Consumption vs. Production Based CO_2 Pricing Policies: Macroeconomic Trade-Offs and Carbon Leakage

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Abstract:

This paper compares the traditional environmental tax reform for CO_2 emissions with a taxation scheme that taxes CO_2 emissions embodied in consumption instead of domestic production in the framework of a unilateral policy of the EU27. The embodied emissions are taxed independently of their origin. The CO_2 tax rates applied are identical and revenues of the new CO_2 tax are in both cases recycled via lower social security contributions of employers as well as of employees. The analysis is done with a DYNK (Dynamic New Keynesian) model covering 59 industries and five groups of household income for the EU27. The domestically (within the EU 27) embodied CO_2 emissions are calculated by unitary shocks for each commodity in the DYNK model. The emissions embodied in imports from Non-EU 27 as well as the resulting carbon leakage from an EU 27 perspective are calculated using a simple MRIO (Multi-Regional Input-Output) model. The results show the different macroeconomic results, driven by the different impact of the taxation schemes on price competitiveness of EU 27 firms. These differences in trade effects also drive the differences in leakage and show considerable negative leakage effects in the case of taxing embodied CO_2 emissions. Both taxation schemes are also regressive for household incomes, but in a very different magnitude.

Introduction

Environmental tax reform and CO_2 pricing policies in one world region in the form of unilateral climate policy lead to problems of price competitiveness of the manufacturers in this region and to 'carbon leakage', i.e. relocation of energy and emission intensive production to the other world regions without climate policy, thereby causing possibly higher emissions per output globally and harming domestic industry. The studies based on model simulations estimate the potential of carbon leakage between 15 and 30% of the emissions avoided domestically by the climate policy measures.

The literature on carbon leakage in the case of a unilateral climate policy of the 'Kyoto countries' identifies different potential channels for or carbon leakage. One mechanism is working via international energy markets and has led to the formulation of the 'green paradox'. Unilateral climate policy in a significant part of the world economy leads to lower world energy demand and that might in turn lead to lower world energy prices and therefore stimulate energy demand in those regions that are not constrained by climate policy.

The most important channel is the relocation of industries to other countries that do not face carbon constraints due to the higher costs and output prices in the climate policy regions. Large part of the literature consists of CGE model simulations on this channel (for example: Burniaux, Oliveira Martin, 2000, Paltsev, 2000). The mechanism for leakage is that domestic output of energy intensive activities is crowded out by imports according to the Armington elasticities traditionally used in these models.

In order to avoid the negative impacts on price competitiveness, several studies have analysed the potential of border tax adjustments with ambiguous results as far as the welfare impact is concerned (Lockwood and Whalley, 2008 and Dong and Whalley, 2009). Recently, as an alternative to border tax adjustment, the idea of taxing the carbon footprint has been discussed (Eichner and Pethig, 2015, or McAusland and Najjar, 2015). This paper deals with the idea of taxing the consumption CO_2 footprint within the EU 27 and compares the socio-economic as well as the environmental impact of this unilateral climate policy strategy with traditional green tax reform. For the environmental impact an estimate of leakage is considered. Taxing the CO_2 footprint while in parallel reducing payroll taxes in a revenue neutral manner is seen as a special case of ‘fiscal devaluation’ as far as the impact on the price system is concerned.

The two alternative policy schemes have different impacts on the price system and on leakage. Green tax reform reduces some output prices and raises others, depending on the relative labour and emission intensity of an industry and raises consumer prices, which in turn increase wage costs. Environmental fiscal devaluation unambiguously reduces output prices and raises consumer prices, thereby improving price competitiveness. Green tax reform exhibits carbon leakage in the range of the findings of the literature, whereas environmental tax reform leads to relatively higher ‘negative leakage’.

In section 2 of the paper the DYNK model for the EU 27 is described. Achieving policy targets for resource use without violating economic and social targets requires the decoupling of resource use from income or GDP. Impact analysis on the reduction of GHG emissions is often based on partial models of the energy system without taking into account the socio-economic feedbacks of the instruments applied. The repercussions of policies that are successful in reducing emission and resource use can be positive, via a 'rebound effect', or negative, if the economic costs dominate the benefits and are not compensated by other measures. These repercussions usually do not work through one direct impact channel, but by the interplay of different feedbacks. Therefore, a comprehensive modelling approach like the DYNK model is needed in order to take into account all linkages between the physical flows that are to be reduced and key variables in the economic system.

In section 3 two different policy scenarios are formulated and simulation results for both scenarios are presented and discussed. Section 4 draws some conclusions.

2. The model

The model approach applied can be characterized as a DYNK (DYnamic New Keynesian) model with rigidities and institutional frictions. In that aspect, the DYNK model bears some similarities with the DSGE (Dynamic Stochastic General Equilibrium) approach, as it explicitly describes an adjustment path towards a long-run equilibrium. This feature of dynamic adjustment towards equilibrium is most developed in the consumption block and in the macroeconomic closure via a fixed short and long-term path for the public deficit. The term 'New Keynesian' refers to the existence of a log-run full employment equilibrium, which will not be reached in the short run, due to institutional rigidities. These rigidities include liquidity constraints for consumers (deviation from the permanent income hypothesis), and wage bargaining (deviation from the competitive labour market). Depending on the magnitude of the distance to the long-run equilibrium, the reaction of macroeconomic aggregates to policy shocks can differ substantially.

The model describes the inter-linkages between 59 industries as well as the consumption of five household income groups by 47 consumption categories. The model is closed by endogenizing parts of public expenditure in order to meet the mid-term stability program for public finances in the EU 27.

2.1 Household behaviour and private consumption

The consumption decision of households in the DYNK model is modeled along the lines of the 'buffer stock model' of consumption (Carroll, 1997), including consumption of durables and nondurables (Luengo-Prado, 2006).

Durable demand and total nondurables

Consumers maximize the present discounted value of expected utility from consumption of nondurable commodity and from the service provided by the stocks of durable commodity:

$$\max_{(C_t,K_t)} V = E_0\left\{\sum_{t=0}^{\infty}\beta^t U(C_t,K_t)\right\} \tag{1}$$

Specifying a CRRA utility function yields:

$$U(C_t,K_t) = \frac{C_t^{1-\rho}}{1-\rho} + \varphi\frac{K_t^{1-\rho}}{1-\rho} \tag{2}$$

where φ is a preference parameter and $\rho > 0$ implies risk aversion of consumers.

The budget constraint in this model without adjustment costs for the durables stock is given by the definition of assets, A_t:

$$A_t = (1+r)(1-t_r)A_{t-1} + YD_t - C_t - (K_t - (1-\delta)K_{t-1}) \tag{3}$$

In (3) the sum of C_t and $\left(K_t - (1-\delta)K_{t-1}\right)$ represents total consumption, i.e. the sum of nondurable and durable expenditure (with depreciation rate of the durable stock, □). The gross profit income rA_{t-1} is taxed with tax rate t_r. These taxes therefore reduce the flow of net lending of households that accumulates to future assets. Disposable household income excluding profit income, YD_t, is given as the balance of net wages $(1-t_S-t_Y)w_tH_t$ and net operating surplus accruing to households $(1-t_Y)\Pi_{h,t}$, plus unemployment benefits transfers with UN_t as unemployed persons and br as the benefit replacement rate, measured in terms of the after tax wage rate, plus other transfers Tr_t:

$$YD_t = (1-t_S-t_Y)w_tH_t + (1-t_Y)\Pi_{h,t} + brw_t(1-t_S-t_Y)UN_t + Tr_t \tag{4}$$

The following taxes are charged on household income: social security contributions with tax rate t_S, which can be further decomposed into an employee and an employer’s tax rate (t_{wL} and t_L) and income taxes with tax rate t_Y. The wage rate w_t is the wage per hour and H_t are total hours demanded by firms. Wage bargaining between firms and unions takes place over the employee’s gross wage, i.e. w_t (1 - t_L).

All the income categories are modelled at the level of quintiles q of household incomes (q = 1…5):

$$YD_t = \sum_q (1-t_{S,q}-t_{Y,q})w_{t,q}H_{t,q} + (1-t_{Y,q})\Pi_{t,q} + Tr_{t,q} \tag{5}$$

The wage income, i.e. the product of wage rates and hours worked, is determined at the level of three skill levels (s) and is distributed according to the shares of these wage categories ($w_{q,s}$) across the quintiles in order to derive $w_{t,q}H_{t,q}$. Defining $\mathbf{y}^{\mathrm{w}}_{\mathrm{q,t}}$ as the (column) vector of wages by quintiles (whose elements are $w_{t,q}H_{t,q}$) and multiplying the matrix $\mathbf{S}_{\mathrm{q,s}}$ of the shares $w_{q,s}$ with the (column) vector of wages by skill levels, $\mathbf{y}^{\mathrm{w}}_{\mathrm{s,t}}$, yields the (column) vector of wages by quintiles: $\mathbf{y}^{\mathrm{w}}_{\mathrm{q,t}} = \mathbf{S}_{\mathrm{q,s}}\mathbf{y}^{\mathrm{w}}_{\mathrm{s,t}}$.

