# Is there a tension between 'green growth' and regional 'levelling up'? Impacts of introducing an infrastructure-intensive carbon transport and storage industry to service the UK's regional manufacturing clusters

By Karen Turner*[a], Julia Race[b], Oluwafisayo Alabi[a], Christian Calvillo[a], Antonios Katris[a] and Kim Swales[c]

a. Centre for Energy Policy, School of Government and Public Policy, University of Strathclyde, Glasgow, United Kingdom

b. Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, United Kingdom

c. Fraser of Allander Institute, Department of Economics, University of Strathclyde, Glasgow, United Kingdom.

* Corresponding author: Karen Turner, McCance Building, 16 Richmond Street, Glasgow, G1 1XQ, UK; email karen.turner@strath.ac.uk; tel 00 44 (0) 141 548 3198

## ACKNOWLEDGEMENT AND DATA STATEMENT

The research reported here has been supported by the Bellona Foundation, with funding from the Children's Investment Fund Foundation (CIFF), building on earlier work supported by a Flexible Fund Project of the UK Carbon Capture and Storage Research Centre (UKCCSRC, EPSRC Grant ref: EP/K000446/2). Karen Turner also acknowledges the support of the Research Council of Norway via the PLATON project led by CICERO, Oslo.

The CGE model used in this study is calibrated using a 2016 UK Social Accounting Matrix (SAM) developed for this project, publicly available at: https://doi.org/10.15129/ad64a94c-152d-4ec7-a3a5-4e4a13576a3a.

**ABSTRACT**

The UK Industrial Decarbonisation Strategy identifies carbon capture and storage (CCS) as a route to decarbonising regional industry clusters while safeguarding supported jobs and income. The potential for carbon capture in these clusters, together with offshore and supply chain capability developed in the oil and gas industry, provides the foundation for a new regional $CO_2$ Transport and Storage (T&S) industry. The UK Government has already identified policy challenges around the probable requirement to initially oversize the indivisible T&S infrastructure, to lower unit costs and build user confidence. One key issue is guaranteeing demand for the T&S industry output and how any public intervention may be funded, with potential wider economy multiplier effects identified as a source of benefit to offset costs, and a route to helping deliver wider 'Green Growth' and regional 'levelling up' agendas. Here, we develop a CGE model of the UK economy through scenarios involving the staged infrastructure investment required for the new T&S sector. We consider the potential direct and economy-wide impacts of introducing a T&S industry, where government guarantees demand for output but can recover costs from households or emitters. We find that the need to recover costs, particularly in a supply constrained economy, will offset new industry multiplier effects. While establishing that a T&S industry could deliver regional and wider economy gains, the aim of moving to 'polluter pays' approach poses a risk damaging the industrial cluster activity that policymakers look to CCS to safeguard, with wider economy impacts potentially concentrated in host regions.

**Keywords:** CGE models; carbon capture and storage; economy-wide impacts; industrial decarbonisation; new industry development; regional industry clusters; competitiveness.

## 1. Introduction

This paper develops a multi-sector economy-wide computable general equilibrium (CGE) model of the UK economy to investigate the impacts of introducing a new CO2 Transport and Storage (T&S) sector. This sector supplies regional capacity to support decarbonisation of industrial clusters across the UK mainland (England, Scotland and Wales). We consider key issues associated with the introduction of such a new sector; in particular, the implications of its infrastructure intensity, with emphasis on the likely need for early/upfront investment and action to guarantee demand for the initial capacity. We examine the challenges of funding the sector and especially moving to a 'polluter pays' approach at least in the medium term (BEIS, 2021a). This could undermine the notion that T&S could contribute to UK Green Growth. It also potentially conflicts with the UK Government's 'levelling up' agenda in the regions where the main cluster activity is located (PMO, 2021).

We build on existing works on the difficulties encountered in introducing new sectors providing emissions reducing services in input-output (Leontief, 1970; Schäfer & Stahmer, 1989) and/or CGE modelling frameworks (e.g. Nestor & Pasurka, 1995; Phimister & Roberts, 2017). We also draw on an extensive literature that considers the economic problems posed by CCS as a decarbonisation solution (see Turner et al., 2021, for a review). These include works with particular focus on the challenges of enabling the carbon capture element of CCS within polluting industries (e.g. Liang et al., 2010). We also acknowledge, but do not address here, other social and decision-making concerns around CCS (e.g. see Cuppen et al., 2015), together with regional impacts and planning issues for low carbon transition actions more generally (see Balta-Ozkan et al., 2015, for a review).

We judge this to be an important early contribution in modelling impacts of new sectors servicing decarbonisation agendas. To our knowledge, there are no previous works focussing on the policy, and associated general equilibrium modelling, challenges of introducing the new infrastructure intensive industry implied by T&S for CCS in an economy-wide setting. Moreover, the paper provides more generic insights relevant to the low carbon/net zero transition challenge such as creating hydrogen networks and/or increased electrification to decarbonise heat. That is, around the need to create new capacity in contexts where demand levels and sources, production conditions, pricing etc. for new 'low carbon' industry across different regional locations and timeframes are unknown and/or challenging, and where significant public support may be required to ensure utilisation of capacity and reduce risk for private actors.

