CrossMark

The Carbon Footprint of European Households and Income Distribution

Mark Sommer, Kurt Kratena *

WIFO, Arsenal, Obj. 20, A-1030 Vienna, Austria

ABSTRACT

This paper calculates the carbon footprint of private consumption in the EU27 by five groups of household income, using a fully fledged macroeconomic input-output model covering 59 industries and five groups of household income for the EU27. Due to macroeconomic feedback mechanisms, this methodology – besides induced intermediate demand – also quantifies: (i) private consumption induced in the other household groups, (ii) impacts on other endogenous final demand components, and (iii) negative feedback effects due to output price effects of household demand. The carbon footprint is calculated separately for the consumption vector of each of the five income groups. The simulation results yield a non-linear income elasticity of direct and indirect emissions at each income level: the value of the direct footprint income elasticity decreases from 1.32 (first quintile) to 0.69 (fourth quintile). The value of the indirect footprint income elasticity is always below unity and decreases from 0.89 to 0.62. The results in general reveal a relative decoupling effect: the share of the top income group in income (45%) is much larger than its share in the carbon footprint (37%) and vice versa for the bottom income group (6% in income and 8% in footprint).

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The environmental impact of inequality in the income distribution has been the object of many theoretical and empirical studies. The main question was, if reducing inequality and rising incomes along the growth process might "automatically" decrease environmental pressure. The "strong" version of this hypothesis where environmental pressure (emissions, energy/resource use) per head is even reduced with income growth, is the "Environmental Kuznets Curve" (EKC). The general result of the literature is that some relative decoupling of environmental pressure from income can be identified, but that does not suffice to reduce absolute environmental pressure. The empirical studies comprise econometric studies in the spirit of the EKC literature (Ravallion et al., 2000; Borghesi, 2000) as well as studies that combine input-output (IO) or life-cycle methods with others to quantify the footprint of different income groups (Weber and Matthews, 2008, and more recently Chancel and Piketty, 2015).

Since the seminal paper of Boyce (1994), most authors find a negative relationship between inequality and emissions, i.e. higher inequality leads to lower emissions. Borghesi (2000) discusses these findings in the light of the literature and concludes with mixed evidence: positive effects of inequality on emissions (poor households using less efficient equipment and more energy/resources) and negative effects (rich households consuming more aggregate energy/resources) might balance.

The studies that use input-output (IO) analysis for calculating the footprint usually calculate direct and indirect emissions of households, and often yield the result that indirect emissions have a higher share in total footprint for high income households than for low income. Parikh et al. (2009) as well as Weber and Matthews (2008) show that for top income households the share of indirect carbon (CO_2 equivalents, i.e. GHG emissions, including CH_4 and N_2O) emissions is significantly higher than for households at the bottom of the income distribution.

One objective of the literature consists in deriving an income elasticity of carbon emissions, either from a cross section or an aggregate time series dataset. Weber and Matthews (2008), who combine IO analysis with econometric estimation find an expenditure elasticity between 0.6 and 0.8 and an income elasticity between 0.35 and 0.52. Lenzen et al. (2006) review this work on elasticities and derive a similar range, but conclude that the literature exhibits a large heterogeneity of estimated elasticity values. It must be noted that the methodology consists of calculating the carbon footprint in a first step and then applying econometric analysis on these results in a second step. The econometric analysis, which attempts to identify the households' reactions, therefore is not integrated with the IO analysis used for calculating the footprint. Another study (Duarte et al., 2015) also uses a CGE model to calculate the full macroeconomic impact of household behavior, but the consequences for emissions are attributed from outside from the results of an IO model (though the IO database is the same as the one for the CGE model). The recent study by Chancel and Piketty (2015) combines footprint calculations from a MRIO analysis with income distribution data via income elasticity values taken from the literature.

* Corresponding author.
 E-mail address: kurt.kratena@cesarecon.es (K. Kratena).

The existing literature has not yet used IO approaches that integrate household behavior for deriving the footprint of different income groups, from which the income elasticity can be derived directly, without any further econometric analysis. This paper attempts to fill this gap and derives an income elasticity that incorporates macroeconomic (or general equilibrium) feedbacks and therefore is not limited to the ceteris paribus condition that needs to hold for the elasticity values estimated in the literature. This study finds that the income elasticity of the carbon footprint considerably decreases when moving from bottom to top income. The income elasticity of the direct carbon footprint is 1.32 for the first quintile and still above unity for the second quintile and then decreases to a value of 0.69. The income elasticity of the indirect carbon footprint is always below unity and decreases from 0.89 for the first quintile to 0.62 for the fourth quintile. Another result that is found and is not in line with the established literature is that indirect emissions play a more important role (in relative terms) for bottom income households. The main reason for this seems to be the CH_4 emissions from agricultural products.

The model used is a hybrid between an econometric IO and a CGE model and splits the consumption block into five groups of household income (quintiles). Aggregate consumption depends on income, wealth and liquidity constraints, consumption by commodity on prices as well. Production is modeled via a Translog model that is fully integrated into the IO structure. Besides that, the model also comprises a block for the labor market and one for the public sector. The analysis in this paper extends the existing literature by the following features: (i) consumption of each household group induces consumption in the other groups via an income and wealth multiplier, (ii) consumption of each household group induces wage and price effects due to the demand pull, and (iii) consumption of durables reacts in a non-linear form, so that energy consumption linked to the durable stock shows non-linear reactions with respect to income as well.

These effects partly magnify the carbon footprint (comprising the carbon equivalent of all GHGs) compared to traditional static IO analysis ((i)) and partly diminish it ((ii)). The non-linear property ((iii)) yields a heterogenous income elasticity of the footprint across income groups. This is an *ex post* elasticity from model simulation results, including all macroeconomic feedbacks.

The paper is organized as follows: Section 2 describes the methodology of calculating direct, domestic indirect and imported indirect carbon footprint for the five household income groups. Section 3 reports the results for the carbon footprint by quintile and calculates the model simulation income elasticity. In Section 4 some conclusions are drawn. A detailed model description with an emphasis on consumption, production and trade can be found in the Appendix.

2. Methodology and Data

The DYNK (DYnamic New Keynesian) model approach applied in this study is a hybrid between an econometric IO and a CGE model and is characterized by the integration of rigidities and institutional frictions. These rigidities include liquidity constraints for consumers (deviation from the permanent income hypothesis), and wage bargaining (deviation from the competitive labor market). In the long-run the model works similarly to a CGE model, and explicitly describes an adjustment path towards a long-run equilibrium. The model describes the inter-linkages between 59 industries as well as the consumption of five household income groups by 47 consumption categories and covers the EU 27 (as one economy).

The IO core of the model is based on Supply-Use tables for Europe (EUROSTAT) and intermediate demand is split into domestic and imported commodities. Instead of deriving a technical coefficient matrix (inputs of intermediate commodities per unit of industry output) from the use matrix, this modeling step is split into two parts in the DYNK model. First, vectors of total input coefficients per unit of industry output for domestic and imported commodities (v_D and v_M) are defined.

The commodity structure below this level is then in a second step defined by use structure matrices S^m and S^d with column sum equal to unity. A further distinction within the use matrix is between non-energy and energy commodities. The commodity balance for non-energy commodities is then defined by applying the use structure matrices S_{NE}^m and S_{NE}^d as well as the diagonal matrices of the factor shares defined above, $\hat{V}_D$ and $\hat{V}_M$. Multiplying the use structure matrix with the corresponding factor share matrix and with the column vector of output in current prices gives the sum of intermediate demand by commodity. The procedure for energy commodities is the same, with use structure matrices S_E^m and S_E^d (where the column sum over both matrices yields one), and diagonal matrix $\hat{V}_E$. The full commodity balance is given by adding the column vectors of domestic consumption (c^d), capital formation (cf^d) and public consumption (cg^d). Capital formation is endogenous as well and derived from capital demand by industry in the Translog model, applying the capital formation matrix (for details see the Appendix). The (column vector) of the domestic output of commodities in current prices, $p^D q^D$, is transformed into the (column vector) of output in current prices, $p_Q q$, by applying the market shares matrix, C (industries ∗ commodities) with column sum equal to one:

$$p^D q^D = \left[\hat{V}_D S_{NE}^d \right] p_Q q + \left[\hat{V}_E S_E^d \right] p_Q q + c^d + cf^d + ex^d + st^d + cg^d \qquad (1)$$

$$p_Q q = C p_D q_D \qquad (2)$$

These two equations describe the core IO model of the system and can be solved in a loop for equilibrium values of output ($p_Q q$ and $p^D q^D$), once final demand categories (c^d, cf^d, ex^d, st^d and cg^d) and matrices ($\hat{V}_D$, $\hat{V}_E$, S_{NE}^d and S_E^d) are given.

