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Methodological and Ideological Options

## Policy options for funding carbon capture in regional industrial clusters: What are the impacts and trade-offs involved in compensating industry competitiveness loss?

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## ABSTRACT

Carbon capture and storage (CCS) is a technically feasible deep decarbonisation solution. Still it is not widely adopted, arguably due to some basic political economy and policy challenges. One issue is the large infrastructure needs of transporting and storing CO<sub>2</sub>. However, a more fundamental challenge in the current UK industrial policy landscape is concern over introducing new costly capital requirements in industries that need to retain competitiveness in a world that has not yet fully signed up to the 'net-zero' transition demanded by the more ambitious 1.5 degrees Celsius warming target of the Paris Agreement. We take the example of high-value chemicals industries operating in the UK devolved region of Scotland and use an economy-wide computable general equilibrium (CGE) model to consider the nature and potential extent of export, GDP and employment losses under different illustrative polluter/government/taxpayer pays approaches to meeting the higher cost requirements. We conclude that the value from subsidising capture activity depends on the extent of export demand response to competitiveness losses resulting from firms bearing CO<sub>2</sub> capture costs. However, outcomes reflect trade-offs across different types of sectors and employment, and are also dependent on labour market responses to changing wage and unemployment rates.

### 1. Introduction

On 12th December 2015, the 21st Conference of the Parties (COP) set ambitious climate change targets. These committed signatory governments to deep decarbonisation territorial greenhouse gas (GHG) emissions targets so as to limit catastrophic global temperature rise and enable a carbon-neutral world sometime between 2050 and 2100 (UNFCCC, 2015). Against this commitment, better known as the Paris Agreement, the UK national and devolved governments adopted the recommendations of the Committee on Climate Change (CCC) to reduce GHG generated within the UK to net-zero by 2050 (CCC, 2019).<sup>1</sup> The CCC recommended a 2045 nearer-term target for Scotland due to that devolved region's unique natural resource and industrial/infrastructure capacity. This includes both natural carbon capture (trees, forests and peatlands) and the foundations for a carbon capture and storage system

that could utilise the on and offshore capacity developed through the concentration of the UK oil and gas industry and supply chain activity in Scotland.

The UK national and devolved context is an important and useful setting for analysing the role and challenges of carbon capture and storage (CCS) as a net-zero solution for two reasons. First, in response to the CCC (2019), the UK Government became the first EU and G7 nation to legislate a 2050 target to become a net-zero carbon economy (in the territorial emissions context of UNFCCC agreements) with all devolved authorities legislating in line with this (Priestly, 2019). Second, since 2016, the policy landscape around CCS in the UK has shifted significantly with national energy and climate policy now falling within the portfolio of the Department for Business, Energy and Industrial Strategy. Here, the main role identified for CCS is in supporting industrial decarbonisation in line with the UK Industrial Strategy, with focus on

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<sup>1</sup> The Committee on Climate Change is an independent statutory public body, formed under the UK Climate Change Act 2008. It advises the United Kingdom national and devolved Governments and Parliaments on tackling and preparing for climate change.

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sustaining the competitiveness and domestic supply chain activity of relatively high productivity and wage sectors such as petrochemicals and other chemicals manufacturing (BEIS, 2017, 2018).

Emissions-intensive manufacturing industries cluster in a number of UK regional locations and the devolved governments have varying degrees of responsibility and policy levers at their disposal in managing emissions mitigation and economic performance. This highlights the importance of adopting both a devolved nation and regional focus. Two of the main industrial clusters are located in South Wales and at Grangemouth in the Eastern Central Belt of Scotland. The net-zero target includes the ambition of delivering one net-zero-emissions cluster by 2040 and at least one low-carbon cluster by 2030. Industry actors present at all UK regional clusters have ambitions, and potential for public support (including through an Industrial Strategy Challenge Fund now established by the UK Government) to contribute to meeting these targets, and there is, in practice, a high level of policy coordination between national and devolved governments. However, we set our initial analyses in the context of the Scottish cluster. The Scottish Government (2019) has ambitions, and devolved powers, to support decarbonisation of the Scottish regional cluster in ways, particularly with CCS, which would exploit skills, capacity and infrastructure developed in hosting much of the UK oil and gas industry, while ensuring the sustainability of GDP generation and relatively high wage jobs in manufacturing and supply chain activity.

Thus, an important research question arises: how might the competitiveness of regional manufacturing activities, and, consequently, GDP, employment and income generation at industrial sites and throughout domestic supply chains be impacted if carbon capture requirements are imposed? Do potential losses in this regard underpin a case for subsidising and socialising costs, even on an interim basis (until competing nations take similar costly action), on both domestic and international climate policy grounds, to achieve domestic emissions reductions and prevent offshoring of emissions, jobs and GDP?

We locate our central premise in the context set out above. A full-scale CCS solution would necessarily involve capturing and transporting CO<sub>2</sub> to a secure storage site, where Scotland has the resources to develop comparative advantage on the basis of its established oil and gas industry and supply chain capacity. However, the biggest challenge – in terms of the number of participants and distribution of costs – is to incentivise the participation of individual firms within those industries that need to decarbonise. Crucially, for these firms, and in addition to other barriers to investment, such as CCS ‘cross chain’ risk (for example if storage facilities fail to provide capacity), CO<sub>2</sub> capture would involve not only upfront investment but a long-run commitment to operating with a higher level of capital equipment. This presents competitiveness risks, at least in the short to medium term, where firms are operating in a global marketplace that is not yet fully ‘signed up’ to net-zero.

We use a multi-sector economy-wide CGE scenario modelling approach in the pursuit of a solution to this conundrum. We simulate how the operational capital costs of capture act to trigger mechanisms that impact firms, their employees and other stakeholders, and ripple out across the wider economy. We focus on the case of Scotland as a nation within the UK. Scotland’s devolved government has powers that allow it to reallocate its own spending or raise income taxes in order to support subsidy action. It also has interest in leading the UK Government’s Industrial Clusters Mission’s aim to decarbonise at least one cluster by 2030/40 and in deployment CCS. This could, of course, involve joint action with the UK Government even in prioritising action at the Scottish Grangemouth cluster, but we focus attention at this stage on the Scottish Government taking full fiscal responsibility for subsidy action.

## 2. Articulating and addressing the policy challenge

### 2.1. A shifting UK national and devolved policy landscape

The key recent CCS policy development in the UK is a shift in attention from addressing the challenge of decarbonising energy supply to supporting industrial decarbonisation and clean growth. This was initially introduced as a central theme of the basic UK Industrial Strategy (BEIS, 2017) prior to UK legislation on net-zero in 2019. CCS is the subject of a linked ‘Action Plan’ (BEIS, 2018) and an Industrial Cluster Mission that commits to delivery of the world’s first net-zero cluster by 2040 and at least one low carbon cluster by 2030.<sup>2</sup>

This change in policy landscape disrupts at least the application of the previous model proposed for full-chain CCS in the UK, which focussed primarily on decarbonisation of the power/energy supply sector as the driver of CCS, with industrial capture following, subject to the resolution of a range of policy challenges. This model was most notably set out in the Oxburgh report, the outcome of a UK Parliamentary Advisory Group (PAGCCS, 2016) that followed the cancellation of a previous UK CCS Commercialisation competition. This competition incorporated a Scottish project linking transport and storage of CO<sub>2</sub> in offshore storage sites in the North Sea to capture at the Peterhead gas-fired power station. Essentially, enabling industrial capture is now set as the primary question, while those around transport and storage (T&S) infrastructure are to be considered largely outside of the power-setting driving the Oxburgh model.