## 2. Background and context

A number of nations, such as the Netherlands, Norway and the UK, have the potential to repurpose skills and infrastructure developed through existing oil and gas industries to transport CO2 to offshore geological storage sites. These countries are currently exploring the development of carbon capture and storage (CCS) deep carbon emissions reduction and transition solution particularly for emissions intensive industries. In the UK and the Netherlands, this aligns with large-scale domestic capture demand residing within regional manufacturing clusters. Norway has a smaller industry capture base but capacity to develop an export-intensive CO2 T&S sector (SINTEF, 2018). This would potentially link to $CO_2$ transport network capability emerging in the Netherlands, where offshore storage capacity is limited. For example, the pilot CCS project at the international industrial hub of the Port of Rotterdam (Porthos, 2019) focuses not only on large-scale domestic capture but also on

developing a conduit to North Sea storage for $CO_2$ transported from regional clusters in various European nations (European Commission, 2021).

In the UK, an ‘Industrial Clusters mission’ (BEIS 2019), together with the evolving industrial and linked ‘green growth’ strategies, focuses on six regional industry clusters across England, Scotland and Wales (BEIS, 2017, 2018, 2021b; HM Government, 2020; HM Treasury, 2021). Delivery of one net zero and four low carbon clusters by 2030/2040 is considered necessary to be consistent with the UK’s ‘net zero’ (territorial emissions generation) commitments (UK Legislation, 2019). The role of CCS is prominent in current policy development. CCS would link regional industrial cluster activity to offshore storage sites through pipelines and/or shipping. For example, a CCUS Infrastructure Fund will support sequenced investment and deployment of $CO_2$ T&S capability and capacity in different sites off the Scottish (east) and English (east and west) coasts (BEIS 2021c). These will service proximate capture activity within industry clusters and other emission sources in the three mainland nations (BEIS, 2021a). It is envisaged that the initial linked proximate T&S capacity and capture activity sets the foundations for a more integrated future expansion to the UK carbon network. This would act to enable capture at industry clusters not involved in the initial sequencing, and for sequestration capacity to be utilised in different ways (potentially including export of T&S services to capturers in other nations).

In earlier policy debate around CCS, much attention concentrated on project economics and costs per tonne of $CO_2$ capture and sequestration (Budinis et al, 2018; IEA, 2016). However, the economic and industrial policy challenge goes beyond this largely technical focus,

particularly where public support may be required (IEAGHG, 2020).[1] For example, the UK policy proposition would involve front-loading public support for CCS programmes in two phases, each involving up to two regional clusters and linked T&S capacity, to deploy by 2025 and 2030 respectively (BEIS, 2021a) in order to help meet the Industrial Decarbonisation Mission's 2030/40 targets. Policy concern in this regard lies in the broader challenge of building user confidence and reducing unit costs over time in the context of a new industry where the indivisibility accompanying capital-intensive infrastructure may lead to initial oversizing of capacity. This brings two specific challenges. First, how can demand for new T&S industry output be guaranteed to ensure the required infrastructure investment? Second, where government acts to provide such a guarantee, how are the costs of doing to be ultimately recovered?

Some useful and fundamental research questions emerge concerning the trade-offs involved in the development of national CCS capacity via a build-up servicing regional sequestration needs. What regional and national impacts on employment and other aspects of economic activity might emerge in different timeframes from establishing and operating a new T&S industry? What are the macroeconomic and distribution impacts of government guaranteeing demand for an initially over-sized sector under different funding approaches?

Here we develop an existing computable general equilibrium (CGE) model of the UK economy, UKENVI, to specify scenarios for investment in, and the operation of, a new T&S industry where regional capacity is linked to proximate emissions. We consider this sector as sharing characteristics of the nation's existing oil and gas industry, but requiring investment

[1] Similar comments apply to the wider social and societal challenge of climate-centred policy (Shove, 2010)

in new, and potentially initially oversized, capacity to deliver T&S services to four of the largest regional industry clusters. The investment scenarios reflect (but do not pre-empt) the UK Government's current 'cluster sequencing' approach (BEIS, 2021a).

We investigate the direct regional, and indirect economy-wide, employment and value-added impacts of delivering an initially publicly supported T&S industry. The type of support studied involves either government's financing a deficit or by socialising costs through a lump sum transfer from UK households. These options are compared to adopting a user or 'polluter pays' model at least in the medium term. We explore how wage flexibility in labour markets limits both the possible positive and negative impacts of the introduction of T&S. International trade responses to changes in the competitiveness of capture industries, largely based in the regional clusters linked to the new T&S industry, are the key drivers of the outcomes of using the 'polluter pays' option. This identifies a potential source of tension between the UK Government's 'green growth' and 'levelling up' agendas in the context of industrial decarbonisation.

## 3. Developing our UKENVI CGE model to incorporate a new T&S industry

### 3.1 Basic CGE model configuration and calibration

We conduct our analyses using UKENVI, a multi-sector economy-wide computable general equilibrium (CGE) model of the UK, customised to accommodate energy and climate policy actions involving large scale investments and their user uptake. The model has previously been applied to electricity network upgrades and projected roll-out of electric vehicles (Alabi

et al., 2020). It offers a range of model closures corresponding to different time periods of analysis, labour market configurations and public funding options. Below we specify how we simulate the dynamic adjustments made by the UK economy in response to a series of regional industry investments to first enable and then maintain T&S capacity for CCS. We also outline the alternative labour market closures and public funding mechanisms employed in our scenario simulations.

