DRAFT - Estimating Energy Substitution Parameters in GTAP-E

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Abstract

The production structure of GTAP-E includes an energy and capital composite alongside other factors of production. The elasticity of substitution between capital and energy is therefore highly important to the output of the model, yet by default, it is set to the same value across all sectors and countries. This paper uses OECD panel data from 2000-2016 and covering 30 countries to estimate elasticities for capital-energy substitution. Estimates are produced for capital-energy substitution over 7 sectors, 5 of which are then mapped across to GTAP sectors. These estimated parameters are used in both a FTA model, and the results are compared with both the default GTAP-E parameters and less specific estimated values from existing literature. This allows us to determine the magnitude of impact on model output from using statistically estimated parameters, and from using parameters disaggregated by country and sector.

Keywords: GTAP-E, sustainability, capital-energy substitution, translog function, OECD, CGE Modelling, Climate Policy

1. Introduction

Computable General Equilibrium models that feature energy substitution as part of their production structure, such as the Global Trade Analysis Project's (GTAP) energy and environmental extension (GTAP-E), are critical to analysis of trade policy, and in particular the intersection of policy concerning climate, energy, and international trade. As a result, it is necessary to ensure that the inputs to the underlying model structure are as accurately specified as possible. This paper addresses two questions: firstly, what does recent data suggest about the values of elasticities of capital-energy and inter-fuel substitution; and secondly, how would use of these parameters impact the results of GTAP-E models for both Free Trade Agreement (FTA) and Carbon Border Adjustment Mechanism (CBAM) analysis.

Applied General Equilibrium (AGE) models of international trade, including the GTAP family of models, rely on parameters, endowments (labour, capital, land, etc) and trade data to generate price and welfare effects. Since the endowments and trade data are easily quantifiable, the results of AGE models are largely determined by the choice of functional form in the consumer and producer's maximisation problem and by the behavioural parameters, most of them elasticities, which reflect the sensitivity of consumers and firms to changes in relative prices. An AGE model of perfect competition assumes that production rests on a Constant Elasticity of Substitution (CES) functional form which exhibits constant returns to scale and on technology parameters such as the valued added production elasticity of substitution between primary factors.

The numerical analysis in this paper employs the GTAP-E model version 7, member of the Global Trade Analysis Project family of models (1997). The GTAP model is a widely used, static, multisector, multiregion applied general equilibrium model. It is based on a detailed database with broad coverage of (trade) distortions and explicit statistics on transport margins. Firms use constant-returns-to-scale technologies, except for the resource sectors with an upward-sloping supply function, where a fixed factor is in the production technology to construct a diminishing-returns-technology. Import demand is modelled through the Armington assumption of imperfect substitutability between domestic and imported goods and between imported goods from different regions. The model assumes a global mediate between world savings and investments, and a region-specific equation for consumer demand that allows for different responses to price income changes across regions. GTAP-E has the same structure as GTAP, but production structure and consumption structure include a more detailed description of substitution possibilities among different sources of energy, and a more detailed relationship between capital and energy. A further description of the model's features is given by Truong (1999).

We employ the methodology of Costantini and Paglialunga (2014) in estimating sector specific GTAP-E elasticities using OECD-STAN data, which provides employment, capital stocks, gross output and value added, with the environmental accounts (energy use and emissions). The output of the GTAP-E model under these estimated parameters will then be compared to the default specification.

2. Literature Review

There are a number of papers in existing literature that examine parameter estimation in CGE models, the sensitivity of model output and even seek to validate model performance against historic data.

Koetse et al. (2008) provides a meta-analysis of the substantial number of estimates of capital-energy substitution, although the most recent data in the studies covered by the analysis is from 1990. The analysis covers a total of 631 estimated elasticities, which show without exception that there is substantial substitution between capital and energy, highlighting their potential importance to analysis for policy-making.

Beckman et al. (2011) take a full set of estimated capital-energy and inter-fuel substitution elasticities from across existing literature and test their performance against default GTAP-E parameters in predicting volatility in oil prices from 1980-2005. They find that the estimated parameters outperform the defaults by a significant margin (error is reduced from 76% to 4%), highlighting the importance of accurate parameter specification. The parameters used by Beckman et al. are generalised over all countries, and for capital-energy substitution, over all sectors.

