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How responsible is a region for its carbon emissions? An empirical general equilibrium analysis

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Abstract

CO_2 reduction targets tend to be set in terms of the amount of pollution emitted within a given region. However, there is increasing public and policy interest in the notion of a carbon footprint, or CO_2 generated globally to serve final consumption demand within a region. This raises an issue in that, despite the local economic benefits, the latter involves effectively absolving the region of responsibility for CO_2 generation. Using a CGE model of Wales, we illustrate by simulating an increase in export demand for the output of an industry (metal production) that is both carbon and export intensive and generally produces to meet intermediate rather than final demands. The key result is economic growth accompanied by a widening gap between regional CO_2 generation and the carbon footprint, raising questions as to the identification of precisely 'whose' carbon footprint these additional emissions should be allocated to.

Keywords: computable general equilibrium modelling; input-output accounting; CO_2 targets; carbon footprints; environmental responsibility

JEL codes: D57, D58, O18, O44, Q56

1. Introduction

The 2009 Copenhagen Climate Change conference focused attention on the methods and underlying principles that inform climate change targets. Climate change targets following the Kyoto Protocol are broadly based on a production accounting principle (PAP), or emissions produced within given geographical boundaries of the economy in question. An alternative approach is a consumption accounting principle (CAP), where the focus is on emissions produced globally to meet consumption demand within the national (or regional) economy (Munksgaard and Pedersen, 2001). Increasingly popular environmental footprint measures, including ecological and carbon footprints, attempt to measure environmental impacts based on CAP methods. The perception that human consumption decisions lie at the heart of the climate change problem is the impetus driving pressure on policymakers for a more widespread use of CAP measures.

Globally the emissions accounted for under the production and consumption accounting principles would be equal. However, at regional or national level emissions embodied in trade lead to differences under the two principles. Specifically, under a PAP measure, the generation of emissions in producing goods and services to meet export demand is charged to the producing region or nation's emissions account. Under a CAP measure, these emissions would be charged to the region or nation where the final consumption demand charged with ultimately driving this activity may be located. That is, under CAP, emissions embodied (directly or indirectly) in a region or nation's imports replace emissions embodied in export production, alongside domestic emissions to support domestic final consumption (which is common to both measures).

However, as public and policy enthusiasm for CAP measures grows (see Wiedmann, 2009, for a review), this paper raises the question as to whether it is appropriate entirely to attribute responsibility for emissions resulting from production decisions throughout (often quite complex) supply chains to final consumers, particularly where these consumers may be located in other regions, nations and jurisdictions.

To illustrate our argument we first produce base year results for regional carbon emissions calculated on PAP and CAP principles to reveal the differences in, and perspectives offered by, the two approaches. We then take the example of a decision to increase production in a regional industry where production is both carbon intensive and export intensive and examine the differential impacts on the alternative measures. We also examine the economic impacts of this increased activity on the regional economy. The economic benefit derived by local consumers raises questions as to whether it is appropriate to absolve them of all responsibility for emissions embodied in export production. We believe that this provides a first step in the process of understanding the concept of shared responsibility for pollution generation based on key economic indicators such as GDP/value-added (see Lenzen *et al*, 2007). Moreover, the case study focuses on an industry where the output produced tends to be used as an intermediate input to other production sectors (be they domestic or external) rather than directly serving final demands. This complicates matters in terms of identifying the location of the final consumers to whom emissions embodied in export production should be allocated.

The analysis involves two empirical techniques. The first is input-output accounting. Application of regional and interregional input-output accounting techniques to attribute pollution generation to different production and consumption activities has become commonplace particularly in the ecological economics literature (see Munksgaard and Pedersen, 2001, and Turner *et al*, 2007, for methods; and Wiedmann, 2009, for a review). A CGE framework (which integrates the input-output accounts as its core database) is then employed to model the economy-wide impacts of a change in activity, and the results are used to derive 'post-shock' input-output accounts that may be employed to examine impacts on pollution generation under both PAP and CAP measures. The key advantage offered by the CGE analysis is a more flexible and theory-consistent approach to modelling changes in both production and consumption activity levels than is possible using a conventional demand-driven input-output model, particularly in tracing factor market adjustments and resulting price and income induced effects in different time periods.

The empirical example in this paper focuses on a current policy issue in the case of Wales, a region of the UK with devolved responsibility for sustainable development. We provide a brief overview of the policy context of the Welsh case study in the next section. However, while some of the issues raised may be of specific interest to Wales, we contend that similar types of problems are faced by both regional and national policymakers around the world. In the third section we use the input-output accounting framework to consider base year carbon measures for Wales under CAP and PAP. This is followed in the fourth section with an overview of the CGE model and discussion of the results of simulating an increase in export demand to Welsh metal manufacturing in the fifth. Discussion and conclusions follow in the final section.

2. Policy context – carbon generation and attribution in the Welsh economy

In this section of the paper we provide some context for carbon accounting in the Welsh economy, together with some background on the regional Metal Manufacturing sector which provides our case study.

Compared to other parts of the UK, industrial production in Wales is intensive in carbon dioxide emissions. For example in 2008 CO_2 (equivalent[1]) emissions per capita for Wales were 14 tonnes per capita, compared to an England and Scotland averages of just over 8 tonnes per capita (Welsh Assembly Government, 2010). This reflects an economy with a relatively high level of manufacturing compared to most other parts of the UK, and speaks to specific types of pollution intensive manufacturing activity (see below).

The reporting of carbon dioxide emissions for Wales are on production accounting principles (PAP) reflecting direct emissions from specific 'pollution points'. However, we suggest that this type of reporting on a production accounting perspective might provide misleading intelligence for the policy

[1] In our empirical analysis we report in terms of CO_2 as carbon. The conversion factor to CO_2 equivalent is 12/44.

community. For example, achieving emissions targets following Kyoto and Copenhagen could result from a 'do-nothing' scenario in Wales as in the period to 2020 older polluting industries with ageing capital move offshore, and with Welsh annual PAP emissions sensitive to output in just a few plants (metal manufacturing among them – indeed in 2007, the top four pollution points in Wales contributed almost 50% of reported carbon dioxide emissions – NAfW, 2009). A concern is that structural change could lead to the achievement of regional pollution 'targets' but because the region merely imports goods connected with high levels of pollution..