The final demand categories (c^d, cf^d, ex^d, st^d and cg^d) comprise energy and non-energy commodities, are all in current prices and are all – except stock changes (st^d) – endogenous. The export vector ex^d is calibrated with price elasticity of unity for all commodities and therefore is constant in current prices. The vector of public consumption cg^d is determined in the public sector block of the model in order to close the model with a predetermined public deficit.

2.1. Household Demand and Direct Carbon Footprint of Households

The consumption block differentiates between different stages and separability is assumed between these stages. The separability assumption in that context also implies that the dynamic decision process is disentangled as lined out in Attanasio and Weber (1995). At the first stage, the demand for durables (real estate property and vehicles) is modeled in a way consistent with the version of the buffer stock model described in Luengo-Prado (2006). Further, total nondurable demand is also specified in a way consistent with the main properties of the buffer stock model (excessive smoothing, excess sensitivity). All model parameters are based on dynamic estimation of panel data for Europe (1995–2011), in the first stage for 14 EU countries (Belgium, Czech Republic, Denmark, Germany, France, Italy, Cyprus, Lithuania, Austria, Poland, Portugal, Romania, Slovakia, Finland). The data for the estimation of consumption demand functions are mainly taken from EUROSTAT's National Accounts. The 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 the 14 EU countries. A crucial variable at this first stage of consumers' demand is the down payment for durable purchases (see the Appendix for details). Once the full model is set up with the integrated consumption block, the property of 'excess sensitivity' can be tested. Excess sensitivity describes the empirical fact that the growth rate of consumption – partly – reacts to the lagged growth rate of disposable (or labor) income. The full model presented here is run until 2050, so that endogenous

disposable household income is generated. Then excess sensitivity is tested by setting up the regressions that Hall (1978) proposed to test the influence of transitory income shocks on consumption. That means regressing the growth rates for durable ($C_{dur,t}$) and nondurable consumption ($C_{nondur,t}$) for each quintile (q) on lagged disposable income growth (without profit income) for each quintile, generated by the full model (Table 1). Profit income is not included, because it is endogenous and depends on equity built up, which in turn is a result of the inter-temporal optimization. Luengo-Prado (2006) also carries out excess sensitivity tests with her calibrated model, based on US household survey data and confronts these results with US stylized macroeconomic facts. The excess sensitivity coefficients, i.e. the marginal propensity of consumption (MPC) with respect to lagged income change, found by Luengo-Prado (2006) are 0.16 (nondurables) and 0.26 (durables). The results from the model solution until 2050 (Table 1) clearly reveal that for the 5th and partly for the 4th quintile durable and nondurable consumption do not statistically significantly depend on transitory income shocks. The MPC is higher in general for lower income households and for situations with higher liquidity constraints (higher down payment θ). The 'low θ scenario' corresponds to a financial regime, where the relationship debt to durable stock does not significantly decrease, i.e. no major debt deleveraging by households occurs. The 'high θ scenario' corresponds to debt deleveraging so that the relationship debt to durable stock in the long-run decreases to its values before 2002, i.e. before the main expansion of household debt began. The multiplier of policies that influence income is therefore not constant, but depends on the financial market environment (liquidity constraints) and the income groups that are most affected.

At the second stage, energy consumption, disaggregated into: heating, electricity and fuels for transport, is modeled as a service demand in terms of utilization of the capital (durable) stock. Therefore, it links energy demand (in monetary and physical units) to the durable stock (houses, vehicles, appliances). An important variable is the average energy efficiency of the corresponding durable stocks (dwelling for heating, vehicles for fuels for transport, and appliances for electricity). The transport part allows for substitution between public transport services and private car transport. For this second stage, the model parameters are based on estimations with an EU 27 country panel (1995–2011). The energy expenditure of households is based on EUROSTAT, the Energy Accounts from the WIOD database, as well as IEA Energy Prices. Energy efficiency for electricity and for heating is calculated from the ODYSSEE database. Efficiency of the car fleet is taken from a revised version of the GAINS project database. All equations have been estimated in a dynamic autoregressive distributed lag (ADL) specification. The price elasticity values (Table 2) found here for heating, transport fuel and electricity (around – 0.8) are outside the

Table 1
Excess sensitivity of consumption w.r.t. lagged disposable income (without profit income).

Sensitivity, low θ					
	1st quintile	2nd quintile	3rd quintile	4th quintile	5th quintile
dlog(C_{dur})	0.45***	0.38***	0.30**	0.21	0.14
	(0.15)	(0.16)	(0.16)	(0.16)	(0.16)
dlog(C_{nondur})	0.94***	0.76***	0.58***	0.38***	−0.03
	(0.41)	(0.20)	(0.15)	(0.12)	(0.13)

Sensitivity, high θ					
	1st quintile	2nd quintile	3rd quintile	4th quintile	5th quintile
dlog(C_{dur})	0.44***	0.40**	0.33***	0.26**	0.20
	(0.13)	(0.14)	(0.14)	(0.14)	(0.14)
dlog(C_{nondur})	1.02***	0.86***	0.69***	0.49***	0.09
	(0.37)	(0.18)	(0.14)	(0.12)	(0.09)*

* Indicates significance at the 10% level.
** Indicates significance at the 5% level.
*** Indicates significance at the 1% level.

Table 2
Price and expenditure elasticity of energy and non-energy demand of households (EU 27 panel 1995–2011, EU 6 cross section, 2004/2005).

Nondurable Consumption	Own price Elasticity	Expenditure elasticity	
		Time series	Cross section
Food	−0.14	0.85	0.61
Clothing	−0.64	1.04	1.28
Furniture/equipment	−1.06	1.11	1.46
Health	−0.83	0.98	1.20
Communication	−0.89	0.96	0.68
Recreation/accomodation	−0.50	1.08	1.27
Financial services	−0.94	1.33	1.00
Other	−0.68	1.09	1.00

range established by the existing literature for the energy price elasticity. That can be explained by two factors. First, the elasticity values presented here measure the service price elasticity and the reaction of service demand to both price changes and improvements of energy efficiency in the durable stock. Service price have been almost constant in the sample period used for estimation due to energy efficiency improvements, whereas demand has increased considerably. This is consistent with part of the literature on the (price) rebound effect that finds rebound effects of 100% in some cases. Second, the elasticity values calculated here are conditional on the stock of durables thereby implicitly assuming a unitary elasticity of energy demand to the durable stock as a strong driving force of demand (Table 2).

Finally, the third stage contains the model of non-energy nondurable consumption, modeled in a flexible demand system (AIDS model). This third step is again split into two nests: (i) an aggregate level of eight categories, described in an AIDS model, and (ii) a detailed model of 47 COICOP categories, explained by sub-shares of the aggregate categories that change over time and can be changed exogenously for model simulation purposes. The econometric estimation has been carried out for an EU 27 country panel (1995–2009) from EUROSTAT National Accounts, as well as for data from the household survey 20,004/2005 for six EU countries: Austria, France, Italy, Slovakia, Spain and UK (Salotti et al., 2015). For the cross section model no price variance across time is available and therefore the AIDS model only estimates the expenditure term. The main results of the estimation of the demand system for non-energy nondurables are the expenditure elasticity from both models (panel and cross section) and the price elasticity from the panel data model (Table 2). The price elasticity shows considerable heterogeneity across categories. For the expenditure elasticity values the results of both models differ considerably. While the expenditure elasticity of the panel data model is mainly distributed around unity, the expenditure elasticity of the cross-section model differs largely between categories.

The first stage yields (column) vectors of total nondurable consumption ($\mathbf{c}_{nondur}$) and of investment in owned houses ($\mathbf{c}_{hous}$) and in vehicles ($\mathbf{c}_{veh}$) by quintile (q). From the second stage one derives (column) vectors of fuel, heat, and electricity consumption, again by quintile (q): $\mathbf{c}_{fuel}$, $\mathbf{c}_{heat}$, and $\mathbf{c}_{el}$.