Financial assets of households are built up by saving after durable purchasing has been financed, and the constraint for lending is:

$$A_t + (1-\theta)K_t \geq 0 \tag{6}$$

This term represents voluntary equity holding, $Q_{t+1} = A_t + (1 - \theta)K_t$, as the equivalent of the other part of the durable stock (θK_t) needs to be held as equity. The consideration of the collateralized constraint is operationalized in a down payment requirement parameter θ, which represents the fraction of durables purchases that a household is not allowed to finance. One main variable in the buffer stock-model of consumption is ‘cash on hand’, X_t, measuring the household’s total resources:

$$X_t = (1 + r_t)(1 - t_r)A_{t-1} + (1 - \delta)K_{t-1} + YD_t \tag{7}$$

Total consumption is then defined as:

$$CP_t = C_t + K_t - (1 - \delta)K_{t-1} = r_t(1 - t_r)A_{t-1} + YD_t - (A_{t-1} - A_t) \tag{8}$$

In (8) the last term represents net lending, so total consumption is the sum of durable and nondurable consumption or the difference between disposable income and net lending.

The model solution works via deriving the first order conditions for $\frac{\partial U_t}{\partial C_t}$ and $\frac{\partial U_t}{\partial K_t}$ taking into account $\frac{\partial C_t}{\partial K_t}$. Luengo-Prado (2006) arrives at an intra-temporal equilibrium relationship between C_t and K_t (mostly following Chah, et al., 1995) as one solution of the model, where the constraint is not binding, or (which is equivalent) the down payment share θ equals the user costs $\frac{r+\delta}{1+r}$. For all other cases, where the collateral constraint is binding, Luengo-Prado (2006) has shown that this relationship can be used to derive policy functions for C_t and K_t and formulate both as functions of the difference between cash on hand and the equity that the consumer wants to hold in the next period. A non-linear consumption function for durables, similar to the function described in Luengo-Prado and Sørensen (2004) for nondurables, is assumed, stating that consumers seek for an equilibrium relationship of durables per household, *h*. This is based on the concave shape of the policy functions for consumption in Luengo-Prado (2006), where at higher levels of ‘cash on hand’ a proportionally larger part of voluntary equity is accumulated. Therefore, with higher levels of durables per households, the marginal propensity of investment in durables, C_{Kt} with respect to X_t decreases ($\beta_{K,4} < 0$) according to:

$$\log C_{dur,t} = \beta_K + \beta_{K,1}\log X_t + \beta_{K,2}\theta_{Ct} + \beta_{K,3}\log\left(p_{dur,t}(r_t+\delta)\right) + \beta_{K,4}\log X_t \log\left(K_{t-1}/h_{t-1}\right) \tag{9}$$

Note that $C_{dur,t}$ is equal to K_t - (1 - δ)K_{t-1} in equation (8). The down payemt parameter θinLuengo-Prado (2006) represents a long-term constraint between the liabilities stock and the durable stock of households that is imposed on financial markets and might change over time. Changes in this constraint on stocks can only be achieved in the long-term by imposing limits to the down payment for durable purchases, θ_{Ct}.

Equation (9) can be seen as the long-run relationship between $C_{dur,t}$ and X_t. The long-run marginal propensity of durable demand to cash on hand depends on the accumulated stock K_t/h_t and is defined by: $\beta_{K,1} + \beta_{K,4}\log\left(K_{t-1}/h_{t-1}\right)$. In the long-run, with rising income, households do not keep the relationship between durables and income constant, but the relationship between voluntary equity holding and income. That corresponds to the long-run solution of the buffer stock model without durables, where all equity accumulation is voluntary, because no collateral constraint is active. Usually, in the buffer stock model, non-stationarity of consumption, income and wealth is dealt with by normalizing the variables by dividing through permanent income. In this paper, instead, the non-stationarity is taken into account by formulating adjustment processes of short-term behavior towards long-run optimal relationships. Therefore, demand for durables is formulated as an error correction mechanism (ECM), like in Caballero, 1993 and Eberly, 1994:

$$d\log C_{dur,t} = \gamma_K + \gamma_{K,1}\log d\log X_t + \gamma_{K,ECM}\begin{bmatrix}\log C_{dur,t-1} - \beta_K + \beta_{K,1}\log X_{t-1} + \beta_{K,2}\theta_{C,t-1} + \\ \beta_{K,3}\log\left(p_{dur,t-1}(r_{t-1}+\delta)\right) + \beta_{K,4}\log X_{t-1}\log\left(K_{t-2}/h_{t-2}\right)\end{bmatrix} \tag{10}$$

In (10) β_K and γ_K are constants (in the panel data regression cross section fixed effects), and $\gamma_{K,ECM}$ represents the ECM parameter with $\gamma_{K,ECM} < 0$. Equation (10) is specified for own houses (dwelling investment) and for vehicles ($C_{hous,t}$ and $C_{veh,t}$). The capital stock for both durables categories ($K_{hous,t}$ and $K_{veh,t}$) accumulates according to the following equation: $K_t = K_{t-1}(1-\delta) + C_{dur,t}$ starting from an estimated initial durable stock in t = 0. The depreciation rates (δ) are specific for both durable categories. Durable consumption is in equation (8) described as an investment (K_t - (1 - δ)K_{t-1}), which is the case for one of the two durable categories, namely expenditure for vehicle purchases. For own houses the consumption data do not contain dwelling investment for own houses, but imputed rents. This is due to the concepts in national accounting, which treat housing different from other durables. The imputed rents are calculated as a simple static user cost: $C_{rent,t} = p_{dur,t}(r_t + \delta)K_t$ The demand function for total nondurable consumption is modeled with a positive marginal propensity of nondurable consumption to ‘cash on hand’ and a negative marginal propensity of total nondurable consumption to the product of the down payment (in percentage of durables) and durable demand:

$$\log C_t = \beta_C + \beta_{C,1} \log X_t + \beta_{C,2}\theta_{Ct} \log C_{dur,t} \qquad (11)$$

This function takes into account that households need to finance the sum of $C_t + \theta_{Ct} C_{dur,t}$, but down payments will not be fully financed by savings in the same period and consumers smooth nondurable consumption accordingly. This smoothing is measured in (11) by the parameter $\beta_{C,2}$.

The long-run marginal propensity of nondurable demand to cash on hand is given by the direct impact ($\beta_{C,1}$) plus the indirect impact via $\theta_{Ct}\log C_{dur,t}$. The latter again depends on $\beta_{K,1} + \beta_{K,4} \log(K_{t-1}/h_{t-1})$, so that the total marginal propensity of nondurable demand to cash on hand is defined by: $\beta_{C,1} + \theta_{Ct}\beta_{C,2}\beta_{K,1} + \theta_{Ct}\beta_{C,2}\beta_{K,4} \log(K_{t-1}/h_{t-1})$.

The second term in this relationship measures the necessary increase in savings for down payments due to an increase in durable demand, induced by a marginal increase in cash on hand. The last term measures the impact of the non-linearity in the reaction of durables demand to cash on hand on savings (and on nondurable demand). Note that as durable demand reacts to the price of durables and nondurable demand is linked to durable demand in (10), there is also an implicit price elasticity for nondurables at work. Like in the case of durable demand, the error correction mechanism (ECM) representation of (10) is:

$$d\log C_t = \gamma_C + \gamma_{C,1} \log d\log X_t + \gamma_{C,ECM}\left[\log C_{t-1} - \beta_C + \beta_{C,1} \log X_{t-1} + \beta_{C,2}\theta_{C,t-1} \log C_{dur,t-1}\right] \qquad (12)$$

The data for the estimation of consumption demand functions are mainly taken from EUROSTAT's National Accounts. That comprises the expenditure data as well as all income components and asset data, which are part of cash on hand. The categories of durable consumption in our model comprise investment in own houses and purchases of vehicles. Due to the specific treatment of housing in the consumption accounts of national accounting, investment in own houses is pooled together with other dwelling investment to derive total dwelling investment. In a first step, a capital stock of housing property was estimated for one year, based on the Household Financial and Consumption Survey (HFCS) of the ECB. By applying property prices from the Bank of International Settlement (BIS) and EUROSTAT population data, a time series of owned houses was constructed for those 14 EU countries where sectoral accounts (income, asset data) were available from 1995 to 2011. A more simple procedure could be applied to vehicles, as the expenditure data are available (C_{veh} in (13)) and no revaluation of the existing stock needed to be taken into account there. For own houses, the dwelling investment (CF_{hous}) was calculated as implicit. Measuring all variables in current prices, the two capital stocks K_{veh} and K_{hous} in current prices accumulate according to the following equations:

$$K_{veh,t} = K_{veh,t-1}\left(1-\delta_{veh}\right)+C_{veh,t} \tag{13}$$

$$K_{hous,t} = \frac{p_{hous,t}}{p_{hous,t-1}}\left[K_{hous,t-1}\left(1-\delta_{hous,t}\right)+CF_{hous,t} / p_{CF,t}\right] \tag{14}$$

In (14) revaluation of the stock is driven by the yearly change in house prices. The price p_{hous} is the price of the housing stock and comprises increases in construction prices (p_{CF}) as well as changes in land prices. The variables C_{veh} and CF_{hous} add up to total gross capital formation by households, a variable that is also found in the sectoral accounts of households in National Accounts. Given the demand and the accumulated stock of owner occupied houses, imputed rents are calculated by applying a user cost formulation. These imputed rents enter the consumption accounts. The expenditure for imputed rents, vehicles and total nondurables adds up to total private consumption.The down payment for durable purchases, θ_{Ct} is calculated by relating the change in liabilities to the durable demands (C_{veh} and CF_{hous}), that gives (1 - θ_{Ct}). The original θ_t from Luengo-Prado (2006) is measured in this model by the relationship (1 – liabilities/durable stock) and can only be controlled by fixing certain values of θ_{Ct} and solving the model to derive the path of θ_t. In an iterative procedure dynamic convergence towards target values of θ_t can then be achieved. The functions for the two durable demand categories and for total nondurables have been estimated with panel data econometrics for 14 EU countries (1995 - 2011), based on EUROSTAT and other sources. The EU 14 countries with a full data set are: (1) Belgium, (2) Czech Republic, (3) Denmark, (4) Germany, (5) France, (6) Italy, (7) Cyprus, (8) Lithuania, (9) Austria, (10) Poland, (11) Portugal, (12) Romania, (13) Slovakia, and (14) Finland.[1]Non-linear relationships of durable consumption and 'cash on hand' have been identified from these estimations. Non-stationarity has not been considered by normalizing by permanent income as is usual in the calibrated versions of the buffer stock model, but by directly carrying out panel data unit root tests and estimating an error correction mechanism (ECM) model.