For these reasons there is value in policymakers considering a consumption as well as a production perspective for emissions accounting. Indeed the espoused sustainable development objectives of the Welsh Assembly Government speak to more global responsibilities grounded in how regional consumption (as well as production) creates externalities from Welsh economy activity. For example, the ecological footprint has been embraced in Wales as one headline regional indicator of sustainable development (Munday and Roberts, 2006).

Expected differences in Welsh resource or pollution footprints relative to the production accounting perspective are grounded in the importance of trade to a small open economy. For example, energy generation, metal manufacturing, oil refining and chemicals are among the largest producers of CO_2 emissions in Wales and are large exporters. In 2010, of total Welsh exports of close to £9bn, around 63% originated in these four sectors.

In summary the carbon intensity of Wales' most important industries, coupled with their pivotal role in supporting regional exports, leads to an *a priori* expectation of a consumption accounting of carbon giving very different results from that derived from a production accounting perspective. Put simply we believe that appropriate policy choices in regions need to be informed by both production and consumption accounting perspectives. However, the use of a consumption accounting approach provides different insights into regional responsibility for CO_2 emissions. Notwithstanding, there are still problems with their uncritical use. Moving from a production to consumption accounting approach for emissions serves to lessen the penalty Wales faces from having high location quotients in industries with high CO_2 intensities and levels. However, it is difficult to escape the fact that these same pollution intensive sectors support high levels of employment and incomes in the regional economy.

The metal manufacturing sector in Wales therefore provides a valuable lens through which to explore the ramifications of different emissions accounting processes and to show how the region benefits from expansion in a relatively pollution intensive sector.

The metal manufacturing sector is never far away from headlines in Wales. Following extensive restructuring during the 1980s and 1990s, the turn of the new Millennium still saw metals production in Wales employing an estimated 12,350 people. Steel making in particular (either as coil, slab, special or coated products) is a critical input for a number of Welsh (and UK/overseas) industries, and at the heart of regional production are the operations of Corus (since 2007 owned by the Tata corporation of India).[2] Much of the steel industry output goes as an input to other manufacturing facilities (including in the Welsh case to other parts of the Corus (Tata) group but also directly to industries such as automotive, construction and packaging in other parts of the UK and overseas).

Steel manufacturing operations are centred on the Port Talbot mill with a capacity of around 5m tonnes of steel output, but with a series of ancillary operations in Wales to process and finish steel. While Wales bears much of the CO_2 emissions from metal manufacturing, the economic contribution of the sector cannot be ignored. Prior research (see Fairbrother and Morgan, 2001) has revealed that sector average gross earnings have been high compared to other manufacturing sectors in Wales. Furthermore the largest parts of the metal manufacturing sector purchased large quantities of goods and services in Wales. For example, in 2000, the time of the most recent economic assessment, it was estimated that in Corus

[2] Foreign ownership may bring another dimension to the issue of responsibility for pollution generation.

operations in Wales alone some £2bn of output was directly supported, and each £1m of Corus spend supported £320,000 of additional economic activity in Wales (Fairbrother and Morgan, 2001).

The scenario modeled in this paper is a simple one. It comprises an increase in the demand for the output of the regional metal manufacturing sector from producers in other parts of the UK and overseas. The scale of the specific scenario modeled below is based on an actual anticipated increase in the demands for steel products produced in Wales. Such a change in final demands is expected to increase the carbon emissions from the metal manufacturing sector, and result in increases in regional emissions recorded on a production accounting principle. However, our analysis permits a different perspective by showing that much of the industry output goes to exports, with only a small proportion supporting final demands in the region. The more complex analysis within the CGE framework also permits a series of feedback effects to be explored which we believe will be of interest to policy makers.

3. Base year CO_2 accounting for Wales

We follow Turner *et al* (2011a) in using an extended regional input-output accounting framework to examine CO_2 attributable to Wales under PAP and CAP measures. The methodological means through which this is undertaken is found in Appendix A. We do not attempt a multi-region input-output analysis, as is increasingly common in input-output applications (see Turner *et al*, 2007, for method; Wiedmann, 2009, for a review of applications), mainly because of the lack of appropriate data to extend the analysis in this way for Wales (Turner *et al.*, 2011b, consider an interregional application for the case of Scotland). Instead we apply an extended single region method where imports are considered through a combined use matrix and their CO_2 content through a vector of direct CO_2 intensities reflecting polluting technology in source countries but weighted by Welsh use of commodities from different geographical sources. We adopt this simpler approach because of the link to a single region CGE modeling framework for Wales. However, we propose that the basic method employed to integrate input-output accounting and CGE modeling in this paper may be easily extended to the multi-region case. For example Turner *et al.* (2011b) integrate the two approaches in a fuller interregional framework).

We also follow Turner *et al* (2011a) in endogenising capital formation within the production process. We use the 2003 Welsh input-output tables. These are reported for 74 defined sectors (see Bryan et al., 2004; WERU, 2007), which we aggregate to the 25 production sectors detailed in Appendix B. Thus, including the *Capital* sector, there are N=26 production sectors and Z=5 final consumer groups (Welsh households and government; exports to the rest of the UK, RUK, and rest of the world, ROW, plus external tourists). Data on direct emissions of CO_2 as carbon for the 25 sectors in Appendix B and for the domestic household sector (the only final consumption group directly generating CO_2) for Wales were derived from information collected as part of the REWARD (2000) project. Data on imports of commodity output i to each Welsh production sector j and final consumer z (for use in estimating equation A.3) were made available by the Welsh Economy Research Unit for RUK and for ROW as a whole. However, in order to reflect the different types of commodity outputs imported from different countries, and the direct carbon intensity of production in the source region/nation, we draw on a dataset made available by colleagues at OECD to construct our weighted pollution vector (see Turner *et al*, 2011c, for more details), with pollution intensities for the RUK drawn from the UK environmental accounts.[3]

As is standard in carbon accounting studies using input-output methods, household expenditure is retained as an exogenous final consumption vector so that pollution generation may be attributed to this consumption. However, in the CGE analysis in Section 5, we are able to consider the impacts of induced (wage) income and consumption effects in the post-shock input-output tables that are used to compute the PAP and CAP measures.