Nondurable non-energy consumption (the vector by quintiles) is then given by:

$$\mathbf{c}_{NE} = \mathbf{c}_{nondur} - \mathbf{c}_{fuel} - \mathbf{c}_{heat} - \mathbf{c}_{el} \qquad (3)$$

The matrix of commodities of non-energy consumption by quintiles ($\mathbf{C}_j$) is in a next step derived from multiplying the matrix of budget shares by quintiles, $\mathbf{W}$ (for details see the Appendix), with the vector of nondurable non-energy consumption (converted into a diagonal matrix):

$$\mathbf{C}_j = \mathbf{W}[\hat{\mathbf{c}}_{NE}] \qquad (4)$$

where $j = 1...8$ are the eight non-energy consumption commodities.

The final result of this procedure is a matrix of durable, energy and non-energy consumption by quintiles (C_C):

$$\mathbf{C}_C = \begin{bmatrix} c_{hous,1} & \cdot & \cdot & \cdot & c_{hous,5} \\ c_{veh,1} & \cdot & \cdot & \cdot & c_{veh,5} \\ c_{fuel,1} & \cdot & \cdot & \cdot & c_{fuel,5} \\ c_{heat,1} & \cdot & \cdot & \cdot & c_{heat,5} \\ c_{el,1} & \cdot & \cdot & \cdot & c_{el,5} \\ .. & .. & .. & .. & .. \\ c_{j,1} & \cdot & \cdot & \cdot & c_{j,5} \\ .. & .. & .. & .. & .. \end{bmatrix}$$

This matrix is then transformed into a consumption matrix by commodities of the input-output core in the DYNK model and quintiles in purchaser prices, $\mathbf{C}_{pp}$, by applying the bridge matrix, $\mathbf{B}_C$:

$$\mathbf{C}_{pp} = \mathbf{B}_C \cdot \mathbf{C}_C \tag{5}$$

The bridge matrix links the classification of consumption commodities (COICOP) to the industry classification of the DYNK model. The consumption vector in purchaser prices and industry classification is derived by summing up over $\mathbf{C}_{pp}$: $\mathbf{c}_{pp} = \mathbf{C}_{pp}\mathbf{e}$ with $\mathbf{e}$ as the diagonal matrix (per quintiles) of the unity vector.

This vector is then split up into a domestic and imported part for each commodity and converted into producer prices by reallocating trade and transport margins to the corresponding industries and subtracting taxes less subsidies. That yields the vectors of total domestic ($\mathbf{c}^d$) and imported ($\mathbf{c}^m$) consumption, with $\mathbf{c} = \mathbf{c}^d + \mathbf{c}^m$, all valued at producer prices. For this converting a matrix of net tax rates (with identical tax rates on domestic and imported commodities) is applied.

The two directly emission relevant energy categories (fuel and heating) of the model of energy consumption need to be directly linked to the energy accounts by user (59 industries plus households) and detailed fuel category (26) in physical units. This is done in two several steps. First, the vector $\begin{bmatrix} c_{fuel} \\ c_{heat} \end{bmatrix}$ is deflated by aggregate prices of fuels and heating, where these energy prices are not specified as deflators, but as monetary values per physical energy unit (TJ). Then the deflated categories, in energy units, are allocated to the 26 energy types (e) of the model by applying fixed sub-shares, s_{ef}. The aggregate prices used for the first step (for fuel and heating, p_f) are defined by the exogenous prices by energy type (p_e) and the corresponding sub-shares: $p_f = \sum_e s_{ef} p_e$. This gives a matrix of direct energy consumption of households by type of energy (e) and quintile (q), whose elements are defined as $c_{e,q} = s_{ef,q} \frac{c_{f,q}}{p_f}$:

$$\mathbf{C}_e = \begin{bmatrix} c_{e1,1} & .. & .. & .. & c_{e1,5} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ c_{e26,1} & .. & .. & .. & c_{e26,5} \end{bmatrix}$$

Applying a (row) vector of fixed CO_2 emission factors per unit of energy type ($\mathbf{em}_{GHG,e}$) as in Table 3 to the physical energy consumption by energy type and quintile finally yields the (row) vector of *direct* CO_2 emissions of household consumption by quintile $\mathbf{EM}_{GHG,q}$:

$$\mathbf{EM}_{GHG,q} = \mathbf{em}_{GHG,e}[\mathbf{C}_e] \tag{6}$$

2.2. Production, Trade and the Indirect Carbon Footprint of Households

The model of production links the above described commodity balances of the IO core model (Leontief technologies) of 59 domestic and imported inputs to a Translog model with K, L, E, M^m (imports) and M^d (domestic) factors (for details see the Appendix). The factor energy (E) is further split up into 26 types of energy, from which carbon emissions of production are derived, a part of which constitutes the domestic indirect carbon emissions of households. The imported indirect carbon emissions of households are taken from simulation results with a MRIO model (Arto et al., 2014).

The Translog specification assumes constant returns to scale and perfect competition and incorporates autonomous technical change for all input factors (i.e. the factor biases) as well as TFP (total factor productivity). 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). For energy inputs the data in physical units (TJ) by energy type and user are used. Energy prices by energy type are exogenous, like in the household block of the model. The systems of output price and factor demand equation by industry across the EU 27 have been estimated applying the Seemingly Unrelated Regression (SUR) estimator for the balanced panel under cross section fixed effects. The estimation results yield values for the own and cross price elasticity for capital, labor, energy, and imported intermediates respectively. The average (un-weighted) own price elasticity of labor as well as of energy is about −0.5, while the own price elasticity of imported intermediates (−0.75) and capital (−0.95) is considerably higher (Table 4). For energy-intensive industries the own price elasticity of energy is lower, but the substitution elasticity between energy and capital is slightly higher than on average. Though, also on average, capital and energy are substitutes (though in several sectors complementary). The rate of factor bias in general is very low, and technical progress slightly energy using and labor saving.

The labor market is characterized by wage bargaining, formalized in wage curves by industry. These wage curves are specified as the employee's gross wage rate per hour by industry. The labor price (index) of the Translog model is then defined by adding the employers' social security contribution to that. Wage data including hours worked are taken from WIOD Sectoral Accounts and are complemented by labor force data from EUROSTAT. The wage equations have been estimated for the full EU 27 panel. Combining the *meta-analysis* of Folmer

Table 3
Parameters for factor demand (price elasticity, factor bias) and wage function.

Production	Own price Elasticity	Cross price Elasticity, E/K	Rate of Factor bias
K, all industries	−0.95		0.00
L, all industries	−0.51		−0.01
E, all industries	−0.53		0.02
E, energy intensive	−0.37	0.20	0.00
all industries		0.15	
M(m)	−0.75		0.02

Table 4
CO_2 emission factor by fuel.

	t CO_2/TJ
Hard coal	93.6
Lignite	103.8
Coke	108.1
Crude oil	73.3
Gasoline	73.3
Kerosene	73.3
Diesel	74.0
Petroleum	74.0
Gasoil	74.0
Liquified gas	65.5
Refinery gas	61.2
Natural gas	55.9
Coke oven gas	41.2
Blast furnace gas	256.8

(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. Table 4 reveals the un-weighted average of the long-run unemployment elasticity of wages across industries (0.06). The long-run productivity elasticity of wages is only about 0.3, whereas the consumer price elasticity is close to unity (0.8).

The set of five energy categories of the model of inter-fuel substitution needs to be directly linked to two parts of the model: (i) the energy accounts by industry and detailed fuel category (26) in physical units (TJ) and (ii) the energy commodities and industries of the use table (NACE/CPA 10, 11, 23, 40) in monetary units. The first link is carried out in the same way as described above for households, i.e. by deflating with a price per unit of physical input (TJ) and applying sub-shares in physical terms. The second link is carried out by applying changes in the structure of the five energy inputs to the use structure matrix of the factor E.

The GHG emissions by industry are therefore derived in a similar way as in the case of households. One main difference is that the GHG emissions by industry do not only comprise CO_2 emissions stemming from energy input, but also CH_4 and N_2O emissions (both measured in carbon equivalent). These emissions are directly linked via a (row) vector of fixed emission factors per unit of output ($\mathbf{em}_{GHG,j}$) to the gross output in constant prices of the industries. The data source for these emissions is the Environmental Accounts (EA) of the WIOD database.

