AGE assessment of interactions between a carbon energy tax and pre-existing taxes

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ABSTRACT

This paper presents an applied general equilibrium model with a detailed representation of the tax system and transfers between agents. We simulate the implementation of a carbon energy tax in Ireland and compare four different methods to recycle its revenue. The extended specification of a tax matrix with separate tax data on all transactions in the economy creates the possibility to perform thorough second-best analysis, *i.e.* to assess interactions of the carbon tax with pre-existing distortionary taxes in more detail than is usually possible in an AGE model. We find that using the revenues to reduce existing taxes may reduce the welfarecost of the carbon tax, but only when the appropriate tax is reduced. Reducing labour taxes leads to worse welfare effects than recycling through a lowering of the VAT. This surprising result is governed by the tightness in the Irish labour market that restricts labour supply.

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1. Introduction

Climate change currently is at the top of the environmental agenda in the European Union (EU). It is caused by the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere. Global political efforts to reduce this problem led to the agreement of the Kyoto Protocol in 1997. The Protocol sets targets to reduce the anthropogenic emissions of GHGs. As part of the EU burden-sharing agreement, Ireland has to limit average annual emissions in the period 2008-2012 to 13 percent above 1990 levels. Irish GHG emissions are already well past this target due to strong economic development in the 1990s. Ireland has the highest per capita emissions in Europe and also faces one of the widest gaps (nearly 18 percent) between forecasted emissions under a business-as-usual scenario and the target. Specific government policy is required to meet the target and the economy will have to undergo structural changes. The government of Ireland has published a National Climate Change Strategy (NCCS) that aims to meet the targets and to minimise the costs of implementation for the economy as a whole (DoE, 2000). Key measures in the Strategy are

- to gradually introduce taxation from 2002, prioritising taxes aimed at CO_2 emissions;
- to participate in the pilot EU emissions trading scheme and in international emissions trading.

The Minister for Finance indicated in his Budget speech for 2003 that the government was proposing to introduce a carbon tax in 2004. In 2005, however, the tax was still not implemented and this proposal was abandoned altogether due to fears for its impact on competitiveness. Oil prices were already increasing strongly. Since January 2005, the 109 installations emitting most CO_2 have been participating in the EU emissions trading scheme. The price of permits hovered around 20 euro per tonne of CO_2 for a while, but occasionally peaked above 30 euro. This paper does not examine the permit system, but under certain circumstances a carbon tax is comparable as it provides the same price incentives.

Clinch and Dunne (2006) found that the main social impediment to environmental tax reform in Ireland is that there is insufficient trust that the government will keep its promise to recycle the revenue from the tax by lowering other taxes. Our paper analyses the impact on welfare of recycling the revenue of a carbon tax in different ways.

The first empirical work assessing the macro-economic effects of imposing a carbon tax on the Irish economy was carried out by Fitz Gerald and McCoy in 1992. They used the ESRI macro-econometric Medium Term Model (HERMES) supplemented by an energy sub-model (Fitz Gerald & McCoy, 1992). Bergin *et al*. (2002) used an improved version of HERMES and found that a carbon tax of 20 euro per tonne of CO_2 would cost the Irish economy relatively little. This tax would not lead to the required emission reduction, however, and all of the additional measures suggested in the NCCS would need to be fully implemented along with an early implementation of the tax. They simulated four ways to use the revenue and concluded that (1) with reduced taxes on labour a welfare improvement is possible; (2) reducing VAT has less attractive macro-economic results but distributional advantages; (3) a lump sum payment to households could have very adverse competitiveness effects and lead to loss of output, which in the long term would affect income levels and employment and (4) a lump sum payment to firms would lead to the biggest loss in GNP. Only the first two instruments lead to lower prices and lower wage rates which would offset the negative impact of the carbon tax on competitiveness.

Scott and Eakins (2002) analysed the distributional implications of this tax. All household groups would gain, on average, from the reform if all households received an average compensation of 247 euro per year. But they warned that many individual households in low-income brackets would be worse off. They recommended a more integrated analysis of the tax and welfare system.

General equilibrium models are a most suitable methodology for this type of analysis[1] because they include all - and possibly a large number of separately distinguished - sectors in the economy and consist of a closed cycle. This facilitates the study of indirect as well as direct effects caused by tax policy measures. Also, they may include possibilities for both inter-fuel substitution and substitution between energy and other factors of production. The first applied general equilibrium (AGE) study on climate change policy that focused specifically on Ireland was limited to the analysis of the impact of emissions trading on manufacturing sectors (Indecon, 2003). The carbon tax and the impact on the agricultural, services and residential sectors were not considered.

Wissema and Dellink (2006) first used an applied general equilibrium (AGE) model for the analysis of the impact of a carbon energy tax on the Irish economy. It emerged that a

[1] For discussions and surveys of AGE models used in climate change and energy policy research, see Bhattacharyya (1996), Conrad (1999), Harrison *et al*. (2000), Devarajan and Robinson (2002), Weyant (2004) and Dellink (2005).

carbon tax in the range of 10 to 15 euro per tonne of CO_2 would achieve the target for reduction of CO_2 emissions from energy use and production of 25.8 percent, while not reducing welfare by more than 0.5 percent. Changes in output levels of 26 sectors and consumption levels of 26 commodities were shown to be more significant and in some cases quite strong. Behavioural responses to the differentiated tax meant that relatively carbon-intensive fuels were replaced by energy sources that caused less or no emissions. Thus, they show that the best response to the carbon tax consists of a mixture of changes in the fuel mix, energy conservation and economic restructuring. Their representation of the tax system is relatively simple, and thus they cannot properly assess the consequences of different recycling schemes.

This paper adds to the literature by extending the AGE model of Wissema and Dellink (2006) with substantial detail regarding taxation and inter-institutional transfers to analyse the impact on the Irish economy of implementation of a revenue-neutral carbon tax. An interesting new feature in this paper is that the carbon tax, though implemented as a tax on energy, is correctly levied per tonne of CO_2, not *ad valorem*, as is common in AGE models.

The strength of this paper lies in the combination of a detailed representation of the tax system and inter-agent transfers on one hand and detail in the modelling of production, consumption and the labour market on the other hand, which are deemed to be decisive factors in Double Dividend analyses. This level of detail allows for the investigation of tax interaction effects and different revenue recycling options.

In the production functions, the energy substitution possibilities are represented by a multi-level nesting structure and the electricity production function has a different tree structure. The consumption side of the model is represented by a linear expenditure system to account for basic and luxury goods, *i.e.* to be able to differentiate income elasticities of different commodities. Furthermore, the model features endogenous supply of labour and endogenous, though constrained, unemployment and real wage rates.

Four different schemes for recycling of the revenue of the carbon tax are compared:

1. A lump-sum transfer to households
2. Reduction of indirect tax rates
3. Reduction of the labour tax rate
4. Reduction of output tax rates.

The next section briefly summarises relevant discussions in the international literature. Section 3 describes the model and data applied. Section 4 presents and analyses the results and conclusions are drawn in Section 5, which also contains a number of recommendations.

2. CONTEXT

In the past couple of decades, a debate has taken place in the international literature about the question of pollution taxes or green taxes, and whether they could produce other benefits than just the environmental dividend, i.e., a 'double dividend' (DD). At first, authors used solely theoretical models which appeared to give conflicting results. Terkla (1984) suggested that effluent taxes are preferred to standards, because they can replace other taxes and lead to efficiency gains. This interaction with pre-existing taxes was emphasised in many papers, such as Lee and Misiolek (1986) who state that the Pigovian tax (P*) is only optimal if there are no other taxes and that the substitution effect of revenues raised by other taxes must be taken into account; Shah and Larsen (1992), who find it is impossible to calculate the effect of a new tax without accounting for existing taxes; Jorgenson and Wilcoxon (1993b), who compare taxes with standards and find the main downside of standards is that they do not provide revenue that can be used to lower other taxes; Carraro and Sourbeyran (1994), who conclude that in a first-best optimal taxation world, environmental protection trades off with unemployment but that, with initial non-optimal taxes, it is possible that fiscal reform will raise employment, increase welfare and lower emissions.

Bovenberg and De Mooij (1994) find that, if there are pre-existing distortionary taxes, environmental taxes tend to exacerbate them even if revenues are used to cut those pre-existing distortionary taxes (p. 1085). The crucial result is that a carbon/energy tax has a higher gross (environmental benefits not counted) welfare cost than income tax. This suggests that a second dividend is unlikely. Increasing a narrow based green tax and reducing a broad based tax such as a labour tax usually worsens the distortion of the tax system. However, their model has a linear production function with labour as the only input.

Theoretical and empirical evidence of the DD was surveyed by Goulder (1995), who defined the 'weak' and 'strong' form of the DD. The weak DD compares two policy changes. The efficiency costs of a revenue-neutral environmental tax reform are lower if the revenue is used to cut distortionary taxes instead of recycled in a lump-sum fashion. The strong form compares equilibrium after a policy change with the status quo. In

Bovenberg and De Mooij (1994), the strong form had been unlikely, but in Bovenberg's 'updated reader's guide' (1999), he shows, with a GE model with only a labour tax and no other production factors, how the strong DD holds if both environmental quality and the tax base (L) go up.