We give a broad account of the model set up and configuration, which is relatively standard for national CGE models. A more detailed UKENVI model listing is provided in Alabi et al. (2020). The model structure includes one endogenous region – the UK – and one exogenous region—the rest of the world (ROW). Three domestic transactor groups are identified - households, firms, and the government and thirty-four commodities and activities. This includes the new $CO_2$ T&S industry (discussed in more detail below).[2] There are four main components of final demand: household consumption, investment, government expenditure and exports to the ROW, all of which can be shocked exogenously, but also respond endogenously to changes in relative prices.

The basic dataset for the model is a UK social accounting matrix (SAM) incorporating the most recently published UK analytical input-output tables for 2016. We treat these data as reflecting the real economy in the effective policy base year of 2021, and report all results in Section 4 in terms of changes from this otherwise unchanging base.

[2] The industrial structure is outlined in Figures 2 and 4 in section 4. See the SAM database at https://doi.org/10.15129/ad64a94c-152d-4ec7-a3a5-4e4a13576a3a for more detail of sector composition.

The SAM provides the values for key structural model parameters, such as the initial size, trade and capital intensity of individual sectors. The SAM data are adjusted so as to create the new Transport and Storage (T&S) sector. This is done by disaggregating the Oil and Gas extraction (O&G) sector meaning that the imposed T&S sector initially has a cost structure identical to that of O&G. The starting size of T&S is set at 0.2% of the original O&G sector. A key difference is that government becomes the central consumer, with purchases offset by an appropriate increase in the indirect business tax paid by other UK industries. This balances the SAM with the base year data adjusted to include the T&S sector whilst maintaining key control totals.

Other parameter values, such as trade elasticities, wage bargaining function parameters and elasticities of substitution in production, are imposed exogenously, drawing from existing econometric studies and informed judgement. Where econometrically parameterised relationships have been introduced, these have been determined using annual data, so that each ‘period’ in the model is interpreted as a single year. A final set of parameter values is determined through calibration of the model so that the base-year exogenous variables reproduce the appropriate base-year endogenous data in the model. The calibration approach taken means that the economy is assumed to be in long-run equilibrium in the base-year period.

In production, local intermediate inputs are combined with imports via an Armington link (Armington, 1969). This composite input is then combined with labour and capital (value-added) to determine each sector’s gross output. Regarding the labour market, we assume a fixed labour force, which sets an upper limit to employment. In our default wage setting

closure, wages are adjusted via an econometrically-parameterised relationship where the bargaining power of the workers, and therefore the level of the real wage, is inversely related to the unemployment rate (Blanchflower and Oswald, 2009). The initial pool of unemployed workers allows flexibility in the employment level. An alternative specification, which we use primarily as a benchmark, has a fixed real wage. In this case the nominal wage adjusts so that the purchasing power of wages remains fixed over time, crucially limiting wage flexibility and its impact on competitiveness.

As will become clear in Section 3.2, T&S investment is exogenously determined period by period. The level of investment simulates the initial oversizing of the sector before the supply of captured $CO_2$ builds up. Investment in all other sectors is endogenous, driven by a recursive dynamic procedure. In each sector the capital stock is updated between periods through a simple capital stock adjustment procedure. Investment covers depreciation of the existing sectoral capital stock and a fraction of the gap between the actual and desired capital stock, where the desired capital stock is a function of sectoral output and input prices. The capital stock is in equilibrium where desired and actual capital stock are equal. At this point net investment is zero, with gross investment simply covering depreciation.

CES (constant elasticity of substitution) production functions are imposed at each level of the production hierarchy for all sectors and a CET (constant elasticity of transformation) function determines shares of marginal output to domestic and export demand, where both are sensitive to changes in relative prices. Our central case assumption is that export and import elasticities take the value of 2.0, but subject this to sensitivity analysis in Section 4.5. A notable exception is the T&S sector, which we constrain to serve domestic demand only: the

export price elasticity is fixed at the lowest value possible, 0.11, to prevent export demand effects.

Household consumption decisions are also determined through a nested CES function, while total demand is linear in real income and homogenous of degree zero in all nominal variables. Real government spending is determined exogenously, with focus here on government's spending on T&S industry output. In turn, where government recovers these direct expenditure costs from households or polluters, lump sum transfers to the public purse are also exogenously imposed. Otherwise the government budget balance is endogenous, with fixed tax rates.

### 3.2 Scenario simulation strategy

The main premise of our analyses involves the introduction of the necessary infrastructure in four industrial clusters so that they become operational and sequester emissions within a 10-year period. We stage this investment on a two-by-two basis based on CAPEX data generated by Calvillo et al. (2021), associated with the development cost of transportation infrastructure and estimates on the cost of storage facilities required to provide to T&S services to each cluster. [3] This infrastructure is introduced via an exogenous investment shock to the T&S sector so that it reaches the appropriate capital stock level for the first two clusters in year 5, and the second two in year 10. Thereafter, there is a fixed level of ongoing investment maintaining capital stock at specific levels and covering the depreciation of capital.

[3] Calvillo et al. (2021) provide CAPEX information for the Grangemouth cluster in Table 6, Humber cluster in Table 8, Teesside cluster in Table 9 and Merseyside cluster in Table 10. Here, to smooth the scale in sequencing investment, we divide the Humber cluster into 'North' and 'South', and linking the former with Teesside.