Okagawa & Ban (2008) carry out a more disaggregated estimation exercise of substitution elasticities between production factors (including capital-energy) within the GTAP-E structure – using OECD data from 1995 to 2004. The resulting parameters were also found to impact results significantly, such that 'the macroeconomic impact of climate policy could be potentially overestimated with conventional parameters.'[1]

Costantini & Paglialunga have made two important contributions to this area in 2014, and with Crespi in 2018. In both papers they seek to produce estimates for capital-energy substitution over multiple manufacturing sectors and a panel of OECD countries, using the OECD-STAN database. Costantini & Paglialunga truncate the data used in their analyses at 2008, in order to avoid introducing confounding

[1] Okagawa & Ban (2008), p.13

effects from the financial crisis and from the first commitment period of the Kyoto Protocol. Their results show that ‘CGE models applying the same value for capital-energy substitution elasticity to all sectors are highly sectors are highly misspecified’, particularly with regard to the economic impacts associated with mitigation policies.

This finding is replicated in Antimiani et al. (2015) consider alternative climate policy instruments using GDynE, a dynamic version of GTAP-E, and compare three alternative sets of elasticity of substitution parameters. These are: standard values from GTAP-E; values derived from analysis by Koetse et al. (2008) on the energy-capital elasticity of substitution values from previous literature and from an analysis carried out by Stern (2012) on the inter-fuel elasticity of substitution values; and thirdly, with parameters that are sector-specific econometrically estimated values for ten manufacturing sectors provided by Costantini and Paglialunga (2014). The simulation exercise reveals that the model produces highly differentiated results when different sets of elasticity parameters are adopted.

This paper seeks to build on Costantini & Paglialunga’s work by adopting their estimation methodology and applying it to more recent panel data from OECD-STAN, covering a period of 2000-2016. Capital-energy substitution elasticities will be estimated across seven sectors, including two service sectors. We will also extend this work by implementing each set of elasticities in a simulation reflecting a fictional FTA, as well as a carbon abatement policy, to determine how the impact of parameter specification differs across policy area.

3. Data and Methods

The methodology for estimating capital-energy substitution elasticities follows Costantini & Paglialunga (2014) as closely as possible while using more recent data and a broader set of sectors. In this way, a capital-labour-energy (KLE) production function is assumed and a dataset representing four variables is constructed: economic output (Y), capital stock (K), labour (L), and energy consumption (E). Filtering for completeness of necessary data and complementarity with other dependencies, we used the following countries and sectors.

Country	ISO Code
Australia	AUS
Austria	AUT
Belgium	BEL
Canada	CAN
Czechia	CZE
Denmark	DNK
Estonia	EST
Finland	FIN
France	FRA
Germany	DEU
Greece	GRC
Hungary	HUN
Ireland	IRL
Italy	ITA
Japan	JPN
Korea	KOR
Latvia	LVA
Lithuania	LTU
Luxembourg	LUX
Mexico	MEX
Netherlands	NLD
Poland	POL
Portugal	PRT
Slovakia	SVK
Slovenia	SVN
Spain	ESP
Sweden	SWE
Turkey	TUR
United Kingdom	GBR
United States of America	USA

Sector	ISIC rev.4 codes
Agriculture, fishing and forestry	D01T03
Mining and quarrying	D05T09
Non-traded services	D41T99
Traded services	D58T66
Food, wood, chemicals and textiles	D10T25
Machinery and electrical equipment	D26T28
Transport equipment and other manufacturing	D29T39

Output and capital stock data is primarily based on data sourced from the OECD's Structural Analysis Database (OECD-STAN).[2] The database provides data on value added, gross fixed capital formation and the corresponding deflators.