[3] Data from the UK Environmental Accounts, constructed by the Office for National Statistics may be downloaded at http://www.statistics.gov.uk/about/methodology_by_theme/Environmental_Accounts/default.asp

3.1 PAP emissions

Estimating equation (A.1), we find that regional CO_2 (as carbon) under PAP (i.e. carbon directly generated in economic activity within the Welsh economy) in the base accounting year of 2003 is 11.75m tonnes. Using equation (A.2) we attribute these PAP emissions to the two types of domestic (households and government) and three types of external (RUK and ROW exports, plus external tourists) final consumption.[4] Just over 65% (7.7m tonnes) are attributable to external demand. Within this, just under a third (31%) is CO_2 produced in the *Metal Manufacturing* sector (Sector 8 in Appendix B) to support external demands. These external demands are both for the sector's own output (2.2m tonnes), but also for the outputs of other sectors (an additional 0.13m tonnes driven by intermediate demands, primarily in sectors 9-13, which account for 82% of *Metal Manufacturing*'s sales to other Welsh sectors).

However, *Metal Manufacturing* is a heavily export-intensive industry, exporting 54% of its output (i.e. to packaging, automotive, and construction sectors) to other UK regions and a further 28% to the rest of the world. It is also highly CO_2-intensive (818.5 tonnes of carbon per £1m output in 2003) and directly accounts for around 21% of total CO_2 generation within Wales (PAP) in the base year of 2003. The only sector contributing more to the PAP measure (just over 31%) is *Electricity*, which is also important in export terms, while *Chemicals and Plastics* is the next largest contributor in all respects, directly accounting for just over 14% of CO_2 generated under PAP, and 18% of CO_2 supported by external demands. With direct CO_2 generation by households (18% or the 2.1m tonnes) being the only other major source under the PAP measure – the remaining 22 production sectors together directly accounting for less than 16% – the structural breakdown of the PAP measure is relatively straightforward. That is, it can be traced back to just a few very CO_2- and export-intensive industries in the Welsh economy (as well as direct emissions from the household

[4] In doing so we decompose the results by examining the production element of (A.2) in more detail: first by using the matrix of final demands to examine how direct carbon generation in each sector is supported by different elements of final demand (i.e. using $\varepsilon^F [[I-A]_R]^{-1} Y_r$)); second, to examine how much carbon both at the sectoral and aggregate levels is supported by final demand for each sector's output (i.e. what is consumed rather than who consumes it, using $\varepsilon^F [[I-A]_R]^{-1} Y_R^*$, where the asterix indicates a transposed matrix).

sector).

3.2 CAP emissions

While introducing final consumption as one of the drivers of pollution generation by attributing emissions produced within the target economy, e^R, to end users, the results above retain a quantitative focus on what Munksgaard and Pedersen (2001) term the 'production accounting principle'. As they demonstrate, in a closed economy with no external trade linkages use of the framework in equation (A.2) would equate to an analysis under the consumption accounting principle, or a 'carbon footprint'.

However, regional economies tend to be very open economies. Included in the final demand vector, $\mathbf{y_R}$, in the calculation of (A.2) are export demands. This means that some carbon emissions generated under the production accounting principle are attributed to *external* demands. Moreover, so far no account has been taken of the emissions that are embodied in imports, which would be added to the target region's account in a carbon footprint calculation. Therefore, the final step of the input-output analysis (using equation (A.3)) focuses on the CAP measure of total CO_2 required to support Welsh domestic (household and government) final consumption. This includes estimation of CO_2 embodied in imports but excludes CO_2 embodied in exports. The result here is 10.9m tonnes.[5] Some 4m tonnes of this are common to both the PAP and CAP measures (CO_2 generated within Wales to support Welsh final consumption). However, the CAP measure replaces the 7.7m tonnes embodied in exports under PAP with 6.8m tonnes of CO_2 embodied in imports. Again, the commodity composition of this is fairly concentrated, with 75% located in imports of the commodity outputs of the RUK and/or ROW *Electricity*, *Chemicals and Plastics*, *Metal Manufacturing* and *Transport and Communications* sectors.

[5] Note that this is a lower figure than that estimated by Turner *et al* (2011a) where a domestic technology assumption is used to estimate the CO_2 content of imports. This is due to several Welsh industries/commodity outputs (particularly sectors 5-8 in Appendix 2) being more CO_2-intensive than their RUK and ROW counterparts (here CO_2 embodied in imports of the commodity outputs of RUK and ROW sectors 5-8 account for 37% of the total).

The basic implication is that, despite running a trade deficit in goods and services in 2003, Wales ran a CO_2 'trade surplus' of just under 1m tonnes. Thus, Wales is a net exporter of CO_2 (i.e. it pollutes more than it requires for its own consumption needs). However, it is also important to note that the relationship is a deficit one with ROW (CO_2 embodied in ROW imports, 3.9m tonnes, is greater than CO_2 embodied in ROW exports – excluding tourists, which are not disaggregated by source outside of Wales – at 2m tonnes). The surplus relationship arises from trade with other UK regions, where CO_2 embodied in exports (5.5m tonnes) is almost double that embodied in imports (2.9m tonnes). Given that UK responsibilities under Kyoto (a PAP measure) lie at the national level, this finding has interesting implications in terms of the devolution of responsibility for sustainable development in the UK. It suggests that a disproportionate level of direct pollution generation (relative to consumption requirements) may be located in peripheral regions. McGregor *et al*, (2008) report a similar finding for Scotland within the UK – mainly due to Scotland's being a net exporter of electricity to the rest of the UK.