This brings forward a range of questions raised by Oxburgh in the industrial decarbonisation context. The key challenge is how uptake of CCS might impact the global competitiveness of UK regional industry players and, thus, the willingness of individual – often international – firms to participate. Firms’ incentives are influenced by how abatement costs are reflected in output prices, and thus competitiveness, in a world and marketplace that has not yet fully signed up to decarbonisation. The enabling role of T&S infrastructure, and the accompanying regulation and design of policy instruments, then comes into play not in terms of energy system development, but as a requirement to support and sustain industrial activity. This is relevant to both the UK’s high value added clusters and the network of up- and down-stream supply chains that ripple throughout the wider UK national and regional economies. This is how the case for CCS is now set out in the UK Industrial Strategy (BEIS, 2017, 2018).<sup>3</sup>

Thus, the research challenge is to understand how the GDP, employment and earnings (mapping to relatively high average industry and supply chain wages) generated by currently emissions-intensive industries would be affected by the introduction of a costly decarbonisation solution like carbon capture. The policy questions then are: to what extent is it possible to sustain such activity; what are the trade-offs involved in terms of potential impacts spilling over to other industries; and where might paying for any public support impact activity and employment levels across the economy? This issue is essentially one of how decarbonisation activity in general, and CCS in particular, is to be paid for, and setting the risks of moving first in bearing the costs, while potentially exploiting opportunities from leading in rolling out technology and industrial activity to support solutions where other nations may ultimately follow. The risk worrying policymakers and the public is that costly decarbonisation solutions will cause currently emissions-intensive industries to lose competitiveness in the UK and move offshore. This would have implications for jobs, earnings and GDP which would extend through regional and national supply chains, but also for

<sup>2</sup> See evolving BEIS on-line policy paper at <https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/missions#industrial-clusters>.

<sup>3</sup> The resetting of the BEIS (2018) ‘policy narrative’ on CCS in an industrial clusters context was informed by our own research – see Turner et al. (2020).

global emissions levels where the carbon intensity of production methods in other locations and/or transportation requirements to support continued use of industry outputs may offset any emissions reductions within the UK.

In short, the policy challenge is one of how to prevent industries from leaving strategic regional locations in UK. That is to say, there is a need to keep these industries engaged with a carbon management system whilst retaining their global competitiveness as the UK takes a leading role on transitioning to net zero. This raises questions of ‘who pays’ and how, both in terms of the feasibility of socialising at least some of the costs, and the extent to which government can raise and use public funds to support industrial decarbonisation activity where it is not clear when a polluter-pays model will become competitive.

## 2.2. How has the challenge of CCS been addressed to date in the wider literature?

At present, a core area of the debate and discourse has concerned what type of policy incentives and intervention can support near- to long-term deployment and rollout of CCS. Jiang et al. (2020) and Groenbergh and de Coninck (2008) review international and national CCS and low-carbon technology policies in relation to the market failures that justify policy and regulatory intervention and incentives. Individual studies have identified a range of policy options which include: command and control instrument (CCS mandate); investment support, such as grants, tax credits, loan guarantees and subsidy by trust funds; and production subsidies in the form of carbon pricing, feed-in price, etc. (Bennett and Heidug, 2014; Von Stechow et al., 2011; Zheng et al., 2011).

In analysing and comparing different policy options with potential to support CCS deployment, a number of methods have been applied in the literature. For example, Finon (2012), Groenbergh and de Coninck (2008) and Von Stechow et al. (2011) use qualitative multi-criteria analysis to suggest characteristics and features that are crucial in the choice and selection of policy to advance deployment. Some studies argue that it is vital that the choice of CCS policy meets certain evaluation criteria. Examples include cost effectiveness, distributional equality, addressing uncertainties and political feasibility (Goulder and Parry, 2008). In some cases, involving learning curve modelling/simulation, criteria are informed by drawing on lessons and experiences from other low carbon technologies and strategies such as renewables energy (Billson and Pourkashanian, 2017) and energy efficiency (Kalkuhl et al., 2015). Other studies focus on the importance of adopting integrated policy architecture and multi policy at different phases of the development of the technology (Krahé et al., 2013; Goulder and Parry, 2008).

The range of approaches is extensive. Yang et al. (2019) applies a real option approach to compare the impacts of different subsidy schemes on the investment benefit of CCS projects. These schemes include initial investment, electricity tariff and CO<sub>2</sub> utilization subsidies. Eckhauser and Herold (2014) employ a stochastic dynamic program (SDP) to simulate the optimal and risk minimising public funding strategy that support the development of full-scale CCS. Attention has also been given to how development, design and implementation of CCS policy actions requires appropriate regulatory frameworks (Fan et al., 2011; Ding et al., 2020; Wilson et al., 2011), promoting public acceptance and willingness (Anderson et al., 2012; Selma et al., 2014) and the techno-economic feasibility and implications (Al-Qayim et al., 2015; van der Spek et al., 2020).

Arguably, most interest has focussed on cost, techno-economic and environmental criteria to incentivise and support CCS deployment, with significant attention given to reducing investment risk, maximising emissions reduction and promotion of public/political acceptability. However, there is a knowledge gap in the literature in terms of the wider political economy consequences of attempting to balance the challenges of sustaining the value contributions of currently emissions-intensive industry with climate policy sustainability. Certainly, in the UK (the

first G7 nation where both national and devolved governments have legislated on mid-century net-zero goals), our experience as policy researchers suggests that this is the primary policy concern/barrier to CCS deployment (Turner et al., 2020). Thus, our contribution is to focus on applying multi-sector economy-wide scenario analysis to consider the potential consequences of rolling out even just the CO<sub>2</sub> capture element of CCS in an industrial context.

## 3. Material and methods

### 3.1. System-wide regional economic modelling

For the simulation analysis, we use AMOSENVI, a multi-sector system-wide computable general equilibrium (CGE) model of Scotland, a UK devolved region. A CGE approach is appropriate where responses to changes in prices and incomes that may result from competitiveness loss and/or policy action reallocate the burden of costs incurred in decarbonisation activity may be expected to impact how the economy adjusts to any disturbance. The model is calibrated on a social accounting matrix (SAM) that incorporates the 2015 input-output tables published by the Scottish Government. These are the most recent data available, which we take to reflect the real economy in the effective policy base year of 2020.

The focus on Scotland reflects the devolved government’s ambition to develop CCS and to deliver the first low/net-zero industrial cluster in the UK. While the devolved and national governments could take joint action in this regard, here we focus on the fact that the Scottish Government has sufficient fiscal power to allow consideration of several funding options for the introduction of carbon capture in Scottish industries. We take the chemicals industry as an example given its dominating presence at the Scottish Grangemouth cluster. A brief overview of those characteristics and assumptions of the model that are most relevant for the current application is provided below. Appendix A details the key elements of the specification required to run the scenarios set out in Section 3.2 and reported in Section 4 (see also Figus et al., 2018).

We adopt a model configuration that disaggregates the production side of the economy into thirty sectors. Three distinct chemicals industries are separately identified which is sufficient to enable a rigorous analysis of scenario outcomes (Appendix B). In the model, each sector minimises costs across labour, capital and a combination of domestically-produced and imported intermediates using a CES nested production function.

Domestic savings rates are determined as an exogenous share of household income. Investment is forward-looking, depending on exogenous depreciation and interest rates, set in extra-regional markets, and quadratic adjustment costs. This means that in each sector the actual capital stock gradually adjusts to its desired level, which is a function of sectoral output and relative input prices. Appendix A gives the precise formulation for the investment path calculation.

In the labour market, for the central case, wages are determined by an econometrically-parameterised real wage bargaining function where power shifts between firms and workers depending on changes in the unemployment rate (Blanchflower and Oswald, 2009).<sup>4</sup> The labour force is adjusted over time, upwards or downwards, by flow equilibrium inter-regional migration where changes in the relative wage and unemployment rates between the Scotland and the RUK determine the migration rate (Layard et al., 1991; Treyz et al., 1993). In the long-run, flow equilibrium inter-regional migration will lead to the original real wage being reinstated; with no assumed change in the RUK economy, there will be outmigration as long as Scottish real wages are below their initial value and immigration as long as they are above.

<sup>4</sup> Although we treat the labour market as unified, wage rates differ across sectors and move proportionately as the regional real wage rate adjusts through bargaining processes.

Scotland trades with two external (exogenous) regions, the rest of UK (RUK) and the rest of the world (ROW). The nominal price of the goods produced in external regions is fixed in all the scenarios and timeframes and this acts as the model numeraire. Both import and export demands in production sectors are sensitive to changes in relative prices between Scotland and the exogenous regions. This has important impacts on activity levels and the trade balance given changes in prices and competitiveness triggered by the introduction of carbon capture activity and any policy response. Our scenarios include consideration of the impacts of different degrees of openness by varying export price sensitivities.