If employment is increased as well, this is called a triple dividend. The debate in Europe focused more on employment because of high unemployment levels. Pireddu and Dufournaud (1996) analyse the Italian case and find that raising energy taxes has a negative impact on households, even after the additional revenue is recycled, given budget neutrality. Energy is difficult to replace in the consumption bundle, which they modelled in detail. However, they find a significant employment boost by raising green taxes and lowering labour taxes. Their model has fixed labour supply, though. Other studies on these issues include Böhringer and Rutherford (1997), Koskela *et al.* (1998), Stiglitz (1999), Hutton and Ruocco (1999), Parry and Bento (2000), Håkonsen (2001), Bovenberg and Goulder (2002) and Goulder and Williams (2003). The choice of model structure and closure clearly affect the conclusions.

Ballard *et al.* (2005) give a recent summary of the DD literature and show how the results change when preferences are not homothetic. Another more recent paper contributes empirical DD evidence for Spain (Manresa & Sancho, 2005). In the flexible version of their model, which incorporates endogenous unemployment and a Cobb-Douglas aggregation of labour and capital, a double and a triple dividend are possible. However, labour supply is inelastic and there is no substitution between energy sources. For revenue recycling, only a reduction in labour taxes is considered. Also, in each scenario the energy taxation simulated, an *ad valorem* tax on all energy with or without an extra petrol tax, is too low to reduce emissions by more than 3.5 percent. As benchmark unemployment is very high at 16 percent, there is much scope for improvement in the Spanish economy of 1990. Chiroleu-Assouline and Fodha (2006) apply an overlapping generations model to analyse the DD issue. The results can be very favourable depending on the initial capital stock and the intertemporal elasticity of substitution, they conclude.

The literature shows very clearly how important it is to have an empirical model which represents the tax system in sufficient detail in order to analyse the interactions of the carbon energy tax with pre-existing taxes. The way in which the labour market is represented can also crucially affect outcomes, especially where the tax burden on labour is significantly changed. Finally, the representation of consumer behaviour substantially affects the results.

3. THE IRISH ENERGY-ENVIRONMENT MODEL WITH TAXATION EXTENSIONS

The model used in this paper builds on the model developed in Wissema and Dellink (2006). It is a structural, real, static model of a small open economy with 7 energy commodities, 19 other commodities, a government, an investment agent, a foreign agent and a single representative household. It incorporates flows of seven energy commodities among producers and between producers and consumers.

For the reasons stated in the concluding remarks of Section 2, this paper enhances the model with the following major extensions:

- Substantially improved detail in the area of taxation and transfers (Section 3.4)
- Endogenous labour supply with time devoted to leisure entering the utility function (Section 3.5)
- Involuntary unemployment is incorporated with both the real wage rate and the unemployment rate endogenous, while subject to a minimum value (Section 3.5)
- consumption is represented by a Linear Expenditure System in which substitution is only possible among the 'luxury' share of purchases (Section 3.3).

The carbon tax introduced in this model is a per-unit or 'specific' tax: it is levied per tonne of CO_2. It is implemented in the model as a tax on energy use. This energy tax is both fuel-specific and sector-specific depending on emission factors that differ according to both the carbon content of the fuel and the combustion technology of the user.

Many standard assumptions of GE models still apply after introducing the extensions: market clearing in all markets except for the labour market, zero excess profits and a balanced budget for each agent (*cf.* Ginsburgh & Keyzer, 1997). It is assumed that the economy is in equilibrium in the benchmark, which is calibrated to 1998 data (see Section 3.7). A policy simulation is implemented as a 'counter-factual' scenario, which consists of an exogenous shock or set of shocks to the system. The model output shows the state of the economy after all markets have reached a new equilibrium, *i.e.*, we conduct a comparative-static analysis.[2] The sectors and commodities are described in Appendix A; Appendix B contains a complete overview of the equations of the model.[3]

[2] Dellink (2005) shows how the modelling framework can be expanded to a fully dynamic analysis and discusses the validity of the comparative-static approach. A good example of a dynamic multi-regional model for climate policy is given in Böhringer & Welsch (2004).

[3] The model code is available upon request.

3.1 Production

A firm can choose the scale of production and the composition of inputs. The output is divided among the produced commodities with a CET[4] function, where the elasticity of transformation is equal to zero for all industries. This perfectly inelastic function ensures that the shares of commodities produced, in terms of quantity, remain the same during all simulations. The production process is represented by a nested production function as depicted in Figure 1 below.[5] The electricity producer has a separate production function (shown in the second panel). In the figure, the Allen elasticities of substitution are indicated with 's: ' and are the same for each industry.[6] The top-level function is a Leontief function (s:0) that determines the producer's demand for the aggregate factor input of labour, capital and energy *LKE* and each of the intermediate (non-energy) inputs *IO(i)*. CES[7] functions are applied for levels two to six of the production function. The elasticities of substitution between labour *L* and composite capital and energy, *KE*, and between aggregate energy *E* and capital *K* are taken from Kemfert (1998).[8]

Elasticities for the *E*, *FOS* and *LIQ* nests are taken from GTAP-EG (Rutherford & Paltsev, 2000). Peat and coal form composite *"SOL"* with an elasticity larger than unity because they are good, but not perfect substitutes. Finally, crude oil and oil products are aggregated in a Leontief function, because crude oil is only used in the oil refinery and there should not be any substitution between these two fuels.

Irish security of energy supply policy prevents a major drop in peat consumption by the electricity generation sector. This situation is approximated by fixing the input of peat per unit of electricity produced in the Leontief function in the top level of the production tree. Since 'RNEW' is defined as electricity produced from renewable resources, substitution is only limited by a lack of capacity in the renewables industry. It is assumed that capacity can be increased and therefore, the elasticity is set fairly high, at 10.

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4 CET = Constant Elasticity of Transformation.

5 The choice for the L-KE nesting structure is based on Kemfert (1998), who concludes that this fits the German industry best overall. GTAP-EG (Rutherford & Paltsev, 2000) inspired the remainder.

6 Unfortunately, sector specific elasticities of substitution are not available in Ireland.

7 CES = Constant Elasticity of Substitution.

8 Kemfert (1998) econometrically estimates L-KE and K-E elasticities for German industry overall to be 0.846 and 0.653, respectively. It is assumed that the Irish economy has equal flexibility to German industry.

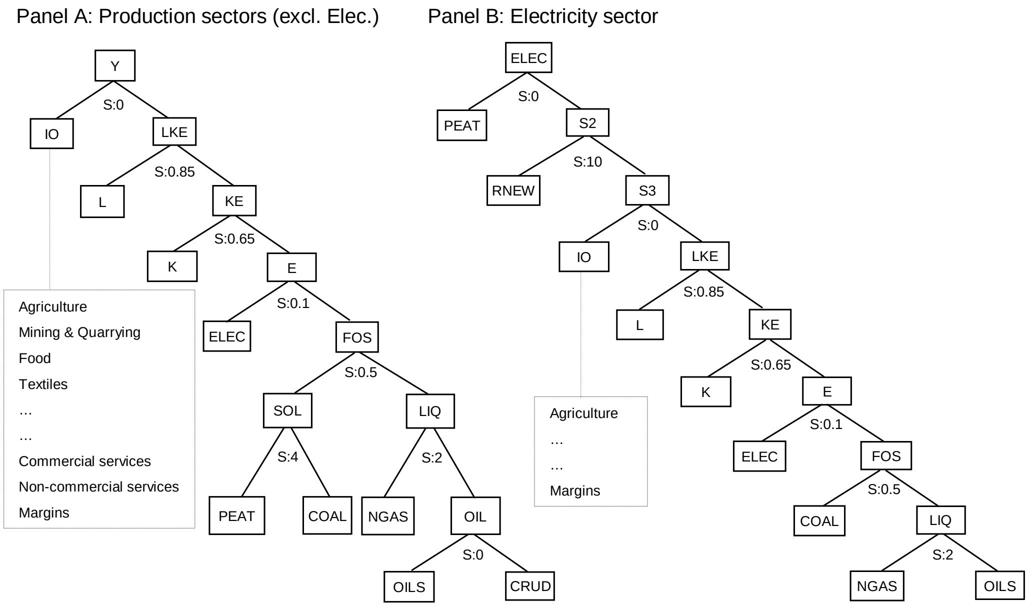

Figure 1. Nesting Structure of the Production Functions

3.2 International Trade

The Armington assumption[9] is applied in combining domestic production *Y* and imports *M*, using a CES function. The resulting homogeneous 'Armington commodities' (quantity *A* valued at price *pa*) are either sold in Ireland or exported. A CET function determines the scope for choice between domestic supply (quantity *D* valued at price *pd*) and export (quantity *E* valued at price *px*). Exports are traded for foreign exchange *pfx*, which is used to pay for imports. The elasticity of substitution between Irish made products and imports (the Armington elasticity in the CES function) as well as the elasticity of transformation between domestic sales and exports in the CET function, are set equal to 4. This creates substantial flexibility in choices about the destination and source of commodities.

