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Essays on Carbon Taxation and Food Demand in Ireland

Ph.D. Thesis

by

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2012

Department of Economics

Dublin University, Trinity College Dublin

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Declaration

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work. I am the first author of the first paper herewith presented, which has been published on an economic journal. My co-supervisor, Prof. R. S. J. Tol, is the second author.

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Summary

This thesis is the collection of three applied studies, two of which deal with distributional effects of carbon taxation in the Irish economy and one, the third, which estimates a micro-econometric model for food demand in Ireland. The two topics are treated separately and, while links between climate policy and food demand can certainly be found, the analyses do not converge. Originally, carbon pricing in Ireland was in fact the sole object of this project. However, as familiarity was gained with the Household Budget Survey (HBS), on which both the first two studies draw, it became clear that it was possible to extract useful and unexploited information on food demand from that source.

The importance of climate policy, in Ireland, has increased enormously in the last few years. During the period of almost three years separating the inception of the first paper and the completion of the second, the Irish Government has introduced a €15 (per ton of CO_2) carbon tax and subsequently raised it to €20. Given the ambition and the commitments of the European Union to drastically abate its own greenhouse gas emissions, a reinforcement of climate policy can be expected. Carbon pricing is not meant to be a "grain of sand in the wheels" of the economy, to make a parallel with James Tobin's tax, but rather to modify consumption and transform production processes radically. Therefore, it is critical that its interactions with the markets and other policies, and ultimately the impact on welfare, be understood and assessed. In this respect, the two papers on distributional effects of carbon taxation – differing in approach, data, time horizon and scope – make a contribution.

The third paper fills, at least in part, two gaps in the Irish applied literature, namely *a)* the lack of estimates of demand elasticities for a wide range of foods and, *b)* the absence of demand models estimated with the national Household Budget Survey and which allow for price effects.

A summary of the three papers follows.

The first paper, "The distributional impact of a carbon tax in Ireland", extends a previous work, which I co-authored, by allowing for the (indirect) impact of carbon taxation on household income through generic consumption, in addition to that (direct) occurring via

final energy prices. The fundamental assumption is that the tax is entirely translated forward and ultimately on consumers. Environmentally extended input-output analysis is used to quantify the incidence of the tax on final prices and thus household expenditure, by income decile. The results are then combined with those from a tax-benefit model which simulates three alternative ways to compensate households for the burden of the tax. The envisaged scenarios compound increases in income tax credit and welfare payments as well as a cut in the lowest band income tax rate. It turns out that the tax would cost the poorest households around €3.5/week and the richest ones €5/week. However, if the revenue is used to increase social benefits and tax credits, households across the income distribution can be made better off without exhausting the total carbon tax revenue.

The second paper, "Distributional effects of carbon pricing in Ireland: A CGE approach using G-EMH", addresses the core question of the first, but extends it further by using Computational General Equilibrium (CGE) analysis. This allows capturing interactions and feedback effects in the economy and, importantly, both the sources- and the uses-side impacts (as they are referred to in the literature of tax incidence) of carbon pricing on households' income. Thus, the analysis is comprehensive and pertains to the medium-, rather than the short-term, as is the case for the first paper.

A variant of the popular GTAP model, G-EMH, was created especially for this study. G-EMH merges GTAP-E, which links energy-related CO_2 emissions and the economy, and GTAP-MH, which allows for multiple households. G-EMH also introduces renewables in the electricity sector, endogenizes labour supply and takes account of income earned by non-residents, none of which are features of the standard GTAP model. The household sector is represented by ten households that correspond to income deciles. The HBS is used to derive incomes and expenditures of those and to estimate elasticities of demand for energy commodities.

The impact of a \$20/tCO_2 revenue neutral tax on Ireland's economy and household income distribution is simulated under five scenarios, which differ from one another in the way the carbon tax revenue is used. It is found that a double dividend – lower emissions and greater economic growth – can be reaped, if only a very modest one in terms of GDP. This is achieved with a tax replacement scheme that either lowers taxes on consumption or on labour income. As regards equity, only if the proceeds of carbon taxation are redistributed to household through the welfare system is the overall impact homogenous across income distribution. Otherwise, the impact is regressive. However, with a reduction

in the tax on consumption, all households are better off than with any of the other schemes, including the one that involves household transfers.

In the third paper, "A QUAIDS model of food demand in Ireland", what has become the most popular model in system demand analysis, the QUAIDS model, is estimated for Irish households' food demand (eight goods) using micro-data from the last four editions of the Household Budget Survey (1987-88, 1994-95, 1999-00, and 2004-05). This is new in the Irish literature in which many demand systems have been estimated, but always using aggregate time-series data. The lack of price information in the HBS is the reason for such a gap in the literature. This work plugs the gap by mapping the disaggregated monthly CPI to the HBS items code and, then, constructing price indices that vary not only over time, but across households too. This way, sufficient price variability is obtained to estimate the model. Income and price elasticities of demand for eight food groups are thus derived, in some cases for the first time in the Irish literature (e.g., for vegetables, fruit, fish). Four versions of the model are estimated: the first is the base model; the second incorporates time controls and socio-demographic effects; the third adds a correction for endogeneity of total food expenditure; the fourth augments the former with an adjustment for censoring in the budget shares (zero-expenditure). All these variations improve the model and impact in some measure on the elasticities derived.

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Paper 1

The distributional impact of a carbon tax in Ireland[1]

1. Introduction

In 2006, Irish greenhouse gas (GHG) emissions were 25 percent higher than in 1990, that is, 11.5 percentage points above the Kyoto target (2008-2012).[2] According to the Government's "National Climate Change Strategy 2007-2012", one fifth of this gap will be bridged through the purchase of carbon credits, for which €290m were allocated. Though there is reason to think that the Government underestimated the cost of compliance with Kyoto,[3] the main focus should be on the target set by the EU for 2020. Indeed, in twelve years Ireland has to cut its emissions outside the EU Emissions Trading Scheme (ETS) by at least 20 percent compared to 2005, with tightly restricted use of flexible mechanisms. Almost 60 percent of the emissions from the non-ETS sector are CO_2 and the rest are methane (CH_4), mostly from cattle. Therefore, any strategy aimed at reducing these emissions should target both CO_2 and CH_4.

A carbon tax - or, more appropriately, a "CO_2 tax"[4]- is a charge to be paid on every fossil fuel, proportional to the quantity of CO_2 produced when it is burnt. Hence, the higher the carbon content (per unit of energy) of a fuel, the bigger its price increase. In principle, a carbon tax is the most cost-effective instrument for reducing CO_2 emissions (Pizer [1999];

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[1] Published in *The Economic and Social Review, Vol. 40, No. 3, Autumn, 2009, pp. 317-338.*

[2] In 2007, emissions were about 10 percentage points above the Kyoto target (EPA [2009a]).

[3] The latest projections of Irish emissions (EPA [2009b]) show that the distance from the Kyoto target is close enough to what is indicated in the "National Climate Change Strategy 2007-2012". However, the Government's figures crucially do not take account of the current economic crisis.

[4] A CO_2 tax is typically specified per metric tonne of CO_2 emitted (€/tCO_2). A tonne of carbon corresponds to 3.67 tonnes of CO_2. A carbon tax *strictu sensu* applies to other greenhouse gases as well.

Nordhaus [2005]; Yohe *et al.* [2007]). In the specific instance, a carbon tax should: 1) apply only to the non-ETS sector; and 2) be as close as possible to the ETS price of carbon (Tol [2007]). This is the case because: 1) if the tax was also levied on emissions covered by the ETS, the cut on these would be offset by an equivalent increase somewhere else in the EU ("carbon leakage"); and 2) the smaller the gap between the tax and the ETS price of carbon, the smaller the welfare loss from distortions in output markets (Bohringer *et al.* [2006]). Such a tax would effectively extend the ETS cap to all CO_2 emissions and, most importantly, thereby strengthen the carbon price signal. The tax assumed in the analysis that follows has both characteristics. Specifically, a €20/tCO_2 tax is considered because that is the average price of carbon one may expect in the second ETS trading period (2008-2012).

In 2004, the Irish Government was close to levying a carbon tax, but eventually abandoned the plan due to concerns about the potential impacts on household income and firms' international competitiveness - the two arguments typically brought up against carbon taxes. Yet, only three years later, the carbon levy again entered the agenda, following the strengthening of EU climate policy and the Greens joining the Government. The "Programme for Government 2007-2012" states that «[a]ppropriate fiscal instruments, including a carbon levy, will be phased in on a revenue-neutral basis over the lifetime of this Government». The tax is not there yet, but the Budget 2010 is most likely to bring it in.

Any policy involving carbon pricing should include some measures to sustain the households and firms most affected by higher energy prices. All the more so in Ireland, where fuel poverty is a relevant issue (Scott *et al.* [2008]) and the economy is one of the most open in the world. As reported above, the Government is supposed to phase in a carbon tax on a revenue-neutral basis, which means other taxes will be cut keeping total State revenues unchanged, or net public spending will stay the same. The whole fiscal reform, depending on existing taxes and distortions in the labour and capital markets, will determine the ultimate outcome of the tax (Fullerton and Metcalf [2001]).

This study focuses on the distributional implications of a €20/tCO_2 tax in Ireland. Microdata from the 2005 Household Budget Survey (HBS) are used to estimate the burden of the levy across the population. In first place, the aim is to establish whether a carbon tax would be regressive, that is, whether it would hit the poor relatively more than the wealthy, and to what extent. The model allows for the increases in both fuel prices and the general cost of living, for which environmentally extended input-output analysis is used.

Subsequently, the results are combined with simulations of a most detailed tax-benefit model - the SWITCH model (Callan *et al.* [2008b]) of the Irish Economic and Social Research Institute (ESRI) - to compare three tax revenue recycling options for re-balancing the household income distribution. The scenarios envisaged compound increases in income tax credit and welfare payments as well as a cut in the lowest band income tax rate.

The paper is structured as follows. Section 2 reviews the relevant literature, with a focus on the studies that regard Ireland. Section 3 illustrates the methodology and data used. Section 4 shows the results. Section 5 concludes.

2. Literature review

The impact of carbon/energy taxes on household income distribution has been investigated in a number of studies. Most of these refer to developed economies, where green taxation has been used, or at least considered, more extensively and consumption of CO_2 related fuels is more even across the population, which fact is at the root of the equity problem. In fact, the literature suggests that carbon/energy taxes generally are, or are expected to be, regressive in developed economies and progressive in developing economies.[5]

As concerns methodologies, partial equilibrium analysis is the standard approach, although, in fact, the supply side is seldom considered. Data on household consumption are used to model household demand and thereby estimate the distributional impact of the tax. Also, the analysis can be confined to final demand of fuels, the "direct impact", or include all goods and services to capture the "indirect impact" too. In the latter case, environmentally extended input-output analysis generally is used, with the assumption that the tax is fully translated into final prices. Moreover, among the most recent works, there are few using computational general equilibrium (CGE) models, with disaggregated households. These models enable wider analysis and are best suited to assessing alternative revenue-recycling options.

Among the earliest studies is one by Poterba (1991), who analyses the distributional effect of a gasoline tax in the US. Using the data from the US Consumer's Expenditure Survey, Poterba (1991) calculates the fractions of household income and expenditure that

[5] This can be explained not only by the difference in household expenditure patterns. Shah and Larsen (1992) argue that "[in developing countries] factors such as market power, price controls, import quotas, rationed foreign exchange, the presence of black markets, tax evasion and urban-rural migration may cast doubt on the regressivity of environmental policies."

are devoted to gasoline purchase. He concludes that the tax is only slightly regressive, especially when expressed as a share of expenditure. On the other hand, Safirova *et al.* (2004) find that the burden of congestion falls disproportionally on the rich (in and around Washington, DC), so that road pricing or fuel taxation would be strongly regressive.

With a view to the project of a European carbon tax, Pearson and Smith (1991) estimate the distributional impact in seven European countries, namely France, Germany, Italy, Netherlands, Spain, the UK and Ireland. Augmenting Poterba's approach by including price elasticities (although they do not estimate any demand system), they find that in the first five countries the tax would be weakly regressive, while it would be significantly regressive in the UK and strongly regressive in Ireland. Using a more comprehensive model (the E3ME model, a sectoral, regionalized, econometric model of the EU), Barker and Köhler (1998) upgrade Pearson and Smith's work and draw similar conclusions.

Hamilton and Cameron (1994) estimate the distributional impact of a carbon tax in Canada. By means of a CGE model, the authors first determine the tax that would bring about a given cut in CO_2 emissions; they then use input-output analysis to translate the tax into all consumer prices and finally apply a micro-simulation model to assess the impact of induced price changes. It turns out that the tax would be moderately regressive. Similarly, Cornwell and Creedy (1996) investigate the distributional impact of a carbon tax in Australia. The combination of micro-data on household consumption and input-output analysis suggests the tax would be regressive.

A few more studies have been conducted with reference to European economies. Labandeira and Labeaga (1999) explore the effect of a carbon tax on Spanish household income. The authors use input-output analysis to estimate price changes and then simulate consumer response via an Almost Ideal Demand System (AIDS), estimated with data from the Spanish Household Expenditure Survey. In contrast with other studies (in addition to those previously mentioned, see Symons *et al.* [2000]), they do not find that a carbon tax in Spain would be regressive.

Tiezzi (2001) simulates the welfare effects of the carbon tax implemented - *de facto* only for one year - in Italy in 1999. Such effects are calculated combining True Cost of Living Indices and Compensating Variation; the parameters are obtained through estimation of an AIDS with household consumption data. The Italian carbon tax is found not to be regressive, since it mainly hits motor fuels and less domestic fuels. Indeed, in

developed economies consumption of motor fuels typically increases with income while that of domestic fuels is even across the population.

Brannlund and Nordstrom (2004) analyse welfare effects of changes in green fiscal policy in Sweden, where a carbon tax was introduced in 1991. They first estimate an econometric model for demand of non-durables (a quadratic AIDS), then assume a doubling of the existing tax and finally compare two revenue-recycling options: lower general VAT and lower VAT on public transport (equivalent to a subsidy to that sector). Both reforms end up being regressive, but the second one also has a regional distributional effect, as households in less populated areas would carry a larger share of the tax burden.

Wier *et al.* (2005) assess the distributional impact of the Danish carbon tax, which was first introduced in 1992. The methodology is standard, but nicely incorporates price changes and substitution effects induced by the tax. The latter is found to be regressive, particularly to the disadvantage of rural households. Still using standard methodology, Kerkhof *et al.* (2008) extend the analysis to taxation of other GHGs - all those regulated under the Kyoto Protocol - and find that multiple taxation not only improves the cost-effectiveness of reducing emissions, but also distributes the tax burden more equally across income groups as compared to a carbon tax on its own. This contribution proves particularly relevant for Ireland, where CH_4 accounts for about one third of total GHG emissions.

Results in the recent CGE literature confirm that the distributional impact of a carbon tax crucially depends on how the revenue is used. In a study applied to the Susquehanna River Basin (a region of the US), Oladosu and Rose (2007) find that a carbon tax would be progressive, since changes in the structure of the economy, higher transfer payments and reduced profits more than offset the regressive direct effects. Yusuf and Resosudamo (2007) find that a carbon tax on its own would be progressive in Indonesia and revenue-recycling through uniform cut in commodity tax rate would reduce the adverse effect on GDP. Particularly encouraging are the results of a study applied to South Africa, as Van Heerden *et al.* (2006) find a "triple dividend" for selected ecological tax reforms: certain mixes of increased energy taxes and reduced food taxes reduce emissions, increase economic output, and reduce the income gap between rich and poor.

Finally, there are at least five studies addressing the distributional effects of a carbon tax with specific reference to Ireland. On the basis of data from the Irish Household Budget Survey (HBS), Scott (1992) predicts that a carbon tax would be markedly regressive in Ireland, because low income households both spend disproportionately more on energy and

generally use fuels with higher carbon contents. Scott and Eakins (2004) essentially repeat the work with more recent data and get similar results. O'Donoghue (1997) estimates both direct and indirect impacts, by using HBS and input-output analysis, and it turns out that the tax burden would be borne more equally by households once the indirect impact is taken into account too. Bergin *et al.* (2002) use an energy-augmented macro-econometric model (ESRI's HERMES model) to forecast energy demand and emissions, with carbon taxation. In relation to the equity issue, the authors argue that reducing VAT through tax revenue-recycling is better than by giving households lump-sum payments because it would affect competitiveness less. Callan *et al.* (2008a) use more recent data than do Scott and Eakins, and combine estimated carbon tax payments with ESRI's micro-simulation tax-benefit model (the SWITCH model) to compare a few revenue-recycling options. They find that a carbon tax on its own would be regressive, as expected, and the preferable way to compensate households would be through modest increases in both welfare payments and tax credit. Note that the paper by Callan *et al.* is, in the essence, very similar to the present one. However, the current paper also estimates the indirect impact of the tax[6], something that Callan *et al.* did not.

3. Methodology and data

Like the standard literature, this study distinguishes between direct and indirect impacts of carbon taxation on household income. The direct impact is here defined as the increase in fuel expenditure due to higher fuel prices, as opposed to the indirect impact, which is the increase in total expenditure (all goods and services but fuels) induced by higher fuel prices. Microdata from the 2005 HBS are used to estimate the two impacts across the household population. However, estimation of the change in the cost of living also requires the use of Ireland's input-output table as well as data of sectoral emissions. The resulting changes in the household income distribution are then combined with simulations of the SWITCH tax-benefit model to evaluate three alternative tax revenue recycling options. Note that all population estimates based on the HBS are obtained by applying HBS household specific grossing-up factors and that the SWITCH model automatically grosses-

[6] As said above, O'Donoghue (1997) estimates the indirect impact of a carbon tax in Ireland too, but using older and aggregated (decile level) household consumption data. Also, he does not deal with revenue recycling.

up the survey data it is based on. Hence, this guarantees that the correspondence between HBS- and SWITCH population income deciles is sufficiently accurate.

There follows a detailed illustration of the three-step analysis sketched: direct impact of the tax, indirect impact and revenue recycling.

3.1 Estimating the direct impact

Microdata from the 2005 HBS (CSO [2007]) are used to calculate household fuel consumption and related CO_2 emissions. The fuels included in the HBS are considered either "home fuels" (gas, electricity, anthracite, coal, turf, turf briquettes, central heating oil, paraffin oil and LPG) or "motor fuels" (petrol, diesel and LPG auto). Since only expenditure on motor fuels is reported in the HBS, quantities of petrol, diesel and LPG auto are derived dividing expenditure by price.[7] Thus, for each household in the sample, weekly fuel quantities are translated into energy (Tonnes of Oil Equivalent [TOE]) and, in turn, into weekly CO_2 emissions, by using standard calorific values and emission coefficients[8] respectively. Finally, weekly[9] tax payments are estimated by applying the assumed €20/tCO_2 tax to emissions so derived.

The method hinges on two important but standard assumptions: 1) fuel prices increase by an amount equal to the tax (i.e. producers entirely shift the tax onto the consumer); 2) consumers do not switch to cleaner fuels when the tax is levied (i.e. zero demand price elasticities). However, we know that in reality the tax pass-through depends on the specific market structures, which are not investigated in this study. Also, we know zero price elasticities are plausible in the very short run, but not over a longer horizon. In light of that, the estimation results can best be interpreted either as first round effects or the "worst case" for consumers.

3.2 Estimating the indirect impact

The same HBS dataset is used to calculate household consumption of all goods and services other than fuels. However, standard emission coefficients for general consumption do not exist and, hence, have to be derived. O'Doherty and Tol (2007) provide the theoretical framework for the purpose.

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[7] The prices prevailing (quarter averages) at the time the survey was taken are applied. The source for data of fuel prices are Sustainable Energy Ireland (petrol and diesel) and Flogas (for LPG auto).
[8] Calorific values and emission coefficients used are reported in Table A1, in the Appendix.
[9] In the HBS, consumption data are by week. In fact, they are averages over two successive weeks.

In the standard input-output model, with $i = 1,2,...,n$ output sectors and $j = 1,2,...,n$ input sectors, production **X** depends on final demand **Y**, through the Leontief matrix **L**:

$$\mathbf{X} = (\mathbf{A} - \mathbf{I})^{-1} \mathbf{Y} = \mathbf{LY} \qquad [1]$$

where **A** is the matrix $a_{ij} = X_{ij}/X_j$.

If sectoral CO_2 emissions (allocated by gas production) are given, a model for total emissions M depending on final demand is obtained by first defining

$$M = \mathbf{BX} \qquad [2]$$

where **B** is the vector of "production coefficients", that is, emissions per unit of production (grams/€), and then combining [2] with [1]

$$M = \mathbf{BLY} \qquad [3]$$

where **BL** is therefore the vector of "consumption coefficients", that is, emission per unit of consumption (grams/€).

Ireland's 2005 input-output table (CSO [2009]) is used. The model comprises 19 NACE[10] sectors (NACE19) because this is the the most disaggregated level for which data of sectoral output and emissions are both available. The NACE19 classification is the following:

1. *Agriculture, fishing and forestry*
2. *Coal, peat, petroleum, metal ores and quarrying*
3. *Food, beverage and tobacco*
4. *Textiles clothing leather and footwear*
5. *Wood and wood products*
6. *Pulp, paper and print prod.*
7. *Chemical prod.*

[10] NACE is the classification of economic activities in the EU.

8. Rubber and plastic prod.

9. Non-metallic mineral prod.

10. Metal prod. excl. machinery and transport equipment

11. Agricultural and industrial machinery

12. Office and data process machines

13. Electrical goods

14. Transport equipment

15. Other manufacturing

16. Fuel, power and water

17. Construction

18. Services (excl. transport)

19. Transport

Production coefficients are calculated using data of sectoral emissions and output published by EPA (2008) and CS0 (2009), respectively. Subsequently, in order to apply the derived consumption coefficients[11] to HBS demand, the HBS code has to be mapped into NACE19.[12] With the consumption microdata (all goods and services but fuels) aggregated in 19 categories, the corresponding consumption coefficients are applied. The indirect impact of the tax is then estimated multiplying the €20/tCO_2 rate by the emissions so derived. At this point, two remarks are needed. First, since most probably only domestic production would be subject to the carbon levy and since the HBS does not specify the origin of the goods and services purchased, consumption coefficients only apply to the share of household demand which is satisfied by domestic production. For example, since 20 percent of "Rubber and plastic" demanded by households is imported, the corresponding consumption coefficient applies only to 80 percent of HBS households' expenditures on "Rubber and plastic".[13] Second, since it is assumed the tax will apply only to the non-ETS sector, the emissions from the activities covered by the EU ETS should not be considered in the determination of the indirect impact of the tax. To take account of this, production coefficients of the sectors corresponding to the EU ETS activities (i.e. 6, 9, 10 and 16 in NACE19) are set equal to zero.

[11] Both production and consumption coefficients for 2005 are reported in the Appendix (table A2).
[12] The mapping code is not reported to economize on space, but it can be requested from the authors.
[13] The shares of imports on final household demand, by NACE19 sector, are reported in Table A3, in the Appendix.

Finally, the method for estimating the indirect impact of the tax is based on a few relevant assumptions: 1) all producers shift the tax downhill, which implies the consumer bears the whole burden of the tax; 2) producers do not switch to less carbon intensive fuels after the tax is levied (i.e. zero supply price elasticities); and 3) consumers do not substitute domestic with imported products (i.e. zero demand price elasticities). Thus, again, in light of these restrictions, the estimation results can best be interpreted either as first round effects or the worst possible scenario for consumers.

3.3 Recycling the revenue

The SWITCH model is regularly used by the Department of Finance for distributional analysis of the impact of the annual budget. It is a model of direct taxes and welfare payments, based on the Survey on Income and Living Conditions (EU SILC, CSO [2006]) - a nationally representative survey capturing the variability in the household population across age, household composition, income, employment, and disability. Here, it is used to analyse the distributional implications of tax revenue recycling.

Income taxes in Ireland are relatively straightforward. A 20% tax is paid on income below €35,400 per year. Above that, a tax of 41% is paid. There is a standard tax credit of €3,660, so that the first €18,300 earned is essentially tax-free. There are additional tax credits for mortgage and rent, for family circumstances, and for disabilities. The Irish benefit system is considerably more complex, with income supplements, child benefits, maternity and homemaker benefits, carers benefits, illness and disability benefits, jobseeker and training benefits, pre-retirement allowances and pensions; many of these benefits come in both an entitlement and a means-tested mode.

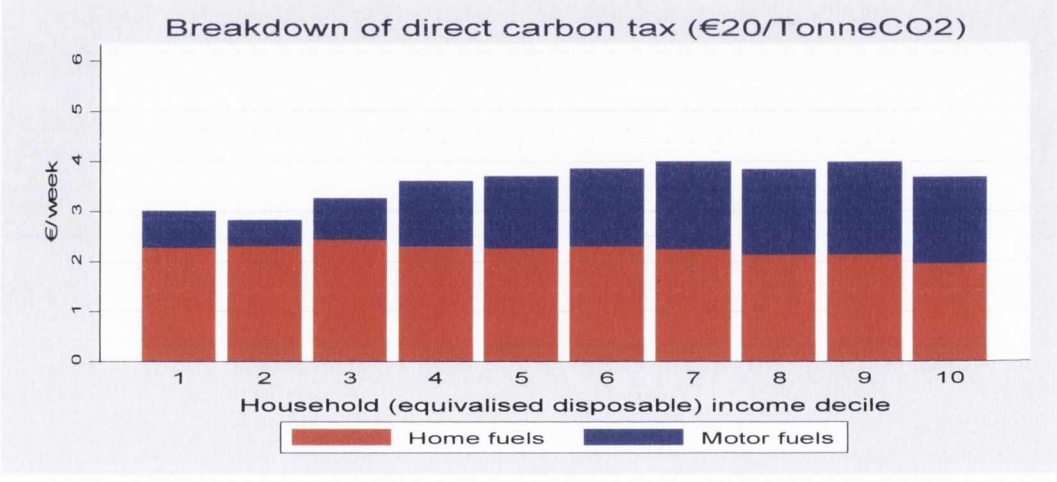
The SWITCH model is used to simulate three revenue recycling options. As in Callan *et al.* (2008b), both the first and second scenarios involve a €2 increase per week in all social welfare payments (pensions, unemployment compensation, short-term illness and long-term disability, one parent families) and a €104 increase per year in basic personal tax credit. The second scenario only differs for one additional measure, namely a €0.8 payment per week for each qualifying child of a social welfare recipient. The third scenario hinges on income taxation. It still provides for the €2 increase in all social welfare payments, which is obviously a measure for reaching low income households, and adds a half percentage point cut of the lowest band income tax rate, that is, from 20% to 19.5%.

4. Results

4.1 Direct impact

It emerges from the data that emissions associated with energy consumption for heating and cooking (home fuels) are virtually constant across the household population. Hence, the same pattern is derived for the related tax payments. Conversely, emissions caused by private transport are increasing with income and, again, the same pattern must apply for the tax payments on consumption of motor fuels. The overall direct impact of the tax is estimated to range across the household distribution between 3 and 4 Euros per week, of which about 2 Euros are invariably against consumption of home fuels (Figure 1).

Figure 1 – The direct impact of the tax.



Note that: 1) emissions and related tax payments for electricity consumption are not considered; and 2) households are sorted by equivalised disposable income.[14] This is the case because: 1) electricity generation is regulated under the EU ETS and price increases of electricity have already been included in the relevant price indices that are used for setting benefits and in wage negotiations; and 2) equivalised disposable income is deemed a better measure of real wealth.

HBS data on energy consumption at home (electricity included) also reveal some facts that are relevant for climate policy and, hence, worth pointing out here. Equivalised energy consumption, measured by "TOE per adult equivalent", is lower for the middle deciles and higher at the edges of the household income distribution. One may assume that this is so because dwellings of low income households are not well insulated, while high

[14] Equivalisation corrects for the size of households by expressing household income as income per adult equivalent. The weights used are: "head of household" = 1; "other adults" = .66; "children (<14)" = .33.

income households use more energy and do it more efficiently too (O'Doherty *et al.* [2008]). This hypothesis seems to be supported by the fact that, for low income deciles, the percentage of dwellings with double glazing is negatively correlated with energy consumption.[15] Moreover, as stressed in previous studies, low income households in Ireland usually make more extensive use of cheaper but more carbon intensive fuels, such as coal and turf. The ratio "Emissions per TOE", measuring the carbon intensity of a mix of fuels, indeed is found to be strongly correlated with income. It so happens that (equivalised) emissions due to heating and cooking are exactly the same for the first and tenth deciles, but energy consumption is higher in the latter. Figures (weekly energy and emissions data) are reported in Table 1.

Table 1 – Home energy consumption & double glazing; home fuels carbon intensity & CO_2 emissions.

Income decile	Energy TOE eq.	Efficiency Double glazing (%)	Fuels tCO_2/TOE	Emissions tCO_2, equivalised	Emissions tCO_2
1	.022	67	4.50	.091	.161
2	.029	60	4.51	.115	.163
3	.026	66	4.37	.103	.170
4	.020	75	4.37	.081	.171
5	.020	77	4.40	.082	.175
6	.021	79	4.21	.084	.177
7	.021	82	4.17	.084	.175
8	.022	83	4.21	.082	.169
9	.024	84	4.15	.092	.168
10	.025	82	4.01	.091	.158

Thus, poor insulation and more extensive use of carbon intensive fuels seem to explain why, at home, low income households are responsible for as much, or slightly more, emissions as high income households. However, variability within deciles is quite high. Further investigation with the use of econometrics could certainly reveal more about the relations highlighted, but that would be beyond the scope of this study.

4.2 Indirect impact

As expected, the indirect impact of the tax turns out to be increasing with the level of income. Specifically, under the assumption that a €20/Ton of CO_2 tax is levied only in the non-ETS sector, and not on imports, the burden of the tax sums to less than €0.5 per week for the first decile and rises up to €1.5 for the tenth. However, if the tax is made to apply to

[15] Unfortunately, data on roof-insulation are not available in the HBS.

imports as well,[16] the cost of living increases more significantly along the household income distribution (around €1 for the first decile, €2.5 for the tenth). This shows that Ireland is responsible for substantial (relative to domestic) CO_2 emissions abroad. Similar results are obtained if the tax is levied in the ETS sector too, but not on imports. Finally, the increase in the cost of living is substantially higher (three times as much as in the first scenario), if the tax applies to both the ETS sector and imports. Figure 2 shows these results.

Figure 2 – The indirect impact of the tax under three different scenarios.

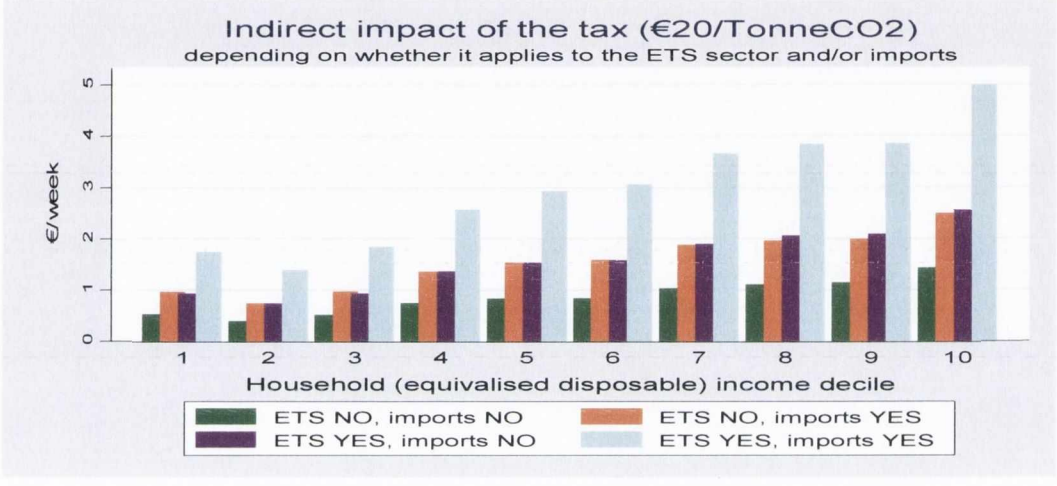
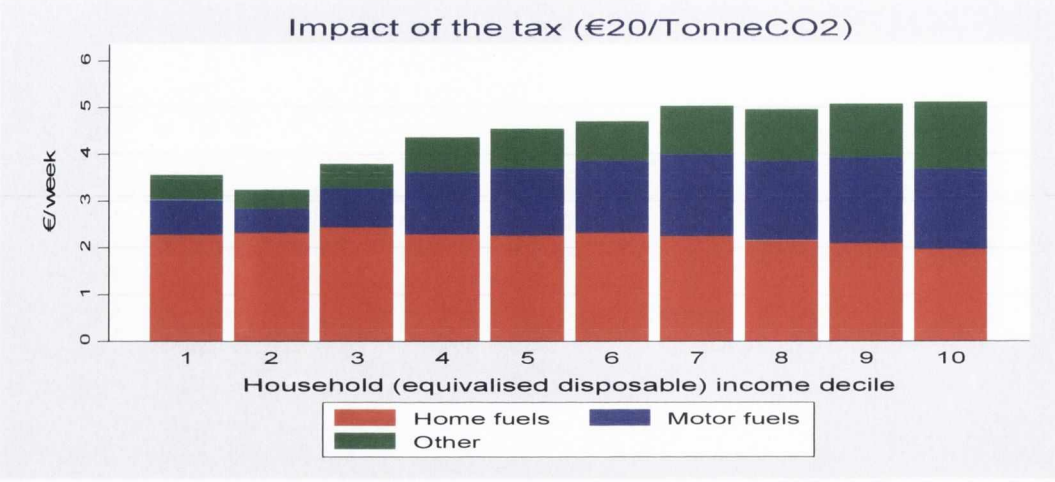


Figure 3 shows the overall impact of the tax, given by the sum of direct and indirect impacts, under the assumption that the tax applies neither to the ETS sector nor to imports. As argued previously, the latter scenario is indeed the most likely and recommendable for Ireland.

[16] Note that, in fact, if the tax was levied on imports too, the price of carbon in the exporting country would be considered (i.e. a €20 rate would be applied only to imports from countries where the price of carbon is zero, whereas a lower rate would be applied to imports from a country where the price of carbon is positive). Also, it is implicitly assumed that carbon intensities of production processes in exporting countries are the same as in Ireland.

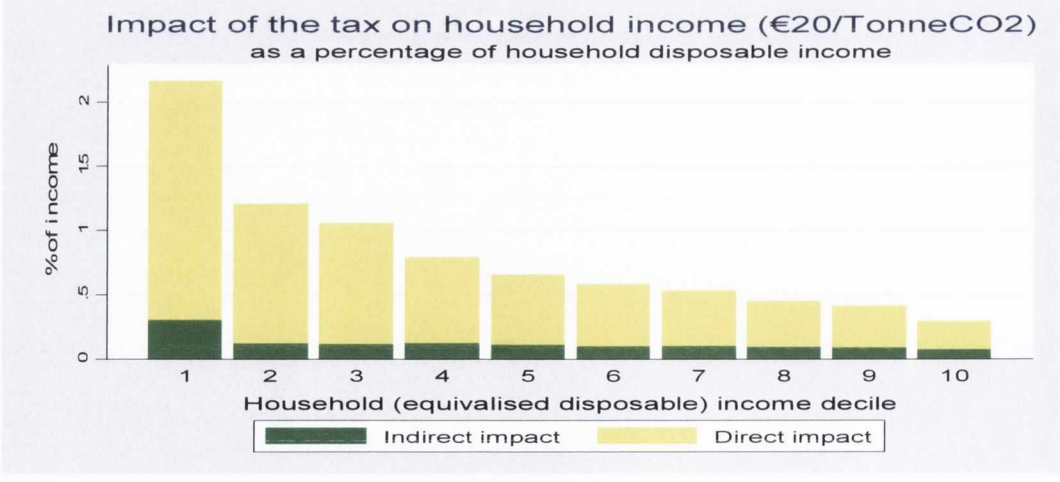
Figure 3 – The overall impact of the tax.



4.3 Tax regressiveness

The regressiveness of the tax here is measured as the ratio between estimated tax payments and household disposable income. In line with the literature specific to Ireland, the carbon tax is markedly regressive as expected: the impact in the first decile is seven times as big as that in tenth decile (see Figure 4). Behind this result is the pattern of direct energy consumption, which is virtually flat across the income distribution.[17]

Figure 4 – Tax regressiveness.



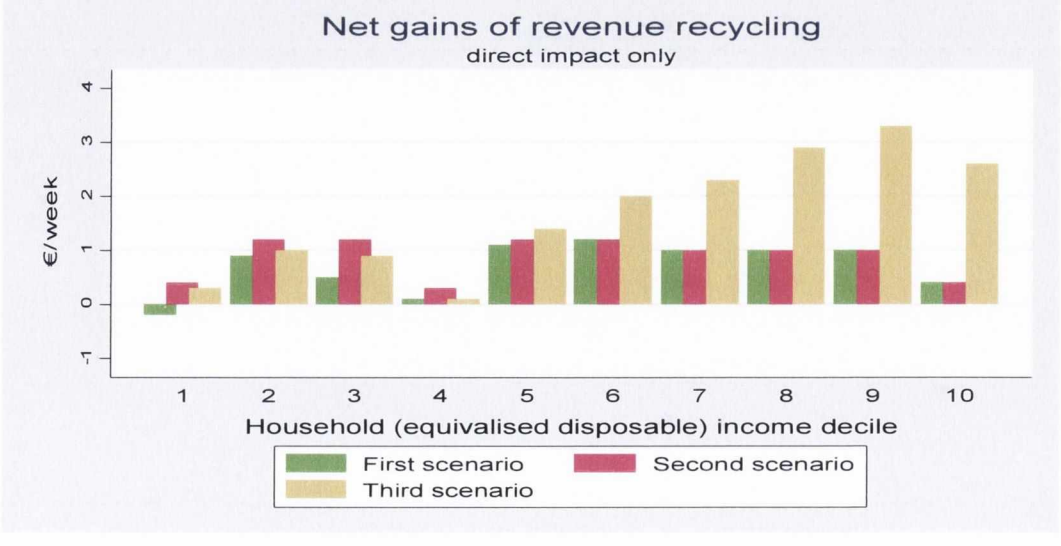
[17] Interestingly, Wier *et al.* (2005) find very similar results for Denmark, though less regressive overall.

Most important, average tax payments exceed 2 percent of disposable income for the poorest decile. Also, variability within the first decile is very high (the coefficient of variation is four times bigger than in the other deciles) and the distribution strongly skewed: only 24 percent of households in the decile have an impact higher than the decile average. This implies that 2.4 percent of Irish households would suffer an impact higher than 2 percent, and, in fact, some of them would suffer impacts way higher than that. Yet, a more careful look at the data reveals that errors in income data are most likely, at least for some of the observations with extremely high impact.

4.4 Recycling the revenue

Figure 5 compares the average net gains associated with the three revenue recycling options considered in this study, when allowing for the compensation of the direct impact only. In the first scenario, the increase in social welfare payments benefits households in the lower deciles, whereas the increased tax credit benefits households in the upper half. Net gains are minimal for deciles 1 (in fact, no gain), 4 and 10. The second option, or scenario, only adds an increase in the qualified child allowance for social welfare recipients, which fact has clear benefits for the lower incomes. As for the third option, i.e. higher benefits and lower tax rate, there are relevant gains across the income distribution, but minimal ones for deciles 1 and 4. Rich households definitely gain more under this scenario.

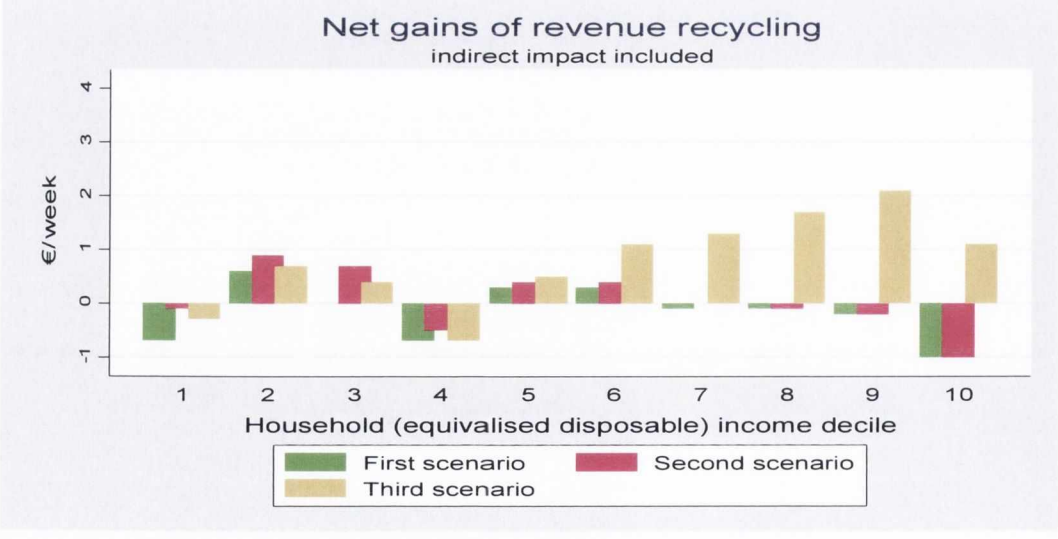
Figure 5 – Tax revenue recycling: compensating the direct impact of the tax.



No doubt, the second scenario is preferable: it improves the first one, which generates negative gains for the first decile, while distributing gains over the deciles more equitably than the third. Moreover, the cost of the second scenario would be €360m, as compared to €423m for the third scenario. Conefrey *et al.* (2008) estimate a €20/tCO_2 tax to generate, in 2010, a revenue stream of about €550m from the non-ETS sector.[18] Therefore, under the second scenario, there would be a substantial amount of money left over after households' compensation (€190m).

Should the government compensate households for the indirect impact of the tax too? Arguably, it should not. The indirect impact, as previously defined, is largely felt as a general increase in prices, which fact has two types of implications: 1) it is supposed to be included already in inflation adjustments of benefits and wages; 2) compensation for the indirect impact would not drive consumer behaviour towards less carbon intensive consumption anyway. Therefore, the tax is likely to be more effective if the revenue destined for the compensation of the higher cost of living is actually used for other purposes. Yet, it is still interesting to compare our three revenue recycling options once again, this time allowing for the indirect impact of the tax as well (Figure 6). Note that the latter refers to the case the tax is levied only in the non-ETS sector, and not on imports: net gains are somewhat lower if tax is levied also in the ETS sector and/or on imports.

Figure 6 – Tax revenue recycling: compensating the indirect impact too.



[18] Note that the €550m estimate allows for the substitution effects induced by the tax.

Most importantly, 55,000 households (equivalent to 3.8% of the total), according to the SWITCH estimates, would not be assisted by the tax/welfare compensation packages here considered. Some of these households would be households with a low self-employment income, subject neither to tax nor eligible for social welfare payments. This is a very serious issue, which, if anything, should be solved for other reasons than climate policy.

5. Conclusions

In view of the emissions target for 2020, Ireland needs major cuts in GHG emissions from the non-ETS sector. Accordingly, the Government is supposed to introduce a carbon tax, which: 1) would be revenue-neutral; 2) should be levied only in the non-ETS sector; and 3) should be close to EU ETS price of carbon. This paper analyses the distributional implications of a €20/tCO_2 tax with such characteristics.

The direct impact of the tax is estimated to range between €3 and €4 per week, per household, across the household population. In line with findings of previous work on Ireland, household energy consumption for heating and cooking is virtually constant across the household population, while consumption of motor fuels is positively related to income. Importantly, there is evidence that, at home, low income households are less energy efficient and rely more on carbon intensive fuels (both facts result in higher tax payments). Besides, note that emissions from Transport and Residential sectors have been growing faster than in the other sectors of the economy over the last few years. That is why a carbon tax in the non-ETS sector is needed.

The indirect impact of the tax is estimated to range between €0.5 and €1.5 per week, per household, across the household population. Since the indirect impact relates to consumption of all goods and services but fuels, it is increasing with income. The increase in the cost of living would be more significant, though still limited, if the tax was applied to imports and/or the ETS sector. However, both circumstances are most unlikely, as taxing imports from countries with more loose carbon restrictions would be technically difficult and levying the tax in the ETS sector is not expedient (carbon leakage).

The overall impact of the carbon tax is markedly regressive, as the average burden is estimated 2.1 percent of disposable income for the first decile, 1.2 percent for the second decile and 0.3 percent for the tenth decile. Yet, the impact distribution is strongly skewed

within the first decile, which fact implies the burden would be smaller than 2.1 percent for most of households in the decile and much higher than that for few households (though still a significant number). Moreover, a few of the observations with highest impacts are found to have spurious income values (making the impact unrealistically large) and the tax would probably be less regressive if compared against total expenditure – a proxy for permanent income – rather than current income.

Three alternative welfare/tax packages for compensating households were simulated. A €2 increase per week in all welfare payments, a €104 increase per year in tax credit and a €0.8 payment per week for each child of social welfare recipients, turns out to be the mix of measures distributing net gains most equitably, while leaving over substantial resources to finance other programs. Specifically, some €190m would be left over and one may consider it only costs about €1000 to install attic or wall cavity insulation in a home (Ryan *et al.* [2008]).

Overall, the results of this study show that distributional concerns should not deter the adoption of a carbon tax in Ireland, if part of the proceeds are redistributed across households. Above all, it should be emphasized that all estimates of the tax impact on household income are conservative because the methodology used allows for substitution effects neither on the supply nor the demand side of the economy (that is why we refer to first-round or immediate effects) and the burden of the tax is entirely borne by consumers too. However, even so, on average households are better off after revenue recycling and substantial resources are left over too. Also, low income households have wider margins for carbon reductions, to be achieved through the use of less carbon intensive fuels and energy efficiency.

The levy of a carbon tax may have further distributional implications through the labour market. Therefore, the use of a general equilibrium approach is a necessary extension of the present study. A general equilibrium approach would also enable the analysis of the tax impact on other fundamental economic measures, such as economic growth and international competitiveness. In relation to the latter, the restrictions on CO_2 put in place in Ireland's most important trading partners should be taken into account as well.

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Appendix

Table A1 - Calorific values and emission coefficients.

Fuel	HBS measure	Calorific value (TOE)	Emission coefficient (tCO_2/TOE)
Gas	Kwh	.000086	2.378
Electricity	Kwh	.000086	7.402 (year 2006)
Anthracite	Kg	.000665	4.110
Coal	Kg	.000665	3.961
Turf loose	Cwt	.015907	4.354
Turf briquettes	Bale	.005538	4.137
Central heating oil	Litre	.000868	3.050
Paraffin oil	Pint	.000473	2.980
LPG	Kg	.001126	2.667
Petrol	Litre	.000804	2.931
Diesel	Litre	.000874	3.050
LPG auto	Litre	.000563	2.670

Table A2 – 2005 Production and consumption coefficients (grams/€).

	With tax in the ETS		Without tax in the ETS	
NACE19 sector	*Production*	*Consumption*	*Production*	*Consumption*
1	120	293	120	184
2	41	170	41	77
3	65	285	65	173
4	176	309	176	224
5	49	52	49	51
6	6	33	0	9
7	18	29	18	21
8	32	760	32	191
9	1925	2105	0	44
10	572	1035	0	68
11	35	213	35	73
12	16	38	16	21
13	13	89	13	43
14	31	409	31	122
15	179	304	179	234
16	3436	4429	0	23
17	11	14	11	11
18	14	129	14	53
19	1047	1319	1047	1200

Table A3 – 2005 Household demand: imports.

NACE19 sector	Household demand: imports (%)
1	46.7
2	36.6
3	51.9
4	95.7
5	43.0
6	54.7
7	90.3
8	67.8
9	77.0
10	27.3
11	89.3
12	96.1
13	82.9
14	96.4
15	67.9
16	0.5
17	0.0
18	4.4
19	9.1

Paper 2

Distributional effects of carbon pricing in Ireland: A CGE approach using G-EMH

1. Introduction

In December 2009, the Irish government introduced carbon taxation. As of January 2012, the tax amounts to €20 per tonne of carbon dioxide (€20/tCO_2) and is levied upstream in the non-ETS sector (EU Emissions Trading Scheme) of the economy.[19] The activities covered by the EU ETS[20] are exempted in order to avoid double regulation, which would be both ineffective and more costly than necessary (Conefrey *et al.* [2008]). As yet, coal and peat are tax exempt.

In the previous decade of sustained economic growth in Ireland, while occasionally at the centre of the political debate, carbon taxation never made its way into legislation. It took a crisis of public finances and the Greens in government to adopt the levy. The need to raise extra fiscal revenues also explains why the tax, contrary to what had been set forth previously, was not implemented as revenue neutral. That is, the yield is not expressly used

[19] In Ireland, the non-ETS sector accounts for about 55% of total CO_2 emissions, and 70% of total greenhouse gas emissions.

[20] These are energy activities (e.g., electricity generation, mineral oil refineries), production and processing of ferrous metals, mineral industries and pulp and paper industries.

("recycled") to counter the potential side effects of the tax, notably the deterioration of firms' competitiveness and the regressive impact on households. These issues should not be overlooked, however. Ireland has indeed a very open economy and, certainly in the short term, the tax without some form of revenue recycling can only be regressive, that is, it affects the poor relatively more than the rich (e.g., Callan *et al.* [2008], Verde and Tol [2009]). As to the longer horizon, no studies exist on the distributional effects of carbon taxation over the medium or long term in Ireland. The present paper is the first to address this question.

In general, the time horizon over which the distributional effects of carbon pricing[21] are assessed has implications for the methods that should be used and, potentially, for the results and the ensuing conclusions. The vast majority of the literature only considers the impact on household income occurring though consumption. That boils down to the increase in consumer prices, of energy in the first place, and, thus, the losses in purchasing power and welfare. As energy is a necessity, at least in developed countries, that usually leads to the conclusion that carbon pricing is regressive. However, while limiting the analysis to the cost of living can be appropriate to appreciate short term effects, the same is not true for the longer horizon. Over time, firms respond to changes in relative prices by modifying production processes and the combination of production factors. Also, to the extent that real wages are affected, workers too may be discouraged in supplying labour. The resulting changes in the remuneration and employment levels of primary factors determine distributional effects, as different households rely in different proportion on labour, capital and transfers as sources of income. Thus, it is necessary to take into account both the uses and the sources of households' income to properly capture distributional effects beyond the short term.

Yet, only few studies in the world literature analyze the distributional effects of carbon pricing over the longer horizon. Presumably, the reason for this is that the levels of data detail and model sophistication which are required are both quite high. First, the pervasiveness of carbon pricing in product and factor markets calls for economy-wide models, such as macro-econometric or Computational General Equilibrium (CGE) models. Secondly, sufficiently flexible production and expenditure functions are needed and, above all, they must be supported with suitable energy data and parameter estimates. Third, the

[21] Carbon pricing only means that emissions are priced, regardless of the instrument that is used, be it taxation or cap-and-trade. If, as in this study, the analysis abstracts from those aspects that differentiate taxation and cap-and-trade one from another (under certain conditions, the two are equivalent), then generically referring to carbon pricing is simply more convenient.

identification of distributional effects requires detailed data, typically survey data, on households' expenditures and incomes. All these elements may not always be readily available and to bring them together in a single framework may not be immediate either.

The present paper adds to this still very limited literature and, as already pointed out, it is the first such application to Irish data. Using CGE analysis, it simulates the medium term impact, interpreted as a three to five year horizon,[22] of a $20/tCO2 carbon tax[23] on the Irish economy. The purpose of this work, conceived before the carbon tax was introduced in Ireland, is not to model the existing carbon regime, but rather, is to investigate the impact of carbon pricing (in a form that is only comparable to the existing one)[24] on the equilibrium of the Irish economy and especially of income distribution. "Is carbon pricing in Ireland regressive beyond the short term?" is the first question we address. The analysis allows for revenue recycling and, in particular, five potential revenue recycling schemes are considered and contrasted. As in the double dividend literature, we verify whether lower emissions and greater economic growth can be achieved at the same time under any of the considered environmental reforms. Finally, we identify which of these schemes is the most preferable according to efficiency, that is, economic growth, and equity criteria.

A variant of the popular GTAP model (Global Trade Analysis Project), G-EMH, has been developed expressly for this study. In particular, G-EMH combines two versions of the standard GTAP model: GTAP-E (Burniaux and Truong [2002], McDougall and Golub [2007]) and GTAP-MH (Gotor and Tsigas [2011]). The first links together energy-related CO_2 emissions and the economy, whereas the second allows for multiple representative households. That is, the household sector is partitioned into groups and each of these is represented by a virtual household assumed to behave as the mean of the group. In this application, the household groups correspond to the deciles of the income distribution.

Though G-EMH was obtained by merging two models, its motivation and scope are specific. Thus, new modelling challenges arise and, indeed, some original features have been introduced. The most significant innovations concern *a)* the endogenization of labour supply, *b)* the introduction of renewables in the electricity sector, and *c)* the distinction

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[22] The CGE model used in this paper is static, since the total stock of capital is fixed. At the same time, capital and labour are assumed perfectly mobile across sectors. This makes simulation results – variations between initial and final equilibria – best interpreted as referring to a three to five year horizon (Beckman *et al.* [2011]).

[23] As in the used global database all input-output and trade flows are expressed in 2004 US$, the Irish carbon tax too is specified in 2004 US$.

[24] A $20/tCO_2$ tax, applied to all emissions and with no distinction between ETS and non-ETS sectors, is not too distant from the existing regime. Furthermore, the $20 rate is sufficiently low to be compatible with the absence of technological change assumed in the simulated scenarios.

between resident and non-resident households. Finally, the GTAP database provides the information needed to operationalize the model. Yet, the breakdown by income decile of households' incomes and expenditures, as well as the estimation of demand elasticities for energy commodities, are based on micro-data from the Irish Household Budget Survey (HBS).

The paper is organized as follows. Section 2 reviews the literature. Section 3 presents the G-EMH model. Section 4 illustrates the data. Section 5 describes the scenarios. Section 6 discusses the results. Section 7 analyzes the sensitivity of results to some critical model parameters. Section 8 concludes.

2. Literature review

A sizeable literature on the economic effects of carbon taxes has been produced over the last twenty-five years. Two main strands can be identified. One of them addresses the question of whether revenue neutral carbon taxes may induce not only an environmental benefit but an economic one too, what is called a double dividend.[25] This comes about as an efficiency gain of the economy (i.e., greater economic growth) when the green levy substitutes other more distortionary, pre-existing taxes. The other bulk of research is concerned with the distributional effects of carbon taxes across households.[26] With few exceptions, there have been no intersections between these two fields of investigation which have largely been explored separately and with distinct methods.

In the double dividend literature, economy-wide models are needed for the simple reason that the interest is in the impact of the environmental tax reform on the economy as a whole. Partial equilibrium analysis is, by contrast, the standard approach in the literature of distributional effects. Input-output or CGE models are often used in a first stage only to determine the impact of the tax on consumer prices and, then, the derived price changes are fed into a micro-simulation model of the household sector. The downside of such approach, however, is that it ignores feedback and general equilibrium effects. Above all, it ignores distributional effects stemming from the sources side of income through changes in wages, rents, transfers, employment.

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[25] Goulder (1995), Bovenberg (1999), and Ballard *et al.* (2005), among others, survey this literature. For a critical perspective, see Fullerton (1999).

[26] Among the early works are those of Pechman (1985) and Poterba (1991). Many more have followed. See Speck (1999) for a then up-to-date literature review. See Fullerton (2009) for a comprehensive survey of the literature through a selection of papers.

It is only in recent years, with the sole exception of Jorgenson *et al.* (1992), that economy-wide models with multiple households have been used to analyze both efficiency and equity effects of carbon pricing together, simultaneously. This may seem surprising as the "macro-micro link" literature, in which economy-wide and micro-simulation models are used in combination, is in fact far from being scant.[27] There are indeed many works that simulate the micro consequences, such as the impact on poverty or income distribution, of macro policy reforms. However, more information and greater model sophistication are needed in order to simulate the effects of carbon pricing than, say, of trade liberalization. Indeed, as already pointed out, the modelling of energy production and consumption poses additional challenges.

Nonetheless, there is obviously common ground between the two types of literature as to how the macro and the micro frameworks are linked. Bourguignon and Savard (2008) identify three approaches in the CGE literature: *a)* the CGE micro-simulation sequential approach, *b)* the representative household approach, and *c)* the integrated multi-household approach. The first corresponds to what, two paragraphs above, was referred to as partial equilibrium approach. With the second, the population of households is partitioned into groups, and each group is represented by a virtual household assumed to behave as the mean of the group. Hence, only between-group variation can be captured, whereas within-group variation is ignored. This is the limitation of such approach and G-EMH, the model used in this paper, precisely belongs to this category. The third approach is an extension of the previous one in that it includes as many representative households as there are actual households in the survey. No doubt this approach is the most powerful, though it does raise some difficulties at the implementation stage: the numerical resolution can be challenging and the reconciliation of macro aggregate data and survey micro-data may be problematic too.

The first part of this section gives a detailed account of the few existing studies that use economy-wide models with multiple households to analyze both efficiency and equity implications of carbon pricing at the same time. Given the absence of similar works for Ireland, the second part recalls those which are nonetheless relevant and provide evidence against which the findings of this study can be contrasted.

2.1 International literature

[27] See Decaluwé *et al.* (1999) for a survey of this literature.

Jorgenson *et al.* (1992) are the first to analyze the distributional impact of carbon pricing using an economy-wide model. A dynamic CGE model of the U.S. economy, IGEM, is used to estimate the economic effects of adopting a sequence of carbon taxes that holds U.S. carbon dioxide emissions constant at the 1990 level. Over 16,000 household types are tracked, classified by demographic characteristics and income level. Revenue neutrality is enforced making the average tax rate on labour income endogenous. Equivalent variations in wealth throughout lifetime are calculated for each household type and combined in a single measure via a social welfare function. The impact of carbon taxation on growth is found to be negative, but modest (less than 0.5% in real GNP, in 2020). The impact on welfare is found to be mildly regressive. However, if equality is measured in absolute terms and the social welfare function reflects high inequality aversion, the effect becomes mildly progressive.

Jorgenson *et al.* (2010) extend Jorgenson *et al.* (1992), update it with new data and apply it to different scenarios. The main methodological innovation concerns the inclusion of leisure in the measure of household welfare. The simulated policies are caps on all GHG emissions in the U.S. which would bring them to 50% and 80% below the 1990 level, over the period 2012-2050. As the price of goods rises relative to leisure, households substitute toward the latter and reduce labour supply. Real GDP falls substantially, by just over 2% and 4% in the less and more stringent scenarios, respectively. Private consumption falls by almost half as much. Yet, the welfare impact is regressive but modest (substantially less than 1% for all of the 244 household types), as the increase in leisure partially offsets the reduction in consumption.

Roson (2003) constructs a dynamic CGE model of the Italian economy to assess the efficiency and equity effects of carbon taxation with revenue recycling in that country. The constraint imposed on emissions reflects the national Kyoto target and the carbon tax rate is endogenously determined. The carbon tax revenue is recycled by lowering either labour taxes or taxes on capital income. Six representative households, classified by income level, and ten time periods are considered. The tax is introduced in the third period. Households maximize utility over an infinite horizon and anticipate the policy shock. A modest double dividend appears only with lower taxes on capital. It is pointed out that Jorgensen and Wilcoxen (1995) find a similar outcome for the U.S. but the underlying mechanisms are different, given the different sizes of the two economies in question. Surprisingly, the double dividend is progressively distributed. This is explained by the distribution of capital

income, which is quite even across households, and the assumptions of symmetric changes in employment levels and equal access to international capital markets for all households.