Domestic household demand is also characterised as a CES nested function, and is sensitive to relative price changes across Scottish sectors and between domestic outputs and imports. Final household disposable expenditure is determined after the deduction of taxes and savings, recalling that we assume a fixed savings rate. In our scenarios, the key drivers of changes in household real incomes and purchasing power are earnings from employment in the production sector and taxes paid to government.

The Scottish Government is the primary government actor. It receives a block grant from UK central Government but has additional revenue raising and devolved spending powers. A range of endogenous revenue sources determines the public budget. However, we assume that the devolved government cannot run up a deficit through fiscal actions, imposing a balanced budget requirement when a subsidy is introduced, so that this must be funded through adjusting other government spending or raising revenues using mechanisms available to the devolved Scottish Government.<sup>5</sup>

### 3.2. Illustrative simulation strategy

All the simulations model the gradual introduction of carbon capture equipment in the Scottish chemicals industries over a 10 year period. Similar to the single ‘end of pipe’ technology treatment of CCS adopted in studies such as Li et al. (2017) and Thepkun et al. (2013), we assume that the carbon capture activity requires increased capital inputs to produce a given level of output. Based on informal information provided by Scottish chemical industry actors, the capital requirement is taken to increase by a “worse case” 50%. This is simulated as an exogenous 50% reduction in capital efficiency, introduced at a rate of 5% per year. To calibrate the results to the UK net-zero timetable we label the initial year of adoption as 2021, so that the capital efficiency reduction reaches 50% by 2030 (year 10). The model is then run on for an additional 40 years with no additional exogenous changes.

To isolate the impacts of these scenarios, we impose no factor productivity changes beyond those introduced directly by the exogenous ‘shocks’. Thus, endogenous changes to prices and incomes drive the adjustment process across the whole economy. Capital and labour supplies adjust through investment and migration processes, where the latter have a particularly important influence on outcomes in the regional economy setting through their impact on the labour market (Partridge and Rickman, 2010). Clearly, AMOSENVI is a simulation, rather than a forecasting, model and the simulations focus purely on the impact of CCS and the subsequent system-wide endogenous changes. In the first instance, we assume that the Scottish chemicals sector is the first in the wider UK industry landscape to adopt carbon capture.

#### 3.2.1. The basic ‘polluter pays’ scenario

The scenarios differ only in the way in which the CCS is financed. In all cases we assume that legislation requires the introduction of the

<sup>5</sup> One qualification we note with the balanced budget treatment in our model is that revenues must offset any existing budget deficit (in addition to the cost of the subsidy). However, this deficit is small in the base year so that impacts are negligible.

technology at the rate and over the time-scale outlined. In the polluter pays case there is no financial assistance from the government to affect the transition so that the additional capital costs are reflected in the price of industry output. In order to focus on chemical industry impacts – which are the industry and climate policy concern (i.e. avoiding ‘offshoring’ of activity and emissions) – we do not force a balanced budget in this scenario, but note that there would be additional negative impacts across the wider economy if this were the case.

#### 3.2.2. Public funding option 1: Reallocating existing government expenditure

Both public funding options considered involve a direct subsidy by the government to the chemicals industries that covers the cost of the additional capital requirement and maps to the gradual capital efficiency loss explained above. The subsidy is to offset the potential loss of competitiveness in the chemicals industries that the requirement to install and operate carbon capture equipment would involve. Under this first public funding option (assuming, as noted earlier, no contribution from the UK Government) the devolved government balances its budget by reducing its spending on other goods and services.

#### 3.2.3. Public funding option 2: Socialising costs through a direct income tax funded subsidy

In this simulation, an identical subsidy is introduced, but the government budget is balanced by increasing the rate of income tax paid by households, rather than any adjustment in existing public spending. Although in the AMOSENVI model income tax is levied at a fixed rate, because higher income households receive more earned income, the income tax incidence is progressive.

#### 3.2.4. Sensitivity analysis: Labour market assumptions and trade responses to relative price changes

One set of sensitivity analyses focusses on the labour market and tracks the impact of allowing a greater degree of wage flexibility in response to changes in labour demand. For this we run the same simulations but under additional, alternative labour market regimes. In one, the nominal wage is held fixed throughout the entire timeframe of our simulations. This implies that nominal wages are held at their RUK level and are impervious to changes in local (Scottish) labour demand and prices. In the second variant, we disallow inter-regional migration. This means that changes in Scottish labour demand will be fully reflected in changes in Scottish real wages, even in the long-run.

The second set of results identifies the impacts of varying the price elasticity of exports. In our central simulations in all three financing options, the elasticity of demand for all exports to RUK and ROW takes the value 2.0. The sensitivity analysis here focusses on the effect of varying the price elasticity of Scottish exports and in particular exports from the chemical industries in the polluter pays option. First, we attempt to replicate the implications of similar polluter pays policies being implemented in the RUK by reducing the export price elasticity faced by the Scottish chemical industries in the RUK market to almost zero. The reasoning is that if the price of RUK chemicals rise in line with those in Scotland, the competitiveness implications would be very low in that market. Indeed, such a scenario would be more relevant than what we set as our central case if there were a high degree of policy coordination and/or industry action to uptake carbon capture as a decarbonisation solution across UK regional clusters. On the other hand, if carbon capture were to be supported in any other ‘leader’ regional context (in the UK or other nations), the central case outcomes identified here for Scotland could provide more generic insight. Second, we simulate the impact of varying the price competitiveness in the chemical industries in ROW by varying the export price elasticity of Scottish chemical industries in that market. We do this in two contexts. In the first, the RUK markets are similarly price competitive. In the second, the elasticity in RUK is again set very low but that in ROW is allowed to vary across a wide range.



#### 4. Model outcomes: Analysis and discussion

Here we report the results of simulating the scenarios set out in Section 3 using the AMOSENVI CGE model of the Scottish economy. The model is used to consider the effects generated by the introduction of CCS to the operational processes of three Scottish chemicals industries - "Petrochemicals", "Other Chemicals" and "Inorganic Chemicals". We simulate this through a 10-year build up to a sustained 50% reduction in capital efficiency in these industries under the three different 'who pays' scenarios.<sup>6</sup>

The results for the impact on key industry, macro-economic and socio-economic variables are given in Table 1. These are expressed as percentage changes relative to base year, 2015, values, taken to apply in real terms at our starting point of 2020. These figures are shown for 2030 and 2050; 2030 is the point at which all CCS has been installed and 2050 the UK target date for reaching net zero. In fact the 2050 results are almost identical to the long-run results calculated where all endogenous variables have fully adjusted in response to the exogenous capital efficiency shocks. Therefore, when we discuss long-run results, these can be interpreted as 2050 results and vice versa.

##### 4.1. The 'polluter pays' scenario

The long-run impact of a reduction in the capital efficiency in the chemical industries will be a relative rise in the price of these commodities. Because the elasticity of substitution between capital and labour in the model is low, at 0.3, the inputs are closely complementary. This implies that a fall in the efficiency of capital will increase the capital intensity of production in these sectors. The increase in price will reduce demand, especially in export markets.

This is confirmed and quantified by the figures reported in column 3 of Table 1. In the long-run, prices in the three chemical sectors increase by between 4.2% and 7.2%, whilst their outputs fall by between 9.5% and 13.9%. Chemical industry employment is lower by 10.1% and exports by 11.4%. This contraction has supply chain implications and the

increase in their prices has more widespread competitive effects. The Scottish GDP therefore falls by 0.18% and the Consumer Price Index increases by 0.046%, with an associated fall in total employment and household expenditure of 0.086% and 0.047% respectively.

The sectoral disaggregation of impacts is shown in Fig. 1 which gives the absolute changes in Full Time Equivalent (FTE) employment. If we focus on the 2050 results, only in construction is there a (small) long-run increase, driven by increased investment in the more capital intensive chemical industries. There are reductions in all other sectors. In the combined chemical sectors, 606 jobs are lost but this only makes up just over 30% of the fall in total employment. The service sector loses a similar number of employees and the remaining 40% is spread across the range of other sectors with the wholesale and retail sectors, education and other manufacturing being relatively hard hit. Fig. 2 gives similar information, identifying the absolute change in real earnings. In this case the total reduction is just under £100 million but over 50% falls in the chemical sectors, emphasising their position as comparatively high wage sectors.