3.3 Consumption

Total domestic supply of each commodity is assumed to exactly meet demand (market clearing). Total demand is made up of intermediate demand and final demand, including household and government consumption, investment and exports. Intermediate demand is dealt with in the discussion of production. Government consumption is driven by the maximisation of a Leontief utility function subject to a budget constraint.

[9] The assumption is that imported and domestically produced commodities are substitutes of each other, but not perfect substitutes. This solves the problem that the same kind of good is found to be both exported and imported in actual trade data which is inconsistent with the Heckscher-Ohlin model under perfect competition (Armington, 1969).

The household sector is represented by a single Representative Agent (RA). The Linear Expenditure System (LES) represents household consumption. Consumption of each commodity is divided into a necessary part and a 'luxury', or supernumerary, part, using income elasticities to specify the correct partition. The system does not allow for changes in necessary purchases, only between luxury expenditures. This ensures that households continue to purchase a minimum necessary amount of all goods, *e.g.* energy for heating and cooking, even when their prices become relatively high.

3.4 Taxation

One of the main distinctive features of the model is its detailed modelling of the tax system. Seven taxes or subsidies are modelled:

1. Indirect taxes less subsidies on products (VAT)
2. Excise tax on oil products
3. Taxes on production (output taxes)
4. Subsidies on production (output subsidies)
5. Labour tax
6. Contributions to social insurance (social security)
7. A counter-factual carbon energy tax.

The carbon energy tax is introduced as a counter-factual scenario. It is implemented on a per-unit basis as described in Section 4. All other taxes are pre-existing, *i.e.* present in the benchmark. All tax revenue is collected by the government. Indirect tax rates on products, net of subsidies, are both user-specific and commodity-specific. They are paid by all users, producers and consumers. Even the government has to pay itself some tax. Any VAT paid that is subject to a rebate, is not included in the benchmark data. Excise tax only applies to oil products and is exogenously fixed. For practical reasons, it is modelled as an *ad valorem* tax. The third tax is a production tax levied on the value of output, regardless whether exported or sold in Ireland. Its rate is specific to each industry. The same is true for the output subsidies. The labour tax and the social security contributions are the two components of the wedge between the gross and net wage.

Together, these taxes form a full matrix that can be laid over all transactions in the SAM, thereby providing sector-specific and commodity-specific tax rates.

3.5 Factors of Production and Savings

Labour supply is endogenous and depends on relative changes in the wage rate and the elasticity of labour supply. This value of the elasticity is set equal to 0.49, a value econometrically estimated for Ireland in 1998 (Doris, 2001). Endogenous involuntary unemployment is controlled by a real wage rate that is rigid downwards. Its minimum value equals the replacement rate, which is 0.65. The assumption is that the net wage can be brought down if necessary but no-one is prepared to work for less than what they would receive in benefits if they were unemployed. If this wage constraint becomes binding, the unemployment rate goes up. The unemployment rate has a minimum bound equal to the benchmark rate of 3 percent, to reflect frictional unemployment (Layard *et al.*, 1991).

The Representative Agent is endowed with time that is either used for labour or for leisure. The time offered on the labour market can be either employed or unemployed. The RA owns all factors of production, *i.e.*, labour *L* and capital *K*. The RA's income is made up of income from the supply of labour as far as it is employed in the production sectors (quantity *LD_net* valued at price *pl*), income from the rental of capital (capital supply *KS* valued at price *pk*) and transfers from the government such as unemployment benefits and pensions. Household savings are equal to the sum of the government's budget surplus and the balance of trade surplus less investments and the value of increases in stock. This ensures that the financial cycle is closed.

3.6 Closure and Welfare Measurement

The choice of exogenous variables is the closure rule of the model. In the model, the shadow price of welfare is chosen as the numéraire, the price relative to which all price changes are evaluated.[10] Welfare is measured as the sum of utility from leisure and utility from consumption. Welfare changes are measured by Hicksian equivalent variation (EV).

The government buys a fixed quantity of public goods and the real budget surplus is fixed (*i.e.*, changes in the price of the aggregate public good, *pg*, are allowed as the prices of produced goods change). This means the tax revenue from the new tax must be matched by a reduction in revenue from another tax or an increase in transfers to households. With world prices fixed, the market for foreign exchange is cleared by fluctuations in the exchange rate. Even though Ireland is in the Euro-zone, two of her main trading partners are the United Kingdom and the United States, both of which have different currencies.

[10] Absolute price levels are undetermined in the model and only relative prices can be assessed.

Labour supply is endogenous, as described in Section 3.5. Capital supply is exogenously fixed. Markets for labour and capital are cleared by endogenous factor prices.

3.7 Calibration and Data

The model is calibrated on benchmark data for the year 1998. The data are contained in a SAM for Ireland, which separately distinguishes seven energy sources and industries (crude oil, oil products, coal, peat, electricity, renewables and natural gas) and comes with satellite emissions data (Wissema & Dellink, 2006; for details about the data and data tables see Wissema, 2006).

The dataset is extended with a comprehensive net tax matrix that provides indirect tax data for each transaction differentiated both by commodity and by sector or agent. It includes VAT as well as excise tax where this is not rebated and subsidies are deducted. Furthermore, sectoral output taxes and subsidies have been separated from the net output tax, such that the output tax rate, *ty*, can be endogenously reduced while subsidy rates, *sy*, remain unchanged. The average labour tax rate is 17.7 percent (ESRI, 2006). Moreover, additional data for the year 1998 on social insurance contributions and inter-agent transfers were derived from the National Income and Expenditure publication (GoI, 2001).[11]

Finally, to calibrate the LES, income elasticities were used to calculate what share of consumption can be deemed necessary as opposed to 'luxury' using a formula proposed by Dellink (2005). The most recent econometrically estimated income elasticities for Ireland were estimated by Conniffe and Scott (1990) for energy commodities in 1987, at mean income. Their statistically significant figures for oil, and electricity were applied. Turf (peat, often from own land) has a negative value, indicating it is an inferior good, and Scott and Eakins (2002) found that solid fuels are more frequently used in low-income households. Therefore, we assumed that consumption of peat in the home is not a luxury. For the other commodities Dutch elasticities were used (*cf.* Dellink, 2005).

4. ENERGY TAX SIMULATIONS

4.1 Introduction

A carbon energy tax is implemented in the model as a counter-factual scenario. Both firms and households have to pay this tax when purchasing energy if their use of the energy

[11] This disaggregation of the fourth quarter of the SAM is far from straightforward because the national accounts are not organised into inter-agent flows. The resulting sub-matrix is not entirely satisfactory for this reason.

commodity causes emissions of CO_2. The tax rate is differentiated according to the emission factor of each energy source, which depends on its carbon content. The carbon tax is technically implemented in the model as an *ad valorem* energy tax, but the rate is endogenously adjusted in such a way that the amount of tax paid is independent of price changes. Thus, the tax is a per-unit or 'specific' tax where the tax base is the quantity purchased, not the value of the purchase.

Four simulations are compared in this paper. For ease of interpretation, the carbon tax level is held constant at 15 euro per tonne of CO_2, a rate that seems appropriate for Ireland to reach its Kyoto targets (*cf.* Wissema & Dellink, 2006). In each simulation, the revenue from the carbon energy tax is recycled in a different way as summarised in Table 1. The model closure is as described in Section 3.7, with endogenous adjustments of either taxes or transfers to recycle the net revenue from the energy tax, according to the simulation. The lump-sum simulation can be used as a base case to compare the other simulations with as it does not interfere with any pre-existing taxes.

Table 1. The simulations

Simulation	**Description of the recycling scheme**
1. Lump sum	Increase the lump-sum transfer to the household
2. VAT	Reduce indirect tax rates
3. Labour tax	Reduce the labour tax rate
4. Output tax	Reduce output tax rates

A table in Appendix C shows the initial situation of different sectors in terms of emission-intensity and tax burden. It helps to explain the results of the different simulations. Sectors with a high emission-intensity will experience more burden from the carbon tax than sectors that use less energy or less carbon-intensive energy sources; sectors that use relatively much labour tend to benefit most from a cut in the labour tax, and so forth. The tables are sorted in order to quickly identify the sectors with the highest or lowest figures. The way in which these dynamics eventually affect the results, however, also depends on the relative size of the sectors.

This section is organised as follows. The next sub-section discusses the main results. Section 4.3 details the findings from each of the simulations in turn. The explanation of results is aided by bar charts and a table, which contain data for all simulations to facilitate comparisons of different simulations.

4.2 Main results

Figure 2 shows that changes in emission levels are nearly the same in each simulation, indicating the relatively small indirect effects on emissions caused by the recycling mechanism. At its 15 euro level, the tax nearly achieves the official Irish CO_2 emission reduction target of 25.8 percent compared to 1998 levels (see Wissema & Dellink, 2006, for a derivation of this target for energy-related emissions) in each of the simulations. Emissions are reduced most in case of a lump-sum transfer to households, because the price incentives are strongest in this case. In all other simulations the energy price increases that result from the introduction of the carbon energy tax, are slightly lessened by reductions in other taxes.

