	0.00	-0.581	0.00	0.050	0.00	0.071	0.00
20	-0.023	0.00	-0.755	0.00	0.089	0.00	0.195	0.00
21t22	0.066	0.00	-0.822	0.00	0.104	0.00	0.108	0.00
24	0.028	0.00	-0.965	0.00	0.384	0.01	0.141	0.00
25	0.175	0.00	-0.967	0.00	0.066	0.00	0.322	0.00
26	0.131	0.00	-0.791	0.00	0.102	0.00	0.173	0.00
27t28	0.065	0.00	-0.568	0.00	-0.115	0.00	0.281	0.00
29	-0.003	0.00	-0.712	0.00	0.000	0.00	0.193	0.00
30t33	0.042	0.00	-0.722	0.00	0.100	0.00	0.308	0.00
34t35	-0.059	0.00	-1.185	0.01	-0.077	0.00	0.430	0.01
36t37	0.056	0.00	-0.967	0.00	-0.071	0.00	0.401	0.00
E	0.376	0.00	-0.701	0.00	-0.071	0.01	0.031	0.00
F	-0.084	0.00	-0.322	0.00	0.101	0.00	0.054	0.00
50	-0.223	0.00	-0.217	0.00	-0.037	0.00	0.086	0.00
51	0.093	0.00	-0.599	0.00	0.108	0.00	0.087	0.00
52	0.200	0.00	-0.565	0.00	0.023	0.00	0.055	0.00
H	0.025	0.00	-0.485	0.00	0.003	0.00	0.064	0.00
60	0.038	0.01	-0.611	0.01	0.219	0.00	0.147	0.00
62	-0.060	0.00	-0.674	0.00	-0.019	0.00	0.268	0.00
63	0.366	0.01	-0.596	0.00	0.077	0.00	0.078	0.00
64	0.237	0.00	-0.789	0.00	0.100	0.00	0.069	0.00
J	0.176	0.00	-0.498	0.00	-0.062	0.00	0.092	0.00
70	1.194	0.10	-0.808	0.02	-0.580	0.11	-0.286	0.06
71t74	0.011	0.00	-0.437	0.00	0.161	0.00	0.053	0.00
L	0.167	0.00	-0.618	0.00	0.002	0.00	0.057	0.00
M	-0.011	0.00	-0.223	0.00	0.008	0.00	0.014	0.00
N	-0.006	0.00	-0.332	0.00	0.084	0.00	0.053	0.00
O	0.060	0.00	-0.696	0.00	0.073	0.00	0.110	0.00

S.E. is the standard error, based on *ex post* forecast values of cost shares

Table 6: Own and cross price and elasticities of E

E	K	S.E.	L	S.E.	E	S.E.	M^m	S.E.
AtB	0.906	0.06	-0.341	0.03	-0.863	0.05	-0.302	0.02
C	-0.075	0.01	-0.108	0.01	-0.770	0.04	0.310	0.02
15t16	-0.190	0.05	0.269	0.02	-0.156	0.13	-0.534	0.11
17t18	-0.706	0.04	0.531	0.03	-0.091	0.02	-0.106	0.01
19	-0.467	0.02	0.525	0.02	-0.651	0.04	-0.512	0.01
20	-0.686	0.06	0.801	0.05	-0.214	0.05	-0.172	0.02
21t22	-0.104	0.01	0.845	0.04	-0.781	0.05	-0.235	0.01
24	-0.119	0.01	0.882	0.04	-0.606	0.04	-0.296	0.01
25	-0.201	0.01	0.544	0.03	-0.713	0.04	0.257	0.01
26	0.008	0.01	0.331	0.02	-0.686	0.05	-0.008	0.00
27t28	0.688	0.04	-0.525	0.04	-0.203	0.03	-0.242	0.02
29	-1.359	0.46	-0.083	0.10	-0.084	0.28	0.293	0.02
30t33	-2.334	0.64	2.209	0.53	-0.365	0.16	-0.180	0.13
34t35	0.287	0.07	-1.139	0.44	-0.069	0.31	-0.453	0.26
36t37	0.292	0.02	-1.182	0.08	-0.270	0.03	0.304	0.02
E	0.432	0.02	-0.084	0.01	-0.589	0.03	-0.113	0.01
F	-0.119	0.08	3.271	0.97	-0.611	0.12	-1.675	0.58
50	-0.325	0.03	-0.905	0.08	-0.245	0.04	0.043	0.00
51	-2.165	0.45	2.840	0.48	-0.253	0.13	0.357	0.05
52	-0.694	0.04	0.440	0.02	-0.726	0.04	-0.100	0.01
H	-1.067	0.20	-0.008	0.06	-0.162	0.13	-0.248	0.05
60	0.170	0.01	0.613	0.03	-0.696	0.04	-0.238	0.01
62	0.345	0.02	-0.054	0.00	-0.651	0.04	0.233	0.01
63	0.430	0.02	0.802	0.04	-1.434	0.07	-0.261	0.02
64	-0.782	0.19	2.063	0.33	-0.628	0.07	-0.468	0.10
J	3.379	1.31	-3.148	1.44	-2.304	0.56	-0.755	0.35
70	10.666	1.75	-11.658	2.04	-0.252	0.14	-0.147	0.03
71t74	-3.348	4.33	6.132	7.10	-0.192	0.98	-1.372	1.79
L	0.646	0.04	0.006	0.01	-0.340	0.02	-0.200	0.01
M	0.912	0.06	0.015	0.03	-1.822	0.10	-0.073	0.01
N	0.174	0.01	2.772	0.38	-2.397	0.25	-0.708	0.13
O	-1.925	1.18	1.396	0.58	-0.250	0.42	-1.161	0.71