Fig. 3 shows the adjustment process as chemical sectors react to the negative capital efficiency shocks. The capital stock increases with a corresponding fall in employment and output, together with the gradual rise in the domestic price of chemicals. The cumulative exogenous negative efficiency shock reaches its maximum in 2030 and remain constant from that point. However, note that the capital in the chemical sectors is still adjusting and does not reach its long-run equilibrium value until around 2038. With the capital stock rising but the efficiency level stabilised, the price of chemical industry outputs registers a slight fall in the years after 2030, and employment and output a slight rise. However, adjustments are being made in other sectors which are less benign. Whilst chemical sectors are net investors, remember that output in other sectors is falling so that they are gradually disinvesting. Therefore, in aggregate by 2030 the Consumer Price Index is lower than its long-run level as are GDP and aggregate employment, though not earnings.

**Table 1**

Comparison of percentage changes in key macroeconomic and socio-economic indicators under different funding options (changes compared to base year values, export price elasticity 2 for all).

Year	Base (2015) values	Polluter pays		Public funding option 1		Public funding option 2	
		2030	2050	2030	2050	2030	2050
GDP (£million)	127,459	-0.168	-0.181	-0.143	-0.176	-0.213	-0.316
CPI (indexed to 1)	1	0.029	0.046	-0.017	0.000	0.051	0.106
Nominal wage pre-tax (indexed to 1)	1	0.006	0.046	-0.032	0.000	0.227	0.354
Real wage pre-tax (indexed to 1)	1	-0.023	0.000	-0.015	0.000	0.177	0.248
Imports (£million)	83,678	-0.051	-0.036	-0.143	-0.139	-0.175	-0.174
Exports (£million), of which	69,061	-0.345	-0.336	0.025	0.000	-0.090	-0.180
Chemical industry exports	1,678	-13.038	-11.379	0.017	0.000	-0.081	-0.154
Total Employment (FTE), of which	2,301,096	-0.063	-0.086	-0.149	-0.181	-0.254	-0.358
Chemical industry employment	6,002	-11.543	-10.090	-0.001	-0.027	-0.183	-0.295
Real Earnings - employment (£million)	72,594	-0.141	-0.135	-0.167	-0.185	-0.067	-0.099
Real Earnings per employee (£)	31,547	-0.079	-0.049	-0.018	-0.003	0.187	0.260
Productivity (£ GDP per FTE)	55,391	-0.105	-0.095	0.007	0.005	0.041	0.042
Real Household Expenditure (£million)	87,439	-0.046	-0.047	-0.102	-0.112	-0.295	-0.356
Price of 'Petrochemicals' output	1	7.368	6.296	-0.009	0.000	0.044	0.083
Price of 'Other Chemicals' output	1	8.149	7.161	-0.008	0.000	0.036	0.069
Price of 'Inorganic Chemicals' output	1	4.932	4.208	-0.007	0.000	0.033	0.061
'Petrochemicals' output	1,353.44	-12.547	-10.863	-0.004	-0.023	-0.125	-0.207
'Other Chemicals' output	527.91	-15.671	-13.922	-0.014	-0.034	-0.130	-0.215
'Inorganic Chemicals' output	309.13	-10.974	-9.461	-0.007	-0.026	-0.128	-0.211

<sup>6</sup> While not reported here, the broad qualitative pattern of outcomes discussed here is unchanged with a smaller shock. Additional simulations also show that allowing the contraction in capital efficiency to build in 10% increments to 2025 simply accelerates the adjustment to the new long-run economy-wide equilibrium.

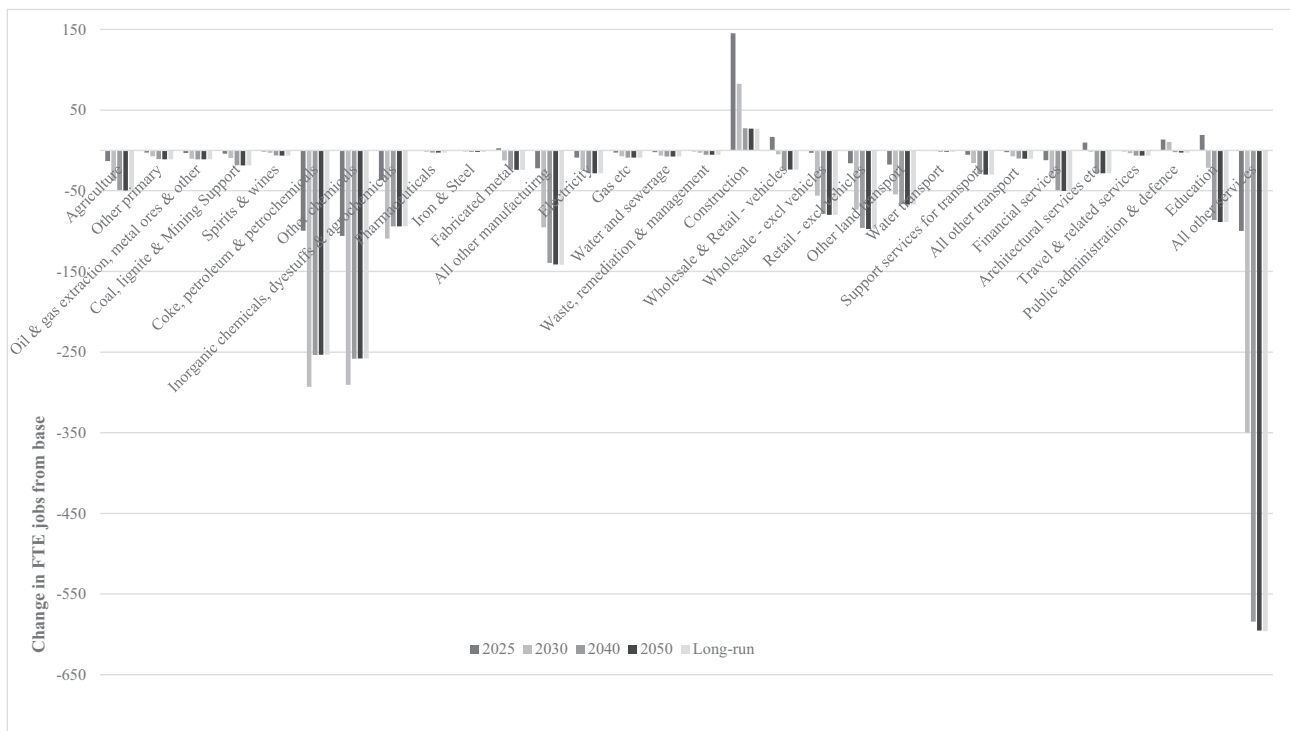


Fig. 1. Sectoral distribution of FTE employment changes - 'polluter pays' for operational capture costs.