Nonetheless, our specific concern here is the implication that CO_2 embodied in export demands is removed from the carbon footprint calculation under CAP. This is because Welsh consumers would be expected to benefit from the location of export-led industries in their region.[6] Moreover, given that *Metal Manufacturing* outputs feed intermediate rather than final demands in other regions/countries, there is also the question of identifying to whose CO_2 footprint the emissions embodied in exports should be allocated. To illustrate these points we now turn to a CGE model of the Welsh economy (which incorporates the input-output accounting framework above) to examine the economic and carbon impacts of an increase in export demand to the *Metal Manufacturing* sector.

4. AMOW – A computable general equilibrium Model Of Wales

[6] Of course if these industries substituted some CO_2-intensive parts of their production process for imports this would be reflected in the carbon footprint.

Where there is a need to model the impact of marginal changes in activity on the wider economy, particularly where there is a need to track adjustment over time in the presence of even short-run constraints, a common approach in regional analysis is to employ CGE techniques (see Partridge and Rickman, 1998; 2010, for reviews). CGE modeling approaches have also become commonplace in examining environmental issues more generally, though more typically at the national level (see e.g. Bergman, 1990; Glomsrød and Wei, 2005; and Wissema and Dellink, 2007). There are, however, a limited number of CGE applications to regional environmental issues, including Despotakis and Fisher (1988), Li and Rose (1995), Hanley *et al*., (2009). See Bergman (2005) for a general review of CGE applied to environmental issues. However, we believe that this paper provides an innovative environmental CGE application that integrates input-output accounting to examine pollution generation under consumption as well as production accounting principles.

4.1 General structure

Here, we follow Turner *et al*. (2011b) in using a regional CGE framework to model the impacts of a change in activity. We then use these model results to inform an input-output analysis that attributes pollution to Welsh consumption activity before and after the change is introduced. Specifically, we use the CGE model results on changes in prices and quantities throughout the economy to derive post-shock input-output tables in value terms.

The Welsh model, named AMOW, is developed using the AMOS (A Model of Scotland) CGE modeling framework, initially developed by Harrigan *et al* (1991) using Scottish data. Here, the model is calibrated on a Welsh Social Accounting Matrix (SAM) for 2003, which incorporates the input-output tables used in the analysis above. Details of the AMOS modeling framework are given in Hanley *et al* (2009). The main features of the model in the current application are as follows:

- There are 3 internal transacting groups (households, firms, government).

- There are 25 production sectors/commodities (see Appendix B).
- There are also two external transactor groups (RUK, ROW). Export demand is price sensitive (Armington, 1969), with elasticity of 2.0 (Gibson, 1990). All other determinants of export demand are exogenous.
- Public expenditure is fixed, in real terms.
- All commodity markets are taken to be competitive.
- Wales is modelled as a small open economy in that the external impacts of changes in Welsh economic activity and prices are assumed to be sufficiently small that they have no significant feedback effect on the Welsh economy. This implies that Wales takes RUK and ROW prices as given, although the price of Welsh goods and services can vary, relative to external prices. A corollary is that Welsh demand for RUK and ROW goods can be met through an infinitely elastic supply at existing RUK and ROW prices
- We assume cost minimisation in production and employ multi-level production functions (with Welsh output prices determined through the price dual). See below.
- The model is recursive dynamic in that there is period-by-period (year-by-year) adjustment of capital and labour stocks via region-specific investment and interregional migration.

Key elements of model specification are in terms of the labour and capital markets, and the nested production function. Taking the labour market first, wages are determined through a regional wage bargaining function taken from econometric work by Layard *et al.* (1991):

(1) $w_{w,t} = \alpha - 0.068u_w + 0.40w_{w,t-1}$

where: w_w and u_w are the natural logarithms of the Welsh real consumption wage and the unemployment rate respectively, t is the time subscript and α is a calibrated parameter.[7] Empirical support for this "wage curve" specification is now widespread, even in a regional context (Blanchflower and Oswald, 1994).

We take net migration to be positively related to the real wage differential and negatively related to the unemployment rate differential between Wales and RUK, in accordance with the econometrically estimated model reported in Layard *et al* (1991). This model is based on that in Harris and Todaro (1970) and adopts the form:

$$(2) \qquad m = \beta - 0.08\left(u_w - u_r\right) + 0.06\left(w_w - w_r\right)$$

where: m is the net in-migration rate (as a proportion of the indigenous population); w_r and u_r are the natural logarithms of the RUK real consumption wage and unemployment rates, respectively, and β is a calibrated parameter. The net migration flows in any period are used to update population at the beginning of the next period, in a manner analogous to the updating of the capital stocks. The regional economy is initially assumed to have zero net migration and ultimately net migration flows re-establish this population equilibrium.

The endogenous investment process is as follows. Within each period of the multi-period simulations using AMOW, both the total capital stock and its sectoral composition are fixed, and commodity markets clear continuously. Each sector's capital stock is updated between periods (starting after the first period simulated) via a simple capital stock adjustment procedure, according to which investment equals depreciation plus some fraction of the gap between the desired and actual capital stock. The desired capital stock is determined on cost-minimisation criteria and the actual stock reflects last period's stock,

[7] Parameter α is calibrated so as to replicate the base period, as is β in equation (2). These calibrated parameters play no part in determining the sensitivity of the endogenous variables to exogenous disturbances. However, the adoption of base-period equilibrium implied by the calibration procedure is an important assumption.

adjusted for depreciation and gross investment. The economy is assumed initially to be in long-run equilibrium, where desired and actual capital stocks are equal.[8]

The nested production function can be specified with constant elasticity of substitution (CES), Cobb-Douglas or Leontief technology at each nest. Here we specify as follows. We allow substitution between capital and labour to form value-added, assuming an elasticity of 0.3 (Harris, 1989). Value-added combines with an intermediate composite in the production of output, assuming Leontief technology (see below). At the bottom nest, we allow substitution between local and imported intermediates to form an intermediates composite, first between domestic and RUK intermediates, then between the resulting UK and ROW composites, with an elasticity of 2.0 (Gibson, 1990) at both these levels. We adopt the Armington (1969) assumption that regional and imported intermediates are imperfect substitutes, where the price of imports is fixed (under the small open economy assumption above) but the price of Welsh intermediates is endogenous and subject to rising marginal costs.