Lowering output tax rates has the most impact here, because sectors with high output tax cost shares include Wholesale and retail trade (TRAD) and Transport by road and water (TRNS), which both have relatively high output levels and relatively high emission factors. These sectors benefit from this recycling scheme more than sectors with lower output tax costs in the benchmark. TRAD increases its output and TRNS, which has the highest emission factor by far (103 tonnes of CO_2 per 100 million euro output, compared with an average of 3.2), decreases its output, and thus its emissions, less in simulation 4 than in the other simulations.

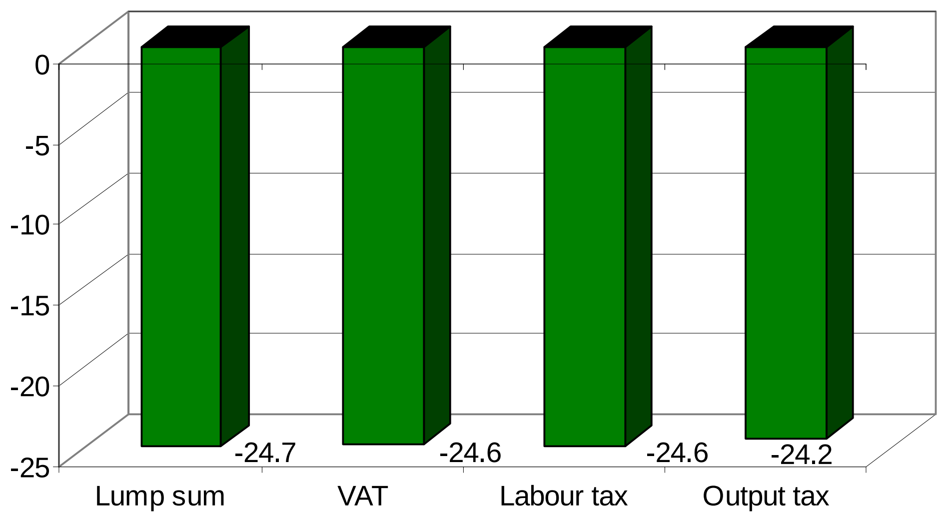

Figure 2. Changes in emissions in each simulation

For simulation 1, changes in output levels of all domestically producing sectors are shown in Figure 3, sorted by magnitude of the change.

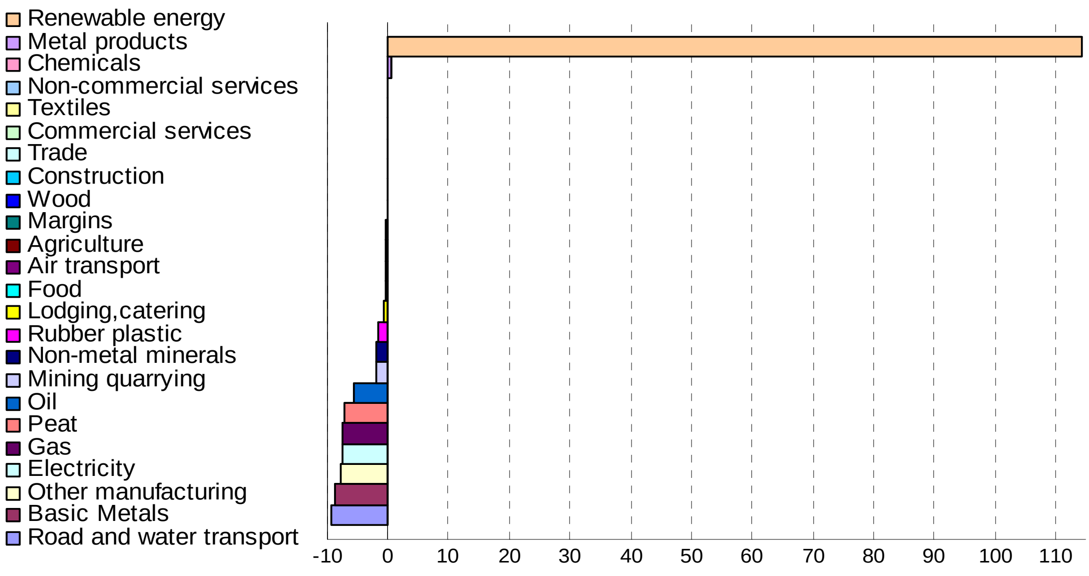

Figure 3. Changes in output levels in simulation1 (lump-sum recycling)

Welfare changes are depicted, for each of the simulations, in Figure 4. The carbon energy tax has a deadweight loss (DWL) that makes the overall tax system less efficient, causing welfare to fall.[12] Though this new DWL may be mitigated by reduced DWLs from reduction of the other taxes, this is by no means certain.[13]

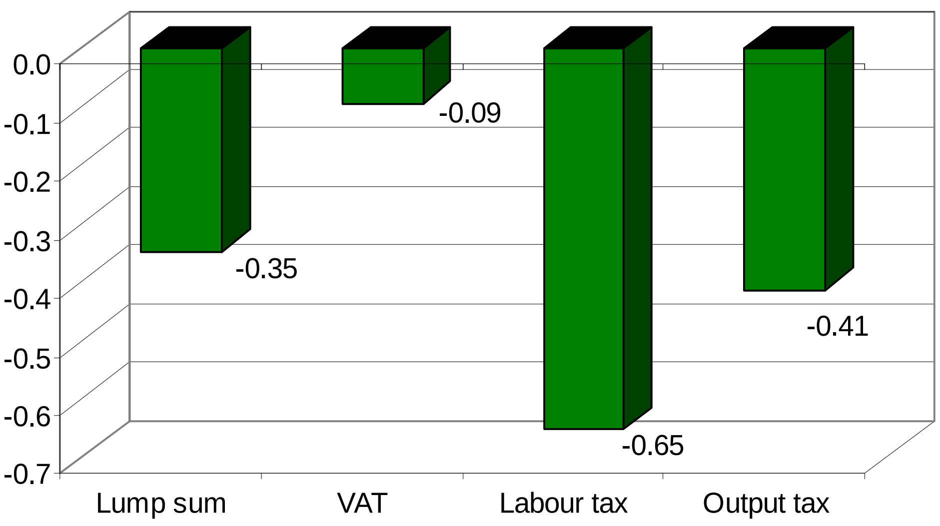

Figure 4. Changes in welfare in each simulation

[12] Note that in the calculation of these welfare impacts the environmental benefits of the policy are not taken into account.

[13] In a second-best setting, insights from partial analyses often do not hold; the combined effect of the new carbon tax and the recycling mechanism can be positive or negative (compare conclusions of Carraro & Sourbeyran (1994) and Bovenberg & De Mooij (1994) as summarised in Section 2 of this paper).

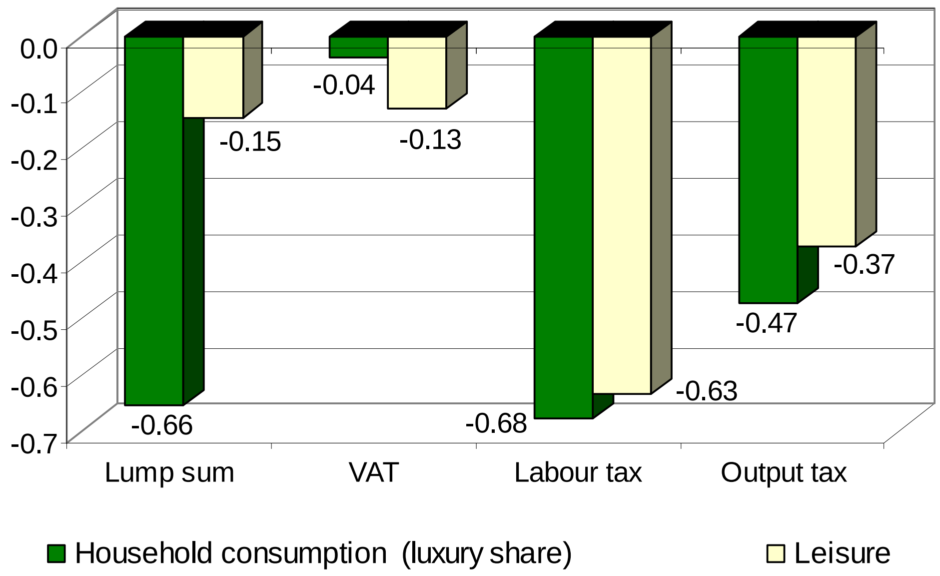

Figure 5. Changes in household luxury consumption and leisure in each simulation

The welfare loss is a result of the combined effect of negative changes in household luxury consumption and leisure. These can be viewed in Figure 5.

A double dividend (DD) of a weak definition may be achieved if a simulation has at least the same environmental benefits and a lower welfare loss than the lump-sum simulation. A small DD occurs in the simulation where VAT rates are cut.