A matrix of energy input in physical units by industry is further constructed, whose elements represent the energy costs in each industry j, ($v_{E,ij}E_j$) divided by given energy prices $p_{E,i}$ and multiplied by the corresponding sub-shares s_{eij}, $s_{eij} \frac{v_{E,ij}E_j}{p_{E,i}}$. Applying the same (row) vector of fixed CO_2 emission factors (Table 3) per unit of energy type ($\mathbf{em}_{GHG,e}$) as in the consumption block to this energy matrix and the (row) vector of fixed emission factors per unit of output ($\mathbf{em}_{GHG,j}$) yields the (row) vector of domestic CO_2 emissions by industry $\mathbf{EM}_{GHG,j}$:

$$\mathbf{EM}_{GHG,j} = \mathbf{em}_{GHG,e}^{d}[E_e] + \mathbf{em}_{GHG}^{d}\mathbf{q} \tag{7}$$

Note that the *indirect* domestic carbon footprint of households by quintile is given by the sum of the energy and the output impact of consumption by quintile ($\frac{d\sum_j E_j}{dc_q} + \frac{d\sum_j q_j}{dc_q}$). In that case, we assume that the change dc_q corresponds to the full consumption of a quintile. Without price changes, the first term in brackets is just proportional to the second term (output impact of consumption of a quintile).

Imports by commodity are in this model determined by the sum of final and intermediate demand by commodity. For this purpose, an import shares matrix for final demand, $\mathbf{M}^f$ is introduced and applied to the total final demand matrix, $\mathbf{F}$ (consisting of the columns of final demand, $\mathbf{c}$, $\mathbf{cf}$, $\mathbf{ex}$, $\mathbf{st}$, $\mathbf{cg}$). The elements of matrix F are treated as constant and could alternatively be modeled via the Armington elasticity. Note that the major part of imports (i.e. intermediate goods) is variable and reacts upon prices. Total imports by commodities $\mathbf{IM}$ are in this framework given by imports of final demand, both energy and non-energy commodities imports and of intermediate inputs (energy), as well as non-energy (the symbol $\otimes$ represents element by element multiplication of two matrices.):

$$\mathbf{IM} = \mathbf{M}^f \otimes \mathbf{F} + \left[\hat{\mathbf{V}}_M \mathbf{S}_{NE}^m\right] \mathbf{p}_Q \mathbf{Q} + \left[\hat{\mathbf{V}}_E \mathbf{S}_E^m\right] \mathbf{p}_Q \mathbf{Q} \tag{8}$$

The GHG emissions of imports (in the rest of the world) by import commodity i are given by a (row) vector of average coefficients of GHG emissions by one unit of import in the EU27 ($\mathbf{em}_{GHG}^m$) derived from a MRIO (multi-regional input-output) model (Arto et al., 2014[1]).

_____
[1] We are indebted to Iñaki Arto for providing us with the aggregate results of his work for the EU27.

The total imported *indirect* carbon footprint of the economy is therefore given as:

$$\mathbf{EM}_{GHG}^{m} = \mathbf{em}_{GHG}^{m}\mathbf{IM} \tag{9}$$

The imported *indirect* carbon footprint of households by quintile is therefore determined by $\frac{d\mathbf{M}}{dc_q}$, where dc_q again stands for the full consumption of a quintile. This is the sum of the final demand import effect (captured in $\mathbf{M}^f$) and the intermediate demand import effect, which is proportional to the output impact $\frac{d\mathbf{q}}{dc_q}$.

2.3. Accounting for the Total Carbon Footprint by Income Group

In this analysis, the DYNK model described above has been used for calculating the carbon footprint of the different household income groups. The total carbon footprint of a quintile (q) is the sum of the *direct* carbon footprint, the *indirect* domestic carbon footprint, and the *indirect* imported carbon footprint of this quintile, where dc_q corresponds to the full consumption of a quintile:

$$\frac{d\mathbf{EM}_{GHG}}{dc_q} = \mathbf{EM}_{GHG,q} + \frac{d\sum_j \mathbf{EM}_{GHG,j}}{dc_q} + \frac{d\mathbf{EM}_{GHG}^m}{dc_q} \tag{10}$$

Note that the first term captures just the direct CO_2 emissions of the respective quintile, whereas the other two terms include indirect effects on CO_2 emissions which partly are due to consumption in other quintiles. This is the main difference between the approach used here and the standard MRIO analysis of footprint. These induced effects that are incorporated in the second and third term in Eq. (10) comprise also endogenous impacts on other final demand components, partly induced by income, partly by price effects. The price effects are due to wage reactions to employment effects and their repercussion on the whole price system. As can be deduced from the results presented in Table 1, though consumption of each quintile will create disposable income in the other four quintiles through a production/income multiplier, the consumption reactions induced by these income effects will be very different. The income induced in the bottom income quintile by consumption in the top income quintile for example converts into consumption with a much higher MPC than the other way around. From Table 1 we can even conclude that pure income effects in the top income quintile will not increase consumption significantly, if no wealth effects are induced for this income group as well.

The footprint is calculated in the following by introducing five exogenous demand shocks separately into the DYNK model from 2015 to 2025 which are equivalent to the consumption vector of the five income quintiles, i.e. to dc_q in (10). The problem is that all consumption is in principle endogenous in the model, so that double counting or overdetermination might occur. One method to deal with that would have been to make consumption of each quintile in each simulation exogenous. One potential problem with this method is that this changes the model structure and truncates links and feedbacks in the model. The other method – chosen here – is to subtract the impact of induced consumption in the quintile that should be fixed exogenously. This subtraction also is biased in the sense that it does not further consider the indirect and induced effects from this induced consumption in the same quintile, but bears the advantage that it does not alter the model structure. Indirect induced carbon footprint of the same quintile is subtracted by applying the same emission coefficients per unit of output to the value that results in the model simulation for induced domestic ($dc_{q,ind}^d$) and imported ($dc_{q,ind}^m$) consumption. For domestic indirect footprint, physical energy coefficients per unit of output have been calculated, $[E_e\mathbf{q}^{-1}]$. The other GHG footprint (CH_4 and N_2O) as well as

indirect imported footprint are already directly linked to output and imports, so the application is straightforward.

$$\frac{d\mathbf{EM}_{GHG}}{d\mathbf{c}_q} = \mathbf{EM}_{GHG,q} + \frac{d\sum_j \mathbf{EM}_{GHG,j}}{d\mathbf{c}_q} + \frac{d\mathbf{EM}_{GHG}^m}{d\mathbf{c}_q} - $$
$$-\mathbf{em}_{GHG,e}^d \left[\mathbf{E}_e \mathbf{q}^{-1}\right] d\mathbf{c}_{q,ind}^d - \mathbf{em}_{GHG}^d d\mathbf{c}_{q,ind}^d - \mathbf{em}_{GHG}^m d\mathbf{c}_{q,ind}^m \qquad (11)$$

This measure of a corrected carbon footprint from the model simulations is taken in the following for analyzing the link between income distribution and footprint.

3. Model Simulation Results

Table 5 shows the aggregate results of the model simulations, namely the economic and environmental impact of the full consumption vector of each quintile in 2025, compared to a baseline scenario. As has been said above already, in this simulation all final demand categories are endogenous and together determine the impact on GDP, together with the IO linkages. The demand shock that corresponds to the consumption vector of each quintile induces some private consumption. As expected, this effect is larger in the case of the bottom quintiles and smaller for the top quintiles. For the top 20% income group this induced consumption effect turns out even negative. The employment impact and the movement towards full employment, especially in the case of the 4th and 5th quintiles, induce wage and price reactions, which in turn affect final demand negatively. In the case of exports this results in a significant demand reduction. These effects show that the consumption of households needs to be seen simultaneously with the other demand categories. Lower consumption in the EU 27 would ceteris paribus lead to higher price competitiveness, which would shift the footprint to exports, i.e. to consumption in the rest of the world.

The impacts of direct carbon footprint of all five income groups in Table 5 add up to the total (100%) of direct household emissions. The impacts of indirect carbon footprint include the imported footprint and therefore add up to more than double of the domestic emission from production. From Table 5 one can already conclude that in these simulations the indirect footprint is important for all income groups and increases less with income than the direct footprint. This last result is different from what the literature has found until now. In the case of the top income group the carbon footprint in Europe and in the rest of the world amounts to more than 70% of European emissions.