Van Heerden *et al.* (2006) use a CGE model similar to ORANI-G to investigate the potential for a double or triple dividend in South Africa. Forty-eight household types (four race groups, twelve income groups) are represented. Cuts in four different energy-related taxes, notably on emissions, fuels, electricity and energy, are considered, in combination with three revenue recycling schemes: lower direct taxes, indirect taxes, and taxes on food consumption only. The focus is on poverty rather than the whole income distribution. They find that a triple dividend can be achieved, in the form of lower emissions, higher GDP, and less poverty (i.e., higher consumption for the poorest households) if any of the four taxes is recycled through a reduction in food prices. However, depending on which tax is reduced, the relative weight of the three dividends changes.

Yusuf and Resosudarmo (2007) analyze the impact of carbon taxation on household income distribution in Indonesia. A modified version of ORANI-G is deployed, with two-hundred household categories. These correspond to the income centiles of urban and rural households. In contrast with most studies from industrialized countries, carbon taxation without revenue recycling is found to be progressive. The change in the use of primary factors following carbon taxation is to the advantage of lower income households. In addition, the expenditure of lower income households, especially in rural areas, is less sensitive to the prices of energy-related commodities. However, neither of the two simulated recycling schemes – a cut of the sales tax rate and a lump-sum transfer to all households - delivers a double dividend.

Oladosu and Rose (2007) use their own CGE model to simulate the impact of carbon taxation on the economy of the Susquehanna River Basin, a geographical region of the U.S. The household sector is disaggregated into nine income brackets. The study is interesting for at least three reasons. First, it applies to a sub-national region and, what is more, a geographical region. Secondly, the authors distinguish between short and long run horizons and results vary in consequence. Third, in contrast with most of the literature applied to industrialized economies, carbon taxation turns out to be mildly progressive. No evidence of a double dividend is found for neither of the two recycling schemes envisaged. As expected, transfers enhance progressivity more than cuts in income taxes.

Rausch *et al.* (2011a) develop USREP, a CGE model of the U.S. economy which comprises eleven sub-regions and, for each of these, eight household income groups. This first application of USREP involves the simulation of a $\$15/tCO_2$-eq carbon price which is

determined via a cap-and-trade scheme. With allowance auctioning, revenues are recycled via transfers, labour, and income taxes. With free allowances, they are returned to households in proportion to capital income. In fact, two versions of the latter are considered, whereby the revenue accruing to the electricity sector is allocated either in proportion to electricity consumption or via lower electricity prices. Under none of the scenarios, economic growth benefits from carbon pricing. However, the latter without recycling is neutral or slightly progressive. Free allowance schemes are found to be highly regressive, while an efficiency-equity tradeoff emerges with allowance auctioning, where transfers and income taxes are at opposite ends.

Rausch *et al.* (2011a) has subsequently been extended in two different directions. Rausch *et al.* (2010) apply a recursive dynamic version of USREP to compare three alternative cap-and-trade schemes for America. These are loosely based on the U.S. Congress bills Waxman-Markey, Kerry-Lieberman, and Cantwell-Collins. All proposals seek similar overall cuts in emissions by 2050, but differ in how allowances and auction revenues would be distributed. There is no trace of a double dividend, as either the allowance revenue is mostly used to make up for the budget deficit (induced by restrictions on emissions and subsequent reduced economic activity) or labour and capital taxes are actually increased to enforce revenue neutrality. The three schemes have similar aggregate costs, but these are greater if labour and capital taxes go up. As for the distributional effects, the authors emphasize the following two results. First, sources-side effects dominate the uses-side effects; a point which is reinforced by the finding that carbon pricing without revenue recycling is neutral to modestly progressive. Secondly, they find there is an efficiency gain to distributing value to wealthier households because less is spent on energy and more goes into savings and investment. This is an additional explanatory reason for the equity-efficiency tradeoff, which is usually justified by the distortionary effects of taxes.

Rausch *et al.* (2011b) extends Rausch *et al.* (2011a) by incorporating 15,588 households from the U.S. CEX survey data as individual agents.[28] To solve such a large model, an algorithm borrowed from Rutherford and Tarr (2008) is used. The latter decomposes the numerical problem into two sub-problems and finds the equilibrium by an iterative procedure between those. The first one finds general equilibrium prices, with household demand replaced by a single representative agent. The second sub-problem

[28] This is the first and, as yet, only work of this literature to use what above has been referred to as integrated multi-household approach.

computes partial equilibrium quantities demanded by each of the 15,588 households, given candidate general equilibrium prices. The algorithm finds the equilibrium of the underlying economy if the sequence of general equilibrium prices and partial equilibrium quantities converge to the true equilibrium prices and quantities. On the whole, results confirm findings in Rausch *et al.* (2011a), but crucially they show how variation in impacts within household sub-groups can swamp the variation across groups.

Rose *et al.* (2011) analyze the distributional effects of California's forthcoming (2012-2020) cap-and-trade scheme, for alternative combinations of allowance allocation and revenue recycling. These involve free allocation of allowances with 0 or 100% pass-through of opportunity costs onto consumers, and full auctioning with revenue recycling via lower personal income taxes or household transfers. A most detailed macroeconometric model, REMI PI^{+}, is adapted to enable distributional analysis. The household sector is subdivided by ten income brackets. The direct costs or savings of the policies are taken from another study and referred to as baseline scenario. The economy grows in all four scenarios: the most with free allowances and 0% opportunity costs pass-through, the least with 100% pass-through. Differences are not large, however. As regards the distributional outcome, a clear efficiency-equity tradeoff emerges between allowance schemes (i.e., free vs. auctioned), but the two recycling options are virtually equivalent.

2.2 Irish literature

There are no studies that estimate the impacts of carbon pricing in Ireland on both growth and household income distribution at the same time. Thus, there follows a review of those which focus on growth, first, and we then turn to the other set of works.

Using HERMES, a macroeconometric model of the Irish economy, Bergin *et al.* (2004) examine the effects of a €20/tCO_2 carbon tax. A number of revenue recycling options are considered and contrasted against a ten year no-tax baseline scenario. With lower taxes on labour, it is found, a double dividend would be achieved.[29] Though the effect would be smaller, the same is true for a reduction in VAT. This results in lower nominal wages to the point it offsets the adverse impact on competitiveness. Besides, a cut in VAT would have a progressive impact on households.

Wissema and Dellink (2007) construct a static CGE model for Ireland based on 1998 data. They find that a carbon tax just above €10/tCO_2 could reduce emissions by some

[29] Fitz Gerald and McCoy (1992) had obtained the same result.

25%, with little impact on overall welfare (less than 1% for a €30/tCO_2 tax). Capital-energy substitution is identified as a critical factor. Wissema (2007) augments the same model by allowing for unemployment and endogenous labour supply and pairs carbon taxation with revenue recycling. She finds lower indirect taxes bring about only a "weak double dividend",[30] whereas a strong negative welfare result is associated with lower labour taxes. This rather striking result is due to households' loss in leisure, which is necessary to meet a higher labour demand in a context of almost full employment.

Conefrey *et al.* (2008) again use HERMES, but in a different manner. They consider a €20/tCO_2 tax, but instead of using a dynamic no-tax baseline scenario, they maintain the economic structure fixed at its 2005 level. This way, they can isolate the equilibrium effects of the tax from any other unrelated changes in the economy – effectively, more a CGE type of exercise. Two recycling options are considered, namely household transfers and lower income taxes. Only with the latter, a double dividend is likely. International competitiveness of manufacturing and services is the main channel through which the hypothesized tax reforms affect the economy. The impact on emissions turns out to be very limited: a reduction of around 2% at most.

Turning to the works focused on the distributional implications of carbon pricing, Scott (1992) finds that the first-round effects of a carbon tax would be markedly regressive.[31] This conclusion is based on the pattern of fuel consumption across household income deciles as it emerges from the 1987 Household Budget Survey (HBS). Scott and Eakins (2004) repeat the work with more recent data and obtain similar results. O'Donoghue (1997), in addition, captures the indirect impact of the tax (occurring through the higher cost of general consumption, not just of fuels) by using HBS and input-output analysis. It turns out that the tax burden is borne more equally by households once the indirect impact is taken into account. Callan *et al.* (2009) and Verde and Tol (2009) are in the spirit of Scott and Eakins (2004) and O'Donoghue (1997), respectively. However, though the approach remains partial equilibrium, they add revenue recycling. This is done by using a micro-simulation tax-benefit model (SWITCH). The two studies, which draw on the same data, conclude that the most equitable way to compensate households is through a modest increase in a mix of welfare payments.

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[30] Weak double dividend means that the change in welfare is preferable (i.e., more positive or less negative) to what is obtained by simply returning the tax revenues to households as lump-sum transfers. It does not mean that the change is positive relative to the pre-tax state – a change which is a strong double dividend.

[31] Two orders of assumptions are implicit in first round effects. First, demand and supply do not adjust to changes in relative prices. Second, the new tax is fully shifted onto the consumer.

Finally, there are a few other empirical works that are related to the literature recalled above. Among these, Healy (2003) and Scott *et al.* (2008), who deal with fuel poverty – an issue of concern in Ireland; Leahy *et al.* (2009), who look at the spatial incidence of carbon taxation – a new perspective on the distributional implications of carbon pricing; Boyle (2000) and a study of Indecon (2002), which focus on the impact of carbon taxation across industries.

3. The model: G-EMH

The GTAP model is a widely used multi-regional CGE model of the global economy, originally created to analyze the economic effects of trade liberalization and operated with data compiled by a team of researchers at Purdue University, in the U.S.[32] With reference to a given year, the GTAP database collects, among other things, input-output tables and both bilateral trade- and tariff data for most countries in the world. It also provides values for all parameters in the model (elasticity estimates). In its most recent version, which refers to 2007, such data are available for 129 regions, 57 production sectors (or goods, since each sector produces only one good) and 5 primary factors. GTAP users can then aggregate regions, sectors and primary factors according to their needs and the type of licence for the software used to solve the model (GEMPACK or GAMS).

A number of adaptations of the GTAP model have been developed over the years in order to better address specific issues. Among these are GTAP-E (Burniaux and Truong [2002]; McDougall and Golub [2007]), which was specially created to analyze the effects of energy/climate policies, and GTAP-MH (Gotor and Tsigas [2011]), which introduces multiple households and thereby allows distributional analysis. G-EMH is thus a new variant that has been created expressly for this study by merging GTAP-E and GTAP-MH. In this section, G-EMH is presented. Since GTAP-E and GTAP-MH are already illustrated in the respective papers, the focus here is on the features that differentiate G-EMH from the two original models.

3.1 "E": Energy

[32] See Hertel (1997) and Narayanan and Walmsley (2008) for the GTAP model and database, respectively. More information and resources can be found on the website www.gtap.agecon.purdue.edu/. There is also an active mailing list, through which GTAP users share their knowledge.

The GTAP-E model modifies the production structure of the standard GTAP model in order to more closely mimic the ability of firms to substitute among alternative fuels as well as between primary factors and energy. It also incorporates CO_2 emissions from the combustion of fossil fuels as well as mechanisms to model regional carbon taxes and international emissions trading.[33] Figure 1 shows GTAP-E's multi-tier CES (Constant Elasticity of Substitution) production function, whereby each nest is identified by one parameter, σ - the elasticity of substitution between pairs of inputs.[34] One may recall that the CES reduces to the Leontief and Cobb-Douglas functions if σ is equal to 0 and 1, respectively. Hence, according to Figure 1, for all sectors/industries (and in all regions), primary factors and energy, on the one hand, and intermediate inputs, on the other, combine in fixed proportions (Leontief). By contrast, some degree of substitutability is allowed at all other levels (see Burniaux and Truong [2002]).[35] All the other parameters, whose values are reported in the Appendix (Table A1), vary across industries.[36]

G-EMH keeps GTAP-E's production structure, but adds some detail to the electricity nest. As Figure 1b shows, two levels are added to the CES structure to introduce different types of electricity technologies. Wind and hydro are separated from all other sources (e.g., fossil fuels, nuclear, other renewables, etc.) in order to isolate the positive impact carbon pricing is expected to have on the former.[37] While a more detailed disaggregation of the electricity sector would be feasible and desirable in certain applications, it would not make the results of this study much more interesting. This is because, in Ireland, the sum of wind and hydro makes up most of total electricity generation from renewables (in 2004, 93%). What is more, adding technologies requires a considerable amount of extra work, as the split of the electricity sector has to be done for all the regions in the model, and it needs

[33] Lee (2008) provides data on emissions, while Ludena (2007) shows how to prepare them for use with the regional-sectoral aggregation of interest. However, things have got easier with the latest version of the GTAP database, GTAP V8, as emissions data now are already found in the dataset.

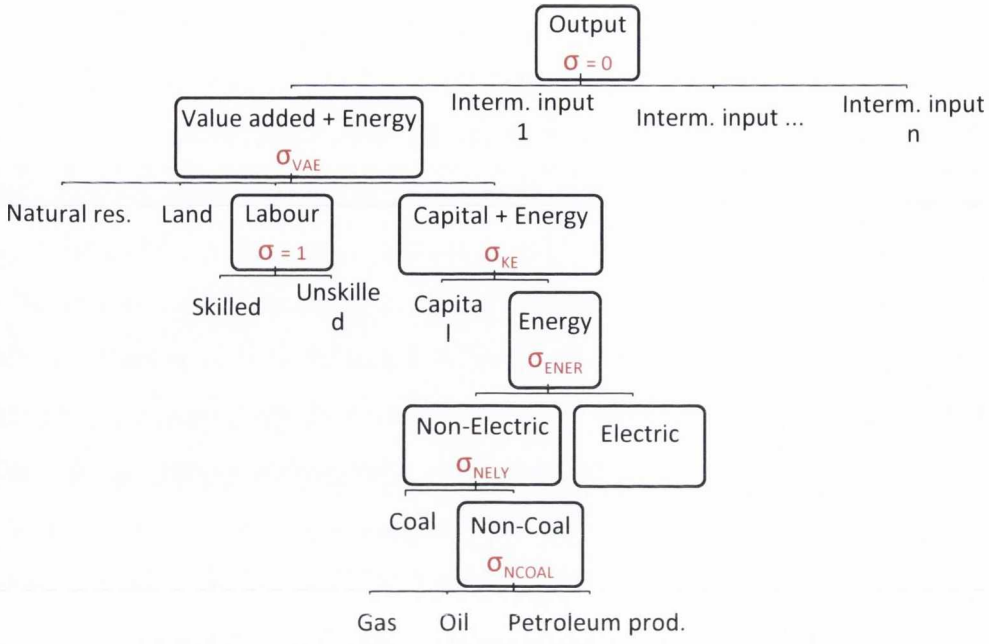
[34] Multi-tier CES production functions are popular in CGE modeling. They are parsimonious in parameters and represent separable, constant returns to scale technologies.

[35] However, as Burniaux and Truong (2002) explain, if $\sigma_{KE} < \sigma_{VAE}$, capital and energy can be complements. This is in fact the case for most industries in GTAP-E and, hence, E-GMH too.

[36] These elasticities do not vary across regions but, as is the case for all GTAP simulations, modelers are free to use different values if they wish so.

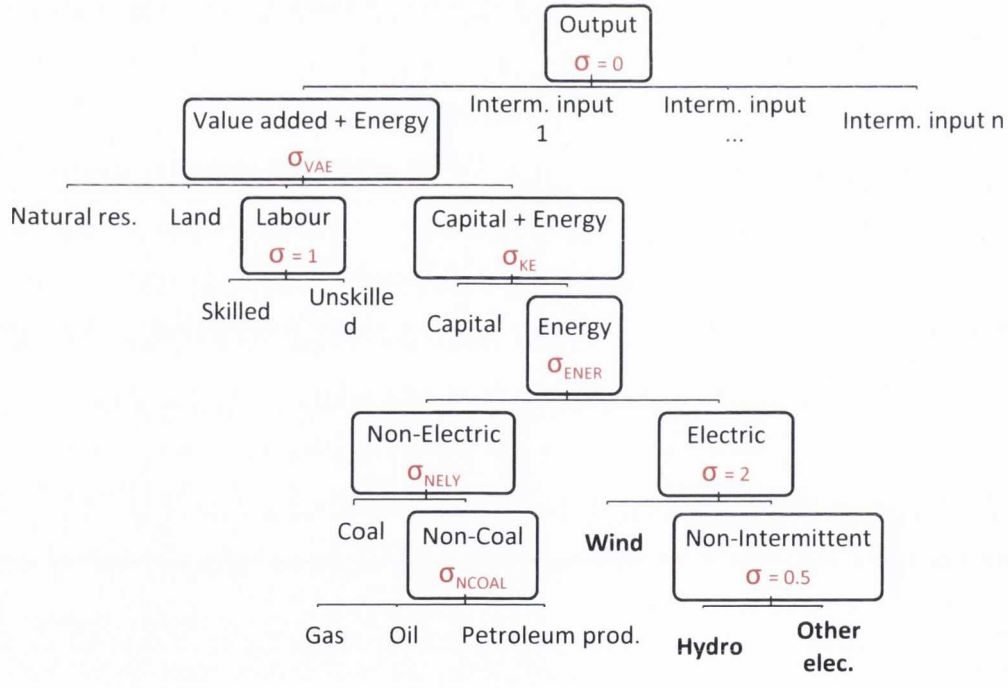
[37] The GTAP facility SplitCom was used to separate wind and hydro from generic electricity in the GTAP database.

Figure 1 – Industries' demand in GTAP-E.



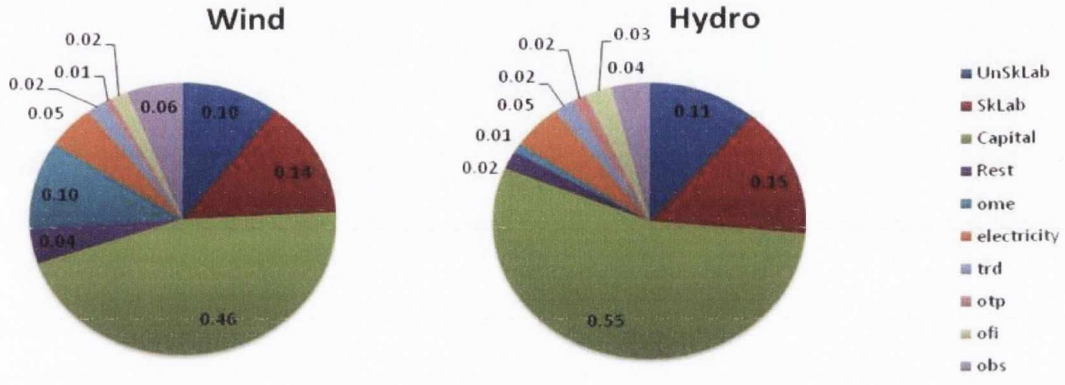
Note: The Armington elasticities and the two relative CES tiers are not shown in this graph. Their values are found in the Appendix (Table A1).

Figure 1b – Industries' demand in G-EMH.



estimates of production functions (i.e., the shares of capital, labour, services, etc., in total costs) and unit production costs ($/kWh) for each technology.[38] Both of these, for wind and hydro, are found in Bosello *et al.* (2011).[39] The values therein were used, in conjunction with data on 2004 electricity output from Renewables Energy Statistics of the International Energy Agency. Figure 2 shows the production functions (expressed as shares of total costs) of wind and hydro thus derived for Ireland.

Figure 2 – Wind and Hydro's production functions.



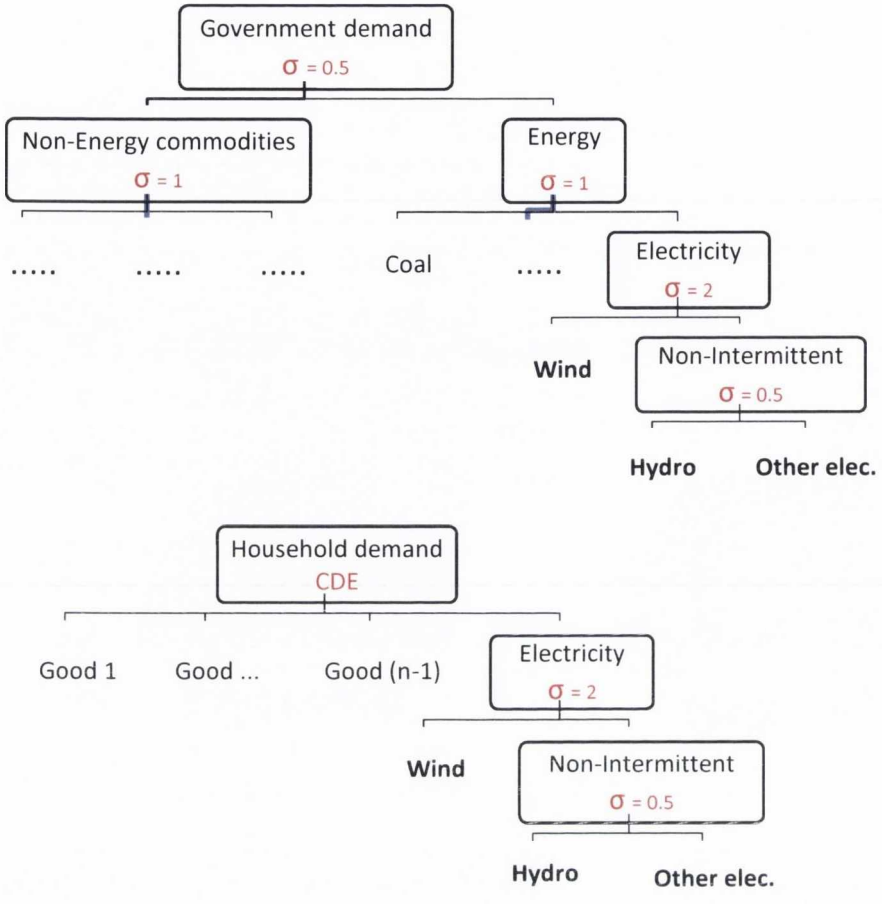
Moreover, each nest necessitates its own elasticity of substitution, σ. The values 2 and 0.5, for "non-intermittent" and wind, and between hydro and "other electricity", respectively, were taken from Bosello *et al.* (2011) too. They reflect the idea that wind more than hydro has the potential to expand if relative prices are tilted by carbon pricing. At the same time, 2 is believed to be a sufficiently low value to prevent unrealistic responses of the wind sector in simulations.

Because the way electricity is generated makes no difference to households or the government, just as for firms, the very same structure of electricity applies in the respective demand functions. Figures 3 shows how the two are represented in G-EMH.

[38] GTAP flows are expressed in monetary value ($m). Hence, unit production costs of electricity are needed to convert physical data of electricity generation into monetary values. Only then, it is possible to split the relevant GTAP flows.

[39] As regards unit costs, 0.07 and 0.05 $/kWh were used for wind and hydro, respectively.

Figure 3 – Government (above) and Household (below) demands in G-EMH.



3.2 "MH": Multiple Households

In standard GTAP there is only one representative household. Therefore, distributional analysis is not viable. Gotor and Tsigas (2011) introduce multiple households. Effectively, they keep the theoretical structure of the standard GTAP model (McDougall [2003]) and replicate it by the number of households.[40] Regional flows are partitioned accordingly, but totals are preserved so that additional information and re-balancing of the GTAP input-output table are not needed.

Accounting relationships

Each household has its own sources of income, which consist of net returns to primary factors (*EVOA*)[41] and "net tax transfers" (*NetTaxTr*). On the uses side, incomes are fully

[40] While in theory there is not a limit to the number of households that may be used, computational capacity may pose a constraint.
[41] EVOA stands for Endowment Value of Output at Agents' prices.

allocated to private commodities (*PRIVEXP*), government services (*GOVEXP*) and savings (*SAVE*). In GTAP notation,

$$\sum_{e \in ENDW} EVOA_{er}^{h} - VDEP_{r}^{h} + NTT_{r}^{h} \equiv Y_{r}^{h} \equiv \sum_{i \in TRAD} PRIVEXP_{ir}^{h} + GOVEXP_{ir}^{h} + SAVE_{r}^{h}$$

$$\forall h \in HH, \forall r \in REG$$

[1]

where *ENDW* is the set of primary factors; *TRAD* is the set of tradeable goods; *HH* is the set of households; *REG* is the set of regions; *VDEP* is capital depreciation; h and r denote the household and region, respectively.

The sums over households of *GOVEXP* and *SAVE* correspond to "government spending" and "gross domestic savings" in national accounts. The sum of households' incomes, Y, is "net domestic product" (i.e., GDP net of capital depreciation). In practical terms, private expenditure and earned income are imputed based on information from national household surveys, whereas government spending and gross domestic savings are spread arbitrarily over households.[42] We ascribe *GOVEXP* and *SAVE* equally to households, but we also verified that alternative distributions bring about virtually identical simulation results.

The sum of net tax transfers, which are given by the difference between total income and net factor income, equals the sum of all tax revenues. These, which in the standard GTAP model accrue to regional income, in GTAP-MH accrue to different households in different (fixed) shares, *NetTaxTrSh*. Therefore, in G-EMH, $NetTaxTrSh_{r}^{h}$ is used also to allocate (across households) the total yield of the carbon tax:

$$CTAX_{r}^{h} = NetTaxTrSh_{r}^{h} \times \left[\left(\sum_{h \in HH} \sum_{i \in TRAD} DPCTAX_{ir}^{h} + IPCTAX_{ir}^{h} + DGCTAX_{ir}^{h} + IGCTAX_{ir}^{h} \right) + \left(\sum_{i \in TRAD} \sum_{j \in PROD} DFCTAX_{ir}^{j} + IFCTAX_{ir}^{j} \right) \right]$$

$$\forall h \in HH, \forall r \in REG$$

[2]

where the total yield of the carbon tax (the sum in square brackets) stems from households' (P), government's (G) and firms'(F) consumption of both domestic produce (D) and imports (I).

[42] Gross domestic savings is given by the sum of households', firms', and government's savings. The GTAP database does not distinguish between these.

The fundamental equation which determines the percentage change[43] in household h's income, y^h, is the following (small letters denote percentage change variables, capital letters indicate level variables):

$$y_r^h = \begin{bmatrix} FY_r^h \times fy_r^h + \\ 100 \times Y_r^h \times del_inctaxr_r^h + INCTAX_r^h \times y_r^h + \\ 100 \times Y_r^h \times del_indtaxr_r^h + INDTAX_r^h \times y_r^h + \\ 100 \times Y_r^h \times del_co2taxr_r^h + CTAX_r^h \times y_r^h + \\ Y_r^h \times incomeslack_r^h \end{bmatrix} / Y_r^h$$

$$\forall h \in HH, \forall r \in REG$$

[3]

where the first four lines in brackets are, in this order, the change in total net factor income and the changes in revenues from income taxes, indirect taxes and carbon taxation; *del_inctaxr*, *del_indtaxr* and *del_co2taxr* are the changes (non-percentage) in the respective revenue-to-income ratios, and Y is the level of income.

Income distribution varies whenever percentage income changes are not identical for all households. Differences across households in the relative importance of different income sources, including household transfers, are therefore at the root of endogenous variations in income distribution. For example, for a given increase in the return on capital, households who rely on capital income relatively more than others will benefit in greater proportion too. It follows that the accuracy of simulation results critically depends on how well the breakdown of income data, by household and source, approximates the actual distribution.

The Non-resident household

In relation to the last consideration, an issue arises specifically with Ireland. The large number of multinationals operating in the country means that a large share of capital income is earned by non-residents. In 2004, the base year in this application, Ireland's Gross National Product was about 14% smaller than GDP. Ignoring this fact would affect our simulation results to some extent, precisely because the derived income shares would not reflect the actual composition of households' income. We therefore address this issue by adding a fictional, eleventh household, *HHNR*, whose function is to "absorb" the share

[43] The GTAP model belongs to the family of CGE models that are expressed in percentage variations, as linear approximation of the "true" model. Still, the solution of the true non-linear model can be guaranteed, to perfectly satisfactory levels of approximation, by partitioning the simulated shock in many small intervals. See Hertel (1997) for a detailed discussion of the intuition, and GEMPACK or GAMS manuals for details on the different solution methods that can be deployed.

of capital income earned by non-residents. This simple expedient, which has not been used in previous applications with GTAP-MH, is neutral to the functioning of the model. That is, it does not require any alteration of the model's equations.

Labour supply

Typically with GTAP and in most CGE simulations, primary factors are held fixed, which is equivalent to assuming their full employment. However, though there was virtually full employment in 2004 Ireland, historically labour supply in Ireland is very elastic owing to migration. To take account of this aspect, one equation is added for labour supply, which is then endogenously determined. The approach is simple and it assumes that the elasticity of labour supply to real wage is both invariant to changes in labour supply and homogenous across households and skill levels. That is,[44]

$$pfactreal_{er}^{h} = pse_{er} - ppriv_{r}^{h}$$

$$\forall h \in HH, \forall e \in LAB, \forall r \in REG$$

[4]

$$qoe_{er}^{h} = \varepsilon_{r} \times pfactreal_{er}^{h}$$

$$\forall h \in HH, \forall e \in LAB, \forall r \in REG$$

[5]

where *pse* is the percentage change in the supply price of labour (i.e., nominal wage net of taxes on labour income); *ppriv* is the (household specific) consumer price index; *pfactreal* is the percentage change in real wage; ε is the elasticity of labour supply; *qoe* is the percentage change in labour supply; *LAB* is the set of labour factors and subscript *e* tells whether labour is skilled or unskilled.

Note that while the real wage is household specific, the nominal wage is not. The reason for this is that wages are negotiated collectively, not by households individually. However, households supply labour in different measure based on their own, specific real wage. Such modeling of labour supply has two important implications for the mechanics of the model and for the expected outcomes of the simulations. First, by raising final prices and, hence, reducing real wages, carbon pricing depresses labour supply.[45] Thus, carbon pricing per se (i.e., ignoring all other effects) has a negative impact on both households' purchasing

[44] Starting from the definition of elasticity of labour supply to real wage, $\varepsilon = \frac{\Delta L/L}{\Delta R/R}$, where $R = \frac{W}{P}$, then $\frac{\Delta L}{L} = \varepsilon \times \frac{\Delta R}{R} \rightarrow \frac{\Delta L}{L} = \varepsilon \times \left(\frac{\Delta W}{W} - \frac{\Delta P}{P}\right)$.

[45] Importantly, this effect is not compensated by an increase in leisure time. As yet, the labour-leisure choice is not modeled in GTAP.

power and employment. In most CGE applications where labour is held fixed, this second channel is ignored. Second, if poor households are affected by carbon pricing relatively more than the richer ones because they allocate greater shares of their income to energy consumption, as is usually the case, they are then penalized twice: as the price index of the real wage is household specific, their labour supply will decline by a greater percentage than that of richer households.

Finally, the clearing condition for the labour as well as the capital markets – both factors are perfectly mobile across sectors – which ensures supply and demand match, is the following:

$$\sum_{h \epsilon HH} RESSHARE_{er}^{h} * qoe_{er}^{h} = \sum_{j \epsilon PROD} SHREM_{ejr} * qfe_{ejr} + endwslack_{er}$$

$$\forall e \in ENDWM, \forall r \in REG$$

[6]

where $RESSHARE_{er}^{h}$ is the share of endowment e supplied by h; qoe_{er}^{h} is the percentage change in h's supply of e; $SHREM_{ejr}$ is the share of e employed by sector j; qfe_{ejr} is the percentage change in j's demand for e; $ENDWM$ is the set of mobile endowments (i.e., unskilled labour, skilled labour and capital).

4. Data

4.1 Regions, sectors and primary factors

Version 7 of the GTAP database (Narayanan and Walmsley [2008]), which depicts the global economy in 2004, is used in this study. Five regions, twenty-five sectors and five primary factors are considered. Both the sectoral and regional aggregations reflect the fact the study is centered on Ireland. As the UK, Europe, and North America are Ireland's main trading partners, each of them constitutes a separate region in the model, with Ireland and "Rest of the World" being the two remaining ones. The sectoral aggregation is based on Ireland's most energy-intensive and export-oriented industries. As regards primary factors, these are land, unskilled labour, skilled labour, capital and natural resources. Table 1 below reports the aggregation of regions, sectors and primary factors used in this application.

Table 4 – Aggregation of sectors, regions and primary factors.

Sectors	Regions	Factors
Fishing *(fsh)*	Ireland	Land
Coal *(coa)*	UK	Unskilled labour
Oil *(oil)*	Rest of Europe	Skilled labour
Gas *(gas)*	North America	Capital
Mining *(omn)*	Rest of the world	Nat. resources
Dairy products *(mil)*		
Other food products *(ofd)*		
Petroleum, coal products *(p_c)*		
Chemical, rubber, plastic products *(crp)*		
Manufacture of non-metallic mineral prod. *(nmm)*		
Manufacture of non-ferrous metals *(nfm)*		
Electronic equipment *(ele)*		
Other machinery and equipment *(ome)*		
Electricity - Hydro *(hydro)*		
Electricity - Wind *(wind)*		
Electricity - Other *(oth_ely)*		
Trade *(trd)*		
Land transport *(otp)*		
Water transport *(wtp)*		
Air transport *(atp)*		
Financial services *(ofi)*		
Insurance *(isr)*		
Business services *(obs)*		
Public admin. and defence, Health, Educ. *(osg)*		
Rest *(Rest)*		

Note: See Chapter 2 of Narayanan and Walmsley (2008) for details on the GTAP database.

To help anticipate the incidence of carbon pricing across sectors, Figures 4a-4c show the respective emissions, emissions intensity and the share of electricity in total costs, as they result from the GTAP database. These emissions correspond to direct use of fossil fuels (primary energy). Emissions generated indirectly through electricity use are not included so that they are not counted twice: they are already imputed to the electricity sector (Figure 4a). Nonetheless, sectors for which electricity is an important factor of production are also vulnerable to carbon pricing to the extent that the latter impacts on electricity prices. Thus, to identify which sectors will suffer greatest increase in production costs through this channel, we show the shares of electricity in total costs (Figure 4c).

Figure 4a – Irish industries' emissions ($MtCO_2$).

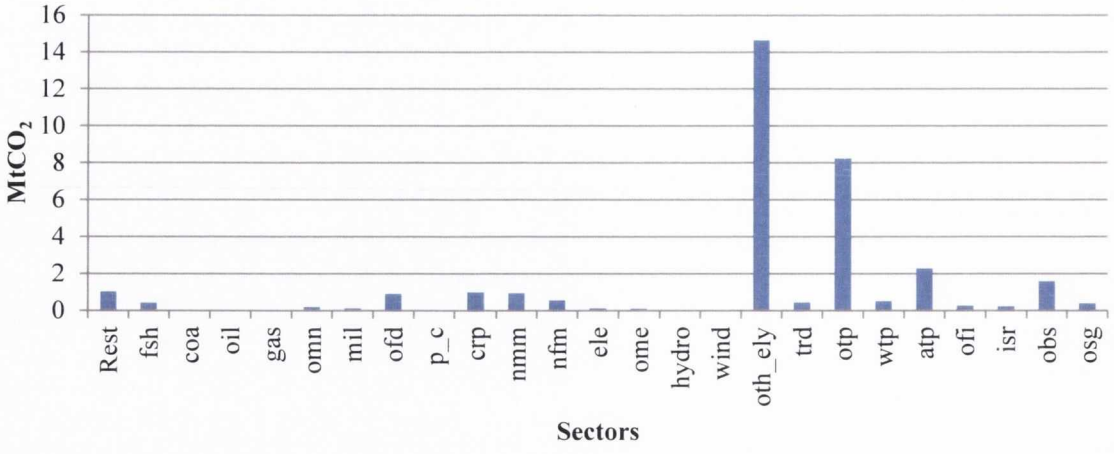


Figure 4b – Irish industries' emissions intensities ($KgCO_2/\$$).

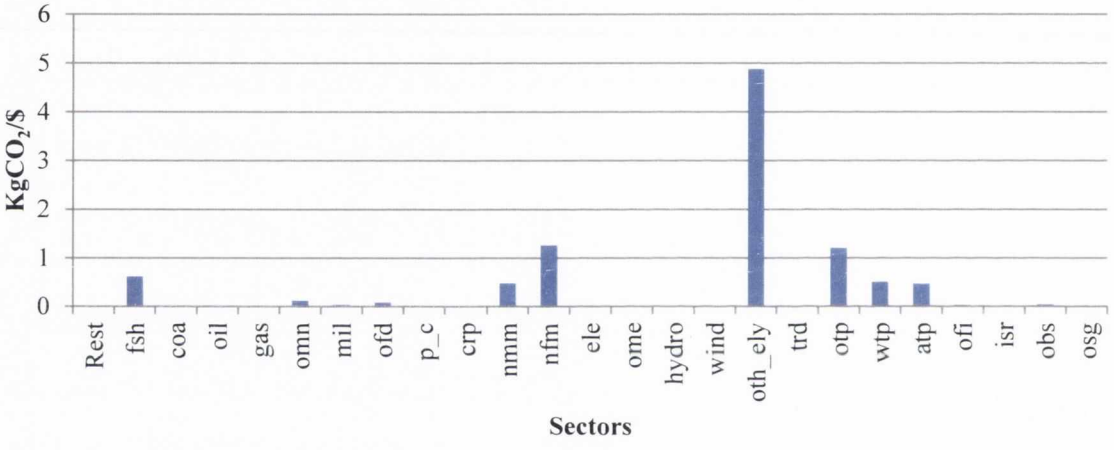
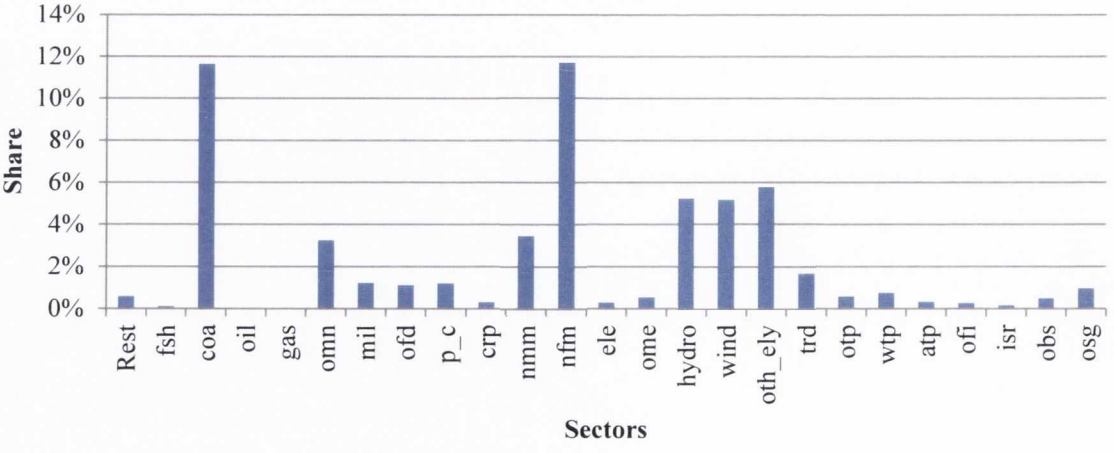


Figure 4c – Share of electricity in total costs of Irish industries (%).



Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *hydro* – Hydro; *wind* – Wind; *oth_ely* – Other electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest*.

Furthermore, the breakdown of Irish firms' and households' total CO_2 emissions ($MtCO_2$), by fuel, is shown in Table 2. Three-fourths of total emissions are generated by firm, one fourth by households.

Table 2 – Emissions by user and fuel ($MtCO_2$).

Fuel (/Sector)	Firms	Households	Total
Coa	6.9	1.7	8.6
Oil	0.0	0.0	0.0
Gas	7.4	1.7	9.1
p_c	19.7	8.2	27.9
Total	33.9	11.6	45.6

Note: "Firms" includes the electricity sector.

4.2 Households

Each region comprises eleven households. The number is the same in all regions only for modeling convenience.[46] For Ireland, they represent the household income deciles and the non-resident household (see Section, 3.2), *HHNR*. For all other regions, the breakdown of the household sector is only fictional, as all households are identical. This choice by no means affects simulation results pertaining to Ireland nor aggregate ones of the other regions. Indeed, if all of a region's households are identical, aggregate results will be the same as if there was only one representative household. This expedient, not used before with GTAP-MH, may be important for future applications of GTAP-MH or G-EMH since no additional information is needed for the regions whose distributional implications are not of interest and which nonetheless the modeler wishes to include in the model.

Uses and sources of income

In order to split Ireland's GTAP data by household income decile, income sources and consumption items of the 2004-2005 Irish Household Budget Survey (HBS) were first mapped to GTAP's factor and commodity classifications. Expenditure and income flows were then disaggregated by decile by applying the respective shares. On the sources side of income, labour income was classified by skill level (skilled vs. unskilled) according to the

[46] In this sense, the model is symmetric. This limitation can be overcome, if needed. It would not require any changes in the theory of the model, but only some tedious coding work.

profession of the head of household.[47] As the model assumes perfect mobility of labour (and capital) across production sectors, there was no need to split labour further by sector. Capital income was determined subtracting total labour income from total earned income, as the difference is largely self-employed and asset income. Rents from land and natural resources were imputed using capital income shares, as the survey contains too little information on those.[48] All sources of income that are not tied to a factor, such as pension payments or household transfers, fall in "net tax transfers", *NetTaxTr*.

In the absence of suitable statistics from national accounts, the amount of capital income allocated to the non-resident household was determined as follows. In the HBS, which only contemplates residents, capital income earned by all households is a third of labour income. Then, assuming labour income in GTAP is earned entirely by residents, a third of that amount is the capital income that can be attributed to those. This meant 26% of capital income was imputed to resident households, while the rest, 74%, went to the non-resident household.[49]

Table 3 reports Ireland's shares of earned income by factor, as found in the GTAP database. Table 4 shows the distribution of earned income, by factor and household, as we derived it based on the HBS.

Table 3 – Earned income by factor.

Factor	Share of earned income (%)
Land	0.6
UnSkLab	25.2
SkLab	18.4
Capital	55.6
NatRes	0.2
Total	100.0

[47] The profession categories in the HBS that were counted as skilled labour are the following: 1) Managers & executives; 2) Business & commerce occupations; 3) Computer software occupations; 4) Scientific & technical occupations; 5) Other professional workers; 6) Professional service & childcare workers; 7) Teachers.

[48] For capital income, what seems to be an inconsistency was found in the GTAP database. According to this, total capital income in Ireland was $59b, in 2004. However, according to the Balance of Payments, that year only foreign income payments amounted to $71b.

[49] One recurring problem with household survey data is underreporting of capital income (e.g., Atkinson *et al.* [1995]). Thus, the allocation of capital income to the non-resident household, in the way described, may potentially be vitiated by this issue. It is the case, however, that the income of the Non-resident household represents 19% of GDP and that the difference between GDP and GNP, what is called "Net factor income from abroad" in National Accounts, for the year in question (2004) amounts to 14% of GDP. Therefore, the discrepancy between the income share allocated to the Non-resident household and the actual one can only be smaller than 5 percentage points because GNP also includes incomes received by Irish residents from abroad.

Table 4 – Distribution of earned income by factor and household (%).

Factor	*HH1*	*HH2*	*HH3*	*HH4*	*HH5*	*HH6*	*HH7*	*HH8*	*HH9*	*HH10*	*HHNR*	Total
Land	0.6	0.4	0.8	1.6	2.2	2.2	3.1	3.3	3.8	7.9	74.0	100.0
UnSkLb	1.1	1.2	2.9	7.0	9.5	13.0	13.9	16.8	17.9	16.7	0.0	100.0
SkLab	0.2	0.3	1.0	2.2	5.6	6.3	11.5	14.2	19.7	38.9	0.0	100.0
Capital	0.6	0.4	0.8	1.6	2.2	2.2	3.1	3.3	3.8	7.9	74.0	100.0
NatRes	0.6	0.4	0.8	1.6	2.2	2.2	3.1	3.3	3.8	7.9	74.0	100.0

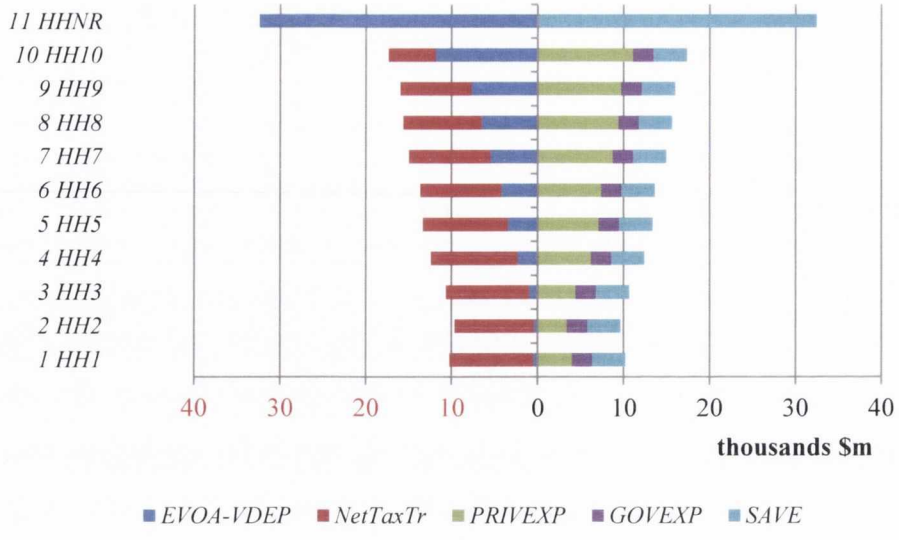
Table 5, instead, shows the breakdown of GDP by household and source. These shares indicate the relative importance of different income sources across households. For example, a given increase in the return to capital income is for the richest decile almost twice as important as for the ninth decile, and nine times as important as for the first decile. By the same token, a given change in net tax transfers (i.e., non-factor income) is for the first decile almost three times as important as for the tenth decile. These proportions are important to get a sense of the likely impact of any given policy on income distribution.

Table 5 – Distribution of income sources (GDP) by household (%).

Source	*HH1*	*HH2*	*HH3*	*HH4*	*HH5*	*HH6*	*HH7*	*HH8*	*HH9*	*HH10*	*HHNR*
NetTaxTr	0.95	0.95	0.90	0.81	0.74	0.69	0.63	0.58	0.52	0.32	0.00
Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UnSkLab	0.02	0.02	0.05	0.11	0.13	0.18	0.17	0.20	0.21	0.18	0.00
SkLab	0.00	0.00	0.01	0.02	0.06	0.06	0.10	0.12	0.17	0.30	0.00
Capital	0.03	0.03	0.05	0.08	0.10	0.10	0.12	0.13	0.14	0.27	1.00
NatRes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

On the uses side of income, as the HBS does not specify the origin of purchased items, it was assumed that if, say, the sixth decile counts for 12% of total household demand for dairy products, that same share applies to both imported and domestically produced dairy products. Government spending and savings were distributed to households in equal amounts (though, as previously mentioned, it was verified that the distribution of *GOVEXP* and *SAVE* does not impact significantly on simulation results).

Figure 5 – Income distribution (GDP), sources and uses.



The approach was different, however, for the non-resident household, *HHNR*. Savings were determined by setting them equal to capital income, and fractions (0.01%) of private and government expenditures were conceded to make the model computationally solvable.[50] The resulting breakdown of Ireland's sources and uses of income, in the form of [1], is reproduced in Figure 5.

4.3 Household demand (CDE expenditure function) and labour supply

In the GTAP model, the Constant Difference of Elasticities (CDE) function (Hanoch [1975]), which has the desirable property of being non-homothetic (i.e., budget shares vary with income levels), governs household demand. Two sets of parameters fully identify the CDE which are called expansion and substitution parameters. All income and price elasticities are complex functions of these parameters and expenditure shares (Hertel [1997]). As with all other model parameters, the GTAP database provides values for the CDE parameters and, thus, implicitly for all demand elasticities. These elasticities, borrowed from applied demand studies, only vary across sets of regions and not individually by region (e.g., EU countries, other OECD countries, etc.). Thus, if the modeler thinks she is in possession of more accurate elasticities than those provided by GTAP, and would rather use those, she will first need to recalibrate the CDE function to

[50] The algorithm does not converge to a solution (i.e., a new equilibrium of the economy is not found) if one or more vectors have only zeros.

her new elasticities.[51] The impact of carbon pricing on households, and on the economy as a whole, partly depends on the responsiveness of the former to price and income changes, and especially on the responsiveness of demands for energy commodities. We have thus estimated own price and income elasticities of Irish households' demands for electricity, coal, gas and petrol, by income decile, in order to recalibrate the CDE function for each representative household.

Micro-data from Ireland's 1987-8, 1994-5, 1999-0 and 2004-5 HBSs were used to estimate the said elasticities. Simple linear regression models (single equations), with time and demographic controls, were fitted for electricity and petrol demands.[52] Given the large number of zeros in the dataset, Tobit models with the same explanatory variables were deployed for coal and gas. All price and income elasticities were evaluated at decile mean values. The CDE function was then recalibrated, separately for each household, to these "target" elasticities of energy commodities and to those found in the GTAP database for the other goods in the model. Different sets of expansion and substitution parameters, identifying the CDE, were thus derived for each representative household.

The prescriptions found in Hertel (1997) for calibration of the CDE function were followed. Only, as our target income elasticities for coal are negative – it turned out to be an inferior good – we relaxed the constraint on its expansion parameter by letting it take negative values.[53] All the other constraints imposed at the stage of calibration guarantee that both the Engel and Cournot aggregation conditions are met. Hence, each household's demand system is theoretically consistent. However, while for electricity, coal, gas and petrol, it is the case that income elasticities get larger with income (as expenditure shares get smaller), the same sort of consistency across households is not guaranteed for the other goods. To achieve that, one would have needed target elasticities by decile for all of the goods in the model.

Table 6 shows for each of the four energy commodities, both the target elasticities and those obtained after calibration.[54] Price elasticities look particularly small, especially

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[51] A second nice property of the CDE is that own-price elasticities, income elasticities and budget shares are sufficient to determine all cross-price elasticities. Therefore, to recalibrate the CDE to new elasticities, one does not need estimates of cross-price elasticities.

[52] Unit values (i.e. expenditure divided by quantity) were used as prices. Only for petrol, the specific CPI was used, as information about quantities was not available.

[53] That constraint guarantees a unique global optimum exists, but it is not a necessary condition. Indeed, there may be an optimum even if not all of the expansion parameters are non-negative. Given the object of this study, it is preferable that coal remain an inferior good after calibration (and, hence, in simulations). Budget shares of coal are very limited anyway.

[54] All households' own price and income elasticities as well as the relative expenditure shares are found in the Appendix (Tables A2-A4).

those of electricity and coal. They are significantly smaller than average values found in the international literature.[55] In Section 7, devoted to sensitivity analysis, we take account of this and assess its implications for simulation results by re-running all the scenarios under greater responsiveness of household demand for energy commodities.

Table 6 – Elasticities of energy commodities, before and after calibration of the CDE function.

	Electricity				**Coal**			
	Target		*After calibration*		*Target*		*After calibration*	
	Price	*Income*	*Price*	*Income*	*Price*	*Income*	*Price*	*Income*
HH1	-0.02	0.09	-0.03	0.15	-0.00	-0.05	-0.01	-0.04
HH2	-0.01	0.10	-0.03	0.16	-0.00	-0.06	-0.01	-0.05
HH3	-0.01	0.13	-0.03	0.16	-0.00	-0.08	-0.01	-0.08
HH4	-0.02	0.16	-0.03	0.18	-0.00	-0.12	-0.01	-0.12
HH5	-0.01	0.19	-0.03	0.21	-0.00	-0.15	-0.01	-0.15
HH6	-0.01	0.22	-0.03	0.23	-0.00	-0.19	-0.01	-0.20
HH7	-0.01	0.25	-0.02	0.26	-0.00	-0.22	-0.01	-0.21
HH8	-0.01	0.28	-0.02	0.28	-0.02	-0.25	-0.02	-0.25
HH9	-0.01	0.32	-0.02	0.32	-0.00	-0.28	-0.01	-0.26
HH10	-0.01	0.42	-0.02	0.44	-0.03	-0.46	-0.04	-0.53
HHNR	-0.01	0.22	-0.02	0.23	-0.01	-0.19	-0.01	-0.18
	Gas				**Petrol**			
	Target		*After calibration*		*Target*		*After calibration*	
	Price	*Income*	*Price*	*Income*	*Price*	*Income*	*Price*	*Income*
HH1	-0.16	0.14	-0.09	0.22	-0.28	0.13	-0.20	0.30
HH2	-0.16	0.18	-0.12	0.23	-0.28	0.16	-0.23	0.31
HH3	-0.12	0.22	-0.12	0.22	-0.27	0.19	-0.24	0.31
HH4	-0.15	0.26	-0.14	0.25	-0.24	0.23	-0.22	0.30
HH5	-0.10	0.27	-0.10	0.27	-0.22	0.27	-0.21	0.32
HH6	-0.11	0.33	-0.11	0.33	-0.22	0.30	-0.21	0.35
HH7	-0.08	0.36	-0.10	0.36	-0.21	0.33	-0.19	0.36
HH8	-0.09	0.42	-0.09	0.42	-0.20	0.37	-0.20	0.38
HH9	-0.11	0.48	-0.11	0.48	-0.20	0.41	-0.20	0.42
HH10	-0.10	0.62	-0.10	0.65	-0.17	0.51	-0.16	0.52
HHNR	-0.12	0.33	-0.12	0.33	-0.23	0.29	-0.23	0.31

Note: For the Non-resident household, averages of target elasticities were used.

Finally, the model allows for endogenous labour supply in the way illustrated in Section 3.2 above. This is done primarily to take into account Ireland's exceptionally high elasticity of labour supply, which is primarily due to migration. In particular, Bergin and Kearney (2007) estimate the elasticity of labour supply to real wages to be about 1.7 for

[55] The lack of price variability in the data that have been used partly explains this outcome. Each wave of the HBS spans 15 months, a lapse of time over which prices of electricity and coal generally vary very little. Using more waves of the HBS helps little in this case because time controls tend to capture most variability in the dependent variable. Indeed, no studies exist that use the HBS to estimate price elasticities despite the fact that quantities are reported (and, hence, unit values can be derived) for electricity, gas and coal.

Ireland, once migration is factored in. We thus used that figure. For the other regions, we used the following values, which are taken from Sandrey *et al.* (2007): 0.1, 0.05 and 0.08, for EU27, U.S. and Rest of the World, respectively.[56]

5. Model closure and simulation scenarios

In CGE jargon, "model closure" refers to the choice of which variables are endogenous and which (all the others) are exogenous. As the word suggests, the first are endogenously determined, while the variables of the second group are given. For the closure to be valid, the number of endogenous variables must be equal to the number of equations and, also, the exogenous variables must be independent (i.e., not linked by equations). The one or more variables that represent the policy reform or, more generally, any "shock" to the system, must be exogenous and the values they are given represent the magnitude of the shock. All the other exogenous variables remain unchanged. Of course, as the system of equations is meant to represent an economic system, the model closure should reflect economic reasoning.

In the standard general equilibrium closure of the GTAP model, prices, quantities of commodities (not primary factors) and regional incomes are endogenous variables, while policy variables, technical change variables and population are exogenous to the model. G-EMH deviates from such setting only in that supplied quantities of skilled and unskilled labour are endogenous too (as per equations [4] to [6] above). Table 7, at the end of this section, reports the full closure.

All the five simulated scenarios have in common the policy shock of a \$20/tCO_2 carbon tax (2004\$) introduced in Ireland and made to apply to all CO_2 emissions, with no exemptions for any fuel or sector.[57] What differentiates the scenarios one from another is the use of the carbon tax yield. In the first scenario, this is recycled back to households through transfer payments. By contrast, the other four scenarios counterbalance carbon taxation with a cut in another tax. In particular, the four considered tax breaks regard, in the order: *a)* final consumption, *b)* the use of labour, *c)* labour income, and *d)* capital

[56] Considering its important role in the mechanics of the model, the elasticity of labour supply too is object of sensitivity analysis (Section 7).

[57] In practical terms, the levy of the \$20/tCO_2 tax is simulated by shocking the variable *NCTAX* (nominal carbon tax rate), only for Ireland, by 73.3. This is because, in GTAP-E, the carbon tax rate is measured in dollars per ton of carbon (tC) and, since the conversion factor CO_2/C is 3.67, \$20/tCO_2 corresponds to \$73.3/tC.

income. The simulation of the last four schemes is implemented with simple changes to the model closure. The practice is called closure swap and in this case it consists in fixing the ratio of total fiscal revenues to GDP, so as to ensure revenue neutrality, and letting the given tax rate be endogenously determined.

The details on motivation, expected effects and implementation of the scenarios are given below.

Household transfers, *"TRANSF"*

In the first scenario, it is assumed that the yield of the carbon tax is redistributed across households via transfer payments, as mimicked by the *NetTaxTrSh* shares (Section 3.2).[58] The scheme is not revenue neutral in the sense that the ratio of total fiscal revenues to GDP can vary after the carbon levy is introduced. As poor households rely on transfer income relatively more than rich ones,[59] this scheme is expected to mitigate the regressive impact of the tax (due to energy related price increases) if the share of taxes in GDP (i.e., the share of income that is redistributed) rises; *vice versa*, it will exacerbate regressiveness. The first outcome is deemed more likely because the carbon tax is not accompanied by measures that favour growth.

Private consumption, *"VAT"*

The combination of the carbon tax and a cut in the tax on private consumption penalizes the demand for CO_2-related energy and, at the same time, favours generic consumption. Considering *a)* that domestic industries benefit from the boost of consumption, *b)* that households are incentivized to substitute non-energy commodities for energy commodities, and *c)* that fossil fuels are largely imported whereas renewables are domestically produced, it is conceivable that this environmental reform have a positive impact on the economy. Moreover, on the supply side, to the extent that real wages fall, labour supply will expand with further beneficial effects. As to the distributional effects, this policy, which may be assimilated to a cut in the VAT rate, certainly mitigates the impact of carbon pricing on the cost of living. However, since energy commodities remain relatively more expensive than other goods, the distributional impact may still result regressive.

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[58] Since the government and private households decisions are not separated in GTAP (more detailed data on intra-institutional transactions would be needed), there is an implied transfer between government and households. In GTAP-MH, and G-EMH, the allocation of this transfer across households is governed by the *NetTaxTrSh* shares.

[59] Recall Table 5 and the made remark that a given change in net tax transfers (i.e., non-factor income) is for the first decile almost three times as important as for the tenth decile (0.95 vs. 0.32).

Revenue neutrality of the tax replacement is assured by fixing each household's tax revenue-to-income ratio. In practical terms, a variable that sums the changes in each household's own share of tax revenues in income, *del_totaltaxr*,[60] was created and then swapped with (the percentage change in) the power of the tax on private consumption, *tp*.[61] The latter is thus determined endogenously, with the former set to 0. A drop in the tax on private consumption implies *tp* is negative.