Households demand a combination of leisure and luxury consumption according to their relative marginal utility. The ratio of leisure over luxury consumption thus decreases when the ratio of the marginal utility of leisure (the shadow price of leisure is the net wage) over the aggregate price of luxury consumption, goes up. This occurs in simulations 1 (lump-sum recycling) and 4 (output tax recycling) and a little in simulation 3 (labour tax recycling) as well. In simulation 2 (VAT recycling), however, the reverse happens, as the reduction in the VAT rate directly stimulates consumption (Figure 5 shows the fall in household consumption is smallest in simulation 2. See also Section 4.3.2). Consumption falls in all simulations due to increased relative prices of carbon-intensive energy (visualised in Figure 6) and, to a lesser extent, emission-intensive commodities, combined with other indirect effects.

One of these indirect effects is the change in relative factor prices. Table 2 shows that the net wage rate, *pl*, and the rental rate, *pk*, fall in all simulations except the second (VAT recycling), relative to the numéraire, *pw*. What matters however, is the change relative factor prices, *pl*/*pk*. This ratio falls in all simulations except the first (lump-sum recycling).

This is explained by the interaction fo a number of mechanisms. First, *pl/pk* increases as a result of capital becoming relatively abundant due to substitution of labour for composite capital-energy (*KE*). The price of aggregate energy increases due to the carbon tax. Both labour and capital are substitutes for energy and substitution takes place in two stages (see Figure 1 for the CES nesting structure and the values of elasticities). The second, related mechanism is that when capital is substituted for energy, *pl/pk* tends to decrease. Because the elasticity of substitution between *L* and *KE* is greater than that between *K* and *E*, the first mechanism outweighs the second and *pl/pk* tends to increase, as observed in simulations 2 to 4.

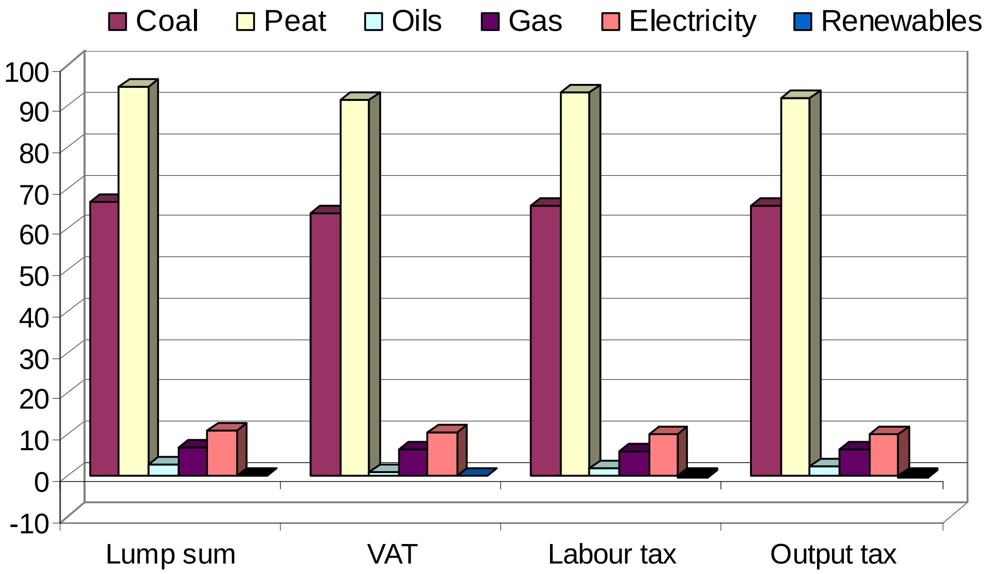

Figure 6. Percentage changes in household energy prices (including taxes) in each simulation

In simulation 1, however, this net tendency of *pl/pk* to increase is more than offset by its tendency to decrease as a result of a third mechanism: the increase in government transfers to households leads to an increase in household income unique to this simulation. This gives households an incentive to lower labour supply and thus decreases the net wage rate (see also Section 4.3.1).

Table 2. Changes in the aggregate price of luxury consumption (pc_{LUX}), factor prices and household income for each simulation

	1. Lump	2. VAT	3. Labour	4. Output
Change in pc_{LUX}	+0.63	-0.11	+0.06	+0.13
Change in net wage rate *pl*	-0.41	+0.07	-0.04	-0.08
Change in rental rate *pk*	-0.33	+0.03	-0.74	-0.35
Labour income	-0.26	+0.21	+0.62	+0.30
Capital income	-0.33	+0.03	-0.74	-0.35
Transfer income	+3.03	-	-	-
Total household income	+0.27	+0.09	-0.09	-0.04

4.3 Detailed results by simulation

4.3.1 Simulation 1: Increase lump-sum transfer

In the first simulation, households receive extra income through an increase in the lump-sum transfer from the government without having to work for it. In a partial analysis, a subsequent decrease in labour supply and an increase in leisure would be expected. But the production side of the economy invokes an opposite reaction. As in all simulations, the new tax causes energy prices to raise and prices of the most carbon-intensive fuels rise sharply (intermediate energy prices raises are similar to consumption energy prices shown in Figure 6). Labour is needed as a substitute for energy (more precisely for the energy-capital composite, *KE*) in order to keep production costs to a minimum. Figure 5 shows that labour demand increases in each simulation. Clearly, labour demand raises most when the revenue is used to lower labour costs, as in the 3rd simulation (see Section 4.5). Labour demand increases as the gross wage falls relative to the composite price of energy commodities and capital. This labour demand effect is stronger than the effect of changes in household income on labour supply. But the latter does explain the relatively strong shift from leisure to consumption in the composition of welfare in simulation 1. As can be observed in Figure 5, the difference between impacts on leisure and consumption is larger in simulation 1 than in all other simulations.

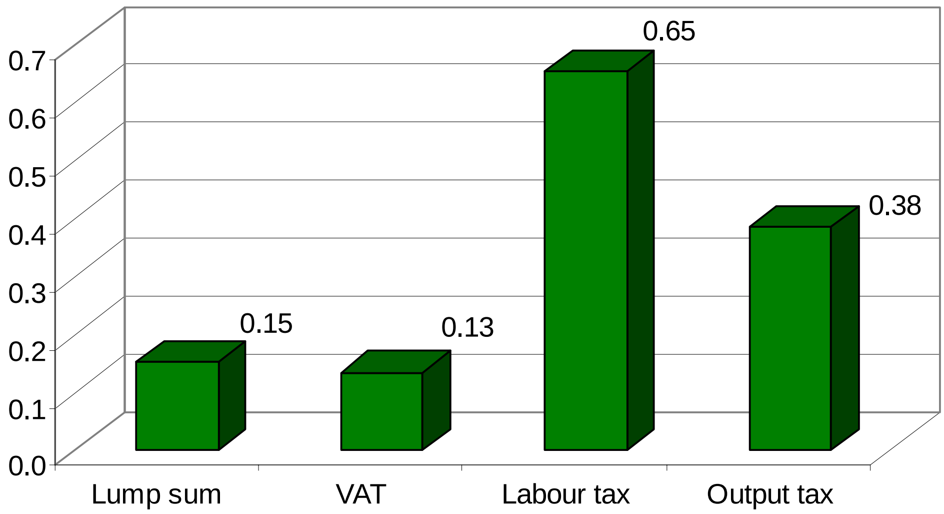

Figure 7. Changes in labour demand in each simulation

4.3.2 Simulation 2: Reduce indirect tax rates

In all simulations, prices of emission-intensive commodities increase as a direct result of the carbon tax. Only in simulations 2 to 4, prices are reduced due to cuts in pre-existing taxes. In case either the labour tax or the output tax is reduced, production costs, and thus output prices, are reduced, and the weighted average price of luxury consumption, pc_{LUX}, still increases, but by less than in the lump-sum simulation (see top row in Table 2).

Only if the VAT rate is reduced, pc_{LUX} actually falls because a change in the VAT rate affects consumer prices directly (and consumers carry most of the burden of VAT) and this turns out to outweigh the direct impact of the carbon tax. Figure 4 confirms that the drop in luxury consumption is smallest in simulation 2. Because the unit value of welfare, pw, is the numéraire and pw is the weighted average is of pc_{LUX} and the net wage rate, pl, the latter two prices are forced to move in opposite directions (relative to the numéraire). Therefore, simulation 2 is the only one where the net wage rate increases, compared to the numéraire. This explains why labour demand increases the least in this simulation, and thus, why leisure decreases the least. Because luxury consumption, which contributes to welfare, increases the most, welfare drops least in the VAT simulation.

4.3.3 Simulation 3: Reduce the labour tax rate

Perhaps surprising is the relatively big welfare loss in the third simulation. Recycling of the carbon tax revenue in simulation 3 leads to a significant reduction in the gross wage. The lower gross wage causes demand for labour to increase more strongly than in other simulations (Figure 5). Several studies found that lowering the labour tax is a good way to try and achieve a DD, because the distortion of the labour market is reduced (Manresa & Sancho, 2005). In the case of Ireland however, the benchmark unemployment rate was only 3 percent and the model does not allow it to drop even further. So the only way labour supply can meet this growing demand is through a cut in leisure (Figure 4). The increase in demand for labour may be relatively strong in the Irish model due to the strong substitution possibilities between labour and capital. Capital supply is fixed and demand must equal supply, so the actual quantity demanded cannot change, but the price of capital drops more than the net wage rate, reflecting the relative abundance of capital in the new equilibrium, compared to the other production inputs (mainly labour and energy, see also Section 4.2).