4.2. Public funding option 1: Reallocating existing government expenditure

It is clear that under a regime in which the polluter pays, the combined chemical sector fails as a strong driver of industrial expansion. Simulating with our default parameter values there is a £190.9 million

long-run fall in chemical exports and a decline in all the primary macroeconomic and socio-economic indicators. We therefore investigate the impact of a policy intervention where a subsidy is paid to neutralise the negative competitiveness effects of the requirement to implement CCS. The subsidy is introduced solely to offset any capital efficiency loss associated with unilateral decarbonisation activity, which could

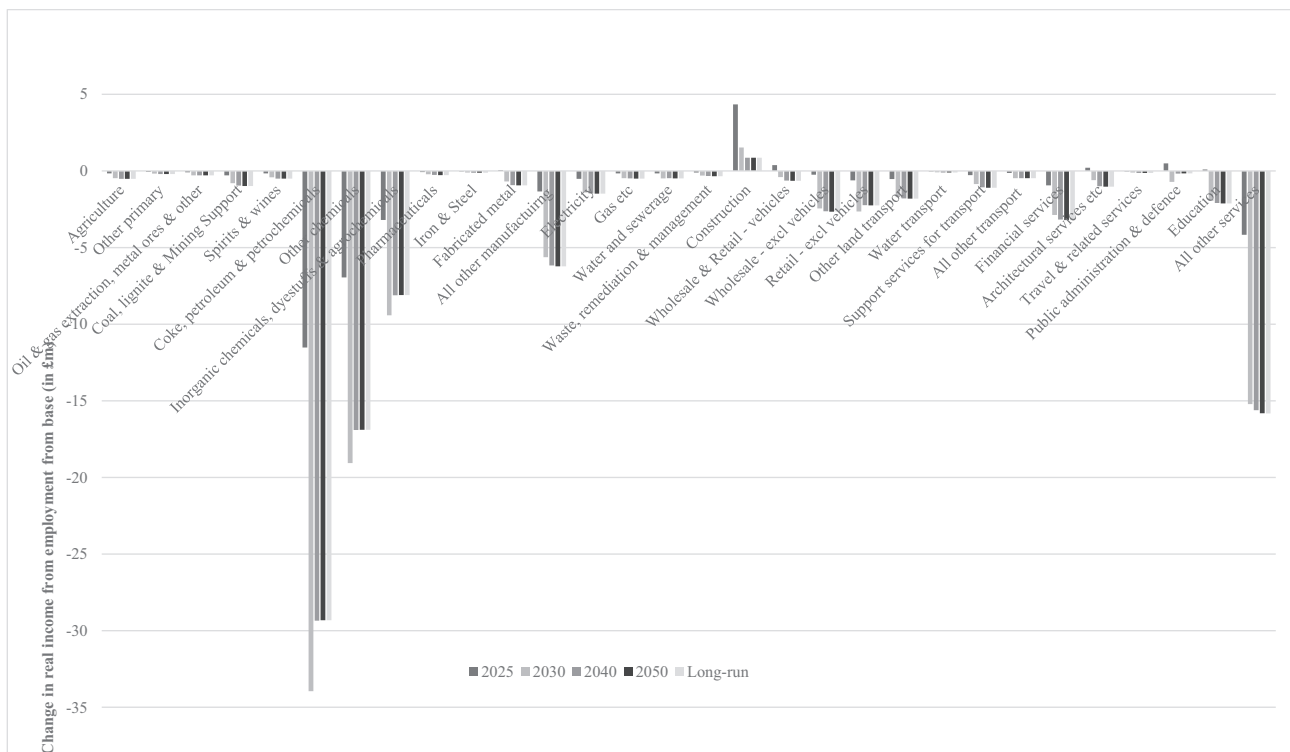


Fig. 2. Sectoral distribution of earnings (£m) changes - 'polluter pays' for operational capture costs.

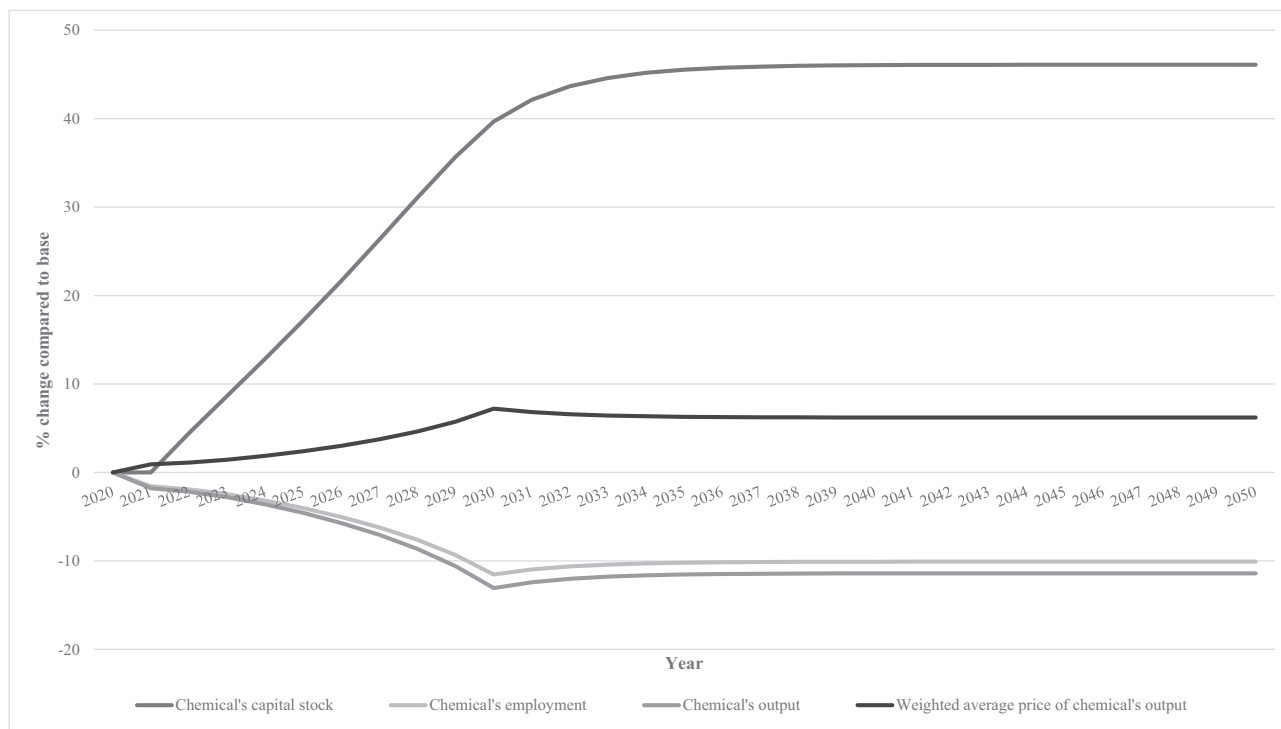


Fig. 3. Evolution of percentage changes in output price, employment, real earnings and output in Scottish chemicals industry due to carbon capture ('polluter pays' scenario, central case).

constitute the basis for exemption from EU State Aid rules. While the subsidy instrument may require/involve action at national UK level, within the current devolution settlement the Scottish Government does have the means to fund interventions by either adjusting the allocation of public spending or raising income tax as discussed in Section 3. The size of the subsidy, and the time path of its payments, is given in the first row of Table 2.

In Table 1, the entries in data columns 4 and 5 give simulation results where the budget is balanced through a corresponding reduction in public expenditure on goods and services. They present the 2030 and 2050 percentage changes in the values of key variables under this scenario. Focussing on the 2050 values, note that the subsidy is wholly effective at neutralising the negative competitiveness effects in the chemical industries; in the long-run the exogenous efficiency shock causes no price variation in this simulation. The nominal wage, the CPI, the real wage and the price of the output of all the chemical industries register zero change, implying that all the economic effects take the form of quantity adjustments.

In all sectors, the zero change in price competitiveness leaves exports unaltered. The negative impact is therefore solely driven by the demand implications of the replacement of public consumption by additional investment in the chemical sectors. This shift in demand has negative effects on economic activity in general because of the relative size of the local economic multiplier associated with public consumption and investment. The multiplier value reflects the strength of local supply chain linkages and induced household consumption generated primarily by changes in wage income. These links are much stronger for public

expenditure than investment. This means that the adverse demand effects of lower public expenditure are greater than the positive impact of higher investment demand.

This is reflected in long-run reductions in GDP, employment and real earnings of 0.18% and a fall of 0.11% in real household expenditure. Note also that there is a change in impact across sectors, which is reported in Fig. 4. The relatively large percentage falls in the output of the labour intensive public services and education sectors mean that whilst the long-run reduction in GDP is similar to that in the 'polluter pays' case, the reduction in employment and real household expenditure is higher.

#### 4.3. Public funding option 2: Adjusting income tax rates

The 2030 and 2050 results where the subsidy is financed through raising the income tax rate are given in columns 6 and 7 of Table 1. The analysis in this case is a little more complex because the financing has supply-side implications. In the long-run, the operation of flow equilibrium migration, together with any real wage determining bargaining process, leads to the reinstatement of the initial post-tax real wage. In this context, this means that any increase in the tax rate produces a corresponding rise in the pre-tax real wage. The cost of labour paid by industry grows, increasing CPI and therefore further increasing the nominal wage as the interaction between the bargaining and migration functions lead to the long-run maintenance of the real post-tax wage.