There follows an intuitive explanation of how carbon taxation is modeled in GTAP-E and of how, in this specific case, the VAT swap works. In GTAP-E, fuel expenditures are valued using three different prices: P_1, the market price; P_2, which includes indirect taxes; P_3, which includes both indirect taxes and the carbon tax. For example, associated with quantity Q_r^h of, say, imported coal consumed by household h in region r, are the following expenditure values:

$$Q_r^h \times P_{1r} = VIPM_r^h$$
$$Q_r^h \times P_{2r} = VIPANC_r^h$$
$$Q_r^h \times P_{3r} = VIPA_r^h$$

where *VIPM*, *VIPANC* and *VIPA* stand for Value of Private Imports, at Market prices, Agents' prices Net of Carbon, and Agents' prices (i.e. final prices), respectively.

The percentage changes (small letters) in the three prices are:

$$p_{1r} = pm_r$$
$$p_{2r} = pm_r + tpm_r + tp_r$$
$$p_{3r} = (pm_r + tpm_r + tp_r)\frac{VIPANC_r^h}{VIPA_r^h} + \left(\frac{CO2DP \times NCTAX}{VIPA_r^h}\right)\% \qquad [7]$$

where *tpm* is the percentage change in the power of the tax on private consumption of imports; *NCTAX* is the change in the carbon tax rate ($/tC), and *CO2DP/VIPA* is the emissions intensity of private consumption of imports (tC/$);

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[60] $del_totaltaxr_r = \sum_h del_ttaxr_r^h$, where $del_ttaxr_r^h = d(T_r^h/Y_r^h)$ and $T_r^h = NetTaxTrSh_r^h \times T_r$.

[61] The power of a proportional tax, T, is $1+T$. In GTAP, the percentage change in the after-tax price, P ($\equiv PM(1+T)$), is thus decomposed as the sum of the percentage change in the pre-tax price, *pm*, and that of the power of the tax, *tp*: $p = pm + tp$. In this case, T is the VAT rate and *tp* the percentage change in the power of VAT.

The difference between *tp* and *tpm* is that the first tax applies to private consumption without distinction, while the second applies only to imports. Furthermore, it is clear from the third equation in [7] that carbon taxation and what for convenience we call the VAT cut exert opposite pressure on the final price, P_3. However, the effect of the carbon tax on fuel prices will dominate, as the VAT revenue is spread over a much wider base (i.e., all goods and services, and not only fossil fuels).

Cost of labour, *"LABFACT"*

A uniform cut in the tax on the use of labour reduces its cost as production factor (equally across sectors and labour types, i.e. skilled and unskilled). While it will not be sufficient to fully compensate energy intensive industries for the extra costs of the carbon tax, labour intensive sectors may get a net benefit. Part of the reduction in labour cost, however, should be offset by the likely reduction in labour supply, which would follow the upward pressure on real wages due to higher energy prices. For this reason, a double dividend seems possible but not very likely. Furthermore, as being a measure that favours labour employment, households who earn greater shares of their income from labour should benefit relatively more than others.

The strategy to assure revenue neutrality is similar to that of the previous scenario: *del_totaltaxr* is swapped with the percentage change in the power of the tax on the use of labour, *tl*. The latter – a "shift variable" – had to be added, as the original equation for the price of labour did not allow for a tax rate that is homogenous across sectors and labour types. The percentage change in the full price of labour *e*, employed by sector *j* in *r*, thus becomes:

$$pfe_{ejr} = pm_{er} + tf_{ejr} + tl_r \qquad [8]$$

where *pm* is the percentage change in the market price of labour *e*, and *tf* is the percentage change in the power of the tax specifically on labour *e*, used by *j*, in *r*.

A cut in the tax on the use of labour implies *tl* is negative.

Labour income, *"LABINC"*

A reduction in the tax of labour income (both skilled and unskilled) pushes nominal wages up and possibly, should it more than offset the upward pressure on consumer prices, real

wages too. If so, then labour supply will expand. That, in turn, would imply cheaper labour for firms with ensuing positive effects on the economy. Whether such mechanism can be sufficient to deliver a double dividend is, again, difficult to guess before running the simulation. For certain, the very high elasticity of labour supply that has been assumed for Ireland (1.7) makes the achievement of a double dividend all the more likely.

Revenue neutrality is assured by swapping *del_totaltaxr* with the percentage change in the power of the tax on labour income, *tll* (this shift variable had to be added too). Because gross labour income is valued at factors' market prices (i.e., prices paid by employers) and net labour income is valued at (lower) supply prices, a cut in the tax on labour income implies that the second gets higher (i.e., the wedge between the two gets smaller). The equation for the percentage change in the supply price of labour *e*, owned by *h* in *r*, is the following:

$$pse_{er}^{h} = pm_{er} + toe_{er}^{h} + tll_{r} \qquad [9]$$

where *toe* is the percentage change in the power of the tax on factor *e*, supplied by *h*, in *r*.

A cut in the tax on earned income implies that *tll* is, this time, positive.

Capital income, *"CAPINC"*

Finally, in the fifth scenario carbon taxation is coupled with a cut in the tax on capital income.[62] In this case, the channel through which economic growth is favoured is domestic and international investment. A cut in the tax on capital income has the effect of raising the return on capital and it thus attracts domestic and foreign savings. One model parameter, *RORFLEX*, measuring the sensitivity of capital movements to differentials in regional returns to capital, is central to this scenario and the relative outcome. In this case too, households who rely on capital income relatively more than others will get proportionally greater benefits from this specific tax recycling scheme.

The implementation strategy is the same as for the cut in the tax on labour income. First, a shift variable, *tk*, is added to the equation for the supply price of capital,

$$pse_{r}^{h} = pm_{r} + toe_{r}^{h} + tk_{r} ,$$

[62] Capital tax recycling is not often encountered in the double dividend literature, but the global GTAP model is well suited to perform this type of scenario.

then, the same *tk*, the percentage change in the power of the tax on capital income, is swapped with *del_totaltaxr*. As before, a drop in the tax on capital income implies *tk* is positive.

Table 7 – Model closure and tax swaps.

Exogenous variables	
pop	Population
ams atm atf ats atd aosec aoreg afcom afsec afreg afall aoall atall	Technical change variables
to tp tm tms tx txs tf tfd tfm tgd tgm tpd tpm toe te tl tll tk	Policy variables
qoe(ENDWNL_COMM,hhlds,REG)	Supply of non-labour endowments
pfactwld	World price of endowments - Numeraire
tradslack endwslack cgdslack profitslack incomeslack psaveslack	Slack variables
au dppriv dpgov dpsave	Distribution parameters
NCTAXB pemp	Carbon tax rate; power of emissions purchases (for emissions trading)
All other variables endogenous	

Scenario	**Swap** exogenized var. = endogenized var.
VAT	*del_totaltaxr("IRL") = tp("IRL")*
LABFACT	*del_totaltaxr("IRL") = tl("IRL")*
LABINC	*del_totaltaxr("IRL") = tll("IRL")*
CAPINC	*del_totaltaxr("IRL") = tk("IRL")*

6. Simulation results

This section presents the results, for Ireland, of the five scenarios just described. Given the sizeable amount of output, the analysis focuses on a few variables of interest. In the first part, emissions abatement and macroeconomic effects are examined together. In the second part, we turn our attention to the effects on income distribution. The sensitivity of the results to variations in a few selected parameters of the model is assessed in the following section. The effects of carbon taxation on the different sectors of the Irish economy and, also, specifically on their exports, are reported in the Appendix.

6.1 Emissions abatement and macroeconomic effects

For ease of exposition, unless differently specified all the results mentioned and discussed in this paragraph are found in Table 8, below.

The simulated $20/tCO2 tax proves to be environmentally effective, as the fall in CO_2 emissions ranges, across the five scenarios, from 10.7% to 11.1%.[63] Accordingly, the yield of the carbon tax, which is negatively related to emissions abatement (as emissions themselves constitute the tax base), ranges from $809m to $812m. This makes around 0.9% of all tax revenues, which is not a negligible share. The general equilibrium elasticity of emissions with respect to the carbon tax rate, that is, the elasticity derived by comparing emissions and carbon tax levels before and after the policy shock, is only -0.08.[64] Thus, if the tax is environmentally effective, its level is quite high too.

Table 8 - Macroeconomic effects and emissions abatement.

	Scenarios				
Variables (% change if not differently specified)	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Real GDP	-0.42	0.03	-0.14	0.01	-0.29
Nominal GDP	-0.06	-0.16	0.13	0.27	0.10
GPD deflator	0.36	-0.19	0.27	0.25	0.39
Gini coefficient	-0.67	0.15	0.18	0.20	0.13
CO2 Emissions	-10.93	-10.77	-10.87	-10.79	-10.92
CO2 Emissions/Real GDP	-10.56	-10.79	-10.75	-10.80	-10.67
Carbon tax revenue, ($m)	811.1	812.6	811.6	812.4	811.2
Employment, unskilled	-0.56	0.42	0.10	0.43	-0.51
Employment, skilled	-0.45	0.46	0.19	0.54	-0.44
Nominal wage, unskilled	0.26	-0.31	0.59	0.78	0.31
Nominal wage, skilled	0.29	-0.33	0.61	0.80	0.30
Investment	-1.37	-0.81	-1.02	-0.86	0.71
Current return on capital	-0.96	-0.57	-0.71	-0.60	0.50
Exports' volume	-0.32	-0.09	-0.13	-0.15	-0.45
Trade balance, change ($m)	210.8	37.1	224.2	32.8	-212.3
Imports value, change ($m)	-387.8	-99.3	-152.4	-169.6	-554.7
Exports value, change ($m)	-598.7	-136.4	-376.6	-202.4	-342.4

Note: In the calculation of the Gini coefficient, the Non-resident household has been excluded. That makes the coefficient a better measure of income dispersion over the resident population.

In the first scenario, *TRANSF*, the impact of the carbon tax on real GDP is negative, as expected, and amounts to -0.42%. The deterioration of international competitiveness, as reflected by the fall in exports (-0.32%), explains this result. By contrast, two of the other four schemes, *VAT* and *LABINC*, suggest that a double dividend – lower emissions and greater economic growth – can be achieved. The impacts on GDP, respectively 0.03% and

[63] The breakdown of emissions abatement by fuel type, and for different elasticities of household demand for energy commodities, is found in the Appendix (Tables A5-A5b).
[64] This elasticity was derived by comparing the emissions achieved by setting the carbon tax rate to $20 and $20.2/tCO2.

0.01%, are only very small. However, given some degree of uncertainty (unavoidable) around the model parameters, it is not so important whether punctual (deterministic) results are positive or negative, as whether they lie close to the region of positive values and how sensitive they are to the parameters' values. The two scenarios are different "in spirit", as lower taxes on consumption and on labour income are meant to operate on the demand and supply side of the economy, respectively. Yet, a fundamental mechanism in determining the outcome of the *VAT* scenario is through the labour market: real wages fall by almost as much as under *LABINC* and, thus, labour supply expands too. The sum of these two effects, cheaper consumption and cheaper labour, explains why the *VAT* scheme delivers the best GDP result. Clearly, the made assumption about the elasticity of labour supply – high and constant – is critical for both scenarios and ultimately for the achievement of a double dividend.

The impacts on GDP under the two remaining scenarios, *LABFACT* and *CAPINC*, are -0.14% and -0.29%, respectively. In the first case, the reduction in labour taxes paid by employers at least partially compensates the increase in production costs (the volume of exports only falls by 0.13%) and, in particular, it favours labour intensive industries.[65] In addition, the tax cut makes labour cheaper relative to the other factors of production. As a result of both these effects, the demand for labour expands. Nevertheless, the mechanism is evidently not sufficient to prevail over the carbon tax and induce positive growth. Still, it turns out to be preferable to a cut in the tax on capital income. Under *CAPINC*, the rate of return on capital improves and attracts new investment (0.71%), but this really is the only positive effect.[66] Irish firms are not supported, directly (as in *LABFACT*) or indirectly (as in *VAT* or *LABINC*), with measures that compensate for the burden of carbon taxation. International competitiveness deteriorates as a result, as shown by the 0.45% fall in the volume of exports – the biggest among the five scenarios.[67]

The percentage variation in the Gini coefficient measures the impact on income distribution. In levels, the coefficient ranges between 0 and 1, the two values representing perfect equality and concentration, respectively. Therefore, a negative variation denotes a move towards a more even distribution, and *vice versa* for a positive one. As here the Gini coefficient refers to the distribution of nominal GNP (spread across resident households as

[65] This is consistent with observed sectoral effects. See Tables A7-A8, in the Appendix.
[66] Investment drops in all the other scenarios due to a fall in the rate of return on capital.
[67] In the first four scenarios, while the volume of exports falls, the trade balance improves.

per equation [1])[68] and not, more accurately, of household income, sign and magnitude of the variation, rather than the level of the coefficient, is what we look at. It is apparent that only in one case, under *TRANSF*, the distribution of income across households becomes more even (-0.67%). The reason for such outcome is that the carbon tax yield adds to the resources redistributed through welfare payments and poor households, relatively more than others, rely on non-factor income. In all other scenarios, the change in the Gini coefficient is positive but significantly smaller too. The impact is modest because the same redistribution mechanism is accompanied by tax breaks that favour either labour or capital income, both of which are supplied in greater proportion by households who are not at the bottom of the distribution. In any case, the Gini coefficient is a single number and, above all, it measures the impact on the distribution of nominal income, while we know carbon pricing affects the cost of living in the first place. In the next paragraph, we examine the effects over the whole income distribution and implicitly take account of differences in household consumption patterns.

6.2 Distributional effects

It has been stressed throughout in this paper that, in the medium or longer term, carbon pricing impacts on households both through the sources and the uses of income. The first channel relates to the change in income following variations in returns to primary factors and their employment. The ownership of factors matters in this respect. The second channel amounts to the change in consumer prices (i.e., the cost of living). In this case, it is the composition – the pattern – of consumption that determines the magnitude of the effect. The two channels are not disjoint, though, because households supply labour in function of the real wage, which in turn depends on consumer prices. In the model used in this paper, each household has its own price index. Therefore, the same households who suffer bigger increases in product prices will also reduce (increase) supply labour more (less) than others whose consumption is less CO_2 intensive.

[68] See the footnote of Table 8.

Figure 6 – Effects on nominal income.

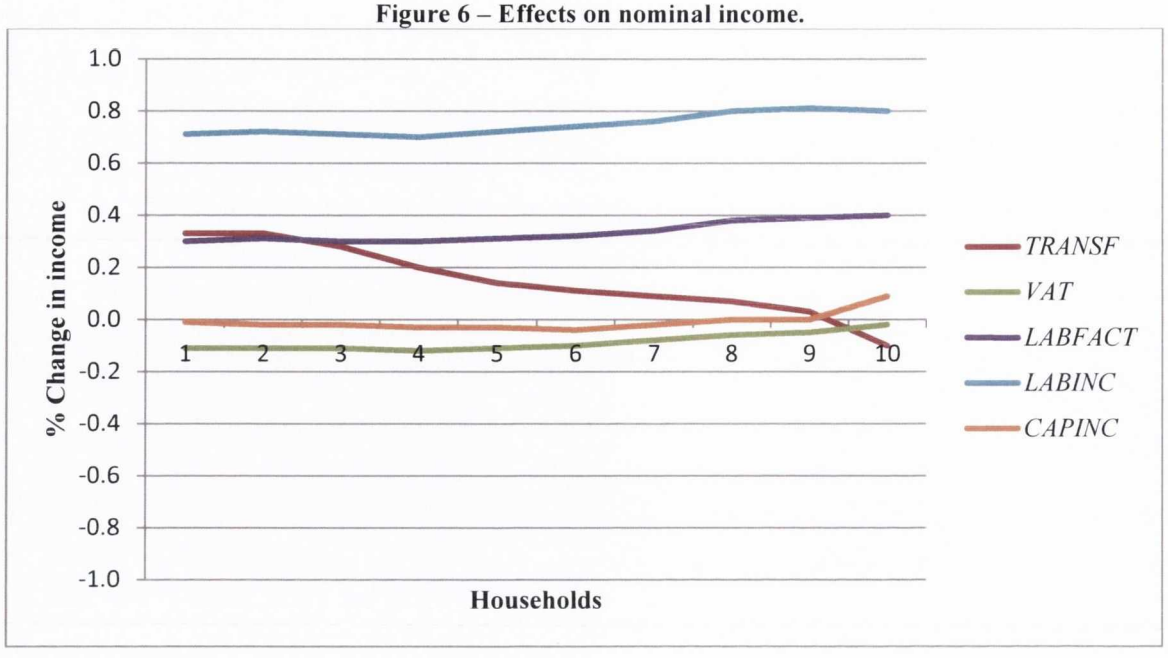


Table 9 – Effects on nominal income, % changes (Figure 6).

	Scenarios					
Household	*TRANSF*	*DEBT*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
HH1	0.33	-0.68	-0.11	0.30	0.71	-0.01
HH2	0.33	-0.68	-0.11	0.31	0.72	-0.02
HH3	0.28	-0.68	-0.11	0.30	0.71	-0.02
HH4	0.20	-0.69	-0.12	0.30	0.70	-0.03
HH5	0.14	-0.68	-0.11	0.31	0.72	-0.03
HH6	0.11	-0.68	-0.10	0.32	0.74	-0.04
HH7	0.09	-0.65	-0.08	0.34	0.76	-0.02
HH8	0.07	-0.63	-0.06	0.38	0.80	0.00
HH9	0.03	-0.62	-0.05	0.39	0.81	0.00
HH10	-0.10	-0.58	-0.02	0.40	0.80	0.09
HHNR	-0.96	-0.90	-0.57	-0.71	-0.60	0.55

Figure 6 shows, for each of the five scenarios, the percentage change in household income across the deciles.[69] The percentage change in nominal GDP, in Table 8, is the weighted average of these percentage variations. A positively inclined curve indicates that the reform is regressive, since the increase (decrease) in richer households' income is proportionally greater (smaller) than that of the less well-off; *vice versa*, a line that has a negative gradient indicates that the reform is progressive, as the increase (decrease) in richer households' income is proportionally smaller (greater) than that of the less well-off. Effectively, the figures of nominal GDP and Gini coefficient, in Table 8, summarize with single statistics position and slope, respectively, of these curves. Thus, nothing that we see in this graph should surprise us. Yet, if contrasted with the analogue in Figure 7, it is

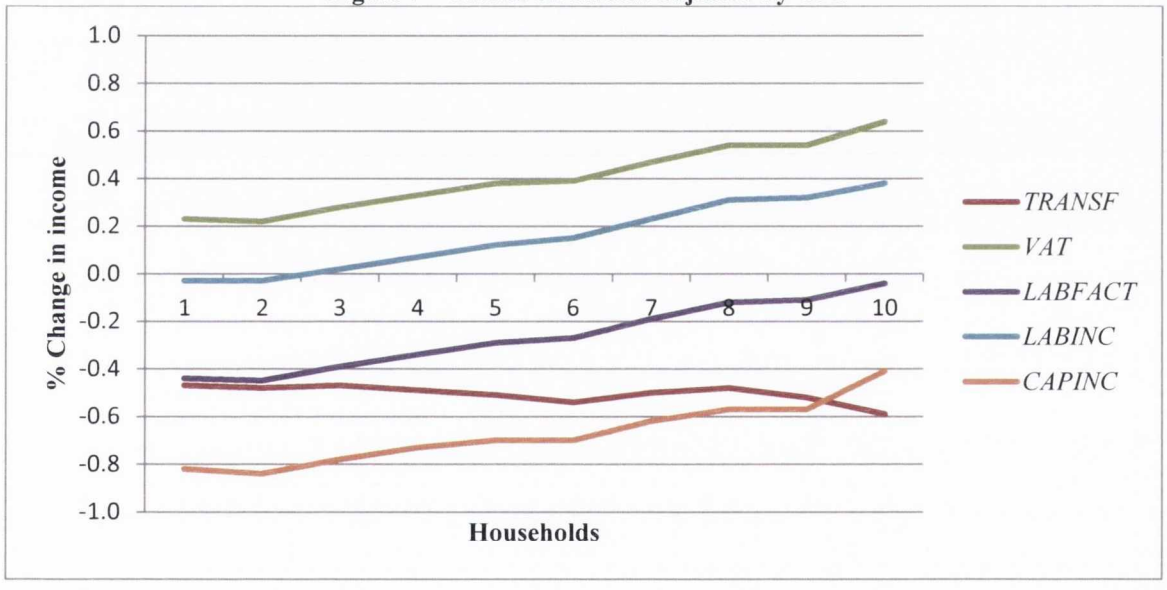
[69] The Non-resident household is not in the graph because we want to focus on household income distribution.

immediately apparent that the whole picture is modified once differences in consumer prices (Table 10), across households and scenarios, are factored in.

Table 10 – Consumer price index by income decile, % changes.

	Scenarios					
Household	*TRANSF*	*DEBT*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
HH1	0.80	-0.34	0.75	0.74	0.82	0.80
HH2	0.81	-0.33	0.76	0.75	0.83	0.81
HH3	0.75	-0.39	0.70	0.69	0.77	0.75
HH4	0.69	-0.45	0.64	0.63	0.71	0.69
HH5	0.66	-0.49	0.60	0.59	0.67	0.66
HH6	0.65	-0.50	0.59	0.58	0.67	0.65
HH7	0.59	-0.55	0.53	0.53	0.61	0.59
HH8	0.55	-0.59	0.50	0.49	0.57	0.55
HH9	0.55	-0.59	0.50	0.49	0.57	0.55
HH10	0.49	-0.65	0.43	0.43	0.51	0.49

Figure 7 – Effects on income adjusted by CPI.



The Irish HBS and household surveys allow depicting consumption patterns in good detail. The derived consumer price indices by income decile, shown in Table 10, can then be regarded with justified confidence. With a carbon tax, poor households face higher prices than rich ones, because their consumption bundles are substantially more carbon intensive (Verde and Tol [2009]).[70] As a result, all the five curves rotate upwards. In other terms, the incidence of carbon taxation becomes more regressive when the impact on

[70] As money or monetary policy are not contemplated in CGE models, increases in prices are real increases relative to inflation.

consumer prices is taken into account. At the same time, the position (height) of the curves changes too, reflecting the difference between nominal and real variations of income.

Two important conclusions are drawn on the basis of this evidence. First, the answer to our research question as to whether carbon pricing (without revenue recycling) is regressive in the medium or longer term is "yes". Indeed, only if the proceeds of carbon pricing are redistributed to households through the existing welfare system – only in this case – the overall impact on real incomes is (virtually) neutral on income distribution.[71] Otherwise, the impact can only be regressive.[72] However – this is the second remark – pairing the carbon tax with a lower tax rate on private consumption makes all households better off. This result is represented, in Figure 7, by the *VAT* curve which lies in its entirety above all the others. Therefore, assuming a Utilitarian or even a Rawlsian type of social welfare function, whereby it is the utility of the poorest household that matters, this turns out to be the most preferable scheme.

7. Sensitivity analysis

The results presented in the previous section are conditional on the structure of the model and its parameters, but presumably are more sensitive to certain features and parameters than to others. It is customary to examine the sensitivity of the results – and hence the robustness of the conclusions – to the variation in one or more parameters deemed to be critical.

We have identified five elasticities on which our results may critically depend and conducted sensitivity analysis. In particular, we have analyzed the sensitivity of the results for real GDP and, when of interest, for the Gini coefficient and emissions, to the following parameters: *a)* elasticity of labour supply, *b)* elasticities of household demand for energy commodities, *c)* elasticities of substitution in the production structure, *d)* elasticities of substitution between domestic products and imports, as well as between different imports sources (so called Armington elasticities) and, *e)* the elasticity of capital movements to differentials in regional returns on capital.

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[71] The same conclusion is drawn by Rausch *et al.* (2001b) – arguably, the state of the art in this area – who simulate a $20 carbon tax on all greenhouse gases (not only carbon dioxide), in the U.S.. Even the magnitude of the impacts is remarkably similar, as it ranges across households from 0.61% to 0.68% of total income.

[72] Unless, of course, the yield of the carbon tax was used to finance a new, more progressive, programme of household transfers.

The software we used to implement and solve the model, GEMPACK, includes a particularly useful tool called Systematic Sensitivity Analysis (SSA). Once the simulation has terminated, the user selects one or more parameters, sets their range of variation (around the current values) and chooses a statistical distribution (triangular or uniform); then, SSA solves the model a number of times, each time giving the parameters in question values drawn from the distribution chosen in previous step. For each endogenous variable, mean and standard deviation are derived based on the results from the performed iterations. The magnitude of the standard deviation measures the sensitivity of the variable of interest to the given parameter(s).

For conducting our sensitivity analysis, in most cases we have used SSA, in the way just described. The results are reported below.

Elasticity of labour supply

Labour supply plays a central role both in the *VAT* and the *LABINC* scenarios, in which real wages are pushed up by lower prices, in the first case, and by lower taxes on labour income, in the second. These two are the only schemes that bring about a double dividend, if a very small one (0.03% and 0.01%, respectively). We thus use SSA and derive the standard deviations of the results for real GDP and Gini coefficient, assuming a uniform distribution for the elasticity in question and letting it vary by 60% around the original value (1.7, for Ireland). The results, expressed in percentage points (p.p.), are shown in Table 11.

Table 11 – SSA with respect to elasticity of labour supply, percentage points (p.p.).

	Scenarios				
Standard dev.	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Real GDP	0.04	0.04	0.01	0.04	0.04
Gini coefficient	0.04	0.06	0.06	0.06	0.06
Mean					
Real GDP	-0.42	0.03	-0.14	0.01	-0.29
Gini coefficient	-0.67	0.15	0.18	0.20	0.13

The standard deviations of both GDP and Gini coefficient are not very large and are relatively homogenous across the scenarios. The only notable exception, in this respect, is the standard deviation of GDP under *LABFACT*, which is only 0.01 p.p. Hence, the impact on GDP, largely driven by the expansion of labour demand in this scenario, is not really sensitive to labour supply.

In most CGE applications, and by default with GTAP, labour supply is fixed. Thus, we wanted to verify how this standard assumption would impact on our results. For this, SSA is not needed: we just set the elasticity of labour supply equal to zero, which is equivalent to having it fixed, and re-ran the scenarios. The results for GDP are reported in Table 12.

Table 12 – Percentage change in real GDP for elasticity of labour supply = 0 and = 1.7.

	Scenarios				
Elast. = 0	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Real GDP	-0.20	-0.16	-0.20	-0.19	-0.09
Elast. = 1.7					
Real GDP	-0.42	0.03	-0.14	0.01	-0.29

These results confirm that the achievement of a double dividend under *VAT* and *LABINC* depends on the responsiveness of labour supply to real wage. It is also confirmed that the *LABFACT* is not very sensitive to the responsiveness of labour supply. Differently, the GDP result substantially improves for both *TRANSF* and *CAPINC*. In fact, in terms of GDP, the latter becomes the first best scenario. In principle, a capital tax swap can deliver a double dividend if it attracts sufficient investment.

Elasticities of household demand for energy commodities

The elasticities of household demand for energy commodities that have been used in the simulations (Table 6) are generally very low, especially price elasticities of electricity and coal. To verify the extent to which these parameters can affect the results, we re-ran the scenarios using the elasticities found in the GTAP database. These are virtually the same for all the deciles, but in this exercise we are not so concerned with distributional effects as with the overall impacts on emissions abatement and GDP. The GTAP income elasticities for electricity, coal, gas and petroleum products range from 0.97 to 0.99 across households, while own price elasticities are -0.80 for petroleum products and -0.78 for the other three commodities. The results are shown in Table 13.

The difference in emissions abatement is substantial: approximately 2.5 p.p., in all the scenarios, which represents a more than 20% increase in abatement. This is remarkable as households only count for about one fourth of CO2 emissions (Table 2, Section 4.1). However, surprisingly perhaps, that emissions abatement is easier does not imply that the carbon tax has a better impact on the economy. The GDP results worsen in all the scenarios, particularly in *VAT* and *LABINC*. The reason for this is that the carbon tax raises

revenue and, the greater this is, the more other taxes can be reduced. To show that such mechanism is behind these results, we report in the same table the tax cuts (endogenous) that accompany the carbon tax in the four scenarios with revenue recycling. They all get smaller if emissions are more easily abated because the base of the carbon tax (i.e., emissions) is smaller. Consequently, the impact of the tax cut is more limited. As regards the *TRANSF* scenario, we note that the slight worsening in GDP is largely due to a fall in revenues from indirect taxes.

Table 13 – Inelastic vs. elastic household demand for energy commodities, % changes.

	Scenarios				
	TRANSF	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Elastic CDE					
Real GDP	-0.46	-0.06	-0.21	-0.08	-0.34
CO_2 emissions	-13.51	-13.22	-13.42	-13.27	-13.53
tp		-0.94			
tl			-0.62		
tll				0.90	
tk					0.90
Inelastic CDE					
Real GDP	-0.42	0.03	-0.14	0.01	-0.29
CO_2 emissions	-10.93	-10.77	-10.87	-10.79	-10.92
tp		-1.06			
tl			-0.72		
tll				1.03	
tk					1.05

Note: For both *tll* (*LABINC*) and *tk* (*CAPINC*) positive values indicate tax reductions (see Section 5).

Supply elasticities

In a recent and rare type of work, Beckman *et al.* (2011) recalibrate some key elasticities of GTAP-E's production structure so that the model can better reproduce the variability of petroleum prices over the 2001-2006 period. They conclude that energy demand in GTAP-E is far too price elastic. We therefore re-ran our five scenarios with the new elasticities indicated by the authors, that is: 0.25 (instead of 1) for substitution between oil and gas (non-coal energy sources), 0.07 (instead of 0.5) for coal/non-coal substitution, and 0.16 (instead of 1) for electricity/non-electricity.[73] Table 14 shows the results of interest.

One noticeable, expected, impact of smaller elasticities is the one on emissions abatement: roughly 2 p.p. lower. The impact on GDP is slightly positive and, again, it has

[73] Refer to Figure 1, in Section 3.1., and Table A1, in the Appendix, for standard GTAP-E elasticities, which have been used in this study.

to do with higher carbon tax revenues which can be used to finance bigger tax cuts. No difference is observed for GDP under *TRANSF*.

Table 14 - Inelastic vs. elastic supply, % changes.

	Scenarios				
	TRANSF	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Inelastic supply					
Real GDP	-0.42	0.04	-0.13	0.03	-0.28
CO_2 emissions	-8.90	-8.72	-8.83	-8.74	-8.89
tp		-1.10			
tl			-0.74		
tll				1.07	
tk					1.08
Elastic supply					
Real GDP	-0.42	0.03	-0.14	0.01	-0.29
CO_2 emissions	-10.93	-10.77	-10.87	-10.79	-10.92
tp		-1.06			
tl			-0.72		
tll				1.03	
tk					1.05

Armington elasticities

The impact of carbon pricing on international competitiveness depends to a great extent on substitutability between domestic products and imports and between different imports sources (i.e., regions). In GTAP, this idea is embodied in Armington elasticities.[74] Using SSA in the way described before, we let Armington elasticities vary by up to 60% and thus derived mean and standard deviation for the percentage change in exports' volume and real GDP. Table 15 shows the results.

Table 15 - SSA with respect to Armington elasticities, percentage points (p.p.).

	Scenarios				
Standard dev.	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Exports' volume	0.07	0.04	0.04	0.04	0.08
Real GDP	0.02	0.01	0.01	0.01	0.02
Mean					
Exports' volume	-0.32	-0.09	-0.13	-0.15	-0.45
Real GDP	-0.42	0.03	-0.14	0.01	-0.29

The sensitivity of exports to variability in Armington elasticities is non-negligible under *TRANSF* and *CAPINC*, while it is only half as important under the three other scenarios. The likely reason for this is that under *VAT*, *LABFACT* and *LABINC*, directly or

[74] Find the used values in Table A1, in the Appendix.

indirectly firms benefit of a reduction in production costs. Hence, they are able to contain price increases. Clearly, this is an aggregate indicator and more pronounced effects are expected at the sectoral level. The impact on GDP is only marginal.

Elasticity of capital movements

In the GTAP model, one parameter called *RORFLEX* determines the responsiveness of investment to a change in the current return on capital, *RORC*, in a given region. Global savings are distributed across regions in such a way that the expected returns on capital, *RORE*, move together in all regions. The greater *RORFLEX*, the smaller is the amount of capital flow that is necessary to re-establish the equality of expected returns. Hence, greater values of *RORFLEX* reflect smaller capital mobility, and *vice versa*. *RORE* and *RORC* are linked by the following equation:

$$RORE_r = RORC_r \times (KE_r/KB_r)^{-RORFLEX_r}$$

where *KB* and *KE* are the beginning- and end-of-period capital stocks, respectively, and minus *RORFLEX* is the elasticity of *RORE* with respect to *KE*.

Greater capital mobility plays to the advantage of a region only if *RORC* improves (i.e., if its change is positive). If, instead, the change in *RORC* is negative, greater capital mobility is detrimental, as it implies greater capital outflow. In our scenarios, *RORC* improves only under *LABINC* (Table 8). The standard value of *RORFLEX*, the one we used, is 10. Using SSA, we let it vary by up to 60% and thus derived mean and standard deviation for the percentage change GDP. Table 16 shows the results.

Table 16 - SSA with respect to elasticity of capital movements, percentage points (p.p.).

	Scenarios				
Standard dev.	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Real GDP	0.05	0.04	0.05	0.05	0.03
Mean					
Real GDP	-0.42	0.03	-0.14	0.01	-0.29

8. Conclusions

The majority of studies on distributional effects of carbon pricing restrict the analysis to the impact on energy prices and, sometimes, on consumer prices in a more general sense.

As poor households typically spend greater shares of their income on energy, at least in developed economies, such studies conclude that carbon pricing is regressive (i.e., the poor are affected relatively more than the rich). This type of analysis and the said conclusion are valid for the immediate or short term effects. By contrast, only few works look at the medium or long term, in which other mechanisms come into play and determine further distributional effects through the sources as well as the uses of households' income. The concurrence of sources- and uses of income impacts, as they are referred to in the public finance literature, implies that the distributional incidence of carbon pricing may be different – notably, not regressive – over a longer time frame. A more comprehensive assessment of such effects is valuable in its own right and, as distributional concerns can be a major hindrance to the adoption of carbon pricing, it is all the more important that medium and long term effects also be taken into account.

The other main concern associated with carbon pricing is the negative impact the latter may have on the economy. In this regard, the double dividend literature tells us that carbon pricing may in fact benefit the economy, not only the environment, if the proceeds are used ("recycled") to reduce other more distortive taxes. Different recycling schemes deliver more or less favourable outcomes in terms of economic growth, but also have different distributional implications. Thus, efficiency and equity effects of carbon pricing with revenue recycling should be assessed together, ideally within the same empirical framework. This is rarely done, however, presumably due to the levels of data detail and model sophistication that are required. Only in recent years, with the notable exception of Jorgenson *et al.* (1992), a number of works with such characteristics have appeared.

This paper simulates the medium term impact of a $\$20/tCO_2$ carbon tax on the Irish economy and the associated level of emissions abatement. In particular, five scenarios are considered, differing from one another in the way the tax revenues are used. Efficiency and equity effects of each of those are assessed together and these are then put in contrast. Given what has been pointed out just above, this work adds to a still very limited literature and it is the first such application to Irish data. A CGE model with multiple representative households, G-EMH, which in turn combines two different versions of the GTAP model, GTAP-E (Burniaux and Truong [2002]; McDougall and Golub [2007]) and GTAP-MH (Gotor and Tsigas [2011]), has been created expressly for our purposes. The contribution of this study is, thus, twofold: it is the first to analyze distributional effects of carbon pricing in Ireland over the medium term; at the same time, it introduces a new tool for

distributional analysis of energy/climate policy, whose applicability is vast considering the scope and popularity of GTAP.

The analysis follows three main research questions, namely: *a)* Is carbon pricing regressive beyond the short term? *b)* Can a double dividend – lower emissions and positive economic growth – be achieved through revenue recycling? *c)* Which of the considered recycling schemes delivers a preferable outcome, both in terms of growth and equity?

In response to the first question, we found that the impact of the carbon tax, without revenue recycling, is regressive over the medium term, as is the case in the shorter horizon. Indeed, only if the proceeds of carbon pricing are redistributed to households through the existing welfare system is the overall impact on real incomes virtually homogenous across households. Otherwise, the impact is regressive. Thus, even if a longer time perspective is taken, distributional implications of carbon pricing remain to be addressed by the policy maker.

Under two of the five scenarios we considered, a double dividend was achieved. The impacts on GDP are only very modest, namely 0.03% and 0.01%. However, given the uncertainty naturally embedded in the model, it is the proximity to the region of positive values and its sensitivity to the model parameters – the likelihood of a positive outcome, rather than punctual predictions – that matters most. The scenarios in question, *VAT* and *LABINC*, involve the recycling of the carbon tax revenues in cuts of the tax rates applied to private consumption and labour income, respectively. While the two schemes are different "in spirit", as one is conceived to operate via the demand side of the economy and the other via the supply side, they both deliver a double dividend thanks to the high responsiveness of labour supply to changes in real wages. Labour supply in Ireland is indeed traditionally highly elastic through migration (Bergin and Kearney [2007]; Conefrey *et al.* [2008]) and even in 2004, the base year in this application, the elasticity of labour supply would have been significantly greater than zero in spite of a context of almost full employment.

Most importantly, similar conclusions were drawn in other Irish comparable works: using different data and approach (macroeconometric model), Bergin *et al.* (2004) find that a double dividend could be achieved if carbon taxation was accompanied with cuts in labour taxes or VAT; Wissema (2007) too finds that a revenue neutral carbon tax coupled with lower indirect taxes can be recommended (although it would deliver only a weak double dividend), while lower labour taxes would not be effective precisely because the elasticity of labour supply was assumed to be very low given low unemployment in the base year. The central role of labour supply is thus confirmed and, at least as far as G-

EMH is concerned, it calls for a refinement of the model whereby migration is explicitly considered. Moreover, based on the results of these studies, including the present one, it seems there is now robust evidence that a swap of carbon taxation with other indirect taxes, such as VAT, can be a sensible way of adopting the former while not depressing the Irish economy.

The two remaining scenarios, *LABFACT* and *CAPINC*, yield some results of interest as well. The first, in which carbon tax revenues are used to cut the tax on the use of labour, so as to reduce its cost, brings about only a slightly negative result for real GDP: -0.14%. Also, in the context of sensitivity analysis *LABFACT* has generally proved the least sensitive to variability in the model parameters, but under no circumstances it comes first in terms of impact on economic growth. Under *CAPINC*, the carbon tax revenues are used to finance a cut in the tax on capital income, thereby incentivizing investment (domestic and international). Such scheme produces a 0.29% decline in GDP. Yet, with the elasticity of labour set equal to zero, as is assumed in most CGE applications, its GDP result,-0.09%, is the best among all the scenarios. In relation to these results, two distinct remarks are in order. First, in general the higher the elasticity of international investment to differentials in returns on capital, the more likely it is that a double dividend be achieved with capital tax recycling. Incidentally, the global GTAP model seems particularly suited for performing this type of scenarios. Secondly, as a large part of capital income, in the case of Ireland, is earned by non-residents, the overall impact of such scheme for the resident population is actually more adverse (more negative or less positive) than what is reflected by GDP.

The third main research question motivating this work is which of the considered policy reforms delivers a preferable outcome, both in terms of efficiency and equity. To answer this question, one needs to refer to a social welfare function that weighs efficiency and equity gains/losses (i.e., the response is conditional to the choice of such function). The five scenarios are contrasted on the basis of percentage changes in real income across the income distribution. In the *VAT* scenario, it turns out, all resident households are better off than with any of the other schemes (in Figure 7, the entire curve of *VAT* lies above all the others). Therefore, assuming a Utilitarian or even a Rawlsian type of social welfare function, whereby it is the utility of the poorest that ultimately matters, the *VAT* scheme comes out on top and a recommendation for the policy maker is thus readily prescribed. This result applies to Ireland, but importantly it may be valid in a more general sense. Indeed, swapping a carbon tax with a VAT cut might be a good idea for at least two –

different – reasons: it supports the economy by incentivizing low-carbon consumption and, at the same time, it guarantees that all households, including retired, unemployed, and students, who may not all be reached with other schemes, would benefit from the tax break. These aspects should be the object of future investigation.

The simulated carbon tax proves to be environmentally effective, as the fall in Ireland's CO_2 emissions ranges from 10.7% to 11.1% across the scenarios. Nonetheless, the general equilibrium elasticity of emissions with respect to the carbon tax rate is only -0.08. Thus, in the absence of technological change, high levels of carbon taxation are needed to abate emissions by any substantial amounts. The economy is not necessarily harmed, however, as demonstrated by the *VAT* and *LABINC* scenarios. In general, any level of carbon pricing with revenue recycling improves the environment and shifts wealth within the economy, rather than destroys it.

Connected to the idea of burden shift is that of winners and losers among economic sectors. Though this study does not focus on sectoral and competitiveness effects, still our simulations disclose some relevant evidence (analyzed in the Appendix). In this regard, we note that: *a)* the wind power industry greatly benefits from carbon pricing under all the scenarios; *b)* some labour intensive sectors expand too, if the carbon tax is accompanied by lower taxes on labour or consumption; *c)* energy- (non renewable) and energy intensive sectors suffer the most. Moreover, among most export oriented industries, some large losses in export volumes are observed, but for sectors that weigh little in Ireland's total exports.

Arguably, the main limitation of the analysis conducted in this paper lies in the high level of aggregation of the household sector. As Rausch *et al.* (2011b) show, differences in the impact of carbon taxation within household groups (e.g., income deciles) can be greater than those between group averages. Aggregating and averaging out is of course a practical solution, but greater detail in the depiction of distributional effects is relevant in its own right and, above all, it may suggest preferable ways of implementing carbon pricing, with important implications for policy making. Thus, an upgrade of the model in this sense, from what has been called the representative household approach to the integrated multi-household approach, is certainly recommendable for the future. Furthermore, three features of the G-EMH model, namely the endogenization of labour supply, the introduction of renewables in the electricity sector and the distinction between resident and non-resident households, serve the purposes for which they have been introduced – sufficiently well, it is believed – but perhaps can be refined too. Finally, explicit modeling of migration and

greater detail in intra-institutional transactions are other developments of G-EMH that also would allow a better assessment of distributional effects of carbon pricing with revenue recycling.

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Appendix

I. Model parameters

Table A1 – CES elasticities in production structure.

	Elasticities of substitution						
Sector	*VAE*	*KE*	*ENER*	*NELY*	*NCOAL*	*ESUBD*	*ESUBM*
Rest	1.17	0.5	1	0.5	1	2.58	6.3
fsh	0.2	0.5	1	0.5	1	1.25	2.5
coa	0.2	0	0	0	0	3.05	6.1
oil	0.2	0	0	0	0	5.2	10.4
gas	0.65	0	0	0	0	10.77	32.49
omn	0.2	0.5	1	0.5	1	0.9	1.8
mil	1.12	0.5	1	0.5	1	3.65	7.3
ofd	1.12	0.5	1	0.5	1	2	4
p_c	1.26	0	0	0	0	2.1	4.2
crp	1.26	0.5	1	0.5	1	3.3	6.6
nmm	1.26	0.5	1	0.5	1	2.9	5.8
nfm	1.26	0.5	1	0.5	1	4.2	8.4
ele	1.26	0.5	1	0.5	1	4.4	8.8
ome	1.26	0.5	1	0.5	1	4.05	8.1
hydro	1.26	0.5	1	0.5	1	2.8	5.6
wind	1.26	0.5	1	0.5	1	2.8	5.6
oth_ely	1.26	0.5	1	0.5	1	2.8	5.6
trd	1.68	0.5	1	0.5	1	1.9	3.8
otp	1.68	0.5	1	0.5	1	1.9	3.8
wtp	1.68	0.5	1	0.5	1	1.9	3.8
atp	1.68	0.5	1	0.5	1	1.9	3.8
ofi	1.26	0.5	1	0.5	1	1.9	3.8
isr	1.26	0.5	1	0.5	1	1.9	3.8
obs	1.26	0.5	1	0.5	1	1.9	3.8
osg	1.26	0.5	1	0.5	1	1.9	3.8

Note: *VAE*: CES between primary factors; *KE*: CES capital - energy; *ENER*: CES non-electricity – electricity; *NELY*: CES coal – non-coal; *NCOAL*: CES between gas, oil and petr. prod.; *ESUBD*: CES domestic – import (Armington); *ESUBM*: CES import – import (Armington).

Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *hydro* – Hydro; *wind* – Wind; *oth_ely* – Other electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest*.

Table A2 – Irish households' CDE income elasticities.

EY	*HH1*	*HH2*	*HH3*	*HH4*	*HH5*	*HH6*	*HH7*	*HH8*	*HH9*	*HH10*	*HHNR*
ely	0.15	0.16	0.16	0.18	0.21	0.23	0.26	0.28	0.32	0.44	0.23
Rest	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00
fsh	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
coa	-0.04	-0.05	-0.08	-0.12	-0.15	-0.20	-0.21	-0.25	-0.26	-0.53	-0.18
oil	0.98	0.98	0.98	0.98	0.97	0.95	0.98	0.97	0.97	0.99	0.97
gas	0.22	0.23	0.22	0.25	0.27	0.33	0.36	0.42	0.48	0.65	0.33
omn	1.03	1.03	1.00	1.00	1.00	1.00	1.01	1.00	1.00	0.99	1.00
mil	0.95	0.97	0.93	0.91	0.92	0.95	0.88	0.87	0.86	0.83	0.90
ofd	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.94	0.94	0.91	1.00
p_c	0.30	0.31	0.31	0.30	0.32	0.35	0.36	0.38	0.42	0.52	0.31
crp	1.11	1.18	1.12	1.10	1.11	1.09	1.06	1.05	1.04	1.05	1.09
nmm	1.03	1.04	1.01	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00
nfm	1.02	1.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00
ele	1.06	1.06	1.03	1.01	1.01	1.00	1.03	1.01	1.01	1.01	1.00
ome	1.06	1.06	1.05	1.01	1.02	1.01	1.02	1.01	1.01	1.01	1.00
trd	1.19	1.22	1.17	1.17	1.16	1.16	1.14	1.13	1.12	1.12	1.15
otp	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
wtp	0.98	0.98	0.97	0.97	0.97	0.96	0.98	0.98	0.97	0.98	0.97
atp	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	1.00
ofi	1.14	1.17	1.12	1.07	1.07	1.05	1.07	1.05	1.05	1.04	1.06
isr	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.98	1.00
obs	1.27	1.23	1.26	1.22	1.18	1.17	1.15	1.14	1.13	1.11	1.16
osg	1.19	1.17	1.13	1.11	1.15	1.13	1.12	1.11	1.10	1.13	1.13

Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *ely* – Electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest*.

Table A3 – Irish households' CDE own price elasticities.

EP	*HH1*	*HH2*	*HH3*	*HH4*	*HH5*	*HH6*	*HH7*	*HH8*	*HH9*	*HH10*	*HHNR*
ely	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02
Rest	-0.87	-0.88	-0.82	-0.81	-0.80	-0.78	-0.85	-0.84	-0.84	-0.85	-0.80
fsh	-0.69	-0.69	-0.69	-0.69	-0.68	-0.69	-0.69	-0.69	-0.69	-0.68	-0.68
coa	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01	-0.04	-0.01
oil	-0.80	-0.79	-0.79	-0.80	-0.80	-0.81	-0.79	-0.80	-0.79	-0.79	-0.80
gas	-0.09	-0.12	-0.12	-0.14	-0.10	-0.11	-0.10	-0.09	-0.11	-0.10	-0.12
omn	-0.84	-0.83	-0.85	-0.87	-0.89	-0.92	-0.85	-0.87	-0.86	-0.88	-0.89
mil	-0.70	-0.70	-0.69	-0.69	-0.68	-0.68	-0.70	-0.69	-0.69	-0.71	-0.68
ofd	-0.77	-0.78	-0.76	-0.76	-0.76	-0.76	-0.76	-0.75	-0.75	-0.76	-0.75
p_c	-0.20	-0.23	-0.24	-0.22	-0.21	-0.21	-0.19	-0.20	-0.20	-0.16	-0.24
crp	-0.83	-0.99	-0.85	-0.84	-0.85	-0.84	-0.83	-0.83	-0.83	-0.83	-0.84
nmm	-0.84	-0.83	-0.84	-0.86	-0.87	-0.91	-0.85	-0.86	-0.85	-0.84	-0.88
nfm	-0.84	-0.83	-0.84	-0.88	-0.90	-0.92	-0.85	-0.87	-0.87	-0.87	-0.90
ele	-0.83	-0.83	-0.83	-0.84	-0.85	-0.87	-0.84	-0.85	-0.84	-0.83	-0.84
ome	-0.83	-0.83	-0.83	-0.84	-0.84	-0.85	-0.84	-0.85	-0.85	-0.84	-0.84
trd	-0.86	-0.86	-0.87	-0.89	-0.92	-0.90	-0.87	-0.88	-0.87	-0.88	-0.92
otp	-0.79	-0.80	-0.79	-0.79	-0.79	-0.79	-0.79	-0.78	-0.78	-0.78	-0.78
wtp	-0.80	-0.79	-0.79	-0.79	-0.79	-0.81	-0.79	-0.80	-0.79	-0.79	-0.79
atp	-0.79	-0.79	-0.79	-0.79	-0.79	-0.79	-0.78	-0.79	-0.79	-0.78	-0.77
ofi	-0.87	-0.87	-0.86	-0.88	-0.87	-0.89	-0.87	-0.88	-0.88	-0.87	-0.88
isr	-0.80	-0.79	-0.79	-0.79	-0.77	-0.79	-0.79	-0.78	-0.78	-0.78	-0.78
obs	-0.98	-0.88	-0.94	-0.95	-0.93	-0.91	-0.98	-0.98	-0.98	-0.97	-0.94
osg	-0.87	-0.86	-0.87	-0.87	-0.89	-0.88	-0.86	-0.87	-0.86	-0.90	-0.89

Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *ely* – Electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest*.

Table A4 – Irish households' budget shares.

Share	*HH1*	*HH2*	*HH3*	*HH4*	*HH5*	*HH6*	*HH7*	*HH8*	*HH9*	*HH10*	*HHNR*
ely	2.5	2.3	2.0	1.9	1.7	1.7	1.5	1.4	1.3	1.1	1.6
Rest	36.1	38.9	36.6	33.8	35.1	35.0	33.8	34.0	33.6	39.5	35.5
fsh	0.3	0.3	0.4	0.3	0.2	0.3	0.3	0.3	0.2	0.3	0.3
coa	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1
oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
gas	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
omn	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
mil	4.0	4.0	3.8	3.1	3.0	2.7	2.5	2.1	1.9	1.6	2.6
ofd	13.6	14.6	13.0	11.4	10.8	9.9	8.9	7.5	6.8	5.9	9.2
p_c	4.3	3.8	4.5	4.6	4.4	4.5	4.2	3.8	3.9	3.2	4.0
crp	4.2	4.0	4.0	4.4	4.1	4.0	4.2	3.9	4.2	3.3	4.0
nmm	0.4	0.7	0.3	0.5	0.6	0.4	0.7	0.8	0.7	1.0	0.7
nfm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ele	1.6	1.5	1.3	1.6	1.4	1.5	1.8	1.6	1.4	1.7	1.5
ome	1.6	1.3	1.8	1.5	1.7	2.1	1.4	1.4	1.4	1.3	1.5
trd	6.4	6.7	6.6	7.9	7.9	8.5	8.7	9.3	9.0	9.0	8.3
otp	2.3	1.4	1.7	2.1	2.1	2.1	2.1	2.2	2.4	2.1	2.1
wtp	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.2
atp	1.8	2.0	1.8	1.7	1.8	1.8	1.7	1.7	1.7	2.0	1.8
ofi	3.8	4.1	3.8	3.5	3.7	3.7	3.5	3.6	3.5	4.1	3.7
isr	2.3	2.4	2.5	3.0	3.7	3.7	3.9	4.3	4.7	5.6	4.0
obs	8.2	6.4	10.3	12.7	10.0	10.2	12.5	13.2	14.6	10.7	11.5
osg	5.9	4.6	4.7	5.5	7.2	7.4	7.8	8.4	8.1	7.2	7.1
Total	100	100	100	100	100	100	100	100	100	100	100

Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *ely* – Electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest*.

II. Emissions abatement and carbon tax revenues

Table A5 – Emissions abatement by fuel (% changes).

	Scenarios				
Fuel	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Overall	**-10.93**	**-10.77**	**-10.87**	**-10.79**	**-10.92**
Coal	-22.03	-22.03	-22.03	-22.00	-22.01
Oil	-15.19	-15.09	-15.15	-15.10	-15.22
Gas	-16.09	-15.99	-16.06	-15.99	-16.08
Petrol. prod.	-5.85	-5.61	-5.76	-5.65	-5.84

Table A6 – Carbon tax revenue by fuel, ($m).

	Scenarios				
Fuel	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Overall	**811.1**	**812.6**	**811.6**	**812.4**	**811.2**
Coal	133.5	133.5	133.5	133.5	133.5
Oil	0.0	0.0	0.0	0.0	0.0
Gas	152.6	152.8	152.6	152.8	152.6
Petrol. prod.	525.0	526.4	525.5	526.1	525.1

Table A5b – Emissions abatement by fuel (% changes), under elastic demand for energy commodities.

	Scenarios				
Fuel	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Overall	**-13.51**	**-13.22**	**-13.42**	**-13.27**	**-13.53**
Coal	-28.48	-28.31	-28.44	-28.31	-28.51
Oil	-18.55	-18.37	-18.49	-18.39	-18.60
Gas	-19.70	-19.47	-19.63	-19.49	-19.72
Petrol. prod.	-6.90	-6.55	-6.78	-6.62	-6.91

Table A6b – Carbon tax revenue by fuel, ($m), under elastic demand for energy commodities.

	Scenarios				
Fuel	*TRANSF*	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Overall	**787.6**	**790.3**	**788.5**	**789.8**	**787.5**
Coal	122.4	122.7	122.5	122.7	122.4
Oil	0.0	0.0	0.0	0.0	0.0
Gas	146.0	146.4	146.1	146.4	146.0
Petrol. prod.	519.2	521.1	519.8	520.7	519.1

III. sectoral effects

Net impacts on output and prices

Carbon taxation impacts on both the supply and the demand of all goods and services. Percentage changes in equilibrium price and quantities of all goods and services (including capital goods or investment, *CGDS*) under the five scenarios are reported in Table A7.

Table A7 - Sectoral effects.

	Scenarios									
	TRANSF		*VAT*		*LABFACT*		*LABINC*		*CAPINC*	
Sectors	*p (%)*	*q (%)*	*p (%)*	*q (%)*	*p (%)*	*q (%)*	*p (%)*	*q (%)*	*p (%)*	*q (%)*
Rest	0.17	-1.02	0.04	-0.23	0.08	-0.56	0.06	-0.34	0.20	-0.59
fsh	0.35	-0.80	0.62	-0.67	0.46	-0.75	0.56	-0.70	0.35	-0.81
coa	-9.58	-18.16	-9.63	-18.10	-9.62	-18.13	-9.61	-18.09	-9.56	-18.16
oil	-0.99	-0.56	-0.96	-0.49	-0.98	-0.51	-0.96	-0.50	-0.98	-0.57
gas	-0.03	-16.26	-0.10	-15.90	-0.09	-16.07	-0.09	-15.95	-0.00	-16.32
omn	0.16	-1.60	0.20	-1.20	0.16	-1.38	0.20	-1.26	0.22	-1.50
mil	0.30	-1.33	0.20	-0.59	0.22	-0.92	0.21	-0.73	0.33	-1.45
ofd	0.38	-0.96	0.28	-0.29	0.31	-0.65	0.29	-0.43	0.41	-1.04
p_c	0.08	-5.46	0.07	-5.23	0.07	-5.37	0.07	-5.27	0.08	-5.45
crp	-0.07	0.33	-0.06	0.34	-0.07	0.37	-0.05	0.31	-0.04	0.19
nmm	1.31	-3.63	1.25	-2.95	1.26	-3.23	1.26	-3.05	1.34	-3.47
nfm	3.55	-19.83	3.50	-19.38	3.51	-19.51	3.51	-19.45	3.57	-19.85
ele	0.02	-0.28	-0.00	-0.03	0.00	-0.09	0.01	-0.09	0.03	-0.28
ome	0.07	-0.72	0.01	-0.12	0.02	-0.30	0.02	-0.22	0.09	-0.66
hydro	0.21	0.97	0.16	1.15	0.17	1.07	0.18	1.16	0.25	0.99
wind	0.22	13.85	0.16	14.05	0.17	13.96	0.18	14.05	0.25	13.86
oth_ely	9.03	-3.84	8.96	-3.67	8.98	-3.75	8.98	-3.66	9.06	-3.83
trd	0.27	-0.77	0.11	-0.14	0.16	-0.40	0.13	-0.25	0.30	-0.76
otp	2.74	-3.37	2.64	-2.78	2.67	-3.05	2.66	-2.86	2.76	-3.37
wtp	1.63	-3.28	1.52	-2.90	1.55	-3.05	1.53	-2.96	1.65	-3.29
atp	1.27	-3.56	1.12	-2.94	1.17	-3.20	1.14	-3.04	1.29	-3.62
ofi	-0.09	-0.17	-0.15	0.34	-0.14	0.12	-0.13	0.24	-0.06	-0.24
isr	0.07	-0.31	-0.05	0.22	-0.02	0.03	-0.03	0.13	0.09	-0.37
obs	-0.02	-0.11	-0.06	0.23	-0.06	0.09	-0.05	0.17	0.01	-0.13
osg	0.25	-0.36	-0.09	0.03	0.02	0.09	-0.04	0.57	0.28	-0.53
CGDS	0.09	-1.37	0.02	-0.81	0.04	-1.02	0.03	-0.86	0.11	0.71

Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *hydro* – Hydro; *wind* – Wind; *oth_ely* – Other electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest.*; *CGDS* – Capital goods (investment).

Different colours denote different stories. Bright blue and orange cells point to the sectors whose output shrinks as a result of the given fiscal reform. Conversely, yellow and green cells are markets in expansion. In particular, the difference between blue and orange sectors is that the price increases and decreases, respectively. Therefore, it can be inferred that for the former (blue) the rise in production costs dominates the change in demand,

while for the latter (orange) the fall in demand dominates the change in production costs. Not surprisingly, energy-intensive industries, for which fossil fuels and electricity make up significant shares of total costs, are the most affected in terms of output. The difference between the "winning" yellow and green sectors is in the sign of the price change too: it is negative for the former, and positive for the latter. Thus, the fall in production costs dominates the change in demand in the case of yellow sectors, while the rise in demand dominates the change in production costs for the green sectors.

Net impacts on exports

While the overall impact on exports is relatively modest (Table 8), some sectors may suffer more than others on the international markets. The shares of exports in sectors' total sales, in the second column of Table A8, indicate which Irish sectors are most export-oriented. The first four are "Chemical, rubber, & plastic products" (*crp*), "Other machinery & equipment" (*ome*), "Insurance & pension funding" (*isr*) and "Electronic equipment" (*ele*). Other sectors too, such as "Fishing" (*fsh*) or "Dairy products" (*mil*), can be considered export-oriented, but they do not weigh as much in Ireland's total exports. This is what the shares in the first column of the same table tell us.