The induced income effects across the other quintiles for the consumption of each quintile are visible in Table 6. The consumption of bottom quintiles induces income for higher income groups, but – as could be seen from Table 5 – that does not induce so much additional consumption. Partly this is also due to price effects resulting from the consumption demand. The total induced income impact in Table 6 can be compared with the direct share of the quintiles in disposable income. This relationship can be interpreted as the income multiplier of each quintile. For the bottom income group this multiplier more than doubles the income weight of the group: the 1st quintile has a share of about 6% in disposable income and induces 5.2% in total disposable

Table 5
Macroeconomic impact of consumption by quintile.

	1st quintil	2nd quintil	3rd quintil	4th quintil	5th quintil
GDP, const. prices	2.7	3.6	4.0	4.2	4.5
Private consumption, const. prices	0.6	0.6	0.5	0.2	−0.2
Capital formation, const. prices	0.0	0.0	0.1	0.1	0.1
Exports, const. prices	−4.6	−7.7	−10.4	−13.7	−21.1
Employment (persons)	4.9	7.2	8.7	10.3	13.7
Unemployment rate (% points)	−4.2	−6.3	−7.7	−9.0	−10.5
GHG emissions, direct	5.4	11.5	17.7	24.8	40.5
GHG emissions, indirect	18.6	31.1	41.3	53.6	83.6
GHG emissions, total	15.3	26.2	35.4	46.5	72.9

Table 6
Cross quintile income impact of consumption by quintile.

	1st quintil	2nd quintil	3rd quintil	4th quintil	5th quintil
Total	5.2	8.1	10.4	12.9	19.6
1st quintile		5.7	7.5	9.7	15.4
2nd quintile	4.6		9.3	11.7	18.2
3rd quintile	4.9	7.7		12.3	19.1
4th quintile	5.2	8.1	10.3		19.8
5th quintile	5.7	8.8	11.2	13.9	

income due to its consumption activity. This multiplier decreases when moving to higher income groups. For the middle (3rd quintile) it is 15% direct income share to 10% induced income and for the top it changes to 45% direct vs. about 20% induced.

The difference in the MPC between income groups and the difference in the structure of the consumption vectors determines the different structures of income, consumption and carbon footprint (Graph 1). The bottom income quintile has a share of 6% in disposable income, 7% in consumption expenditure and 8% in the Carbon footprint, whereas the top income quintile has a share of 45% in disposable income, 42% in consumption expenditure and 37% in the carbon footprint of all households. Except for the top income group, all other groups exhibit shares in the carbon footprint which are higher than those in consumption. This is an indication for a 'relative decoupling' effect, i.e. with higher income the consumption structure changes in a way that leads to a less than proportional increase in carbon footprint. This effect is continuous and rather small when moving from one quintile to the other between the first and the fourth quintile and then exhibits a larger shift when moving from the fourth to the fifth quintile. For the fourth quintile, the share in income is 22% and the share in the carbon footprint is 24%, whereas for the fifth quintile the corresponding values are 45% (income) and 37% (carbon footprint). That means that within the fifth quintile some heterogeneity concerning income and carbon footprint might exist which could only be further analysed by applying more disaggregate income groups, like for example deciles. In absolute terms, the average carbon footprint of all European households is 36.8 t carbon per household or 15.7 t carbon per capita (Graph 2). The bottom income group in Europe has less than half of this footprint, namely 6.1 t carbon per capita and the top income group has less than double (29.2 t carbon per capita).

Two important issues discussed in the literature in this context are the relative importance of direct and indirect footprint and the income elasticity of the footprint. The objective in both cases is to better understand potential counterbalancing effects to the level effect that determines the larger footprint of top income households. These effects could comprise directly and indirectly less emission intensive consumption structures of rich household groups and a different income elasticity that compensate for the dominating effect of much higher consumption levels of these households.

The standard result of the literature (Parikh et al., 2009 as well as Weber and Matthews, 2008) is that for bottom income households direct emissions have a higher share and for top income emissions from heating and driving become less important compared to indirect emissions. As Table 7 reveals that does not hold for the simulation results with the DYNK model. Indirect emissions play a more important role (in relative terms) for bottom income households. The main reason for this seems to be the CH_4 emissions from agricultural products. It can be expected that this effect would even be magnified, if the agricultural sector would be further disaggregated. The emissions - either via energy input or directly – are linked to the monetary value of the agricultural and food industry output. Rich households consume high quality/high price products in a larger amount, the production of which is not necessarily more energy/emission intensive than the same product with a lower quality (meat, wine, etc.). The share of indirect carbon footprint amounts to 91% for the bottom income group and decreases continuously with moving to higher income groups and finally reaches
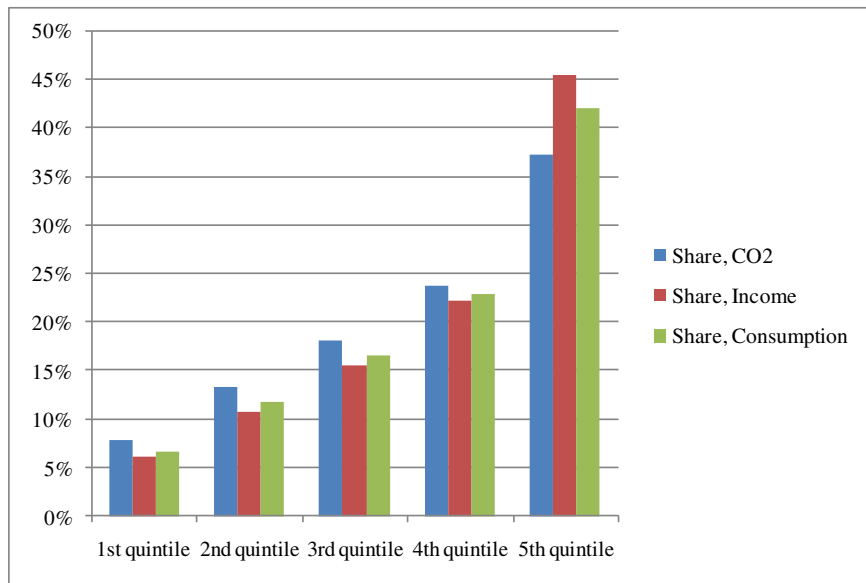
Graph 1. Income, consumption and carbon footprint by quintiles (shares in %).

86% for the top income group. The order across income groups is therefore different from the literature, but our values for the share of indirect emissions lie within the range of the literature which is between 70% and 90% (Parikh et al., 2009; Weber and Matthews, 2008).

The income elasticity of carbon has been widely researched, partly only with econometric methods applied to aggregate data, partly by applying econometrics to results of IO analysis, as in Weber and Matthews (2008). Chakravarty et al. (2009) define a range of the income elasticity of CO_2 emissions of 0.8 to 1. Chancel and Piketty (2015) use income elasticity values for assigning national emissions to income group and – in response to the values found in the literature – apply a range between 0.6 and 1.5 with a core value of 0.9, which according to their review corresponds to the mean value in the literature. It must be noted that the literature so far (to our knowledge) has derived values for the income elasticity of carbon either from econometric studies only or from applying econometrics *ex post* to the outcome of IO analysis. This methodology does not integrate the effects of household behavior into the IO analysis that measures the carbon footprint and therefore does not include feedback mechanisms and interactions between the