The subsequent fall in competitiveness across all industries leads to long-run reductions in GDP, employment and household expenditure of

Table 2

Base-year values and absolute changes in government expenditure and income tax to cover the subsidy to offset operational carbon capture costs (export price elasticity 2 for all).

Year	Base Values	2025	2030	2040	2050	Long-run
Subsidy (£million)	0	69.46	138.92	138.92	138.92	138.92
Government expenditure (£million)	33,993.40	-96.99	-191.74	-204.87	-206.10	-206.24
Income tax (£million)	24,838.50	90.08	201.46	238.11	244.27	245.57

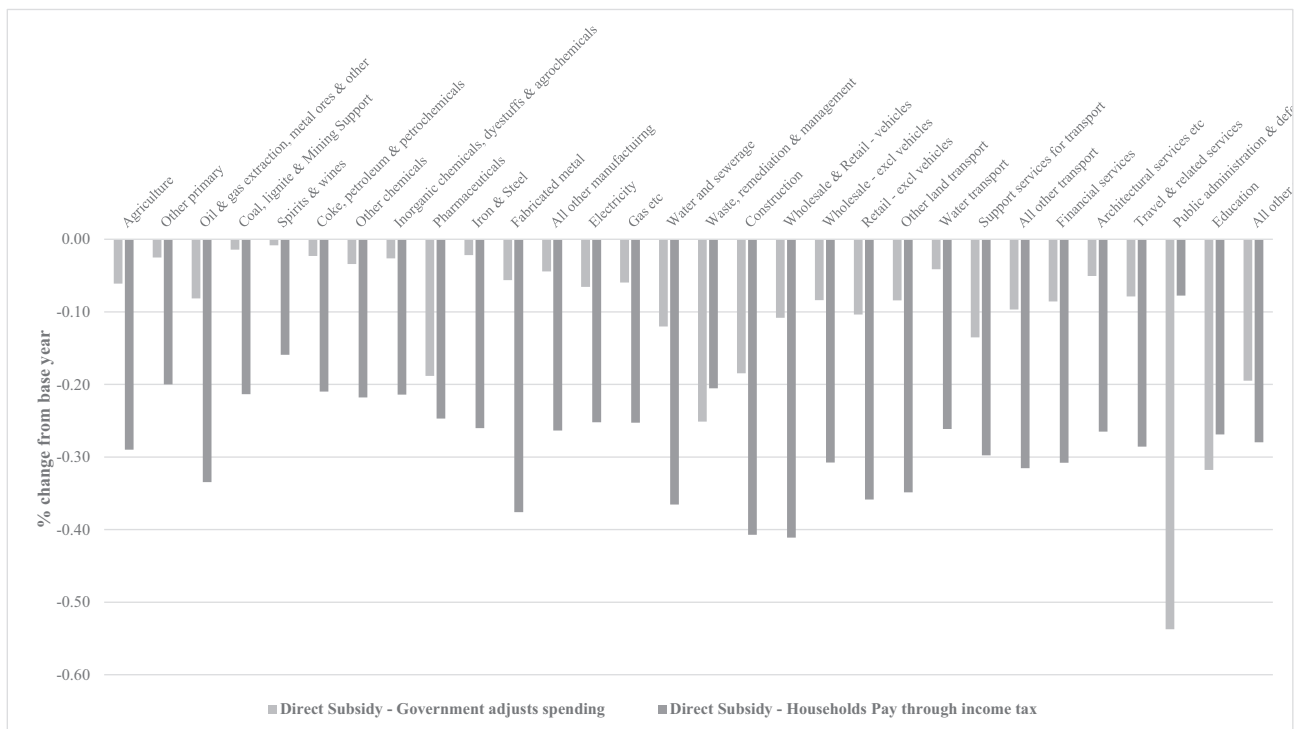


Fig. 4. Long-run percentage changes in total output per sector due to direct subsidisation of carbon capture (public funding options 1 & 2).

0.32%, 0.36% and 0.36% respectively. Fig. 4 gives the long-run percentage output changes, disaggregated by sector. Notice that in this case the impact is spread widely across all industries. The negative impact is greater than in public funding option 1 in all sectors apart from public administration, education and waste management.

Table 2 gives the time paths of the subsidy payments; the reduction in government expenditure for public funding option 1; and the increase in income tax take for option 2. Note that in both options, the change in the public consumption and income tax take is 50 to 75% higher than the subsidy. This is to compensate for the impact of the lower level of economic activity on other endogenous elements of the government budget. Although in all the simulation the bulk of the economic adjustment to the introduction of CCS has occurred by 2030, as is clear from Tables 1 and 2 and Fig. 3, there are still some changes occurring after that. This is more evident where the income tax rate is adjusting to meet the subsidy requirements. In this simulation the interaction between migration, wage setting and investment is more protracted.

## 5. Sensitivity

### 5.1. Labour market closures

The simulation results are potentially sensitive to the specification of the labour market. In the central case we use a bargaining function to set the real wage and a flow equilibrium migration function to determine the labour force. With this combination, although the real wage is flexible in the short and medium terms, in the long run it is fixed. In our first set of sensitivity tests, we run the simulations for the three funding options with two additional labour market set ups. In one, there is a fixed nominal wage but the flow equilibrium migration function still operates.<sup>7</sup> This implies all nominal wage flexibility is suppressed. In the second, migration is turned off, thereby fixing the labour force. This

<sup>7</sup> Whether the migration function is activated or not has, in fact, no impact in the results where the nominal wage is fixed apart from reducing the long-run unemployment rate by allowing outmigration.

increases wage variation as migration no longer works to eliminate movements in the real take-home wage.

The long-run results for all the key endogenous variables are given in Table 3. The information is shown in three sets of columns which represent the three financing alternatives: 'polluter pays' and the public funding options 1 and 2. In each set figures are given for: the central case; the fixed nominal wage; and the fixed labour supply, labour market closures respectively. It is important to note from Table 1 that for all the different funding options, with the central labour market assumptions the nominal wage is constant or increasing and the employment level, and therefore the labour force, falls.<sup>8</sup> In all cases imposing the fixed nominal wage will keep constant or improve the competitiveness of the economy. Similarly where outmigration is not possible, wages will fall relative to the comparable central case. With no migration, the economy will therefore be more competitive than the central case and if nominal wages fall it will be more competitive than the fixed nominal wage.

The results are shown clearly in Table 3; in all cases the nominal wage falls with a fixed labour supply. Therefore, the fall in GDP under all funding options is greater in the central case, less when the nominal wage is fixed and least of all when outmigration is barred. The only exception is that under the funding option 1, where public consumption is reduced, the central and fixed nominal wage outcomes are the same. Again focussing on GDP, changing the labour market characteristics does change the ordering of the funding options. With the central assumption and a fixed labour force, public funding option 1 has the lowest fall in GDP. But with a fixed nominal wage this shifts to public funding 2. However, household expenditure falls least under the polluter pays option with all labour market closures.

### 5.2. Export price sensitivity

The key motivation for subsidising the chemical sectors is to neutralise the negative competitiveness effects for the Scottish chemical

<sup>8</sup> The labour force must fall because in long-run equilibrium the unemployment rate returns to its initial level.



**Table 3**  
Comparison of long-run percentage changes in key macroeconomic and socio-economic indicators under different labour market closures (compared to base year values, RUK & ROW export price elasticity 2).