Energy demand

The energy demand of households comprises fuel for transport, electricity and heating. These demands are part of total nondurable consumption and are modeled in single equations, therefore assuming separability from non-energy nondurable consumption. According to the literature on the rebound effect (e.g.: Khazzoom, 1989), the energy demand is modeled as (nominal) service demand and the service aspect is taken into account by dealing with service prices. The durable stock of households (vehicles, houses, appliances) embodies the efficiency of converting an energy flow into a service level $S = \eta_{ES} E$, where E is the energy demand for a certain fuel and S is the demand for a service inversely linked by the efficiency parameter (η_{ES}) of converting the corresponding fuel into a certain service. For a given conversion efficiency, a service price, p_S, (marginal cost of service) can be derived, which is a function of the energy price and the efficiency parameter. Any increase in efficiency leads to a decrease in the service price and thereby to an increase in service demand ('rebound effect').

$$p_S = \frac{p_E}{\eta_{ES}} \qquad (15)$$

[1]The limiting factor in the data set where the sectoral accounts, which are not available from 1995 on for all EU27.

For transport demand of households we take substitution between public (CP_{pub}) and private transport (CP_{fuel}) into account. For this purpose, a price (pc_{tr}) of the aggregate transport demand, CP_{tr}, is constructed:

$$pc_{tr} = \exp\left[\frac{CP_{fuel}}{CP_{tr}}\log pc_{S,fuel} + \frac{CP_{pub}}{CP_{tr}}\log pc_{pub}\right] \tag{16}$$

The price for fuels, $pc_{S,fuel}$, is defined as a service price. Total transport demand of households depends on this aggregate price as well as on total nondurable expenditure in a log-linear specification, so that the price and expenditure elasticity can be derived directly from the parameters ($\beta_{tr,1}$ and $\beta_{tr,2}$) :

$$\log CP_{tr} = \mu_{tr} + \beta_{tr,1}\log pc_{tr} + \beta_{tr,2}\log C_t \tag{17}$$

In (17) μ_{tr} is a constant or a cross section fixed effect in the panel data model.

The demand for transport fuels is linked to the vehicle stock and depends on the service price of fuels as well as on the endowment of vehicles of the population. The latter term is important because the second car of the household usually is used less in terms of miles driven than the first.

$$\log\left(\frac{CP_{fuel,t}}{K_{veh,t}}\right) = \mu_{fuel} + \gamma_{fuel}\log\left(\frac{p_{fuel,t}}{\eta_{fuel,t}}\right) + \xi_{fuel}\log\left(\frac{K_{veh,t}}{h_t}\right) \tag{18}$$

In (18) μ_{fuel} again is a constant or a cross section fixed effect and γ_{fuel} is the price elasticity under the condition that there is a unitary elasticity of fuel demand to the vehicle stock. Once total transport demand of households and demand for fuels for transport are determined, public transport demand can be derived as a residual.

The equations for heating and electricity demand are analogous to equation (18) and have the following form:

$$\log\left(\frac{CP_{heat,t}}{K_{hous,t}}\right) = \mu_{heat} + \gamma_{heat}\log\left(\frac{p_{heat,t}}{\eta_{heat,t}}\right) + \xi_{heat}\log(dd_{heat}) \tag{19}$$

$$\log\left(\frac{CP_{el,t}}{K_{app,t}}\right) = \mu_{el} + \gamma_{el}\log\left(\frac{p_{el,t}}{\eta_{el,t}}\right) + \xi_{el}\log(dd_{heat}) \tag{20}$$

In both equations the variable heating degree days dd_{heat} is added. All equations also contain autoregressive terms that have been omitted in this presentation. The durable stocks used are the total housing stock ($K_{hous,t}$) and the appliance stock ($K_{app,t}$). The latter is accumulated from consumption of appliances, CP_{app}, which in turn is explained in a log linear specification like total transport demand:

$$\log CP_{app} = \mu_{app} + \beta_{app,1}\log pc_{app} + \beta_{app,2}\log C_t \tag{21}$$

Again, μ_{app} is a constant or a cross section fixed effect. The total housing stock ($K_{hous,t}$) contains the stock of own houses, which is explained above and the stock of houses that are rented by households. The latter is driven by population dynamics.

The energy expenditure of households is based on consumption expenditure data from EUROSTAT, the Energy Accounts from the WIOD database, as well as IEA Energy Prices. In order to calculate service prices, energy efficiency data had to be added. Energy efficiency for electricity is calculated as a weighted average of efficiency of electrical appliances from the ODYSSEE database. The efficiency for heating is approximated by the indicator for heating efficiency in the ODYSSEE database. Heat efficiency of the car fleet could in a revised version also be taken from the database of the GAINS project. The durable stock of households (vehicles, houses, appliances) embodies the efficiency of converting an energy flow into a service level. Policy measures that increase the efficiency of the new durables purchased or speed up the renovation of the durable stock by premature scrapping, therefore lead to less direct energy demand of households and rebound effects from higher service demand. The panel data set resulting from this data collection process comprises all EU 27 countries.

Nondurable (non-energy) demand

The non-energy demand of nondurables is treated in a demand system. The one applied in this DYNK model is the Almost Ideal Demand System (AIDS), starting from the cost function for $C(u, p_i)$, describing the expenditure function (for C) as a function of a given level of utility u

and prices of consumer goods, p_i (see: Deaton and Muellbauer, 1980) . The AIDS model is represented by the well known budget share equations for the *i* nondurable goods in each period:

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_i \log\left(\frac{C}{P}\right) \quad ; \quad i = 1...n,\ 1...k \tag{22}$$

with price index, P_t, defined by $\log P_t = \alpha_0 + \sum_i \alpha_i \log p_{it} + 0.5 \sum_i \sum_j \gamma_{ij} \log p_{it} \log p_{jt}$, often approached by the Stone price index: $\log P_t^* = \sum_k w_{it} \log p_{it}$.

The expressions for expenditure (η_i) and compensated price elasticities (ε_{ij}^C) within the AIDS model for the quantity of each consumption category C_i can be written as (the details of the derivation can be found in Green, and Alston, 1990)[2]:

$$\eta_i = \frac{\partial \log C_i}{\partial \log C} = \frac{\beta_i}{w_i} + 1 \tag{23}$$

$$\varepsilon_{ij}^C = \frac{\partial \log C_i}{\partial \log p_j} = \frac{\gamma_{ij} - \beta_i w_j}{w_i} - \delta_{ij} + \varepsilon_i w_j \tag{24}$$

In (24) δ_{ij} is the Kronecker delta with $\delta_{ij} = 0$ for $i \neq j$ and $\delta_{ij} = 1$ for $i = j$.

The commodity classification $i = 1...n$ in this model comprises the *n* non-energy nondurables: (i) food, and beverages, tobacco, (ii) clothing, and footwear, (iii) furniture and household equipment, (iv) health, (v) communication, (vi) recreation and accomodation, (vii) financial services, and (viii) other commodities and services.

The main results of the estimation of the demand system for non-energy nondurables are expenditure and price elasticities. The expenditure elasticities are closely distributed around unity, the price elasticity shows more heterogeneity across categories. This elasticity mainly determines the reactions to commodity taxation in consumption.

Total household demand

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[2] The derivation oft the budget share w_i with respect to log (C) and log (p_j) is given by β_i and $\gamma_{ij} - \beta_i$ (log(P)) respectively. Applying Shephard's Lemma and using the Stone price approximation, the elasticity formulae can then be derived.