Following the creation of the necessary capital stock, we introduce a demand shock for the output of the T&S sector of sufficient size to fully utilise the capacity. This involves the government providing demand for all T&S output. The direct costs of doing so are financed through borrowing or from UK households (socialising costs) or regional emitters (imposing 'polluter pays'). The demand shock follows the cluster sequencing example we used for investment, meaning that a certain level of demand is introduced in year 5 when the first two clusters (A and B, assumed to be those in Scotland and Teesside/North Humberside – see Table 1 below) become operational, which is then expanded when all 4 clusters become operational in year 10. The demand shock is introduced exogenously as additional purchases from the government, without affecting the government spending on other sectors. The impact of these additional government purchases is therefore reflected in the government budget balance.[4]

We explore two ways in which the government could pass the T&S cost to other parts of the economy. These are introduced in a simplified way to aid analyses of the trade-offs involved in different broad types of approaches rather than attempting to model precisely as-yet-unknown potential UK policy actions around CCS. The first is a 'households pay' approach where a payment, equal to the cost of the government's T&S purchases, is introduced to all UK households, reducing their disposable income in the way that a lump sum tax would do.[5]

[4] Targeted deficit financing for net zero actions has emerged in the UK with the UK Government's new Sovereign Green Bond issue (HMT/DMO, 2021). This will support a range of investment and operational activities, where the former may focus on front-loading public investment to support creation of high return assets, thereby incentivising sustained expansion in private investment (Stern, 2021).

[5] This equates to a non-distortionary tax, though the UK has no such 'lump sum' transfer instruments of the type specified here since the 'poll tax' model of local household taxation in the late 1980s/early 1990s. The ear-marking of tax revenues for specific purposes beyond a few examples, such as the Climate Change Levy, is also resisted by HM Treasury.

The second is a ‘polluter pays’ approach where the government recovers the cost of T&S via increases to the indirect business tax paid by the industries present at the clusters. This impacts the output price, and therefore the competitiveness, of these industries. Here, we focus only on those manufacturing industries identified as emitters in the regional clusters that T&S would service. This excludes sectors, such as ‘Food, beverages and tobacco’ that may be more likely to capture $CO_2$ for use in production processes. The share of the cost faced by each industry is based on information from the UK Pollution Inventory[6] –Table 1 summary breakdown of industry emissions sources in each regional cluster.

To test the implications of our assumptions on the results of our central case, we conduct a series of sensitivity analyses. First, across all scenarios, we use the alternative wage setting specification of fixed real wage as a benchmark to subsequently explore the importance of labour market response where the labour force is fixed so that variation in employment occurs through adjustments in the unemployment rate. Second, for the ‘polluter pays’ scenarios only, we vary the export price elasticities between a low (1.1), medium (2.0) and high (3.0) setting to explore the importance of the external markets responsiveness to the competitiveness losses associated with greater output prices in the sectors using T&S services.

## 4. Results and analysis

[6] Available at https://www.gov.uk/government/statistics/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics-2005-to-2018.

### 4.1 T&S industry outcomes

As set out in Section 3.2, we assume the first phase of investment in T&S capacity creates links to Clusters A and B, respectively Grangemouth in Scotland and Teesside/North Humber in North East England. The investment builds incrementally for four years (2021-2024) until the combined additional capital stock is just over £1.2billion (see Table 1). Thereafter, additional annual investment just maintains this capacity intact. The direct T&S industry employment and value-added/GDP associated with the full operation of the capacity generated in this first phase is 3,026 full-time equivalent (FTE) workers and £385.23million per annum, respectively.

Beginning in 2026, a second four-year phase of T&S investment focuses on Clusters C and D in South Humber in North East England, and Merseyside in North West England. By 2030 T&S capacity to service all four regional industry clusters are online, with a total additional capital stock of just over £2.3billion. Additional annual investment required to cover depreciation settles at £352million and total direct T&S employment is 5,630 FTEs.

**Table 1. Investment costs in T&S capacity to enable sequestration of regional cluster emissions**

| | Investment costs | | | Baseline industry emission sources (KT CO2) | | | | |
|---|---|---|---|---|---|---|---|---|
| Cluster/key features | Additional capital stock introduced (£m) | Total pre-operation investment (£m) | Ongoing annual investment (£m) | Chemicals | Coke and refined petroleum products | Iron, steel and metal | Cement, lime and glass | Others |
| **T&S operational from 2025** | | | | | | | | |
| A (Scotland - Grangemouth) | 430 | 500 | 65 | 1373 | 1638 | 0 | 731 | 83 |
| B (NE England - North Humber/Teeside) | 813 | 940 | 122 | 3523 | 0 | 109 | 41 | 0 |
| **T&S operational from 2030** | | | | | | | | |
| C (NE England - South Humber) | 659 | 864 | 99 | 54 | 3596 | 5032 | 0 | 26 |
| D (NW England - Merseyside) | 442 | 540 | 66 | 865 | 2053 | 54 | 509 | 139 |

The simulations are devised so that for the T&S industry itself, long-run capacity is reached once the exogenously determined staged investment is complete. However, the policy and CGE modelling challenge lies in ensuring that this is in operation at the planned capacity

output. We introduce an accompanying demand shock whereby from 2025 the government purchases the output of the sector on a year-by-year basis. This is at an annual level of just under £1.2billion to 2029, when the industry only services Clusters A and B, rising to just over £2.2billion from 2030 when capacity is in place to sequester emissions from all four clusters (where the level of sectoral emissions in each cluster in Table 1 determines the distribution of cost recovery under 'polluter pays').