household sector and the production structure. In this study the household sector is fully integrated into the IO structure of the DYNK model and relevant feedbacks between consumption, other endogenous final demand components and the production structure of the EU 27 economy are integrated. The income elasticity of the carbon footprint is then calculated on the results of the model simulations. It is defined as the coefficient of the logarithmic difference of the carbon footprint to the logarithmic difference of income between two quintiles: $\frac{\log(d\mathbf{EM}_{GHG}/dc_{q+1}) - \log(d\mathbf{EM}_{GHG}/dc_q)}{\log(yd_{q+1}) - \log(yd_q)}$. In Table 7 the values for the first quintile, i.e. an income elasticity of 1.32 for direct carbon footprint and 0.89 for the indirect carbon footprint, define the reaction of the footprint when moving from the average income of the first quintile to the average income of the second quintile. The income elasticity of the direct carbon footprint is still above unity for the second quintile and then decreases to a value of 0.69. Again, the shift when moving from the fourth to the fifth quintile is larger than in all other cases of moving from one quintile to the next. This is a clear indication that further disaggregating the top 20% households of the income distribution could be worthwhile. The
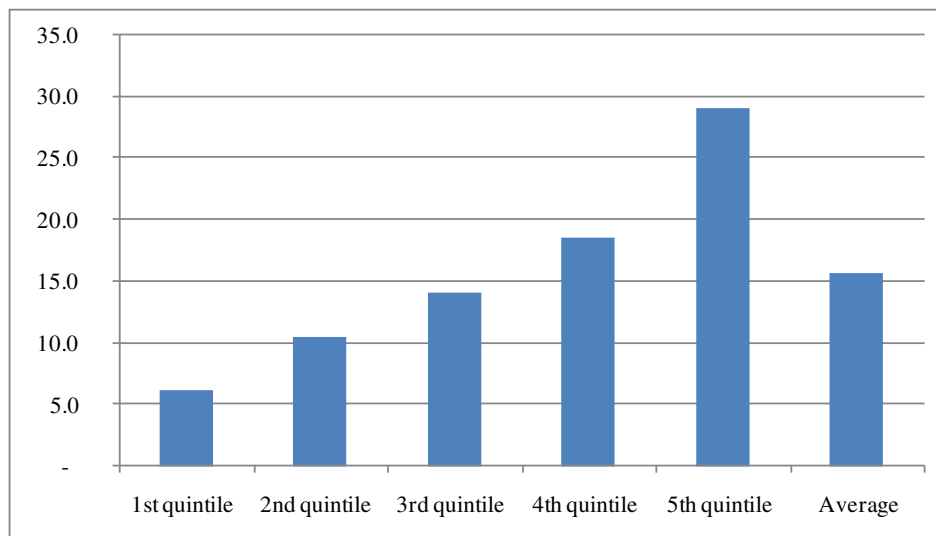
Graph 2. Carbon footprint by quintiles (in t carbon per capita).

Table 7
Direct and indirect CO$_2$e footprint: structure and income elasticity by quintile.

	1st quintile	2nd quintile	3rd quintile	4th quintile	5th quintile
Shares (%)					
Direct	8.7	10.9	12.5	13.3	13.8
Indirect	91.3	89.1	87.5	86.7	86.2
Income elasticity					
Direct	1.32	1.18	0.95	0.69	
Indirect	0.89	0.78	0.74	0.62	

results lead us to assume that within this group the income elasticity might decrease continuously as well and for the last step of 10% or 5% of the income distribution might be considerably smaller. The income elasticity of the indirect carbon footprint is always below unity and decreases from 0.89 for the first quintile to 0.62 for the fourth quintile. As can be easily seen, these values are in general within the range of the literature except for direct emissions. It must – though – be noted here that a large part of the literature does either not differentiate between direct and indirect emissions or not include direct emissions. This high value of the income elasticity of the direct carbon footprint at the bottom of the income distribution of households needs to be seen in the context of the relatively high MPC of low income households for durables (Table 1). The durable stock enters energy consumption (and thereby direct CO$_2$ emissions) with a unitary elasticity (Table 2).

More insights in what might be driving the small 'relative decoupling' effect in our results can be gained by analyzing the commodity structure of consumption on the one hand and the indirect carbon footprint of quintiles on the other hand (Table 8). As can be seen, rich households exhibit considerably lower shares of food and agricultural products in the consumption structure, which are not fully compensated by the higher shares of other emission intensive products (gasoline/diesel, electricity, air transport) in their consumption basket.

4. Conclusions

The objective of this study is fully integrating household behavior of five household income groups into a hybrid model (between CGE and

Table 8
Structure of indirect CO$_2$e footprint and consumption by quintile.

		Quintil 1	Quintil 2	Quintil 3	Quintil 4	Quintil 5
01	Agriculture, hunting and related services					
	share in consumption	3.07	2.92	2.71	2.48	2.02
	share in indirect emissions	8.02	7.58	7.17	6.76	6.10
15	Food products and beverages					
	share in consumption	15.85	14.87	13.59	12.14	9.38
	share in indirect emissions	4.31	4.12	3.95	3.80	3.56
23	Coke, refined petroleum products					
	share in consumption	4.79	5.37	5.88	6.23	5.88
	share in indirect emissions	3.73	3.71	3.76	3.77	3.68
24	Chemicals, chemical products					
	share in consumption	2.00	2.33	2.43	2.56	3.01
	share in indirect emissions	8.63	8.66	8.68	8.73	9.03
32	Radio, television and communication equipment					
	share in consumption	0.56	0.68	0.73	0.79	0.85
	share in indirect emissions	3.49	3.52	3.53	3.55	3.68
34	Motor vehicles, trailers					
	share in consumption	2.15	2.85	3.54	3.99	5.71
	share in indirect emissions	2.04	2.08	2.13	2.17	2.23
40	Electrical energy, gas, steam and hot water					
	share in consumption	2.37	3.25	3.56	3.87	3.76
	share in indirect emissions	11.93	12.86	13.05	13.23	12.73

econometric IO) and deriving the carbon footprint of different income groups from model simulation results. The carbon footprint calculated not only comprises endogenous intermediate demand like in traditional static IO analysis, but also induced consumption in the other groups and other endogenous final demand, as well as wage and price effects due to the demand pull.

The direct and indirect carbon footprint of the five groups exhibit several aspects of a relative decoupling effect: the share of the top income group in income (45%) is much larger than its share in the carbon footprint (37%) and vice versa for the bottom income group (6% in income and 8% in footprint). In per capita terms the bottom income carbon footprint is more than 2.5 times smaller than the average per capita footprint (15.7 t Carbon), whereas the top income footprint is less than twice as large. There is a strong indication in all results that the top 20% income group should be further disaggregated, as one observes a significant shift in all results between the fourth and the fifth quintile. The 'relative decoupling' effect is mainly driven by other indirect GHG emissions (CH$_4$) linked to agricultural production and the relatively high share of food consumption at the bottom of the income distribution. This effect would even be magnified, if the agricultural sector would be further disaggregated. Rich households consume agricultural products with higher prices, but not necessarily with higher energy/emission intensity.

There are several aspects in the results that underline the importance of the general philosophy in this paper of integrating household behavior consistently into the production (IO) structure. The different marginal propensity of consumption for nondurable and durable goods plays an important role in explaining the differences in income vs. carbon footprint shares as well as in the heterogeneity of the income elasticity of the direct carbon footprint. Another important aspect is the difference of consumption in other income groups induced by the consumption of each income group.

Several results of this analysis are different from what the literature has found by applying aggregate econometric analysis or only static IO analysis. One applies to the share of indirect emissions by income groups and the other to the income elasticity of the carbon footprint.

We find – in contrast to the standard result of the literature – that indirect emissions play a more important role (in relative terms) for bottom income households. The main reason for this seems to be the CH$_4$ emissions from agricultural products. The income elasticity of the direct and indirect carbon footprint in this study comprises macroeconomic (or general equilibrium) feedbacks and therefore is not limited to the ceteris paribus condition that needs to hold for the elasticity values estimated in the literature. The values of this elasticity define the reaction of the carbon footprint when ascending from one quintile to the next and are not constant and different from the range found in the literature. The income elasticity of the carbon footprint considerably decreases when moving from bottom to top income. The income elasticity of the direct carbon footprint is 1.32 for the first quintile and still above unity for the second quintile and then decreases to a value of 0.69. The income elasticity of the indirect carbon footprint is always below unity and decreases from 0.89 for the first quintile to 0.62 for the fourth quintile.

Another interesting result is that with macroeconomic feedbacks (additionally to pure IO linkages), indirect effects are more important for bottom income households than for top incomes. The results indicate a small 'relative decoupling', partly due to a higher saving rate and less emission intensive consumption structures of top incomes. This effect results in a less than proportionate rise of the carbon footprint with a rise in income, which – though - does not suffice to compensate for the much higher level of consumption of top incomes.

The results further indicate that future research should split up households in more income groups, especially the top income quintile should be split into its corresponding deciles. Agricultural footprint obviously plays an important rule and should therefore be treated more carefully, at a lower level of aggregation of products and in a way that

corrects for the nominal bias (top income earners consume high priced products).

As far as it comes to policy conclusions, the most important result is that no synergy between policies in favor of more equity and environmental policies can be found. Policy measures that successfully decrease inequality will automatically stimulate the economy (a result corroborated here) and therefore increase the carbon footprint. This increase will be less than proportional due to the mechanisms identified in this study. A policy strategy that aims at a simultaneous reduction of the carbon footprint and of inequality therefore needs to design instruments that explicitly deal with the trade-off.