The household model described determines in three stages the demand for different categories of durables, energy demand and different categories of nondurables. The vector of non-energy nondurable consumption, $(\mathbf{c}_{\mathrm{NE}})$ as described above, is given by multiplying total non-energy nondurable expenditure C with the column vector of budget shares, **w** (all bold characters are vectors or matrices):

$$(\mathbf{c}_{\mathrm{NE}}) = C\mathbf{w} \tag{25}$$

The total consumption vector of categories of consumption in National Accounts (according to the COICOP classification), $\mathbf{c}_{\mathrm{C}}$, is transformed into a consumption vector by commodities of the input-output core in the DYNK model in purchaser prices, $\mathbf{c}_{\mathrm{pp}}$, by applying the bridge matrix, $\mathbf{B}_{\mathrm{C}}$:

$$\mathbf{c}_{\mathrm{pp}} = \mathbf{B}_{\mathrm{C}}\,\mathbf{c}_{\mathrm{C}}\ ;\quad \mathbf{c}_{\mathrm{C}} = \quad \mathbf{c}_{\mathrm{NE}} = \begin{pmatrix} .. \\ \mathbf{c}_{\mathrm{i}} \\ .. \end{pmatrix}\ ;\ \mathbf{c}_{\mathrm{E}} = \begin{pmatrix} .. \\ \mathbf{c}_{\mathrm{f}} \\ .. \end{pmatrix};\quad \mathbf{k} = \begin{pmatrix} .. \\ \mathbf{c}_{\mathrm{j}} \\ .. \end{pmatrix} \tag{26}$$

where i = 1...n, f = 1...k, and j = 1...m.

The bridge matrix links the vectors and has the dimension industries in NACE classification * consumption categories in COICOP classification. Multiplying the vector $\mathbf{c}_{\mathrm{C}}$ in equation (26) by the bridge matrix $\mathbf{B}_{\mathrm{C}}$ and by a diagonal matrix of import shares $\mathbf{C}^{\mathrm{m}}$ or by $\left[\mathbf{I}-\mathbf{C}^{\mathrm{m}}\right]$ with **I** as the identity matrix, yields the vector of imported consumption goods ($\mathbf{c}_{\mathrm{pp}}^{\mathrm{m}}$) and of consumption goods from domestic production ($\mathbf{c}_{\mathrm{pp}}^{\mathrm{d}}$) respectively, both in purchaser prices:

$$\mathbf{c}_{\mathrm{pp}}^{\mathrm{m}} = \hat{\mathbf{C}}^{\mathrm{m}}\mathbf{B}_{\mathrm{C}}\begin{pmatrix} \mathbf{c}_{\mathrm{NE}} \\ \mathbf{c}_{\mathrm{E}} \\ \mathbf{k} \end{pmatrix} \qquad \mathbf{c}_{\mathrm{pp}}^{\mathrm{d}} = \left[\mathbf{I}-\hat{\mathbf{C}}^{\mathrm{m}}\right]\mathbf{B}_{\mathrm{C}}\begin{pmatrix} \mathbf{c}_{\mathrm{NE}} \\ \mathbf{c}_{\mathrm{E}} \\ \mathbf{k} \end{pmatrix} \tag{27}$$

After this multiplication, in a first step, taxes less subsidies are subtracted in order to arrive at consumption vectors net of taxes, $\mathbf{c}_{\mathrm{N}}^{\mathrm{m}}$ and $\mathbf{c}_{\mathrm{N}}^{\mathrm{d}}$:

$$\mathbf{c}_{\mathrm{N}}^{\mathrm{m}} = \left[\mathbf{I}-\hat{\mathbf{T}}_{\mathbf{N}}\right]\mathbf{c}_{\mathrm{pp}}^{\mathrm{m}} \qquad \mathbf{c}_{\mathrm{N}}^{\mathrm{d}} = \left[\mathbf{I}-\hat{\mathbf{T}}_{\mathbf{N}}\right]\mathbf{c}_{\mathrm{pp}}^{\mathrm{d}} \tag{28}$$

In (28), $\hat{\mathbf{T}}_{\mathbf{N}}$ is a diagonal matrix of net tax rates (with identical tax rates on domestic and imported commodities), and total net taxes (taxes less subsidies) from consumption are therefore given by:

$$T_N = \hat{\mathbf{T}}_{\mathbf{N}}\left[\mathbf{c}_{\mathrm{pp}}^{\mathrm{m}} + \mathbf{c}_{\mathrm{pp}}^{\mathrm{d}}\right] \tag{29}$$

By subtracting trade and transport margins as well, we arrive at consumption vectors in basic prices that determine consumption demand by detailed commodity.

2.2 Firm behaviour and production structure

The production side in the DYNK model is analysed within the cost and factor demand function framework, i.e. the dual model, in a Translog specification. The representative producers in each industry all face a unit cost function with constant returns to scale that determines the output price (unit cost), for given input prices. The input quantities follow from the factor demand functions, once all prices are determined. The Translog specification chosen in the DYNK model comprises different components of technological change. Autonomous technical change can be found for all input factors (i.e. the factor biases) and also as the driver of TFP (total factor productivity), measured by a linear and a quadratic component.

Substitution in a K,L,E,M^m,M^d model

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_{Mm} and p_{Md}. Applying Shepard's Lemma yields the cost share equations in the Translog case, which in turn are used to derive the quantities of factor demand for (K), (L), (E), (M^m) and (M^d). For this production system the input prices can be viewed as exogenous. One part of the input prices is determined at national or global factor markets, which applies to the prices of (K), (L), and (E). The price of labour is determined at the labour market via wage functions by industry (see below). The price of capital is formulated as a simple static user cost price index with the following components: (i) the price of investment by industry, (ii) the smoothed interest rate, and (iii) the fixed depreciation rate. The financial market and monetary policy are not described in detail in the DYNK model, therefore the interest rate is assumed as exogenous and is approximated by the smoothed benchmark interest rate. The depreciation rate by industry is fixed (see below for data sources) and the price of investment by industry is endogenously derived from the price system in the DYNK model. The price of energy carriers is assumed to be determined at world markets for energy and is therefore treated as exogenous. Each industry faces a unit cost function for the price (p_Q) of output Q, with constant returns to scale

$$\log p_Q = \alpha_0 + \sum_i \alpha_i \log(p_i) + \frac{1}{2}\sum_i \gamma_{ii}(\log(p_i))^2 + \sum_{i,j}\gamma_{ij}\log(p_i)\log(p_j) + \alpha_t t + \frac{1}{2}\alpha_{tt}t^2 + \sum_i \rho_{ti} t \log(p_i) \tag{30}$$

, 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 (30) 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_{Mm} and p_{Md}. 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:

$$\begin{aligned}
v_K &= [\alpha_K + \gamma_{KK}\log(p_K/p_{Md}) + \gamma_{KL}\log(p_L/p_{Md}) + \gamma_{KE}\log(p_E/p_{Md}) + \gamma_{KM}\log(p_{Mm}/p_{Md}) + \rho_{tK}t] \\
v_L &= [\alpha_L + \gamma_{LL}\log(p_L/p_{Md}) + \gamma_{KL}\log(p_K/p_{Md}) + \gamma_{LE}\log(p_E/p_{Md}) + \gamma_{LM}\log(p_{Mm}/p_{Md}) + \rho_{tL}t] \\
v_E &= [\alpha_E + \gamma_{EE}\log(p_E/p_{Md}) + \gamma_{KE}\log(p_K/p_{Md}) + \gamma_{LE}\log(p_L/p_{Md}) + \gamma_{EM}\log(p_{Mm}/p_{Md}) + \rho_{tE}t] \\
v_M &= [\alpha_M + \gamma_{MM}\log(p_{Mm}/p_{Md}) + \gamma_{KM}\log(p_K/p_{Md}) + \gamma_{LM}\log(p_L/p_{Md}) + \gamma_{EM}\log(p_E/p_{Md}) + \rho_{tM}t]
\end{aligned} \tag{31}$$

The homogeneity restriction for the price parameters $\sum_i \gamma_{ij} = 0$, $\sum_j \gamma_{ij} = 0$ has already been imposed in (31), so that the terms for the price of domestic intermediates p_{Md} have been omitted. In this model, labour and import demand react to changes in the prices of all inputs and changes in time due to the factor biases that can be labour saving or labour using, as well as import saving or import using. The immediate reaction to price changes is given by the own and cross price elasticities. These own- and cross- price elasticities for changes in input quantity x_i can be derived directly, or via the Allen elasticities of substitution (AES), and are given as:

$$\varepsilon_{ii} = \frac{\partial \log x_i}{\partial \log p_i} = \frac{v_i^2 - v_i + \gamma_{ii}}{v_i} \tag{32}$$

$$\varepsilon_{ij} = \frac{\partial \log x_i}{\partial \log p_j} = \frac{v_i v_j + \gamma_{ij}}{v_i} \tag{33}$$

Here, the v_i represent the factor shares in equation (31), and the γ_{ij} the cross-price parameters.