Year	Base (2015) values	Polluter pays			Public funding option 1			Public funding option 2		
		Central case (wage bargaining & migration on)	Fixed nominal wage, migration on	Wage bargaining, migration off	Central case (wage bargaining & migration on)	Fixed nominal wage, migration on	Wage bargaining, migration off	Central case (wage bargaining & migration on)	Fixed nominal wage, migration on	Wage bargaining, migration off
GDP (£million)	127,459	-0.181	-0.158	-0.137	-0.176	-0.176	-0.070	-0.319	-0.101	-0.097
CPI (indexed to 1)	1	0.046	0.032	0.020	0.000	0.000	-0.046	0.108	0.000	-0.002
Nominal wage pre-tax (indexed to 1)	1	0.046	0.000	-0.041	0.000	0.000	-0.154	0.358	0.000	-0.006
Real wage pre-tax (indexed to 1)	1	0.000	-0.032	-0.061	0.000	0.000	-0.107	0.250	0.000	-0.004
Imports (£million)	83,678	-0.036	-0.040	-0.044	-0.139	-0.139	-0.130	-0.174	-0.150	-0.149
Exports (£million), of which	69,061	-0.336	-0.312	-0.291	0.000	0.000	0.079	-0.183	0.000	0.003
Chemical industry exports	1,678	-11.379	-11.364	-11.350	0.000	0.000	0.067	-0.156	0.000	0.003
Total Employment (FTE), of which	2,301,096	-0.086	-0.059	-0.035	-0.181	-0.181	-0.061	-0.361	-0.109	-0.105
Chemical industry employment	6,002	-10.090	-10.062	-10.038	-0.027	-0.027	0.087	-0.298	-0.031	-0.027
Real Earnings - employment (£million)	72,594	-0.135	-0.139	-0.143	-0.185	-0.185	-0.169	-0.100	-0.098	-0.097
Real Earnings per employee (£)	31,547	-0.049	-0.081	-0.109	-0.003	-0.003	-0.108	0.262	0.011	0.007
Productivity (£ GDP per FTE)	55,391	-0.095	-0.099	-0.103	0.005	0.005	-0.009	0.042	0.008	0.007
Real Household Expenditure (£million)	87,439	-0.047	-0.047	-0.048	-0.112	-0.112	-0.095	-0.358	-0.262	-0.261
Price of 'Petrochemicals' output	1	6.296	6.286	6.277	0.000	0.000	-0.036	0.084	0.000	-0.001
Price of 'Other Chemicals' output	1	7.161	7.154	7.147	0.000	0.000	-0.030	0.070	0.000	-0.001
Price of 'Inorganic Chemicals' output	1	4.208	4.201	4.194	0.000	0.000	-0.027	0.062	0.000	-0.001
'Petrochemicals' output	1,353.44	-10.863	-10.845	-10.830	-0.023	-0.023	0.053	-0.210	-0.030	-0.027
'Other Chemicals' output	527.91	-13.922	-13.906	-13.891	-0.034	-0.034	0.046	-0.218	-0.033	-0.029
'Inorganic Chemicals' output	309.13	-9.461	-9.443	-9.427	-0.026	-0.026	0.052	-0.214	-0.030	-0.027

**Table 4**

Comparison of long-run percentage changes in key macroeconomic and socio-economic indicators under different export price elasticities (changes compared to base year values, 'polluter pays' scenario).

Year	Base (2015) values	Chemicals RUK 0.07, ROW 0.5	Chemicals RUK 0.07, ROW 2	Chemicals RUK 0.07, ROW 3	Chemicals RUK 0.07, ROW 5	Chemicals RUK 0.07, ROW 10
GDP (£million)	127,459	-0.065	-0.131	-0.173	-0.208	-0.308
CPI (indexed to 1)	1	0.046	0.046	0.046	0.047	0.047
Nominal wage pre-tax (indexed to 1)	1	0.046	0.046	0.046	0.047	0.047
Real wage pre-tax (indexed to 1)	1	0.000	0.000	0.000	0.000	0.000
Imports (£million)	83,678	0.119	0.036	-0.017	-0.071	-0.211
Exports (£million), of which	69,061	-0.057	-0.209	-0.305	-0.398	-0.647
Chemical industry exports	1,678	-1.756	-6.167	-8.903	-13.919	-24.145
Total Employment (FTE), of which	2,301,096	0.001	-0.052	-0.086	-0.106	-0.177
Chemical industry employment	6,002	-2.553	-6.259	-8.558	-12.766	-21.353
Real Earnings - employment (£million)	72,594	-0.009	-0.080	-0.125	-0.164	-0.276
Real Earnings per employee (£)	31,547	-0.011	-0.028	-0.039	-0.058	-0.098
Productivity (£ GDP per FTE)	55,391	-0.067	-0.080	-0.088	-0.102	-0.131
Real Household Expenditure (£million)	87,439	0.032	-0.012	-0.040	-0.065	-0.135
Price of 'Petrochemicals' output	1	6.279	6.287	6.292	6.301	6.319
Price of 'Other Chemicals' output	1	7.089	7.129	7.154	7.200	7.298
Price of 'Inorganic Chemicals' output	1	4.175	4.190	4.199	4.217	4.255
'Petrochemicals' output	1,353.44	-2.770	-5.931	-7.887	-11.457	-18.711
'Other Chemicals' output	527.91	-6.030	-10.510	-13.272	-18.282	-28.266
'Inorganic Chemicals' output	309.13	-4.616	-7.863	-9.926	-13.801	-22.237

sectors imposed by their adoption of CCS. One rationale is that given that the Scottish Government is committed to zero carbon, the potential role of CCS in these sectors is receiving significant policy and industry attention alongside other, inevitably costly, decarbonisation options. However, if the introduction of CCS leads to these sectors transferring a significant amount of their activity to other countries, this would prove a rather ineffective climate policy.

Moreover, if the Scottish Government believes that subsequently other countries will choose, or will be required, to adopt CCS, then retaining a healthy level of activity in these sectors using CCS technology will give Scotland a competitive advantage at that point. This underpins the notion of decarbonised chemical production as a growth sector. In the simulations where the subsidy is in place, the price of chemicals is unchanged. This means that the results for both public funding options are completely insensitive to varying the export elasticity. However, in the polluter pays case, the impact on these sectors proves to be very sensitive to these demand parameters, which also act in the model as a measure of the degree to which the chemical companies can shift production to sites outwith Scotland. The higher the export elasticity the larger the fall in output in the chemical sectors and all measures of aggregate economic activity as a whole.

There is a second issue concerning the elasticity of demand for chemical exports. If zero carbon is a UK-wide policy objective and if the introduction of CCS is necessary for zero carbon, then in the RUK market Scottish exports from the chemical sectors should not face increased price competition. We therefore run a range of simulations where the elasticity of demand for RUK exports is reduced to 0.07, the lowest for which the model will solve. We then vary the ROW value around the central value of 2.0 and the results are reported in Table 4 and Figs. 5 and 6.<sup>9</sup>

These results in column 3 of Table 4 show that with the central value for the ROW elasticity of 2.0, reducing the RUK elasticity value to 0.07

<sup>9</sup> The results for sensitivity simulations where the RUK and ROW export demand take the same elasticities are given in Table C.1 and Figs. C.1 and C.2 in Appendix C.

lowers the reduction in GDP, employment and household consumption but there are still large declines of 5.9%, 10.5% and 7.9% in the outputs of the three target chemical sectors. However, these figures are clearly sensitive to changes in the ROW elasticity which might be much higher. Increasing its value to 5.0 gives a reduction in the output of the chemical sectors between 11.5% and 18.3%; raising the ROW export elasticity value to 10 increases these figures to 18.7% and 28.3%. These results are illustrated in Fig. 5. As shown in Table 4 and Fig. 6, the increased reductions in Scottish chemicals output is accompanied by larger falls in Scottish GDP, employment and real earnings as the ROW elasticity value rises.

## 6. Conclusions

We have presented an economy-wide analysis how the competitiveness of regional manufacturing activities, and, consequently, economic activity more generally might be impacted if costly carbon capture requirements are imposed to realise national UK and devolved Scottish Government ambitions to decarbonise regional industry clusters. We address the question of whether potential industry and wider economy losses underpin a case for subsidising and socialising costs on both domestic and international climate policy grounds, to achieve domestic emissions reductions and prevent offshoring of emissions, jobs and GDP. We focus on the case of the Scottish chemicals industries and the regional economic impacts that the devolved Scottish Government are likely to be most concerned with in considering whether to use fiscal powers at their disposal to subsidise capture activity, either through reallocating public spending or increasing income taxes.