The fact that household consumption falls most in this simulation can also be partly explained by the greater drop in income. The net fall in income is decomposed in Table 2: income from labour increases (by 1.99%) due to higher labour demand (and the drop in the net wage rate being very small), but income from capital falls by more (-2.73%) due to the lower rental rate. The rental rate drops more in this simulation than in any other (see Table 2).

4.3.4 Simulation 4: Reduce output tax rates

Many of the results for the last simulation are in between those of simulations 1 and 3. Production costs are reduced as in simulation 3, but here the substitution between production factors is not stimulated. Therefore factor prices and labour demand, leisure and welfare are not affected as strongly. Only the reduction in luxury consumption is smaller than in either simulation 1 or 3, but that is mostly caused by the fall in capital income in the labour tax simulation.

5. Sensitivity analysis

Table 3 compares some of the results presented in the previous section with those obtained when the values of elasticities of substitution are changed, one by one. First, the values are varied from 0 to double their default value to test how sensitive welfare results are to changes in the values of these parameters. In Section 5.2, the sensitivity of results for emission reductions to parameter values are analysed.

The model appears to be quite robust with respect to most parameters. Only those elasticities that have the most substantial impact on model results are reported in this sensitivity analysis.

5.1 Sensitivity of welfare results

In simulation 1 (lump-sum recycling), welfare changes are most affected by the elasticity of substitution between labour and the capital-energy composite, s_{LKE}, the elasticity of substitution between capital and energy, s_{KE}, the elasticity of labour supply, s_{LAB}, and the elasticity of substitution in the consumption function, s_{CONS}. Table 3 shows the varying results and similarly for the other simulations.

Table 3. Sensitivity of welfare changes to individual changes in the value of the elasticities of substitution (percent changes in welfare compared to the benchmark)

Simulation	**Lump-sum**				**VAT**			**Labour tax**	**Output tax**	
Parameter[1]	s_{LKE}	s_{KE}	s_{LAB}	s_{CONS}	s_{LKE}	s_{KE}	s_{CET}	s_{LKE}	s_{LKE}	s_{KE}
Default[2]	*0.846*	*0.653*	*0.49*	*1*	*0.846*	*0.653*	*4*	*0.846*	*0.846*	*0.653*
0.0	-0.19	-0.27	-0.28	-0.31	0.05	0.03	-0.34	-0.47	-0.31	-0.36
0.2	-0.24	-0.29	-0.29	-0.32	0.00	0.00	-0.30	-0.53	-0.34	-0.37
0.4	-0.28	-0.30	-0.31	-0.32	-0.03	-0.02	-0.25	-0.57	-0.37	-0.38
0.6	-0.31	-0.32	-0.32	-0.33	-0.06	-0.05	-0.20	-0.61	-0.38	-0.39
0.8	-0.33	-0.33	-0.33	-0.34	-0.08	-0.07	-0.15	-0.63	-0.40	-0.40
1.0	**-0.35**	**-0.35**	**-0.35**	**-0.35**	**-0.09**	**-0.09**	**-0.09**	**-0.65**	**-0.41**	**-0.41**
1.2	-0.36	-0.36	-0.36	-0.35	-0.11	-0.12	-0.03	-0.67	-0.42	-0.42
1.4	-0.37	-0.37	-0.37	-0.36	-0.12	-0.14	0.03	-0.68	-0.43	-0.43
1.6	-0.39	-0.38	-0.38	-0.37	-0.14	-0.16	0.10	-0.69	-0.44	-0.44
1.8	-0.40	-0.40	-0.40	-0.38	-0.15	-0.18	0.18	-0.70	-0.45	-0.45
2.0	-0.41	-0.41	-0.41	-0.38	-0.16	-0.20	0.25	-0.71	-0.46	-0.46

[1] Only those parameters that have the most impact on welfare changes are reported: s_{LKE}, elasticity of substitution between labour and composite capital-energy; s_{KE}, substitution between capital and composite energy; s_{LAB}, elasticity of labour supply; s_{CONS}, elasticity of substitution between commodities for luxury consumption; s_{CET}, elasticity of transformation between domestic sales and exports.

[2] The default value for each elasticity is given in italics in the header row. These default values are independently multiplied by the values in the first column. Welfare changes obtained with only default elasticity values are in the middle row, with which welfare changes above and below can be compared.

Comparing across all simulations, welfare changes are most affected when in simulation 2 the value of the elasticity of transformation between domestic sales and exports, s_{CET}, is changed. This is due to the following mechanisms. The carbon tax raises domestic consumer prices thereby decreasing domestic demand. But due to reduced indirect tax rates in simulation 2, after tax consumer prices actually fall and domestic demand increases.

This pushes net domestic prices, as received by producers, up. Export prices raise a little too, but by much less. Because the prices that the home market offers thus increase more than export prices, firms choose to increase the share of their production they sell in Ireland. This shift towards domestic sales is better possible with higher values of the elasticity of transformation. The highest increase in welfare, therefore, results from an increase in this elasticity in simulation 2. Here, a double dividend is very clear.

After s_{CET}, changes in the elasticity of substitution between labour and the capital-energy composite (s_{LKE}) are most important, especially in simulation 3, where the labour tax is reduced and price incentives to substitute labour for energy are much stronger than in other simulations. The elasticity between capital and energy, s_{KE}, has the least impact in this simulation because energy conservation is achieved more easily by substitution towards labour rather than towards capital. In the other three simulations, the s_{KE} is nearly as important as s_{LKE}, reflecting that energy conservation can take the form of substitution towards labour or capital, depending on the relative scarcity of these factors. Lower values of these two elasticities yield a double dividend in the VAT simulation because the deadweight loss is reduced. However, the emission reduction is reduced simultaneously, necessitating a higher carbon tax level for the reduction target to be met. At the higher carbon tax level, the welfare loss will be higher. Thus, we confirm the common finding that higher substitution possibilities lead to lower welfare costs to achieve a given emission reduction target, but qualify this general result by showing that the opposite holds when the emission tax rate is held constant rather than the emission reduction.

Given the need to meet the emission target, lowering way s_{LKE} and s_{KE} does not guarantee a double dividend. If it were possible to increase the trade-elasticity (s_{CET}), however, this would entail economic benefits while not affecting environmental outcomes, thus leading to a certain double dividend.

The elasticity of labour supply (s_{LAB}) determines the trade-off in welfare between consumption and leisure. In most simulations, even in simulation 3 where the revenue from the carbon tax is used to reduce labour costs, s_{LAB} does not affect changes in welfare much. The elasticity of labour supply is most influential, in simulation 1 (lump-sum recycling). The same is true, to a lesser extent, for the elasticity between commodities for luxury consumption (s_{CONS}). Reason is that both pc_{LUX} and household income increase most in this simulation and these elasticities have a direct impact on consumer behaviour. Increasing their values leads to bigger changes in the consumption pattern and, therefore, to an increase in the distortion of the economy.

Also mildly influential, but only in the first and second simulation, is the value of the elasticity of substitution at the top level (s_{TOP}, not reported here). The top level of the production function is normally Leontief but for the analysis it was changed to Cobb-Douglas. This creates the opportunity to conserve energy by substituting other intermediate inputs for composite labour-capital-energy in order to avoid paying the carbon tax. This tends to distort the economy more and bring down welfare. In case the revenue is recycled to lower indirect tax rates (simulation 2), however, this extra flexibility also gives firms the chance to exploit the lower VAT rates more and thereby reduce output prices. This affects consumer prices and consumption too. Therefore, in this simulation, welfare is reduced by less in case of a Cobb-Douglas function than in the case of a Leontief function in the top level of the production tree.

Higher elasticity values tend to increase the distortionary effect of the carbon tax. Behaviour, in terms of quantities purchased or produced changes more, creating a bigger deadweight loss. The only exception is the elasticity between oils and natural gas (s_{LIQ}), where the effect goes in the opposite direction, but only weakly (not reported in the table). Apparently, the positive effect of greater opportunities for avoiding the carbon tax (by substituting oil for less carbon-intensive gas) outweighs the negative effect of greater distortion in this case.

Thus, it seems that the loss of welfare is mainly determined by the effect of the carbon tax on energy conservation by substitution away from energy, and less by changes in the fuel mix by substitution between different fuels.

5.2 Sensitivity of emission reduction results

Generally, emissions are reduced more strongly when values of the elasticities of substitution are higher. Table 4 shows the results for simulation 1 (lump-sum recycling). The sensitivity is nearly the same in simulations 2, 3 and 4 and therefore these are not reported. Changes in the value of the elasticity between capital and energy (s_{KE}), which represents a possibility for energy conservation, has the strongest effect on changes in emissions.

Higher values of s_{LKE} also reduce emissions further at the given tax level, but the indirect effect that extra labour demand increases incomes and consumption, tends to increase emissions and partly mitigates this elasticity effect. The impact of increasing s_{LIQ} is especially interesting because it further reduces emissions without worsening the welfare impact of the carbon tax.

Table 4 shows that reductions in emissions are greater at higher values for the elasticity of substitution between oil and gas (s_{LIQ}), meaning that greater flexibility in the choice between these fuels helps to lower emissions. Other inter-fuel substitution options appear to be less important.