The deterministic trend t captures the two different sources of autonomous technological change that together influence factor demand, i.e. TFP and the factor bias. The total impact of t on factor x_i is given by:

$$\frac{d \log x_i}{dt} = \frac{\rho_{ti}}{v_i} + \alpha_t + \alpha_{tt} t \tag{34}$$

This impact therefore depends negatively on the share and on the level of technology, due to the term $\alpha_{tt}t$. The factor shares v_i in (31) can be directly used to derive factor demand (in nominal terms), once the output at current prices $p_Q Q$ is given. For given input prices p_L, p_E, p_{Mm} and p_{Md} this can be transformed into factor demand in real terms (hours worked or employees for L and physical energy units for E). A special treatment is applied to the capital input. This is due to the inherent difference between the *ex post* rate of return to K that is implicit in treating operating surplus as the residual in total output and the *ex ante* rate of return to K used for the specification of the price of K (user cost). In economic terms, that represents an imperfect capital market, which can be in disequilibrium (see: Jorgenson, et al., 2013) so that the adjustment of the *ex post* rate of return to K towards the *ex ante* rate of return to K takes time. It is assumed that after the base year, this adjustment takes place instantaneously and the two prices equate in a dynamic form:

$$d \log(p_{K,t}) = d \log\left[p_{CF,t}(r_t + \delta)\right] \tag{35}$$

The price p_{CF} is the price of investment (capital formation) by industry and once p_K is determined, the factor share for K in (31) can be used to determine K_{jt} by industry (j), which in turn determines investment by industry CF_j by inverting the capital accumulation equation:

$$CF_{j,t} = K_{j,t} - (1-\delta)K_{j,t-1} \tag{36}$$

All data for the production system are derived from the WIOD (World Input Output Database) dataset that contains World Input Output Tables (WIOT) in current and previous year's prices, Environmental Accounts (EA), and Socioeconomic Accounts (SEA). The latter are used to derive data for capital and labour, like the base year capital stock and depreciation rates as well as labour compensation by hour and by person. From the EA we use data of energy use by 25 energy carriers in physical units (TJ) and CO_2 emissions and combine the physical energy inputs with information on energy prices from the IEA to get a full system of energy quantities and prices. The WIOT in current and previous year's prices have been used to derive quantities and prices for (M^m) and (M^d).The system of the unit cost function and the factor cost shares has been estimated with panel data econometrics for 23 EU countries with time series from 1995 to 2009. The systems have been estimated applying the Seemingly Unrelated Regression (SUR) estimator for balanced panels under cross section fixed effects for each of the 35 industries (345 observations). The estimation results yield own and cross price elasticities for capital, labour, energy, and imported intermediates respectively. The own price elasticity of labour is on average about -0.5, with relatively high values in some manufacturing industries. The own price elasticity of energy is very heterogenous across industries and rather high in energy intensive industries.These elasticities have then in turn been used to calibrate the production system for the DYNK model base year (2005) for the EU 27.

Intermediate input demand and factor prices

The factors E, M^m, and M^d are aggregates of the use matrix from the supply and use table system, which is the framework of this DYNK model. The aggregate E comprises four energy industries/commodities, and M^m, M^d the other 55 non-energy industries/commodities.

In a second nest, the factor E is split up into aggregate categories of energy (coal, oil, gas, renewable, electricity/heat) in a Translog model. The unit cost function of this model determines the bundle price of energy, p_E, and the cost shares of the five aggregate energy types:

$$\log p_E = \alpha_0 + \sum_i \alpha_{E,i} \log(p_{E,i}) + \frac{1}{2}\sum_i \gamma_{E,ii} (\log(p_{E,i}))^2 + \sum_{i,j} \gamma_{E,ij} \log(p_i) \log(p_j) + \sum_i \rho_{tE,i} t \log(p_{E,i}) \quad (37)$$

$$v_{E,i} = \left[\alpha_{E,i} + \sum_{i,j} \gamma_{E,ij} \log(p_{E,i}) + \rho_{tE,i} t \right] \quad (38)$$

This set of energy categories is directly linked to the energy commodities/industries of the use table.

The domestic as well as the import matrix are converted into 'use structure matrices' $\mathbf{S}^{\mathrm{m}}_{\mathrm{NE}}$ and $\mathbf{S}^{\mathrm{d}}_{\mathrm{NE}}$ by dividing by the column sum of total domestic and imported non-energy intermediates, respectively. Intermediate inputs by commodity are determined by multiplying diagonal matrices of the factor shares in (31), $\hat{\mathbf{V}}_{\mathrm{D}}$ and $\hat{\mathbf{V}}_{\mathrm{M}}$ with the 'use structure matrices' and with the column vector of output in current prices. The full commodity balance is given by adding the column vector of domestic consumption (equation (28)), capital formation by domestic goods, and other domestic final demand (exports $\mathbf{ex}^{\mathrm{d}}$, changes in stocks $\mathbf{st}^{\mathrm{d}}$ and public consumption $\mathbf{cg}^{\mathrm{d}}$). The capital formation vector by domestic goods is derived by multiplying the vector of investment by industry $\mathbf{cf_j}$ (equation (36)) with the capital structure matrix for investment, derived from the capital formation matrix (investment by industry * investment by commodity) for domestic investment demand: $\mathbf{cf}^{\mathrm{d}} = \mathbf{B}^{\mathrm{d}}_{\mathrm{K}} \mathbf{cf}_{\mathrm{j}}$. The total investment structure matrix is made up of domestic and imported investment structures ($\mathbf{B}^{\mathrm{d}}_{\mathrm{K}}$ and $\mathbf{B}^{\mathrm{m}}_{\mathrm{K}}$) and has column sum of one like the private consumption bridge matrix.

The (column vector) of the domestic output of commodities in current prices, $\mathbf{p}^{\mathrm{D}}\mathbf{Q}^{\mathrm{D}}$, is transformed into the (column vector) of output in current prices, $\mathbf{p}_{\mathrm{Q}}\mathbf{Q}$, by applying the market shares matrix, $\mathbf{C}$ (industries * commodities) with column sum equal to one:

$$\mathbf{p}^{\mathrm{D}}\mathbf{Q}^{\mathrm{D}} = \left[\hat{\mathbf{V}}_{\mathrm{D}} \mathbf{S}^{\mathbf{d}}_{\mathbf{NE}} \right] \mathbf{p}_{\mathrm{Q}}\mathbf{Q} + \mathbf{c}^{\mathrm{d}} + \mathbf{cf}^{\mathrm{d}} + \mathbf{ex}^{\mathrm{d}} + \mathbf{st}^{\mathrm{d}} + \mathbf{cg}^{\mathrm{d}} \quad (39)$$

$$\mathbf{p}_{\mathrm{Q}}\mathbf{Q} = \mathbf{C}\mathbf{p}_{\mathrm{D}}\mathbf{Q}_{\mathrm{D}} \quad (40)$$

The final demand categories in (39), i.e. $\mathbf{c}^{\mathrm{d}}$, $\mathbf{cf}^{\mathrm{d}}$, $\mathbf{ex}^{\mathrm{d}}$, $\mathbf{st}^{\mathrm{d}}$ and $\mathbf{cg}^{\mathrm{d}}$ are all in current prices.

Factor prices are exogenous for the derivation of factor demand, but are endogenous in the system of supply and demand. Some factor prices are directly linked to the output prices p_Q which are determined in the same system. All user prices are the weighted sum of the domestic price p^d and the import price, p^m. The import price of commodity i in country s is given as the weighted sum of the commodity prices of the k sending countries ($p^{d,k}$)

$$p_{i,s}^{m} = \sum_{k=1}^{s-1} w_{mk,s} \, p^{d,k} \tag{41}$$

This is derived from an inter-regional input-output system from the WIOD database. This gives one domestic price per user for each commodity (i.e. no price differentiation for domestic goods) and different import prices per user for each commodity, given by the different country source structure of imports of the same commodity by user. Once this user specific prices for intermediate goods are given, the 'use structure matrices' ($\mathbf{S}_{\mathrm{NE}}^{\mathrm{m}}$ and $\mathbf{S}_{\mathrm{NE}}^{\mathrm{d}}$) can be applied in order to derive the price vectos $\mathbf{p}_{\mathrm{Mm}}$ and $\mathbf{p}_{\mathrm{Md}}$:

$$\mathbf{p}_{\mathrm{Mm}} = \mathbf{p}^{\mathrm{m}}\mathbf{S}_{\mathrm{NE}}^{\mathrm{m}} \qquad \mathbf{p}_{\mathrm{Md}} = \mathbf{p}^{\mathrm{d}}\mathbf{S}_{\mathrm{NE}}^{\mathrm{d}} \tag{42}$$

The price of capital is based on the user cost of capital: $u_K = p_{CF}(r+\delta)$ with p_{CF} 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_{CF} can be defined as a function of the domestic commodity prices and import prices, given the input structures for investment, derived from the capital formation matrix described above for domestic and imported investment demand:

$$\mathbf{p}_{\mathrm{CF}} = \mathbf{p}^{\mathrm{m}}\mathbf{B}_{\mathrm{K}}^{\mathrm{m}} + \mathbf{p}^{\mathrm{d}}\mathbf{B}_{\mathrm{K}}^{\mathrm{d}} \tag{43}$$

It is important to note that by these input-output loops in the model, indirect effects or feedback effects of prices occur and factor demand reactions therefore differ from what the *ceteris paribus* price and substitution elasticities indicate. All user prices (for example the price of private consumption) can further be aggregated in order to derive the aggregate price index of the corresponding demand aggregate.