S.E. is the standard error, based on *ex post* forecast values of cost shares

Table 7: Own and cross price and elasticities of M^m

M^m	K	S.E.	L	S.E.	E	S.E.	M^m	S.E.
AtB	0.258	0.02	0.241	0.02	-0.161	0.01	-0.836	0.05
C	-0.096	0.01	0.001	0.01	0.257	0.01	-0.518	0.03
15t16	-0.060	0.00	0.087	0.01	-0.094	0.01	-0.841	0.05
17t18	0.040	0.00	0.006	0.00	-0.013	0.00	-0.660	0.04
19	-0.312	0.02	-1.568	0.07	-0.512	0.01	-0.802	0.04
20	0.044	0.00	0.261	0.01	-0.030	0.00	-0.520	0.03
21t22	0.122	0.01	0.124	0.01	-0.024	0.00	-0.788	0.04
24	0.352	0.02	0.089	0.01	-0.045	0.00	-0.578	0.03
25	0.094	0.01	0.268	0.01	0.027	0.00	-0.789	0.04
26	0.080	0.00	0.280	0.02	-0.006	0.00	-0.808	0.04
27t28	0.008	0.00	0.228	0.01	-0.044	0.00	-0.735	0.04
29	0.031	0.00	0.193	0.01	0.018	0.00	-0.775	0.04
30t33	0.057	0.00	0.213	0.01	-0.003	0.00	-0.680	0.04
34t35	0.084	0.00	0.243	0.01	-0.014	0.00	-0.669	0.04
36t37	-0.045	0.00	0.574	0.03	0.031	0.00	-0.898	0.05
E	0.464	0.03	0.081	0.01	-0.448	0.03	-0.562	0.03
F	-0.166	0.01	0.095	0.01	-0.123	0.01	-0.592	0.03
50	0.111	0.01	0.264	0.01	0.006	0.00	-0.817	0.04
51	0.076	0.01	0.326	0.02	0.058	0.00	-0.728	0.04
52	-0.492	0.03	0.384	0.02	-0.040	0.00	-0.859	0.05
H	-0.265	0.02	0.311	0.02	-0.083	0.00	-0.787	0.04
60	-0.444	0.03	0.738	0.04	-0.466	0.04	-0.552	0.03
62	0.000	0.00	0.332	0.02	0.171	0.01	-0.706	0.04
63	-0.046	0.01	0.172	0.01	-0.054	0.00	-0.695	0.04
64	0.031	0.01	0.190	0.01	-0.071	0.00	-0.758	0.04
J	-0.440	0.03	0.400	0.02	-0.092	0.01	-0.578	0.04
70	0.850	0.05	-0.460	0.06	-0.004	0.00	-0.687	0.05
71t74	0.030	0.01	0.195	0.01	-0.191	0.01	-0.772	0.04
L	-0.213	0.01	0.471	0.03	-0.061	0.00	-0.815	0.04
M	0.192	0.01	0.242	0.02	-0.064	0.00	-0.855	0.05
N	0.063	0.00	0.312	0.02	-0.151	0.01	-0.838	0.05
O	-0.145	0.01	0.516	0.03	-0.322	0.02	-0.772	0.04

S.E. is the standard error, based on *ex post* forecast values of cost shares

Table 8: Parameter values of the ADL model for vintage effects on energy efficiency

	η_t		η_t		η_t	
	21t22		26		27t28	
η_{t-1}	0.8636	***	0.7276	***	0.6884	***
	(0.035)		(0.037)		(0.155)	
I_t/K_t	0.0566	*	0.0213	*	-0.1689	
	(0.038)		(0.017)		(0.441)	
I_{t-1}/K_{t-1}	0		0.0157		0.4199	
			(0.017)		(0.600)	
long run elasticity	0.415		0.136		0.806	

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