To adjust for purchasing price parity (PPP), value added benchmark PPP coefficients for 2005 were sourced from the GGDC Productivity Level Database which itself is based on the International Comparisons Program.[3] These coefficients were then extrapolated over the rest of the period to form a time-series of coefficients for each sector and country using the deflators provided in the OECD-STAN database.[4]

Gross fixed capital formation data from OECD-STAN is transformed into an estimated time-series of capital stock for each country using the Perpetual Inventory Method, as described in Costantini & Paglialunga (2014). Under this method, initial capital stock (K) for country i and sector j is estimated by the following equation:

$$K_{ij(t=0)} = \frac{I_{ij(t=0)}}{g_{ij} + d}$$

Based on the PPP adjusted gross fixed capital formation (I), annual growth rate (g) of each sector in each country and a depreciation rate (d) of 15%. Each subsequent year's capital stock is determined by the accumulation function:

$$K_{ij(t)} = K_{ij(t-1)} \cdot I_{ij(t)}$$

Data on gross energy use is sourced from the WIOD environmental accounts dataset.[5]

In order to use this dataset to estimate capital-energy elasticities, Costantini & Paglialunga use a Translog production function to calculate the Allen Elasticity of Substitution (AES). This is a symmetric elasticity, as opposed to the Morishima Elasticity of Substitution used elsewhere in literature.[6] This results in the following assumed specification of production.

$$(1)\ lnY_{ijt} = \alpha_0 + \beta_K \cdot lnK_{ijt} + \beta_E \cdot lnE_{ijt} + \beta_L \cdot lnL_{ijt} + \frac{1}{2}\left[\beta_{KK} \cdot \left(lnK_{ijt}\right)^2 + \beta_{EE} \cdot \left(lnE_{ijt}\right)^2 + \beta_{LL} \cdot \left(lnL_{ijt}\right)^2\right] + \beta_{KL} \cdot \left(lnK_{ijt} \cdot lnL_{ijt}\right) + \beta_{KE} \cdot \left(lnK_{ijt} \cdot lnE_{ijt}\right) + \beta_{LE} \cdot \left(lnL_{ijt} \cdot lnE_{ijt}\right) + \varepsilon_{ijt}$$

Elasticities are then estimated using the between estimator (BE) which Costantini & Paglialunga select based on the work of Stern (2012) and Huak & Wacziarg (2009) in showing that BE has less bias than

[2] https://www.oecd.org/sti/ind/stanstructuralanalysisdatabase.htm
[3] https://www.rug.nl/ggdc/productivity/pld/
[4] Methodology described at: https://datahelpdesk.worldbank.org/knowledgebase/articles/665452-how-do-you-extrapolate-the-ppp-conversion-factors
[5] https://op.europa.eu/en/publication-detail/-/publication/df9c194b-81ba-11e9-9f05-01aa75ed71a1/language-en
[6] See Koetse et al (2008) p.4 for discussion of the difference and its consequences for estimation

other estimators, including fixed effects, random effects, and other general method of moments estimators. Costantini & Paglialunga also compare the results of the BE estimator over their 18-year period to mean value estimations over shorter, 4-year time periods. They conclude that the longer, medium-term period BE estimator results produce more valuable estimations for CGE models than shorter term estimates. We follow this by employing the BE estimator over the full width of the dataset from 2000 to 2016.

Once the Translog production function has been estimated in this way, we follow the standard approach to get to the Allen elasticities of substitution of a three-input production function (KLE). This involves calculating the cost shares of each input, assuming constant returns to scale, and using these to construct the bordered Hessian matrix. Following Costantini & Paglialunga, we specifically estimate the capital-energy AES:

$$(2)\ AES\ (\sigma_{KE}) = \frac{|H_{KE}|}{|H|}$$

4. Estimation Results

Values for the Allen capital-energy elasticity of substitution (σ_{KE}) are presented in table 1 below. Those in bold are within the expected range 0-1, which are used in section 5 for model simulation. For example, if energy prices rise, then elasticities within this range imply substitution away from energy towards capital. However, the increase in demand for capital is less than proportionate to the increase in the price for energy.

Sector	*AES (σ_{KE})*
Agriculture, fishing, and forestry	**0.18**
Mining and quarrying	1.31
Food, wood, chemicals, textiles	-0.63
Machinery and electrical equipment	**0.60**
Transport equipment and other manufacturing	**0.22**
Financial and IT services	**0.39**
Other services	**0.08**

The estimates show that “Other services” and “Agriculture, fishing and forestry” display the least substitution between capital and energy across the time period with an elasticity of 0.08 and 0.18 respectively. On the other side of the scale, “machinery and equipment” and “Financial and IT services” show the largest substitution possibilities, with an elasticity of 0.60 and 0.39, respectively. Taking “Agriculture, fishing and forestry” as an example, these results suggest that there is more friction when substituting away from energy intensive production processes (e.g fuel to operate harvesting machinery) towards capital intensive processes (e.g electric machinery for harvesting).