Our results show that the extent of losses under a polluter pays approach are very much dependent on the extent to which the impact of additional operating capital costs on industry output prices affects the competitiveness of the Scottish industry in wider UK and global markets. Thus, the implied value of subsidy action, which involves trade-offs in terms of GDP, employment and earnings losses in other parts of the Scottish economy, very much depends on the extent to which potential trade responses can be anticipated. In turn, the extent of potential costs

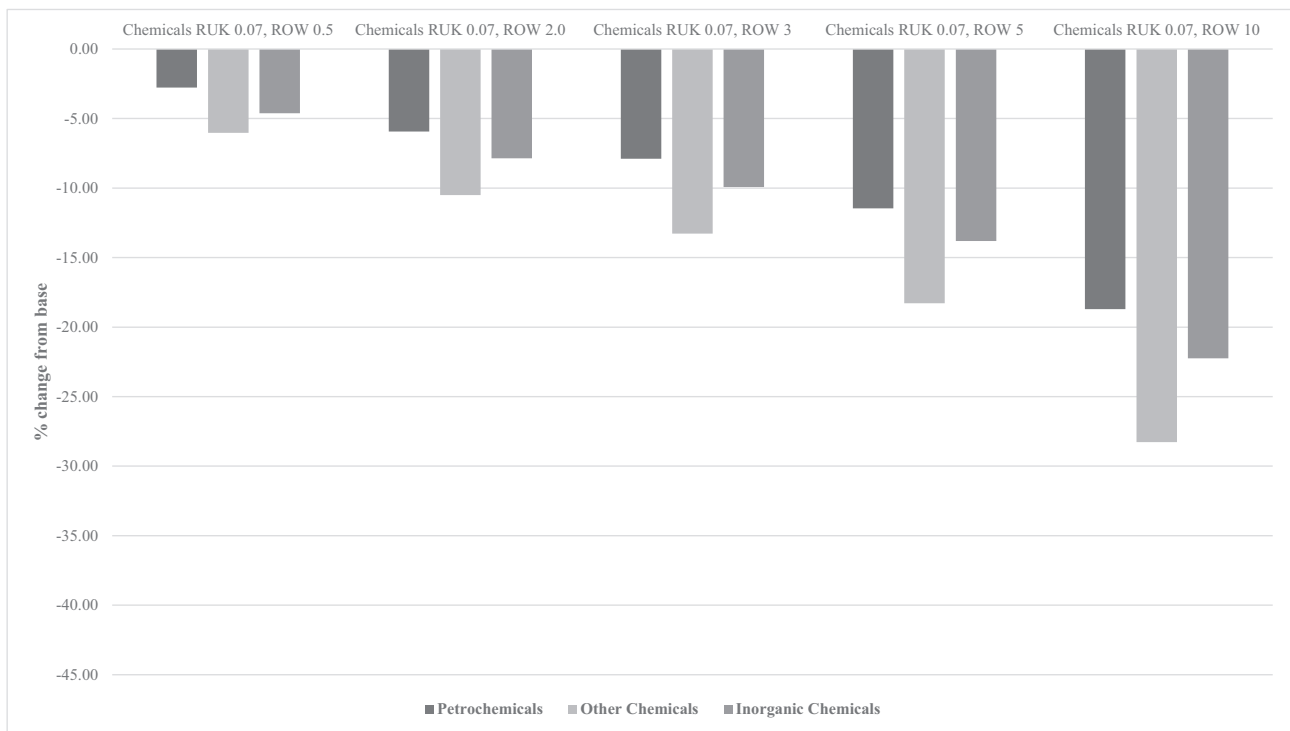


Fig. 5. Comparison of percentage changes in long-run output in Scottish chemicals industries due to different export price elasticities ('polluter pays' scenario).

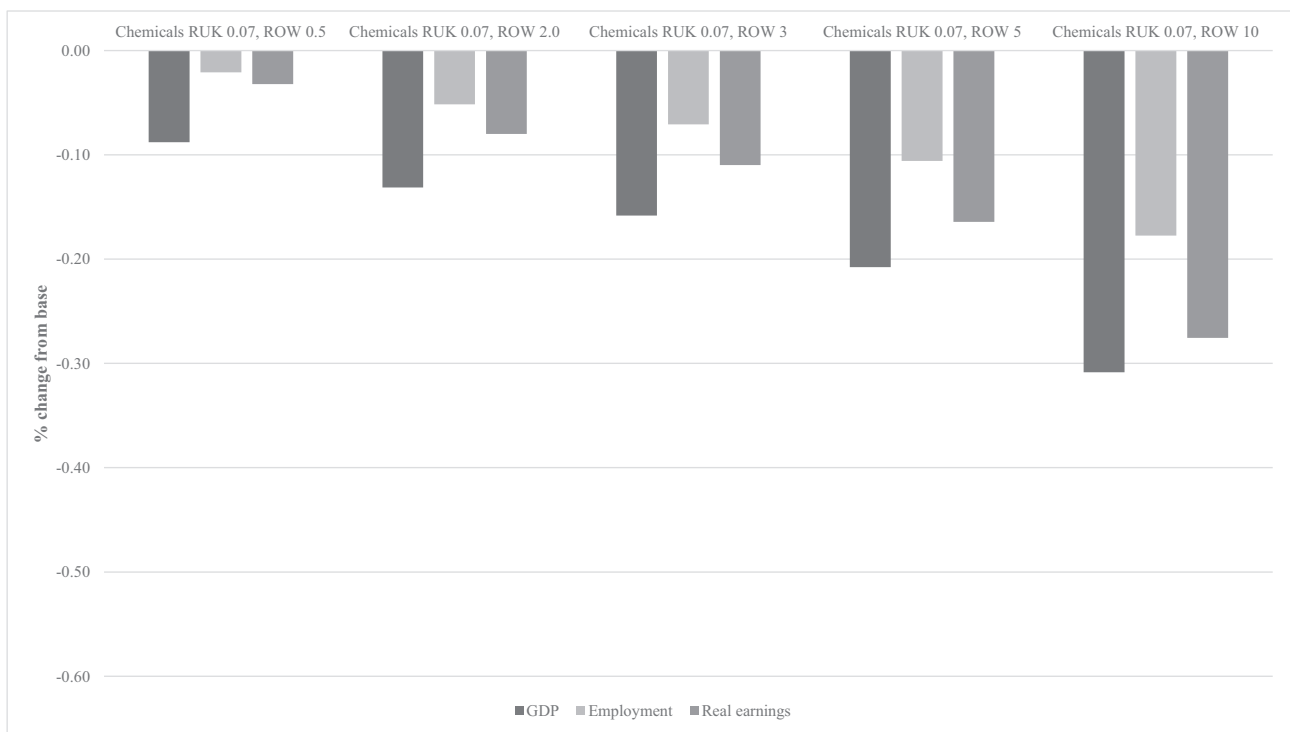


Fig. 6. Comparison of percentage changes in GDP, employment and real earnings due to different export price elasticities ('polluter pays' scenario).

across different parts of the economy under all scenarios is dependent on how regional labour markets respond to any changes in wage and unemployment rates and the degree of price sensitivity of exports of Scottish chemicals to the rest of the world.

The critical outcome emerging from our CGE analyses is that the economy is likely to contract regardless of 'who pays', with this being a

question of the extent and distribution of net losses. Thus, where the economy is likely to respond to price and income effects in the types of ways simulated here, the key policy implication emerging is the need to identify and enable solutions that allow the challenging, but likely essential, implementation of industrial carbon capture in a manner where the distribution of costs is acceptable to society. If not, there is a

need to investigate how undesirable impacts could be offset, or compensated. The most direct challenge for CCS in this regard is whether the deployment of full chain CCS could potentially generate sufficient GDP, income and revenue to justify policy action to protect the competitiveness of capturing firms, in addition to a range of other likely demands on public resources in supporting infrastructure and regulatory requirements. Such questions are of particular strategic policy interest in Scotland, where existing offshore and supply chain capacity associated with the oil and gas industry would be crucial in enabling CO<sub>2</sub> transport and storage.

### Data statement

The model used in this study is calibrated using a 2015 Scottish Social Accounting Matrix (SAM) developed for this project. The SAM is publically available at this address: <https://doi.org/10.15129/11baf0c3-eeca-41e7-9939-a31964062a0e>

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2021.106978>.

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