The T&S industry outcomes are determined exogenously. They do not vary, regardless of the modelled conditions or endogenous responses in the wider economy. We are therefore primarily concerned here with tracking the endogenous effect of this stimulus on activity in the other sectors of the UK economy. Will the adoption of T&S be a driver of green growth? How does the approach to funding the T&S activity effect key macroeconomic indicators of concern to policymakers, including employment (BEIS, 2021a)? Further, particularly in the context of the UK Government's 'levelling up agenda', how do these national effects feedback to those industries located in the regional clusters that the new T&S industry services?

### 4.2 Economy-wide implications – unconstrained multipliers at the national level?

Previous policy attention and narratives around the potential wider economic impacts of CCS have focussed on the value of the appropriate input-output (IO) employment multipliers (BEIS, 2018; ZEP, 2018). Moreover, multiplier data produced by the Office for National Statistics have been used to generate figures for the UK Oil and Gas (O&G) industry (Turner et al., 2019). In the present paper, this industry is assumed to have an identical input structure

to the new T&S sector. These figures suggest that each direct job in the O&G sector supports up to 10 indirect and induced UK jobs.

These multiplier values are calculated using accepted IO modelling techniques (Miller and Blair, 2009). However, their replication in response to even marginal shocks to the economy require rather extreme assumptions regarding the elasticity of supply and passivity of prices. These assumptions are likely to hold only over the long-run and under specific economic conditions (McGregor et al., 1996; Gillespie et al., 2001). CGE modelling is less restrictive, allowing a greater role for scarcity and price sensitivity. Nonetheless, the IO figures provide a useful starting point to frame our CGE simulation results.

As introduced in Section 3.1, two key model characteristics are central to the simulation results. These are the nature of the labour market and the way in which the increased government expenditure is to be funded. We adopt two alternative wage-setting closures: either a fixed or bargained real wage. We also employ three funding options: deficit funding, socialising the cost through household taxation, and ‘polluter pays’. The impacts on a range of aggregate UK economic variables for 2040, - the key timeframe for outcomes of the UK Government’s Industrial Clusters Mission (BEIS, 2019) - are given in Table 2. Period-by period and industrially disaggregated employment changes (wage bargaining only) are reported in Figures 1 and 2 respectively.

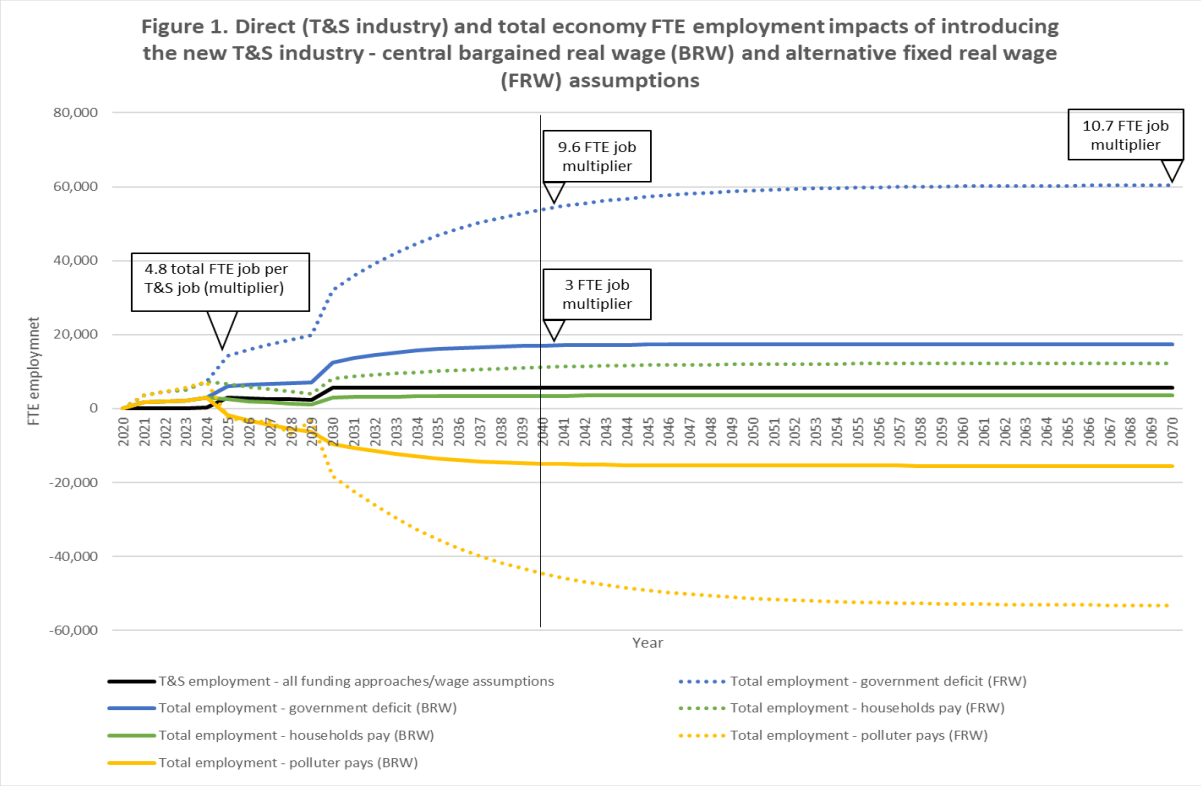



Figure 1 shows that whilst long-run equilibrium has not necessarily been reached by 2040, in all the option combinations it is close. The very rapid adjustment is explained by the fact that the T&S sector, which receives the direct demand shock, is constrained to be in long-run equilibrium from 2030. Endogenous capacity adjustment is only required in the sectors that experience subsequent indirect and induced effects. It is therefore valid to discuss the results reported in Table 2 as being at, or close to, long-run equilibrium.