5. Model Simulation and Results

The elasticities estimated in this paper that fall into the expected range of [0-1] are matched to GTAP sectors to run simulations. GTAP sectors that do not have a suitable estimated elasticity retain their default value. The full parameter table for capital-energy substitution resulting from this is included in the appendix. Where sectors did not have values estimated or where the estimated values fell outside the range – the GTAP-E default values are used.

For capital-energy substitution elasticities that are estimated at a multisectoral level (i.e. 3 and 4), these sectors are matched from the ISIC classification to GTAP sectors using the concordance table in the appendix.

These elasticities and our own estimates are inputted into two different model scenarios:

A. Carbon price shock scenario – Real carbon prices are set to $5 in all countries. The aggregation used is 32 countries and 64 sectors.

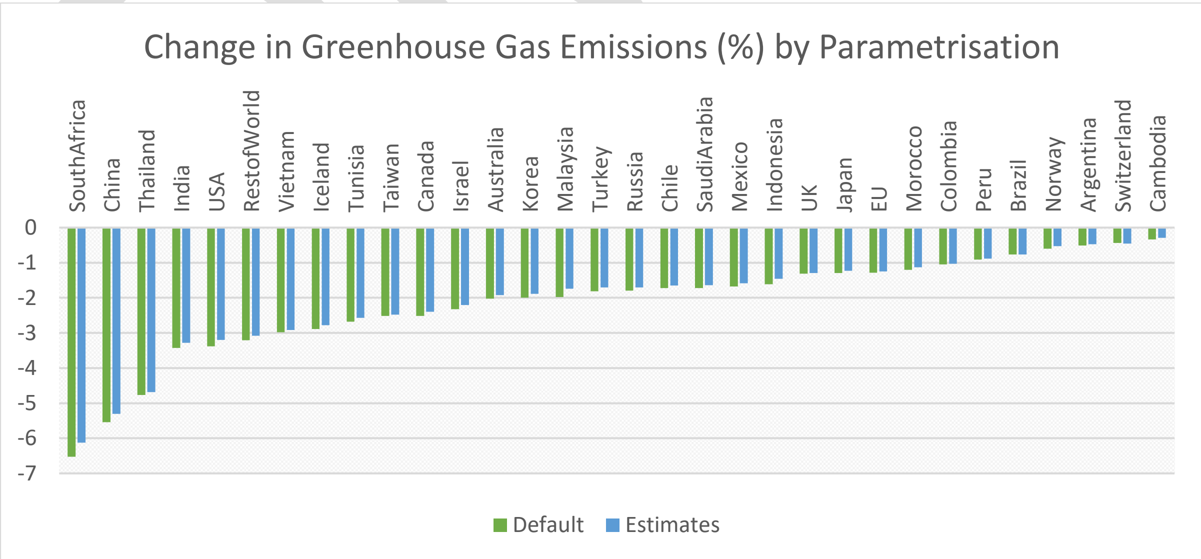
B. Fictional FTA scenario – tariff and non-tariff measures are bilaterally liberalised between the UK and the USA. The same aggregation is used as in scenario a.

In both scenarios the standard closure rules are used, with the addition of a capital swap for both the UK and the USA in scenario B. In scenario A the real price of carbon is made exogenous in the closure swap in order to implement shocks to carbon prices.