Percentage variations in export volumes show the said four largest exporters do not suffer substantial losses in any of the five scenarios. The most adversely affected sector is, by far, "Non-ferrous metals" (*nfm*). This sector sells 60% of its output abroad, though that only makes 0.2% of overall Irish exports. It is so badly penalized because it is very energy intensive: electricity is almost 12% of total costs (Figure 4c). Other adversely affected sectors are, in order, "Other transport" (land transport) (*otp*), "Other non-metallic mineral products" (*nmm*), "Water transport" (*wtp*) and "Air transport" (*atp*).

There are also some sectors whose exports' volume increases nonetheless – if only slightly. In Table A8, these are highlighted in bright blue. For "Chemical, rubber, & plastic products" (*crp*) and "Other financial services" (*ofi*), the sign is positive in all the scenarios. To follow, "Electronic equipment" (*ele*), "Insurance services" (*isr*) and "Business services" (*obs*) exhibit positive or only very limited negative variations.

Table A8 – Effects on exports.

	Exports		Scenarios				
			TRANSF	*VAT*	*LABFACT*	*LABINC*	*CAPINC*
Sectors	*Share of Ireland's exports*	*Share of sector's sales*	*% Change in export volumes*				
Rest	7.8	20.9	-1.05	-0.24	-0.48	-0.36	-1.21
fsh	0.2	39.2	-0.81	-1.42	-1.06	-1.29	-0.80
coa	0	0.4					
oil	0	0					
gas	0	0.1					
omn	0.3	23.8	-0.25	-0.32	-0.26	-0.31	-0.35
mil	1.2	45.3	-1.94	-1.26	-1.44	-1.36	-2.08
ofd	2.2	29.2	-1.43	-1.04	-1.14	-1.09	-1.51
p_c	0	7.3	-0.38	-0.34	-0.35	-0.35	-0.39
crp	37.7	84.4	0.40	0.35	0.41	0.33	0.25
nmm	0.3	21.5	-6.87	-6.56	-6.63	-6.62	-7.00
nfm	0.2	60.3	-24.99	-24.66	-24.74	-24.72	-25.10
ele	13.6	71.3	-0.15	0.01	-0.01	-0.03	-0.27
ome	9.4	75.8	-0.58	-0.03	-0.18	-0.13	-0.73
hydro	0	0					
wind	0	0					
oth_ely	0	0					
trd	1.9	11.7	-1.02	-0.41	-0.59	-0.50	-1.13
otp	0.6	12.8	-9.24	-8.92	-9.01	-8.97	-9.30
wtp	0.1	20.8	-3.18	-2.96	-3.03	-2.99	-3.21
atp	1.8	53.2	-4.50	-3.99	-4.15	-4.06	-4.56
ofi	2.3	28.9	0.33	0.56	0.51	0.50	0.22
isr	7.3	73.1	-0.25	0.19	0.06	0.12	-0.32
obs	12.4	42.8	0.08	0.23	0.21	0.18	-0.03
osg	0.8	4.2	-0.94	0.33	-0.08	0.14	-1.03

Legend: *fsh* – Fishing; *coa* – Coal; *oil* – Oil; *gas* – Gas; *omn* – Mining; *mil* – Dairy prod.; *ofd* – Other food; *p_c* – Petroleum, coal prod.; *crp* – Chemical, rubber, plastic prod.; *nmm* – Manuf. Of non-metallic mineral prod.; *nfm* – Manuf. of non-ferrous metals; *ele* – Electronic equipm.; *ome* – Other machinery and equipm.; *hydro* – Hydro; *wind* – Wind; *oth_ely* – Other electricity; *trd* – Trade; *otp* – Land transp.; *wtp* – Water transp.; *atp* – Air transp.; *ofi* – Financial serv.; *isr* – Insurance; *obs* – Business serv.; *osg* - Public admin. and defence, Health, Educ.; *Rest.*; *CGDS* – Capital goods (investment).

Paper 3

A QUAIDS Model of Food Demand in Ireland

1. Introduction

The only existing demand system of food demand in Ireland was estimated almost forty years ago, by Casey (1973). It was an application of Stone's (1954) Linear Expenditure System (LES), for 15 items, on aggregate time-series data spanning 1947-1967. The results of that exercise are obsolete not only because the data are old, but also because more flexible models have become available in the meanwhile and some foods that are central to Irish households' diet today, such as fruit and vegetables, were not considered by the author at the time. Other applied demand studies only cover few types of foods and drinks, namely alcoholic beverages (Walsh and Walsh [1970], Thom [1984], Eakins and Gallagher [2003]), meat products (Buttimer and O'Neill [1973], Cowan and Herlihy [1982], Boyle [1996], Newman *et al.* [2001], Newman *et al.* [2002]) and food services (Newman *et al.* [2003], Keelan *et al.* [2008], Keelan *et al.* [2009]). Within this literature, all works of the last decade or so, with the exception of Eakins and Gallagher (2003), use micro-data from the Irish Household Budget Survey (HBS), whereas older ones all use aggregate time-series data. The advantage of using micro-data is that socio-demographic effects can be captured. For these studies, however, that comes at a price: as the HBS only reports expenditures, and not prices or quantities, price effects are ignored.[75] Therefore, price elasticities are not derived.

[75] Quantities are reported only for a very limited number of items. If quantities are reported, unit values can be used instead of actual prices.

Thus, estimates of income elasticities exist only for very few types of food, while price elasticities are even fewer, and older. What is more, none of the latter has ever been derived using micro-data. This is quite an important gap in the Irish literature. Indeed, it is possible to think of many empirical questions whose answers would require some estimate of demand elasticities for given types of food. For example, "what would the yield be of an X percentage point increase in the VAT rate applied to foods?"[76]; "What would the impact on fish sales be of an X percent increase in sale prices?"; "What would the impact on the agri-food sector be if the economy were to shrink by X percent?" Moreover, the current public debate too points to the relevance of food demand elasticities specifically derived from micro level data. Indeed, various public health policies have been discussed which should be informed with estimates of different consumers' responsiveness to changes in food prices. The Irish Government has been considering taxing sugar sweetened drinks as well as foods high in fat and salt to reduce the number of people overweight. Also, it will most likely impose minimum prices on alcoholic beverages in order to fight alcoholism. The effectiveness of all such measures, which have already been adopted in other countries (e.g., Denmark, France and Italy) and may well become increasingly common in future, rests on the responsiveness of the targeted consumers to induced price changes. Therefore, to anticipate the magnitude of the intended effects, estimates of price elasticities, by consumer type, are needed. The HBS would be one major information source to draw on, but, again, it has never been used for such purpose because it only reports expenditure data.

This paper attempts to overcome such a limitation as it estimates a system of demand for food with HBS micro-data. The strategy consists in using the Consumer Price Index (CPI) instead of actual prices or unit values, which are not available. This is a common approach in applied demand analysis: if the dependent variables of the demand equations are expenditure shares, and not expenditure or quantity levels, it is then legitimate to use the variability in price indices to explain the variability in budget shares. Naturally, one first needs to map the survey to the CPI and, in order to derive as much price variability as possible, the mapping must be done for the highest level of CPI commodity disaggregation that is available. This is a lengthy procedure, which might explain why no one has ever undertaken it. However, the mapping can be fairly accurate as the expenditure weights used in the construction of the CPI are based on the HBS itself.

[76] With few exceptions, foods in Ireland are VAT zero-rated.

One typical issue arising when using aggregate price indices is that price variability in the sample may not be sufficient to identify the model parameters. In this application, the variability of the monthly disaggregated (five-digit) CPI can be exploited, because the HBS reports the month when households were interviewed. Ideally, additional variability could have been introduced with regional price indices, but the Irish statistical office does not publish spatial sub-indices of the CPI. Hence, to ensure sufficient price variability is present in the data, the following has been done here. First, the last four waves of the HBS (1987-88, 1994-95, 1999-00 and 2004-05) are used.[77] This is possible thanks to the fact that the surveys are relatively homogenous.[78] Second, following other authors, such as Labeaga (1999), Tiezzi (2005) and Balli and Tiezzi (2010) among others, price indices are derived which vary not only over time but across households too.

The Quadratic Almost Ideal Demand System (QUAIDS) of Banks *et al.* (1997) is then estimated for food demand in Ireland.[79] The model comprises the following eight aggregates: bread and cereals, meat, fish, dairy products, fruit, vegetables, alcohol, and a residual category for all other types of food. That seemed a meaningful partition of food demand and, with regard to the size of the system and the number of parameters to be estimated, computationally manageable too. Alcoholic and non-alcoholic beverages as well as away from home food are included too (both fall in the residual category) so as to better comply with the usual implicit assumption of weak separability between food demand and consumption of other goods.[80]

The basic version of the QUAIDS model is augmented with time controls and socio-demographic effects, incorporated by demographic translation (Pollack and Wales [1981]). Moreover, both estimation issues of potential endogeneity of total food expenditure and data censoring, given the non-negligible proportion of zeros in some of the budget shares, are addressed with appropriate correction procedures. Finally, income and price elasticities

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[77] Micro-data from the 2009-2010 HBS are not available yet.

[78] The detail of the survey increases over the years, with new items being added. Therefore, care is needed to work out expenditure aggregates that can be compared across years.

[79] Incidentally, a fairly large number of Irish studies estimate static or dynamic versions of the AIDS model (Deaton and Muellbauer [1980]). There is none, as far as I am aware, that estimates a QUAIDS model. Both Lyons *et al.* (2009) and Madden (1993) estimate dynamic versions of the AIDS model for total consumption; Divisekera and Deegan (2010) and O'Hagan and Harrison (1984) both estimate standard AIDS models for expenditures of foreign tourists in Ireland; Eakins and Gallagher (2003) and Thom (1984) both estimate dynamic AIDS models for alcohol demand; finally, Boyle (1996) estimates a variant of the AIDS model for meat demand. All of these use aggregate time-series data.

[80] Let q^A be some subvector (e.g., food aggregates) of the commodity vector q (e.g., total consumption) so that $q = (q^A, q^{\bar{A}})$. q^A is then said to be weakly separable if the direct utility function takes the form $u = v(v_A(q^A), q^{\bar{A}})$, where $v_A(q^A)$ is the subutility function associated with q^A. Choices over q^A are consistent independent of the vector $q^{\bar{A}}$.

are derived for each of the four estimated versions of the model in order to highlight the specific impacts of socio-demographics effects and the said corrections for endogeneity and censoring.

The paper is structured as follows. Section 2 introduces the QUAIDS model and shows how socio-demographic effects can be incorporated. Section 3 deals with potential endogeneity of total expenditure and data censoring in estimation of demand systems and illustrates how both these issues are addressed in this application. Section 4 illustrates the estimated model and the data, with a focus on the derivation of household-specific price indices. Section 5 presents and discusses the results. Section 6 concludes.

2. The QUAIDS model

Over the last three decades, the Almost Ideal Demand System (AIDS) of Deaton and Muellbauer (1980) has been the workhorse of applied demand analysis. The model features a number of desirable theoretical properties. First, it is flexible, in the sense that it can approximate a wide range of preferences.[81] Second, it satisfies the axioms of choice exactly. Third, it can be interpreted in terms of economic models of consumer behaviour when applied to either aggregate or disaggregated data. Moreover, its estimation can be relatively simple. Arguably, the main limitation of the AIDS model is that it restricts the budget shares – the dependent variables – to be linear in the logarithm of total expenditure, something that may not correspond to observed data (e.g., Lewbel [1991], Blundell *et al.* [1993], Banks *et al.* [1997]). The QUAIDS model of Banks *et al.* (1997) is, thus, an expedient generalization of the AIDS model which, with an additional quadratic term in the log of total expenditure, allows for greater variety of Engel curves.[82]

2.1 Derivation

The QUAIDS model stems from a generalization of PIGLOG preferences based on the following indirect utility ($V(\boldsymbol{p}, x)$) function:[83]

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[81] In particular, it can approximate any demand system arbitrarily to first-order.

[82] According to Lewbel's (1991) definition of "rank" of a demand system, namely the dimension of the space spanned by its Engel curves, the AIDS model is a rank two model, while QUAIDS is rank three.

[83] Demands having expenditure shares that are linear in the logarithm of total expenditure, as in the Translog (Christensen *et al.* [1975]) and AIDS models, are called Price-Independent Generalized logarithmic (Muellbauer [1976]) and arise from indirect utility functions that are linear in the log of total expenditure. The term *[ln x – ln a(p)] / b(p)*, within [1], is the indirect utility function of PIGLOG demand systems.

$$\ln V = \left\{ \left[\frac{\ln x - \ln a(\boldsymbol{p})}{b(\boldsymbol{p})} \right]^{-1} + \lambda(\boldsymbol{p}) \right\}^{-1}$$

[1]

where x is total expenditure (in this application, total food expenditure), $\boldsymbol{p}$ is a vector of prices (in this application, the prices of eight food aggregates), and $a(\boldsymbol{p})$, $b(\boldsymbol{p})$ and $\lambda(\boldsymbol{p})$ are price indices of specific forms.[84]

Specifically,

$$\ln a(\boldsymbol{p}) = \alpha_0 + \sum_{i=1}^{N} \alpha_i \ln p_i + \frac{1}{2} \sum_{i=1}^{N} \sum_{i=j}^{N} \gamma_{ij} \ln p_i \ln p_j$$

[2]

$$b(\boldsymbol{p}) = \prod_{i=1}^{N} p_i^{\beta_i}$$

[3]

$$\lambda(\boldsymbol{p}) = \sum_{i=1}^{N} \lambda_i \ln p_i , \quad with \quad \sum_{i=1}^{N} \lambda_i = 0$$

[4]

where N is the number of goods considered.

Application of Roy's identity to [1] gives the QUAIDS budget share equations:

$$w_i = \alpha_i + \sum_{j=1}^{N} \gamma_{ij} \ln p_j + \beta_i \, ln \left[\frac{x}{a(\boldsymbol{p})} \right] + \frac{\lambda_i}{b(\boldsymbol{p})} \left\{ \ln \left[\frac{x}{a(\boldsymbol{p})} \right] \right\}^2$$

[5]

where $w_i = p_i q_i / x$.

To allow for integrability (i.e., consistency of the system with utility maximization, subject to a budget constraint), three sets of restrictions are imposed on the parameters.[85]

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[84] "The choice of the functions $a(\mathbf{p})$ and $b(\mathbf{p})$ is governed partly by the need for a flexible functional form. However, the main justification is that this particular choice leads to a system of demand functions with the desirable properties which we demonstrate."(Deaton and Muellbauer [1980])

[85] Integrability also requires that the expenditure function be concave in prices – the negativity property. This condition cannot be imposed directly on the parameters because it implies inequality restrictions. Thus, the standard procedure is to verify after estimation that for most data points – or at least at mean values – the Slutsky matrix is negative semidefinite (i.e., all the eigenvalues are non-positive). Should this not be the case,

The following constraints ensure that adding-up, homogeneity and (Slutsky-) symmetry, in that order, are globally satisfied:

$$\sum_{i=1}^{N} \alpha_i = 1, \quad \sum_{i=1}^{N} \gamma_{ij} = 0, \quad \sum_{i=1}^{N} \beta_i = 0, \quad \sum_{i=1}^{N} \lambda_i = 0 \qquad [6]$$

$$\sum_{j=1}^{N} \gamma_{ij} = 0, \ for\ any\ i \qquad [7]$$

$$\gamma_{ij} = \gamma_{ji}, \ for\ any\ i\ and\ j \qquad [8]$$

Finally, total expenditure and price elasticities are derived by differentiating the budget shares in [5]. Budget and uncompensated price elasticities are thus given by the following functions of parameters and variables' levels:

$$ex_i = 1 + w_i^{-1} \underbrace{\left[\beta_i + \frac{2\lambda_i}{b(\boldsymbol{p})} \ln\left(\frac{x}{a(\boldsymbol{p})}\right)\right]}_{\mu_i} \equiv 1 + w_i^{-1}\mu_i \qquad [9]$$

$$ep_{ij} = w_i^{-1} \underbrace{\left\{\gamma_{ij} - \mu_i\left(\alpha_j + \sum_{l}^{N} \gamma_{jl}\, ln\, p_l\right) - \frac{\lambda_i \beta_j}{b(\boldsymbol{p})}\left[ln\left(\frac{x}{a(\boldsymbol{p})}\right)\right]^2\right\}}_{\mu_{ij}} - \delta_{ij} \equiv w_i^{-1}\mu_{ij} - \delta_{ij} \qquad [10]$$

where μ_i and μ_{ij} are, respectively, $\partial E(w_i)/\partial ln(x)$ and $\partial E(w_i)/\partial ln(p_j)$; δ_{ij} is the Kronecker delta.

2.2 Socio-demographic effects

Allowing for heterogeneous preferences in demand models by including demographics is a natural thing to do when household level data are used. Socio-demographic effects are typically incorporated in demand systems in two ways, namely by demographic translation (Pollack and Wales [1981]) or demographic scaling (Barten [1964]). The first assumes that

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one may want to impose the negativity condition implementing one of the methods suggested by Moschini (1998) and Ryan and Wales (1998).

the constant terms in the share equations vary across households and they can be expressed as linear functions of socio-demographic variables. The second is more flexible in that it allows also other parameters of the demand system, such as the coefficients for prices and expenditure, to depend on demographics.[86] The drawback of demographic scaling is that it exacerbates nonlinearities, making estimation of all the more difficult. For this reason, demographic translation is used in this paper.[87]

Thus, a set of variables for socio-demographic effects, and time controls if needed, is added to [5], which becomes:

$$w_i = \alpha_i + \sum_{r=1}^{V} \rho_{ir} d_r + \sum_{j=1}^{N} \gamma_{ij} \ln p_j + \beta_i \ln\left[\frac{x}{a(\boldsymbol{p})}\right] + \frac{\lambda_i}{b(\boldsymbol{p})}\left\{\ln\left[\frac{x}{a(\boldsymbol{p})}\right]\right\}^2 \qquad [11]$$

where d's are the newly added variables and ρ's the respective (budget share specific) coefficients.

For the budget shares to still add up to 1, $\sum_{i=1}^{N} \rho_{ir} = 0$ must be imposed in addition to the other parametric restrictions above. Furthermore, newly added variables enter $a(\boldsymbol{p})$ in [2]. Adding variables can be computationally costly, however, as the number of parameters to be estimated rises rapidly with those.[88]

3. Estimation issues

3.1 Expenditure endogeneity

In the literature of demand analysis, total expenditure has long been recognized to be potentially endogenous, for it may be correlated with other factors that also affect demand behavior and, yet, are not included in the model (LaFrance [1991]). Estimation ignoring expenditure endogeneity may therefore lead to inconsistent parameter estimates. In cross-sectional demand studies, such as this one, the usual procedure to control for endogeneity is instrumental variables. Following Blundell and Robin (1999), we control for potential endogeneity of total expenditure using an extension, to systems of equations, of Hausman's (1978) two-step augmented regression technique.

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[86] Both methods are special cases of the "modifying function" approach (Lewbel [1985]).
[87] See Moro and Sckokai (2000) for a particularly rich modeling of socio-demographic effects in a QUAIDS model.
[88] Socio-demographic effects are budget share specific.

Let us first consider the econometric version of the QUAIDS model in [11], where h denotes the household and u_i^h is the error term:

$$w_i^h = \alpha_i + \sum_{r=1}^{V} \rho_{ir} d_r^h + \sum_{j=1}^{N} \gamma_{ij} \ln p_j^h + \beta_i \, ln\left[\frac{x^h}{a(\boldsymbol{p^h})}\right] + \frac{\lambda_i}{b(\boldsymbol{p^h})}\left\{\ln\left[\frac{x^h}{a(\boldsymbol{p^h})}\right]\right\}^2 + u_i^h$$

[11']

In the first stage, a reduced-form equation is estimated for $ln(x^h) = \boldsymbol{I}^{h\prime}\boldsymbol{\psi} + v^h$, where $\boldsymbol{I}$ is a vector of explanatory variables that includes all those in [11'] (i.e., prices, demographic variables and time controls) and the instrument(s) for x, $\boldsymbol{\psi}$ is the vector of parameters, and v the error term. In the second stage, the residuals from this regression, $\widehat{v^h}$, are included as an additional explanatory variable back in the budget share equations:

$$w_i^h = \alpha_i + \sum_{r=1}^{V} \rho_{ir} d_r^h + \sum_{j=1}^{N} \gamma_{ij} \ln p_j^h + \beta_i \, ln\left[\frac{x^h}{a(\boldsymbol{p^h})}\right] + \frac{\lambda_i}{b(\boldsymbol{p^h})}\left\{\ln\left[\frac{x^h}{a(\boldsymbol{p^h})}\right]\right\}^2 + k_i\widehat{v^h} + \varepsilon_i^h$$

[12]

The parameters k_i thus provide a test of exogeneity of total expenditure for each budget share, as under the null hypothesis of total expenditure being exogenous they should be zero. Should k_i turn out to be significantly different from zero, it would prove endogeneity was an issue and the correction was needed. The OLS estimates of the parameters in this augmented regression are identical to the Two-Stage Least Squares estimator.

Following Banks et al. (1997), we use total household income as instrument for food expenditure. In general, a good instrumental variable must meet two conditions: it must be *a)* relevant, that is, it must be correlated with the endogenous variable, and *b)* exogenous, which means it is not correlated with the error term. If the number of instruments is greater than that of endogenous variables, the validity of the sets of instruments can be formally tested (with the Sargan test). Otherwise, if there are as many instruments as endogenous variables, the relevance condition can still be easily tested, while exogeneity can only be assumed (the Sargan test cannot be performed). Our case is the second and we thus test for the relevance of income, by determining whether it is statistically significant in the reduced form regression for food expenditure (Wooldridge [2002]), and assume that it (income) is exogenous.

3.2 Zero expenditure

One of the challenges often posed by household micro survey data is how to properly handle large proportions of observations with no consumption of items whose demand is to be analysed.[89] In the presence of censored data, while OLS regression produces biased estimates, in principle Maximum Likelihood works just fine.[90] In single-equation models with limited dependent variable, ML estimation of the Tobit model and its generalizations (e.g., Cragg [1971], Blundell and Meghir [1987]) can be straightforward. With systems of equations, however, direct estimation by ML becomes difficult because of the need to evaluate multiple integrals in the Likelihood function.[91] The two-step procedure proposed by Heien and Wessells (1990), extending Heckman's (1976) selection model to systems of equations, offered great promise as a practical solution to this computational barrier, but almost ten years later it was shown to be inconsistent by Shonkwiler and Yen (1999).[92] The same authors proposed an alternative method – again a two-step procedure that, however, keeps all observations in the second stage – which is proved to yield a consistent estimator. The Shonkwiler and Yen approach for censoring in demand systems has since become the most popular and we also apply it in this study.

The Shonkwiler and Yen approach consists of the following. Consider a structure in which censoring of each commodity *i* is governed by a separate stochastic process. Let the dichotomous variable d_i^h take the form

$$d_i^h = \begin{cases} 1 & if\ \boldsymbol{z}_i^{h\prime}\boldsymbol{\tau}_i + \nu_i^h > 0 \\ 0 & otherwise \end{cases} \qquad [13]$$

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[89] Different reasons can be invoked to explain the non-occurrence of purchases: *a)* the household does not purchase the item for economic reasons, as the good was too pricey or the household too poor ("corner solution"); *b)* the household does not participate in the market for non-economic reasons (e.g., vegetarians will not buy meat); *c)* the survey is shorter than the good's purchasing cycle thus failing to include a positive purchase by a consuming household ("infrequency of purchase").

[90] Applying OLS on uncensored values only is not a good solution both because many observations would be lost and most likely a selection bias would be introduced.

[91] That is why various theoretical models for censored demand systems (e.g., Amemiya [1974], Wales and Woodland [1983], Lee and Pitt [1986]) have seen virtually no use in empirical studies.

[92] Heien and Wessels' estimator is inconsistent because "in contrast to two-step procedures based only on nonlimit observations (e.g., Heckman), estimation of a censored system requires a procedure that uses the whole sample since each dependent variable may have a different pattern of censoring (in terms of limit and nonlimit outcomes)." With Shonkwiler and Yen's procedure, all observations – zero budget shares too – are used in the second-stage estimation.

where $\boldsymbol{z}_i^h$ is a vector of exogenous explanatory variables and $\boldsymbol{\tau}_i$ a conformable vector of coefficients. The equation specific error term,v_i^h, is distributed normally with zero mean and unit variance.

The observed expenditure shares are then given by

$$\left(w_i^h\right)^{obs} = w_i^h \times d_i^h \qquad [14]$$

Assuming that $\left(v_i^h,\ u_i^h\right)$ are distributed bivariate normally with covariance $Cov\left(v_i^h, u_i^h\right) = \delta_i$,[93] consistent parameters in the latent share equation (w_i^h) can be recovered by estimating the observed share equations

$$\left(w_i^h\right)^{obs} = \Phi(\boldsymbol{z}_i^{h\prime}\widehat{\boldsymbol{\tau}}_i)\, w_i^h + \delta_i\varphi(\boldsymbol{z}_i^{h\prime}\widehat{\boldsymbol{\tau}}_i) + \sigma_i^h \qquad [15]$$

where $\boldsymbol{z}_i^{h\prime}\widehat{\boldsymbol{\tau}}_i$ are predicted indices from the first step Probit estimation of the equations in [13] and φ and Φ are, respectively, the standard normal density- and cumulative density functions.

Therefore, in the first step of the procedure, Probit models are estimated for the occurrence of positive consumption (using sets of relevant regressors, $\boldsymbol{z}_i$). The predicted probabilities of positive consumption (Φ) and the values of the Normal function (φ) are then used in the second stage, which is the estimation, by ML or Seemingly Unrelated Regression (SUR), of the system in [15]. The required assumptions are that *a)* the errors of the original budget share equations, $\boldsymbol{u}$, and those of the censoring processes, $\boldsymbol{v}$, are normally distributed, and *b)* the binary censoring processes are independent one from another as well as from all other budget shares.

As a result of the correction for censoring, the formulae for total expenditure- and price elasticities adjust too. For the goods subject to censoring, [9] and [10] become:

$$ex_i = 1 + w_i^{-1}\mu_i\, \Phi(\boldsymbol{z}_i'\widehat{\boldsymbol{\tau}}_i)$$

$$ep_{ij} = w_i^{-1}\mu_{ij}\, \Phi(\boldsymbol{z}_i'\widehat{\boldsymbol{\tau}}_i) - \delta_{ij} \qquad [9']$$

[93] If the QUAIDS with the correction for expenditure endogeneity is considered (i.e.,[12] instead of [11']), u_i^h is replaced by ε_i^h.

Finally, one problem arises with Shonkwiler and Yen's approach. The deterministic components of the augmented system ([15]) do not sum to one if the parametric restrictions for adding-up ([6]) are imposed. Indeed, imposing the restrictions when using Shonkwiler and Yen's approach implies that the system of latent budget shares ([11']) is theoretically consistent but not that of observed budget shares ([15]), which is what we ultimately care about. In the literature, some authors just ignore this fact, while others prefer not to impose any restrictions at all. Yen *et al.* (2003) offer a practical, though ad hoc, solution whereby one of the equations, naturally corresponding to the residual category, is dropped and the system of *n-1* observed budget shares is estimated along with the identity $w_n = 1 - \sum_{i=1}^{n-1} w_i$. As a compromise, we use this approach, with the usual parametric restrictions imposed.[94]

4. Model and data

4.1 Model

Four versions of the QUAIDS model are estimated in this study. In ascending order of complexity, *Model 1* is the basic version, as it appears in [5]; *Model 2* allows for time and socio-demographic effects by demographic translation and it therefore corresponds to [11]; *Model 3*, in addition to time controls and socio-demographic effects, corrects for potential endogeneity of total food expenditure using Blundell and Robin's (1999) two-step method and it thus corresponds to [12]; *Model 4* augments *Model 3* with censoring adjustments (zero-expenditure) for fish's, fruit's and alcohol's budget share equations, as per Shonkwiler and Yen's (1999) approach, and corresponds to [15].

Given our need to customize the base model, a function evaluator program for the STATA software package has been created expressly for this exercise.[95] The program is implemented through the -nlsur- command which fits the model by Feasible Generalized

[94] With this procedure, the parameter estimates are not invariant to the commodity identified as the "omitted commodity". Moreover, because the share of the latter is treated as the residual, there is no guarantee that the predicted share will be nonnegative. More sophisticated approaches for censored demand systems, alternative to Shonkwiler and Yen's two-step procedure, are found in Perali and Chavas (2000), Yen *et al.* (2003), Dong *et al.* (2004) and, more recently, Tiffin and Matthieu (2010).

[95] This program can certainly be of use to other STATA users because: *a)* it estimates the original version of the QUAIDS model, and not its common linear approximation that uses the Stone price index; *b)* it allows bootstrapping the elasticities at a given point (e.g., at mean values). The help with this which I received from Brian Poi, who at the time worked for StataCorp, is invaluable.

Nonlinear Least Squares (Cameron and Trivedi [2005]). Standard errors of both price and expenditure elasticities, which are complex functions of the coefficients ([9], [10]), were obtained via non-parametric bootstrap (200 draws).

4.2 Data

The QUAIDS model estimated for Irish households' food demand comprises the following eight aggregates (in this order):

1) *Bread and cereals* {Bread, Flour, Biscuits, Cakes, Breakfast cereals, Other cereals} – *"Bread"*

2) *Meat* {Beef, Lamb, Pork, Bacon, Poultry, Other meat products}

3) *Fish* {Fresh fish, Frozen/tinned/smoked fish}

4) *Dairy products and eggs* {Milk, Cheese, Other milk products, Eggs} – *"Dairy"*

5) *Fruit* {Fresh fruit, Other fruit}

6) *Vegetables* {Potatoes, Fresh vegetables, Tinned vegetables, Frozen vegetables, Other vegetable products} – *"Veg"*

7) *Alcohol* {Beer at home, Wine at home, Spirits at home, Beer out, Wine out, Spirits out}

8) *Rest*

The partition of the aggregates reflects the classification of the CPI for food items in that each subgroup (in braces) has its own CPI datum. That was required to derive the prices of the aggregates (see Section 4.3 below). Aggregates 1) to 6) only cover home consumption, while *Alcohol* includes both home and away from home consumption. *Rest* is a residual category, which includes all sorts of home food consumption which are not already in 1) - 7) as well as generic expenditure on food away from home. It is given by the sum of 18 different CPI subgroups. Summary statistics of the data used (budget shares and prices), by survey year, are reported in Tables A1 - A4, in the Appendix.

The variables added to the basic version of the QUAIDS model by the method of demographic translation, and also used in both first steps of the procedures to correct for endogeneity and censoring, are *HBS87*, *HBS94*, *HBS99*, *HBS04*, *Summer*, *Urban*, *Adult*, *Educ*, *Malesh*, *Age*, *Unemplsh*, *Und5sh* and *Ovr64sh*, as defined in Table 1, below. These variables were selected as they proved to be the most relevant in results from previously estimated single equations models.

Table 1- Variables definitions.

Variable	Variable definition
HBS87, HBS94, HBS99, HBS04	Survey year dummy variables
Summer	Warm season dummy (1 if April to September; 0 if October to March)
Urban	Urban household dummy (1 if urban; 0 if rural)
Adult	Household size (number of equivalent adults)
Educ	HoH's education level (0 No formal education; 1 Primary; 2 Junior cert.; 3 Leaving cert.; 4 Sub degree; 5 Primary degree; 6 Higher university degree)
Malesh	Share of males in the household.
Age	HoH's age.
Unemplsh	Household's "own" unemployment rate (sum of unemployed household members divided by the sum of members who are older than 13)
Und5sh	Share of household members who are younger than 5 years old
Ovr64sh	Share of household members who are older than 64 years old

4.3 Prices

Price information to estimate the QUAIDS model was taken from the monthly five-digit disaggregated CPI. The observations from the four used surveys cover on the whole 60 different months (each survey covers five quarters) and this made an equal number of data points available. However, in order to have prices varying across households, as well as over time, household specific price indices were derived for each of the eight aggregates. Specifically, the expenditures on the $N = 8$ aggregates are given by the sum of n_i subgroup expenditures for which specific CPI sub-indexes are available. The prices of the aggregates used in estimation are thus derived as weighted averages (the weights being households' expenditure shares) of the sub-indices:

$$P_{it}^{h} = \sum_{j}^{n_i} w_j^h p_{jt}$$

[16]

where P_i is the price of aggregate i, p_j is the CPI of subgroup j, w is the relative expenditure share in i ($\sum_j^{n_i} w_j = 1$), and subscripts h and t indicate the household and time period, respectively.

This is equivalent to deriving implicit prices by dividing current prices expenditures by constant prices expenditures.

One obvious drawback of this approach is that price variability across households diminishes as time gets closer to the CPI base year (2006, in our case). This follows from the fact that the CPI is equal to 1 for all subgroup goods in the base year. Therefore, there is necessarily less price variability across households from the 2004-05 HBS survey than over those from the 1987-88 HBS. Nonetheless, this technique has been used in several published studies (e.g. Labeaga [1999], Tiezzi [2005], Balli and Tiezzi [2010]). Graphs 1 to 8 plot household specific price indices, thus derived, over time. The first fifteen time periods, t, correspond to the 1987-88 HBS; the second set of fifteen periods corresponds to the 1994-95 HBS; so on for the two remaining survey rounds.

Figure 1 – Household specific price index of *Bread and cereals*.

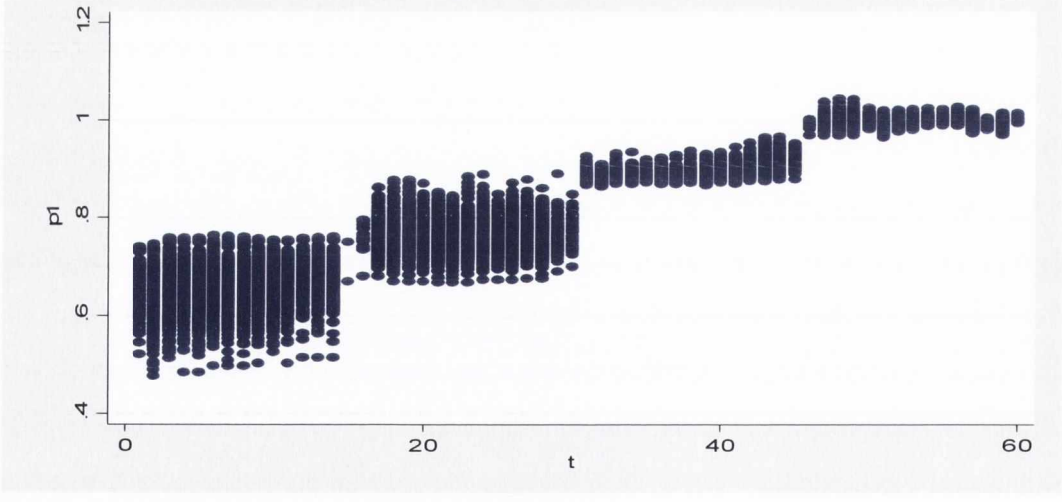


Figure 2 – Household specific price index of *Meat*.

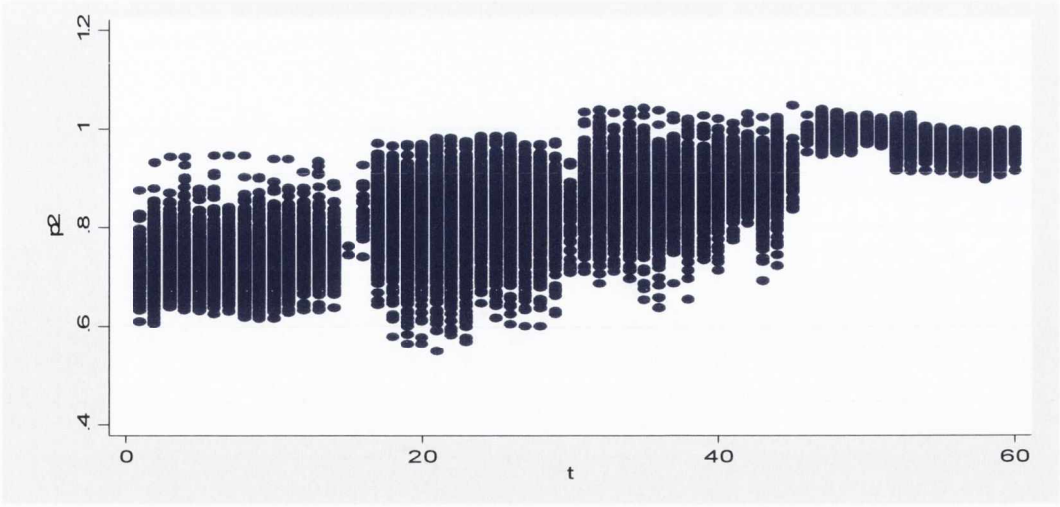


Figure 3 – Household specific price index of *Fish*.

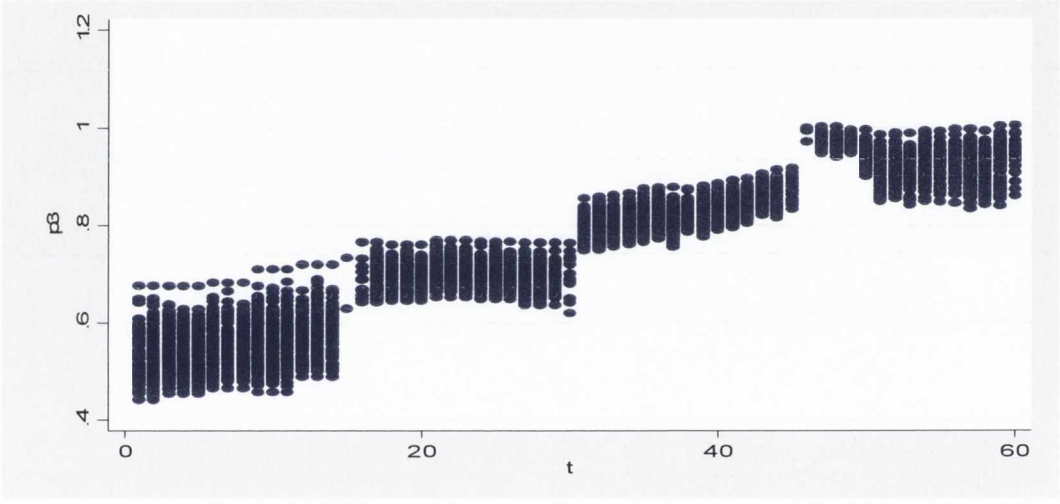


Figure 4 – Household specific price index of *Dairy products*.

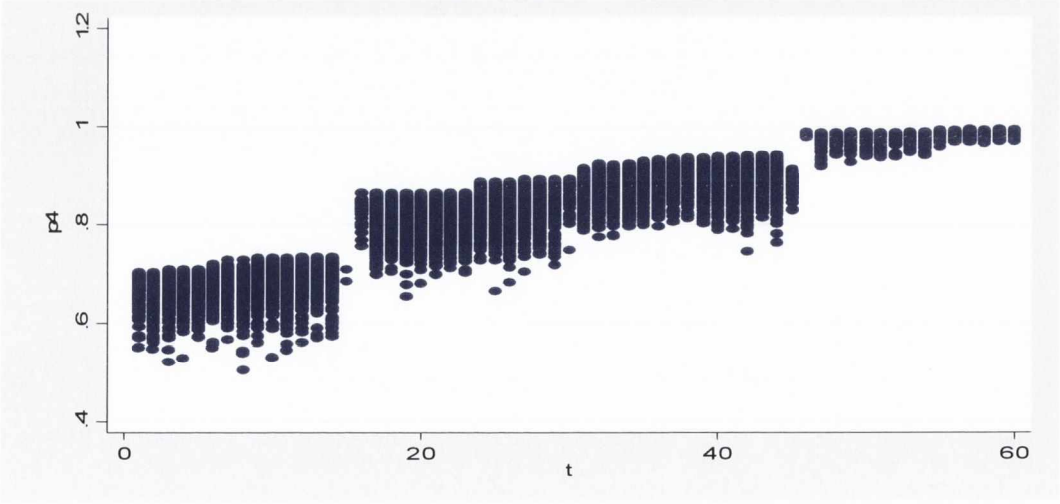


Figure 5 – Household specific price index of *Fruit*.

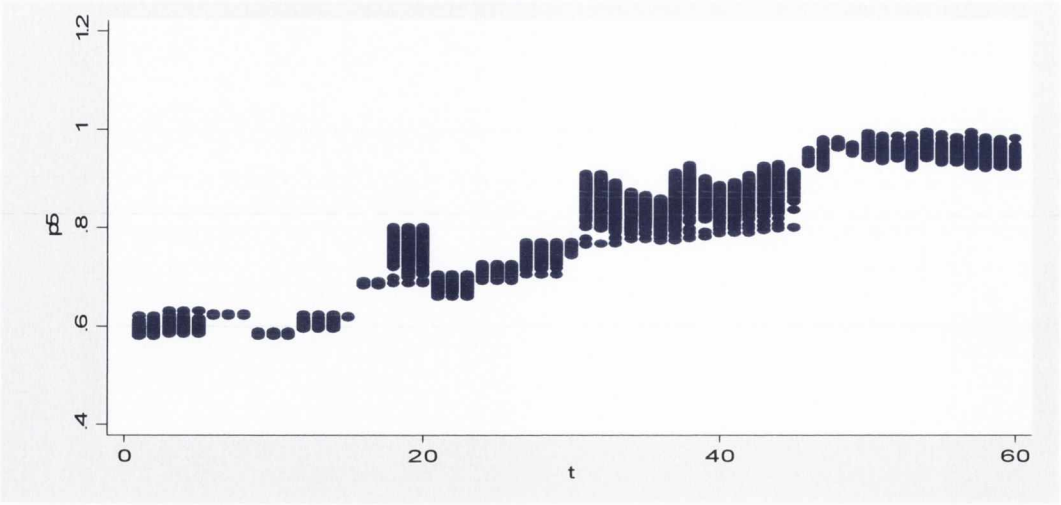


Figure 6 – Household specific price index of *Veg*.

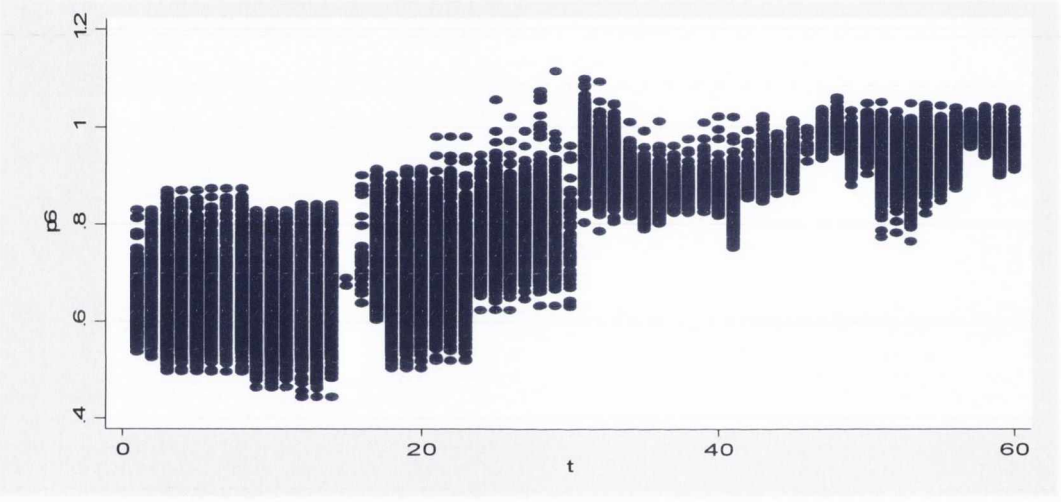


Figure 7 – Household specific price index of *Alcohol*.

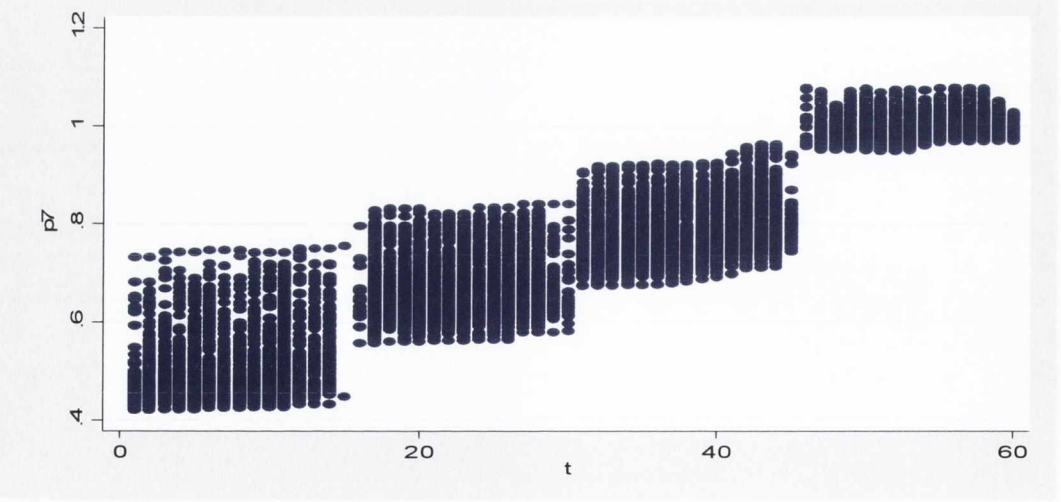
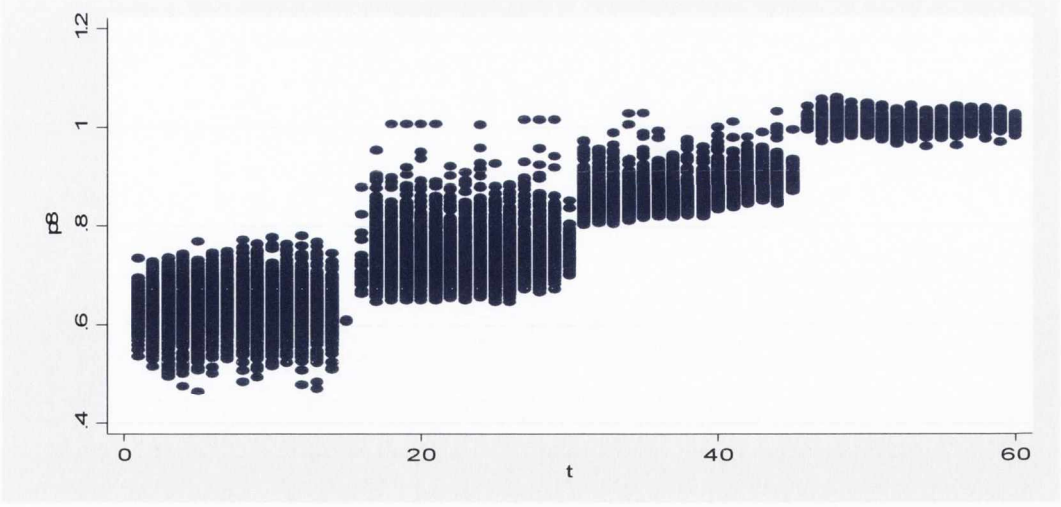


Figure 8 – Household specific price index of *Rest.*



5. Results

The four versions of the model which have been estimated all have a large number of parameters (49, 133, 140 and 143, for *Model 1* to *4*, respectively). Their estimated values are reported in the Appendix (Tables A5 and A6). Between 90% and 92% of the parameters, depending on the model's version, are statistically significant at the 95% level. Most of the coefficients corresponding to time controls and socio-demographic effects, in *Models 2 to 4*, are significant. Both in *Models 3* and *4*, all coefficients of the residuals from the first stage of Blundell and Robin's procedure are significant, which implies the correction for endogeneity of total food expenditure is indeed recommended with this sample.[96] The same is true, in *Model 4*, for the censoring (zero-expenditure) correction in fish's, fruit's and alcohol's budget shares, as the three corresponding coefficients turn out to be statistically significant.[97] Therefore, all the variations that have been considered and implemented in this paper, namely time controls and demographic effects, and both the corrections for potential endogeneity of total expenditure and for zero-expenditure, improve to some extent the base model.

However, the most direct way to appreciate the differences among the four models is to compare the elasticities they produce, which is also what we are ultimately interested in. Because we use cross-sectional data, which are supposed to represent equilibrium values,

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[96] The results of the first-stage reduced form for total food expenditure are found in the Appendix (Table A7). Note that the coefficient of income is significant, which indicates it (income) is a relevant instrument for food expenditure.

[97] The results of the first-stage estimates of the censoring process for fish, fruit and alcohol consumption are found in the Appendix too (Tables A8 to A10).

these elasticities are to be interpreted as long-run elasticities. For each model, Table 2 shows the resulting food budget elasticities (i.e., the elasticities of demand with respect to total food expenditure), evaluated at mean values, with the respective 95% confidence intervals. Blue shaded cells indicate that values therein are greater than one.

Table 2 – Food budget elasticities.

	Model 1			**Model 2**		
		95%CI			95%CI	
Bread	0.70	0.69	0.72	0.59	0.59	0.59
Meat	0.80	0.79	0.81	0.80	0.79	0.82
Fish	0.81	0.77	0.85	0.80	0.76	0.85
Dairy	0.70	0.69	0.70	0.52	0.51	0.53
Fruit	0.76	0.75	0.77	0.69	0.68	0.69
Veg	0.78	0.78	0.78	0.66	0.65	0.67
Alcohol	1.68	1.68	1.69	1.91	1.89	1.93
Rest	1.10	1.10	1.10	1.13	1.11	1.15
	Model 3			**Model 4**		
		95%CI			95%CI	
Bread	0.56	0.53	0.60	0.55	0.51	0.59
Meat	0.61	0.57	0.64	0.62	0.58	0.65
Fish	0.99	0.89	1.08	0.67	0.54	0.79
Dairy	0.47	0.44	0.51	0.46	0.42	0.50
Fruit	0.96	0.90	1.02	0.73	0.65	0.81
Veg	0.48	0.45	0.52	0.49	0.46	0.53
Alcohol	1.85	1.81	1.90	1.14	1.02	1.26
Rest	1.30	1.27	1.33	1.68	1.60	1.77

All models are concordant in finding that *Alcohol* and *Rest* are the only luxury types of food (their elasticities are greater than 1), as one would expect (food away from home is included in *Rest*). On the whole, the food budget elasticities of *Dairy*, *Bread* and *Veg* take the lowest values, while those of *Fish* and *Fruit* get closer to 1 (for these two, in *Model 3*, the upper limit of the confidence interval is actually just above 1). In this sense, the four models agree. Nonetheless, some significant differences are observed. In the base model, *Model 1*, the elasticities of all goods other than *Alcohol* and *Rest* range between .7 and .8, while greater variation is observed with the other three models. The differences between *Model 1* and *Model 2* for some foods are far from negligible, the largest ones being for *Alcohol* and *Dairy* (the elasticity of the first gets bigger, that of the second shrinks). This fact proves that allowing for time controls and socio-demographic effects is important. Moreover, the effect of correcting for expenditure endogeneity, in passing from *Model 2* to *Model 3*, is modest for *Alcohol* and *Dairy*, this time, but more substantial for the other types of food. Thus, in this case too, the impact on the elasticities that are derived is not negligible. The zero-expenditure adjustment, in *Model 4*, concerns *Fruit*, *Fish* and *Alcohol*. The respective elasticities get somewhat smaller, but this is an obvious consequence of the

fact that, as the formula in [9'] shows, they are multiplied by the probability of positive consumption, that is, a number that is less than 1. The elasticity of the residual food category, *Rest*, is affected too, however.

The elasticities we have just reviewed are food budget elasticities, that is, the elasticities of demand with respect to total food expenditure. This is just to recall that they are not income elasticities.[98] The latter, however, more than food budget elasticities, can be of use in many different applications. The income elasticity of i, ey_i (y standing for income), can be derived as the product of i's food budget elasticity, ex_i, and the income elasticity of demand for food (total), ey_x. That is,

$$ey_i \equiv \frac{\partial q_i/q_i}{\partial y/y} = \frac{\partial q_i/q_i}{\partial x/x} \times \frac{\partial x/x}{\partial y/y} \equiv ex_i \times ey_x \qquad [15]$$

Thus, following Zheng and Henneberry (2010), income elasticities of total food demand were first obtained from the regression

$$x = \alpha_0 + \delta_1 hbs_{94} + \delta_1 hbs_{99} + \delta_1 hbs_{04} + \beta_1 y + \beta_2 y^2 + \varepsilon\,, \qquad [16]$$

where $hbs_{94} - hbs_{04}$ are dummies for the survey years, y is income and ε the error term.

as

$$ey_x = (\beta_1 + 2\beta_2 y) \times y/x \qquad [17]$$

The income elasticity of food type *i*, ey_i ([17]), evaluated at sample mean values, was then bootstrapped too. The ey_i's thus obtained, from *Model 4*, are shown in Table 3. Because total food expenditure is income inelastic (i.e., $ey_x < 1$), income elasticities are lower than food budget elasticities (i.e., $ey_i < ex_i$). *Rest*, which is largely food away from home, is the only one that still turns out to be a luxury good. All the others, starting with *Dairy*, *Veg* and *Bread*, are necessities.

[98] Income or total expenditure do not enter the model, as this is estimated only for food demand under the assumption of weak separability.

Table 3 – Income elasticities from *Model 4*.

	Model 4		
	Elasticity	**95%CI**	
Bread	0.40	0.37	0.42
Meat	0.44	0.42	0.47
Fish	0.48	0.39	0.57
Dairy	0.33	0.30	0.36
Fruit	0.52	0.46	0.58
Veg	0.36	0.33	0.38
Alcohol	0.82	0.73	0.91
Rest	1.21	1.15	1.27

Turning to the responsiveness of food demand to changes in prices, uncompensated (Marshallian) price elasticities at sample mean values, from *Model 4*, are reported in Table 4. This time, blue shaded cells indicate that the given *ij* price elasticity is: *a)* positive, *b)* different from zero at the 1% significance level, and *c)* has the same sign as the elasticity of *ji* (which is different from zero at the 1% level too). The same applies to green shaded cells, except that this colour is associated with negative elasticities. Hence, *ij* elasticities in non-shaded cells are either not significant at the 1% or have a different sign from the reciprocal *ji*, while blue and green cells denote pairs of foods that are substitutes and complements, respectively.[99] Own-price elasticities – all significant at the 1% level – are of course on the main diagonal.

Table 4 – Uncompensated (Marshallian) elasticities from *Model 4*.

	Bread	*Meat*	*Fish*	*Dairy*	*Fruit*	*Veg*	*Alcohol*	*Rest*
Bread	-1.91	-0.06	0.15	-0.01	-0.13	-0.05	0.36	1.10
Meat	0.08	-1.48	-0.08	-0.17	-0.01	-0.06	-0.04	1.13
Fish	0.86	-0.31	-2.90	0.24	-0.22	-0.03	0.64	0.91
Dairy	0.15	-0.30	0.02	-1.19	-0.19	-0.19	0.09	1.17
Fruit	-0.34	-0.11	-0.17	-0.53	-1.35	0.22	0.67	0.85
Veg	0.11	-0.12	-0.05	-0.23	0.13	-1.55	0.20	1.01
Alcohol	0.11	-0.11	0.09	-0.02	0.12	0.04	-1.94	0.61
Rest	0.11	0.57	0.13	0.29	0.08	0.21	0.31	-3.37

All own-price elasticities are negative, as expected, and greater than 1 in absolute value. Also, in general, they look high. In particular, those of *Fish* and *Alcohol* (both with large proportions of zeros in the dataset), are probably greater than one would expect.[100] However, it must be recalled that these are long-run elasticities and, therefore, they are expected to be on the large side. In any case, given the absence of comparable estimates in the Irish literature, it is difficult to make a definitive judgement about the plausibility of

[99] All price elasticities (at mean values) with 95% confidence intervals, from models *1-4*, are in the Appendix (Tables A11 – A14).

[100] As for *Rest*, larger elasticities for the residual aggregate are the norm in the literature.

these elasticities. Only for alcohol, previous comparable estimates exist and suggest that the result here is not unrealistic after all. Both in Eakins and Gallagher (2003) and in Thom (1984), own-price elasticities for wine and spirits can be well above 1,[101] while they are about half as much for beer. In this application, the alcohol aggregate includes not only different types of alcohol, such as beer, wine and spirits, but also alcohol consumed away from home. Thus, the presence of the latter determines a higher elasticity for the aggregate. Other comparable estimates in the Irish literature do not exist, but Andreyeva *et al.* (2010) carry out an extended meta-analysis of price elasticities of demand for food, in the U.S. The authors review 160 studies, which use different sample and methodology, and, for sixteen food groups, work out means, confidence intervals and ranges of the estimates they found. All our elasticities are bigger than the averages derived by Andreyeva *et al.* (2010), but they are generally very close (just below or just above) to the upper limits of the said ranges.

As concerns cross-price elasticities, according to Table 4 above, the following pairs of aggregates are substitutes: {*Bread, Fish*}, {*Bread, Alcohol*}, {*Fish, Alcohol*}, {*Veg, Fruit*}, {*Veg, Alcohol*}, {*Fruit, Alcohol*}, {Rest, *Bread*}, {*Rest, Meat*} {*Rest, Fish*}, {*Rest, Dairy*}, {*Rest, Fruit*} {*Rest, Veg*}, and {*Rest, Alcohol*}. These pairs of substitutes are plausible in that they all involve the foods which were found to be, or to be closest to, luxuries (Table 2), namely *Fish*, *Fruit*, *Alcohol* and *Rest*. The following pairs, instead, correspond to complements: {*Bread, Fruit*}, {*Meat, Fish*}, {*Meat, Dairy*}, {*Meat, Veg*}, {*Fish, Fruit*}, {*Dairy, Fruit*} and {*Dairy, Veg*}.

6. Conclusions

There is only one published study that estimates a system of demand for food demand in Ireland and it is almost thirty years old (Casey [1973]). It was an application of the Linear Expenditure System, which is a very restrictive model too. In the Irish literature, estimates of income elasticities of demand only exist for few types of food, namely meat products, alcoholic beverages and food services, while price elasticities are even fewer, and older. Yet, it is possible to think of a variety of relevant research questions which require

[101] In Thom (1984), long-run own-price elasticities are -1.61 for wine and -1.29 to -1.54 for spirits; in Eakins and Gallagher (2003), they are -1.60 and -0.75, respectively.

estimates of elasticities for food demand.[102] Moreover, none of the elasticities mentioned above has ever been derived using Irish micro-data. The advantage of micro data, over aggregate data, is that information on individuals' or households' characteristics (available with the former) allows differentiating estimates by consumer type. This can be useful not only for business strategies, but for policy analysis as well. The use of fiscal instruments to address public health issues, such as obesity and alcoholism, has been contemplated by the Irish government and may become increasingly common. In these cases, having a sense of the responsiveness of different consumers to induced price changes would allow predicting the effectiveness of the measures in question. Thus, there is quite an important gap in the Irish food literature which consists of *a)* the lack of estimates of demand elasticities for a range of foods (e.g., vegetables, fruit and fish), *b)* an even greater lack of price elasticities and, *c)* an absolute lack of price elasticities estimated with micro-data. There is a reason, though, at least for *c)*: the national Household Budget Survey (HBS), which would be the natural source of information for this type of task, does not report prices or quantities and, hence, price effects cannot be immediately derived. The purpose of this paper is precisely to attempt to overcome such limitation, that is, to produce new, long due, estimates of food demand elasticities and, in so doing, verifying whether the HBS may in fact be utilized to estimate models that include prices.