However, within the Welsh, RUK and ROW composites, we assume Leontief technology in combining the 25 commodity outputs in each case. We also assume Leontief technology in the combination of intermediates and value-added in production of gross output. The main motivation is so that we can reasonably assume a Leontief relationship between CO_2 generation and output. This is more common to input-output analysis and not necessary in a CGE framework, even where we are generating post-shock input-output tables (the output-pollution coefficient may change). However, due to a lack of information in terms of sources of sectoral CO_2 (energy-use, processes etc), at this time we retain the Leontief

[8]Our treatment is wholly consistent with sectoral investment being determined by the relationship between the capital rental rate and the user cost of capital. The capital rental rate is the rental that would have to be paid in a competitive market for the (sector specific) physical capital: the user cost is the total cost to the firm of employing a unit of capital. Given that we take the interest, capital depreciation and tax rates to be exogenous, the capital price index is the only endogenous component of the user cost. If the rental rate exceeds the user cost, desired capital stock is greater than the actual capital stock and there is therefore an incentive to increase capital stock. The resultant capital accumulation puts downward pressure on rental rates and so tends to restore equilibrium. In the long run, the capital rental rate equals the user cost in each sector, and the risk-adjusted rate of return is equalised between sectors.

assumption, particularly given the importance of non-energy related carbon generation in *Metal Manufacturing* production.

The simulation results reported here have been subjected to sensitivity analysis with respect to key parameter values. Space constraints preclude reporting of the results in this paper. However, given that we do not impose any lasting supply constraints, the long-run results are not sensitive to the values assigned to key parameters such as trade and substitution elasticitites. The short-run adjustment path of key variables is slightly affected, but there is no qualitative impact.[9] The only qualitative impact is observed when we impose alternative labour market closures, but the impact is small during the adjustment period only (the long-run results are not affected – see footnote 10 below).

4.2 Simulation Strategy

We simulate a £90m permanent expansion in export demand for the output of Welsh *Metal Manufacturing* sector. As indicated above, the scale of this shock is based on a current anticipated expansion in Welsh steel production that has driven increased investment in the sector. We introduce the stimulus in the form of a 3.7% permanent step increase in exogenous export demand from each RUK and ROW for output of Welsh *Metal Manufacturing* sector (the £90m expansion is split proportionately between the dominant RUK export demand and ROW demand). This is introduced in the first period simulated. We model the export demand shock as anticipated in the *Metal Manufacturing* sector so that 100% of the gap between actual and desired capital stock is filled in any one period.

Note that the results in the next section are generally reported in terms of percentage changes from the base year values (with some absolute values reported for carbon indicators). Because the economy is taken to be in full (long-run) equilibrium prior to the export demand shock and this is the only disturbance

[9] The reader is referred to an earlier working paper version of the current paper where parametric sensitivity results are reported in an appendix (http://www.management.stir.ac.uk/documents/SEDP-2011-06-Turner-Munday-McGregor-Swales.pdf).

introduced, the results are best interpreted as being the proportionate changes over and above what would have happened, *ceteris paribus*, without the demand stimulus. Given that the CGE model uses annual SAM data, we take each 'period' in the adjustment process to be one year.

5. CGE simulation results

The impacts of the export demand stimulus to Welsh *Metal Manufacturing* are reported in Table 1 for periodic intervals as the economy adjusts to long-run equilibrium. In this new long-run equilibrium, given that we model a pure demand shock with no lasting constraints on supply, there is an expansion in all quantities but all prices return to their base year levels. However, in the early periods after the stimulus is introduced, observe that increased labour demand causes the real wage rate to rise and the unemployment rate to fall. This stimulates in-migration to Wales from RUK, which continues until real wages and unemployment return to their base year equilibrium rates (but with higher employment and population). Similarly, increased demand for capital increases the capital rental rate in all sectors (shown in Table 1 for *Metal Manufacturing*). This triggers an increase in investment and, consequently, capital stocks throughout the economy, but particularly in the targeted *Metal Manufacturing* sector.

The expansion in activity is largely concentrated in *Metal Manufacturing* itself. The results in Table 1 show that the capital stock adjusts fairly rapidly (given the treatment explained above to reflect investment activity in anticipation of increased export demand). Output adjusts faster, through substitution in favour of labour in the composition of value-added while capital stocks catch up. However, note that the price of *Metal Manufacturing* output is pushed up in the short-run due to the increase in demand in the presence of short-run supply constraints on labour, capital and intermediates inputs from other Welsh sectors. This induces a temporary substitution effect in favour of imported intermediates (the price of which is exogenous) in what is already an import-intensive sector. Imported intermediates increase faster than output and the use of domestically produced intermediates but this effect slows as

Welsh production becomes less supply constrained (so that only an income effect on imports lasts into the long-run).

Table 1. Impacts of a £90million increase in export demand to the Welsh *Metal Manufacturing* sector

	Base year (2003) Values	% change from base year equilibrium Period 2	Period 5	Period 10	Period 20	Period 25	Long-run
Metal Manufacturing sector:							
Output (£m)	2,960	3.143	3.376	3.400	3.419	3.423	3.432
Capital stock	318	2.737	3.381	3.404	3.420	3.424	3.432
Employment (000s)	13.9	3.229	3.375	3.399	3.418	3.423	3.432
Value-added (£m)	641.8	3.143	3.376	3.400	3.419	3.423	3.432
Capital rental rate (£m)	0.35	1.722	0.051	0.024	0.010	0.007	0.000
Price of output (indexed to 1 in base)	1	0.135	0.023	0.013	0.005	0.003	0.000
Exports (£m)	2,424	3.435	3.666	3.687	3.703	3.707	3.714
Imports (£m)	1,189	3.273	3.398	3.412	3.424	3.427	3.432
CO2 as carbon generation (kilo-tonnes)	2,423	3.143	3.376	3.400	3.419	3.423	3.432
Aggregate economic activity:							
GDP (income measure) (£m)	34,600	0.060	0.096	0.129	0.163	0.171	0.188
Household consumption (£m)	29,844	0.140	0.160	0.180	0.200	0.205	0.214
Total local consumption (HH plus Govt) (£m)	42,446	0.091	0.112	0.127	0.141	0.144	0.150
Investment (£m)	5,242	0.116	0.122	0.144	0.164	0.169	0.179
CPI (indexed to 1 in base)	1	0.056	0.041	0.025	0.011	0.007	0.000
Exports (£m)	24,957	0.239	0.278	0.306	0.338	0.346	0.361
Imports (£m)	36,742	0.336	0.348	0.353	0.359	0.361	0.364
Real T-H consumption wage (£000s)	12.60	0.061	0.029	0.015	0.006	0.004	0.000
Total employment (000s):	1,267	0.049	0.086	0.118	0.149	0.157	0.172
Unemployment rate (%)	3.4	-0.535	-0.259	-0.133	-0.054	-0.035	0.000
Total population (000s)	2,931	0.024	0.073	0.111	0.147	0.156	0.172