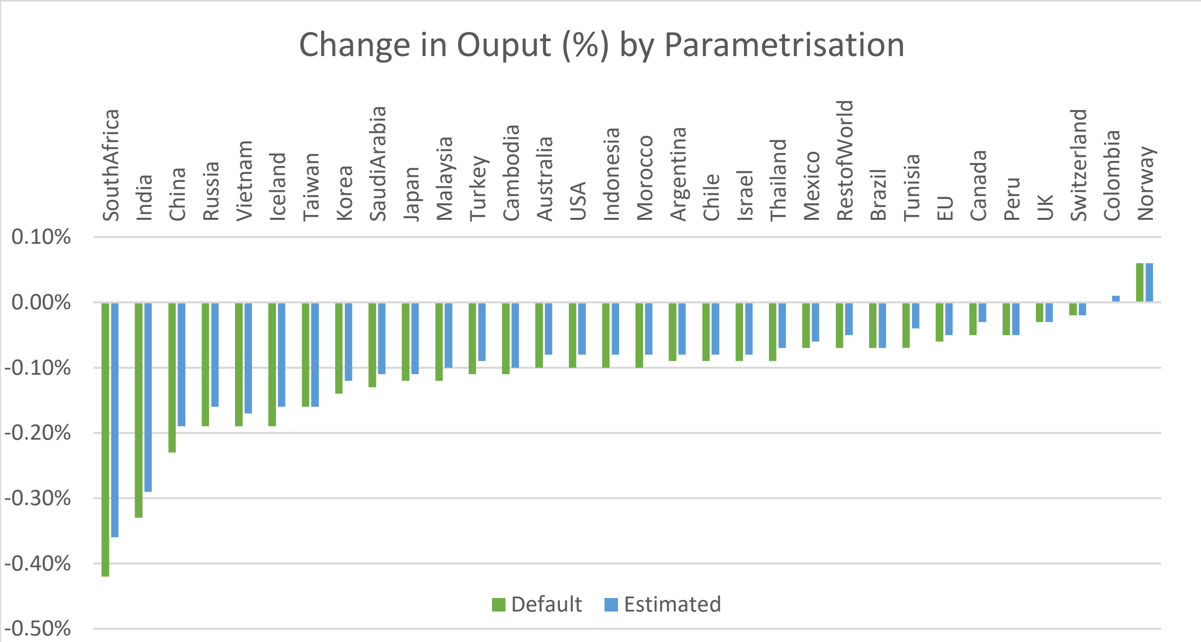
Model A - $5 Carbon Tax

This simulation imposes a $5 carbon tax on every region in the aggregation – increasing costs of production in proportion to their emissions of carbon dioxide. The motivation of this policy is to reduce greenhouse gas emissions, but generally comes at the cost of causing a contraction in output as production costs increase.

The results of the model show that using our estimated parameters for capital-energy substitution leads to results indicating a reduced effectiveness in greenhouse gas abatement from the imposition of a $5 carbon tax. With default elasticities, global greenhouse gas emissions fall by 3.33%, compared with a 3.18% decrease with estimates – a 4.5% reduction in abatement. This is pattern is relatively consistent on a country basis as shown below.



The contraction in world output is also smaller under the estimated elasticities than the default specification. World output falls by 0.12% with default elasticities and 0.10% under the estimated elasticities. This suggests that the 'cost' to the economy of implementing a carbon tax may be overestimated by the default GTAP-E specification.



Taken together, the results of these simulations imply that if the default elasticities of capital-energy substitution are too elastic – as our analysis suggests – then policymakers may overestimate both the impact and the cost of carbon abatement measures like a carbon price. In both senses, this could encourage lower than optimal carbon prices to be adopted.