We begin by considering the results in the second data column in Table 2. These are for a fixed real wage and deficit financing. These results reflect an outcome with no effective labour market constraints coupled with the simplest form of financing in which the government simply runs a deficit so as to purchase the demand for T&S output. The model is also close to long-run equilibrium with very small changes in prices. This means that the cost

minimising technical production coefficients show almost no change so that the model operates much like an extended (investment endogenous) IO system.

**Table 2. Key UK macroeconomic impacts by 2040 of introducing the T & S industry - alternative funding and wage assumptions**

| | | Fixed Real Wage | | | Bargained Real Wage | | |
|---|---|---|---|---|---|---|---|
| | | Public funding approach | | | Public funding approach | | |
| | Base values (2016) | Deficit | Household Transfer | Polluter pays | Deficit | Household Transfer | Polluter pays |
| Government demand for T & S (£million) | | 2193 | 2193 | 2193 | 2193 | 2193 | 2193 |
| Government budget balance (£million) | -517 | -1064 | 432 | -1165 | -1586 | 320 | -766 |
| GDP (£million) | 1,751,690 | 3685 | 1187 | -2554 | 1739 | 773 | -977 |
| GDP (% change) | 1,751,690 | 0.210 | 0.068 | -0.146 | 0.099 | 0.044 | -0.056 |
| T&S industry employment (FTE) | | 5630 | 5630 | 5630 | 5630 | 5630 | 5630 |
| Employment (FTE) | 29,300,731 | 53873 | 11181 | -44621 | 17037 | 3464 | -14912 |
| Employment multiplier | | 9.6 | 2.0 | -7.9 | 3.0 | 0.6 | -2.6 |
| Employment (% change) | 29,300,731 | 0.184 | 0.038 | -0.152 | 0.058 | 0.012 | -0.051 |
| Unemployment (% change) | 5% | -3.493 | -0.725 | 2.893 | -1.105 | -0.225 | 0.967 |
| Nominal wage - index to 1 (% change) | 1 | 0.029 | 0.005 | 0.228 | 0.255 | 0.052 | 0.050 |
| Real wage - index to 1 ( % change) | 1 | 0.000 | 0.000 | 0.000 | 0.126 | 0.025 | -0.109 |
| CPI - index to 1 (% change) | 1 | 0.029 | 0.005 | 0.228 | 0.129 | 0.026 | 0.159 |
| Exports (% change) | 477,563 | -0.057 | -0.010 | -0.661 | -0.248 | -0.051 | -0.505 |
| Imports (% change) | 515,335 | 0.270 | 0.035 | 0.149 | 0.311 | 0.044 | 0.122 |
| Household consumption (% change) | 1,185,745 | 0.208 | -0.091 | -0.055 | 0.185 | -0.095 | -0.038 |
| Total investment (% change) | 310,036 | 0.275 | 0.089 | -0.181 | 0.153 | 0.064 | -0.070 |

The small (0.029%) increase in CPI, which has a similarly small impact on the nominal wage and competitiveness, means that there is some crowding out of exports, which fall by 0.057%. But note the more substantial increase in household consumption, investment and GDP, all of which increase by over 0.2%. Total employment increases by almost 54,000 jobs, making the employment multiplier 9.6. Although government expenditure on the T&S sector is £2,193million, the expansion in activity generates additional taxes covering over 50% of this, so that the additional borrowing is only £1,061million. The very high employment multiplier generated in this analysis suggests that T&S would be a very effective source of 'green growth'. However, note that almost all supply side and funding constraints are removed in this particular simulation.

### 4.3 Adding a labour market and financing constraints

The impact of simply introducing an active labour market, in the form of a wage curve, to the simulation results can be seen from comparing the figures in data column 2 in Table 2 with those in column 5. Note that the wage curve is our preferred labour market closure. With the introduction of the wage curve, the 0.058% expansion in employment is enough to increase the real wage 0.126% with knock implications for the prices in general, with the CPI rising by 0.125%. The fall in competitiveness limits the increase in GDP and employment to less than half and a third respectively of their values with the fixed real wage. However, the impact is still substantial. The GDP increases by almost 0.1%, there are still positive changes in household expenditure and investment, and the employment multiplier takes a value of 3. What is really restricting the expansion is the 0.248% reduction in exports, and the 0.311% increase in imports.