Table 4. Changes in emissions results resulting from changes in individual elasticities in simulation 1 (lump-sum recycling) (percent changes in emissions compared to the benchmark)

Elasticity[1]	Default Value	Low[2] (%)	Default (%)	High[3] (%)
s_{TOP}[4]	0	n/a	-24.71	-27.88
s_{RNEW}	10	-23.68	-24.71	-26.27
s_{LKE}	0.846	-23.34	-24.71	-26.03
s_{KE}	0.653	-19.38	-24.71	-29.67
s_{LIQ}	2	-22.66	-24.71	-26.21

[1] Only those parameters that have the most impact on emission reductions are reported: s_{TOP}, elasticity of substitution in the top level of production functions; s_{RNEW}, elasticity of substitution between renewable energy and all other inputs in the second level of the electricity production function; s_{LKE}, elasticity of substitution between labour and composite capital-energy; s_{KE}, substitution between capital and composite energy and s_{LIQ}, substitution between Oil products and Natural gas.

[2] Low = 0.4 * [default value]

[3] High = 1.6 * [default value]

[4] This Leontief function has an elasticity of substitution of zero. This has been changed to 1, creating a Cobb-Douglas function, in the 'High elasticities' column.

Increasing the value of s_{KE} and/or s_{LKE} means that substitution away from energy is easier and this leads to a stronger drop in energy use and emissions. On the other hand, it also leads to a higher level of distortion of the economy and therefore to a larger decrease in welfare. A greater elasticity of substitution means that, *ceteris paribus*, the demand for energy is more price elastic. Tax theory shows that the dead weight loss of a tax is higher when demand for the taxed commodity is more price elastic.[14] However, with higher elasticities, a lower tax level is required in order to meet the abatement target. The drop in welfare is much smaller at lower tax levels.

[14] The taxes investigated in this paper are introduced in a second-best situation and they will interact with existing distortionary taxes, so the rationale given above is only a partial explanation.

5.3 *Conclusions of the sensitivity analysis*

Our model results are not greatly affected by changes in most of the parameter values. Doubling the most influential elasticities, those that affect the possibilities for energy conservation by substitution towards labour, s_{LKE}, or capital, s_{KE}, leads to greater welfare costs, but still does not change the qualitative conclusions if the tax level is kept constant.

However, a lower tax level can achieve the emission target when the possiblities for energy conservation are thus increased, as emissions are reduced more strongly. Thus, the extra welfare costs due to increased flexibility can be lessened because the lower tax level causes less economic distortion.

Therefore, it is worthwhile to invest in energy conservation as this could lead to a double dividend. It is also interesting to look into possible measures to increase the options for substitution between oil and gas as this enhances emission reductions without negatively affecting welfare.

6. CONCLUSIONS AND RECOMMENDATIONS

It is important that policy makers are well informed about the possible effects of the implementation of carbon taxation and any simultaneous tax measures or sets of measures. Any proper analysis needs to take due account of existing energy taxes and other distortionary taxes and subsidies. A computable general equilibrium model with specific detail in taxation and energy use is the most suitable methodology for this purpose.

Given the limitations and assumptions of the present model and data as described in Sections 2 and 3, the following conclusions can be drawn. First, recycling the revenue from the carbon energy tax through reductions in indirect tax rates clearly has the most favourable results in terms of welfare. The fact that the model shows a small decrease in welfare even in this case, means that the strong double dividend cannot be achieved, but it does not seem all that far off. Both reducing the VAT rate and reducing output taxes are preferred to transferring the revenue from the new tax to households in a lump-sum, because in both cases production costs are reduced. This result corresponds broadly to findings in Bergin *et al.* (2002).

Secondly, contrary to their findings and those of many other authors, this study finds a strong negative welfare result in case the revenue from the carbon tax is used to lower the labour tax. This result is caused by the reduction of leisure as a result of the need to meet growing labour demand. Most other models dealing with this topic do not feature endogenous labour supply, or if they do, there is scope to reduce unemployment. In Ireland, however, unemployment was quite low in the year 1998 and the model is restricted in order to have a minimum level of frictional unemployment. Thus, the common recommendation that environmental taxes can best replace labour taxes requires the qualification that when the labour market is tight, *i.e.* unemployment is low, such a tax reform will be worse than more general tax reductions that stimulate the economy.

Thirdly, while model results are not greatly affected by changes in most of the parameter values, the most influential elasticities are those that affect the possibilities for energy conservation by substitution towards labour, s_{LKE}, or capital, s_{KE}. In case the carbon tax level is kept constant, increasing their values implies welfare is reduced more strongly while the emission target is overschot. However, when the possiblities for energy conservation are thus increased and emissions are reduced more strongly, a lower, less distortionary, carbon tax level can achieve the emission target. Therefore, we conclude that for Ireland, energy conservation appears to be the key to a double dividend. Measures to increase options for substitution between oil and gas also deserve attention as they enhance emission reductions, beit only mildly, without negatively affecting welfare.

As usual, there are several possibilities to ameliorate the analysis. It is important to assess the impact of different combinations of policy measures on income distribution in general and on the welfare of households of different income groups in particular. Low-income households need special attention because a carbon energy tax may push certain households into poverty and enhance the existing problems with fuel-poverty (Healy, 2003). This paper uses a single representative household and therefore does not offer this kind of insight. For this analysis it would be necessary to separately distinguish different income groups and model the relevant linkages between these household groups and the rest of the economy, including the government, in sufficient detail.

Other possible improvements to the model include enhancing the representation of the energy industry. This can be achieved by disaggregating renewable energy commodities and introducing imperfect competition; a feature that is especially relevant in energy markets. The representation of demand for energy can be improved by modelling the use of renewable energy sources, such as solar energy, by households, possibly through the definition of consumption bundles. Since climate change is a long term problem, the introduction of intertemporal dynamics is recommended. The introduction of bottom-up technologies to abate emissions of greenhouse gases would make the model more realistic, though this is less essential for CO_2 than for other greenhouse gases. It is further recommended to introduce emissions trading and to model foreign energy policies. Finally, it is possible and desirable to include other greenhouse gases than carbon dioxide and even to incorporate other environmental problems and solutions. Different environmental problems and their solutions tend to interact and are best analysed in an integrated manner (Dellink, 2005; Dellink & Van Ierland, 2006).

In summary, this paper shows that a carbon energy tax, *i.e.* a specific energy tax related to emissions of carbon dioxide from energy use, can achieve the required emission reductions while incurring only a very modest overall welfare cost. In the Irish context, the most favourable manner in which to recycle its revenue is by lowering the VAT rate. Lowering output taxes is the second most preferred option, while lowering labour taxes will only worsen the problems of a tight labour market.

APPENDIX A SECTORS AND COMMODITIES

The sectors and commodities have the same acronyms, because each commodity is produced mainly by one corresponding sector. Each industry can thus be regarded as the main producer or manufacturer of the product with the same acronym. Table A.1 therefore gives descriptions of commodities only.

Table A.1. Commodities in the ESAM and the Model

Model Acronyms	Descriptions
AGFF	Agriculture, forestry and fishing
MINE	Mining and quarrying products
CRUD	Crude oil
COAL	Coal
PEAT	Peat
FOOD	Food, beverages and tobacco products
TEXT	Textiles, wearing apparel, leather and leather products
WOOD	Wood and wood products (excl furniture), pulp, paper and print
CHEM	Chemical products and man-made fibres
RBPL	Rubber and plastics
NMIN	Other non-metallic mineral products (glass, concrete, stone)
METL	Basic metals
MTPR	Fabricated metal products, machinery and equipment
OMAN	Furniture and other manufactured goods n.e.c.
OILS	Oil products
NGAS	Natural gas
ELEC	Electricity
RNEW	Renewable energy (electricity from)
CONS	Construction work
TRAD	Wholesale and retail trade
LDCT	Lodging and catering (includes bars)
TRNS	Transport services by land and water
AIRT	Air transport services
SVCC	Services – Commercial
SVCN	Services – Non-commercial
MARG	Margins

Appendix B Model Equations

Indices

en	energy commodities	CRUD, COAL, PEAT, OILS, NGAS, ELEC, RNEW
f	agents	HOU, GOV, INV, RoW
i	commodities	1, …, 26 (see Appendix A)
j	industries	1, …, 26 (see Appendix A)

Alias *f*, *ff*

Variables

A_i	Armington supply of commodity *i*
BoPdef	Balance of international payments deficit
CBAS	Necessary share of aggregate household consumption
CD_i	Household demand (necessary+luxury) for commodity *i*
CLUX	Supernumerary share of aggregate household consumption
D_i	Domestic demand for commodity *i*
endtl	Endogenous labour tax multiplier
endty	Endogenous output tax multiplier
endSocSec	Endogenous social security contributions multiplier
endVAT	Endogenous value added tax multiplier
E	Aggregate exports
ED_i	Export demand for commodity *i*
G	Aggregate public good
GD_i	Government demand for commodity *i*
GovSur	Government budget surplus
HouSav	Household savings
I	Aggregate investment
$ID_{i,j}$	Intermediate demand for commodity *i* by industry *j*
IncTax	Income tax other than from labour
$INVD_i$	Investment demand for commodity *i*
K_j	Capital demand industry *j*