Appendix A. The DYNK Model

A.1. Household behavior and private consumption

A.1.1. Durable demand and total nondurables

Starting point for determining total private consumption is the buffer-stock model, developed by Deaton (1991) and Carroll (1997). We apply a specification, where buffer-stock saving is not motivated by income uncertainty, but by down payments for purchase of durables, as laid down in Luengo-Prado (2006). 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:

$$\max_{(C_t, K_t)} V = E_0 \left\{ \sum_{t=0}^{\infty} \beta^t U(C_t, K_t) \right\} \tag{A1}$$

Specifying a CRRA utility function and a budget constraint the model can be solved in terms of first order conditions, but not in terms of explicit demand functions. The budget constraint in this model without adjustment costs for the durables stock is given by the definition of assets, A_t:

$$A_t = (1+r)(1-t_r)A_{t-1} + YD_t - C_t - (K_t - (1-\delta)K_{t-1}) \tag{A2}$$

In (A2) the sum of C_t and $(K_t - (1-\delta)K_{t-1})$ represents total consumption, i.e. the sum of nondurable and durable expenditure (with depreciation rate of the durable stock, δ). The gross profit income rA_{t-1} (with interest rate r) is taxed with tax rate t_r. Disposable household income excluding profit income, YD_t, is given as the balance of net wages $(1-t_S-t_Y)w_t H_t$ and net operating surplus accruing to households $(1-t_Y)\Pi_{h,t}$, plus transfers Tr_t:

$$YD_t = (1-t_S-t_Y)w_t H_t + (1-t_Y)\Pi_{h,t} + Tr_t \tag{A3}$$

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 modeled at the level of quintiles q of household incomes ($q = 1...5$):

$$YD_t = \sum_q \left[(1-t_{S,q}-t_{Y,q})w_{t,q}H_{t,q} + (1-t_{Y,q})\Pi_{t,q} + Tr_{t,q} \right] \tag{A4}$$

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

$$A_t + (1-\theta)K_t \geq 0 \tag{A5}$$

This term represents voluntary equity holding, 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: $X_t = (1+r_t)(1-t_r)A_{t-1} + (1-\delta)K_{t-1} + YD_t$. The model is specified here in the form of demand functions that are consistent with the model properties. These comprise non-linear consumption functions for durables, which are based on the concave shape of the policy functions for consumption in Luengo-Prado (2006), and where, with higher levels of durables per households (K_t/h_t), the marginal propensity of investment in durables, C_{Kt} with respect to X_t decreases. The down payment parameter θ in Luengo-Prado (2006) represents a long-term constraint between the liabilities stock and the durable stock of households and is specified here by imposing limits to the down payment for durable purchases. Durables in this model are owned houses (dwelling investment) and vehicles. The long-run demand functions for the two durable categories ($C_{dur,t}$) is a function of 'cash on hand' (X_t), the down payment for durable purchases (θ_{Ct}), as well as static user costs of durables, $p_{dur,t}(r_t + \delta)$

$$\log C_{dur,t} = \log C_{dur,t} \left[\log X_t, \theta_{Ct}, \log(p_{dur,t}(r_t + \delta)), \log(K_{t-1}/h_{t-1}) \right] \tag{A6}$$

The long-run demand function for total nondurable consumption is a function of 'cash on hand' and down payments for durable purchases ($\theta_{Ct} \log C_{dur,t}$)

$$\log C_{nondur,t} = \log C_{nondur,t} \left[\log X_t, \theta_{Ct} \log C_{dur,t} \right] \tag{A7}$$

The latter considers that households need to finance down payments, and will not do so by savings in the same period but will smooth nondurable consumption accordingly. The estimation is carried out as error correction panel data estimation and the results are used to calibrate the model at the level of the 5 quintiles of income, which are characterized by different values for the durable stocks per household. Therefore, the model contains growth rates for $C_{dur,t}$ and $C_{nondur,t}$ for each quintile (q).

A.1.2. Energy demand

The energy demand of households comprises fuel for transport, electricity and heating. These demands are part of total nondurable consumption and separability from non-energy nondurable consumption is assumed. In line with the literature on the rebound effect (e.g.: Khazzoom, 1989), the energy demand is modeled as (nominal) service demand and the service aspect is dealt with via 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: $p_S = p_E/\eta_{ES}$. Any increase in efficiency leads to a decrease in the service price and thereby to an increase in service demand ("rebound effect").

For transport demand of private households we take substitution between public (C_{pub}) and private transport (C_{fuel}) into account. The price for fuels, $pc_{S,fuel}$, is defined as a service price. Total transport demand of households depends on the composite price of private and public transport, as well as on total nondurable expenditure. 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.

$$\log\left(\frac{C_{fuel,t}}{K_{veh,t}}\right) = \mu_{fuel} + \gamma_{fuel} \log\left(\frac{p_{fuel,t}}{\eta_{fuel,t}}\right) + \xi_{fuel} \log\left(\frac{K_{veh,t}}{h_t}\right) \tag{A8}$$

In (A8) μ_{fuel} 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.

The equations for heating and electricity demand are analogous to Eq. (A8) and have the following form:

$$\log\left(\frac{C_{heat,t}}{K_{hous,t}}\right) = \mu_{heat} + \gamma_{heat} \log\left(\frac{p_{heat,t}}{\eta_{heat,t}}\right) + \xi_{heat} \log(dd_{heat}) \tag{A9}$$

$$\log\left(\frac{C_{el,t}}{K_{app,t}}\right) = \mu_{el} + \gamma_{el} \log\left(\frac{p_{el,t}}{\eta_{el,t}}\right) + \xi_{el} \log(dd_{heat}) \tag{A10}$$

In both equations the variable heating degree days dd_{heat} is added. 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, C_{app}, which in turn is explained in a log linear specification like total transport demand.

A.1.3. 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 budget share equations for the i nondurable goods in each period:

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_i \log\left(\frac{C}{P}\right); \quad i = 1...n, 1...k \tag{A11}$$

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]:

$$\eta_i = \frac{\partial \log C_i}{\partial \log C} = \frac{\beta_i}{w_i} + 1 \tag{A12}$$

$$\varepsilon_{ij}^C = \frac{\partial \log C_i}{\partial \log p_j} = \frac{\gamma_{ij} - \beta_i w_j}{w_i} - \delta_{ij} + \varepsilon_i w_j \tag{A13}$$

In (13) 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.

---

[2] The derivation of 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.

A.2. Firm Behavior and Production Structure

A.2.1. Substitution in a K,L,E,M^m,M^d Model

The 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}. Each industry faces a unit cost function for the price (p_Q) of output Q, with constant returns to scale

$$\log p_Q = \alpha_0 + \sum_i \alpha_i \log(p_i) + \frac{1}{2}\sum_i \gamma_{ii}(\log(p_i))^2$$
$$+ \sum_{i,j} \gamma_{ij} \log(p_i) \log(p_j) + \alpha_t t + \frac{1}{2}\alpha_{tt}t^2 + \sum_i \rho_{ti} t \log(p_i) \tag{A14}$$

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, TFP is measured by α_t, and α_{tt}. Shepard's Lemma yields the cost share equations in the Translog case, which in this case of five inputs can be written as:

$$v_K = [\alpha_K + \gamma_{KK} \log(p_K/p_{Md}) + \gamma_{KL} \log(p_L/p_{Md}) + \gamma_{KE} \log(p_E/p_{Md}) + \gamma_{KM} \log(p_{Mm}/p_{Md}) + \rho_{tK}t]$$
$$v_L = [\alpha_L + \gamma_{LL} \log(p_L/p_{Md}) + \gamma_{KL} \log(p_K/p_{Md}) + \gamma_{LE} \log(p_E/p_{Md}) + \gamma_{LM} \log(p_{Mm}/p_{Md}) + \rho_{tL}t]$$
$$v_E = [\alpha_E + \gamma_{EE} \log(p_E/p_{Md}) + \gamma_{KE} \log(p_K/p_{Md}) + \gamma_{LE} \log(p_L/p_{Md}) + \gamma_{EM} \log(p_{Mm}/p_{Md}) + \rho_{tE}t]$$
$$v_M = [\alpha_M + \gamma_{MM} \log(p_{Mm}/p_{Md}) + \gamma_{KM} \log(p_K/p_{Md}) + \gamma_{LM} \log(p_L/p_{Md}) + \gamma_{EM} \log(p_E/p_{Md}) + \rho_{tM}t]$$
$$\tag{A15}$$