2.3 Labour market

The wage curves are specified as the employee’s gross wage rate per hour by industry, i.e. w_t (1 - t_L). The labour price (index) of the Translog model is then defined by adding the employers' social security contribution to that. Combining the *meta-analysis* of Folmer (2009) on the empirical wage curve literature with a basic wage bargaining model from Boeters and Savard (2013) gives a specification for the sectoral hourly wages. These functions describe the responsiveness of hourly wages to labour productivity (industry, aggregate), consumer prices, hours worked per employee, and the rate of unemployment. The inclusion of the variable ' hours worked per employee' corresponds to a bargaining model, where firms and workers (or unions) bargain over wages and hours worked simultaneously (Busl and Seymen, 2013). The basic idea is that the gains in labour productivity can be used for cutting hours worked and wage increases simultaneously. While unions formally bargain over an hourly wage rate, they also take annual (or monthly) wage income per head into account (for example for minimum wage considerations). We specify the wage function in a way that the hours can be determined in a first step and then the hourly wage rate is determined. A bargaining over hours that leads to less hours worked, would *ceteris paribus* lower annual wage income per head. Therefore unions, in consequence, bargain an increase in the hourly wage rate, so income per year does not fall in the proportional amount of working time reduction. This specification follows the assumption that the productivity increase is never fully compensated only by a reduction of working time, but split up into working time reduction and wage increase. The parameter estimated for labour productivity in the wage curve therefore is conditional on this impact of working time on hourly wages.

In the search model firms and workers bargain over the distribution of the value of a successful match and the wage rate can be derived from the optimality conditions of the problem (see: Boeters and Savard, 2013):

$$w = \frac{\left(1-t^m\right)\lambda\left(\rho + \frac{s}{ur}\right)}{\pi_V\left(1-br\right)\left(1-t^a\right)}\gamma \tag{44}$$

In (44) t^m and t^a represent marginal vs. average income tax rates, therefore, if we assume a proportional tax system for simplicity (and for the sake of data availability) this wage equation can be reduced to:

$$w = \frac{\lambda\left(\rho + \dfrac{s}{ur}\right)}{\pi_V (1 - br)} \gamma \tag{45}$$

In this wage equation, λ is the parameter measuring the bargaining power of workers, ρ is the discount rate, s the (exogenous) separation rate, π_V the probability of filling a vacancy and ur the rate of unemployment. The cost of an open vacancy for the firm is measured by γ and br is the wage replacement rate of the unemployment benefit. The separation rate could be endogenized in the labour demand block and usually depends on workers' productivity, like in Faia, et al. (2013). As Boeters and Savard (2013) point out, some of these variables are difficult to measure or derive from official data. One important property of the wage function is the reaction of the wage rate to the unemployment rate, which according to the empirical 'wage curve' literature is about -0.1. Taking these theoretical considerations as a starting point we derive the following log-linearized wage curve by industry:

$$\begin{aligned} \log w_{j,t}(1 - t_{L,t}) &= \alpha_{w,j} + \sum_{t=t-n}^{t} \beta_{1,wj} \log pc_t + \sum_{t=t-n}^{t} \beta_{2,wj} \log(Q_{j,t} / H_{j,t}) + \\ &+ \sum_{t=t-n}^{t} \beta_{3,wj} \log(Q_t / H_t) + \sum_{t=t-n}^{t} \beta_{4,wj} \log(ur^* / ur_t) - \sum_{t=t-n}^{t} \beta_{5,wj} \log(H_{j,t} / L_{j,t}) \end{aligned} \tag{46}$$

The specification in (46) takes into account different lags of variables, including the consumer price, and the industry (*j*) productivity or alternatively the aggregate productivity of the economy. The term ur^*/ur_t considers the unemployment elasticity of the wage rate in terms of the difference to the equilibrium rate ur^*, measured in that case as the minimum rate in the sample used for estimation. The estimation of the parameter $\beta_{4j,w}$ yields the same result (only with $\beta_{4j,w} > 0$) as the parameter of the unemployment rate elasticity in the traditional wage curve, because all the variance in the term ur^*/ur_t stems from changes in the unemployment rate. The specification of the unemployment term as a gap to full employment (ur^*/ur_t) yields a NAWRU characteristic: wage inflation increases with approximation to full employment.

Due to non-stationarity of the variables, an autoregressive term is also included. The separation rate and the probability of filling a vacancy have not been included into (46) due to data availability and the income replacement rate of the unemployment benefit did not yield significant results in the panel data estimation across European countries. The stylized facts on the latter phenomenon reveal that there is no clear correlation between the generosity of the unemployment benefit regulation and the unemployment rate.

Labour supply is given by age and gender (*g*) specific participation rates of the *k* age groups of the population at working age (16-65) and evolves over time according to demographic change (age group composition) and logistic trends of the participation rates. Therefore, labour supply does not react endogenously to policy shocks. Unemployed persons are the difference between labour supply and employment, for given hours worked per person:

$$UN_t = \sum_{k,g} \pi_{k,g,t}\, pop_{k,g,t} - w_t H_t \left(\frac{L_t}{H_t} \frac{1}{w_t} \right) \tag{47}$$

Total wages are given in analogy to the other factor inputs (E, M^m, and M^d) by multiplying the factor shares from the K, L, E, M^m, M^d Translog model, in that case $\hat{\mathbf{V}}_{\mathrm{L}}$, with the column vector of output in current prices and summing up (with $\mathbf{i'}$ as the summation vector): $w_t H_t = \mathbf{i'} \left\lfloor \hat{\mathbf{V}}_{\mathrm{D,t}} \mathbf{p}_{\mathrm{Q,t}} \mathbf{Q_t} \right\rfloor$.

Wage data including hours worked are taken from WIOD Sectoral Accounts and are complemented by labour force data from EUROSTAT. The wage equations have been estimated for the full EU 27 panel including lags of some of the independent variables as well as of the wage rate per hour (ADL specification). The unweighted average across industries of the long-run unemployment elasticity (ur^*/ur_t) is about 0.09. The long-run productivity elasticity of wages is almost unity.

2.4 Government and model closure

The public sector balances close the model and show the main interactions between households, firms and the general government. As we put special emphasis on labour market policies, unemployment benefits are separated from the other social expenditure categories.

Taxes from households and firms are endogenized via tax rates and the path of the deficit per GDP share according to the EU stability programs is included as a restriction.

Wage income of households is taxed with social security contributions (tax rates t_{wL} and t_L) and wage income plus operating surplus accruing to households are taxed with income taxes (tax rate t_Y). Additionally, households' gross profit income is taxed with tax rate t_r. Taxes less subsidies are not only levied on private consumption, but also on the other final demand components in purchaser prices ($\mathbf{f_{pp}}$, comprising capital formation, changes in stocks, exports, and public consumption) as well as on gross output. Total tax revenues of government, T_t, are given with:

$$T_t = (t_{wL} + t_L) w_t H_t + t_Y (w_t H_t + \Pi_{h,t}) + t_r r_t A_{t-1} + \hat{\mathbf{T}}_{\mathrm{N}} \left[\mathbf{c}_{\mathrm{pp},t} + \mathbf{f}_{\mathrm{pp},t} + \mathbf{p}_{\mathrm{Q,t}} \mathbf{Q_t} \right] \tag{48}$$

Taxes less subsidies and profit income in (48) also include the economic activity of the public sector itself. The expenditure side of government is made up of unemployment transfers ($brw_t(1 - t_S - t_Y)UN_t$) and other transfers to households (Tr), public investment (cf_{gov}) and public consumption (cg). Additionally, the government pays interest with interest rate r_{gov} on the stock of public debt, D_{gov}. The change in this public debt is equal to negative government net lending, which is then given by:

$$\begin{aligned}\Delta D_{gov,t} = {} & brw_t (1 - t_S - t_Y) UN_t + Tr_t + cf_{gov,t} + cg_t + r_{gov,t} D_{gov,t-1} - (t_{wL} + t_L) w_t H_t - t_Y (w_t H_t + \Pi_{h,t}) \\ & - t_r r_t A_{t-1} - \hat{\mathbf{T}}_{\mathrm{N}} \left[\mathbf{c}_{\mathrm{pp},t} + \mathbf{f}_{\mathrm{pp},t} + \mathbf{p}_{\mathrm{Q,t}} \mathbf{Q}_{\mathrm{t}} \right]\end{aligned} \tag{49}$$

In that specification, tax revenues and unemployment benefits are endogenous and can from a policy perspective be influenced by changing tax rates or the unemployment benefit replacement rate. The model is closed by further introducing a public budget constraint, specified via the stability program for public finances of Spain that defines the future path of government net lending to GDP ($p_y Y$). The latter can be defined as the difference between total output $p_Q Q$ and intermediate demand ($p_E E$, $p_{Mm} M^m$, $p_{Md} M^d$). Linking public investment with a fixed ratio (w_{cf}) to public consumption and introducing the net lending to GDP constraint, public consumption is then derived as the endogenous variable that closes the model:

$$cg\left(1+w_{cf}\right)=\Delta D_{gov,t}/p_yY-r_{gov,t}D_{gov,t-1}-brw_t\left(1-t_S-t_Y\right)UN_t-Tr+\left(t_{wL}+t_L\right)w_tH_t$$
$$+t_Y(w_tH_t+\Pi_{h,t})+t_rr_tA_{t-1}+\hat{\mathbf{T}}_{\mathrm{N}}\left[\mathbf{c}_{\mathrm{pp},t}+\mathbf{f}_{\mathrm{pp},t}+\mathbf{p}_{\mathrm{Q,t}}\mathbf{Q}_{\mathrm{t}}\right] \quad (50)$$

Therefore, transfers and tax rates are treated like fiscal policy variables, whereas public consumption and investment adjust according to the net lending to GDP constraint. Public investment can be still treated as a policy variable, as the public investment ratio (w_{cf}) could be altered.