The QUAIDS model of Banks *et al.* (1997) has been estimated for Irish households' food demand using the HBS, in combination with the disaggregated (five-digit) Consumer Price Index (CPI), which is the source of price information. The system includes eight food groups: bread and cereals, meat, fish, eggs and dairy products, fruit, vegetables, alcoholic beverages, and the remainder. One typical issue that arises when using aggregate price indices, instead of actual prices or unit values, is that price variability may not be sufficient to identify the model parameters. Therefore, to avoid this problem, the last four waves of the HBS (1987-88, 1994-95, 1999-00 and 2004-05) have been used and, in addition, price indices were derived which vary not only over time (monthly) but across households too. The feasibility of estimation critically depends on this expedient.

Four versions of the QUAIDS have been estimated: the first one is the base model; the second incorporates time controls and socio-demographic effects; the third adds a correction for potential endogeneity of total food expenditure; the fourth augments the former with an adjustment for censoring in the budget shares (zero-expenditure). All these

[102] Not least, applications with Computational General Equilibrium models always need estimates of such parameters.

variations improve the model and their impacts are reflected on the elasticities derived. All income elasticities are well within the range of realistic values. *Rest*, which encompasses all other non-specified types of food, including generic food away from home, is the only aggregate that turns out to be a luxury (i.e., income elasticity is greater than 1), as one would expect. Income elasticities of the other goods range from 0.33, for eggs and dairy products, to 0.82, for alcoholic beverages. As regards own-price elasticities, these appear to be on the large side, since they are all well above 1. It should be recalled, however, that these are long-run elasticities (as they stem from cross-sectional data) and, as such, are expected to be larger. In any case, it is difficult to say more about the plausibility of these elasticities in the absence of comparable estimates in the Irish literature.

All in all, the work presented in this paper has produced relatively satisfactory results. First, new estimates of demand elasticities for a few food aggregates have been provided. Secondly, it has been demonstrated that, with the disaggregated monthly CPI, price information can be introduced in the HBS, and models of demand which include price effects can then be estimated. The relevance of such advancement calls for more similar applications, which could also greatly benefit from the additional information that will be available soon with the 2009-10 HBS.

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Appendix

Table A1- Budget shares & prices 1987-88 HBS

	Obs.	Mean	SD	Min	Max
w1	7695	7695	0.13	0.06	0.00
w2	7695	7695	0.22	0.10	0.00
w3	7695	7695	0.02	0.02	0.00
w4	7695	7695	0.13	0.07	0.00
w5	7695	7695	0.03	0.03	0.00
w6	7695	7695	0.08	0.04	0.00
w7	7695	7695	0.12	0.14	0.00
w8	7695	7695	0.28	0.14	0.00
p1	7695	7695	0.67	0.04	0.49
p2	7695	7695	0.73	0.04	0.61
p3	7695	7695	0.58	0.08	0.44
p4	7695	7695	0.69	0.03	0.50
p5	7695	7695	0.60	0.02	0.58
p6	7695	7695	0.65	0.08	0.44
p7	7695	7695	0.49	0.06	0.42
p8	7695	7695	0.57	0.07	0.40

Table A2 – Budget shares & prices 1994-95 HBS

	Obs	Mean	SD	Min	Max
w1	7853	0.12	0.06	0.00	0.77
w2	7853	0.19	0.11	0.00	0.74
w3	7853	0.02	0.03	0.00	0.57
w4	7853	0.11	0.07	0.00	1.00
w5	7853	0.03	0.03	0.00	0.41
w6	7853	0.08	0.05	0.00	0.47
w7	7853	0.14	0.16	0.00	0.95
w8	7853	0.31	0.16	0.00	1.00
p1	7865	0.76	0.02	0.67	0.89
p2	7865	0.82	0.06	0.55	0.99
p3	7865	0.72	0.04	0.62	0.77
p4	7865	0.83	0.03	0.65	0.89
p5	7865	0.74	0.04	0.66	0.80
p6	7865	0.74	0.08	0.50	1.11
p7	7865	0.66	0.05	0.56	0.84
p8	7865	0.68	0.06	0.55	1.02

Table A3- Budget shares & prices 1999-00 HBS

	Obs.	Mean	SD	Min	Max
w1	7631	0.12	0.06	0.00	0.66
w2	7631	0.17	0.10	0.00	0.82
w3	7631	0.02	0.03	0.00	0.31
w4	7631	0.10	0.06	0.00	0.69
w5	7631	0.03	0.03	0.00	0.37
w6	7631	0.08	0.05	0.00	0.60
w7	7631	0.16	0.16	0.00	1.00
w8	7631	0.32	0.14	0.00	1.00
p1	7644	0.88	0.02	0.81	0.97
p2	7644	0.88	0.05	0.64	1.05
p3	7644	0.85	0.04	0.75	0.92
p4	7644	0.89	0.03	0.75	0.94
p5	7644	0.88	0.03	0.77	0.93
p6	7644	0.88	0.05	0.75	1.10
p7	7644	0.78	0.05	0.68	0.96
p8	7644	0.80	0.06	0.68	1.03

Table A4 – Budget shares & prices 2004-05 HBS

	Obs	Mean	SD	Min	Max
w1	6879	0.11	0.07	0.00	0.84
w2	6879	0.16	0.11	0.00	0.79
w3	6879	0.01	0.03	0.00	0.44
w4	6879	0.09	0.06	0.00	1.00
w5	6879	0.04	0.04	0.00	0.46
w6	6879	0.08	0.05	0.00	0.71
w7	6879	0.18	0.17	0.00	1.00
w8	6879	0.33	0.16	0.00	1.00
p1	6882	1.00	0.01	0.96	1.06
p2	6882	0.98	0.02	0.90	1.05
p3	6882	0.95	0.04	0.84	1.01
p4	6882	0.98	0.01	0.92	0.99
p5	6882	0.94	0.01	0.92	1.00
p6	6882	0.96	0.04	0.76	1.06
p7	6882	0.99	0.03	0.95	1.08
p8	6882	0.98	0.02	0.92	1.05

Table A5 – Estiamated coefficients of Models 1 and 2.

		Model 1					Model 2			
Variable		*Coeff.*	*Std. Err.*	*z*	*p-value*		*Coeff.*	*Std. Err.*	*z*	*p-value*
Constant	a1	0.14	0.00	41.86	0.00		0.17	0.00	38.40	0.00
	a2	0.16	0.01	20.24	0.00		0.08	0.01	7.82	0.00
	a3	0.00	0.00	1.39	0.16		-0.02	0.00	-7.27	0.00
	a4	0.16	0.00	33.67	0.00		0.19	0.01	32.19	0.00
	a5	0.04	0.00	12.49	0.00		0.01	0.00	2.36	0.02
	a6	0.07	0.00	19.02	0.00		0.09	0.01	17.44	0.00
	a7	0.15	0.02	9.54	0.00		0.17	0.02	9.11	0.00
Expend.	b1	-0.02	0.00	-7.31	0.00		-0.02	0.00	-8.30	0.00
	b2	0.07	0.01	10.91	0.00		0.10	0.01	15.75	0.00
	b3	0.01	0.00	8.42	0.00		0.02	0.00	10.62	0.00
	b4	-0.01	0.00	-1.38	0.17		-0.02	0.00	-5.88	0.00
	b5	0.02	0.00	7.89	0.00		0.03	0.00	10.68	0.00
	b6	0.04	0.00	13.44	0.00		0.04	0.00	14.15	0.00
	b7	-0.08	0.01	-6.43	0.00		-0.10	0.01	-9.36	0.00
Prices	g11	-0.07	0.00	-15.17	0.00		-0.06	0.00	-13.32	0.00
	g12	0.04	0.00	12.48	0.00		0.01	0.00	3.24	0.00
	g13	0.02	0.00	8.44	0.00		0.01	0.00	3.52	0.00
	g14	0.01	0.00	2.07	0.04		-0.02	0.00	-4.37	0.00
	g15	-0.01	0.00	-2.05	0.04		-0.03	0.00	-7.97	0.00
	g16	-0.01	0.00	-4.33	0.00		-0.01	0.00	-3.85	0.00
	g17	-0.04	0.00	-15.94	0.00		0.04	0.00	11.26	0.00
	g22	-0.20	0.01	-29.79	0.00		-0.23	0.01	-26.16	0.00
	g23	0.00	0.00	-0.80	0.42		0.01	0.00	5.48	0.00
	g24	0.06	0.00	14.76	0.00		0.00	0.00	1.00	0.32
	g25	0.02	0.00	5.97	0.00		0.02	0.00	4.39	0.00
	g26	0.01	0.00	3.31	0.00		0.01	0.00	1.91	0.06
	g27	-0.09	0.00	-18.68	0.00		0.09	0.01	11.68	0.00
	g33	-0.07	0.00	-39.83	0.00		-0.06	0.00	-37.30	0.00
	g34	0.02	0.00	8.82	0.00		0.01	0.00	2.73	0.01
	g35	0.00	0.00	0.67	0.50		0.00	0.00	-0.18	0.86
	g36	0.02	0.00	14.01	0.00		0.01	0.00	8.93	0.00
	g37	0.02	0.00	12.47	0.00		0.02	0.00	11.17	0.00
	g44	-0.04	0.01	-6.34	0.00		-0.11	0.01	-14.06	0.00
	g45	-0.05	0.00	-13.34	0.00		-0.03	0.00	-5.48	0.00
	g46	0.00	0.00	-1.64	0.10		0.00	0.00	-0.97	0.33
	g47	-0.07	0.00	-22.31	0.00		0.05	0.00	10.85	0.00
	g55	-0.06	0.00	-15.77	0.00		-0.03	0.01	-4.70	0.00
	g56	0.05	0.00	24.03	0.00		0.03	0.00	15.26	0.00
	g57	0.05	0.00	22.68	0.00		0.05	0.00	16.08	0.00
	g66	-0.12	0.00	-45.06	0.00		-0.13	0.00	-45.28	0.00
	g67	0.02	0.00	7.06	0.00		0.05	0.00	14.65	0.00
	g77	0.07	0.01	7.87	0.00		-0.41	0.01	-29.96	0.00
Expend. sq.	l1	0.00	0.00	-1.61	0.11		0.00	0.00	-8.94	0.00
	l2	-0.02	0.00	-14.70	0.00		-0.02	0.00	-19.73	0.00
	l3	0.00	0.00	-9.14	0.00		0.00	0.00	-10.96	0.00
	l4	0.00	0.00	-6.33	0.00		-0.01	0.00	-10.64	0.00
	l5	0.00	0.00	-10.50	0.00		-0.01	0.00	-14.67	0.00
	l6	-0.01	0.00	-17.95	0.00		-0.01	0.00	-22.04	0.00
	l7	0.04	0.00	16.02	0.00		0.06	0.00	26.93	0.00
HBS87	t11						0.03	0.00	21.27	0.00
	t21						0.01	0.00	4.49	0.00
	t31						0.02	0.00	44.17	0.00
	t41						-0.03	0.00	-20.91	0.00
	t51						0.02	0.00	12.12	0.00
	t61						0.00	0.00	6.81	0.00

	t71						0.00	0.00	2.88	0.00
HBS94	t12						0.06	0.00	19.40	0.00
	t22						-0.12	0.00	-32.51	0.00
	t32						0.00	0.00	13.46	0.00
	t42						0.00	0.00	6.74	0.00
	t52						0.00	0.00	5.37	0.00
	t62						0.00	0.00	-5.61	0.00
	t72						0.06	0.00	19.47	0.00
HBS99	t13						0.00	0.00	3.48	0.00
	t23						0.02	0.00	22.33	0.00
	t33						0.01	0.00	20.39	0.00
	t43						-0.02	0.00	-23.64	0.00
	t53						-0.02	0.00	-7.28	0.00
	t63						0.00	0.00	1.29	0.20
	t73						0.00	0.00	-0.85	0.39
Adult	t14						0.06	0.00	30.18	0.00
	t24						0.01	0.00	4.42	0.00
	t34						-0.08	0.00	-54.66	0.00
	t44						0.00	0.00	-4.05	0.00
	t54						0.00	0.00	-4.25	0.00
	t64						0.00	0.00	1.19	0.24
	t74						-0.01	0.00	-3.40	0.00
Summer	t15						0.00	0.00	3.46	0.00
	t25						0.01	0.00	10.91	0.00
	t35						0.00	0.00	2.25	0.02
	t45						0.00	0.00	2.88	0.00
	t55						0.00	0.00	-4.04	0.00
	t65						-0.02	0.00	-5.08	0.00
	t75						-0.01	0.01	-1.04	0.30
Urban	t16						0.01	0.00	4.41	0.00
	t26						0.03	0.00	21.73	0.00
	t36						-0.01	0.00	-8.28	0.00
	t46						0.06	0.00	29.08	0.00
	t56						-0.02	0.00	-19.34	0.00
	t66						0.00	0.00	-1.48	0.14
	t76						0.01	0.00	11.46	0.00
Educ_hoh	t17						-0.20	0.01	-39.87	0.00
	t27						-0.01	0.00	-6.71	0.00
	t37						0.00	0.00	-2.09	0.04
	t47						0.00	0.00	-6.91	0.00
	t57						-0.02	0.00	-18.14	0.00
	t67						0.00	0.00	-0.58	0.56
	t77						0.00	0.00	0.45	0.66
Malesh	t18						0.02	0.00	21.10	0.00
	t28						0.00	0.00	3.46	0.00
	t38						0.00	0.00	-1.76	0.08
	t48						-0.02	0.00	-23.40	0.00
	t58						0.08	0.00	22.58	0.00
	t68						-0.01	0.00	-10.65	0.00
	t78						0.00	0.00	2.26	0.02
Age	t19						0.03	0.00	12.65	0.00
	t29						-0.07	0.00	-22.21	0.00
	t39						0.00	0.00	0.13	0.90
	t49						0.00	0.00	6.98	0.00
	t59						-0.01	0.00	-16.13	0.00
	t69						0.01	0.00	5.71	0.00
	t79						0.01	0.00	4.89	0.00
Unemplsh	t110						0.00	0.00	6.15	0.00

	t210						0.02	0.00	41.69	0.00
	t310						0.01	0.00	10.41	0.00
	t410						0.00	0.00	-3.97	0.00
	t510						0.02	0.00	14.33	0.00
	t610						0.05	0.01	8.92	0.00
	t710						0.00	0.00	-1.08	0.28
Und5sh	t111						0.04	0.00	27.37	0.00
	t211						0.02	0.00	17.05	0.00
	t311						0.00	0.00	0.67	0.51
	t411						0.01	0.00	26.38	0.00
	t511						0.00	0.00	6.78	0.00
	t611						-0.04	0.00	-16.08	0.00
	t711						0.00	0.00	0.14	0.89
Ovr65sh	t112						0.00	0.00	-2.64	0.01
	t212						0.00	0.00	5.55	0.00
	t312						0.00	0.00	-5.70	0.00
	t412						0.00	0.00	-9.92	0.00
	t512						0.00	0.00	-6.25	0.00
	t612						0.00	0.01	-0.13	0.89
	t712						-0.05	0.00	-11.04	0.00
Endog. Corr.	n1									
	n2									
	n3									
	n4									
	n5									
	n6									
	n7									
Zero-exp. corr.	d3									
	d5									
	d7									

Table A6 – Estimated coefficients of Models 3 and 4.

		Model 3					Model 4			
Variable		*Coeff.*	*Std. Err.*	*z*	*p-value*		*Coeff.*	*Std. Err.*	*z*	*p-value*
Constant	a1	0.19	0.00	40.42	0.00		0.19	0.00	41.55	0.00
	a2	0.13	0.01	11.69	0.00		0.14	0.01	12.92	0.00
	a3	-0.02	0.00	-7.92	0.00		-0.17	0.02	-8.71	0.00
	a4	0.21	0.01	33.04	0.00		0.21	0.01	34.20	0.00
	a5	-0.01	0.00	-2.10	0.04		-0.02	0.01	-3.38	0.00
	a6	0.11	0.01	19.37	0.00		0.11	0.01	20.38	0.00
	a7	0.10	0.02	5.34	0.00		0.06	0.04	1.75	0.08
Expend.	b1	-0.04	0.00	-13.08	0.00		-0.04	0.00	-13.52	0.00
	b2	0.06	0.01	8.00	0.00		0.05	0.01	7.89	0.00
	b3	0.02	0.00	10.90	0.00		0.05	0.00	10.87	0.00
	b4	-0.03	0.00	-8.74	0.00		-0.04	0.00	-9.13	0.00
	b5	0.04	0.00	15.35	0.00		0.05	0.00	13.16	0.00
	b6	0.03	0.00	8.59	0.00		0.03	0.00	8.46	0.00
	b7	-0.05	0.01	-4.18	0.00		-0.04	0.02	-2.21	0.03
Prices	g11	-0.05	0.00	-11.93	0.00		-0.05	0.00	-11.35	0.00
	g12	0.01	0.00	2.88	0.00		0.01	0.00	3.57	0.00
	g13	0.01	0.00	3.03	0.00		0.01	0.00	4.34	0.00
	g14	-0.02	0.00	-4.85	0.00		-0.02	0.00	-4.45	0.00
	g15	-0.03	0.00	-8.24	0.00		-0.03	0.00	-6.94	0.00
	g16	-0.01	0.00	-3.30	0.00		-0.01	0.00	-2.64	0.01
	g17	0.04	0.00	13.07	0.00		0.04	0.00	11.32	0.00
	g22	-0.22	0.01	-25.64	0.00		-0.21	0.01	-24.64	0.00
	g23	0.01	0.00	5.81	0.00		0.01	0.00	4.29	0.00
	g24	0.00	0.00	0.09	0.93		0.00	0.00	0.77	0.44
	g25	0.02	0.00	4.97	0.00		0.02	0.00	5.17	0.00
	g26	0.01	0.00	2.96	0.00		0.01	0.00	3.92	0.00
	g27	0.09	0.01	12.36	0.00		0.08	0.01	10.61	0.00
	g33	-0.06	0.00	-37.25	0.00		-0.10	0.00	-36.10	0.00
	g34	0.01	0.00	2.88	0.00		0.01	0.00	3.88	0.00
	g35	0.00	0.00	-0.19	0.85		-0.01	0.00	-2.53	0.01
	g36	0.01	0.00	8.79	0.00		0.02	0.00	7.84	0.00
	g37	0.02	0.00	10.25	0.00		0.03	0.00	8.41	0.00
	g44	-0.11	0.01	-14.86	0.00		-0.12	0.01	-14.98	0.00
	g45	-0.02	0.00	-3.25	0.00		-0.01	0.01	-2.20	0.03
	g46	0.00	0.00	-1.21	0.23		0.00	0.00	-0.67	0.50
	g47	0.05	0.00	12.39	0.00		0.05	0.00	11.13	0.00
	g55	-0.04	0.01	-7.44	0.00		-0.05	0.01	-7.15	0.00
	g56	0.03	0.00	14.84	0.00		0.04	0.00	15.20	0.00
	g57	0.04	0.00	14.59	0.00		0.04	0.00	12.93	0.00
	g66	-0.12	0.00	-44.76	0.00		-0.12	0.00	-44.75	0.00
	g67	0.05	0.00	15.09	0.00		0.05	0.00	14.22	0.00
	g77	-0.43	0.01	-31.31	0.00		-0.51	0.02	-27.58	0.00
Expend. sq.	l1	0.00	0.00	-8.84	0.00		0.00	0.00	-9.24	0.00
	l2	-0.02	0.00	-19.56	0.00		-0.02	0.00	-20.44	0.00
	l3	0.00	0.00	-10.93	0.00		-0.01	0.00	-10.58	0.00
	l4	-0.01	0.00	-10.56	0.00		-0.01	0.00	-11.02	0.00
	l5	-0.01	0.00	-14.80	0.00		-0.01	0.00	-13.66	0.00
	l6	-0.01	0.00	-21.93	0.00		-0.01	0.00	-22.57	0.00
	l7	0.06	0.00	26.74	0.00		0.06	0.00	21.39	0.00
HBS87	t11	0.03	0.00	22.65	0.00		0.03	0.00	21.31	0.00
	t21	0.01	0.00	5.97	0.00		0.01	0.00	4.86	0.00
	t31	0.03	0.00	31.87	0.00		0.03	0.00	32.58	0.00
	t41	-0.03	0.00	-21.00	0.00		-0.02	0.00	-19.98	0.00
	t51	0.01	0.00	9.60	0.00		0.01	0.00	6.59	0.00
	t61	0.00	0.00	2.45	0.01		0.00	0.00	2.02	0.04

	t71	0.00	0.00	2.83	0.01		0.01	0.00	4.18	0.00
HBS94	t12	0.07	0.00	22.02	0.00		0.06	0.00	20.62	0.00
	t22	-0.13	0.00	-33.64	0.00		-0.14	0.01	-28.18	0.00
	t32	0.00	0.00	-2.44	0.02		0.00	0.00	-1.61	0.11
	t42	0.00	0.00	6.79	0.00		0.01	0.00	8.64	0.00
	t52	0.01	0.00	9.18	0.00		0.01	0.00	11.13	0.00
	t62	0.00	0.00	-2.89	0.00		0.00	0.00	-3.19	0.00
	t72	0.06	0.00	19.62	0.00		0.06	0.00	19.50	0.00
HBS99	t13	0.00	0.00	2.77	0.01		0.01	0.00	7.91	0.00
	t23	0.02	0.00	24.36	0.00		0.02	0.00	23.51	0.00
	t33	0.01	0.00	18.54	0.00		0.01	0.00	19.22	0.00
	t43	-0.02	0.00	-23.70	0.00		-0.02	0.00	-22.95	0.00
	t53	-0.01	0.00	-2.60	0.01		0.00	0.00	0.05	0.96
	t63	0.00	0.00	-1.33	0.19		0.00	0.00	1.50	0.14
	t73	0.00	0.00	-1.01	0.32		0.00	0.00	-0.85	0.39
Adult	t14	0.06	0.00	31.30	0.00		0.06	0.00	30.55	0.00
	t24	0.01	0.00	7.25	0.00		0.01	0.00	6.24	0.00
	t34	-0.10	0.00	-40.34	0.00		-0.11	0.00	-33.44	0.00
	t44	0.00	0.00	-3.98	0.00		0.00	0.00	-4.10	0.00
	t54	0.00	0.00	-5.19	0.00		-0.01	0.00	-7.11	0.00
	t64	0.00	0.00	-2.09	0.04		0.00	0.00	-2.14	0.03
	t74	-0.01	0.00	-3.25	0.00		-0.01	0.00	-3.56	0.00
Summer	t15	0.00	0.00	-0.15	0.88		0.00	0.00	-1.90	0.06
	t25	0.01	0.00	10.01	0.00		0.02	0.00	10.61	0.00
	t35	0.00	0.00	2.66	0.01		0.00	0.00	2.82	0.01
	t45	0.00	0.00	2.87	0.00		0.00	0.00	3.74	0.00
	t55	0.00	0.00	-1.32	0.19		0.00	0.00	0.62	0.54
	t65	-0.03	0.00	-8.15	0.00		-0.03	0.00	-8.39	0.00
	t75	-0.01	0.01	-1.21	0.23		0.00	0.01	-0.39	0.70
Urban	t16	0.01	0.00	5.89	0.00		0.01	0.00	4.77	0.00
	t26	0.03	0.00	22.68	0.00		0.03	0.00	22.16	0.00
	t36	-0.01	0.00	-8.23	0.00		-0.01	0.00	-8.02	0.00
	t46	0.06	0.00	29.20	0.00		0.06	0.00	21.79	0.00
	t56	-0.02	0.00	-22.45	0.00		-0.02	0.00	-15.64	0.00
	t66	0.00	0.00	-0.46	0.65		-0.01	0.00	-3.52	0.00
	t76	0.01	0.00	5.08	0.00		0.01	0.00	5.20	0.00
Educ_hoh	t17	-0.21	0.01	-40.81	0.00		-0.23	0.01	-32.45	0.00
	t27	-0.01	0.00	-8.40	0.00		-0.01	0.00	-9.62	0.00
	t37	0.00	0.00	-2.15	0.03		0.00	0.00	-2.44	0.02
	t47	0.00	0.00	-3.86	0.00		0.00	0.00	-3.73	0.00
	t57	-0.02	0.00	-14.27	0.00		-0.01	0.00	-12.38	0.00
	t67	-0.01	0.00	-2.50	0.01		-0.01	0.00	-2.59	0.01
	t77	-0.02	0.00	-5.26	0.00		-0.02	0.00	-5.39	0.00
Malesh	t18	0.02	0.00	22.65	0.00		0.02	0.00	21.74	0.00
	t28	0.01	0.00	5.12	0.00		0.00	0.00	4.10	0.00
	t38	0.00	0.00	-2.04	0.04		0.00	0.00	-1.93	0.05
	t48	-0.01	0.00	-19.65	0.00		-0.01	0.00	-19.59	0.00
	t58	0.07	0.00	18.57	0.00		0.07	0.01	11.76	0.00
	t68	-0.01	0.00	-6.91	0.00		-0.02	0.00	-7.96	0.00
	t78	0.00	0.00	3.47	0.00		0.01	0.00	4.56	0.00
Age	t19	0.04	0.00	15.33	0.00		0.03	0.00	14.38	0.00
	t29	-0.08	0.00	-23.74	0.00		-0.09	0.00	-20.44	0.00
	t39	0.00	0.00	0.94	0.35		0.00	0.00	1.07	0.29
	t49	0.00	0.00	5.98	0.00		0.00	0.00	8.31	0.00
	t59	-0.01	0.00	-11.83	0.00		-0.01	0.00	-12.24	0.00
	t69	0.01	0.00	3.49	0.00		0.01	0.00	3.38	0.00
	t79	0.00	0.00	1.15	0.25		0.00	0.00	1.24	0.22
Unemplsh	t110	0.00	0.00	5.34	0.00		0.02	0.00	9.66	0.00

	t210	0.02	0.00	34.01	0.00		0.02	0.00	34.65	0.00
	t310	0.01	0.00	10.58	0.00		0.01	0.00	10.90	0.00
	t410	0.00	0.00	-2.08	0.04		0.00	0.00	-1.95	0.05
	t510	0.02	0.00	17.65	0.00		0.02	0.00	17.40	0.00
	t610	0.07	0.01	10.88	0.00		0.08	0.01	10.01	0.00
	t710	0.01	0.00	4.69	0.00		0.01	0.00	5.19	0.00
Und5sh	t111	0.04	0.00	28.39	0.00		0.04	0.00	28.13	0.00
	t211	0.03	0.00	20.40	0.00		0.03	0.00	21.46	0.00
	t311	0.00	0.00	0.52	0.60		0.00	0.00	-0.01	0.99
	t411	0.01	0.00	22.56	0.00		0.01	0.00	20.96	0.00
	t511	0.00	0.00	5.37	0.00		0.00	0.00	7.52	0.00
	t611	-0.04	0.00	-15.96	0.00		-0.04	0.00	-16.31	0.00
	t711	-0.01	0.00	-3.47	0.00		-0.01	0.00	-3.57	0.00
Ovr65sh	t112	-0.01	0.00	-5.55	0.00		-0.01	0.00	-7.15	0.00
	t212	0.00	0.00	0.42	0.67		0.00	0.00	4.66	0.00
	t312	0.00	0.00	-5.87	0.00		0.00	0.00	-5.07	0.00
	t412	0.00	0.00	-7.66	0.00		0.00	0.00	-7.50	0.00
	t512	0.00	0.00	-3.75	0.00		0.00	0.00	-4.21	0.00
	t612	0.00	0.01	0.13	0.90		0.00	0.01	-0.28	0.78
	t712	-0.03	0.01	-6.14	0.00		-0.04	0.01	-5.64	0.00
Endog. Corr.	n1	0.02	0.00	11.97	0.00		0.02	0.00	13.65	0.00
	n2	0.05	0.00	12.62	0.00		0.06	0.00	15.52	0.00
	n3	0.00	0.00	-3.43	0.00		-0.02	0.00	-6.23	0.00
	n4	0.02	0.00	7.45	0.00		0.02	0.00	9.17	0.00
	n5	-0.02	0.00	-12.41	0.00		-0.02	0.00	-10.74	0.00
	n6	0.01	0.00	8.21	0.00		0.02	0.00	10.16	0.00
	n7	-0.06	0.01	-8.81	0.00		-0.03	0.01	-3.23	0.00
Zero-exp. corr.	d3						0.10	0.01	9.10	0.00
	d5						0.05	0.01	9.28	0.00
	d7						0.15	0.01	11.04	0.00

Table A7 – Estimation results of reduced-form for logarithm of total food expenditure .

	Coeff.	Std. Err. (rob.)	t	p-value
lnp1	0.1177	0.0568	2.07	0.038
lnp2	-0.1257	0.0449	-2.80	0.005
lnp3	-0.1858	0.0298	-6.24	0.000
lnp4	-0.9565	0.0769	-12.44	0.000
lnp5	-0.0695	0.0766	-0.91	0.364
lnp6	-0.1142	0.0287	-3.97	0.000
lnp7	-0.1655	0.0337	-4.91	0.000
lnp8	-0.7352	0.0630	-11.68	0.000
hbs_d1	-0.9036	0.0611	-14.80	0.000
hbs_d2	-0.4855	0.0371	-13.09	0.000
hbs_d3	-0.1912	0.0185	-10.32	0.000
Urban	-0.0360	0.0055	-6.55	0.000
educ_hoh	-0.0208	0.0035	-5.85	0.000
Malesh	0.1865	0.0097	19.20	0.000
Age	0.0761	0.0055	13.78	0.000
Adult	0.2989	0.0038	79.13	0.000
Summer	0.0085	0.0057	1.49	0.137
und5sh	-0.0523	0.0260	-2.01	0.044
ovr65sh	-0.2209	0.0130	-17.05	0.000
Unemplsh	-0.0722	0.0164	-4.39	0.000
Lninc	0.2748	0.0050	55.38	0.000
Constant	3.0587	0.0303	100.82	0.000
R-sq.	0.5580			
N	26747			

Table A8 – Estimation results of probit model for Fish consumption (zero-expenditure correction).

	Coeff.	Std. Err. (rob.)	z	p-value
hbs_d1	0.3915	0.0252	15.56	0.000
hbs_d2	0.3591	0.0243	14.80	0.000
hbs_d3	0.3684	0.0234	15.76	0.000
Urban	0.1316	0.0167	7.87	0.000
educ_hoh	0.0147	0.0109	1.35	0.178
Malesh	-0.0877	0.0295	-2.97	0.003
Age	0.0895	0.0170	5.26	0.000
Adult	0.2014	0.0126	15.94	0.000
Summer	-0.0077	0.0159	-0.48	0.630
und5sh	0.1230	0.0799	1.54	0.124
ovr65sh	-0.0461	0.0393	-1.17	0.241
Unemplsh	-0.1560	0.0504	-3.10	0.002
Lninc	0.1405	0.0153	9.16	0.000
_cons	-1.1243	0.0938	-11.98	0.000
Constant	0.0341			
N	26747			

Table A9 – Estimation results of probit model for Fruit consumption (zero-expenditure correction).

	Coeff.	Std. Err. (rob.)	z	p-value
hbs_d1	0.0732	0.0370	1.98	0.048
hbs_d2	-0.0402	0.0361	-1.11	0.265
hbs_d3	-0.0152	0.0364	-0.42	0.675
Urban	-0.0458	0.0247	-1.85	0.064
educ_hoh	0.1919	0.0190	10.12	0.000
Malesh	-0.6091	0.0388	-15.70	0.000
Age	0.1035	0.0262	3.95	0.000
Adult	0.3600	0.0253	14.24	0.000
Summer	-0.0048	0.0234	-0.21	0.836
und5sh	0.1148	0.1227	0.94	0.350
ovr65sh	-0.1091	0.0527	-2.07	0.038
Unemplsh	-0.4340	0.0606	-7.16	0.000
Lninc	0.2967	0.0215	13.80	0.000
Constant	-0.1940	0.1557	-1.25	0.213
Pseudo R-sq.	0.1433			
N	26747			

Table A10 – Estimation results of probit model for Alcohol consumption (zero-expenditure correction).

	Coeff.	Std. Err. (rob.)	z	p-value
hbs_d1	0.0854	0.0290	2.95	0.003
hbs_d2	0.1605	0.0281	5.71	0.000
hbs_d3	0.1196	0.0271	4.41	0.000
Urban	0.2310	0.0185	12.49	0.000
educ_hoh	0.1011	0.0136	7.44	0.000
Malesh	0.6325	0.0321	19.70	0.000
Age	0.0985	0.0193	5.09	0.000
Adult	0.0839	0.0143	5.85	0.000
Summer	0.0012	0.0177	0.07	0.946
und5sh	-0.0040	0.0908	-0.04	0.965
ovr65sh	-0.4654	0.0443	-10.51	0.000
Unemplsh	0.2510	0.0558	4.50	0.000
Lninc	0.5133	0.0209	24.50	0.000
Constant	-1.3310	0.1059	-12.57	0.000
Pseudo R-sq.	0.1380			
N	26747			

Table A11 – Price elasticities (uncompensated) from Model 1.

ij	ep_{ij}	SE	95% CI		ij	ep_{ij}	SE	95% CI	
1_1	-1.58	0.06	-1.70	-1.46	5_1	-0.15	0.11	-0.36	0.06
1_2	0.50	0.04	0.42	0.59	5_2	0.41	0.07	0.27	0.55
1_3	0.06	0.02	0.02	0.10	5_3	-0.05	0.05	-0.15	0.05
1_4	0.25	0.05	0.16	0.35	5_4	-1.21	0.09	-1.39	-1.03
1_5	-0.05	0.03	-0.12	0.01	5_5	-1.77	0.11	-1.98	-1.57
1_6	-0.02	0.03	-0.07	0.03	5_6	0.91	0.05	0.80	1.01
1_7	-0.56	0.03	-0.61	-0.51	5_7	0.92	0.06	0.81	1.04
1_8	0.68	0.03	0.63	0.73	5_8	0.23	0.07	0.09	0.36
2_1	0.37	0.03	0.31	0.43	6_1	-0.01	0.04	-0.08	0.07
2_2	-1.10	0.03	-1.16	-1.04	6_2	-0.01	0.04	-0.09	0.06
2_3	0.02	0.01	0.00	0.05	6_3	0.17	0.02	0.14	0.21
2_4	0.28	0.03	0.23	0.34	6_4	-0.18	0.04	-0.25	-0.11
2_5	0.11	0.01	0.09	0.14	6_5	0.43	0.03	0.38	0.48
2_6	0.02	0.02	-0.01	0.05	6_6	-1.49	0.03	-1.55	-1.43
2_7	-0.86	0.03	-0.91	-0.81	6_7	-0.34	0.04	-0.41	-0.27
2_8	0.64	0.03	0.57	0.70	6_8	0.75	0.04	0.68	0.82
3_1	0.44	0.15	0.15	0.73	7_1	-0.57	0.02	-0.62	-0.53
3_2	-0.17	0.13	-0.43	0.09	7_2	-1.22	0.03	-1.28	-1.15
3_3	-3.34	0.10	-3.54	-3.15	7_3	0.03	0.01	0.00	0.06
3_4	0.70	0.14	0.43	0.98	7_4	-0.90	0.03	-0.96	-0.85
3_5	-0.12	0.12	-0.35	0.11	7_5	0.19	0.02	0.16	0.23
3_6	0.77	0.08	0.62	0.93	7_6	-0.23	0.02	-0.27	-0.19
3_7	0.37	0.09	0.19	0.56	7_7	-0.75	0.05	-0.84	-0.66
3_8	0.55	0.11	0.33	0.77	7_8	1.77	0.04	1.69	1.86
4_1	0.28	0.05	0.18	0.39	8_1	0.21	0.01	0.19	0.23
4_2	0.42	0.04	0.33	0.50	8_2	0.31	0.02	0.27	0.36
4_3	0.11	0.02	0.06	0.15	8_3	0.03	0.01	0.01	0.05
4_4	-0.35	0.07	-0.50	-0.20	8_4	0.13	0.01	0.10	0.16
4_5	-0.42	0.03	-0.48	-0.35	8_5	0.02	0.01	0.00	0.04
4_6	-0.15	0.03	-0.20	-0.10	8_6	0.17	0.01	0.15	0.19
4_7	-1.09	0.04	-1.16	-1.01	8_7	0.97	0.02	0.93	1.02
4_8	0.51	0.04	0.44	0.58	8_8	-2.91	0.03	-2.97	-2.84

Table A12 – Price elasticities (uncompensated) from Model 2.

ij	ep_{ij}	SE	95% CI		ij	ep_{ij}	SE	95% CI	
1_1	-1.82	0.08	-1.98	-1.67	5_1	-0.81	0.11	-1.03	-0.60
1_2	-0.17	0.05	-0.26	-0.08	5_2	0.06	0.09	-0.12	0.24
1_3	0.00	0.02	-0.04	0.05	5_3	-0.18	0.05	-0.28	-0.09
1_4	0.07	0.06	-0.04	0.19	5_4	-0.88	0.11	-1.09	-0.67
1_5	-0.30	0.03	-0.36	-0.23	5_5	-0.99	0.14	-1.26	-0.71
1_6	-0.07	0.03	-0.12	-0.01	5_6	0.50	0.06	0.38	0.62
1_7	0.42	0.04	0.35	0.50	5_7	0.93	0.08	0.78	1.08
1_8	1.22	0.04	1.13	1.30	5_8	0.76	0.06	0.63	0.88
2_1	0.05	0.03	-0.01	0.11	6_1	0.02	0.04	-0.07	0.10
2_2	-1.74	0.05	-1.84	-1.64	6_2	-0.42	0.05	-0.51	-0.32
2_3	0.04	0.02	0.01	0.07	6_3	0.04	0.02	0.00	0.07
2_4	-0.11	0.03	-0.17	-0.05	6_4	-0.21	0.04	-0.29	-0.13
2_5	0.07	0.02	0.03	0.11	6_5	0.23	0.03	0.18	0.29
2_6	-0.10	0.02	-0.15	-0.06	6_6	-1.64	0.04	-1.72	-1.56
2_7	0.02	0.04	-0.05	0.09	6_7	0.19	0.04	0.11	0.28
2_8	1.43	0.04	1.34	1.52	6_8	1.27	0.04	1.19	1.35
3_1	0.59	0.16	0.27	0.90	7_1	-0.02	0.04	-0.09	0.05
3_2	0.10	0.15	-0.20	0.40	7_2	0.02	0.05	-0.09	0.12
3_3	-3.36	0.11	-3.57	-3.14	7_3	0.21	0.02	0.18	0.25
3_4	-0.33	0.15	-0.62	-0.04	7_4	-0.10	0.03	-0.16	-0.04
3_5	-0.32	0.10	-0.52	-0.12	7_5	0.22	0.02	0.17	0.27
3_6	0.33	0.09	0.16	0.50	7_6	0.03	0.03	-0.02	0.08
3_7	0.86	0.11	0.64	1.09	7_7	-2.16	0.08	-2.31	-2.02
3_8	1.36	0.12	1.12	1.61	7_8	-0.17	0.05	-0.27	-0.06
4_1	0.17	0.06	0.05	0.30	8_1	0.35	0.02	0.31	0.38
4_2	-0.41	0.05	-0.50	-0.31	8_2	0.78	0.03	0.73	0.84
4_3	-0.13	0.02	-0.17	-0.08	8_3	0.10	0.01	0.08	0.12
4_4	-1.10	0.08	-1.25	-0.94	8_4	0.34	0.01	0.32	0.37
4_5	-0.33	0.04	-0.40	-0.26	8_5	0.08	0.01	0.06	0.10
4_6	-0.20	0.03	-0.26	-0.13	8_6	0.28	0.01	0.25	0.30
4_7	0.14	0.04	0.07	0.21	8_7	0.19	0.03	0.14	0.24
4_8	1.30	0.04	1.22	1.37	8_8	-3.13	0.03	-3.20	-3.06

Table A13 – Price elasticities (uncompensated) from Model 3.

ij	ep_{ij}	SE	95% CI		ij	ep_{ij}	SE	95% CI	
1_1	-1.78	0.07	-1.93	-1.64	5_1	-1.12	0.13	-1.38	-0.86
1_2	-0.09	0.05	-0.18	0.01	5_2	0.15	0.11	-0.06	0.35
1_3	-0.01	0.02	-0.05	0.03	5_3	-0.19	0.05	-0.28	-0.10
1_4	0.08	0.05	-0.03	0.18	5_4	-0.89	0.12	-1.12	-0.67
1_5	-0.34	0.04	-0.42	-0.26	5_5	-1.33	0.15	-1.63	-1.02
1_6	-0.04	0.03	-0.09	0.01	5_6	0.49	0.06	0.38	0.61
1_7	0.41	0.04	0.34	0.49	5_7	0.83	0.08	0.68	0.98
1_8	1.20	0.05	1.11	1.30	5_8	1.11	0.08	0.95	1.27
2_1	0.07	0.03	0.01	0.13	6_1	0.09	0.04	0.01	0.17
2_2	-1.58	0.05	-1.69	-1.48	6_2	-0.23	0.05	-0.32	-0.14
2_3	-0.03	0.01	-0.06	-0.01	6_3	0.00	0.02	-0.04	0.04
2_4	-0.17	0.03	-0.22	-0.12	6_4	-0.23	0.04	-0.31	-0.16
2_5	0.03	0.02	-0.01	0.07	6_5	0.23	0.03	0.18	0.29
2_6	-0.08	0.02	-0.12	-0.04	6_6	-1.59	0.03	-1.66	-1.52
2_7	0.03	0.04	-0.05	0.11	6_7	0.23	0.04	0.14	0.31
2_8	1.12	0.04	1.05	1.19	6_8	1.02	0.05	0.92	1.11
3_1	0.34	0.16	0.04	0.65	7_1	0.03	0.03	-0.03	0.10
3_2	0.18	0.15	-0.12	0.48	7_2	0.02	0.05	-0.08	0.12
3_3	-3.35	0.11	-3.56	-3.14	7_3	0.19	0.01	0.16	0.22
3_4	-0.44	0.15	-0.74	-0.14	7_4	-0.02	0.03	-0.07	0.04
3_5	-0.40	0.10	-0.60	-0.20	7_5	0.18	0.02	0.15	0.22
3_6	0.32	0.10	0.13	0.50	7_6	0.08	0.03	0.03	0.13
3_7	0.79	0.12	0.55	1.02	7_7	-2.08	0.08	-2.24	-1.93
3_8	1.58	0.13	1.31	1.84	7_8	-0.27	0.05	-0.37	-0.17
4_1	0.21	0.06	0.09	0.33	8_1	0.26	0.02	0.22	0.30
4_2	-0.37	0.05	-0.46	-0.28	8_2	0.53	0.03	0.48	0.58
4_3	-0.13	0.02	-0.18	-0.09	8_3	0.12	0.01	0.11	0.14
4_4	-1.11	0.07	-1.25	-0.97	8_4	0.30	0.02	0.26	0.34
4_5	-0.30	0.04	-0.37	-0.22	8_5	0.12	0.01	0.10	0.14
4_6	-0.19	0.03	-0.25	-0.14	8_6	0.17	0.01	0.14	0.20
4_7	0.13	0.04	0.06	0.20	8_7	0.11	0.03	0.06	0.16
4_8	1.29	0.05	1.20	1.39	8_8	-2.92	0.04	-3.00	-2.85

Table A14 – Price elasticities (uncompensated) from Model 4.

ij	ep_{ij}	SE	95% CI		ij	ep_{ij}	SE	95% CI	
1_1	-1.91	0.08	-2.05	-1.76	5_1	-0.34	0.15	-0.64	-0.05
1_2	-0.06	0.05	-0.16	0.03	5_2	-0.11	0.10	-0.31	0.10
1_3	0.15	0.03	0.09	0.20	5_3	-0.17	0.05	-0.27	-0.08
1_4	-0.01	0.05	-0.12	0.09	5_4	-0.53	0.12	-0.77	-0.29
1_5	-0.13	0.05	-0.23	-0.04	5_5	-1.35	0.15	-1.64	-1.05
1_6	-0.05	0.03	-0.10	0.01	5_6	0.22	0.07	0.08	0.35
1_7	0.36	0.04	0.28	0.43	5_7	0.67	0.08	0.53	0.82
1_8	1.10	0.05	1.01	1.20	5_8	0.85	0.09	0.67	1.03
2_1	0.08	0.03	0.02	0.15	6_1	0.11	0.04	0.03	0.19
2_2	-1.48	0.06	-1.59	-1.37	6_2	-0.12	0.05	-0.21	-0.02
2_3	-0.08	0.02	-0.11	-0.04	6_3	-0.05	0.02	-0.10	0.00
2_4	-0.17	0.03	-0.22	-0.12	6_4	-0.23	0.04	-0.30	-0.15
2_5	-0.01	0.02	-0.06	0.03	6_5	0.13	0.03	0.06	0.19
2_6	-0.06	0.02	-0.10	-0.02	6_6	-1.55	0.03	-1.62	-1.49
2_7	-0.04	0.04	-0.12	0.04	6_7	0.20	0.05	0.11	0.29
2_8	1.13	0.04	1.06	1.21	6_8	1.01	0.05	0.91	1.11
3_1	0.86	0.12	0.63	1.09	7_1	0.11	0.02	0.07	0.16
3_2	-0.31	0.12	-0.55	-0.07	7_2	-0.11	0.04	-0.18	-0.04
3_3	-2.90	0.09	-3.07	-2.72	7_3	0.09	0.01	0.06	0.11
3_4	0.24	0.11	0.03	0.46	7_4	-0.02	0.02	-0.05	0.02
3_5	-0.22	0.07	-0.36	-0.08	7_5	0.12	0.01	0.09	0.15
3_6	-0.03	0.07	-0.16	0.11	7_6	0.04	0.02	0.00	0.07
3_7	0.64	0.10	0.44	0.84	7_7	-1.94	0.08	-2.09	-1.79
3_8	0.91	0.14	0.63	1.20	7_8	0.61	0.07	0.47	0.75
4_1	0.15	0.06	0.03	0.27	8_1	0.11	0.03	0.06	0.17
4_2	-0.31	0.05	-0.41	-0.22	8_2	0.57	0.03	0.51	0.62
4_3	0.02	0.03	-0.04	0.08	8_3	0.13	0.02	0.10	0.16
4_4	-1.19	0.07	-1.34	-1.05	8_4	0.29	0.02	0.25	0.33
4_5	-0.19	0.05	-0.28	-0.10	8_5	0.08	0.01	0.05	0.11
4_6	-0.19	0.03	-0.25	-0.13	8_6	0.21	0.02	0.18	0.24
4_7	0.09	0.04	0.02	0.16	8_7	0.31	0.04	0.23	0.38
4_8	1.17	0.05	1.07	1.28	8_8	-3.37	0.06	-3.49	-3.26

Codes

G-EMH Code (Paper 2)