Upward pressure on the price of labour and capital means the price of output rises in the early periods, which acts to dampen export demand so that the full 3.7% increase in exports is not realised initially (and this in turn limits the required expansion in capital stock and employment). Finally, given the Leontief assumption regarding the output-carbon relationship, carbon emissions grow in line with output from the outset.

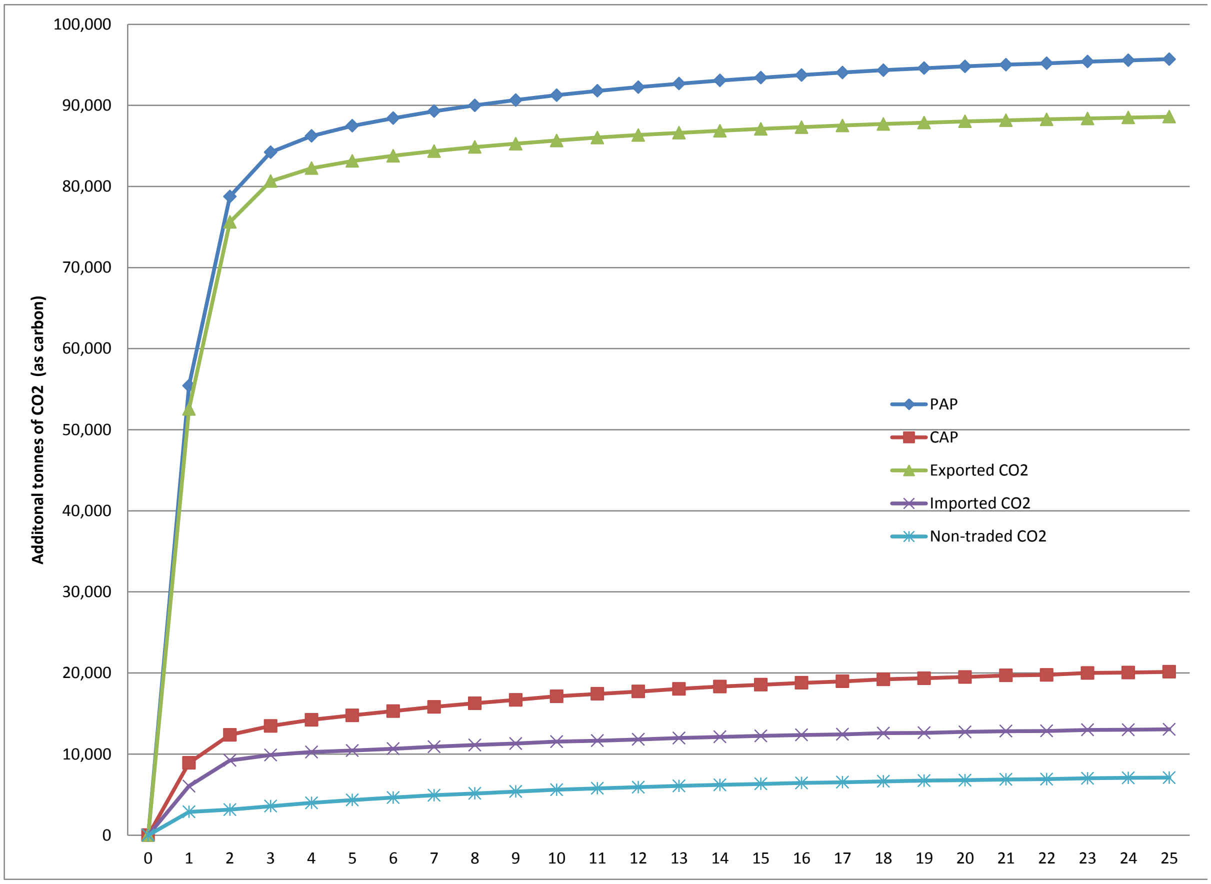
The export demand stimulus in *Metal Manufacturing* has a positive impact on the Welsh economy from the outset. Over time, GDP expands by 0.188%, aggregate household consumption by 0.214%, and employment and population by 0.172%. However, in the short- to medium-run, before labour and capital stocks are fully adjusted, there are price changes, stemming from upward pressure on wages and capital rental rates. This causes some crowding out of activity in the initial stages, with output levels falling in some sectors as prices rise (reducing competitiveness) though for most sectors the positive indirect (multiplier) effect of increased intermediate demands dominates.[10]

While the net increase in export demand throughout is concentrated in *Metal Manufacturing* (increases in output prices in all sectors cause a contraction in exports elsewhere), the increase in imports is driven by substitution and income effects throughout the economy. Even in some sectors where there is a contraction in activity in early periods, there is an increase in imports as producers substitute away from more costly local production in favour of imported goods, the price of which has not changed (e.g. *Metal Products*, which, in the base year, purchased 17% of its local intermediates from *Metal Manufacturing* suffers a 0.027% contraction in activity but increases its imports by 0.03%). However, over time, as the spike in Welsh prices dissipates (due to in-migration of labour pushing real wage rates back to their pre-shock levels and capital formation returning capital rental rates in all sectors to a level equal to the user cost of capital), these substitution effects disappear and the long-run increase in imports is driven by the general increase in activity (i.e. the use of all inputs to production increases as activity levels increase across the economy). The stimulus to each sector depends on its importance in the supply chain serving the *Metal Manufacturing* sector (i.e. the multiplier effect of the initial demand stimulus).