3. Simulations

3.1 Alternative GHG pricing scenarios

The political targets, formulated in roadmaps for GHG emission reduction prescribe significant reductions in resource use linked to domestic production (GHG emissions), as well as to domestic consumption (GHG footprint). The main instrument discussed in this context is the introduction of prices/taxes for GHG emissions and for the GHG footprint. At the same time, the problem of 'leakage' is identified in a scenario of a "go-it-alone" European climate policy. Higher costs for European producers due to these taxes may lead to relocation of energy-intensive production. This in turn may hurt growth of income and jobs in Europe while leaving GHG emissions unchanged or even higher on a global scale.

In the end, the genuine source of leakage is consumer demand in Europe. Given this demand, producers outside Europe will increase their energy use, if European producers of energy-intensive goods are not competitive. One can think of two possible strategies to overcome leakage: (i) increasing energy efficiency more than proportionally, so that costs do not rise or (ii) taxing embodied emissions in order to reduce European demand for energy-intensive products. Alternative (i) may be achieved by additionally spurring technical change via using part of the tax revenues for directed technical change. In the following, we analyse the socio-economic impact of alternative (ii) and compare it with the results of 'classical green tax' reform, applying the DYNK model for the EU 27 economy.

Two different tax reform schemes have been analysed with the DYNK model for the EU 27 in order to understand the options for dealing with the challenges of absolute decoupling, price competitiveness of European manufacturing and leakage:

(i) the classical 'Green Tax Reform' where GHG emissions are taxed on an increasing scale and social security contributions (employers' and employees') are reduced simultaneously so that (*ex post*) public revenue neutrality is guaranteed (ii) an 'Environmental Fiscal Devaluation' where GHG emissions embodied in private consumption are taxed at the same rate and on the same increasing scale as in (i) above, and revenue neutrality is also achieved by the same rule for social security contributions as in (i). This tax reform can be seen as a special case of fiscal devaluation, i.e. a change in the tax system that mimics the price effects of a devaluation of the currency by rising taxes on consumption (higher prices of domestic consumption) and lowering taxes on labour (lower prices of exports). In the case of environmental fiscal devaluation consumption prices rise due to taxation of embodied emissions, and export prices decrease due to lower social security contribution. Note that in the concept of 'Environmental Fiscal Devaluation' all consumption goods are taxed irrespective of their origin (like in the case of the Danish fat tax), so that no inconsistency with international trade agreements arises.

The tax rates for GHG emissions have been determined in line with the EU Roadmap for a low-carbon economy, starting off with a tax rate of 25 €/t of CO_2 equivalent (in € of 2005) in 2015 and rising continuously to 250 €/t of CO_2 equivalent (in € of 2005).

Implementation in the case of 'Green Tax Reform' is straightforward, as the tax rates lead to higher effective input prices for energy in production and consumption. In the case of 'Environmental Fiscal Devaluation', the embodied emissions had in a first step to be quantified by simulating unitary consumption demand increases for all 59 commodities in the DYNK model. The results of these simulations yield a rough one-point-in-time estimate of domestic emission contents for each consumption category. From these results, the relationship between the outcome in terms of emissions and the shock in consumption demand can be calculated, which gives 'implicit coefficients' of embodied domestic emissions. Induced imports of each consumption category are also accounted for in monetary units as part of the simulation results. Hence, what is not directly included into the calculation of embodied emissions and resource use are all indirect effects in the rest of the world linked to European consumer demand. The correct way to deal with such effects would be a simulation with a MRIO (multi-regional input-output) model, which was beyond the scope of this research. Accounting for these indirect effects is approximated by taking the results for implicit coefficients of imported emissions of the EU 27 from a MRIO model, based on the WIOD database. The *ex post* revenue neutrality via lower social security contributions is implemented as an additional constraint in the public sector block of the DYNK model which guarantees that the social security contribution rate is endogenously determined in the model solution at a level consistent with *ex post* revenue neutrality.

3.2 Macroeconomic, social and environmental impact of the GHG pricing scenario

'Green Tax Reform' has different short- and long-run effects on the labour market (Table 1), but a consistent negative impact (compared with the 'baseline') on GDP. This is due to price increases that in turn have a negative impact on exports as well as on household disposable income. The effective price of fossil energy rises due to CO_2 taxation; since fossil energy is not only a factor of production, but also a consumption good (fuels for cars and heating), the consumer price level increases more that the producer price level. This in turn has repercussions on the wage bargaining process, so that in the long-run, employees' gross wage rate increases more than in the 'baseline', offsetting a large part of the lower social security contributions until 2050.

>>>Table 1: Macroeconomic effects of "Green Tax Reform" (difference to baseline in %)

The labour market effect, driven by the change in relative prices between energy and resources on the one hand and labour on the other, is positive until 2030 (compared with the 'baseline'), turning negative thereafter due to the increasing negative output effect. It is, however, important to note that the annual difference in GDP growth to the 'baseline' is rather small, with only 0.15% p.a. (Graph 1).The main result of this scenario for the environment is that absolute decoupling of energy consumption and of GHG emissions from GDP is possible. This is not the case for DMC per capita for the material tax rate implemented in this scenario. This may, however, be the case for a higher tax on minerals than the one assumed here, based on the literature.

>>>>>>> Graph 1: Impact of "Green Tax Reform" on GDP, emissions and energy use

Comparing the results for energy consumption and GHG emissions with those from the impact analysis of the EU Roadmap for a low carbon economy, we note that in our model the reductions of energy use and emissions at the same CO_2 price level are considerably smaller. This is due to the fact that the EU Roadmap foresees several other instruments besides pricing of CO_2, like the support for renewables, and the widespread diffusion of other carbon-saving technologies like CCS (carbon capture and storage) and nuclear energy. These additional instruments are absent in our scenario of 'Green Tax Reform', only the share of renewables also doubles, induced by the CO_2 price hike.

The leakage in terms of GHG emissions amounts to 4% in 2050, but, as explained above, this estimate (which represents the lower bound of what the literature finds about GHG leakage) might be strongly biased downwards due to our resort to EU 27 technology in terms of embodied emissions and resource use.

>>>>>> Table 2: Employment effects of "Green Tax Reform" (difference to baseline in %)

Table 2 shows the employment effects of the 'Green Tax Reform' scenario across industries in 2020. The average employment effect of 0.33% is the result of very heterogeneous effects by industry, with job losses in the public sector (due to cuts in public expenditure in order to meet the deficit target) and high employment gains in the electricity sector (due to substitution towards labour inputs) as well as in some manufacturing and service sectors. The transport sector also loses jobs from the 'baseline' scenario.

'Environmental Fiscal Devaluation' increases both output (GDP) and employment in the short- as well as in the long-run compared with the 'baseline' scenario. The negative impact on consumption is smaller than in the case of 'Green Tax Reform', though the price effect on fossil fuels directly used by households (fuels for cars and for heating) is the same. An important positive impact on GDP in this scenario stems from the reduction of imports. The difference between the two schemes is explained by the differential impact on price competitiveness and exports. The changes in the price system lift exports above the 'baseline' until 2030. This in turn raises employment in addition to the positive effect of lower social security contributions, and also boosts disposable income. The macroeconomic effects clearly show the mechanism of fiscal devaluation: demand is shifted from domestic to foreign sources, leading to a positive net impact on GDP. The average growth rate of GDP is about 0.1% p.a. higher than in the 'baseline' (Graph 2).

>>>>>>> Table 3: Macroeconomic effects of "Environmental Fiscal Devaluation" (difference to baseline in %)

>>>>>> Graph 2: Impact of "Environmental Fiscal Devaluation" on GDP, emissions and energy use

While the scenario of 'Environmental Fiscal Devaluation' improves all environmental outcomes *vis-à-vis* the 'baseline', the desired absolute decoupling is not achieved (Graph 2).
As all imports are reduced in this scenario, due to the taxation of the embodied environmental impact on consumption, also GHG emissions abroad decrease. 'Environmental Fiscal Devaluation' in Europe therefore reduces emissions and resource use on a global scale by more than within the EU 27, yielding a negative leakage effect. As has been explained above, our estimates of leakage are biased downwards by using the European technology as a proxy for the technology of EU imports.

Conclusions

The results presented above clearly show potential synergies and trade-offs between different environmental, economic and social policy goals. At the same time they also reveal the potential contribution of Europe to the global problem of resource use. The results for leakage are probably biased downwards. The option of Environmental Fiscal Devaluation should not be in opposition to international trade agreements, as consumption goods are taxed like in the case of an excise duty (e.g. tobacco) irrespective of their origin.

Price instruments (taxation schemes) that fully impute environmental costs to European consumers and producers lead to a loss in price competitiveness and to leakages of emissions as well as resource use. This may give rise to conflicts between different environmental targets. In the case of European unilateral action, the leakage problem can only be dealt with by directly addressing embodied emissions and resource use in European final consumption. A policy that fully includes environmental costs for European consumers and producers is more efficient in reaching environmental goals and may actually achieve absolute decoupling. Such a policy, although slightly reducing the average growth rate of GDP, may still have potential positive mid-term effects on the labour market.