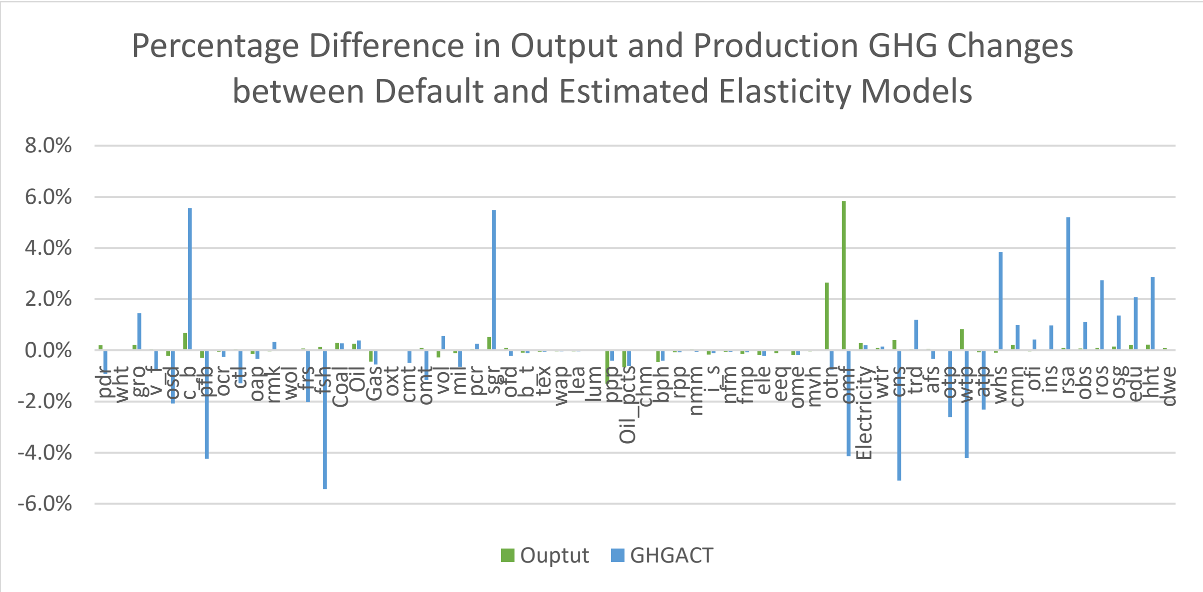
The results of the model are expected, given the value of the input elasticity estimates are mostly lower than their default values. Elasticities closer to 0 suggest that producers will substitute away from energy less in response to increases in energy input prices caused by carbon abatement policies and so emissions and output are less responsive to the policy than under the default specification.

Model B – Fictional US-UK FTA

This simulation mimics a Free Trade Agreement scenario and involves full liberalisation of all tariffs between the UK and USA, with a closure swap that fixes the price of capital and makes its quantity endogenously determined. Free trade agreements are often expansionary to the partner country and world economies, and thereby result in increases in greenhouse gas emissions associated with the additional output – although effects vary considerably across FTAs. This simulation was chosen for the relatively large trading relationship with the USA, so that any differences from the change in parameters might be more visible in results – however unlike scenario A, the results are minimal at the global level and predominately affect the UK, and to a lesser extent the USA.

The results show that total UK greenhouse gas emissions increase is -0.5% lower with the estimated elasticities, falling from an 0.115% increase to a 0.114% increase. This is replicated when looking at emissions from production (a 0.7% decrease in effect when using estimated elasticities), and as expected the largest differences between the default and estimated specifications lie in sectors where the elasticities have been modified the most (i.e. agriculture and services).

UK output expansion is only 0.001% smaller when using the estimated elasticities compared to their default values – in both models UK output grows by 0.0741%. In only 2 out of the 64 sectors is divergence between the models greater than 1%: otn (other transport equipment) and omf (other manufacturing), where the capital-energy elasticity of substitution was reduced from 0.5 to 0.22.



6. Conclusion

In conclusion, estimation of capital-energy substitution using relatively recent panel data suggests there is a significant degree of variation across different sectors, and that the default values used in GTAP models may overestimate the substitutability of capital and energy in most sectors. In particular, we found agriculture and non-traded services to exhibit relatively inelastic substitution between capital and energy. Two sectors generated estimates that we considered to be outside the feasible range given the modelling assumptions of CGE models: mining and quarrying ($\sigma_{KE} = 1.31$), and food, wood, chemicals and textiles ($\sigma_{KE} = -0.61$). Further research may be required to determine if it is plausible that the elasticities of these sectors could lie outside the range of [0-1].

When inputted to the GTAP model, the impact of using estimated elasticities varied by the kind of policy being simulated. We find that there are noticeable reductions in the size of the impact of carbon pricing on both greenhouse gas emissions and output when using estimated capital-energy substitution, reflecting the implied inflexibility of production to changes in energy pricing of lowering capital-energy substitution elasticities for most sectors.

In contrast, the changes in model results for an FTA scenario are minimal, particularly output changes at the national level which remain effectively the same under both specifications.