L_j Labour demand industry *j*

LEIS Leisure demand

LS Labour supply

lsum Lump sum tax rebatement multiplier

M_i Imports of commodity *i*

pc_{BAS} Weighted average price of basic necessity share of consumption

pc_{LUX} Weighted average price of luxury share of consumption

pd_i Price of domestically supplied commodity *i*

pfx Foreign exchange rate

pk Capital rental rate

pl Net wage rate

px_i Export price commodity *i*

py_i Price of domestically produced commodity *i*

SD_i Stock additions of commodity *i*

$te_{en,j}$ Carbon energy tax rate on energy commodity *en* used in industry *j*

$tef_{en,f}$ Carbon energy tax rate on energy commodity *en* consumed by agent *f*

$transfer_{f,ff}$ Lump sum transfers between agents

ur Unemployment rate

Welfare Total utility for measuring Hicksian equivalent variation

$Y_{j,i}$ Production of commodity *i* by industry *j*

Parameters

$BasShare_i$ Necessary minimum (basic) share of consumption of commodity *i*

RepRate Replacement rate

ssc Social security contribution rate

sy_j Output subsidy industry *j*

$texcj_{i,j}$ Excise tax rate industry *j*

$texcf_{i,f}$ Excise tax rate agent *f*

$tfd_{i,f}$ Indirect tax rate on commodity *i* consumed by agent *f*

$tid_{i,j}$ Indirect tax rate on commodity *i* used in industry *j*

TIME Time endowment

tl Labour tax rate

ty_j Output tax rate industry *j*

ur0 Unemployment rate in the benchmark

Equations

Production functions

$Y_{j,i} = CES(IO_{1,j},\ldots, IO_{26,j}, L_j, K_j) \quad \forall j$

Zero-profit in production

$0 = \Sigma_j \{(1\text{-}endty \cdot ty_j\text{-}sy_j) \cdot \Sigma_i (py_i \cdot Y_{j,i}) - \Sigma_i [(1+endVAT \cdot tid_j+te_i+texcj_{i,j}) \cdot pd_i \cdot ID_{i,j}] - (1+\text{tl}) \cdot pl \cdot L_j - pk \cdot K_j\} \quad \forall j$

Labour market

$TIME = LS + LEIS$

$\Sigma_j L_j = (1\text{-}ur) \cdot LS$

$ur \geq ur0$

$pl \geq RepRate$

Household

$CLUX = Cobb\text{-}Douglas([1\text{-}BasShare_1] \cdot CD_1,\ldots, [1\text{-}BasShare_{26}] \cdot CD_{26})$

$CBAS = Leontief(BasShare_1 \cdot CD_1,\ldots, BasShare_{26} \cdot CD_{26})$

$Welfare = CES(CLUX, LEIS; \sigma=0.49)$

$pc_{LUX} \cdot CLUX = \Sigma_i \{(1+ endVAT \cdot tfd_{i,HOU}+te_i+texf_{i,HOU}) \cdot pd_i \cdot [1\text{-}BasShare_i] \cdot CD_i\}$

$pc_{BAS} \cdot CBAS = \Sigma_i \{(1+ endVAT \cdot tfd_{i,HOU}+te_i+texf_{i,HOU}) \cdot pd_i \cdot BasShare_i \cdot CD_i\}$

$\Sigma_j \{(1\text{-}tl\text{-}ssc) \cdot pl \cdot L_j + pk \cdot K_j\} + lsum \cdot transfer_{GOV,HOU} + \Sigma_{f\,[f \neq GOV]} (transfer_{f,HOU})$
$\quad + (1\text{-}tl\text{-}ssc) \cdot pl \cdot LEIS = Welfare + pcBAS \cdot CBAS + IncTax + HouSav$

Government

$G = Leontief(GD_1,\ldots, GD_{26})$

$IncTax + \Sigma_j \{endty \cdot ty_j \cdot py_j \cdot Y_j + tl \cdot pl \cdot LD_j + \Sigma_{en} (te_{en,j} \cdot pd_i \cdot ID_{en,j})$
$\quad + \Sigma_i [(endVAT \cdot tid_{i,j}+texcj_{i,j}) \cdot pd_i \cdot ID_{i,j}]\}$
$\quad + \Sigma_{en} \{tef_{en,HOU} \cdot pd_{en} \cdot CD_{en}\} + \Sigma_i \{(endVAT \cdot tfd_{i,HOU}+texcf_{i,HOU}) \cdot pd_i \cdot CD_i$
$\quad + endVAT \cdot (tfd_{i,GOV} \cdot GD_i + tfd_{i,INV} \cdot INVD_i) \cdot pd_i$
$\quad + (endVAT \cdot tfd_{i,RoW}+texcf_{i,RoW}) \cdot px_i \cdot ED_i\} + \Sigma_f (transfer_{f,GOV})$
$\quad = \Sigma_i \{(1 + endVAT \cdot tfd_{GOV}) \cdot pd_i \cdot GD\}_i + \Sigma_{j,i} \{sy_j \cdot py_i \cdot Y_{j,i}\} + \Sigma_f (transfer_{GOV,f}) +$
$\quad GovSur;$

where $en \in i$

G is fixed; determines *lsum*, *endVAT*, *endtl* or *endty* when the others are fixed

Rest of the World

$E = Cobb\text{-}Douglas(ED_1,\dots, ED_{26})$

$\Sigma_i \{pfx \cdot M_i - (1 + endVAT \cdot tfd_{i,RoW} + texcf_{i,RoW}) \cdot px_i \cdot ED_i\} + \Sigma_f \{transfer_{f,RoW}\}$

$= BoPdef$ (fixed); determines pfx

Investment

$I = Cobb\text{-}Douglas(INVD_1,\dots, INVD_{26})$

$\Sigma_i \{(1+ endVAT \cdot tid_j) \cdot pd_i \cdot INVD_i + \Sigma_i SD_i\} = HouSav + GovSur + BoPdef$

International trade

$A_i = CES(M_i, \Sigma_j \{Y_{j,i}\}; \sigma=4)$

$A_i = CET(D_i, ED_i; \sigma=4)$

Market clearing

$M_i + \Sigma_j \{Y_{j,i}\} = A_i = D_i + ED_i$

$D_i = \Sigma_j \{ID_{i,j}\} + CD_i + GD_i + INVD_i + SD_i$

$\Sigma_j L_j = (1\text{-}ur) \cdot LS$; determines pl and ur

$\Sigma_j K_j = KS$ (fixed); determines pk

APPENDIX C RELEVANT BENCHMARK DATA

Table C.1. Sectors sorted by emission-intensity and cost shares of VAT, labour and output tax

Sector[1]	Emission intensity[2]	Sector	VAT cost share	Sector	Labour cost share	Sector	Output tax cost share
TRNS	103.4	CHEM	0.013	SVCN	0.63	TRAD	0.021
ELEC	47.2	WOOD	0.010	TRAD	0.38	LDCT	0.019
METL	20.6	ELEC	0.010	LDCT	0.33	MINE	0.019
OMAN	7.8	NGAS	0.010	MINE	0.28	PEAT	0.019
NMIN	6.8	RNEW	0.010	PEAT	0.28	AIRT	0.016
TRAD	4.3	LDCT	0.010	SVCC	0.24	TRNS	0.014
MINE	4.2	FOOD	0.010	TRNS	0.24	TEXT	0.011
AGFF	3.4	TRAD	0.009	RBPL	0.22	NMIN	0.010
PEAT	2.0	RBPL	0.008	NMIN	0.22	ELEC	0.007
OILS	1.6	AIRT	0.008	AIRT	0.21	NGAS	0.007
NGAS	1.6	SVCC	0.007	CONS	0.19	RNEW	0.007
LDCT	1.6	SVCN	0.006	ELEC	0.17	FOOD	0.007
SVCN	1.6	CONS	0.006	RNEW	0.17	SVCC	0.006
SVCC	1.6	MINE	0.005	OILS	0.16	AGFF	0.005
CHEM	1.5	PEAT	0.005	OMAN	0.16	RBPL	0.004
RBPL	1.5	TRNS	0.005	TEXT	0.15	OMAN	0.003
FOOD	1.2	METL	0.004	NGAS	0.15	OILS	0.003
TEXT	0.9	MTPR	0.004	FOOD	0.10	METL	0.003
MTPR	0.1	NMIN	0.004	WOOD	0.09	SVCN	0.001
WOOD	0.1	OMAN	0.003	MTPR	0.09	WOOD	0.001
AIRT	0.0	OILS	0.003	AGFF	0.06	MTPR	0.001
CONS	0.0	TEXT	0.002	CHEM	0.04	CHEM	0.001
RNEW	0.0	AGFF	0.001	METL	0.04	CONS	0.000
Average	3.2	Average	0.007	Average	0.19	Average	0.004

1. Sectors CRUD, COAL and MARG are not listed as these do not have emissions or these production costs.

2. Unit: tonnes of CO_2 per 100 million euro.