(TABLO file for GEMPACK)

```
!< CODE STRUCTURE >!

!<
I)
    PRELIMINARIES
            Files
            Sets
            Base data (read statements)
                Saving
                Government consumption
                Private consumption
                Firms
                Global bank
                International trade and transport
                Carbon dioxide emissions
                Carbon taxation
            Common variables (i.e. used in more than one module)
            Common coefficients (i.e. used in more than one module)
                Key derivatives of the base data
                Regional expenditure and income
                Tax receipts
                Miscellaneous coefficients

II)
    MODULES (model's equations)
            1. Government consumption
                    1-0. Module-specific variables
                    1-1. Composite tradeables
                    1-2. Notational links
                    1-3. Non-intermittent electricity nest
                    1-4. Electricity nest
                    1-5. Energy nest
                    1-6. Non-energy nest
                    1-7. Top of the government consumption structure
            2. Private consumption
                    2-0. Module-specific variables
                    2-1. Composite tradeables
                    2-2. Notational links
                    2-3. Non-intermittent electricity nest
                    2-4. Electricity nest
                    2-5. Top of the private consumption structure (CDE)
            3. Firms
                    3-0. Module-specific variables
                    3-1. Factor employment taxation
                    3-2. Composite intermediates nest
                    3-3. Notational links
                    3-4. Input-augmenting technological change
                    3-5. Non-coal energy nest
                    3-6. Non-electricity energy nest
                    3-7. Non-intermittent electricity nest
                    3-8. Electricity nest
                    3-9. Energy nest
                    3-10. Capital-energy nest
                    3-11. Labour nest
                    3-12. Value-added-energy nest
                    3-13. Top of the production structure
                    3-14. Output taxation
            4. Investment, Global bank, and Savings
                    4-0. Module-specific variables
                    4-1. Equations of notational convenience
                    4-2. Rate of return equations
                    4-3. Global bank
                    4-4. Price index of aggregate global composite capital goods
                    4-5. Price of saving
```

```
            5. International trade
                    5-1. Export prices
                    5-2. Demand for Imports
            6. International transport services
                    6-0. Module-specific variables and coefficients
                    6-1. Demand for global transport services
                    6-2. Supply of transport services
            7. International emissions trade
            8. Regional household
                    8-0. Module-specific coefficients
                    8-1. Supply of endowments by the regional household
                    8-2. Carbon dioxide emissions
                    8-3. Carbon tax rate
                    8-4. Carbon tax revenue
                    8-5. Computation of regional income
                    8-6. Regional household demand system
                    8-7. Aggregate utility
            9. Equilibrium conditions
                    9-1. Market clearing conditions
                    9-2. Walras' Law

III)
    APPENDIX (summary indices)
            Appendix-specific variables and coefficients
            Factor price indices
            Regional terms of trade
            GDP indices (value, price and quantity)
            Aggregate trade indices (value, price and quantity)
                    Common variables and coefficients
                    Value indices for aggregate trade
                    Price indices for aggregate trade
                    Quantity indices for aggregate trade
            Trade balance indices
            Real energy price index
>!
```

```
!<================================================================
                            G-EMH
    ================================================================>!

!<----------------
    I. PRELIMINARIES
    ---------------->!

!<-----
    Files
    ----->!

File GTAPSETS # file with set specification #;
File GTAPDATA # file containing all base data #;
File GTAPPARM # file containing behavioural parameters #;

!<----
    Sets
    ---->!

Coefficient VERNUM # version of GTAP data #;
Read VERNUM from file GTAPDATA header "DVER";
Update VERNUM = 0.0;

Set HHLDS # households in each region # read elements from file GTAPSETS header "nH01";
Set REG # regions in the model # read elements from file GTAPSETS header "H1";
Set TRAD_COMM # traded commodities # read elements from file GTAPSETS header "H2";
Set MARG_COMM # margin commodities # read elements from file GTAPSETS header "MARG";
Subset MARG_COMM is subset of TRAD_COMM;
Set NMRG_COMM # non-margin commodities # = TRAD_COMM - MARG_COMM;
Set CGDS_COMM # capital goods commodities # read elements from file GTAPSETS header "H9";
Set ENDW_COMM # endowment commodities # read elements from file GTAPSETS header "H6";
Set PROD_COMM # produced commodities # = TRAD_COMM union CGDS_COMM;
```

```
Set DEMD_COMM # demanded commodities # = ENDW_COMM union TRAD_COMM;
Set NSAV_COMM # non-savings commodities # = DEMD_COMM union CGDS_COMM;
Subset PROD_COMM is subset of NSAV_COMM;

Coefficient (integer,parameter)(all,i,ENDW_COMM) SLUG(i) # sluggish primary factor endowments #;
Read SLUG from file GTAPPARM header "SLUG";

Set ENDWS_COMM # sluggish endowment commodities # = (all,i,ENDW_COMM: SLUG(i)>0);
Set ENDWM_COMM # mobile endowment commodities # = ENDW_COMM - ENDWS_COMM;
Set ENDWC_COMM # capital endowment commodity # (capital);
Subset ENDWC_COMM is subset of ENDW_COMM;
Set ENDWNC_COMM # non-capital endowment commodity # = ENDW_COMM - ENDWC_COMM;
Set ENDWL_COMM # labour endowments # (unsklab, sklab);
Set ENDWNL_COMM # non-labour endowments # (capital, land, natres);
Subset ENDWL_COMM is subset of ENDWM_COMM;
Subset ENDWNL_COMM is subset of ENDW_COMM;
Set EGY_COMM # energy commodities # read elements from file GTAPSETS header "EGY";
Subset EGY_COMM is subset of TRAD_COMM;
Set CTAX_COMM # commodities subject to carbon tax # read elements from file GTAPSETS header "CTAX";
Subset CTAX_COMM is subset of EGY_COMM;

Set BLOC #trading blocs# read elements from file GTAPPARM header "TRBL";
Mapping REGTOBLOC from REG to BLOC;
Read (by_elements) REGTOBLOC from file GTAPPARM header "MAPB";

!<----------------------------
    Base data (read statements)
    ----------------------------
    Saving
    Government consumption
    Private consumption
    Firms
    Global bank
    International trade and transport
    Carbon dioxide emissions
    Carbon taxation
>!

!<
    Saving
    ------>!

Variable (all,r,REG) psave(r) # price of savings #;
Variable (all,h,HHLDS)(all,r,REG) qsave(h,r) # regional demand for net savings #;
Coefficient (all,h,HHLDS) (all,r,REG) SAVE(h,r) # expend on net savings at agent's prices #;
Update (all,h,HHLDS)(all,r,REG) SAVE(h,r) = psave(r) * qsave(h,r);
Read SAVE from file GTAPDATA header "SAVE";

!<
    Government consumption
    ---------------------->!

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) pgd(i,h,s) # price of domestic i in government
consumption in s #;
Variable (orig_level=VDGM)(all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) qgd(i,h,s) # government hhld
demand for domestic i in region s #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDGA(i,h,r) # government consumption
expenditure on domestic i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDGA(i,h,r) = pgd(i,h,r) * qgd(i,h,r);
Read VDGA from file GTAPDATA header "VDGA";

Variable (orig_level=1.0)(all,i,NSAV_COMM)(all,r,REG) pm(i,r) # market price of commodity i in
region r #;
Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) tgd(i,h,r) # tax on domestic i purchased by
government hhld in r #;
Coefficient (ge 0) (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDGANC(i,h,r)
    # carbon-tax-excl. value of government consumption of domestic i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDGANC(i,h,r) = tgd(i,h,r) * pm(i,r) * qgd(i,h,r);
Read VDGANC from file GTAPDATA header "DGNC";

Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDGM(i,h,r) # government consumption
expenditure on domestic i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDGM(i,h,r) = pm(i,r) * qgd(i,h,r);
Read VDGM from file GTAPDATA header "VDGM";
```

```
Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) pgm(i,h,s) # price of imports of i in government
consumption in s #;
Variable (orig_level=VIGM)(all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) qgm(i,h,s) # government hhld
demand for imports of i in region s #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIGA(i,h,r) # government consumption
expenditure on imported i #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIGA(i,h,r) = pgm(i,h,r) * qgm(i,h,r);
Read VIGA from file GTAPDATA header "VIGA";

Variable (orig_level=1.0)(all,i,TRAD_COMM)(all,r,REG) pim(i,r) # market price of composite import i
in region r #;
Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) tgm(i,h,r) # tax on imported i purchased by
gov't hhld in r #;
Coefficient (ge 0) (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIGANC(i,h,r)
    # carbon-tax-excl. value of government consumption of imported i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIGANC(i,h,r) = tgm(i,h,r) * pim(i,r) *
qgm(i,h,r);
Read VIGANC from file GTAPDATA header "IGNC";

Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIGM(i,h,r) # gov't consumption
expenditure on i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIGM(i,h,r) = pim(i,r) * qgm(i,h,r);
Read VIGM from file GTAPDATA header "VIGM";

!<
    Private consumption
    ------------------->!

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) ppd(i,h,s) # price of domestic i to private
households in s #;
Variable (orig_level=VDPM)(all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) qpd(i,h,s) # private hhld
demand for domestic i in region s #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDPA(i,h,r) # private consumption
expenditure on domestic i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDPA(i,h,r) = ppd(i,h,r) * qpd(i,h,r);
Read VDPA from file GTAPDATA header "VDPA";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) atpd(i,h,r) # power of tax on domestic i
purchased by private hhld in r #;
Coefficient (ge 0) (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDPANC(i,h,r) # carbon-tax-exclusive
value of private consumption of domestic product #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDPANC(i,h,r) = atpd(i,h,r) * pm(i,r) *
qpd(i,h,r);
Read VDPANC from file GTAPDATA header "DPNC";

Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDPM(i,h,r) # private consumption
expenditure on domestic i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VDPM(i,h,r) = pm(i,r) * qpd(i,h,r);
Read VDPM from file GTAPDATA header "VDPM";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) ppm(i,h,s) # price of imports of i by private
households in s #;
Variable (orig_level=VIPM)(all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) qpm(i,h,s) # private hhld
demand for imports of i in region s #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIPA(i,h,r) # private consumption
expenditure on imported i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIPA(i,h,r) = ppm(i,h,r) * qpm(i,h,r);
Read VIPA from file GTAPDATA header "VIPA";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) atpm(i,h,r) # power of tax on imported i
purchased by private hhld in r #;
Coefficient (ge 0) (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIPANC(i,h,r) # carbon-tax-exclusive
value of private consumption of imported i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIPANC(i,h,r) = atpm(i,h,r) * pim(i,r) *
qpm(i,h,r);
Read VIPANC from file GTAPDATA header "IPNC";

Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIPM(i,h,r) # private consumption
expenditure on i in r #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VIPM(i,h,r)= pim(i,r) * qpm(i,h,r);
Read VIPM from file GTAPDATA header "VIPM";

!<
```

```
    Firms
    ----->!

Variable (all,h,HHLDS)(all,i,ENDW_COMM)(all,r,REG) pse(i,h,r) # supply price of endowment i in
region r #;
Variable (orig_level=EVOM)(all,h,HHLDS)(all,i,ENDW_COMM)(all,r,REG) qoe(i,h,r) # supply of
endowement i in region r #;

Variable (all,i,PROD_COMM)(all,r,REG) ps(i,r) # supply price of commodity i in region r #;
Variable (orig_level=VOM)(all,i,PROD_COMM)(all,r,REG) qo(i,r) # industry output of commodity i in
region r #;

Coefficient (ge 0)(all,h,HHLDS)(all,i,ENDW_COMM)(all,r,REG) EVOA(i,h,r) # value of commodity i
output in region r #;
Update (all,h,HHLDS)(all,i,ENDW_COMM)(all,r,REG) EVOA(i,h,r) = pse(i,h,r) * qoe(i,h,r);
Read EVOA from file GTAPDATA header "EVOA";

Coefficient (all,h,HHLDS)(all,i,ENDW_COMM)(all,r,REG) EVOM(i,h,r) # value of commodity i output in
region r at market prices #;
Update (all,h,HHLDS)(all,i,ENDW_COMM)(all,r,REG) EVOM(i,h,r) = pm(i,r) * qoe(i,h,r);
Read EVOM from file GTAPDATA header "EVOM";

Variable (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) pfe(i,j,r) # firms' price for endowment
commodity i in ind. j, region r #;
Variable (orig_level=VFM)(all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) qfe(i,j,r)  # demand for
endowment i for use in ind. j in region r #;
Coefficient (ge 0)(all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) EVFA(i,j,r) # producer expenditure
on i by j in r at agent's prices #;
Update (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) EVFA(i,j,r) = pfe(i,j,r) * qfe(i,j,r);
Read EVFA from file GTAPDATA header "EVFA";

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) pfd(i,j,s) # price index for domestic
purchases of i by j in region s #;
Variable (orig_level=VDFM)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) qfd(i,j,s)  # domestic good
i demanded by industry j in region s #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VDFA(i,j,r) # purchases of domestic
i for use by j in region r #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VDFA(i,j,r) = pfd(i,j,r) * qfd(i,j,r);
Read VDFA from file GTAPDATA header "VDFA";

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) tfd(i,j,r) # tax on domestic i purchased by
j in r #;
Coefficient (ge 0) (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VDFANC(i,j,r) # carbon-tax-
exclusive value of domestic i for use by j in region r #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VDFANC(i,j,r) = tfd(i,j,r) * pm(i,r) *
qfd(i,j,r);
Read VDFANC from file GTAPDATA header "DFNC";

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) pfm(i,j,s) # price index for imports of i by
j in region s #;
Variable (orig_level=VIFM)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) qfm(i,j,s) # demand for i
by industry j in region s #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VIFA(i,j,r) # purchases of imported
i for use by j in region r #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VIFA(i,j,r) = pfm(i,j,r) * qfm(i,j,r);
Read VIFA from file GTAPDATA header "VIFA";

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) tfm(i,j,r) # tax on imported i purchased by
j in r #;
Coefficient (ge 0) (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VIFANC(i,j,r) # carbon-tax-
exclusive value of imported i for use by j in region r #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VIFANC(i,j,r) = tfm(i,j,r) * pim(i,r) *
qfm(i,j,r);
Read VIFANC from file GTAPDATA header "IFNC";

Variable (all,i,ENDWS_COMM)(all,j,PROD_COMM)(all,r,REG) pmes(i,j,r) # market price of sluggish
endowment i used by j in r #;
Coefficient (ge 0)(all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) VFM(i,j,r) # producer expenditure
on i by j in r valued at mkt prices #;
Update (all,i,ENDWM_COMM)(all,j,PROD_COMM)(all,r,REG) VFM(i,j,r) = pm(i,r) * qfe(i,j,r);
Update (all,i,ENDWS_COMM)(all,j,PROD_COMM)(all,r,REG) VFM(i,j,r) = pmes(i,j,r) * qfe(i,j,r);
Read VFM from file GTAPDATA header "VFM";

Coefficient (ge 0)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VIFM(i,j,r) # purchases of imports
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```
i for use by j in region r #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VIFM(i,j,r) = pim(i,r) * qfm(i,j,r);
Read VIFM from file GTAPDATA header "VIFM";

Coefficient (ge 0)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VDFM(i,j,r) # purchases of domestic
i for use by j in region r #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) VDFM(i,j,r) = pm(i,r) * qfd(i,j,r);
Read VDFM from file GTAPDATA header "VDFM";

!<
    Global bank
    ---------->!

Variable (all,h,HHLDS)(all,r,REG) kb(h,r) # beginning-of-period capital stock in r #;
Variable (all,r,REG) pcgds(r) # price of investment goods = ps("cgds",r) #;
Coefficient (ge 0)(all,h,HHLDS)(all,r,REG) VDEP(h,r) # value of capital depeciation in r
(exogenous) #;
Update (all,h,HHLDS)(all,r,REG) VDEP(h,r) = kb(h,r) * pcgds(r);
Read VDEP from file GTAPDATA header "VDEP";

!<
    International trade and transport
    --------------------------------->!

Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) pms(i,r,s) # domestic price for good i supplied
from r to region s #;
Variable (orig_level=VXMD)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) qxs(i,r,s) # export sales of
commodity i from r to region s #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VIMS(i,r,s) # imports of i from r to s
valued at domestic mkt prices #;
Update (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VIMS(i,r,s) = pms(i,r,s) * qxs(i,r,s);
Read VIMS from file GTAPDATA header "VIMS";

Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) pcif(i,r,s) # CIF world price of commodity i
supplied from r to s #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VIWS(i,r,s) # imports of i from r to s
valued CIF (tradeables only) #;
Update (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VIWS(i,r,s) = pcif(i,r,s) * qxs(i,r,s);
Read VIWS from file GTAPDATA header "VIWS";

Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) pfob(i,r,s) # FOB world price of commodity i
supplied from r to s #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VXWD(i,r,s) # exports of i from r to s
valued FOB (tradeables only) #;
Update (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VXWD(i,r,s) = pfob(i,r,s) * qxs(i,r,s);
Read VXWD from file GTAPDATA header "VXWD";

Coefficient (ge 0)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VXMD(i,r,s) # exports of i from r to s
valued at mkt prices (tradeables only) #;
Update (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VXMD(i,r,s) = pm(i,r) * qxs(i,r,s);
Read VXMD from file GTAPDATA header "VXMD";

Variable (orig_level=VST)(all,m,MARG_COMM)(all,r,REG) qst(m,r) # sales of m from r to international
transport #;
Coefficient (ge 0)(all,m,MARG_COMM)(all,r,REG) VST(m,r) # exprts of m from r for int'l trnsport
valued at mkt p (tradeables only) #;
Update (all,m,MARG_COMM)(all,r,REG) VST(m,r) = pm(m,r) * qst(m,r);
Read VST from file GTAPDATA header "VST";

!<
    Carbon Dioxide Emissions
    ------------------------>!

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) gco2fd(i,j,r) # carbon dioxide emissions
from firms' usage of domestic product #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,j,PROD_COMM) (all,r,REG) CO2DF(i,j,r) # carbon dioxide
emissions from firms' usage of domestic product #;
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2DF(i,j,r) = gco2fd(i,j,r);
Read CO2DF from file GTAPDATA header "CODF";

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) gco2fm(i,j,r) # carbon dioxide emissions
from firms' usage of imports #;
Coefficient (ge 0)(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2IF(i,j,r) # carbon dioxide
emissions from firms' usage of imports #;
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```
Update (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2IF(i,j,r) = gco2fm(i,j,r);
Read CO2IF from file GTAPDATA header "COIF";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2gd(i,h,r) # carbon dioxide emissions from
government consumption of dom. product #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2DG(i,h,r) # carbon dioxide emissions
from government consumption of dom. product #;
Update (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2DG(i,h,r) = gco2gd(i,h,r);
Read CO2DG from file GTAPDATA header "CODG";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2gm(i,h,r) # carbon dioxide emissions from
government consumption of imports #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2IG(i,h,r) # carbon dioxide emissions
from government consumption of imports #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2IG(i,h,r) = gco2gm(i,h,r);
Read CO2IG from file GTAPDATA header "COIG";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2pd(i,h,r) # carbon dioxide emissions from
private consumption of domestic product #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2DP(i,h,r) # carbon dioxide emissions
from private consumption of domestic product #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2DP(i,h,r) = gco2pd(i,h,r);
Read CO2DP from file GTAPDATA header "CODP";

Variable (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2pm(i,h,r) # carbon dioxide emissions from
private consumption of imports #;
Coefficient (ge 0)(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2IP(i,h,r)
# carbon dioxide emissions from private consumption of imports #;
Update (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) CO2IP(i,h,r) = gco2pm(i,h,r);
Read CO2IP from file GTAPDATA header "COIP";

!<
    Carbon Taxation
    --------------->!

Variable (change) (all,b,BLOC) NCTAXB(b) # nominal carbon tax rate (current USD per tonne of
carbon) #;
Coefficient (all,r,REG) NCTAXLEV(r) # nominal carbon tax rate (current USD per tonne of carbon) #;
Update (change) (all,r,REG) NCTAXLEV(r) = NCTAXB(REGTOBLOC(r));
Read NCTAXLEV from file GTAPDATA header "NTAX";

!<----------------
    Common VARIABLES
    ---------------->!

Variable (all,h,HHLDS)(all,r,REG) y(h,r) # regional household income in region r #;
Variable (all,r,REG) preg(r) # income deflator #;
Variable (all,h,HHLDS)(all,r,REG) pop(h,r) # regional population #;
Variable (all,i,ENDWS_COMM)(all,j,PROD_COMM)(all,r,REG) qoes(i,j,r) # supply of sluggish endowment
i used by j in r #;
Variable (all,i,ENDW_COMM)(all,r,REG) endwslack(i,r) # slack variable in endowment market clearing
condition #;

Variable (all,h,HHLDS)(all,r,REG) pgov(h,r) # price index for gov't hhld expenditure in region r #;
Variable (all,h,HHLDS)(all,r,REG) yg(h,r) # regional government consumption expenditure in region r
#;
Variable (all,h,HHLDS)(all,r,REG) ug(h,r) # per capita utility from gov't expend. in region r #;
Variable (all,h,HHLDS)(all,r,REG) ppriv(h,r) # price index for private consumption expenditure in
region r #;
Variable (all,h,HHLDS)(all,r,REG) uepriv(h,r) # elasticity of cost wrt utility from private
consumption #;
Variable (all,h,HHLDS)(all,r,REG) yp(h,r) # regional private consumption expenditure in region r #;
Variable (all,h,HHLDS)(all,r,REG) up(h,r) # per capita utility from private expend. in region r #;

Variable (all,i,PROD_COMM)(all,r,REG) to(i,r) # output tax in region r #;
Variable (all,i,ENDW_COMM)(all,h,HHLDS)(all,r,reg) toe(i,h,r) # income tax on h in region r # ;

Variable (orig_level=VIM)(all,i,TRAD_COMM)(all,s,REG) qim(i,s) # aggregate imports of i in region
s, market price weights #;
Variable globalcgds # global supply of capital goods for NET investment #;
Variable pcgdswld # world average price of capital goods (net investment weights) #;

Variable (all,r,REG) gco2t(r) # carbon dioxide emissions #;
Variable (change) (all,r,REG) DVCO2TRA(r) # net emissions trading revenue #;
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```
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrgc(h,r) # change in ratio of government
consumption tax to INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrpc(h,r) # change in ratio of private consumption
tax to INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxriu(h,r) # change in ratio of tax on intermediate
usage to INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrfu(h,r) #change in ratio of tax on primary
factor usage to INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrout(h,r) # change in ratio of output tax to
INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrexp(h,r) # change in ratio of export tax to
INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrimp(h,r) # change in ratio of import tax to
INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_taxrinc(h,r) # change in ratio of income tax to
INCOME #;
Variable (change) (all,h,HHLDS)(all,r,REG) del_co2tax(h,r) # change in ratio of carbon tax to
INCOME #;

!<-------------------
    Common COEFFICIENTS
    -------------------
    Key derivatives of the base data
    Regional expenditure and income
    Tax receipts
    Miscellaneous coefficients
>!

!<
    Key derivatives of the base data
    -------------------------------->!

Coefficient (all,i,DEMD_COMM)(all,j,PROD_COMM)(all,r,REG) VFAD(i,j,r) # producer expend. on i by j
in r valued at agent's prices #;
Formula (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) VFAD(i,j,r) = EVFA(i,j,r);
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) VFAD(i,j,s) = VDFA(i,j,s) + VIFA(i,j,s);

Coefficient (all,i,NSAV_COMM)(all,r,REG) VOA(i,r) # value of commodity i output in region r at
agent's prices #;
Formula (all,i,ENDW_COMM)(all,r,REG) VOA(i,r) = sum(h,HHLDS, EVOA(i,h,r));
Formula (all,i,PROD_COMM)(all,r,REG) VOA(i,r) = sum(j,DEMD_COMM, VFAD(j,i,r));

Coefficient (all,i,TRAD_COMM)(all,r,REG) VDM(i,r) # domestic sales of i in r at mkt prices
(tradeables only) #;
Formula (all,i,TRAD_COMM)(all,r,REG) VDM(i,r) = sum(h,HHLDS,VDPM(i,h,r)) + sum(h,HHLDS,VDGM(i,h,r))
+ sum(j,PROD_COMM, VDFM(i,j,r));

Coefficient (all,i,PROD_COMM)(all,r,REG) VOM(i,r) # value of commodity i output in region r at
market prices #;
Formula (all,m,MARG_COMM)(all,r,REG) VOM(m,r) = VDM(m,r) + sum(s,REG, VXMD(m,r,s)) + VST(m,r);
Formula (all,i,NMRG_COMM)(all,r,REG) VOM(i,r) = VDM(i,r) + sum(s,REG, VXMD(i,r,s));
Formula (all,h,CGDS_COMM)(all,r,REG) VOM(h,r) = VOA(h,r);

!<
    Regional expenditure and income
    -------------------------------->!

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VGAT(i,h,r) # government cons. expenditure on
i in r at agent's prices #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) VGAT(i,h,s) = VDGA(i,h,s) + VIGA(i,h,s);
Coefficient (all,h,HHLDS)(all,r,REG) GOVEXP(h,r) # government expenditure in region r #;
Formula (all,h,HHLDS)(all,r,REG) GOVEXP(h,r) = sum(i,TRAD_COMM, VGAT(i,h,r));

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) VPAT(i,h,r) # private hhld expenditure on i
in r valued at agent's prices #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,s,REG) VPAT(i,h,s) = VDPA(i,h,s) + VIPA(i,h,s);
Coefficient (all,h,HHLDS)(all,r,REG) PRIVEXP(h,r) # private consumption expenditure in region r #;
Formula (all,h,HHLDS)(all,r,REG) PRIVEXP(h,r) = sum(i,TRAD_COMM, VPAT(i,h,r));

Coefficient (all,h,HHLDS)(all,r,REG) EXPshare(h,r) # private consumption expenditure shares in
region r #;
Formula (all,h,HHLDS)(all,r,REG) EXPshare(h,r) = PRIVEXP(h,r)/sum(hh,HHLDS, PRIVExp(hh,r));
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Coefficient (all,h,HHLDS)(all,r,REG) INCOME(h,r) # Level of expenditure, which equals NET income in
region r #;
Formula (all,h,HHLDS)(all,r,REG) INCOME(h,r) = PRIVEXP(h,r) + GOVEXP(h,r) + SAVE(h,r);

Coefficient (all,r,REG) INCOMER(r) # Level of expenditure, which equals NET income in region r #;
Formula (all,r,REG) INCOMER(r) = sum(h,HHLDS, PRIVEXP(h,r) + GOVEXP(h,r) + SAVE(h,r));

!<
    Tax receipts
    ------------>!

Coefficient (all,h,HHLDS)(all,r,REG) FY(h,r) # primary factor income in r net of depreciation #;
Formula (all,h,HHLDS)(all,r,REG) FY(h,r) = sum(i,ENDW_COMM, EVOA(i,h,r)) - VDEP(h,r);
Coefficient (all,h,HHLDS)(all,r,REG) NetTaxTr(h,r) # net tax transfer to household h in region r #;
Formula (all,h,HHLDS)(all,r,REG) NetTaxTr(h,r) = INCOME(h,r) - FY(h,r);
Coefficient (all,h,HHLDS)(all,r,reg) NetTaxTrSh(h,r);
Formula (all,h,HHLDS)(all,r,reg) NetTaxTrSh(h,r) = NetTaxTr(h,r)/sum(hh,HHLDS, NetTaxTr(hh,r));

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) DFTAX(i,j,r) # ordinary tax on
intermediate usage of domestic product #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) DFTAX(i,j,r) = VDFANC(i,j,r) - VDFM(i,j,r);

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) DFCTAX(i,j,r) # carbon tax on
intermediate usage of domestic product #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) DFCTAX(i,j,r) = VDFA(i,j,r) - VDFANC(i,j,r);

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) IFTAX(i,j,r) # ordinary tax on
intermediate usage of imports #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) IFTAX(i,j,r) = VIFANC(i,j,r) - VIFM(i,j,r);

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) IFCTAX(i,j,r) # carbon tax on
intermediate usage of imports #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) IFCTAX(i,j,r) = VIFA(i,j,r) - VIFANC(i,j,r);

Coefficient (all,h,HHLDS)(all,r,REG) TIU(h,r) # firms' tax payments on intermediate goods usage in
r #;
Formula (all,h,HHLDS)(all,r,REG) TIU(h,r) = NetTaxTrSh(h,r) * sum(i,TRAD_COMM, sum(j,PROD_COMM,
DFTAX(i,j,r) + IFTAX(i,j,r)));

!<
    Taxes on private consumption
    - - - - - - - - - - - - - - -->!

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DPTAX(i,h,r) # ordinary tax on private
consumption of domestic product #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DPTAX(i,h,r) = VDPANC(i,h,r) - VDPM(i,h,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DPCTAX(i,h,r) # carbon tax on private
consumption of domestic product #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DPCTAX(i,h,r) = VDPA(i,h,r) - VDPANC(i,h,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IPTAX(i,h,r) # ordinary tax on private
consumption of imports #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IPTAX(i,h,r) = VIPANC(i,h,r) - VIPM(i,h,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IPCTAX(i,h,r) # carbon tax on private
consumption of imports #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IPCTAX(i,h,r) = VIPA(i,h,r) - VIPANC(i,h,r);

Coefficient (all,h,HHLDS)(all,r,REG) TPC(h,r) # ordinary tax on private consumption #;
Formula (all,h,HHLDS)(all,r,REG) TPC(h,r) = NetTaxTrSh(h,r) * sum(hh,HHLDS, sum(i,TRAD_COMM,
DPTAX(i,hh,r) + IPTAX(i,hh,r)));

!<
    Taxes on Government Consumption
    - - - - - - - - - - - - - - - ->!

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DGTAX(i,h,r) # ordinary tax on government
consumption of domestic product #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DGTAX(i,h,r) = VDGANC(i,h,r) - VDGM(i,h,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DGCTAX(i,h,r) # carbon tax on gov. cons. of
domestic good i in region r #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) DGCTAX(i,h,r) = VDGA(i,h,r) - VDGANC(i,h,r);
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Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IGTAX(i,h,r) # ordinary tax on government
consumption of imports #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IGTAX(i,h,r) = VIGANC(i,h,r) - VIGM(i,h,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IGCTAX(i,h,r) # carbon tax on government
consumption of imports #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) IGCTAX(i,h,r) = VIGA(i,h,r) - VIGANC(i,h,r);

Coefficient (all,h,HHLDS)(all,r,REG) TGC(h,r) # government consumption tax payments in r #;
Formula (all,h,HHLDS)(all,r,REG) TGC(h,r) = NetTaxTrSh(h,r) * sum(hh,HHLDS, sum(i,TRAD_COMM,
DGTAX(i,hh,r) + IGTAX(i,hh,r)));

!<
    Other Taxes
    - - - - - ->!

Coefficient (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) ETAX(i,j,r) # tax on use of endowment
good i by industry j in region r #;
Formula (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) ETAX(i,j,r) = VFAD(i,j,r) - VFM(i,j,r);
Coefficient (all,h,HHLDS)(all,r,REG) TFU(h,r) # firms' tax payments on primary factor usage in r #;
Formula (all,h,HHLDS)(all,r,REG) TFU(h,r) = NetTaxTrSh(h,r) * sum(i,ENDW_COMM, sum(j,PROD_COMM,
ETAX(i,j,r)));

Coefficient (all,i,ENDW_COMM)(all,h,HHLDS)(all,r,REG) ITAX(i,h,r) # income tax on endowment i from
h in region r #;
Formula (all,i,ENDW_COMM)(all,h,HHLDS)(all,r,REG) ITAX(i,h,r) = EVOM(i,h,r) - EVOA(i,h,r);

Coefficient (all,i,PROD_COMM)(all,r,REG) PTAX(i,r) # output tax on good i in region r #;
Formula (all,i,PROD_COMM)(all,r,REG) PTAX(i,r) = VOM(i,r) - VOA(i,r);

Coefficient (all,h,HHLDS)(all,r,REG) TOUT(h,r) # production tax payments in r #;
Formula (all,h,HHLDS)(all,r,REG) TOUT(h,r) = NetTaxTrSh(h,r) * sum(i,PROD_COMM, PTAX(i,r));

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) XTAXD(i,r,s) # tax on exports of good i from
source r to destination s #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) XTAXD(i,r,s) = VXWD(i,r,s) - VXMD(i,r,s);
Coefficient (all,h,HHLDS)(all,r,REG) TEX(h,r) # export tax payments in r #;
Formula (all,h,HHLDS)(all,r,REG) TEX(h,r) = NetTaxTrSh(h,r) * sum(i,TRAD_COMM, sum(s,REG,
XTAXD(i,r,s)));

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) MTAX(i,r,s) # tax on imports of good i from
source r in destination s #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) MTAX(i,r,s) = VIMS(i,r,s) - VIWS(i,r,s);
Coefficient (all,h,HHLDS)(all,r,REG) TIM(h,r) # import tax payments in r #;
Formula (all,h,HHLDS)(all,r,REG) TIM(h,r) = NetTaxTrSh(h,r) * sum(i,TRAD_COMM, sum(s,REG,
MTAX(i,s,r)));

!<
    Miscellaneous Coefficients
    -------------------------->!

Coefficient (parameter)(all,i,TRAD_COMM) ESUBD(i) # region-generic el. of sub. domestic/imported
for all agents #;
Read ESUBD from file GTAPPARM header "ESBD";

Coefficient (all,r,REG) NHHLDS(r);
Formula (all,r,REG) NHHLDS(r) = sum(i,HHLDS, 1);

Coefficient (all,h,HHLDS)(all,r,REG) REGINV(h,r) # regional GROSS investment in r (value of "cgds"
output) #;
Formula (all,h,HHLDS)(all,r,REG) REGINV(h,r) = (1/NHHLDS(r)) * sum(k,CGDS_COMM, VOA(k,r));

Coefficient(all,h,HHLDS) (all,r,REG) NETINV(h,r) # regional NET investment in region r #;
Formula (all,h,HHLDS)(all,r,REG) NETINV(h,r) = (1/NHHLDS(r)) * sum(k,CGDS_COMM, VOA(k,r)) -
VDEP(h,r);
Coefficient GLOBINV # global expenditures on net investment #;
Formula GLOBINV = sum(r,REG, sum(h,HHLDS,NETINV(h,r)));

Coefficient(all,r,REG)(all,i,TRAD_COMM) CO2(r,i) # carbon dioxide emissions (millions of tonnes of
carbon) #;
Formula (all,r,REG)(all,i,TRAD_COMM) CO2(r,i) = sum(j,PROD_COMM, CO2DF(i,j,r)) + sum(j,PROD_COMM,
CO2IF(i,j,r)) + sum(h,HHLDS, CO2DG(i,h,r) + CO2IG(i,h,r)) + sum(h,HHLDS, CO2DP(i,h,r) +
CO2IP(i,h,r));
```

```
Coefficient (all,r,REG) CO2T(r) # carbon dioxide emissions (millions of tonnes of carbon) #;
Formula (all,r,REG) CO2T(r) = sum(i,CTAX_COMM, CO2(r,i));
Coefficient (all,b,BLOC) CO2TB(b) # carbon dioxide emissions (millions of tonnes of carbon) #;
Formula (all,b,BLOC) CO2TB(b) = sum(r,REG: REGTOBLOC(r) = b, CO2T(r));

!<------------------------------
    II. MODULES (model's equations)
    ------------------------------

    1. Government consumption
    2. Private consumption
    3. Firms
    4. Investment, Global bank, and Savings
    5. International trade
    6. International transport services
    7. International emissions trade
    8. Regional household
    9. Equilibrium conditions
>!

!<-------------------------
    1. Government consumption
    -------------------------
    1-0. Module-specific variables
    1-1. Composite tradeables
    1-2. Notational Links
    1-3: Non-intermittent electricity nest
    1-4: Electricity nest
    1-5. Energy nest
    1-6. Non-energy nest
    1-7. Top of the government consumption structure
>!

!<
    1-0. Module-specific variables
    ------------------------------>!

Set SUBG_COMM # subutilities in government consumption # (ntrm, elyg, eny, neny);
Set GOV_COMM # commodities demanded by government # = TRAD_COMM union SUBG_COMM;

Variable (all,i,GOV_COMM)(all,h,HHLDS)(all,r,REG) pg(i,h,r) # government consumption price for
commodity i in region r #;
Variable (all,i,GOV_COMM)(all,h,HHLDS)(all,r,REG) qg(i,h,r) # government hhld demand for commodity
i in region r #;
Variable (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) pgt(i,h,r) # government consumption price for
commodity i in region r #;
Variable (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) qgt(i,h,r) # government hhld demand for
commodity i in region r #;

Coefficient (all,i,GOV_COMM)(all,h,HHLDS)(all,r,REG) VGA(i,h,r) # government expend. on i in r
valued at agent's prices #;
Coefficient (all,i,SUBG_COMM)(all,h,HHLDS)(all,r,REG) VGAS(i,h,r) # government expend. on i in r
valued at agent's prices #;

!<
    1-1. Composite tradeables
    ------------------------->!

Zerodivide (zero_by_zero) default 1;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVDGANC(i,h,r) # share of carbon-tax-excl.
value of gov. consumption of domestic i in r #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVDGANC(i,h,r) = VDGANC(i,h,r) / VDGA(i,h,r);
Zerodivide (zero_by_zero) off;

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2DGVDGA(i,h,r) # emissions intensity of
government consumption of domestic i in r #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2DGVDGA(i,h,r) = CO2DG(i,h,r) / VDGA(i,h,r);
Zerodivide (zero_by_zero) off;

Equation GHHDPRICE
# taxation of government consumption of domestic product #
(all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) pgd(i,h,r)= SHVDGANC(i,h,r) * (pm(i,r) + tgd(i,h,r)) +
```

```
100.0 * CO2DGVDGA(i,h,r) * NCTAXB(REGTOBLOC(r));

Zerodivide (zero_by_zero) default 1;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVIGANC(i,h,r) # share of carbon-tax-excl.
value of gov. consumption of imported i in r #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVIGANC(i,h,r)=VIGANC(i,h,r) / VIGA(i,h,r);
Zerodivide (zero_by_zero) off;

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2IGVIGA(i,h,r) # emissions intensity of
government consumption of imported i in r #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2IGVIGA(i,h,r) = CO2IG(i,h,r) / VIGA(i,h,r);
Zerodivide (zero_by_zero) off;

Equation GHHIPRICES
# taxation of government consumption of imports # (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG)
pgm(i,h,r) = SHVIGANC(i,h,r) * (pim(i,r) + tgm(i,h,r)) + 100.0 * CO2IGVIGA(i,h,r) *
NCTAXB(REGTOBLOC(r));

Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG) GMSHR(i,h,s) # share of imports for gov't
hhld at agent's prices #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG) GMSHR(i,h,s) = VIGA(i,h,s) / VGAT(i,h,s);

Equation GCOMPRICE
# government consumption price for composite commodities #
(all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG) pgt(i,h,s) =  GMSHR(i,h,s) * pgm(i,h,s) + [1 -
GMSHR(i,h,s)] * pgd(i,h,s);

Equation GHHLDAGRIMP
# government consumption demand for aggregate imports # (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG)
qgm(i,h,s) = qgt(i,h,s) + ESUBD(i) * [pgt(i,h,s) - pgm(i,h,s)];

Equation GHHLDDOM
# government consumption demand for domestic goods #
(all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG) qgd(i,h,s) = qgt(i,h,s) + ESUBD(i) * [pgt(i,h,s) -
pgd(i,h,s)];

Equation TGCRATIO
# change in ratio of government consumption tax payments to regional income #
(all,h,HHLDS)(all,r,REG) 100.0 * INCOME(h,r) * del_taxrgc(h,r) + TGC(h,r) * y(h,r) =
NetTaxTrSh(h,r)* [sum(hh,HHLDS, sum(i,TRAD_COMM, VDGANC(i,hh,r) * tgd(i,hh,r) + DGTAX(i,hh,r) *
[pm(i,r) + qgd(i,hh,r)])) + sum(hh,HHLDS, sum(i,TRAD_COMM, VIGANC(i,hh,r) * tgm(i,hh,r) +
IGTAX(i,hh,r) * [pim(i,r) + qgm(i,hh,r)]))];

!<
    1-2. Notational links
    ---------------------->!

Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) VGA(i,h,r) = VGAT(i,h,r);

Equation PGTEQ
# prices into the government consumption system #
(all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) pgt(i,h,r) = pg(i,h,r) ;

Equation QGTEQ
# quantities from the government consumption system #
(all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) qgt(i,h,r) = qg(i,h,r) ;

!<
    1-3: Non-intermittent electricity nest
    ---------------->!

Set NTRM_COMM # inputs into non-intermittent ely subproduction # read elements from file GTAPSETS
header "NTRM";
Subset NTRM_COMM is subset of TRAD_COMM;

Formula (all,h,HHLDS)(all,r,REG) VGAS("ntrm",h,r) = sum(i,NTRM_COMM, VGA(i,h,r));
Formula (all,h,HHLDS)(all,r,REG) VGA("ntrm",h,r) = VGAS("ntrm",h,r);

Coefficient GSIZE_NTRMG # size of ELYG_COMM set #;
Formula GSIZE_NTRMG = sum(i,NTRM_COMM, 1);

Coefficient (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG) GSHNTRM(i,h,r);
Formula (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG: VGAS("ntrm",h,r) = 0) GSHNTRM(i,h,r) = 1.0 /
```

```
GSIZE_NTRMG;
Formula (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG: VGAS("ntrm",h,r) > 0) GSHNTRM(i,h,r) = VGA(i,h,r)
/ VGAS("ntrm",h,r);

Equation Eq_NTRMG
(all,h,HHLDS)(all,r,REG) pg("ntrm",h,r) = sum(k,NTRM_COMM, GSHNTRM(k,h,r)* pg(k,h,r));

Coefficient (parameter)(all,r,REG) ELNTRM(r) # elasticity of substitution in non-intermitt. ely
subproduction #;
Read ELNTRM from file GTAPPARM header "ELNT";

Equation NTRMGDEMAND
# demand for inputs into energy subconsumption # (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG)
qg(i,h,r) = qg("ntrm",h,r) - ELNTRM(r) * [pg(i,h,r) - pg("ntrm",h,r)];

!<
    1-4: Electricity nest
    ---------------->!

Set ELYG_GCOMM # inputs into ely gov't subdemand # read elements from file GTAPSETS header "ELY";
Subset ELYG_GCOMM is subset of GOV_COMM;

Formula (all,h,HHLDS)(all,r,REG) VGAS("elyg",h,r) = sum(i,ELYG_GCOMM, VGA(i,h,r));
Formula (all,h,HHLDS)(all,r,REG) VGA("elyg",h,r) = VGAS("elyg",h,r);

Coefficient GSIZE_ELYG # size of ELYG_COMM set #;
Formula GSIZE_ELYG = sum(i,ELYG_GCOMM, 1);

Coefficient (all,i,ELYG_GCOMM)(all,h,HHLDS)(all,r,REG) GSHELYG(i,h,r);
Formula (all,i,ELYG_GCOMM)(all,h,HHLDS)(all,r,REG: VGAS("elyg",h,r) = 0) GSHELYG(i,h,r) = 1.0 /
GSIZE_ELYG;
Formula (all,i,ELYG_GCOMM)(all,h,HHLDS)(all,r,REG: VGAS("elyg",h,r) > 0) GSHELYG(i,h,r) =
VGA(i,h,r) / VGAS("elyg",h,r);

Equation ELYGPRICE
(all,h,HHLDS)(all,r,REG) pg("elyg",h,r) = sum(k,ELYG_GCOMM, GSHELYG(k,h,r)* pg(k,h,r));

Coefficient (parameter)(all,r,REG) ELGELY(r);
Read ELGELY from file GTAPPARM header "ELEL";

Equation ELYGDEMAND
# demand for inputs into energy subconsumption # (all,i,ELYG_GCOMM)(all,h,HHLDS)(all,r,REG)
qg(i,h,r) = qg("elyg",h,r) - ELGELY(r) * [pg(i,h,r) - pg("elyg",h,r)];

!<
    1-5. Energy nest
    ---------------->!

Set ENY_GCOMM (coa, oil, gas, p_c, elyg);
Subset ENY_GCOMM is subset of GOV_COMM;

Formula (all,h,HHLDS)(all,r,REG) VGAS("eny",h,r) = sum(i,ENY_GCOMM, VGA(i,h,r));
Formula (all,h,HHLDS)(all,r,REG) VGA("eny",h,r) = VGAS("eny",h,r);

Coefficient GSIZE_ENY # size of ENY_GCOMM set #;
Formula GSIZE_ENY = sum(i,ENY_GCOMM, 1);

Coefficient (all,i,ENY_GCOMM)(all,h,HHLDS)(all,r,REG) GSHENY(i,h,r) # share of i in cost of energy
subutility #;
Formula (all,i,ENY_GCOMM)(all,h,HHLDS)(all,r,REG: VGAS("eny",h,r) = 0) GSHENY(i,h,r) = 1.0 /
GSIZE_ENY;
Formula (all,i,ENY_GCOMM)(all,h,HHLDS)(all,r,REG: VGAS("eny",h,r) > 0) GSHENY(i,h,r) = VGA(i,h,r) /
VGAS("eny",h,r);

Equation ENYGPRICE
# price of energy subutility # (all,h,HHLDS)(all,r,REG) pg("eny",h,r) = sum(k,ENY_GCOMM,
GSHENY(k,h,r)* pg(k,h,r));

Coefficient (parameter) (all,r,REG) ELGENY(r) # elasticity of subst. in energy subconsumption #;
Read ELGENY from file GTAPPARM header "EGEN";

Equation ENYGDEMAND
# demand for inputs into energy subconsumption # (all,i,ENY_GCOMM)(all,h,HHLDS)(all,r,REG)
qg(i,h,r) = qg("eny",h,r) - ELGENY(r) * [pg(i,h,r) - pg("eny",h,r)];
```

```
!<
    1-6. Non-Energy nest
    ------------------->!

Set NENY_GCOMM # non-energy subutility commodities # = TRAD_COMM - EGY_COMM;

Formula (all,h,HHLDS)(all,r,REG) VGAS("neny",h,r) = sum(i,NENY_GCOMM, VGA(i,h,r));
Formula (all,h,HHLDS)(all,r,REG) VGA("neny",h,r) = VGAS("neny",h,r);

Coefficient GSIZE_NENY # size of NENY_GCOMM set #;
Formula GSIZE_NENY = sum(i,NENY_GCOMM, 1);

Coefficient (all,i,NENY_GCOMM)(all,h,HHLDS)(all,r,REG) GSHNENY(i,h,r) # share of i in cost of non-
energy subutility #;
Formula (all,i,NENY_GCOMM)(all,h,HHLDS)(all,r,REG: VGAS("neny",h,r) = 0) GSHNENY(i,h,r) = 1.0 /
GSIZE_NENY;
Formula (all,i,NENY_GCOMM)(all,h,HHLDS)(all,r,REG: VGAS("neny",h,r) > 0) GSHNENY(i,h,r) =
VGA(i,h,r) / VGAS("neny",h,r);

Equation NENYGPRICE
# price of non-energy subutility # (all,h,HHLDS)(all,r,REG) pg("neny",h,r) = sum(k,NENY_GCOMM,
GSHNENY(k,h,r)* pg(k,h,r));

Coefficient (parameter)(all,r,REG) ELGNENY(r) # elasticity of substitution in non-energy
subconsumption #;
Read ELGNENY from file GTAPPARM header "EGNN";

Equation NENYGDEMAND
# demand for inputs into non-energy subconsumption # (all,i,NENY_GCOMM)(all,h,HHLDS)(all,r,REG)
qg(i,h,r) = qg("neny",h,r) - ELGNENY(r) * [pg(i,h,r) - pg("neny",h,r)];

!<
    1-7. Top of the government consumption structure
    ------------------------------------------------>!

Set UG_COMM # inputs into top of government consumption structure # (eny, neny);
Subset UG_COMM is subset of GOV_COMM ;

Equation GPRICEINDEX
# definition of price index for aggregate gov't purchases # (all,h,HHLDS)(all,r,REG) pgov(h,r) =
sum(i,UG_COMM, [VGA(i,h,r) / GOVEXP(h,r)] * pg(i,h,r));

Coefficient (parameter) (all,r,REG) ELGUG(r) # elasticity of substitution in the top of government
consumption nest #;
Read ELGUG from file GTAPPARM header "EGUG";

Equation GOVDMNDS
# government consumption demands for top nest commodities # (all,i,UG_COMM)(all,h,HHLDS)(all,r,REG)
qg(i,h,r) - pop(h,r) = ug(h,r) - ELGUG(r) * [pg(i,h,r) - pgov(h,r)];

Equation GOVU
# utility from government consumption in r # (all,h,HHLDS)(all,r,REG) yg(h,r) - pop(h,r) =
pgov(h,r) + ug(h,r);

!<----------------------
    2. Private consumption
    ----------------------
    2-0. Module-specific variables
    2-1. Composite tradeables
    2-2. Notational links
    2-3. Non-intermittent electricity nest
    2-4. Electricity nest
    2-5. Top of the private consumption structure (CDE)
>!

!<
    2-0. Module-specific variables
    ------------------------------>!

Set SUBP_COMM # subutilities in private consumption # (elyp, ntrm);
Set PRIV_COMM # commodities demanded in private consumption # = TRAD_COMM union SUBP_COMM;

Variable (all,i,PRIV_COMM)(all,h,HHLDS)(all,r,REG) pp(i,h,r) # private consumption price for
```

```
commodity i in region r #;
Variable (all,i,PRIV_COMM)(all,h,HHLDS)(all,r,REG) qp(i,h,r) # private hhld demand for commodity i
in region r #;
Variable (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) ppt(i,h,r) # private consumption price for
commodity i in region r #;
Variable (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) qpt(i,h,r) # private hhld demand for commodity i
in region r #;

Coefficient (all,i,PRIV_COMM)(all,h,HHLDS)(all,r,REG) VPA(i,h,r) # private hhld expend. on i in r
valued at agent's prices #;
Coefficient (all,i,SUBP_COMM)(all,h,HHLDS)(all,r,REG) VPAS(i,h,r) # private hhld expend. on i in r
valued at agent's prices #;

!<
    2-1. Composite tradeables
    ------------------------->!

Variable (all,r,REG) tp(r) # comm.-, source-gen. shift in tax on private cons. #;
Variable (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) tpd(i,h,r) # comm.-, source-spec. shift in tax
on private cons. of dom. #;
Equation TPDSHIFT
# permits uniform consumption tax change # (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) atpd(i,h,r) =
tpd(i,h,r) + tp(r);

Zerodivide (zero_by_zero) default 1;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVDPANC(i,h,r) # share of carbon-tax-excl.
value of priv. consumption of dom. product #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVDPANC(i,h,r) = VDPANC(i,h,r) / VDPA(i,h,r);
Zerodivide (zero_by_zero) off;

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2DPVDPA(i,h,r) # emissions intensity of
private consumption of domestic product #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2DPVDPA(i,h,r) = CO2DP(i,h,r) / VDPA(i,h,r);
Zerodivide (zero_by_zero) off;

Equation PHHDPRICE
# taxation of private consumption of domestic product # (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG)
ppd(i,h,r) = SHVDPANC(i,h,r) * (pm(i,r) + atpd(i,h,r)) + 100.0 * CO2DPVDPA(i,h,r) *
NCTAXB(REGTOBLOC(r));

Variable (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) tpm(i,h,r) # comm.-, source-spec. shift in tax
on private cons. of imp. #;

Equation TPMSHIFT
# permits uniform consumption tax change # (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) atpm(i,h,r) =
tpm(i,h,r) + tp(r);

Zerodivide (zero_by_zero) default 1;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVIPANC(i,h,r) # share of carbon-tax-excl.
value of priv. consumption of imports #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) SHVIPANC(i,h,r) = VIPANC(i,h,r) / VIPA(i,h,r);
Zerodivide (zero_by_zero) off;

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2IPVIPA(i,h,r) # emissions intensity of
private consumption of imports #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) CO2IPVIPA(i,h,r) = CO2IP(i,h,r) / VIPA(i,h,r);
Zerodivide (zero_by_zero) off;

Equation PHHIPRICES
# taxation of private consumption of imports # (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) ppm(i,h,r)
= SHVIPANC(i,h,r) * (pim(i,r) + atpm(i,h,r)) + 100.0 * CO2IPVIPA(i,h,r) * NCTAXB(REGTOBLOC(r));

Equation TPCRATIO
# change in ratio of private consumption tax payments to regional income # (all,h,HHLDS)(all,r,REG)
100.0 * INCOME(h,r) * del_taxrpc(h,r) + TPC(h,r) * y(h,r) = NetTaxTrSh(h,r)*[sum(hh,HHLDS,
sum(i,TRAD_COMM, VDPANC(i,hh,r) * atpd(i,hh,r) + DPTAX(i,hh,r) * [pm(i,r)  + qpd(i,hh,r)])) +
sum(hh,HHLDS, sum(i,TRAD_COMM, VIPANC(i,hh,r) * atpm(i,hh,r) + IPTAX(i,hh,r) * [pim(i,r) +
qpm(i,hh,r)]))];

Coefficient (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG) PMSHR(i,h,s) # share of imports for priv hhld
at agent's prices #;
Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG) PMSHR(i,h,s) = VIPA(i,h,s) / VPAT(i,h,s);
```

```
Equation PCOMPRICE
# private consumption price for composite commodities # (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG)
ppt(i,h,s) = PMSHR(i,h,s) * ppm(i,h,s) + [1 - PMSHR(i,h,s)] * ppd(i,h,s);

Equation PHHLDDOM
# private consumption demand for domestic goods # (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG)
qpd(i,h,s) = qpt(i,h,s) + ESUBD(i) * [ppt(i,h,s) - ppd(i,h,s)];

Equation PHHLDAGRIMP
# private consumption demand for aggregate imports # (all,i,TRAD_COMM)(all,h,HHLDS)(all,s,REG)
qpm(i,h,s) = qpt(i,h,s) + ESUBD(i) * [ppt(i,h,s) - ppm(i,h,s)];

!<
    2-2. Notational Links
    ---------------------->!

Formula (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) VPA(i,h,r) = VPAT(i,h,r);

Equation PPTEQ
# prices into the private consumption system # (all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) ppt(i,h,r)
= pp(i,h,r) ;

Equation QPTEQ
# quantities from the private consumption system #
(all,i,TRAD_COMM)(all,h,HHLDS)(all,r,REG) qpt(i,h,r) = qp(i,h,r) ;

!<
    2-3. Non-intermittent electricity nest
    --------------------------------------->!

Formula (all,h,HHLDS)(all,r,REG) VPAS("ntrm",h,r) = sum(i,NTRM_COMM, VPA(i,h,r));
Formula (all,h,HHLDS)(all,r,REG) VPA("ntrm",h,r) = VPAS("ntrm",h,r);

Coefficient PSIZE_NTRM # size of ENY_PCOMM set #;
Formula PSIZE_NTRM = sum(i,NTRM_COMM, 1);

Coefficient (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG) PSHNTRM(i,h,r) # share of i in cost of energy
subutility #;
Formula (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG: VPAS("ntrm",h,r) = 0) PSHNTRM(i,h,r) = 1.0 /
PSIZE_NTRM;
Formula (all,i,NTRM_COMM)(all,h,HHLDS)(all,r,REG: VPAS("ntrm",h,r) > 0) PSHNTRM(i,h,r) = VPA(i,h,r)
/ VPAS("ntrm",h,r);

Equation NTRMPPRICE
# price of energy subutility # (all,h,HHLDS)(all,r,REG) pp("ntrm",h,r) = sum(k,NTRM_COMM,
PSHNTRM(k,h,r)* pp(k,h,r));

Equation NTRMPDEMAND
# demand for inputs into energy subconsumption # (all,i, NTRM_COMM)(all,h,HHLDS)(all,r,REG)
qp(i,h,r) = qp("ntrm",h,r) - ELNTRM(r) * [pp(i,h,r) - pp("ntrm",h,r)];

!<
    2-4. Electricity nest
    ---------------------->!

Set ELYP_PCOMM # inputs into ely gov't subdemand # read elements from file GTAPSETS header "ELY";
Subset ELYP_PCOMM is subset of PRIV_COMM;

Formula (all,h,HHLDS)(all,r,REG) VPAS("elyp",h,r) = sum(i,ELYP_PCOMM, VPA(i,h,r));
Formula (all,h,HHLDS)(all,r,REG) VPA("elyp",h,r) = VPAS("elyp",h,r);

Coefficient PSIZE_ELYP # size of ENY_PCOMM set #;
Formula PSIZE_ELYP = sum(i,ELYP_PCOMM, 1);

Coefficient (all,i,ELYP_PCOMM)(all,h,HHLDS)(all,r,REG) PSHELYP(i,h,r) # share of i in cost of
energy subutility #;
Formula (all,i,ELYP_PCOMM)(all,h,HHLDS)(all,r,REG: VPAS("elyp",h,r) = 0) PSHELYP(i,h,r) = 1.0 /
PSIZE_ELYP;
Formula (all,i,ELYP_PCOMM)(all,h,HHLDS)(all,r,REG: VPAS("elyp",h,r) > 0) PSHELYP(i,h,r) =
VPA(i,h,r) / VPAS("elyp",h,r);

Equation ELYPPRICE
```

```
# price of energy subutility # (all,h,HHLDS)(all,r,REG) pp("elyp",h,r) = sum(k,ELYP_PCOMM,
PSHELYP(k,h,r)* pp(k,h,r));

Coefficient (parameter)(all,r,REG) ELPELYP(r) # elasticity of substitution in energy subconsumption
#;
Read ELPELYP from file GTAPPARM header "ELEL";

Equation ELYPDEMAND
# demand for inputs into energy subconsumption # (all,i,ELYP_PCOMM)(all,h,HHLDS)(all,r,REG)
qp(i,h,r) = qp("elyp",h,r) - ELPELYP(r) * [pp(i,h,r) - pp("elyp",h,r)];

!<
    2-5. Top of the private consumption structure (CDE)
    ---------------------------------------------------->!

Set ELEC (hydro, wind, oth_ely);
Subset ELEC is subset of TRAD_COMM;
Set NELYP_PCOMM #inputs into private non-energy subutility# = TRAD_COMM - ELEC;
Set ELYP # pravite energy composite # (elyp);
Set UP_COMM # inputs into top of private consumption structure # = ELYP + NELYP_PCOMM;
Subset UP_COMM is subset of PRIV_COMM ;

Coefficient (parameter)(all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) INCPAR(i,h,r) # expansion parameter
in the CDE minimum expenditure function #;
Read INCPAR from file GTAPPARM header "INCP";

Coefficient (parameter)(all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) SUBPAR(i,h,r) # substitution
parameter in CDE minimum expenditure function #;
Read SUBPAR from file GTAPPARM header "SUBP";

Coefficient (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) PSHUP(i,h,r) # share of private hhld
consumption devoted to good i in r #;
Formula (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) PSHUP(i,h,r) = VPA(i,h,r) / sum(k,UP_COMM,
VPA(k,h,r));

Coefficient (all,h,HHLDS)(all,r,REG) UELASPRIV(h,r) # elasticity of cost wrt utility from private
consumption #;
Formula (all,h,HHLDS)(all,r,REG) UELASPRIV(h,r) = sum(i,UP_COMM, PSHUP(i,h,r) * INCPAR(i,h,r));

Coefficient (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) ALPHA(i,h,r) # 1 - sub. parameter in the CDE
minimum expenditure function #;
Formula (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) ALPHA(i,h,r) = 1 - SUBPAR(i,h,r);

Coefficient (all,i,UP_COMM)(all,k,UP_COMM)(all,h,HHLDS)(all,r,REG) APE(i,k,h,r) # Allen partial
elst. of sub. between composite i and k in r #;
Formula (all,i,UP_COMM)(all,k,UP_COMM)(all,h,HHLDS)(all,r,REG) APE(i,k,h,r) = ALPHA(i,h,r) +
ALPHA(k,h,r) - sum(n,UP_COMM, PSHUP(n,h,r) * ALPHA(n,h,r));
Formula (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG)
    APE(i,i,h,r) = 2.0 * ALPHA(i,h,r) - sum(n,UP_COMM, PSHUP(n,h,r) * ALPHA(n,h,r))- ALPHA(i,h,r) /
PSHUP(i,h,r);

Coefficient (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) EY(i,h,r) # income elast. of private hhld
demand for i in r #;
Formula (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) EY(i,h,r) = [1.0 / sum(n,UP_COMM, PSHUP(n,h,r) *
INCPAR(n,h,r))] * [INCPAR(i,h,r) * [1.0 - ALPHA(i,h,r)] + sum(n,UP_COMM, PSHUP(n,h,r) *
INCPAR(n,h,r) * ALPHA(n,h,r))] + [ALPHA(i,h,r) - sum(n,UP_COMM, PSHUP(n,h,r) * ALPHA(n,h,r))];

Coefficient (all,i,UP_COMM)(all,k,UP_COMM)(all,h,HHLDS)(all,r,REG) EP(i,k,h,r) # uncomp. elast. of
private hhld demand for i wrt price of k in r #;
Formula (all,i,UP_COMM)(all,k,UP_COMM)(all,h,HHLDS)(all,r,REG) EP(i,k,h,r) = 0;
Formula (all,i,UP_COMM)(all,k,UP_COMM)(all,h,HHLDS)(all,r,REG) EP(i,k,h,r) = [APE(i,k,h,r) -
EY(i,h,r)] * PSHUP(k,h,r);

Equation PRIVDMNDS
# private consumption demands for composite commodities # (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG)
qp(i,h,r) - pop(h,r) = sum(k,UP_COMM, EP(i,k,h,r) * pp(k,h,r)) + EY(i,h,r) * [yp(h,r) - pop(h,r)];

Equation PHHLDINDEX
# price index for private consumption expenditure # (all,h,HHLDS)(all,r,REG) ppriv(h,r) =
sum(i,UP_COMM, PSHUP(i,h,r) * pp(i,h,r));

Equation PRIVATEU
# computation of utility from private consumption in r # (all,h,HHLDS)(all,r,REG) yp(h,r) -
pop(h,r) = ppriv(h,r) + UELASPRIV(h,r) * up(h,r);
```

```
Coefficient (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) XWCONSHR(i,h,r) # expansion-parameter-weighted
consumption share #;
Formula (all,i,UP_COMM)(all,h,HHLDS)(all,r,REG) XWCONSHR(i,h,r) = PSHUP(i,h,r) * INCPAR(i,h,r) /
UELASPRIV(h,r);

Equation UTILELASPRIV
# elasticity of expenditure wrt utility from private consumption # (all,h,HHLDS)(all,r,REG)
uepriv(h,r) = sum(i,UP_COMM, XWCONSHR(i,h,r) * [pp(i,h,r) + qp(i,h,r) - yp(h,r)]);

!<--------
    3. Firms
    --------
    3-0. Module-specific variables
    3-1. Factor employment taxation
    3-2. Composite intermediates nest
    3-3. Notational links
    3-4. Input-augmenting technological change
    3-5. Non-coal energy nest
    3-6. Non-electricity energy nest
    3-7. Non-intermittent electricity nest
    3-8. Electricity nest
    3-9. Energy nest
    3-10. Capital-energy nest
    3-11. Labour nest
    3-12. Value-added-energy nest
    3-13. Top of the production structure
    3-14. Output taxation
>!

!<
    3-0. Module-specific variables
    ------------------------------>!

Set SUBPR_COMM # subproducts # (vaen, labor, ken, eny, nely, ncoal, ntrm, ely);
Set FIRM_COMM # commodities demanded by firms # = DEMD_COMM union SUBPR_COMM;

Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) pft(i,j,r) # firms' price for commodity i
for use by j in r #;
Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) qft(i,j,r) # demand for commodity i for use
by j in region r #;
Variable (all,i,FIRM_COMM)(all,j,PROD_COMM)(all,r,REG) pf(i,j,r) # firms' price for commodity i for
use by j in r #;
Variable (all,i,FIRM_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r) # demand for commodity i for use
by j in r #;
Variable (all,i,FIRM_COMM)(all,j,PROD_COMM)(all,r,REG) af(i,j,r) # factor i augmenting tech change
in sector j of r #;
Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) ams(i,r,s) # import i from region r augmenting
tech change in region s #;
Coefficient (all,i,FIRM_COMM)(all,j,PROD_COMM)(all,r,REG) VFA(i,j,r) # producer expend. on i by j
in r valued at agent's prices #;
Coefficient (all,i,SUBPR_COMM)(all,j,PROD_COMM)(all,r,REG) VFAS(i,j,r) # producer expend. on i by j
in r valued at agent's prices #;

!<
    3-1. Factor employment taxation
    ------------------------------>!

Variable (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) tf(i,j,r) # tax on primary factor i used by
j in region r #;
Equation MPFACTPRICE
# eq'n links domestic and firm demand prices # (all,i,ENDWC_COMM)(all,j,PROD_COMM)(all,r,REG)
pfe(i,j,r) = tf(i,j,r) + pm(i,r);

Variable (all,r,REG) tl(r);
Equation LABPRICE
(all,i,ENDWL_COMM)(all,j,PROD_COMM)(all,r,REG) pfe(i,j,r) = tl(r) + tf(i,j,r) + pm(i,r);

Equation SPFACTPRICE
# eq'n links domestic and firm demand prices # (all,i,ENDWS_COMM)(all,j,PROD_COMM)(all,r,REG)
pfe(i,j,r) = tf(i,j,r) + pmes(i,j,r);

Equation TFURATIO
# change in ratio of tax payments on factor usage to regional income # (all,h,HHLDS)(all,r,REG)
```

```
100.0 * INCOME(h,r) * del_taxrfu(h,r) + TFU(h,r) * y(h,r) = NetTaxTrSh(h,r)
 *[sum(i,ENDWC_COMM, sum(j,PROD_COMM, VFAD(i,j,r) * tf(i,j,r) + ETAX(i,j,r) * [pm(i,r) +
qfe(i,j,r)])) + sum(i,ENDWL_COMM, sum(j,PROD_COMM, VFAD(i,j,r) * [tl(r) + tf(i,j,r)] + ETAX(i,j,r)
* [pm(i,r) + qfe(i,j,r)])) + sum(i,ENDWS_COMM, sum(j,PROD_COMM, VFAD(i,j,r) * tf(i,j,r) +
ETAX(i,j,r) * [pmes(i,j,r) + qfe(i,j,r)]))];

!<
    3-2. Composite intermediates nest
    --------------------------------->!

Zerodivide (zero_by_zero) default 1;
Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHVDFANC(i,j,r) # share of carbon-tax-
excl. value of domestic i for use by j in region r #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHVDFANC(i,j,r) = VDFANC(i,j,r) /
VDFA(i,j,r);
Zerodivide (zero_by_zero) off;

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2DFVDFA(i,j,r) # emissions intensity of
domestic i for use by j in region r #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2DFVDFA(i,j,r) = CO2DF(i,j,r) /
VDFA(i,j,r);
Zerodivide (zero_by_zero) off;

Equation DMNDDPRICE
# taxation of intermediate usage of domestic product #
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) pfd(i,j,r) = SHVDFANC(i,j,r) * (pm(i,r) + tfd(i,j,r))
+ 100.0 * CO2DFVDFA(i,j,r) * NCTAXB(REGTOBLOC(r));

Zerodivide (zero_by_zero) default 1;
Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHVIFANC(i,j,r) # share of carbon-tax-
excl. value of imported i for use by j in region r #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHVIFANC(i,j,r) = VIFANC(i,j,r) /
VIFA(i,j,r);
Zerodivide (zero_by_zero) off;

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2IFVIFA(i,j,r) # emissions intensity of
imported i for use by j in region r #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) CO2IFVIFA(i,j,r) = CO2IF(i,j,r) /
VIFA(i,j,r);
Zerodivide (zero_by_zero) off;

Equation DMNDIPRICES
# taxation of intermediate usage of imports # (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
pfm(i,j,r) = SHVIFANC(i,j,r) * (pim(i,r) + tfm(i,j,r)) + 100.0 * CO2IFVIFA(i,j,r) *
NCTAXB(REGTOBLOC(r));

Equation TIURATIO
# change in ratio of tax payments on intermediate goods to regional income #
(all,h,HHLDS)(all,r,REG) 100.0 * INCOME(h,r) * del_taxriu(h,r) + TIU(h,r) * y(h,r) =
NetTaxTrSh(h,r)* [sum(i,TRAD_COMM, sum(j,PROD_COMM, VDFANC(i,j,r) * tfd(i,j,r) + DFTAX(i,j,r) *
[pm(i,r) + qfd(i,j,r)])) + sum(i,TRAD_COMM, sum(j,PROD_COMM, VIFANC(i,j,r) * tfm(i,j,r) +
IFTAX(i,j,r) * [pim(i,r) + qfm(i,j,r)]))];

Zerodivide (zero_by_zero) default 0;
Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) FMSHR(i,j,s) # share of firms' imports in
dom. composite, agent's prices #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) FMSHR(i,j,s) = VIFA(i,j,s) / VFAD(i,j,s);
Zerodivide (zero_by_zero) off;

Equation ICOMPRICE
# industry price for composite commodities # (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
pft(i,j,r) = FMSHR(i,j,r) * pfm(i,j,r) + [1 - FMSHR(i,j,r)] * pfd(i,j,r);

Equation INDIMP
# industry j demands for composite import i # (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG)
qfm(i,j,s) = qft(i,j,s) - ESUBD(i) * [pfm(i,j,s) - pft(i,j,s)];

Equation INDDOM
# industry j demands for domestic good i # (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,s,REG) qfd(i,j,s)
= qft(i,j,s) - ESUBD(i) * [pfd(i,j,s) - pft(i,j,s)];

!<
```

```
    3-3. Notational links
    ---------------------->!

Formula (all,i,DEMD_COMM)(all,j,PROD_COMM)(all,r,REG) VFA(i,j,r) = VFAD(i,j,r);

Equation PFEEQ
# Input endowment prices into the production system.# (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG)
pf(i,j,r) = pfe(i,j,r);

Equation PFTEQ
# Input tradables prices into the production system. #
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) pf(i,j,r) = pft(i,j,r);

Equation QFEEQ
# Output endowment quantities from the production system. #
(all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) qfe(i,j,r) = qf(i,j,r);

Equation QFTEQ
# Output tradables quantities from the production system. #
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) qft(i,j,r) = qf(i,j,r);

!<
    3-4. Input-augmenting technological change
    ------------------------------------------>!

Variable (all,i,FIRM_COMM) afcom(i) # factor i augmenting tech change, worldwide #;
Variable (all,j,PROD_COMM) afsec(j) # factor augmenting tech change in sector j, worldwide #;
Variable (all,r,REG) afreg(r) # factor augmenting tech change in region r #;
Variable (all,i,FIRM_COMM)(all,j,PROD_COMM)(all,r,REG) afall(i,j,r) # input i augmenting tech
change in sector j of r #;

Equation AFWORLD
# sector/region specific rate of factor i augmenting tech change #
(all,i,FIRM_COMM)(all,j,PROD_COMM)(all,r,REG) af(i,j,r) = afcom(i) + afsec(j) + afreg(r) +
afall(i,j,r);

!<
    3-5. Non-coal energy nest
    ------------------------->!

Set NCOAL_COMM # inputs into non-coal energy subproduction # read elements from file GTAPSETS
header "NCOA";
Subset NCOAL_COMM is subset of TRAD_COMM;

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("ncoal",j,r) = sum(i,NCOAL_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("ncoal",j,r) = VFAS("ncoal",j,r);

Coefficient SIZE_NCOAL # size of NCOAL_COMM set #;
Formula SIZE_NCOAL = sum(i,NCOAL_COMM, 1);

Coefficient (all,i,NCOAL_COMM)(all,j,PROD_COMM)(all,r,REG) CSHNCOAL(i,j,r) # share of i in cost to
j of non-coal energy subproduct #;
Formula (all,i,NCOAL_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ncoal",j,r) = 0) CSHNCOAL(i,j,r) = 1.0