Price instruments (taxation schemes) that put the full burden of environmental costs on the European consumer, by invoking his global responsibility, are tantamount to fiscal devaluation by increasing price competitiveness and shifting demand from domestic to foreign sources. Such policy is not very efficient with regard to environmental goals and is unlikely to achieve absolute decoupling. Since it reduces the global environmental impact of the European consumer, it would lead to negative leakage.

The two alternative taxation schemes analysed here represent two different policy options that could be chosen by different European countries. Countries in a good competitive position and with high environmental ambitions in energy and climate policies could directly opt for the "Green Tax Reform". Countries with low environmental ambitions in energy and climate policies and more severely hit by the Great Recession could in the short-term opt for the "Environmental Fiscal Devaluation".

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Table 1: Macroeconomic effects of "Green Tax Reform" (difference to baseline in %)

	2015	2020	2030	2050
GDP, const. prices	-0.03	-0.54	-2.20	-5.79
Private Consumption, const. prices	-0.33	-1.55	-4.92	-11.13
Capital formation, const. prices	0.00	-0.01	-0.04	-0.09
Exports, const. prices	-0.19	-1.12	-3.92	-9.64
Employment (persons)	0.31	0.25	-0.20	-0.84
Employment (hours)	0.31	0.26	-0.17	-0.80
Unemployment (persons)	-2.21	-2.01	2.09	16.93
Unemployment rate (% points)	-0.27	-0.22	0.18	0.80
GHG emissions, households	-5.35	-7.98	-11.78	-14.80
GHG emissions, production	-9.81	-17.41	-30.03	-43.04
GHG emissions, total	-8.56	-14.79	-25.04	-35.34
GHG emissions, Leakage	-0.07	0.30	2.31	11.14

Graph 1: Impact of "Green Tax Reform" on GDP, emissions and energy use

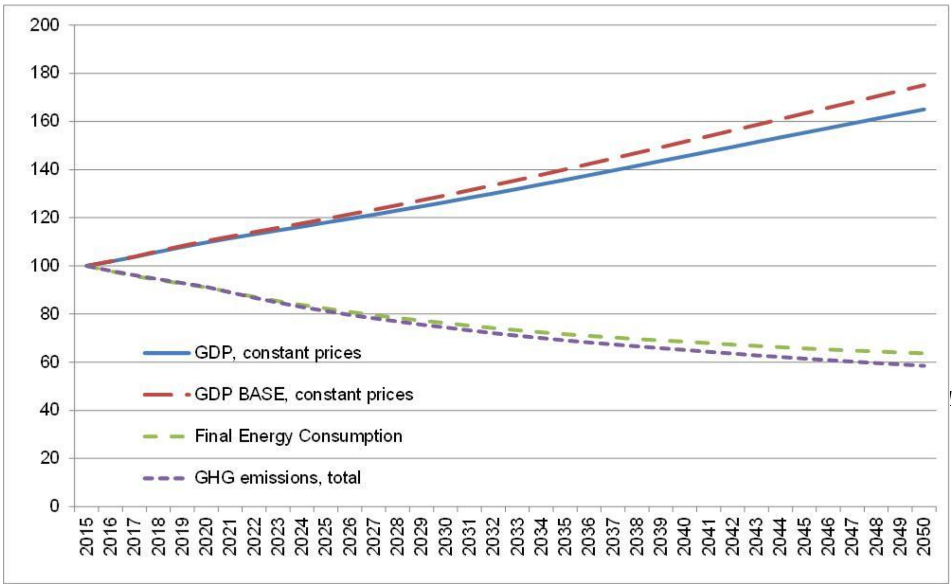
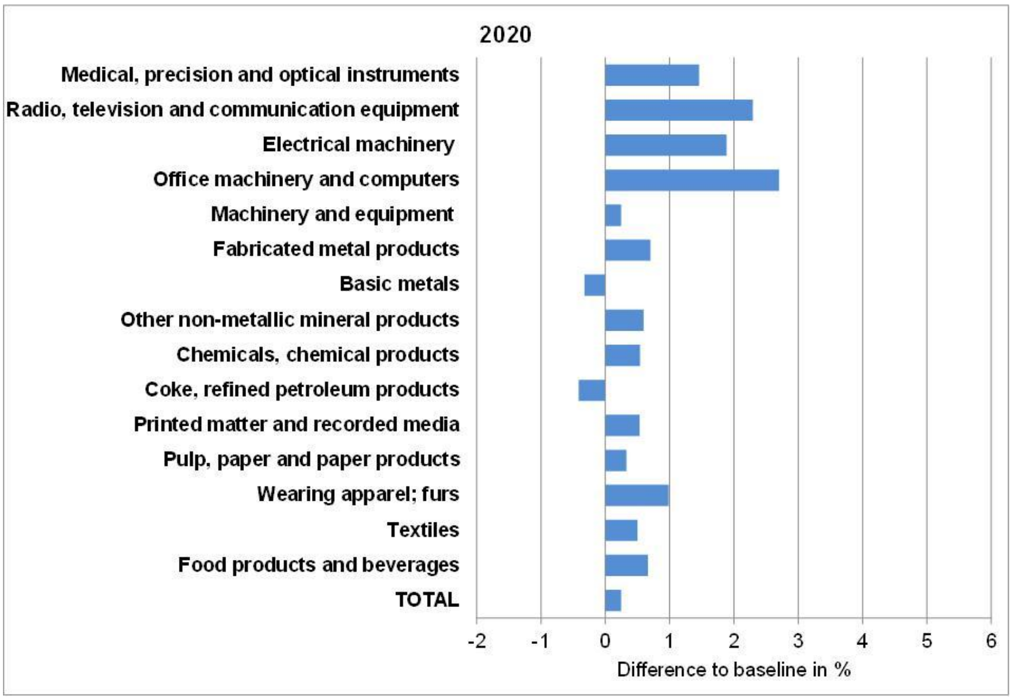


Table 2: Employment effects of "Green Tax Reform" (difference to baseline in %)



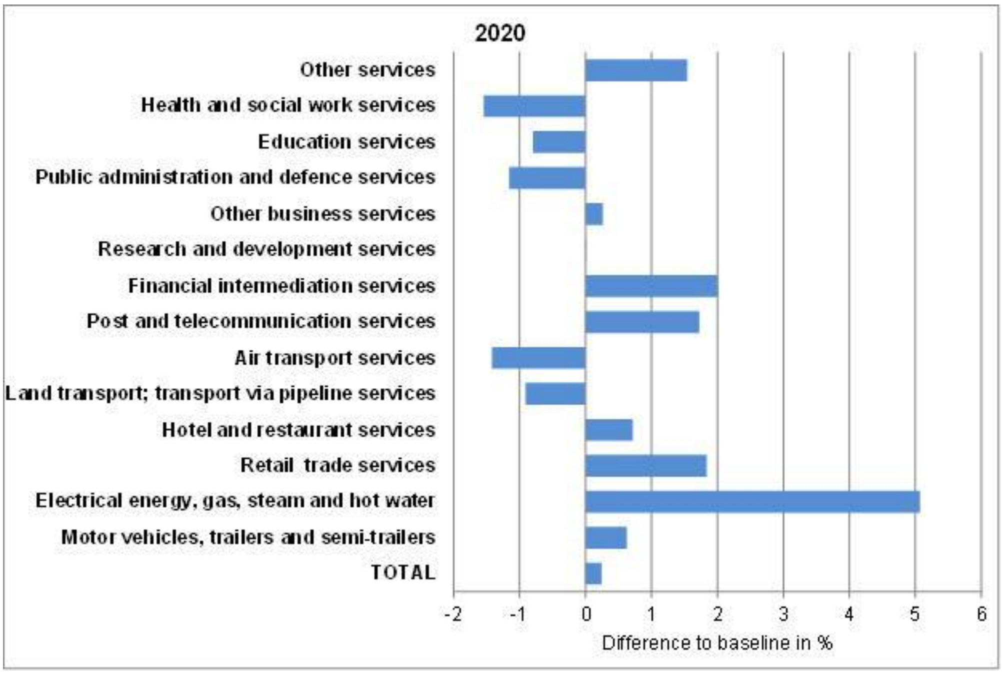


Table 3: Macroeconomic effects of "Environmental Fiscal Devaluation" (difference to baseline in %)

	2015	2020	2030	2050
GDP, const. prices	0.34	1.11	2.39	4.62
Private Consumption, const. prices	0.02	-0.58	-1.94	-3.36
Capital formation, const. prices	0.00	0.00	0.00	-0.01
Exports, const. prices	0.32	0.92	1.28	-1.10
Employment (persons)	0.30	0.74	1.32	2.03
Employment (hours)	0.29	0.72	1.26	1.78
Unemployment (persons)	-2.18	-6.09	-13.93	-40.84
Unemployment rate (% points)	-0.27	-0.66	-1.21	-1.93
GHG emissions, households	-3.61	-7.19	-10.45	-10.16
GHG emissions, production	-0.42	-1.52	-3.82	-10.02
GHG emissions, total	-1.32	-3.10	-5.64	-10.05
GHG emissions, Leakage	-0.42	-1.12	-2.54	-4.78

Graph 2: Impact of "Environmental Fiscal Devaluation" on GDP, emissions and energy use