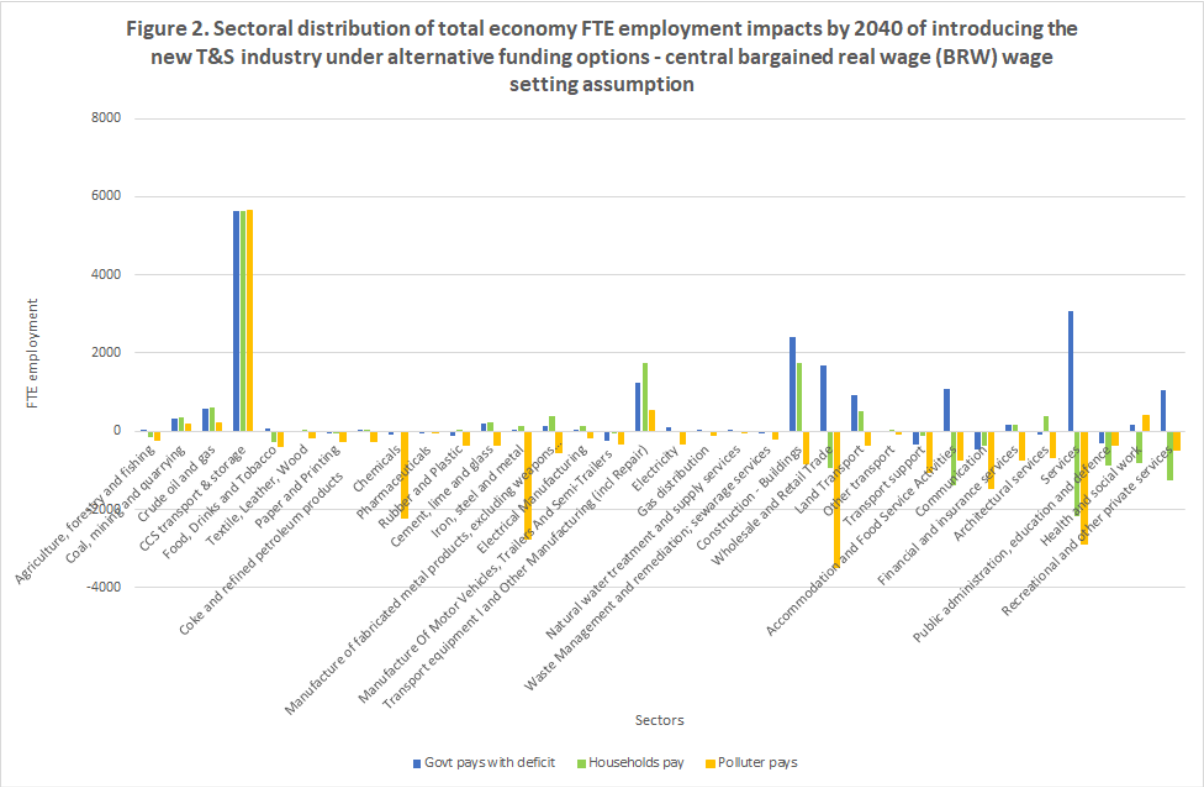
The more constrained outcomes are reflected in a quicker adjustment to the long-run equilibrium than is shown in the fixed real wage case. This is apparent from Figure 1. Also, increased amounts of crowding out are apparent from the negative change in employment experienced by a limited number of sectors, as indicated in Figure 2. Note also from Table 2 that the additional tax income equals just over 27% of the T&S expenditure so that the government deficit only increases by £1,586million (but with this increased tax take only around one half that with the fixed real wage).

Recall that we have not as yet introduced an active form of financing for the public expenditure on T&S. A very straightforward way of doing this is to socialise the cost by introducing a non-distortive lump sum tax on consumption. Essentially, in this case households directly pay for the T&S industry. The increase in expenditure on the output of

the T&S sector is now matched by an equal reduction in income available for consumption. However, there is still a net demand stimulus because T&S expenditure is less import intensive than household consumption.

Introducing financing through taxing households in a model where the wage is set by wage bargaining gives the results reported in the sixth data column in Table 2. Note that adding this form of financing limits the increase in GDP to 0.044%, less than a half of the value with deficit financing, but now with the limited expansion delivering a net positive change in the public budget. The employment multiplier falls by 80% to 0.6. As expected, household consumption in this case falls, by 0.095%. Figure 2 demonstrates that most sectors of the economy still experience net gains in employment, with the main ‘winners’ being those involved in servicing the T&S supply chain and its construction needs. Most sectors do not experience much impact. However, 12 of the 34 sectors do now register employment reductions, with the main ‘losers” being sectors predominately servicing export or household demand, including more labour/wage intensive domestic service sectors. Sectors in which employment falls lose a total of 1,802 jobs.

The same comparison can be made to identify the impact of socialising the T&S costs through household taxation where the real wage is fixed. This involves comparing the results in columns 2 and 3 of Table 2. The scale of the aggregate adjustments with the fixed real wage are larger because the wage bargaining process cushions any expansion or contraction in output that is accompanied by corresponding changes in employment.




## 4.4 National and regional impacts if Government imposes a ‘polluter pays’ approach

Beyond the 2040, it is unlikely that the UK Government would support T&S – or CCS more generally - through deficit financing or socialisation of costs. This motivates consideration of a simple ‘polluter pays’ model. In this approach the government still guarantees demand for T&S output but passes the direct costs to emitters/capture firms in the regional clusters in each time period in line with emissions sequestered. However, while the intention may be to transfer costs to the consumption of the goods produced by the industries that need to reduce emissions, the employment trajectory in Figure 1 and the aggregate results in the final column of Table 2 show that the costs are more widely spread through a contraction of the UK economy. Moreover, in all cases, despite recovering direct T&S expenditure costs, the

contraction delivers net negative public budget outcomes that substantially erode the benefits of recovering those direct costs.

These results reflect a crucial shift in the driver of outcomes, because this funding mechanism has both direct demand and supply-side implications. It directly changes the cost structure, and therefore the price of the heavily internationally traded outputs of capture industries. With the wage curve labour market closure, imposing a 'polluter pays' approach triggers a 0.505% reduction in exports. This is accompanied by a fall in GDP and employment of just over 0.05%, with investment and household consumption also declining. Figure 1 indicates that total employment begins to fall as soon as the pollution payments are imposed; the employment multiplier is consistently negative in this case.