/ SIZE_NCOAL;
Formula (all,i,NCOAL_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ncoal",j,r) > 0) CSHNCOAL(i,j,r) =
VFA(i,j,r) / VFAS("ncoal",j,r);

Equation NCOALPRICE
# price of non-coal energy # (all,j,PROD_COMM)(all,r,REG) pf("ncoal",j,r) = sum(k,NCOAL_COMM,
CSHNCOAL(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG) ELNCOAL(j,r) # elasticity of substitution in
non-coal energy subproduction #;
Read ELNCOAL from file GTAPPARM header "ELNC";

Equation NCOALDEMAND
# demand for inputs into non-coal energy subproduction #
(all,i,NCOAL_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r) = -af(i,j,r) + qf("ncoal",j,r) -
ELNCOAL(j,r) * [pf(i,j,r) - af(i,j,r) - pf("ncoal",j,r)];

!<
    3-6. Non-electricity energy nest
    -------------------------------->!
```

```
Set NELY_COMM # inputs into non-electricity energy subproduction # read elements from file GTAPSETS
header "NELY";
Subset NELY_COMM is subset of FIRM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("nely",j,r) = sum(i,NELY_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("nely",j,r) = VFAS("nely",j,r);

Coefficient SIZE_FUEL # size of NELY_COMM set #;
Formula SIZE_FUEL = sum(i,NELY_COMM, 1);

Coefficient (all,i,NELY_COMM)(all,j,PROD_COMM)(all,r,REG) CSHNELY(i,j,r) # share of i in cost to j
of non-electricity energy subproduct #;
Formula (all,i,NELY_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("nely",j,r) = 0) CSHNELY(i,j,r) = 1.0 /
SIZE_FUEL;
Formula (all,i,NELY_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("nely",j,r) > 0) CSHNELY(i,j,r) =
VFA(i,j,r) / VFAS("nely",j,r);

Equation NELYPRICE
# price of non-electricity energy subproduct # (all,j,PROD_COMM)(all,r,REG) pf("nely",j,r) =
sum(k,NELY_COMM, CSHNELY(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG) ELNEL(j,r) # elasticity of substitution in
non-electricity energy subproduction #;
Read ELNEL from file GTAPARM header "ELNE";

Equation NELYDEMAND
# demand for inputs into non-electricity energy subproduction #
(all,i,NELY_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r) = -af(i,j,r) + qf("nely",j,r) - ELNEL(j,r)
* [pf(i,j,r) - af(i,j,r) - pf("nely",j,r)];

!<
    3-7. Non-intermittent electricity nest
    -------------------------------------->!

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("ntrm",j,r) = sum(i,NTRM_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("ntrm",j,r) = VFAS("ntrm",j,r);

Coefficient SIZE_NTRM # size of NTRM_COMM set #;
Formula SIZE_NTRM = sum(i,NTRM_COMM, 1);

Coefficient (all,i,NTRM_COMM)(all,j,PROD_COMM)(all,r,REG) CSHNTRM(i,j,r) # share of i in cost to j
of non-intermittent ely subproduct #;
Formula (all,i,NTRM_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ntrm",j,r) = 0) CSHNTRM(i,j,r) = 1.0 /
SIZE_NTRM;
Formula (all,i,NTRM_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ntrm",j,r) > 0) CSHNTRM(i,j,r) =
VFA(i,j,r) / VFAS("ntrm",j,r);

Equation Eq_NTRM
# price of non-intermitt. ely # (all,j,PROD_COMM)(all,r,REG) pf("ntrm",j,r) = sum(k,NTRM_COMM,
CSHNTRM(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Equation NTRMDEMAND
# demand for inputs into non-interm. ely subproduction #
(all,i,NTRM_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r) = -af(i,j,r) + qf("ntrm",j,r) - ELNTRM(r) *
[pf(i,j,r) - af(i,j,r) - pf("ntrm",j,r)];

!<
    3-8. Electricity nest
    --------------------->!

Set ELY_COMM # inputs into ely subproduction # read elements from file GTAPSETS header "ELY";
Subset ELY_COMM is subset of FIRM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("ely",j,r) = sum(i,ELY_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("ely",j,r) = VFAS("ely",j,r);

Coefficient SIZE_ELY # size of ELY_COMM set #;
Formula SIZE_ELY = sum(i,ELY_COMM, 1);

Coefficient (all,i,ELY_COMM)(all,j,PROD_COMM)(all,r,REG) CSHELY(i,j,r) # share of i in cost to j of
ely subproduct #;
Formula (all,i,ELY_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ely",j,r) = 0) CSHELY(i,j,r) = 1.0 /
SIZE_ELY;
Formula (all,i,ELY_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ely",j,r) > 0) CSHELY(i,j,r) =
```

```
VFA(i,j,r) / VFAS("ely",j,r);

Equation Eq_ELY
# price of ely # (all,j,PROD_COMM)(all,r,REG) pf("ely",j,r) = sum(k,ELY_COMM, CSHELY(k,j,r) *
[pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter)(all,r,REG) ELELY(r) # elasticity of substitution in ely subproduction #;
Read ELELY from file GTAPPARM header "ELEL";

Equation ELYDEMAND
# demand for inputs into ely subproduction # (all,i,ELY_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r)
= -af(i,j,r) + qf("ely",j,r) - ELELY(r) * [pf(i,j,r) - af(i,j,r) - pf("ely",j,r)];

!<
    3-9. Energy nest
    ---------------->!

Set ENY_COMM # inputs into energy subproduction # read elements from file GTAPSETS header "ENY";
Subset ENY_COMM is subset of FIRM_COMM;

Coefficient SIZE_ENY # size of ENY_COMM set #;
Formula SIZE_ENY = sum(i,ENY_COMM, 1);

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("eny",j,r) = sum(i,ENY_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("eny",j,r) = VFAS("eny",j,r);

Coefficient (all,i,ENY_COMM)(all,j,PROD_COMM)(all,r,REG) CSHENY(i,j,r) # share of i in cost to j of
energy subproduct #;
Formula (all,i,ENY_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("eny",j,r) = 0) CSHENY(i,j,r) = 1.0 /
SIZE_ENY;
Formula (all,i,ENY_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("eny",j,r) > 0) CSHENY(i,j,r) =
VFA(i,j,r) / VFAS("eny",j,r);

Equation ENYPRICE
# price of energy subproduct # (all,j,PROD_COMM)(all,r,REG) pf("eny",j,r) = sum(k,ENY_COMM,
CSHENY(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG) ELEN(j,r) # elasticity of substitution in
energy subproduction #;
Read ELEN from file GTAPPARM header "ELEN";

Equation ENYDEMAND
# demand for inputs into energy subproduction # (all,i,ENY_COMM)(all,j,PROD_COMM)(all,r,REG)
qf(i,j,r) = -af(i,j,r) + qf("eny",j,r) - ELEN(j,r) * [pf(i,j,r) - af(i,j,r) - pf("eny",j,r)];

!<
    3-10. Capital-energy nest
    ------------------------->!

Set KEN_COMM # inputs into capital-energy subproduction # read elements from file GTAPSETS header
"KEN";
Subset KEN_COMM is subset of FIRM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("ken",j,r) = sum(i,KEN_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("ken",j,r) = VFAS("ken",j,r);

Coefficient SIZE_KEN # size of KEN_COMM set #;
Formula SIZE_KEN = sum(i,KEN_COMM, 1);

Coefficient (all,i,KEN_COMM)(all,j,PROD_COMM)(all,r,REG) CSHKEN(i,j,r) # share of i in cost to j of
capital-energy subproduct #;
Formula (all,i,KEN_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ken",j,r) = 0) CSHKEN(i,j,r) = 1.0 /
SIZE_KEN;
Formula (all,i,KEN_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ken",j,r) > 0) CSHKEN(i,j,r) =
VFA(i,j,r) / VFAS("ken",j,r);

Equation CAPENPRICE
# price of capital-energy subproduct # (all,j,PROD_COMM)(all,r,REG) pf("ken",j,r) = sum(k,KEN_COMM,
CSHKEN(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG) ELKE(j,r) # elasticity of substitution in
capital-energy subproduction #;
Read ELKE from file GTAPPARM header "ELKE";
```

```
Equation CAPENDEMAND
# demand for inputs into capital-energy subproduction #
(all,i,KEN_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r)= -af(i,j,r) + qf("ken",j,r)- ELKE(j,r) *
[pf(i,j,r) - af(i,j,r) - pf("ken",j,r)];

!<
    3-11. Labour nest
    ----------------->!

Set LABOR_COMM # inputs into value-added-energy subproduction # read elements from file GTAPSETS
header "LABO";
Subset LABOR_COMM is subset of ENDWM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("labor",j,r) = sum(i,LABOR_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("labor",j,r) = VFAS("labor",j,r);

Coefficient SIZE_LABOR;
Formula SIZE_LABOR = sum(i,LABOR_COMM, 1);

Coefficient (all,i,LABOR_COMM)(all,j,PROD_COMM)(all,r,REG) CSHLABOR(i,j,r);
Formula (all,i,LABOR_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("labor",j,r) = 0) CSHLABOR(i,j,r) = 1.0
/ SIZE_LABOR;
Formula (all,i,LABOR_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("labor",j,r) > 0) CSHLABOR(i,j,r) =
VFA(i,j,r) / VFAS("labor",j,r);

Equation LABORPRICE
(all,j,PROD_COMM)(all,r,REG) pf("labor",j,r) = sum(k,LABOR_COMM, CSHLABOR(k,j,r) * [pf(k,j,r) -
af(k,j,r)]);

Coefficient (parameter) (all,r,REG) ESLAB(r);
Read ESLAB from file GTAPPARM header "ESLA";

Equation LABORDEMAND
# demand for inputs into value-added-energy subproduction #
(all,i,LABOR_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r) = -af(i,j,r) + qf("labor",j,r) - ESLAB(r)
* [pf(i,j,r) - af(i,j,r) - pf("labor",j,r)];

!<
    3-12. Value-added-energy nest
    ----------------------------->!

Set VAEN_COMM # inputs into value-added-energy subproduction # read elements from file GTAPSETS
header "VAEN";
Subset VAEN_COMM is subset of FIRM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG) VFAS("vaen",j,r) = sum(i,VAEN_COMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG) VFA("vaen",j,r) = VFAS("vaen",j,r);

Coefficient SIZE_VAEN # size of VAEN_COMM set #;
Formula SIZE_VAEN = sum(i,VAEN_COMM, 1);

Coefficient (all,i,VAEN_COMM)(all,j,PROD_COMM)(all,r,REG) CSHVAEN(i,j,r) # share of i in cost to j
of value-added-energy subproduct #;
Formula (all,i,VAEN_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("vaen",j,r) = 0) CSHVAEN(i,j,r) = 1.0 /
SIZE_VAEN;
Formula (all,i,VAEN_COMM)(all,j,PROD_COMM)(all,r,REG: VFAS("vaen",j,r) > 0) CSHVAEN(i,j,r) =
VFA(i,j,r) / VFAS("vaen",j,r);

Equation VAENPRICE
# price of value-added-energy subproduct # (all,j,PROD_COMM)(all,r,REG) pf("vaen",j,r) =
sum(k,VAEN_COMM, CSHVAEN(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG) ESUBVA(j,r) # elasticity of substitution in
value-added-energy subproduction #;
Read ESUBVA from file GTAPPARM header "ESBV";

Equation VAENDEMAND
# demand for inputs into value-added-energy subproduction #
(all,i,VAEN_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r) = -af(i,j,r) + qf("vaen",j,r) - ESUBVA(j,r)
* [pf(i,j,r) - af(i,j,r) - pf("vaen",j,r)];

!<
    3-13. Top of the production structure
```

```
    ------------------------------------>!

Set TOP_COMM # inputs into top of production structure # read elements from file GTAPSETS header
"TOP";
Subset TOP_COMM is subset of FIRM_COMM;

Variable (all,j,PROD_COMM)(all,r,REG) ao(j,r) # output augmenting technical change in sector j of r
#;
Variable (all,j,PROD_COMM) aosec(j) # output augmenting tech change of sector j, worldwide #;
Variable (all,r,REG) aoreg(r) # output augmetning tech change in region r #;
Variable (all,j,PROD_COMM)(all,r,REG) aoall(j,r) # output augmenting technical change in sector j
of r #;
Equation AOWORLD
# sector/region specific average rate of output augmenting tech change #
(all,j,PROD_COMM)(all,r,REG) ao(j,r) = aosec(j) + aoreg(r) + aoall(j,r);

Coefficient (Parameter)(all,j,PROD_COMM) ESUBT(j) # elasticity of substitution at top of production
structure #;
Read ESUBT from file GTAPPARM header "ESBT";

Variable (all,j,PROD_COMM)(all,r,REG) profitslack(j,r) # slack variable in the zero profit equation
#;

Coefficient (all,j,PROD_COMM)(all,r,REG) VFATOT(j,r) # total cost of inputs into j in r #;
Formula (all,j,PROD_COMM)(all,r,REG) VFATOT(j,r) = sum(i,TOP_COMM, VFA(i,j,r));

Coefficient SIZE_TOP # size of TOP_COMM set #;
Formula SIZE_TOP = sum(i,TOP_COMM, 1);

Coefficient (all,i,TOP_COMM)(all,j,PROD_COMM)(all,r,REG) CSHTOP(i,j,r) # share of i in total costs
of j in r #;
Formula (all,i,TOP_COMM)(all,j,PROD_COMM)(all,r,REG: VFATOT(j,r) = 0.0) CSHTOP(i,j,r) = 1.0 /
SIZE_TOP;
Formula (all,i,TOP_COMM)(all,j,PROD_COMM)(all,r,REG: VFATOT(j,r) > 0.0) CSHTOP(i,j,r) = VFA(i,j,r)
/ VFATOT(j,r);

Equation ZEROPROFITS
# industry zero pure profits condition # (all,j,PROD_COMM)(all,r,REG) ps(j,r) + ao(j,r) =
sum(i,TOP_COMM, CSHTOP(i,j,r) * [pf(i,j,r) - af(i,j,r)]) + profitslack(j,r);

Equation TOPDEMAND
# sector demands for factor-energy subproduct and intermediate inputs #
(all,i,TOP_COMM)(all,j,PROD_COMM)(all,r,REG) qf(i,j,r)= -af(i,j,r) + qo(j,r) - ao(j,r) - ESUBT(j) *
[pf(i,j,r) - af(i,j,r) - ps(j,r) - ao(j,r)];

!<
    3-14. Output taxation
    ---------------------->!

Equation OUTPUTPRICES
# Eq'n links pre- and post-tax supply prices for all industries. # (all,i,PROD_COMM)(all,r,REG)
ps(i,r) = to(i,r) + pm(i,r);

Equation TOUTRATIO
# change in ratio of output tax payments to regional income # (all,h,HHLDS)(all,r,REG) 100.0 *
INCOME(h,r) * del_taxrout(h,r) + TOUT(h,r) * y(h,r) = NetTaxTrSh(h,r) * sum(i,PROD_COMM, VOA(i,r) *
[-to(i,r)] + PTAX(i,r) * [pm(i,r) + qo(i,r)]);

!<--------------------------------------
    4. Investment, Global bank, and Savings
    --------------------------------------
    4-0. Module-specific variables
    4-1. Equations of notational convenience
    4-2. Rate of return equations
    4-3. Global bank
    4-4. Price index of aggregate global composite capital goods
    4-5. Price of saving
>!

!<
    4-0. Module-Specific Variables
    ------------------------------>!

Variable (all,h,HHLDS)(all,r,REG) rental(h,r) # rental rate on capital = ps("capital",r) #;
```

```
Variable (all,h,HHLDS)(all,r,REG) ke(h,r) # end-of-period capital stock in r #;
Variable (all,r,REG) rore(r) # expected net rate of return on capital stock in r #;
Variable (all,r,REG) rorc(r) # current net rate of return on capital stock in r #;
Variable (all,r,REG) qcgds(r) # output of capital goods sector = qo("cgds",r) #;

!<
    4-1. Equations of notational convenience
    ---------------------------------------->!

Variable (all,h,HHLDS)(all,r,REG) ksvces(h,r) # capital services = qo("capital",h,r) #;

Equation KAPSVCES
# eq'n defines a variable for capital services. # (all,h,HHLDS)(all,r,REG) ksvces(h,r) =
qoe("capital",h,r);

Equation KAPRENTAL
# eq'n defines a variable for capital rental rate # (all,h,HHLDS)(all,r,REG) rental(h,r) =
pse("capital",h,r);

Equation CAPGOODS
# eq'n defines a variable for gross investment # (all,r,REG) qcgds(r) = qo("cgds",r);

Equation PRCGOODS
# eq'n defines the price of cgds # (all,r,REG) pcgds(r) = ps("cgds",r);

Equation KBEGINNING
# associates change in cap. services w/ change in cap. stock # (all,h,HHLDS)(all,r,REG) kb(h,r) =
ksvces(h,r);

Coefficient (ge 0)(all,h,HHLDS)(all,r,REG) VKB(h,r) # value of beginning-of-period capital stock in
region r #;
Update (all,h,HHLDS)(all,r,REG) VKB(h,r) = pcgds(r) * kb(h,r);
Read VKB from file GTAPDATA header "VKB";

Coefficient (all,h,HHLDS)(all,r,REG) INVKERATIO(h,r) # ratio of gross investment to end-of-period
capital stock in r #;
Formula (all,h,HHLDS)(all,r,REG) INVKERATIO(h,r) = REGINV(h,r) / [VKB(h,r) + NETINV(h,r)];

Equation KEND
# Ending capital stock equals beginning stock plus net investment. # (all,h,HHLDS)(all,r,REG)
ke(h,r) = INVKERATIO(h,r) * qcgds(r) + [1.0 - INVKERATIO(h,r)] * kb(h,r);

!<
    4-2. Rate of return equations
    ----------------------------->!

Coefficient (all,i,ENDW_COMM)(all,h,HHLDS)(all,r,REG) RESShare(i,h,r);
Formula (all,i,ENDW_COMM)(all,h,HHLDS)(all,r,REG) RESShare(i,h,r) = EVOM(i,h,r) / sum(hh,HHLDS,
EVOM(i,hh,r));

Coefficient (all,r,REG) GRNETRATIO(r) # ratio of GROSS/NET rates of return on capital in r #;
Formula (all,r,REG) GRNETRATIO(r) = sum(h,HHLDS,EVOA("capital",h,r)) /
sum(h,HHLDS,(EVOA("capital",h,r)-VDEP(h,r)));

Equation RORCURRENT
# current rate of return on capital in region r # (all,r,REG) rorc(r) = GRNETRATIO(r) *
[sum(h,HHLDS, RESShare("capital",h,r)*rental(h,r)) - pcgds(r)];

Coefficient (parameter)(all,r,REG) RORFLEX(r) # flexibility of expected net ROR on capital stock in
r wrt investment #;
Read RORFLEX from file GTAPPARM header "RFLX";

Coefficient (all,h,HHLDS)(all,r,REG) VKBShare(h,r);
Formula (all,h,HHLDS)(all,r,REG) VKBShare(h,r) = VKB(h,r) / sum(hh,HHLDS, VKB(hh,r));

Equation ROREXPECTED
# expected rate of return depends on the current return and investment # (all,r,REG) rore(r) =
rorc(r) -RORFLEX(r)*sum(hh,HHLDS, VKBShare(hh,r)*[ke(hh,r)-kb(hh,r)]);

!<
    4-3. Global bank
    ---------------->!

Coefficient (integer,parameter) RORDELTA # binary coefficient to switch mechanism of allocating
```

```
investment funds #;
Read RORDELTA from file GTAPPARM header "RDLT";

Variable rorg # global net rate of return on capital stock #;
Variable (all,r,REG) cgdslack(r) # slack variable for qcgds(r) #;

Equation RORGLOBAL
# either gross investment or expected rate of return in region r #
(all,r,REG) RORDELTA * rore(r) + [1 - RORDELTA] * [sum(g,HHLDS,REGINV(g,r)) /
sum(g,HHLDS,NETINV(g,r))] * qcgds(r)- [(sum(g,HHLDS, VDEP(g,r))/sum(g,HHLDS,NETINV(g,r)))*
[1/sum(g,HHLDS, VKB(g,r))]*sum(g,HHLDS, VKB(g,r)*kb(g,r)) ] = RORDELTA * rorg + [1 - RORDELTA] *
globalcgds + cgdslack(r);

Equation GLOBALINV
# either expected global rate of return or global net investment # RORDELTA * globalcgds + [1 -
RORDELTA] * rorg = RORDELTA * sum(r,REG,[sum(h,HHLDS, REGINV(h,r))/GLOBINV] * qcgds(r)-
[sum(h,HHLDS, VDEP(h,r)) / GLOBINV] * [1/sum(hh,HHLDS, VKB(hh,r))]*sum(h,HHLDS, VKB(h,r)*kb(h,r)))+
[1 - RORDELTA] * sum(r,REG, sum(h,HHLDS, [NETINV(h,r) / GLOBINV]*rore(r)));

!<
    4-4. Price index of aggregate global composite capital goods
    ------------------------------------------------------------>!

Equation PRICGDS
# eq'n generates a price index for the aggregate global cgds composite # pcgdswld = sum(r,REG,
[sum(h,HHLDS, NETINV(h,r)) / GLOBINV] * pcgds(r));

!<
    4-5. Price of saving
    -------------------->!

Variable (all,r,REG) psaveslack(r) # slack variable for the savings price equation #;

Coefficient (all,h,hhlds)(all,r,REG) xShare(h,r);
Formula (all,h,HHLDS)(all,r,REG) xShare(h,r) = (NetInv(h,r)-Save(h,r)) /GLOBINV;

Equation SAVEPRICE
# savings price # (all,r,REG) psave(r) = pcgds(r) + sum(h,HHLDS, sum(s,REG, xShare(h,s)*pcgds(s)))
+ psaveslack(r);

!<----------------------
    5. International trade
    ----------------------

    5-1. Export prices
    5-2. Demand for imports
>!

!<
    5-1. Export prices
    ------------------>!

Variable (all,i,TRAD_COMM)(all,r,REG) tx(i,r) # dest.-gen. change in subsidy on exports of i from r
#;
Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) txs(i,r,s) # dest.-spec. change in subsidy on
exports of i from r to s #;

Equation EXPRICES
# eq'n links agent's and world prices # (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) pfob(i,r,s) =
pm(i,r) - tx(i,r) - txs(i,r,s);

Equation TEXPRATIO
# change in ratio of export tax payments to regional income # (all,h,HHLDS)(all,r,REG) 100.0 *
INCOME(h,r) * del_taxrexp(h,r) + TEX(h,r) * y(h,r) = NetTaxTrSh(h,r) * sum(i,TRAD_COMM, sum(s,REG,
VXMD(i,r,s) * [-tx(i,r) - txs(i,r,s)] + XTAXD(i,r,s) * [pfob(i,r,s) + qxs(i,r,s)]));

!<
    5-2. Demand for imports
    ----------------------->!

Variable (all,i,TRAD_COMM)(all,s,REG) tm(i,s) # source-gen. change in tax on imports of i into s #;
Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) tms(i,r,s) # source-spec. change in tax on imports
of i from r into s #;
```

```
Equation MKTPRICES
# eq'n links domestic and world prices # (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) pms(i,r,s) =
tm(i,s) + tms(i,r,s) + pcif(i,r,s);

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) MSHRS(i,r,s) # share of imports from r in
import bill of s at mkt prices #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) MSHRS(i,r,s) = VIMS(i,r,s) / sum(k,REG,
VIMS(i,k,s));
Equation DPRICEIMP
# price for aggregate imports # (all,i,TRAD_COMM)(all,s,REG) pim(i,s) = sum(k,REG, MSHRS(i,k,s) *
[pms(i,k,s) - ams(i,k,s)]);

Variable (orig_level=1.0)(all,i,TRAD_COMM)(all,r,REG) pr(i,r) # ratio of domestic to imported
prices in r #;

Equation PRICETGT
# eq'n defines target price ratio to be attained via the variable levy #
(all,i,TRAD_COMM)(all,s,REG) pr(i,s) = pm(i,s) - pim(i,s);

Coefficient (parameter)(all,i,TRAD_COMM) ESUBM(i) # region-generic el. of sub. among imports of i
in Armington structure #;
Read ESUBM from file GTAPPARM header "ESBM";

Equation IMPORTDEMAND
# regional demand for disaggregated imported commodities by source #
(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) qxs(i,r,s) = -ams(i,r,s) + qim(i,s)- ESUBM(i) * [pms(i,r,s)
- ams(i,r,s) - pim(i,s)];

Equation TIMPRATIO
# change in ratio of import tax payments to regional income # (all,h,HHLDS)(all,r,REG) 100.0 *
INCOME(h,r) * del_taxrimp(h,r) + TIM(h,r) * y(h,r) = NetTaxTrSh(h,r) * sum(i,TRAD_COMM, sum(s,REG,
VIMS(i,s,r) * [tm(i,r) + tms(i,s,r)] + MTAX(i,s,r) * [pcif(i,s,r) + qxs(i,s,r)]));

!<----------------------------------
    6. International transport services
    ----------------------------------
    6-0. Module-specific variables and coefficients
    6-1. Demand for global transport services
    6-2. Supply of transport services
>!

!<
    6-0. Module-specific variables and coefficients
    ------------------------------------------------>!

Variable (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) qtmfsd(m,i,r,s) # international
usage margin m on i from r to s #;
Variable (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) atmfsd(m,i,r,s) # tech change in
m's shipping of i from region r to s #;
Variable (all,m,TRAD_COMM) atm(m) # tech change in mode m, worldwide #;
Variable (all,i,TRAD_COMM) atf(i) # tech change shipping of i, worldwide #;
Variable (all,r,REG) ats(r) # tech change shipping from region r #;
Variable (all,s,REG) atd(s) # tech change shipping to s #;
Variable (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) atall(m,i,r,s) # tech change in
m's shipping of i from region r to s #;
Variable (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) ptrans(i,r,s) # cost index for international
transport of i from r to s #;
Variable (all,m,MARG_COMM) qtm(m) # global margin usage #;
Variable (all,m,MARG_COMM) pt(m) # price of composite margins services, type #;

Coefficient (ge 0) (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTMFSD(m,i,r,s) # int'l
margin usage, by margin, freight, source, and destination #;
Update (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTMFSD(m,i,r,s) = pt(m) *
qtmfsd(m,i,r,s);
Read VTMFSD from file GTAPDATA header "VTWR";

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTFSD(i,r,s) # aggregate value of svces in the
shipment of i from r to s #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTFSD(i,r,s) = sum(m,MARG_COMM, VTMFSD(m,i,r,s));

Coefficient (all,m,MARG_COMM) VTMUSE(m) # international margin services usage, by type #;
Formula (all,m,MARG_COMM) VTMUSE(m) = sum(i,TRAD_COMM, sum(r,REG, sum(s,REG, VTMFSD(m,i,r,s))));

Coefficient (all,m,MARG_COMM) VTMPROV(m) # international margin services provision #;
```

```
Formula (all,m,MARG_COMM) VTMPROV(m) = sum(r,REG, VST(m,r));

Coefficient (all,r,REG) VTRPROV(r) # international margin supply, by region #;
Formula (all,r,REG) VTRPROV(r) = sum(m,MARG_COMM, VST(m,r));

Coefficient VT # international margin supply #;
Formula VT = sum(m,MARG_COMM, sum(r,REG, VST(m,r)));

!<
    6-1. Demand for global transport services
    ----------------------------------------->!

Equation QTRANS_MFSD
# bilateral demand for transport services  #
(all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) qtmfsd(m,i,r,s) = qxs(i,r,s) -
atmfsd(m,i,r,s);

Coefficient (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTMUSESHR(m,i,r,s) # share of
i,r,s usage in global demand for m #;
Formula (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTMUSESHR(m,i,r,s) = VTFSD(i,r,s)
/ VT;
Formula (all,m,MARG_COMM: VTMUSE(m) <> 0.0)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG)
VTMUSESHR(m,i,r,s) = VTMFSD(m,i,r,s) / VTMUSE(m);

Equation TRANS_DEMAND
# global demand for margin m # (all,m,MARG_COMM) qtm(m) = sum(i,TRAD_COMM, sum(r,REG, sum(s,REG,
VTMUSESHR(m,i,r,s) * qtmfsd(m,i,r,s))));

!<
    6-2. Supply of transport services
    --------------------------------->!

Coefficient (all,m,MARG_COMM)(all,r,REG) VTSUPPSHR(m,r) # share of region r in global supply of
margin m #;
Formula (all,m,MARG_COMM)(all,r,REG) VTSUPPSHR(m,r) = VTRPROV(r) / VT;
Formula (all,m,MARG_COMM: VTMPROV(m) <> 0.0)(all,r,REG) VTSUPPSHR(m,r) = VST(m,r) / VTMPROV(m);

Equation PTRANSPORT
# generate price index for composite transportation services # (all,m,MARG_COMM) pt(m) = sum(r,REG,
VTSUPPSHR(m,r) * pm(m,r));

Coefficient VTUSE # international margin services usage #;
Formula VTUSE = sum(m,MARG_COMM, sum(i,TRAD_COMM, sum(r,REG, sum(s,REG, VTMFSD(m,i,r,s)))));

Coefficient (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VTFSD_MSH(m,i,r,s) # share of
margin m in cost of getting i from r to s #;
Formula (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG) (all,s,REG: VTFSD(i,r,s) > 0.0)
VTFSD_MSH(m,i,r,s) = VTMFSD(m,i,r,s) / VTFSD(i,r,s);
Formula (all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG) (all,s,REG: VTFSD(i,r,s) = 0.0)
    VTFSD_MSH(m,i,r,s) = VTMUSE(m) / VTUSE;

Equation TRANSCOSTINDEX
#  generates flow-specific modal average cost of transport index #
(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) ptrans(i,r,s) = sum(m,MARG_COMM, VTFSD_MSH(m,i,r,s) *
[pt(m) - atmfsd(m,i,r,s)]);

Equation TRANSTECHANGE
#  generates flow-specific average rate of technical change #
(all,m,MARG_COMM)(all,i,TRAD_COMM)(all,r,REG)(all,s,REG) atmfsd(m,i,r,s) = atm(m) + atf(i) + ats(r)
+ atd(s) + atall(m,i,r,s);

Equation TRANSVCES
# generate demand for regional supply of global transportation service #
(all,m,MARG_COMM)(all,r,REG) qst(m,r) = qtm(m) + [pt(m) - pm(m,r)];

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VIWSCOST(i,r,s) # value of imports calculated
as total cost of imports #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) VIWSCOST(i,r,s) = VXWD(i,r,s) + VTFSD(i,r,s);

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) FOBSHR(i,r,s) # FOB share in VIW #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) FOBSHR(i,r,s) = VXWD(i,r,s) / VIWSCOST(i,r,s);

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) TRNSHR(i,r,s) # transport share in VIW #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) TRNSHR(i,r,s) = VTFSD(i,r,s) / VIWSCOST(i,r,s);
```

```
Equation FOBCIF
# eq'n links FOB and CIF prices for good i shipped from region r to s #
(all,i,TRAD_COMM)(all,r,REG)(all,s,REG)
pcif(i,r,s) = FOBSHR(i,r,s) * pfob(i,r,s) + TRNSHR(i,r,s) * ptrans(i,r,s);

!<--------------------------------
    7. International emissions trade
    -------------------------------->!

Variable (all,r,REG) gco2q(r) # emissions quota #;
Coefficient (ge 0) (all,r,REG) CO2Q(r) # emissions quota (millions of tonnes of carbon) #;
Update (all,r,REG) CO2Q(r) = gco2q(r);
Read CO2Q from file GTAPDATA header "CO2Q";

Variable (all,r,REG) pemp(r) # power of emissions purchases#;
Equation PEMPURCH(all,r,REG) pemp(r) = gco2t(r) - gco2q(r);

Equation EMTRADING
# net emissions trading revenue # (all,r,REG) DVCO2TRA(r) = CO2Q(r) * NCTAXLEV(r) * 0.01 * gco2q(r)
- CO2T(r) * NCTAXLEV(r) * 0.01 * gco2t(r) + [CO2Q(r) - CO2T(r)] * NCTAXB(REGTOBLOC(r));

Variable (all,b,BLOC) gco2tb(b) # carbon dioxide emissions #;
Variable (all,b,BLOC) gco2qb(b) # emissions quota#;

Equation TOTALEMISSIONSB # CO2 emissions #
(all,b,BLOC) CO2TB(b) * gco2tb(b) = sum(r,REG: REGTOBLOC(r) = b, CO2T(r) * gco2t(r));

Coefficient (all,b,BLOC) CO2QB(b) # emissions quota (millions of tonnes of carbon)#;
Formula (all,b,BLOC) CO2QB(b) = sum(r, REG: REGTOBLOC(r)=b, CO2Q(r));

Equation EMISSQUOTA
# emissions quota # (all,b,BLOC) CO2QB(b) * gco2qb(b) = sum(r, REG: REGTOBLOC(r) = b, CO2Q(r) *
gco2q(r));

Variable (all,b,BLOC) pempb(b) # power of emissions purchases#;

Equation PEMPURCHB(all,b,BLOC) pempb(b) = gco2tb(b) - gco2qb(b);

!< ---------------------
    8. Regional Household
    ---------------------
    8-0. Module-specific coefficients
    8-1. Supply of endowments by the regional household
    8-2. Carbon dioxide emissions
    8-3. Carbon tax rate
    8-4. Carbon tax revenue
    8-5. Computation of regional income
    8-6. Regional household demand system
    8-7. Aggregate utility
>!

!<
    8-0. Module-specific coefficients
    -------------------------------->!

Coefficient (all,h,HHLDS)(all,r,REG) XSHRPRIV(h,r) # private expenditure share in regional income
#;
Formula (all,h,HHLDS)(all,r,REG) XSHRPRIV(h,r) = PRIVEXP(h,r) / INCOME(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) XSHRGOV(h,r) # government expenditure share in regional income
#;
Formula (all,h,HHLDS)(all,r,REG) XSHRGOV(h,r) = GOVEXP(h,r) / INCOME(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) XSHRSAVE(h,r) # saving share in regional income #;
Formula (all,h,HHLDS)(all,r,REG) XSHRSAVE(h,r) = SAVE(h,r) / INCOME(h,r);

Variable (all,r,REG)(all,i,CTAX_COMM) gco2(r,i) # carbon dioxide emissions #;
Variable (change, levels) (all,r,REG)(all,i,CTAX_COMM) VCTAX(r,i) # carbon tax revenue #;

Variable (all,h,HHLDS)(all,r,REG) uelas(h,r) # elasticity of cost of utility wrt utility #;
Variable(all,h,HHLDS)(all,r,REG) dppriv(h,r) # private consumption distribution parameter #;
Variable (all,h,HHLDS)(all,r,REG) dpgov(h,r) # government consumption distribution parameter #;
Variable (all,h,HHLDS)(all,r,REG) dpsave(h,r) # saving distribution parameter #;
```

```
!<
    8-1. Supply of endowments by the regional household
    ---------------------------------------------------->!

variable (all,r,reg) te(r);
Variable (all,r,REG) tk(r);
variable (all,r,reg) tll(r);

Equation KINCPRICES
# eq'n links pre- and post-tax capital supply prices # (all,h,HHLDS)(all,i,ENDWC_COMM)(all,r,REG)
pse(i,h,r) = toe(i,h,r) + tk(r) + te(r) + pm(i,r);

Equation FACTORINCPRICES
# eq'n links pre- and post-tax endowment supply prices # (all,h,HHLDS)(all,i,ENDWS_COMM)(all,r,REG)
pse(i,h,r) = toe(i,h,r) + te(r) + pm(i,r);

Equation LABPRICENET
(all,i,ENDWL_COMM)(all,h,HHLDS)(all,r,REG) pse(i,h,r) = toe(i,h,r) + tll(r) + te(r) + pm(i,r);

Coefficient (all,h,HHLDS)(all,r,REG) TINC(h,r) # income tax payments in r #;
Formula (all,h,HHLDS)(all,r,REG) TINC(h,r) = NetTaxTrSh(h,r) * sum(i,ENDW_COMM, sum(hh,HHLDS,
ITAX(i,hh,r)));

Equation TINCRATIO
# change in ratio of income tax payments to regional income # (all,h,HHLDS)(all,r,REG) 100.0 *
INCOME(h,r) * del_taxrinc(h,r) + TINC(h,r) * y(h,r)
 = NetTaxTrSh(h,r) * [sum(hh,HHLDS, sum(i,ENDWNC_COMM, EVOA(i,hh,r)*[-toe(i,hh,r)-te(r)]
+ITAX(i,hh,r)*[pm(i,r) + qoe(i,hh,r)]) + sum(i,ENDWC_COMM, EVOA(i,hh,r)*[-toe(i,hh,r)-te(r)-tk(r)]
+ITAX(i,hh,r)*[pm(i,r) + qoe(i,hh,r)]))];

Coefficient (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) REVSHR(i,j,r);
Formula (all,i,ENDW_COMM)(all,j,PROD_COMM)(all,r,REG) REVSHR(i,j,r) = VFM(i,j,r) / sum(k,PROD_COMM,
VFM(i,k,r));

Equation ENDW_PRICE
# eq'n generates the composite price for sluggish endowments # (all,i,ENDWS_COMM)(all,r,REG)
pm(i,r) = sum(k,PROD_COMM, REVSHR(i,k,r) * pmes(i,k,r));

Coefficient (parameter)(all,i,ENDW_COMM)(all,r,reg) ETRAE(i,r) # elst. of transformation for
sluggish primary factor endowments #;
Read ETRAE from file GTAPPARM header "ETRE";

Equation ENDW_SUPPLY
# eq'n distributes the sluggish endowments across sectors #
(all,i,ENDWS_COMM)(all,j,PROD_COMM)(all,r,REG) qoes(i,j,r) = sum(h,HHLDS,
RESshare(i,h,r)*qoe(i,h,r)) - endwslack(i,r) + ETRAE(i,r) * [pm(i,r) - pmes(i,j,r)];

!<
    8-2. Carbon dioxide emissions
    ----------------------------->!

Equation PDEMISSIONS
# carbon dioxide emissions from private consumption of domestic product #
(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2pd(i,h,r) = qpd(i,h,r);

Equation PIEMISSIONS
# carbon dioxide emissions from private consumption of imports #
(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2pm(i,h,r) = qpm(i,h,r);

Equation GDEMISSIONS
# carbon dioxide emissions from government consumption of domestic product #
(all,h,HHLDS)(all,i, TRAD_COMM)(all,r,REG) gco2gd(i,h,r) = qgd(i,h,r);

Equation GIEMISSIONS
# carbon dioxide emissions from government consumption of imports #
(all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) gco2gm(i,h,r) = qgm(i,h,r);

Equation FDEMISSIONS
# carbon dioxide emissions from firms' usage of domestic product #
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) gco2fd(i,j,r) = qfd(i,j,r);

Equation FIEMISSIONS
# carbon dioxide emissions from firms' usage of imports #
```

```
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) gco2fm(i,j,r) = qfm(i,j,r);

Equation CEMISSIONS
# carbon dioxide emissions #
(all,r,REG)(all,i,CTAX_COMM) CO2(r,i) * gco2(r,i) = sum(j,PROD_COMM, CO2IF(i,j,r) * gco2fm(i,j,r) +
CO2DF(i,j,r) * gco2fd(i,j,r)) + sum(h,HHLDS, CO2DG(i,h,r) * gco2gd(i,h,r) + CO2IG(i,h,r) *
gco2gm(i,h,r)) + sum(h,HHLDS, CO2DP(i,h,r) * gco2pd(i,h,r) + CO2IP(i,h,r) * gco2pm(i,h,r));

Equation TOTALEMISSIONS
# carbon dioxide emissions #
(all,r,REG) CO2T(r) * gco2t(r) = sum(i,CTAX_COMM, CO2(r,i) * gco2(r,i));

Variable gco2tw # total world emissions #;
Equation WORLDEMISS
# total world emissions # sum(r,REG, CO2T(r)) * gco2tw = sum(r,REG, CO2T(r) * gco2t(r));

!<
    8-3. Carbon tax rate
    ---------->!

Variable (change)(all,r,REG) RCTAX(r) # real carbon tax rate (1997 USD per tonne of carbon) #;
Coefficient (all,r,REG) PIND(r) # income deflator #;

Variable (all,h,HHLDS)(all,r,REG) p(h,r) # price index for disposition of income by regional
household #;
Equation PRICEINDEXREG
# price index for disposition of income by regional household # (all,h,HHLDS)(all,r,REG) p(h,r) =
XSHRPRIV(h,r) * ppriv(h,r) + XSHRGOV(h,r)  * pgov(h,r) + XSHRSAVE(h,r) * psave(r);

Coefficient (all,h,HHLDS)(all,r,REG) PINDH(h,r) # income deflator #;
Update (all,h,HHLDS)(all,r,REG) PINDH(h,r) = p(h,r);
Formula (initial) (all,h,HHLDS)(all,r,REG) PINDH(h,r) = 1.0;

Equation PRICEINDEXPREG
# price index for disposition of income by regional household # (all,r,REG) INCOMER(r)*preg(r)
 = sum(h,HHLDS, INCOME(h,r) * p(h,r));

Update (all,r,REG)PIND(r) = preg(r);
Formula (initial) (all,r,REG) PIND(r) = 1.0;

Equation REALTAXCH
# real carbon tax rate # (all,r,REG) RCTAX(r) = [1.0 / PIND(r)] * [NCTAXB(REGTOBLOC(r)) - 0.01 *
NCTAXLEV(r) * preg(r)];

Variable (orig_level = 1.0)(all,b,BLOC) pb(b) # income deflator #;

Coefficient (all,b,BLOC) INCOMEB(b) # Net income in bloc #;
Formula (all,b,BLOC) INCOMEB(b) = sum(r,REG: REGTOBLOC(r) = b, INCOMER(r));

Equation PIND_b
# income deflator # (all,b,BLOC) INCOMEB(b) * pb(b) = sum(r,REG: REGTOBLOC(r) = b, INCOMER(r) *
preg(r));

Variable (change)(all,r,BLOC) RCTAXB(r) # real carbon tax rate (1997 USD per tonne of carbon) #;
Coefficient (all,b,BLOC) PINDB(b) # income deflator #;
Update (all,b,BLOC) PINDB(b) = pb(b);
Formula (initial) (all,b,BLOC) PINDB(b) = 1.0;

Coefficient (all,b,BLOC) NCTAXLEVB(b) # nominal carbon tax rate (current USD per tonne of carbon)
#;
Formula (all,b,BLOC) NCTAXLEVB(b) = sum(r,REG: REGTOBLOC(r) = b, NCTAXLEV(r) * CO2T(r))/ CO2TB(b);

Equation REALTAXCHB
# real carbon tax rate # (all,b,BLOC) RCTAXB(b) = [1.0 / PINDB(b)] * [NCTAXB(b) - 0.01 *
NCTAXLEVB(b) * pb(b)];

!<
    8-4. Carbon tax revenue
    ---------->!

Variable (default = levels);
Equation (default = levels);
Formula (default = initial);
```

```
Variable (all,r,REG)(all,i,CTAX_COMM) CO2_L(r,i) # Level of emissions #;
Variable (change)(all,r,REG) NOMCTAX_L(r) # Level of carbon tax in nominal #;

Formula (all,r,REG)(all,i,CTAX_COMM) CO2_L(r,i) = CO2(r,i);

Equation (linear) E_CO2
# CO2 emissions # (all,r,REG)(all,i,CTAX_COMM) p_CO2_L(r,i) = gco2(r,i);

Formula (all,r,REG) NOMCTAX_L(r) = NCTAXLEV(r);

Equation (linear) E_TAXLEV
# carbon tax rate # (all,r,REG) c_NOMCTAX_L(r) = NCTAXB(REGTOBLOC(r));

Formula & Equation VALCTAX
# carbon tax revenue # (all,r,REG)(all,i,CTAX_COMM) VCTAX(r,i) = CO2_L(r,i) * NOMCTAX_L(r);

Formula (default = always);
Equation (default = linear);
Variable (default = linear);

!<
    8-5. Computation of regional income
    ----------------------------------->!

Variable (all,h,HHLDS)(all,r,REG) fincome(h,r) # factor income at market prices net of depreciation
#;

Equation FACTORINCOME
# factor income at market prices net of depreciation # (all,h,HHLDS)(all,r,REG) FY(h,r) *
fincome(h,r) = sum(i,ENDW_COMM, EVOA(i,h,r) * [pse(i,h,r) + qoe(i,h,r)]) - VDEP(h,r)  * [pcgds(r) +
kb(h,r)];

Variable (change)(all,h,HHLDS)(all,r,REG) del_indtaxr(h,r) # change in ratio of indirect taxes to
INCOME in r #;

Equation DINDTAXRATIO
# change in ratio of indirect taxes to INCOME in r # (all,h,HHLDS)(all,r,REG) del_indtaxr(h,r) =
del_taxrpc(h,r)  + del_taxrgc(h,r)  + del_taxriu(h,r) + del_taxrfu(h,r)
+ del_taxrout(h,r) + del_taxrexp(h,r) + del_taxrimp(h,r);

Variable (change)(all,h,HHLDS)(all,r,REG) del_ttaxr(h,r) # change in ratio of taxes to INCOME in r
#;

Equation DTAXRATIO
# change in ratio of taxes to INCOME in r #
(all,h,HHLDS)(all,r,REG) del_ttaxr(h,r) = del_taxrpc(h,r)  + del_taxrgc(h,r)  + del_taxriu(h,r) +
del_taxrfu(h,r) + del_taxrout(h,r) + del_taxrexp(h,r) + del_taxrimp(h,r)+ del_taxrinc(h,r) +
del_co2tax(h,r);

Coefficient (all,h,HHLDS)(all,r,reg) INCshares(h,r);

Variable (change)(all,r,REG) del_totaltaxr(r);

Equation Eq_for_totaltaxr
(all,r,REG) del_totaltaxr(r) = sum(h,HHLDS, Income(h,r) * del_ttaxr(h,r));

Variable (all,h,HHLDS)(all,r,REG) incomeslack(h,r) # slack variable in the expression for regional
income #;

Coefficient (all,h,HHLDS)(all,r,REG) INDTAX(h,r) # indirect tax receipts in r #;
Formula (all,h,HHLDS)(all,r,REG) INDTAX(h,r) = NetTaxTrSh(h,r) * [sum(j,HHLDS, TPC(j,r)  + TGC(j,r)
+ TIU(j,r) + TFU(j,r) + TOUT(j,r) + TEX(j,r) + TIM(j,r))];

Variable (change)(all,h,HHLDS)(all,r,REG) DVCO2TRAH(h,r);

Equation DTRADINGREV
(all,h,HHLDS)(all,r,REG) DVCO2TRAH(h,r) = NetTaxTrSh(h,r) * DVCO2TRA(r);

Variable (change)(all,i,CTAX_COMM)(all,h,HHLDS)(all,r,REG) VCTAXH(r,h,i);

Equation DCTAXREV
(all,i,CTAX_COMM)(all,h,HHLDS)(all,r,REG) VCTAXH(r,h,i) = NetTaxTrSh(h,r) * c_VCTAX(r,i);

Coefficient (all,h,HHLDS)(all,r,REG) CTAX(h,r);
```

```
Formula (all,h,HHLDS)(all,r,REG) CTAX(h,r) = NetTaxTrSh(h,r)*{sum(hh,HHLDS,
sum(i,TRAD_COMM,DPCTAX(i,hh,r)+DGCTAX(i,hh,r)+IPCTAX(i,hh,r)+IGCTAX(i,hh,r))) + sum(ii,TRAD_COMM,
sum(j,PROD_COMM, DFCTAX(ii,j,r) + IFCTAX(ii,j,r)))};

Equation CTAXRATIO
# change in ratio of carbon tax payments to regional income # (all,h,HHLDS)(all,r,REG) 100.0 *
INCOME(h,r) * del_co2tax(h,r) + CTAX(h,r) * y(h,r) = NetTaxTrSh(h,r)*{sum(hh,HHLDS,sum(i,TRAD_COMM,
VDPA(i,hh,r)*[ppd(i,hh,r)+qpd(i,hh,r)] - VDPANC(i,hh,r)*[atpd(i,hh,r)+pm(i,r)+qpd(i,hh,r)]  +
VDGA(i,hh,r)*[pgd(i,hh,r)+qgd(i,hh,r)] - VDGANC(i,hh,r)*[tgd(i,hh,r)+pm(i,r)+qgd(i,hh,r)] +
VIPA(i,hh,r)*[ppm(i,hh,r)+qpm(i,hh,r)] - VIPANC(i,hh,r)*[atpm(i,hh,r)+pim(i,r)+qpm(i,hh,r)] +
VIGA(i,hh,r)*[pgm(i,hh,r)+qgm(i,hh,r)] - VIGANC(i,hh,r)*[tgm(i,hh,r)+pim(i,r)+qgm(i,hh,r)])) +
sum(j,PROD_COMM, sum(ii,TRAD_COMM, VDFA(ii,j,r)*[pfd(ii,j,r)+qfd(ii,j,r)] -
VDFANC(ii,j,r)*[tfd(ii,j,r)+pm(ii,r)+qfd(ii,j,r)] + VIFA(ii,j,r)*[pfm(ii,j,r)+qfm(ii,j,r)] -
VIFANC(ii,j,r)*[tfm(ii,j,r)+pim(ii,r)+qfm(ii,j,r)]))};

Equation REGIONALINCOME
# regional income = sum of primary factor income and indirect tax receipts #
(all,h,HHLDS)(all,r,REG) INCOME(h,r) * y(h,r) = FY(h,r) * fincome(h,r) + 100.0 * INCOME(h,r) *
del_taxrinc(h,r) + TINC(h,r) * y(h,r) + 100.0 * INCOME(h,r) * del_indtaxr(h,r) + INDTAX(h,r) *
y(h,r) + 100.0 * INCOME(h,r) * del_co2tax(h,r) + CTAX(h,r) * y(h,r) + INCOME(h,r) *
incomeslack(h,r);

!<
    8-6. Regional household demand system
    ------------------------------------->!

Variable (all,h,HHLDS)(all,r,REG) dpav(h,r) # average distribution parameter shift, for EV calc. #;

Equation DPARAV
# average distribution parameter shift # (all,h,HHLDS)(all,r,REG) dpav(h,r) = XSHRPRIV(h,r) *
dppriv(h,r) + XSHRGOV(h,r)  * dpgov(h,r) + XSHRSAVE(h,r) * dpsave(h,r);

Equation UTILITELASTIC
# elasticity of cost of utility wrt utility # (all,h,HHLDS)(all,r,REG) uelas(h,r) = XSHRPRIV(h,r) *
uepriv(h,r) - dpav(h,r);

Equation PRIVCONSEXP
# private consumption expenditure # (all,h,HHLDS)(all,r,REG) yp(h,r) - y(h,r) = -[uepriv(h,r) -
uelas(h,r)] + dppriv(h,r);

Equation GOVCONSEXP
# government consumption expenditure # (all,h,HHLDS)(all,r,REG) yg(h,r) - y(h,r) = uelas(h,r) +
dpgov(h,r);

Equation SAVING
# saving # (all,h,HHLDS)(all,r,REG) psave(r) + qsave(h,r) - y(h,r) = uelas(h,r) + dpsave(h,r);

!<
    8-7. Aggregate utility
    ---------------------->!

Variable (all,h,HHLDS)(all,r,REG) au(h,r) # input-neutral shift in utility function #;
Variable (all,h,HHLDS)(all,r,REG) dpsum(h,r) # sum of the distribution parameters #;

Coefficient (all,h,HHLDS)(all,r,REG) DPARSUM(h,r) # sum of distribution parameters #;
Read DPARSUM from file GTAPDATA header "DPSM";
Update (all,h,HHLDS)(all,r,REG) DPARSUM(h,r) = dpsum(h,r);

Coefficient(all,h,HHLDS) (all,r,REG) UTILELAS(h,r) # elasticity of cost of utility wrt utility #;
Formula(all,h,HHLDS) (all,r,REG) UTILELAS(h,r) =[UELASPRIV(h,r) *XSHRPRIV(h,r) + XSHRGOV(h,r) +
XSHRSAVE(h,r)] / DPARSUM(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) DPARPRIV(h,r) # private consumption distribution parameter #;
Formula (all,h,HHLDS)(all,r,REG) DPARPRIV(h,r) = UELASPRIV(h,r) * XSHRPRIV(h,r) / UTILELAS(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) DPARGOV(h,r) # government consumption distribution parameter
#;
Formula (all,h,HHLDS)(all,r,REG) DPARGOV(h,r) = XSHRGOV(h,r) / UTILELAS(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) DPARSAVE(h,r) # saving distribution parameter #;
Formula(all,h,HHLDS) (all,r,REG) DPARSAVE(h,r) = XSHRSAVE(h,r) / UTILELAS(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) UTILPRIV(h,r) # utility from private consumption #;
Formula (initial)(all,h,HHLDS)(all,r,REG) UTILPRIV(h,r) = 1.0;
```

```
Update(all,h,HHLDS) (all,r,REG) UTILPRIV(h,r) = up(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) UTILGOV(h,r) # utility from government consumption #;
Formula (initial)(all,h,HHLDS)(all,r,REG) UTILGOV(h,r) = 1.0;
Update (all,h,HHLDS)(all,r,REG) UTILGOV(h,r) = ug(h,r);

Coefficient (all,h,HHLDS)(all,r,REG) UTILSAVE(h,r) # utility from saving #;
Formula (initial)(all,h,HHLDS)(all,r,REG) UTILSAVE(h,r) = 1.0;
Update (change) (all,h,HHLDS)(all,r,REG) UTILSAVE(h,r) = [[qsave(h,r) - pop(h,r)] / 100] *
UTILSAVE(h,r);

Variable (all,h,HHLDS)(all,r,REG) u(h,r) # per capita utility from aggregate hhld expend. in region
r #;
Equation UTILITY
# regional household utility # (all,h,HHLDS)(all,r,REG) u(h,r) = au(h,r) + DPARPRIV(h,r) *
loge(UTILPRIV(h,r)) * dppriv(h,r) + DPARGOV(h,r) * loge(UTILGOV(h,r)) * dpgov(h,r) + DPARSAVE(h,r)
* loge(UTILSAVE(h,r)) * dpsave(h,r) + [1.0 / UTILELAS(h,r)] * [y(h,r) - pop(h,r) - p(h,r)];

Equation DISTPARSUM
# sum of the distribution parameters # (all,h,HHLDS)(all,r,REG) DPARSUM(h,r) * dpsum(h,r) =
DPARPRIV(h,r) * dppriv(h,r) + DPARGOV(h,r) * dpgov(h,r) + DPARSAVE(h,r) * dpsave(h,r);

!< -------------------------
    9. Equilibrium conditions
    -------------------------
    9-1. Market clearing conditions
    9-2. Walras' law
>!

!<
    9-1. Market clearing conditions
    ------------------------------>!

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHRDFM(i,j,r) # share of dom. prod. i
used by sector j in r at mkt prices #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHRDFM(i,j,r) = VDFM(i,j,r) / VDM(i,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRDPM(i,h,r) # share of domestic prod. of i
used by private HHLDS in r #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRDPM(i,h,r) = VDPM(i,h,r) / VDM(i,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRDGM(i,h,r) # share of imports of i used by
gov't HHLDS in r #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRDGM(i,h,r) = VDGM(i,h,r) / VDM(i,r);

Variable (orig_level=VDM)(all,i,TRAD_COMM)(all,r,REG)qds(i,r) # domestic sales of commodity i in r

Equation MKTCLDOM
# eq'n assures market clearing for domestic sales # (all,i,TRAD_COMM)(all,r,REG) qds(i,r) =
sum(j,PROD_COMM, SHRDFM(i,j,r) * qfd(i,j,r)) + sum(h,HHLDS,SHRDPM(i,h,r) * qpd(i,h,r)) +
sum(h,HHLDS,SHRDGM(i,h,r) * qgd(i,h,r));

Coefficient (all,i,TRAD_COMM)(all,r,REG) SHRDM(i,r) # share of domestic sales of i in r #;
Formula (all,i,TRAD_COMM)(all,r,REG) SHRDM(i,r) = VDM(i,r) / VOM(i,r);

Coefficient (all,m,MARG_COMM)(all,r,REG) SHRST(m,r) # share of sales of m to global transport
services in r #;
Formula (all,m,MARG_COMM)(all,r,REG) SHRST(m,r) = VST(m,r) / VOM(m,r);

Coefficient (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) SHRXMD(i,r,s) # share of export sales of i to s
in r #;
Formula (all,i,TRAD_COMM)(all,r,REG)(all,s,REG) SHRXMD(i,r,s) = VXMD(i,r,s) / VOM(i,r);

Variable (all,i,TRAD_COMM)(all,r,REG) tradslack(i,r) # slack variable in tradeables market clearing
condition #;

Equation MKTCLTRD_MARG
# eq'n assures market clearing for margins commodities # (all,m,MARG_COMM)(all,r,REG) qo(m,r) =
SHRDM(m,r) * qds(m,r) + SHRST(m,r) * qst(m,r) + sum(s,REG, SHRXMD(m,r,s) * qxs(m,r,s)) +
tradslack(m,r);

Equation MKTCLTRD_NMRG
# eq'n assures market clearing for the non-margins commodities # (all,i,NMRG_COMM)(all,r,REG)
qo(i,r) = SHRDM(i,r) * qds(i,r) + sum(s,REG, SHRXMD(i,r,s) * qxs(i,r,s)) + tradslack(i,r);
```

```
Coefficient (all,i,TRAD_COMM)(all,r,REG) VIM(i,r) # value of imports of commodity i in r at
domestic market prices #;
Formula (all,i,TRAD_COMM)(all,r,REG) VIM(i,r) = sum(j,PROD_COMM, VIFM(i,j,r)) + sum(h,HHLDS,
[VIPM(i,h,r) + VIGM(i,h,r)]);

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHRIFM(i,j,r) # share of import i used by
sector j in r #;
Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG) SHRIFM(i,j,r) = VIFM(i,j,r) / VIM(i,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRIPM(i,h,r) # share of import i used by
private HHLDS in r #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRIPM(i,h,r) = VIPM(i,h,r) / VIM(i,r);

Coefficient (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRIGM(i,h,r) # the share of import i used by
gov't HHLDS in r #;
Formula (all,h,HHLDS)(all,i,TRAD_COMM)(all,r,REG) SHRIGM(i,h,r) = VIGM(i,h,r) / VIM(i,r);

Equation MKTCLIMP
# eq'n assures mkt clearing for imported goods entering each region # (all,i,TRAD_COMM)(all,r,REG)
qim(i,r) = sum(j,PROD_COMM, SHRIFM(i,j,r) * qfm(i,j,r)) + sum(h,HHLDS,SHRIPM(i,h,r) * qpm(i,h,r)) +
sum(h,HHLDS,SHRIGM(i,h,r) * qgm(i,h,r));

Coefficient (all,i,ENDWM_COMM)(all,j,PROD_COMM)(all,r,REG) SHREM(i,j,r) # share of mobile endowment
i used by sector j at mkt prices #;
Formula (all,i,ENDWM_COMM)(all,j,PROD_COMM)(all,r,REG) SHREM(i,j,r) = VFM(i,j,r) / sum(h,PROD_COMM,
VFM(i,h,r));

Coefficient (parameter)(all,r,REG) ELAB(r) # Elasticity of labour supply #;
Read ELAB from file GTAPPARM header "ELAB";

Equation Eq_for_qoe
# Labour supply # (all,h,HHLDS)(all,i,ENDWL_COMM)(all,r,REG) qoe(i,h,r) = ELAB(r) *
pfactreal(i,h,r);

Equation MKTCLENDWM
# eq'n assures mkt clearing for perfectly mobile endowments in each r #
(all,i,ENDWM_COMM)(all,r,REG) sum(j,HHLDS, RESShare(i,j,r)*qoe(i,j,r)) =
 sum(j,PROD_COMM, SHREM(i,j,r) * qfe(i,j,r)) + endwslack(i,r);

Equation MKTCLENDWS
# eq'n assures mkt clearing for imperfectly mobile endowments in each r #
(all,i,ENDWS_COMM)(all,j,PROD_COMM)(all,r,REG) qoes(i,j,r) = qfe(i,j,r);

!<
    9-2. Walras' law
    ---------------->!

Variable walras_sup # supply in omitted market--global supply of cgds composite #;

Equation WALRAS_S
# Extra eq'n computes change in supply in the omitted market. # walras_sup = pcgdswld + globalcgds;

Variable walras_dem # demand in the omitted market--global demand for savings #;

Equation WALRAS_D
# Extra eq'n computes change in demand in the omitted market. # GLOBINV * walras_dem = sum(r,REG,
sum(h,HHLDS,SAVE(h,r) * [psave(r) + qsave(h,r)]));

Variable walraslack # slack variable in the omitted market #;

Equation WALRAS
# Check Walras' Law.  Value of "walraslack" should be zero. # walras_sup = walras_dem + walraslack;

!<-------------------------------
    III. APPENDIX (summary indices)
    -------------------------------
    Appendix-specific variables and coefficients
    Factor price indices
    Regional terms of trade
    GDP indices (value, price and quantity)
    Aggregate trade indices (value, price and quantity)
    Trade balance indices
    Real energy price index
```

```
>!

!<
    Appendix-specific variables and coefficients
    ------------------------------------------->!

Variable (all,i,TRAD_COMM)(all,s,REG) vxwfob(i,s) # value of merchandise regional exports, by
commodity, FOB #;
Variable (all,i,TRAD_COMM)(all,s,REG) viwcif(i,s) # value of merchandise regional imports, by
commodity, CIF #;
Variable (all,r,REG) vxwreg(r) # value of merchandise exports, by region #;
Variable (all,r,REG) viwreg(r) # value of merchandise imports, by region, at world prices #;

Coefficient (all,i,TRAD_COMM)(all,r,REG) VXW(i,r) # value of exports by comm. i and region r at FOB
prices #;
Formula (all,m,MARG_COMM)(all,r,REG) VXW(m,r) = sum(s,REG, VXWD(m,r,s)) + VST(m,r);
Formula (all,i,NMRG_COMM)(all,r,REG) VXW(i,r) = sum(s,REG, VXWD(i,r,s));

Coefficient (all,r,REG) VXWREGION(r) # value of exports by region r at FOB prices #;
Formula (all,r,REG) VXWREGION(r) = sum(i,TRAD_COMM, VXW(i,r));

Coefficient (all,i,TRAD_COMM)(all,s,REG) VIW(i,s) # value of commodity imports i into s at CIF
prices #;
Formula (all,i,TRAD_COMM)(all,s,REG) VIW(i,s) = sum(r,REG, VIWS(i,r,s));
Coefficient (all,r,REG) VIWREGION(r) # value of commodity imports by region r at CIF prices #;
Formula (all,r,REG) VIWREGION(r) = sum(i,TRAD_COMM, VIW(i,r));

!<
    Factor price indices
    -------------------->!

Variable (orig_level=1.0)(all,i,ENDW_COMM)(all,h,HHLDS)(all,r,REG) pfactreal(i,h,r) # ratio of
return to primary factor i to CPI in r #;

Equation REALRETURN
# eq'n defines the real rate of return to primary factor i in region r #
(all,i,ENDW_COMM)(all,h,HHLDS)(all,s,REG) pfactreal(i,h,s) = pse(i,h,s) - ppriv(h,s);

Coefficient (all,r,REG) VENDWREG(r) # value of primary factors, at mkt prices, by region #;
Formula (all,r,REG) VENDWREG(r) = sum(i,ENDW_COMM, sum(h,HHLDS, EVOM(i,h,r)));

Variable (orig_level=1.0)(all,r,REG) pfactor(r) # market price index of primary factors, by region
#;

Equation PRIMFACTPR
# computes % change in price index of primary factors, by region # (all,r,REG) VENDWREG(r) *
pfactor(r) = sum(i,ENDW_COMM, sum(h,HHLDS, EVOM(i,h,r) * pm(i,r)));

Coefficient VENDWWLD # value of primary factors, at mkt prices, worldwide #;
Formula VENDWWLD = sum(r,REG, VENDWREG(r));
Variable (orig_level=1.0) pfactwld # world price index of primary factors #;

Equation PRIMFACTPRWLD
# computes % change in global price index of primary factors # VENDWWLD * pfactwld = sum(r,REG,
VENDWREG(r) * pfactor(r));

!<
    Regional terms of trade
    ----------------------->!

Variable (orig_level=1.0)(all,r,REG) psw(r) # index of prices received for tradeables produced in r
#;

Equation REGSUPRICE
# estimate change in index of prices received for tradeables i produced in r # (all,r,REG)
VXWREGION(r) * psw(r) = sum(i,TRAD_COMM, sum(s,REG, VXWD(i,r,s) * pfob(i,r,s))) + sum(m,MARG_COMM,
VST(m,r) * pm(m,r));

Variable (orig_level=1.0)(all,r,REG) pdw(r) # index of prices paid for tradeables used in region r
#;

Equation REGDEMPRICE
# estimate change in index of prices paid for tradeable products used in r # (all,r,REG)
VIWREGION(r) * pdw(r) = sum(i,TRAD_COMM, sum(k,REG, VIWS(i,k,r) * pcif(i,k,r)));
```

```
Variable (orig_level=1.0)(all,r,REG) tot(r) # terms of trade for region r: tot(r) = psw(r) - pdw(r)
#;

Equation TOTeq
# terms of trade equation computed as difference in psw and pdw # (all,r,REG) tot(r) = psw(r) -
pdw(r);

!<
    GDP Indices (value, price and quantity)
    ---------------------------------------->!

Coefficient (all,r,REG) GDP(r) # Gross Domestic Product in region r #;
Formula (all,s,REG) GDP(s) = sum(h,HHLDS, sum(i,TRAD_COMM, VPAT(i,h,s)) + sum(i,TRAD_COMM,
VGAT(i,h,s))) + sum(k,CGDS_COMM, VOA(k,s)) + sum(i,TRAD_COMM, sum(r,REG, VXWD(i,s,r))) +
sum(m,MARG_COMM, VST(m,s)) - sum(i,TRAD_COMM, sum(r,REG, VIWS(i,r,s)));

Variable (all,r,REG) vgdp(r) # change in value of GDP #;
Equation VGDP_r
# change in value of GDP # (all,r,REG) GDP(r) * vgdp(r) = sum(h,HHLDS,sum(i,TRAD_COMM, VGAT(i,h,r)
* [qg(i,h,r) + pg(i,h,r)]) + sum(i,TRAD_COMM, VPAT(i,h,r) * [qp(i,h,r) + pp(i,h,r)]) + REGINV(h,r)
* [qcgds(r) + pcgds(r)]) + sum(i,TRAD_COMM, sum(s,REG, VXWD(i,r,s) * [qxs(i,r,s) + pfob(i,r,s)])) +
sum(m,MARG_COMM, VST(m,r) * [qst(m,r) + pm(m,r)]) - sum(i,TRAD_COMM, sum(s,REG,VIWS(i,s,r) *
[qxs(i,s,r) + pcif(i,s,r)]));

Variable (orig_level=1.0)(all,r,REG) pgdp(r) # GDP price index #;

Equation PGDP_r
# GDP price index # (all,r,REG) GDP(r) * pgdp(r) = sum(i,TRAD_COMM, sum(h,HHLDS, VGAT(i,h,r) *
pg(i,h,r))) + sum(i,TRAD_COMM, sum(h,HHLDS, VPAT(i,h,r) * pp(i,h,r))) + sum(h,HHLDS,REGINV(h,r)) *
pcgds(r) + sum(i,TRAD_COMM, sum(s,REG, VXWD(i,r,s) * pfob(i,r,s))) + sum(m,MARG_COMM, VST(m,r) *
pm(m,r)) - sum(i,TRAD_COMM, sum(s,REG, VIWS(i,s,r) * pcif(i,s,r)));

Variable (orig_level=GDP)(all,r,REG) qgdp(r) # GDP quantity index #;

Equation QGDP_r
# GDP quantity index # (all,r,REG) GDP(r) * qgdp(r) = sum(i,TRAD_COMM, sum(h,HHLDS, VGAT(i,h,r) *
qg(i,h,r))) + sum(i,TRAD_COMM, sum(h,HHLDS,VPAT(i,h,r) * qp(i,h,r))) + sum(h,HHLDS, REGINV(h,r)) *
qcgds(r) + sum(i,TRAD_COMM, sum(s,REG, VXWD(i,r,s) * qxs(i,r,s))) + sum(m,MARG_COMM, VST(m,r) *
qst(m,r)) - sum(i,TRAD_COMM, sum(s,REG, VIWS(i,s,r) * qxs(i,s,r)));

Variable (all,i,PROD_COMM)(all,r,REG) compvalad(i,r) # composition of value added for good i and
region r #;

Equation COMPVALADEQ
# track change in composition of value added # (all,i,PROD_COMM)(all,r,REG) compvalad(i,r) =
qo(i,r) - qgdp(r);

!<
    Aggregate Trade Indices (value, price and quantity)
    ---------------------------------------------------
    Common variables and coefficients
    Value indices for aggregate trade
    Price indices for aggregate trade
    Quantity indices for aggregate trade
>!

!<
    Common variables and coefficients
>!

Variable (orig_level=1.0)(all,i,TRAD_COMM)(all,r,REG) pxw(i,r) # aggregate exports price index of i
from region r #;

Coefficient (all,i,TRAD_COMM) VXWCOMMOD(i) # value of world exports by commodity i at FOB prices #;
Formula (all,i,TRAD_COMM) VXWCOMMOD(i) = sum(r,REG, VXW(i,r));

Coefficient VXWLD # value of commodity exports, FOB, globally #;
Formula VXWLD = sum(r,REG, VXWREGION(r));

Coefficient (all,i,TRAD_COMM) VIWCOMMOD(i) # global value of commodity imports, CIF, by commodity
#;
Formula (all,i,TRAD_COMM) VIWCOMMOD(i) = sum(r,REG, VIW(i,r));
```

```
Coefficient (all,i,TRAD_COMM)(all,r,REG) PW_PM(i,r) # ratio of world to domestic prices #;
Formula (all,i,TRAD_COMM)(all,r,REG) PW_PM(i,r) = sum(s,REG, VXWD(i,r,s)) / sum(s,REG,
VXMD(i,r,s));
Coefficient (all,i,TRAD_COMM)(all,r,REG) VOW(i,r) # value of output in r at FOB including
transportation services #;
Formula (all,m,MARG_COMM)(all,r,REG) VOW(m,r) = VDM(m,r) * PW_PM(m,r) + sum(s,REG, VXWD(m,r,s)) +
VST(m,r);
Formula (all,i,NMRG_COMM)(all,r,REG) VOW(i,r) = VDM(i,r) * PW_PM(i,r) + sum(s,REG, VXWD(i,r,s));

Coefficient (all,i,TRAD_COMM) VWOW(i) # value of world supply at world prices for i #;
Formula (all,i,TRAD_COMM) VWOW(i) = sum(r,REG, VOW(i,r));

Coefficient (all,i,TRAD_COMM) VWOU(i) # value of world output of i at user prices #;
Formula (all,i,TRAD_COMM) VWOU(i) = sum(s,REG, sum(h,HHLDS, [VPAT(i,h,s) + VGAT(i,h,s)]
+ sum(j,PROD_COMM, VFA(i,j,s))));

!<
    Value indices for aggregate trade
    ---------------------------------->!

Equation VREGEX_ir_MARG
# the change in FOB value of exports of m from r # (all,m,MARG_COMM)(all,r,REG) VXW(m,r) *
vxwfob(m,r) = sum(s,REG, VXWD(m,r,s) * [qxs(m,r,s) + pfob(m,r,s)]) + VST(m,r) * [qst(m,r) +
pm(m,r)];

Equation VREGEX_ir_NMRG
# the change in FOB value of exports of commodity i from r # (all,i,NMRG_COMM)(all,r,REG) VXW(i,r)
* vxwfob(i,r) = sum(s,REG, VXWD(i,r,s) * [qxs(i,r,s) + pfob(i,r,s)]);

Equation VREGEX_r
# computes % change in value of merchandise exports, by region # (all,r,REG) VXWREGION(r) *
vxwreg(r) = sum(i,TRAD_COMM, VXW(i,r) * vxwfob(i,r));

Variable (all,i,TRAD_COMM) vxwcom(i) # value of global merchandise exports by commodity #;

Equation VWLDEX_i
# computes % change in FOB value of global exports, by commodity # (all,i,TRAD_COMM) VXWCOMMOD(i) *
vxwcom(i) = sum(r,REG, VXW(i,r) * vxwfob(i,r));

Variable vxwwld # value of world trade #;

Equation VWLDEX
# computes % change in value of global exports # VXWLD * vxwwld = sum(r,REG, VXWREGION(r) *
vxwreg(r));

Equation VREGIM_is
# the change in CIF value of imports of commodity i into s # (all,i,TRAD_COMM)(all,s,REG) VIW(i,s)
* viwcif(i,s) = sum(r,REG, VIWS(i,r,s) * [pcif(i,r,s) + qxs(i,r,s)]);

Equation VREGIM_s
# computes % change in value of imports, CIF basis, by region # (all,s,REG) VIWREGION(s) *
viwreg(s) = sum(i,TRAD_COMM, VIW(i,s) * viwcif(i,s));

Variable (all,i,TRAD_COMM) viwcom(i) # value of global merchandise imports i, at world prices #;

Equation VWLDIM_i
# computes % change in value of global imports, by commodity # (all,i,TRAD_COMM) VIWCOMMOD(i) *
viwcom(i) = sum(s,REG, VIW(i,s) * viwcif(i,s));

Variable (all,i,TRAD_COMM) valuew(i) # value of world supply of good i #;

Equation VWLDOUT
# change in value of world output of comm. i at FOB prices # (all,i,TRAD_COMM) VWOW(i) * valuew(i)
= sum(r,REG, VOW(i,r) * [pxw(i,r) + qo(i,r)]);

Variable (all,i,TRAD_COMM) valuewu(i) # value of world supply of good i at user prices #;

Equation VWLDOUTUSE
# change in value of world output of commodity i at user prices # (all,i,TRAD_COMM) VWOU(i) *
valuewu(i) = sum(s,REG, sum(h,HHLDS,VPAT(i,h,s) * [pp(i,h,s) + qp(i,h,s)]) + sum(h,HHLDS,
VGAT(i,h,s) * [pg(i,h,s) + qg(i,h,s)]) + sum(j,PROD_COMM, VFAD(i,j,s) * [pft(i,j,s) +
qft(i,j,s)]));

!<
```

```
    Price indices for aggregate trade
    ---------------------------------->!

Equation PREGEX_ir_MARG
# change in FOB price index of exports of m from r # (all,m,MARG_COMM)(all,r,REG) VXW(m,r) *
pxw(m,r) = sum(s,REG, VXWD(m,r,s) * pfob(m,r,s)) + VST(m,r) * pm(m,r);

Equation PREGEX_ir_NMRG
# change in FOB price index of exports of commodity i from r # (all,i,NMRG_COMM)(all,r,REG)
VXW(i,r) * pxw(i,r) = sum(s,REG, VXWD(i,r,s) * pfob(i,r,s));

Variable (orig_level=1.0)(all,r,REG) pxwreg(r) # price index of merchandise exports, by region #;

Equation PREGEX_r
# computes % change in price index of exports, by region # (all,r,REG) VXWREGION(r) * pxwreg(r) =
sum(i,TRAD_COMM, VXW(i,r) * pxw(i,r));

Variable (orig_level=1.0)(all,i,TRAD_COMM) pxwcom(i) # price index of global merchandise exports by
commodity #;

Equation PWLDEX_i
# computes % change in price index of exports, by commodity # (all,i,TRAD_COMM) VXWCOMMOD(i) *
pxwcom(i) = sum(r,REG, VXW(i,r) * pxw(i,r));

Variable (orig_level=1.0) pxwwld # price index of world trade #;

Equation PWLDEX
# computes % change in price index of global exports # VXWLD * pxwwld = sum(r,REG, VXWREGION(r) *
pxwreg(r));

Variable (all,i,TRAD_COMM)(all,r,REG) piw(i,r) # world price of composite import i in region r #;

Equation PREGIM_is
# change in CIF price index of imports of commodity i into s # (all,i,TRAD_COMM)(all,s,REG)
VIW(i,s) * piw(i,s) = sum(r,REG, VIWS(i,r,s) * pcif(i,r,s));

Variable (orig_level=1.0)(all,r,REG) piwreg(r) # price index of merchandise imports, by region #;

Equation PREGIM_s
# computes % change in price index of imports, by region # (all,s,REG) VIWREGION(s) * piwreg(s) =
sum(i,TRAD_COMM, VIW(i,s) * piw(i,s));

Variable (orig_level=1.0)(all,i,TRAD_COMM) piwcom(i) # price index of global merchandise imports by
commodity #;

Equation PWLDIM_i
# computes % change in price index of imports, by commodity # (all,i,TRAD_COMM) VIWCOMMOD(i) *
piwcom(i) = sum(s,REG, VIW(i,s) * piw(i,s));

Variable (all,i,TRAD_COMM) pw(i) # world price index for total good i supplies #;

Equation PWLDOUT
# change in index of world prices, FOB, for total production of i # (all,i,TRAD_COMM) VWOW(i) *
pw(i) = sum(r,REG, VOW(i,r) * pxw(i,r));

Variable (orig_level=1.0)(all,i,TRAD_COMM) pwu(i) # world price index for total good i supplies at
user prices #;

Equation PWLDUSE
# change in index of user prices for deflating world production of i # (all,i,TRAD_COMM) VWOU(i) *
pwu(i) = sum(s,REG, sum(h,HHLDS, VPAT(i,h,s) * pp(i,h,s))
                  + sum(h,HHLDS, VGAT(i,h,s) * pg(i,h,s))
                  + sum(j,PROD_COMM, VFAD(i,j,s) * pft(i,j,s)) );

!<
    Quantity indices for aggregate trade
    ------------------------------------>!

Variable (orig_level=VXW)(all,i,TRAD_COMM)(all,r,REG) qxw(i,r) # aggregate exports of i from region
r, FOB weights #;

Equation QREGEX_ir_MARG
# change in volume of exports of margin commodity m from r # (all,m,MARG_COMM)(all,r,REG) VXW(m,r)
```

```
* qxw(m,r) = sum(s,REG, VXWD(m,r,s) * qxs(m,r,s)) + VST(m,r) * qst(m,r);

Equation QREGEX_ir_NMRG
# change in volume of exports of non-margin commodity i from r # (all,i,NMRG_COMM)(all,r,REG)
VXW(i,r) * qxw(i,r) = sum(s,REG, VXWD(i,r,s) * qxs(i,r,s));

Variable (orig_level=VXWREGION)(all,r,REG) qxwreg(r) # volume of merchandise exports, by region #;

Equation QREGEX_r
# computes % change in quantity index of exports, by region # (all,r,REG) VXWREGION(r) * qxwreg(r)
= sum(i,TRAD_COMM, VXW(i,r) * qxw(i,r));

Variable (orig_level=VXWCOMMOD)(all,i,TRAD_COMM) qxwcom(i) # volume of global merchandise exports
by commodity #;

Equation QWLDEX_i
# computes % change in quantity index of exports, by commodity # (all,i,TRAD_COMM) VXWCOMMOD(i) *
qxwcom(i) = sum(r,REG, VXW(i,r) * qxw(i,r));

Variable (orig_level=VXWLD) qxwwld # volume of world trade #;

Equation QWLDEX
# computes % change in quantity index of global exports # VXWLD * qxwwld = sum(r,REG, VXWREGION(r)
* qxwreg(r));

Variable (all,i,TRAD_COMM)(all,s,REG) qiw(i,s) # aggregate imports of i into region s, CIF weights
#;

Equation QREGIM_is
# change in volume of imports of commodity i into s # (all,i,TRAD_COMM)(all,s,REG) VIW(i,s) *
qiw(i,s) = sum(r,REG, VIWS(i,r,s) * qxs(i,r,s));

Variable (orig_level=VIWREGION)(all,r,REG) qiwreg(r) # volume of merchandise imports, by region #;

Equation QREGIM_s
# computes % change in quantity index of imports, by region #
(all,s,REG) VIWREGION(s) * qiwreg(s) = sum(i,TRAD_COMM, VIW(i,s) * qiw(i,s));

Variable (orig_level=VIWCOMMOD)(all,i,TRAD_COMM) qiwcom(i) # volume of global merchandise imports
by commodity #;

Equation QWLDIM_i
# computes % change in quantity index of imports, by commodity # (all,i,TRAD_COMM) VIWCOMMOD(i) *
qiwcom(i) = sum(s,REG, VIW(i,s) * qiw(i,s));

Variable (all,i,TRAD_COMM) qow(i) # quantity index for world supply of good i #;

Equation QWLDOUT
# change in index of world production of i # (all,i,TRAD_COMM) VWOW(i) * qow(i) = sum(r,REG,
VOW(i,r) * qo(i,r));

Variable (orig_level=VWOU)(all,i,TRAD_COMM) qowu(i) # quantity index for world supply of good i at
user prices #;

Equation QWLDOUTU
# change in index of world production of i evaluated at user prices # (all,i,TRAD_COMM) VWOU(i) *
qowu(i) = sum(s,REG, sum(h,HHLDS, VPAT(i,h,s) * qp(i,h,s) + VGAT(i,h,s) * qg(i,h,s)) +
sum(j,PROD_COMM, VFAD(i,j,s) * qft(i,j,s)));

!<
    Trade balance indices
    ---------------------->!

Variable (change)(all,i,TRAD_COMM)(all,r,REG) DTBALi(i,r) # change in trade balance by i and by r,
$ US million #;

Equation TRADEBAL_i
# computes change in trade balance by commodity and by region # (all,i,TRAD_COMM)(all,r,REG)
DTBALi(i,r) = [VXW(i,r) / 100] * vxwfob(i,r) - [VIW(i,r) / 100] * viwcif(i,r);

Variable (change)(all,r,REG) DTBAL(r) # change in trade balance X - M, $ US million #;

Equation TRADEBALANCE
# computes change in trade balance (X - M), by region # (all,r,REG) DTBAL(r) = [VXWREGION(r) / 100]
```

```
* vxwreg(r) - [VIWREGION(r) / 100] * viwreg(r);

Variable (change) (all,r,REG) DTBALCTRA(r) # balance on current account #;

Equation TRAEMTRADBAL # balance on current account #
(all,r,REG) DTBALCTRA(r) = DTBAL(r) + DVCO2TRA(r);

Coefficient (all,r,REG) TBALCTRA(r) # balance on current account #;
Formula (all,r,REG) TBALCTRA(r) = VXWREGION(r) - VIWREGION(r) + [CO2Q(r) - CO2T(r)] * NCTAXLEV(r);
Formula (all,h,HHLDS)(all,r,reg) INCshares(h,r)=Income(h,r)/sum(hh,HHLDS,Income(hh,r));
Coefficient (all,r,REG) TBAL(r) # trade balance for region r #;
Formula (all,r,REG) TBAL(r) = VXWREGION(r) - VIWREGION(r);

Variable (change)(all,r,REG) DTBALR(r) # change in ratio of trade balance to regional income #;

Equation DTBALRATIO
# change in ratio of trade balance to regional income # (all,r,REG) 100 * sum(h,HHLDS,INCOME(h,r))
* DTBALR(r) =  100 * DTBAL(r) - TBAL(r) * sum(h,HHLDS, INCshares(h,r)*y(h,r));

!<
    Real energy price index
    ---------------------->!

Coefficient (all,i,EGY_COMM)(all,r,REG) TOTDEM(i,r) # energy usage at agents' prices #;
Formula (all,i,EGY_COMM)(all,r,REG) TOTDEM(i,r) = sum{j,PROD_COMM, VDFA(i,j,r)} + sum{j,PROD_COMM,
VIFA(i,j,r)} + sum(h,HHLDS, [VDPA(i,h,r) + VIPA(i,h,r)]) + sum(h,HHLDS, [VDGA(i,h,r) +
VIGA(i,h,r)]);

Variable (all,i,EGY_COMM)(all,r,REG) vdem(i,r) # money value of energy usage at agents' prices #;

Equation TOTVALEN
# money value of energy usage at agents' prices # (all,i,EGY_COMM)(all,r,REG) TOTDEM(i,r) *
vdem(i,r) = sum{j,PROD_COMM, VDFA(i,j,r)*[pfd(i,j,r) + qfd(i,j,r)]} + sum{j,PROD_COMM,
VIFA(i,j,r)*[pfm(i,j,r) + qfm(i,j,r)]} + sum{h,HHLDS, VDPA(i,h,r)*[ppd(i,h,r) + qpd(i,h,r)]} +
sum{h,HHLDS, VIPA(i,h,r)*[ppm(i,h,r) + qpm(i,h,r)]} + sum{h,HHLDS, VDGA(i,h,r)*[pgd(i,h,r) +
qgd(i,h,r)]} + sum{h,HHLDS, VIGA(i,h,r)*[pgm(i,h,r) + qgm(i,h,r)]};

Variable (all,i,EGY_COMM)(all,r,REG) qdem(i,r) # agents'-prices-weighted energy usage quantity
index #;

Equation TOTQUAEN
# agents'-prices-weighted energy usage quantity index # (all,i,EGY_COMM)(all,r,REG) TOTDEM(i,r) *
qdem(i,r) = sum{j,PROD_COMM, VDFA(i,j,r)*qfd(i,j,r)} + sum{j,PROD_COMM, VIFA(i,j,r)*qfm(i,j,r)} +
sum{h,HHLDS, VDPA(i,h,r)*qpd(i,h,r)} + sum{h,HHLDS, VIPA(i,h,r)*qpm(i,h,r)} + sum{h,HHLDS,
VDGA(i,h,r)*qgd(i,h,r)} + sum{h,HHLDS, VIGA(i,h,r)*qgm(i,h,r)};

Variable (all,i,EGY_COMM)(all,r,REG) apen(i,r) # real energy price index #;

Equation AVPRICE
# real energy price index # (all,i,EGY_COMM)(all,r,REG) apen(i,r) = vdem(i,r) - qdem(i,r) -
pgdp(r);

!< ====
    END
    ==
```