[10] We ran additional simulations (not reported here due to space constraints) where we examine the impact of fixing the real wage. However, this only acts to speed up the adjustment process through smaller increases in output prices, with migration hastened through a bigger change in the unemployment differential with RUK (unemployment falls by more in the initial periods of adjustment as the real wage is unchanged). The long-run result is unchanged.

To study the impacts on CO_2 emissions, we use the CGE model results to generate post-shock input-output tables for each period. The CGE model reports all quantity changes in real terms (including those induced by changes in household wage income earned in the production sectors) but also provides information on price changes throughout the system, which allows us to derive post-shock input-output tables reported in the conventional value format. The post-shock input-output tables for each period following the export demand stimulus are then used to repeat the analysis of the PAP and CAP (DTA) measures using equations A.1-A.3. The headline results are included in Table 2 (in terms of the percentage change relative to the base year) and Figure 1 provides a breakdown of the composition of the PAP and CAP indicators.

Figure 1. Additional CO2 (as carbon) embodied in Welsh trade flows as a result of a £90million (3.7%) increase in export demand to the Welsh *Metal Manufacturing* sector



The first thing to note from both Table 1 and Figure 1 is that the increase in the PAP measure is considerably bigger than the increase in CAP. This is because most of the growth in activity, and related carbon emissions, is in *Metal Manufacturing* production to meet the exogenous increase in export demand (though the dominance of *Metal Manufacturing* in the PAP effect is slightly reduced as supply constraints ease and the multiplier effects spread throughout the economy: in year 2, the increase in direct *Metal Manufacturing* CO_2 emissions accounts for 97% of the change in PAP (by the long-run this is 85%). For both the PAP and CAP measures, the long-run increase in domestic CO_2 emissions supported by Welsh demand is just 0.19%, which, taken with the 0.21% increase in CO_2 embodied in imports, account for the total increase in the CAP measure, which increases by 0.2%.

In all periods, the total change in the CAP measure is driven by changes in household consumption, given that public consumption is held fixed. The means that the percentage rise in CAP emissions is less than the corresponding percentage rise in household consumption. Further, the CO_2 embedded in imports per unit of expenditure for household consumption is greater than for public consumption. Therefore as the ratio of private to public expenditure rises, the carbon intensity of imports increases,, particularly in the case of carbon embodied in imports from ROW (which rise by 0.21% by the long-run).

To help put these changes into perspective in 'sustainable development' terms, Table 1 includes results for the CO_2-intensity of GDP and per capita emissions under both PAP and CAP. Both GDP and Welsh population grow (the latter through in-migration). PAP emissions grow markedly faster than GDP, though GDP closes the gap to some extent over time, but the increase in the PAP CO_2-intensity of GDP is 0.64% by the long-run. PAP emissions outstrip population growth to an even greater extent with the result that per capita CO_2 emissions grow by 0.66% over time. CAP emissions, on the other hand, are more in line with GDP growth, as is consumption, and, after an initial (small) spike in the CAP CO_2-intensity of GDP (only peaking at 0.06%) there is only a very small increase in this ratio into the long-run. The growth in CAP CO_2 per capita is slightly larger, with a peak of just under 0.1% but settling down to a 0.03% increase over the long-run. This reflects the increase in embedded CO_2 attributable to the rise in per capita household income which more than offsets the fall in CO_2 embedded in the lower public expenditure per head.

6. Conclusions and directions for continued/future research

The key result from the integrated IO and CGE analysis above is that the Welsh economy benefits from an export-led economic expansion focussed in a highly carbon-intensive industry, but with an environmental cost in that CO_2 generation within Wales rises (PAP) by more than the increase in GDP and consumption. This is evidenced by the gap between the CAP and PAP measures in Figure 1. The estimated carbon footprint (CAP) does rise, particularly with increased 'pollution leakage' through increased carbon embodied in imports. However, the much smaller increase in CAP than in PAP, taken alongside the base case scenario where (perhaps unusually for a developed economy) Wales runs a 'carbon trade surplus', suggests that Wales would benefit from a shift in accounting perspective towards carbon footprint type measures. However, such a shift would raise an important issue in terms of how and to whom responsibility for the additional increase in PAP emissions over that in CAP would be attributed. This may be more straightforward, and pertinent, in the case of emissions embodied in exports to the rest of the UK and future research involving an interregional input-output and CGE modelling framework may help inform in this respect (as well as raising interesting issues regarding the location of carbon-intensive heavy manufacturing industries in peripheral regions).

However, more generally it may also be argued that Wales has instigated the change in activity brought about by the export expansion, particularly given the investment made to facilitate it. Moreover, Welsh decisions could further impact the structure of the economy and pollution problem under both CAP and PAP perspectives (for example if firms choose to import some of their CO_2 requirements in order to lower their own direct emissions). Issues such as these raise questions as to what the CAP and PAP impacts tell us in terms of the sustainability of economic growth and who should be held responsible for carbon generation in different jurisdictions. Perhaps the answer in trying to take a more consumption-orientated focus is not as straightforward as subtracting carbon embodied in exports and adding that embodied in imports, but rather some form of shared responsibility criteria is required, between producers and consumers generally and/or between importing and exporting countries.

The issue of how economic benefit may impact on carbon measures is addressed in a literature that focuses on the development of a shared responsibility measure. For example, Lenzen *et al.* (2007), in an extended input-output analysis, suggest that a share of responsibility should be retained by producers based on the value added contribution of output. This would be a possibility in the case examined here and CGE analysis of the type presented here would help motivate and consider what a shared responsibility measure should focus on in different scenarios. Similarly, it may be useful to develop interregional input-output, CGE and/or fuller lifecycle analysis methods to consider different accounting perspectives, such as supplier responsibilities for the ultimate consumption use of their production outputs. Future research may also be usefully extended to cost-benefit analysis to consider different accounting perspectives in the context of consumer and/or producer 'willingness to pay' for the environmental costs that accompany the additional economic benefits generated by a scenario such as that modelled here.