Future research may benefit from examining capital-energy substitution in a more granular dataset, potentially including firm level data to develop estimates specific to one or more countries. The inter-fuel elasticities of substitution introduced in GTAP-E could also be investigated with a similar methodology to determine the sensitivity of model results to their specification, particularly with regard to modelling energy and decarbonisation policies. Finally, using econometrically estimated elasticities in a wider range of policy scenarios would shed greater light on where modelling may benefit most from improving the accuracy of the underlying parameters.

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Appendix

Regional aggregation used in modelling

Argentina, Australia, China, Japan, Korea, Canada, Mexico, USA, UK, EU, Switzerland, Norway, Turkey, Rest of World, Brazil, Cambodia, Chile, Colombia, India, Indonesia, Israel, Malaysia, Morocco, Taiwan, Peru, Russia, Saudi Arabia, South Africa, Thailand, Tunisia, Vietnam, Iceland

GTAP sectors, ISIC groupings and estimated elasticities

GTAPE	ISIC	ISIC.desc	*AES* (σ_{KE})
pdr	D01T03	Agriculture, fishing and forestry	0.184237
wht	D01T03	Agriculture, fishing and forestry	0.184237
gro	D01T03	Agriculture, fishing and forestry	0.184237
v_f	D01T03	Agriculture, fishing and forestry	0.184237
osd	D01T03	Agriculture, fishing and forestry	0.184237
c_b	D01T03	Agriculture, fishing and forestry	0.184237
pfb	D01T03	Agriculture, fishing and forestry	0.184237
ocr	D01T03	Agriculture, fishing and forestry	0.184237
ctl	D01T03	Agriculture, fishing and forestry	0.184237
oap	D01T03	Agriculture, fishing and forestry	0.184237
rmk	D01T03	Agriculture, fishing and forestry	0.184237
wol	D01T03	Agriculture, fishing and forestry	0.184237
frs	D01T03	Agriculture, fishing and forestry	0.184237
fsh	D01T03	Agriculture, fishing and forestry	0.184237
Coal	N/A	N/A	0.0
Oil	N/A	N/A	0.0
Gas	N/A	N/A	0.0
oxt	N/A	N/A	0.0
cmt	D01T03	Agriculture, fishing and forestry	0.184237
omt	D01T03	Agriculture, fishing and forestry	0.184237
vol	D01T03	Agriculture, fishing and forestry	0.184237
mil	D01T03	Agriculture, fishing and forestry	0.184237
pcr	D01T03	Agriculture, fishing and forestry	0.184237
sgr	D01T03	Agriculture, fishing and forestry	0.184237
ofd	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
b_t	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
tex	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
wap	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
lea	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
lum	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
ppp	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
Oil_pcts	N/A	N/A	0
chm	D10T25	Wood, chemicals, textiles and food manufacturing	0.5

bph	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
rpp	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
nmm	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
i_s	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
nfm	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
fmp	D10T25	Wood, chemicals, textiles and food manufacturing	0.5
ele	D26T28	Machinery and electrical equipment	0.595503
eeq	D26T28	Machinery and electrical equipment	0.595503
ome	D26T28	Machinery and electrical equipment	0.595503
mvh	D29T39	Transport equipment and other manufacturing	0.223458
otn	D29T39	Transport equipment and other manufacturing	0.223458
omf	D29T39	Transport equipment and other manufacturing	0.223458
Electricity	N/A	N/A	0.5
wtr	D41T99	Non-traded services	0.081966
cns	D41T99	Non-traded services	0.081966
trd	D41T99	Non-traded services	0.081966
afs	D41T99	Non-traded services	0.081966
otp	D41T99	Non-traded services	0.081966
wtp	D41T99	Non-traded services	0.081966
atp	D41T99	Non-traded services	0.081966
whs	D41T99	Non-traded services	0.081966
cmn	D58T66	Traded services	0.38581
ofi	D58T66	Traded services	0.38581
ins	D58T66	Traded services	0.38581
rsa	D41T99	Non-traded services	0.081966
obs	D41T99	Non-traded services	0.081966
ros	D41T99	Non-traded services	0.081966
osg	D41T99	Non-traded services	0.081966
edu	D41T99	Non-traded services	0.081966
hht	D41T99	Non-traded services	0.081966
Dwe	N/A	N/A	0.5