QUAIDS Code (Paper 3)
(Stata do file)

```
.global ngoods = 8
.global nminus1 = $ngoods - 1

* The program below, "nlsurquaids", defines the QUAIDS model (8-1=7 budget shares) with parameter
constraints.

.capture program drop nlsurquaids
.program nlsurquaids, rclass

.version 10

* Variables
.syntax varlist(min=35 max=35) if, at(name)
.tokenize `varlist'
.args w1 w2 w3 w4 w5 w6 w7 lnp1 lnp2 lnp3 lnp4 lnp5 lnp6 lnp7 lnp8 lnexp hbs_d1 hbs_d2 hbs_d3 adult
summer urban educ_hoh malesh age unemplsh und5sh ovr65sh res prob_w3 den_w3 prob_w5 den_w5 prob_w7
den_w7

* Coefficients
.tempname r1 r2 r3 r4 r5 r6 r7 r8
.scalar `r1' = `at'[1,1]
.scalar `r2' = `at'[1,2]
.scalar `r3' = `at'[1,3]
.scalar `r4' = `at'[1,4]
.scalar `r5' = `at'[1,5]
.scalar `r6' = `at'[1,6]
.scalar `r7' = `at'[1,7]
.scalar `r8' = 1 - `r1' - `r2' - `r3' - `r4' - `r5' - `r6' - `r7'
.tempname t11 t12 t13 t14 t15 t16 t17 t18 t19 t110 t111 t112
.tempname t21 t22 t23 t24 t25 t26 t27 t28 t29 t210 t211 t212
.tempname t31 t32 t33 t34 t35 t36 t37 t38 t39 t310 t311 t312
.tempname t41 t42 t43 t44 t45 t46 t47 t48 t49 t410 t411 t412
.tempname t51 t52 t53 t54 t55 t56 t57 t58 t59 t510 t511 t512
.tempname t61 t62 t63 t64 t65 t66 t67 t68 t69 t610 t611 t612
.tempname t71 t72 t73 t74 t75 t76 t77 t78 t79 t710 t711 t712
.tempname t81 t82 t83 t84 t85 t86 t87 t88 t89 t810 t811 t812
.scalar `t11' = `at'[1,8]
.scalar `t21' = `at'[1,9]
.scalar `t31' = `at'[1,10]
.scalar `t41' = `at'[1,11]
.scalar `t51' = `at'[1,12]
.scalar `t61' = `at'[1,13]
.scalar `t71' = `at'[1,14]
.scalar `t81' = - `t11' - `t21' -`t31' -`t41' -`t51' - `t61' - `t71'
.scalar `t12' = `at'[1,15]
.scalar `t22' = `at'[1,16]
.scalar `t32' = `at'[1,17]
.scalar `t42' = `at'[1,18]
.scalar `t52' = `at'[1,19]
.scalar `t62' = `at'[1,20]
.scalar `t72' = `at'[1,21]
.scalar `t82' = - `t12' - `t22' -`t32' -`t42' -`t52' - `t62' - `t72'
.scalar `t13' = `at'[1,22]
.scalar `t23' = `at'[1,23]
.scalar `t33' = `at'[1,24]
.scalar `t43' = `at'[1,25]
.scalar `t53' = `at'[1,26]
.scalar `t63' = `at'[1,27]
.scalar `t73' = `at'[1,28]
.scalar `t83' = - `t13' - `t23' -`t33' -`t43' -`t53' - `t63' - `t73'
.scalar `t14' = `at'[1,29]
.scalar `t24' = `at'[1,30]
.scalar `t34' = `at'[1,31]
.scalar `t44' = `at'[1,32]
.scalar `t54' = `at'[1,33]
.scalar `t64' = `at'[1,34]
```

```
.scalar `t74' = `at'[1,35]
.scalar `t84' = - `t14' - `t24' -`t34' -`t44' -`t54' - `t64' - `t74'
.scalar `t15' = `at'[1,36]
.scalar `t25' = `at'[1,37]
.scalar `t35' = `at'[1,38]
.scalar `t45' = `at'[1,39]
.scalar `t55' = `at'[1,40]
.scalar `t65' = `at'[1,41]
.scalar `t75' = `at'[1,42]
.scalar `t85' = - `t15' - `t25' -`t35' -`t45' -`t55' - `t65' - `t75'
.scalar `t16' = `at'[1,43]
.scalar `t26' = `at'[1,44]
.scalar `t36' = `at'[1,45]
.scalar `t46' = `at'[1,46]
.scalar `t56' = `at'[1,47]
.scalar `t66' = `at'[1,48]
.scalar `t76' = `at'[1,49]
.scalar `t86' = - `t16' - `t26' -`t36' -`t46' -`t56' - `t66' - `t76'
.scalar `t17' = `at'[1,50]
.scalar `t27' = `at'[1,51]
.scalar `t37' = `at'[1,52]
.scalar `t47' = `at'[1,53]
.scalar `t57' = `at'[1,54]
.scalar `t67' = `at'[1,55]
.scalar `t77' = `at'[1,56]
.scalar `t87' = - `t17' - `t27' -`t37' -`t47' -`t57' - `t67' - `t77'
.scalar `t18' = `at'[1,57]
.scalar `t28' = `at'[1,58]
.scalar `t38' = `at'[1,59]
.scalar `t48' = `at'[1,60]
.scalar `t58' = `at'[1,61]
.scalar `t68' = `at'[1,62]
.scalar `t78' = `at'[1,63]
.scalar `t88' = - `t18' - `t28' -`t38' -`t48' -`t58' - `t68' - `t78'
.scalar `t19' = `at'[1,64]
.scalar `t29' = `at'[1,65]
.scalar `t39' = `at'[1,66]
.scalar `t49' = `at'[1,67]
.scalar `t59' = `at'[1,68]
.scalar `t69' = `at'[1,69]
.scalar `t79' = `at'[1,70]
.scalar `t89' = - `t19' - `t29' -`t39' -`t49' -`t59' - `t69' - `t79'
.scalar `t110' = `at'[1,71]
.scalar `t210' = `at'[1,72]
.scalar `t310' = `at'[1,73]
.scalar `t410' = `at'[1,74]
.scalar `t510' = `at'[1,75]
.scalar `t610' = `at'[1,76]
.scalar `t710' = `at'[1,77]
.scalar `t810' = - `t110' - `t210' -`t310' -`t410' -`t510' - `t610' - `t710'
.scalar `t111' = `at'[1,78]
.scalar `t211' = `at'[1,79]
.scalar `t311' = `at'[1,80]
.scalar `t411' = `at'[1,81]
.scalar `t511' = `at'[1,82]
.scalar `t611' = `at'[1,83]
.scalar `t711' = `at'[1,84]
.scalar `t811' = - `t111' - `t211' -`t311' -`t411' -`t511' - `t611' - `t711'
.scalar `t112' = `at'[1,85]
.scalar `t212' = `at'[1,86]
.scalar `t312' = `at'[1,87]
.scalar `t412' = `at'[1,88]
.scalar `t512' = `at'[1,89]
.scalar `t612' = `at'[1,90]
.scalar `t712' = `at'[1,91]
.scalar `t812' = - `t112' - `t212' -`t312' -`t412' -`t512' - `t612' - `t712'
.tempname b1 b2 b3 b4 b5 b6 b7 b8
.scalar `b1' = `at'[1,92]
.scalar `b2' = `at'[1,93]
.scalar `b3' = `at'[1,94]
.scalar `b4' = `at'[1,95]
.scalar `b5' = `at'[1,96]
.scalar `b6' = `at'[1,97]
.scalar `b7' = `at'[1,98]
```

```
.scalar `b8' = - `b1' - `b2' - `b3' - `b4' - `b5' - `b6' - `b7'
.tempname g11 g12 g13 g14 g15 g16 g17 g18
.tempname g21 g22 g23 g24 g25 g26 g27 g28
.tempname g31 g32 g33 g34 g35 g36 g37 g38
.tempname g41 g42 g43 g44 g45 g46 g47 g48
.tempname g51 g52 g53 g54 g55 g56 g57 g58
.tempname g61 g62 g63 g64 g65 g66 g67 g68
.tempname g71 g72 g73 g74 g75 g76 g77 g78
.tempname g81 g82 g83 g84 g85 g86 g87 g88
.scalar `g11' = `at'[1,99]
.scalar `g12' = `at'[1,100]
.scalar `g13' = `at'[1,101]
.scalar `g14' = `at'[1,102]
.scalar `g15' = `at'[1,103]
.scalar `g16' = `at'[1,104]
.scalar `g17' = `at'[1,105]
.scalar `g18' = -`g11' - `g12' - `g13' -`g14' - `g15' - `g16' - `g17'
.scalar `g21' = `g12'
.scalar `g22' = `at'[1,106]
.scalar `g23' = `at'[1,107]
.scalar `g24' = `at'[1,108]
.scalar `g25' = `at'[1,109]
.scalar `g26' = `at'[1,110]
.scalar `g27' = `at'[1,111]
.scalar `g28' = -`g21' - `g22' - `g23' -`g24' - `g25' - `g26' - `g27'
.scalar `g31' = `g13'
.scalar `g32' = `g23'
.scalar `g33' = `at'[1,112]
.scalar `g34' = `at'[1,113]
.scalar `g35' = `at'[1,114]
.scalar `g36' = `at'[1,115]
.scalar `g37' = `at'[1,116]
.scalar `g38' = -`g31' - `g32' - `g33' -`g34' - `g35' - `g36' - `g37'
.scalar `g41' = `g14'
.scalar `g42' = `g24'
.scalar `g43' = `g34'
.scalar `g44' = `at'[1,117]
.scalar `g45' = `at'[1,118]
.scalar `g46' = `at'[1,119]
.scalar `g47' = `at'[1,120]
.scalar `g48' = -`g41' - `g42' - `g43' -`g44' - `g45' - `g46' - `g47'
.scalar `g51' = `g15'
.scalar `g52' = `g25'
.scalar `g53' = `g35'
.scalar `g54' = `g45'
.scalar `g55' = `at'[1,121]
.scalar `g56' = `at'[1,122]
.scalar `g57' = `at'[1,123]
.scalar `g58' = -`g51' - `g52' - `g53' -`g54' - `g55' - `g56' - `g57'
.scalar `g61' = `g16'
.scalar `g62' = `g26'
.scalar `g63' = `g36'
.scalar `g64' = `g46'
.scalar `g65' = `g56'
.scalar `g66' = `at'[1,124]
.scalar `g67' = `at'[1,125]
.scalar `g68' = -`g61' - `g62' - `g63' -`g64' - `g65' - `g66' - `g67'
.scalar `g71' = `g17'
.scalar `g72' = `g27'
.scalar `g73' = `g37'
.scalar `g74' = `g47'
.scalar `g75' = `g57'
.scalar `g76' = `g67'
.scalar `g77' = `at'[1,126]
.scalar `g78' = -`g71' - `g72' - `g73' -`g74' - `g75' - `g76' - `g77'
.scalar `g81' = `g18'
.scalar `g82' = `g28'
.scalar `g83' = `g38'
.scalar `g84' = `g48'
.scalar `g85' = `g58'
.scalar `g86' = `g68'
.scalar `g87' = `g78'
.scalar `g88' = -`g81' - `g82' - `g83' -`g84' - `g85' - `g86' - `g87'
.tempname l1 l2 l3 l4 l5 l6 l7 l8
```

```
.scalar `l1' = `at'[1,127]
.scalar `l2' = `at'[1,128]
.scalar `l3' = `at'[1,129]
.scalar `l4' = `at'[1,130]
.scalar `l5' = `at'[1,131]
.scalar `l6' = `at'[1,132]
.scalar `l7' = `at'[1,133]
.scalar `l8' = -`l1' - `l2' - `l3' -`l4' - `l5' - `l6' - `l7'
.tempname n1 n2 n3 n4 n5 n6 n7
.scalar `n1' = `at'[1,134]
.scalar `n2' = `at'[1,135]
.scalar `n3' = `at'[1,136]
.scalar `n4' = `at'[1,137]
.scalar `n5' = `at'[1,138]
.scalar `n6' = `at'[1,139]
.scalar `n7' = `at'[1,140]
.tempname d3 d5 d7
.scalar `d3' = `at'[1,141]
.scalar `d5' = `at'[1,142]
.scalar `d7' = `at'[1,143]

* First price index
.quietly {
.tempvar lnpindex
.gen double `lnpindex' = 0 + (`r1' + `t11'*`hbs_d1' + `t12'*`hbs_d2' + `t13'*`hbs_d3' +
`t14'*`adult' + `t15'*`summer' + `t16'*`urban' + `t17'*`educ_hoh' + `t18'*`malesh' + `t19'*`age' +
`t110'*`unemplsh' + `t111'*`und5sh' + `t112'*`ovr65sh')*`lnp1' +
(`r2' + `t21'*`hbs_d1' + `t22'*`hbs_d2' + `t23'*`hbs_d3' + `t24'*`adult' + `t25'*`summer' +
`t26'*`urban' + `t27'*`educ_hoh' + `t28'*`malesh' + `t29'*`age' + `t210'*`unemplsh' +
`t211'*`und5sh' + `t212'*`ovr65sh')*`lnp2' +
(`r3' + `t31'*`hbs_d1' + `t32'*`hbs_d2' + `t33'*`hbs_d3' + `t34'*`adult' + `t35'*`summer' +
`t36'*`urban' + `t37'*`educ_hoh' + `t38'*`malesh' + `t39'*`age' + `t310'*`unemplsh' +
`t311'*`und5sh' + `t312'*`ovr65sh')*`lnp3' +
(`r4' + `t41'*`hbs_d1' + `t42'*`hbs_d2' + `t43'*`hbs_d3' + `t44'*`adult' + `t45'*`summer' +
`t46'*`urban' + `t47'*`educ_hoh' + `t48'*`malesh' + `t49'*`age' + `t410'*`unemplsh' +
`t411'*`und5sh' + `t412'*`ovr65sh')*`lnp4' +
(`r5' + `t51'*`hbs_d1' + `t52'*`hbs_d2' + `t53'*`hbs_d3' + `t54'*`adult' + `t55'*`summer' +
`t56'*`urban' + `t57'*`educ_hoh' + `t58'*`malesh' + `t59'*`age' + `t510'*`unemplsh' +
`t511'*`und5sh' + `t512'*`ovr65sh')*`lnp5' +
(`r6' + `t61'*`hbs_d1' + `t62'*`hbs_d2' + `t63'*`hbs_d3' + `t64'*`adult' + `t65'*`summer' +
`t66'*`urban' + `t67'*`educ_hoh' + `t68'*`malesh' + `t69'*`age' + `t610'*`unemplsh' +
`t611'*`und5sh' + `t612'*`ovr65sh')*`lnp6' +
(`r7' + `t71'*`hbs_d1' + `t72'*`hbs_d2' + `t73'*`hbs_d3' + `t74'*`adult' + `t75'*`summer' +
`t76'*`urban' + `t77'*`educ_hoh' + `t78'*`malesh' + `t79'*`age' + `t710'*`unemplsh' +
`t711'*`und5sh' + `t712'*`ovr65sh')*`lnp7' +
(`r8' + `t81'*`hbs_d1' + `t82'*`hbs_d2' + `t83'*`hbs_d3' + `t84'*`adult' + `t85'*`summer' +
`t86'*`urban' + `t87'*`educ_hoh' + `t88'*`malesh' + `t89'*`age' + `t810'*`unemplsh' +
`t811'*`und5sh' + `t812'*`ovr65sh')*`lnp8'
.forvalues i = 1/$ngoods {
.forvalues j = 1/$ngoods {
.replace `lnpindex' = `lnpindex' + 0.5*`g`i''`j''*`lnp`i''*`lnp`j''
}
}

* Second price index
.tempvar bp
.gen double `bp' = 0
.forvalues i = 1/$ngoods {
.replace `bp' = `bp' + `lnp`i''*`b`i''
}
.replace `bp' = exp(`bp')

* System of equations
.replace `w1' = `r1' + `t11'*`hbs_d1' + `t12'*`hbs_d2' + `t13'*`hbs_d3' + `t14'*`adult' +
`t15'*`summer' + `t16'*`urban' + `t17'*`educ_hoh' + `t18'*`malesh' + `t19'*`age' +
`t110'*`unemplsh' + `t111'*`und5sh' + `t112'*`ovr65sh' + `g11'*`lnp1' + `g12'*`lnp2' + `g13'*`lnp3'
+ `g14'*`lnp4' + `g15'*`lnp5' + `g16'*`lnp6' + `g17'*`lnp7' + `g18'*`lnp8' +
`b1'*(`lnexp' - `lnpindex') + `l1'/`bp'*(`lnexp' - `lnpindex')^2 + `n1'*`res'

.replace `w2' = `r2' + `t21'*`hbs_d1' + `t22'*`hbs_d2' + `t23'*`hbs_d3' + `t24'*`adult' +
`t25'*`summer' + `t26'*`urban' + `t27'*`educ_hoh' + `t28'*`malesh' + `t29'*`age' +
`t210'*`unemplsh' + `t211'*`und5sh' + `t212'*`ovr65sh' + `g21'*`lnp1' + `g22'*`lnp2' + `g23'*`lnp3'
+ `g24'*`lnp4' + `g25'*`lnp5' + `g26'*`lnp6' + `g27'*`lnp7' + `g28'*`lnp8' +
`b2'*(`lnexp' - `lnpindex') + `l2'/`bp'*(`lnexp' - `lnpindex')^2 + `n2'*`res'
```

```
.replace `w3' = (`r3' + `t31'*`hbs_d1' + `t32'*`hbs_d2' + `t33'*`hbs_d3' + `t34'*`adult' +
`t35'*`summer' + `t36'*`urban' + `t37'*`educ_hoh' + `t38'*`malesh' + `t39'*`age' +
`t310'*`unemplsh' + `t311'*`und5sh' + `t312'*`ovr65sh' + `g31'*`lnp1' + `g32'*`lnp2' + `g33'*`lnp3'
+ `g34'*`lnp4' + `g35'*`lnp5' + `g36'*`lnp6' + `g37'*`lnp7' + `g38'*`lnp8' +
`b3'*(`lnexp' - `lnpindex') + `l3'/`bp'*(`lnexp' - `lnpindex')^2 + `n3'*`res')*`prob_w3' +
`d3'*`den_w3'

.replace `w4' = `r4' + `t41'*`hbs_d1' + `t42'*`hbs_d2' + `t43'*`hbs_d3' + `t44'*`adult' +
`t45'*`summer' + `t46'*`urban' + `t47'*`educ_hoh' + `t48'*`malesh' + `t49'*`age' +
`t410'*`unemplsh' + `t411'*`und5sh' + `t412'*`ovr65sh' + `g41'*`lnp1' + `g42'*`lnp2' + `g43'*`lnp3'
+ `g44'*`lnp4' + `g45'*`lnp5' + `g46'*`lnp6' + `g47'*`lnp7' + `g48'*`lnp8' +
`b4'*(`lnexp' - `lnpindex') + `l4'/`bp'*(`lnexp' - `lnpindex')^2 + `n4'*`res'

.replace `w5' = (`r5' + `t51'*`hbs_d1' + `t52'*`hbs_d2' + `t53'*`hbs_d3' + `t54'*`adult' +
`t55'*`summer' + `t56'*`urban' + `t57'*`educ_hoh' + `t58'*`malesh' + `t59'*`age' +
`t510'*`unemplsh' + `t511'*`und5sh' + `t512'*`ovr65sh' + `g51'*`lnp1' + `g52'*`lnp2' + `g53'*`lnp3'
+ `g54'*`lnp4' + `g55'*`lnp5' + `g56'*`lnp6' + `g57'*`lnp7' + `g58'*`lnp8' +
`b5'*(`lnexp' - `lnpindex') + `l5'/`bp'*(`lnexp' - `lnpindex')^2 + `n5'*`res')*`prob_w5' +
`d5'*`den_w5'

.replace `w6' = `r6' + `t61'*`hbs_d1' + `t62'*`hbs_d2' + `t63'*`hbs_d3' + `t64'*`adult' +
`t65'*`summer' + `t66'*`urban' + `t67'*`educ_hoh' + `t68'*`malesh' + `t69'*`age' +
`t610'*`unemplsh' + `t611'*`und5sh' + `t612'*`ovr65sh' + `g61'*`lnp1' + `g62'*`lnp2' + `g63'*`lnp3'
+ `g64'*`lnp4' + `g65'*`lnp5' + `g66'*`lnp6' + `g67'*`lnp7' + `g68'*`lnp8' +
`b6'*(`lnexp' - `lnpindex') + `l6'/`bp'*(`lnexp' - `lnpindex')^2 + `n6'*`res'

.replace `w7' = (`r7' + `t71'*`hbs_d1' + `t72'*`hbs_d2' + `t73'*`hbs_d3' + `t74'*`adult' +
`t75'*`summer' + `t76'*`urban' + `t77'*`educ_hoh' + `t78'*`malesh' + `t79'*`age' +
`t710'*`unemplsh' + `t711'*`und5sh' + `t712'*`ovr65sh' + `g71'*`lnp1' + `g72'*`lnp2' + `g73'*`lnp3'
+ `g74'*`lnp4' + `g75'*`lnp5' + `g76'*`lnp6' + `g77'*`lnp7' + `g78'*`lnp8' +
`b7'*(`lnexp' - `lnpindex') + `l7'/`bp'*(`lnexp' - `lnpindex')^2 + `n7'*`res')*`prob_w7' +
`d7'*`den_w7'
}
.end



* The program below, "estimate", estimates the QUAIDS model above and then calculates price and
expenditure elasticities at sample mean values. As elasticities are scalars, they can be
bootstrapped.

.capture program drop estimate
.program estimate, rclass

.nlsur quaids @ w1 w2 w3 w4 w5 w6 w7 lnp1-lnp8 lnexp hbs_d1 hbs_d2 hbs_d3 adult summer urban
educ_hoh malesh age unemplsh und5sh ovr65sh res prob_w3 den_w3 prob_w5 den_w5 prob_w7 den_w7,
ifgnls nequations(7) param(r1 r2 r3 r4 r5 r6 r7 t11 t12 t13 t14 t15 t16 t17 t18 t19 t110 t111 t112
t21 t22 t23 t24 t25 t26 t27 t28 t29 t210 t211 t212 t31 t32 t33 t34 t35 t36 t37 t38 t39 t310 t311
t312 t41 t42 t43 t44 t45 t46 t47 t48 t49 t410 t411 t412 t51 t52 t53 t54 t55 t56 t57 t58 t59 t510
t511 t512 t61 t62 t63 t64 t65 t66 t67 t68 t69 t610 t611 t612 t71 t72 t73 t74 t75 t76 t77 t78 t79
t710 t711 t712 b1 b2 b3 b4 b5 b6 b7 g11 g12 g13 g14 g15 g16 g17 g22 g23 g24 g25 g26 g27 g33 g34 g35
g36 g37 g44 g45 g46 g47 g55 g56 g57 g66 g67 g77 l1 l2 l3 l4 l5 l6 l7 n1 n2 n3 n4 n5 n6 n7 d3 d5 d7)


* Elasticities @ sample mean values

.collapse (mean) w1-w${ngoods} lnp1-lnp${ngoods} lnexp hbs_d1 hbs_d2 hbs_d3 adult summer urban
educ_hoh malesh age unemplsh und5sh ovr65sh res prob_w3 den_w3 prob_w5 den_w5 prob_w7 den_w7

* ar
.mat ar = J($ngoods, 1, 0)
.sca lastr = 1
.forvalues i = 1/$nminus1 {
.mat ar[`i', 1] = _b[/r`i']
.sca lastr = lastr - _b[/r`i']
}
.mat ar[$ngoods, 1] = lastr


* ti
.mat ti = J($ngoods, 12, 0)
.forvalues j = 1/12 {
.forvalues i = 1/$nminus1 {
```

```
.mat ti[`i', `j'] = _b[/t`i'`j']
}
.sca lastt = 0
.forvalues i = 1/$nminus1 {
.sca lastt = lastt - ti[`i', `j']
}
.mat ti[$ngoods, `j'] = lastt
}


* alpha
.sca a1 = ar[1,1] + ti[1,1]*hbs_d1[1] + ti[1,2]*hbs_d2[1] + ti[1,3]*hbs_d3[1] + ti[1,4]*adult[1] +
ti[1,5]*summer[1] + ti[1,6]*urban[1] + ti[1,7]*educ_hoh[1] + ti[1,8]*malesh[1] + ti[1,9]*age[1] +
ti[1,10]*unemplsh[1] + ti[1,11]*und5sh[1] + ti[1,12]*ovr65sh[1]
.sca a2 = ar[2,1] + ti[2,1]*hbs_d1[1] + ti[2,2]*hbs_d2[1] + ti[2,3]*hbs_d3[1] + ti[2,4]*adult[1] +
ti[2,5]*summer[1] + ti[2,6]*urban[1] + ti[2,7]*educ_hoh[1] + ti[2,8]*malesh[1] + ti[2,9]*age[1] +
ti[2,10]*unemplsh[1] + ti[2,11]*und5sh[1] + ti[2,12]*ovr65sh[1]
.sca a3 = ar[3,1] + ti[3,1]*hbs_d1[1] + ti[3,2]*hbs_d2[1] + ti[3,3]*hbs_d3[1] + ti[3,4]*adult[1] +
ti[3,5]*summer[1] + ti[3,6]*urban[1] + ti[3,7]*educ_hoh[1] + ti[3,8]*malesh[1] + ti[3,9]*age[1] +
ti[3,10]*unemplsh[1] + ti[3,11]*und5sh[1] + ti[3,12]*ovr65sh[1]
.sca a4 = ar[4,1] + ti[4,1]*hbs_d1[1] + ti[4,2]*hbs_d2[1] + ti[4,3]*hbs_d3[1] + ti[4,4]*adult[1] +
ti[4,5]*summer[1] + ti[4,6]*urban[1] + ti[4,7]*educ_hoh[1] + ti[4,8]*malesh[1] + ti[4,9]*age[1] +
ti[4,10]*unemplsh[1] + ti[4,11]*und5sh[1] + ti[4,12]*ovr65sh[1]
.sca a5 = ar[5,1] + ti[5,1]*hbs_d1[1] + ti[5,2]*hbs_d2[1] + ti[5,3]*hbs_d3[1] + ti[5,4]*adult[1] +
ti[5,5]*summer[1] + ti[5,6]*urban[1] + ti[5,7]*educ_hoh[1] + ti[5,8]*malesh[1] + ti[5,9]*age[1] +
ti[5,10]*unemplsh[1] + ti[5,11]*und5sh[1] + ti[5,12]*ovr65sh[1]
.sca a6 = ar[6,1] + ti[6,1]*hbs_d1[1] + ti[6,2]*hbs_d2[1] + ti[6,3]*hbs_d3[1] + ti[6,4]*adult[1] +
ti[6,5]*summer[1] + ti[6,6]*urban[1] + ti[6,7]*educ_hoh[1] + ti[6,8]*malesh[1] + ti[6,9]*age[1] +
ti[6,10]*unemplsh[1] + ti[6,11]*und5sh[1] + ti[6,12]*ovr65sh[1]
.sca a7 = ar[7,1] + ti[7,1]*hbs_d1[1] + ti[7,2]*hbs_d2[1] + ti[7,3]*hbs_d3[1] + ti[7,4]*adult[1] +
ti[7,5]*summer[1] + ti[7,6]*urban[1] + ti[7,7]*educ_hoh[1] + ti[7,8]*malesh[1] + ti[7,9]*age[1] +
ti[7,10]*unemplsh[1] + ti[7,11]*und5sh[1] + ti[7,12]*ovr65sh[1]
.sca a8 = ar[8,1] + ti[8,1]*hbs_d1[1] + ti[8,2]*hbs_d2[1] + ti[8,3]*hbs_d3[1] + ti[8,4]*adult[1] +
ti[8,5]*summer[1] + ti[8,6]*urban[1] + ti[8,7]*educ_hoh[1] + ti[8,8]*malesh[1] + ti[8,9]*age[1] +
ti[8,10]*unemplsh[1] + ti[8,11]*und5sh[1] + ti[8,12]*ovr65sh[1]
.mat alpha = J(8, 1, 0)
.forvalues i = 1/$ngoods {
.mat alpha[`i', 1] = a_`i'
}

* beta
.mat beta = J($ngoods, 1, 0)
.sca lastb = 0
.forvalues i = 1/$nminus1 {
.mat beta[`i', 1] = _b[/b`i']
.sca lastb = lastb - _b[/b`i']
}
.mat beta[$ngoods, 1] = lastb

* lambda
.mat lambda = J($ngoods, 1, 0)
.sca lastl = 0
.forvalues i = 1/$nminus1 {
.mat lambda[`i', 1] = _b[/l`i']
.sca lastl = lastl - _b[/l`i']
}
.mat lambda[$ngoods, 1] = lastl

* gamma
.mat gamma = J($ngoods, $ngoods, 0)
.forvalues i = 1/$nminus1 {
.forvalues j = `i'/$nminus1 {
.mat gamma[`i', `j'] = _b[/g`i'`j']
.if (`i' != `j') {
.mat gamma[`j', `i'] = _b[/g`i'`j']
}
}
* last column
.sca lastg = 0
.forvalues t = 1/$nminus1 {
.sca lastg = lastg - gamma[`i', `t']
}
.mat gamma[`i', $ngoods] = lastg
.mat gamma[$ngoods, `i'] = lastg
```

```
}
* last element
.sca lastg = 0
.forvalues t = 1/$nminus1 {
.sca lastg = lastg - gamma[$ngoods, `t']
}
.mat gamma[$ngoods, $ngoods] = lastg


* lnpindex
.sca lnpindex = 0 + alpha[1,1]*lnp1[1] + alpha[2,1]*lnp2[1] + alpha[3,1]*lnp3[1] +
alpha[4,1]*lnp4[1] + alpha[5,1]*lnp5[1] + alpha[6,1]*lnp6[1] + alpha[7,1]*lnp7[1] +
alpha[8,1]*lnp8[1]
.forvalues i = 1/$ngoods {
.forvalues j = 1/$ngoods {
.sca lnpindex = lnpindex + 0.5*gamma[`i',`j']*lnp`i'[1]*lnp`j'[1]
}
}
.sca bp = 0
.forvalues i = 1/$ngoods {
.sca bp = bp + lnp`i'[1]*beta[`i',1]
}
.sca bp = exp(bp)


* Expenditure elasticities
.forvalues i = 1/$ngoods {
.sca mu_`i' = beta[`i',1]+2*lambda[`i',1]/bp*(lnexp[1] - lnpindex)
.if (`i' == 3) {
.sca mu_`i' = mu_`i' *prob_w3[1]
}
.if (`i' == 5) {
.sca mu_`i' = mu_`i' *prob_w5[1]
}
.if (`i' == 7) {
.sca mu_`i' = mu_`i' *prob_w7[1]
}
}
.forvalues i = 1/$ngoods {
.sca inc_`i' = 1 + mu_`i'/ w`i'[1]
}

* Uncompensated price elasticities
.forvalues i = 1/$ngoods {
.forvalues j = 1/$ngoods {
.sca glnp = 0
.forvalues k = 1/$ngoods {
.sca glnp = glnp + gamma[`j',`k']*lnp`k'[1]
}
.sca eta_`i'_`j' = 1/w`i'[1]*(gamma[`i',`j'] -
.mu_`i'*(alpha[`j',1] + glnp)- lambda[`i',1]*beta[`i',1]/bp*(lnexp[1] - lnpindex)^2)
.if (`i' == 3) {
.sca eta_`i'_`j' = eta_`i'_`j' *prob_w3[1]
}
.if (`i' == 5) {
.sca eta_`i'_`j' = eta_`i'_`j' *prob_w5[1]
}
.if (`i' == 7) {
.sca eta_`i'_`j' = eta_`i'_`j' *prob_w7[1]
}
.if (`i' == `j') {
.sca eta_`i'_`j' = eta_`i'_`j' - 1
}
}
}
.forvalues i = 1/$ngoods {
.return sca inc_`i' = inc_`i'
.forvalues j = 1/$ngoods {
.return sca eta_`i'_`j' = eta_`i'_`j'
}
}


* Matrix of expenditure elasticities
```

```
.mat expend = J($ngoods, 1, 0)
.forvalues i = 1/$ngoods {
.mat expend[`i', 1] = inc_`i'
}

* Matrix of price elasticities (uncomp.)
.mat price = J($ngoods, $ngoods, 0)
.forvalues i = 1/$ngoods {
.forvalues j = `i'/$ngoods {
.mat price[`i', `j'] = eta_`i'_`j'
}
}

.end

.estimate
```