The homogeneity restriction for the price parameters $\sum_i \gamma_{ij} = 0, \sum_j \gamma_{ij} = 0$ has already been imposed in (A15), so that the terms for the price of domestic intermediates p_{Md} have been omitted. The immediate ceteris paribus reaction to price changes is given by the own and cross price elasticity. These own- and cross- price elasticities for changes in input quantity x_i are given as:

$$\varepsilon_{ii} = \frac{\partial \log x_i}{\partial \log p_i} = \frac{v_i^2 - v_i + \gamma_{ii}}{v_i} \tag{A16}$$

$$\varepsilon_{ij} = \frac{\partial \log x_i}{\partial \log p_j} = \frac{v_i v_j + \gamma_{ij}}{v_i} \tag{A17}$$

Here, the v_i represent the factor shares in Eq. (A15), and the γ_{ij} the cross-price parameters. The rate of factor bias, i.e. the impact of t on factor x_i without considering TFP is given by:

$$\frac{d \log x_i}{dt} = \frac{\rho_{ti}}{v_i} \tag{A18}$$

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 ($p^{d,k}$). Once the (user specific) import prices for intermediate goods are given, the price vectors of total domestic ($\mathbf{p}_{Md}$) and imported ($\mathbf{p}_{Mm}$) intermediate inputs by industry can be calculated. Within the bundle of intermediate inputs (M^m and M^d), which comprises 55 non-energy industries/commodities, Leontief technology is assumed. These bundles are defined by the 'use structure matrices' ($\mathbf{S}_{NE}^m$ and $\mathbf{S}_{NE}^d$) with column sum of unity.

$$\mathbf{p}_{Mm} = \mathbf{p}^m \mathbf{S}_{NE}^m \qquad \mathbf{p}_{Md} = \mathbf{p}^d \mathbf{S}_{NE}^d \tag{A19}$$

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 for domestic ($\mathbf{B}_K^d$) and imported ($\mathbf{B}_K^m$) investment demand:

$$\mathbf{p}_{CF} = \mathbf{p}^m \mathbf{B}_K^m + \mathbf{p}^d \mathbf{B}_K^d \tag{A20}$$

The price of labor is endogenous as well and determined in the labor market. The prices of energy types are assumed to be determined at world markets for energy and are therefore treated as exogenous. A specific feature of capital is that two prices of this input can be formulated: (i) the *ex post* rate of return to K (derived from operating surplus) and (ii) the *ex ante* rate of return to K, i.e. the user cost. In economic terms, that represents an imperfect capital market, which can be in disequilibrium (see: Jorgenson et al., 2013). It is assumed that after the base year, this adjustment takes place instantaneously.

A.2.2. Energy Inputs in Production and the Domestic Indirect Carbon Footprint of Households

The aggregate E comprises four 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:

$$\log p_E = \alpha_0 + \sum_i \alpha_{E,i} \log(p_{E,i}) + \frac{1}{2}\sum_i \gamma_{E,ii}\left(\log(p_{E,i})\right)^2 \\ + \sum_{i,j} \gamma_{E,ij} \log(p_i) \log(p_j) + \sum_i \rho_{tE,i} t \log(p_{E,i}) \tag{A21}$$

$$v_{E,i} = \left[\alpha_{E,i} + \sum_{i,j} \gamma_{E,ij} \log(p_{E,i}) + \rho_{tE,i} t\right] \tag{A22}$$

In some cases the elasticity of inter-fuel substitution is very close to zero, but most industries show a value of straying around -0.5. The cross price elasticity also show negative signs in a large number of industries, indicating complementarity between fuels.

A.3. Government and Model Closure

The public sector balances close the model and show the main interactions between households, firms and the general government. 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. The expenditure side of government is made up of 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 model is closed by further fixing the public budget constraint, that defines the future path of government net lending to GDP ($p_y Y$). 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:

$$cg(1 + w_{cf}) = \Delta D_{gov,t}/p_y Y - r_{gov,t} D_{gov,t-1} - Tr + (t_{wL} + t_L)w_t H_t \\ + t_Y(w_t H_t + \Pi_{h,t}) + t_r r_t A_{t-1} + \hat{\mathbf{T}}_N\left[\mathbf{c}_{pp,t} + \mathbf{f}_{pp,t} + \mathbf{p}_{Q,t}\mathbf{Q}_t\right] \tag{A23}$$

References

Arto, I., Rueda-Cantuche, J.M., Peters, G.P., 2014. Comparing the GTAP-MRIO and WIOD databases for carbon footprint analysis. Econ. Syst. Res. 26 (3), 327–353.

Attanasio, O., Weber, G., 1995. Is consumption growth consistent with intertemporal optimization? Evidence from the consumer expenditure survey. J. Polit. Econ. 103, 1121–1157.

Boeters, S., Savard, L., 2013. The Labor Market in Computable General Equilibrium Models. In: Dixon, P., Jorgenson, D.W. (Eds.), Handbook of CGE Modeling vol. 1. Elsevier.

Borghesi, S., 2000. Income Inequality and the Environmental Kuznets Curve. Fondazione Eni Enrico Mattei, Nota di Lavoro 83.2000, Milano p. 2000.

Boyce, J.K., 1994. Inequality as a cause of environmental degradation. Ecol. Econ. 11, 169–178.

Carroll, C.D., 1997. Buffer-stock saving and the life cycle/permanent income hypothesis. Q. J. Econ. 112, 1–55.

Chakravarty, S., Chikkatur, A., de Conick, H., Paccala, S., Socolow, R., Tavoni, M., 2009. Sharing global carbon emission reductions among one billion high emitters. Proc. Natl. Acad. Sci. 106, 11884–11888.

Chancel, L., Piketty, T., 2015. Carbon and Inequality: From Kyoto to Paris. Trends in the Global Inequality of Carbon Emissions (1998–2013) & Prospects for an Equitable Adaptation Fund (available at: http://piketty.pse.ens.fr/files/ChancelPiketty2015.pdf).

Deaton, A., 1991. Saving and liquidity constraints. Econometrica 59, 1221–1248.

Deaton, A., Muellbauer, J., 1980. An almost ideal demand system. Am. Econ. Rev. 70 (3, June), 312–326.

Duarte, R., Feng, K., Hubacek, K., Sánchez-Chóliz, J., Sarasa, C., Sun, L., 2015. Modeling the carbon consequences of pro-environmental consumer behavior. Appl. Energy 2015, 1–9.

Folmer, K., 2009. Why Do Macro Wage Elasticities Diverge? CBP Discussion Paper No. 122

Green, R.D., Alston, J.M., 1990. Elasticities in AIDS models. Am. J. Agric. Econ. 72, 442–445.

Hall, R.E., 1978. Stochastic implications of the life cycle-permanent-income hypothesis: theory and evidence. J. Polit. Econ. 86, 971–987.

Jorgenson, D.W., Goettle, R., Ho, M., Wilcoxen, P., 2013. Energy, the Environment and US Economic Growth. In: Dixon, P., Jorgenson, D.W. (Eds.), Handbook of CGE Modeling vol. 1. Elsevier, p. 2013.

Khazzoom, J.D., 1989. Energy savings from more efficient appliances: a rejoinder. Energy J. 10, 157–166.

Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., Schaeffer, R., 2006. A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. Energy 21, 181–207.

Luengo-Prado, M.J., 2006. Durables, nondurables, down payments and consumption excesses. J. Monet. Econ. 53, 1509–1539.

Parikh, J., Panda, M., Ganesh-Kumar, A., Singh, V., 2009. Carbon emission structure of Indian economy. Energy 34, 1024–1031.

Ravallion, M., Heil, M., Jalan, J., 2000. Carbon Emissions and Income Inequality. Oxford Economic Papers pp. 651–669.

Salotti, S., Montinari, L., Amores, A.F., Rueda-Cantuche, J.M., 2015. Total Expenditure Elasticity of Non-durable Consumption of European Households. JRC Technical Report EUR 27081 ENEuropean Union:p. 2015 http://dx.doi.org/10.2791/625913.

Weber, C.,.L., Matthews, H.S., 2008. Quantifying the global and distributional aspects of American household carbon footprint. Ecol. Econ. 66 (2008), 379–391.