More generally, value may be added in future research by using input-output methods to analyse the sequence of both economic and environmental impacts throughout the target economy and on its trade partners using the post-shock input-output tables generated using the method proposed here. For example, Dietzenbacher and Romero (2007) propose a method to break down the sequence of impacts from a shock to a single sector through rounds of backward and forward multiplier effects that would permit a decomposition of results modelled throughout the adjustment process using CGE techniques. [11]

[11] We are grateful to an anonymous referee for suggestions on potential extensions to the research reported here.

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APPENDIX A. THE INPUT-OUPUT ACCOUNTING FRAMEWORK

Equations	
(A.1) PAP – direct emissions	$\mathbf{e^R} = \boldsymbol{\varepsilon}^\mathbf{P}\mathbf{x_R} + \boldsymbol{\varepsilon}^\mathbf{C}\mathbf{y_R^*}$
(A.2) PAP – attribution to end users	$\mathbf{e^R} = \boldsymbol{\varepsilon}^\mathbf{P}[[\mathbf{I} - \mathbf{A}]_\mathbf{R}]^{-1}\mathbf{y_r} + \boldsymbol{\varepsilon}^\mathbf{C}\mathbf{y_R^*}$
(A.3) CAP – attribution to local consumers	$\mathbf{e^T} = \boldsymbol{\varepsilon}^\mathbf{P}_\mathbf{W}[\mathbf{I} - (\mathbf{A_R} + \mathbf{A_M})]^{-1}(\mathbf{y_R^R} + \mathbf{y_M^R}) + \boldsymbol{\varepsilon}^\mathbf{C}\mathbf{y_R^*}$

VARIABLES, DIMENSIONS AND NOTATION

e^R PAP emissions generated within the region (scalar)

e^T CAP emissions generated within the region (scalar)

$\boldsymbol{\varepsilon}^\mathbf{P}$ 1xN vector of direct output-carbon coefficients with elements $\varepsilon_i=e_i/x_i$; e_i is the physical amount of carbon directly generated by production sector i in producing output j (i=j=1,..N).

$\boldsymbol{\varepsilon}^\mathbf{C}$ 1xZ vector of direct final expenditure-pollution coefficients with elements $\varepsilon_z=e_z/y_z$; e_z is the physical amount of emissions generated by final consumption group z in the process of its total final expenditure, y_z.

$\boldsymbol{\varepsilon}^\mathbf{P}_\mathbf{W}$ 1xN vector of weighted direct pollution intensities for each commodity output j, with weights attached to the direct carbon intensity of output in each country, s, given by the share of commodity output j from region/country s in total Welsh use of commodity output j.

$\mathbf{x_R}$ 1XN vector of outputs, where N=1,…,26 (25 production sectors plus capital formation)

$\mathbf{I}$ NxN identity matrix

$\mathbf{A_R}$ NxN regional inter-industry input-output matrix reported for i=j=1,…,N industries/commodity outputs; elements a_{ij} give the input of regional industry i required per monetary unit of regional output j (capital endogenised where inputs i given by capital formation from each sector and output j is total other value-added)

$\mathbf{A_M}$ NxN matrix reported for i=j=1,…,N industries/commodity outputs imported intermediate inputs to production.

$\mathbf{y_R}$* Zx1 vector of total final expenditure on regional outputs (asterix indicates transpose)

$\mathbf{y_R}$ Nx1 vector of total final expenditure on output of each regional sector *i*.

$\mathbf{y_R^R}$ Nx1 vector of regional household and government expenditures on output of each regional sector i.

$\mathbf{y_M^R}$ Nx1 vector of regional household and government expenditures on imports of commodity output of each external sector i.

APPENDIX B. CLASSIFICATION OF PRODUCTION SECTORS/COMMODITY OUTPUTS AND DIRECT CO_2 INTENSITIES IN THE WELSH INPUT-OUTPUT AND CGE FRAMEWORKS

	Welsh 74	Tonnes CO2 as carbon per £1m output		
Sector/commodity output	sector IO	Wales	RUK (UK)	ROW
1 Agriculture, Forestry & Fishing	1,2	38.09	76.99	267.90
2 Mining, Extraction & Quarrying	3,4	133.55	207.12	114.73
3 Mfr - Food & Drink	5 to 11	26.57	40.06	38.20
4 Mfr - Textiles & Clothing	12,13	14.37	60.32	43.17
5 Mfr - Wood & Paper	14 to 16	59.06	44.77	43.18
6 Mfr - Chemicals & Plastics	17 to 22	384.30	139.36	138.82
7 Mfr - Non-metallic Mineral Products	23,24	395.52	325.08	432.66
8 Mfr - Metal Manufacturing	25,26	818.50	483.74	651.12 *
9 Mfr - Metal Products	27,28	10.99	22.31	16.65 *
10 Mfr - Machinery	29 to 31	7.76	12.73	12.69
11 Mfr - Electrical Engineering	32 to 37	3.58	12.43	14.39
12 Mfr - Vehicles & Transport	38,39	7.64	14.55	6.53
13 Other Manufacturing	40,41	33.09	45.96	846.46
14 Electricity	42	1,379.58	1,480.80	292.62
15 Gas & Water	43,44	33.63	50.84	42.23 *
16 Construction	45	12.23	15.34	5.69
17 Wholesale & Retail	46 to 48	19.61	15.24	98.70
18 Hotels, Restaurants & Catering	49	12.08	10.83	98.70
19 Transport & Communications	50 to 55	127.55	153.83	140.69 *
20 Finance	56,57	8.78	1.81	27.13
21 Other Business Services	58 to 67	8.75	3.81	27.13
22 Public Admin & Defence	69	25.41	21.02	27.13
23 Education	70	7.15	10.84	27.13
24 Health & Sanitary	71,73	12.81	13.64	27.13
25 Other Services (incl. Social work)	72,74	11.55	9.16	27.13
Household direct CO_2 intensity		71.39		

* In some cases, the OECD data (see Turner et al, 2011c) gave odd results and are replaced with averages of the UK and Welsh intensities