With the 'polluter pays' and the default model parameter values it is clearly difficult to maintain the notion that T&S can form the basis for 'green growth'. Once the construction stage is completed, activity in the wider economy begins to fall. Moreover, if we adopt the fixed real wage labour market closure, there is an even larger negative impact on all aggregate economic variables; GDP, employment, exports, investment and household consumption. This can be seen from comparing the results data columns 4 and 7 in Table 2 and the corresponding employment time lines in Figure 1. Again, the real wage flexibility offered by the wage curve cushions the negative impact on competitiveness.

In the UK the role of T&S (and CCS in general) has been explicitly linked to the 'levelling up' agenda seen as central to the national Government's economic strategy. An element of this strategy is the stimulation of the so-called 'left behind' parts of the country. In this

narrative, it might be thought that even if the UK economy as a whole were negatively affected, those areas in which T&S development took place would benefit, so that a degree of levelling up would occur.

While our UK model is not set up to fully consider regional impacts, some important regional implications can be imputed (and would be worthy of future research). This is reflected most in the sectoral employment results reported in Figure 2. The geographic spread of sectoral impacts under the 'households pay' case will be primarily driven by the distribution of the population across the country as a whole. However, under 'polluter pays' negative impacts are likely to be concentrated in those cluster regions where the main capture industries identified in Table 1 are located. These are the industries bearing the cost of guaranteeing demand for T&S output.

Figure 2 shows that some of the main sectoral losers under 'polluter pays' are those emitting/capture industries (particularly 'Chemicals' and 'Iron, Steel and Metal') largely located in the regional clusters now directly meeting the costs of guaranteeing demand for T&S industry output. That is, the wider economy contraction observed involves 'off-shoring' of these industries, where the loss in international competitiveness means that demand within the UK for those industry outputs might still be met, but now by overseas producers.

Moreover, when employment is shed in cluster industries, the contraction in total UK household spending is likely to be skewed towards the host regions. In turn, this means that the (more labour- and household spending-intensive) service sector industry losses reported in Figure 2 are also likely to be more concentrated in the localities where those suffering the

most job losses reside. Essentially, T&S combined with ‘polluter pays’ is not a positive contributor to the Government’s industrial strategy, either on a ‘green growth’ or ‘levelling up’ basis.

### 4.5 Sensitivity of ‘polluter pays’ results to export elasticities

The above ‘polluter pays’ outcomes are dependent on the imposed value of the export elasticities, which have been given a default value of 2.0 in all scenarios so far. These elasticities determine the impact of the competitiveness reduction that drives the economic contraction. Note that we implicitly assume that competitors in other nations are not similarly bearing T&S (or other comparable decarbonisation) costs, and/or that their own governments are somehow cushioning the price impact. That is to say, we focus on the export elasticities to consider the impact of stronger or weaker competitiveness effects.

We rerun both the ‘polluter pays’ scenarios with higher (3.0) and lower (1.1) values on export price elasticities. Universally higher elasticity values are motivated by the likelihood that the capture firms in the regional industry clusters are largely selling intermediate or process outputs into complex global supply chain. They are thereby most at risk of investment/carbon leakage (European Commission, 2018). In Table 3 we report sensitivity analyses for the 2040 results for the wage bargaining and fixed real wage closures under the polluter pays. For each labour market option we present figures for the low, default and high export elasticity simulations. The corresponding employment time paths are given in Figure 3, with sectoral outcomes presented in Figure 4, highlighting results from the extreme ‘worst’ (fixed real

wage with greatest export response) and ‘best’ (bargained real wage with most limited export response) cases from Table 3.

**Table 3. Sensitivity of key UK macroeconomic impacts in 2040 of introducing the T & S industry under polluter pays - with alternative wage setting and export sensitivities**

| | Base values (2016) | Fixed Real Wage | | | Bargained Real Wage | | |
|---|---|---|---|---|---|---|---|
| | | Trade 1.1 | Trade 2.0 | Trade 3.0 | Trade 1.1 | Trade 2.0 | Trade 3.0 |
| Government demand for T & S (£million) | 21 | 2193 | 2193 | 2193 | 2193 | 2193 | 2193 |
| Government budget balance (£million) | -517 | -687 | -1165 | -1582 | -543 | -766 | -920 |
| GDP (£million) | 1,751,690 | -902 | -2554 | -4004 | -343 | -977 | -1527 |
| GDP (% change) | 1,751,690 | -0.052 | -0.146 | -0.229 | -0.020 | -0.056 | -0.087 |
| Employment (FTE) | 29,300,731 | -18659 | -44621 | -67616 | -7275 | -14912 | -20142 |
| Employment (% change) | 29,300,731 | -0.064 | -0.152 | -0.231 | -0.025 | -0.051 | -0.069 |
| Unemployment (% change) | 5% | 1.210 | 2.893 | 4.385 | 0.472 | 0.967 | 1.306 |
| Nominal wage - index to 1 (% change) | 1 | 0.249 | 0.228 | 0.202 | 0.152 | 0.050 | -0.038 |
| Real wage - index to 1 ( % change) | 1 | 0.000 | 0.000 | 0.000 | -0.053 | -0.109 | -0.147 |
| CPI - index to 1 (% change) | 1 | 0.249 | 0.228 | 0.202 | 0.206 | 0.159 | 0.109 |
| Exports (% change) | 477,563 | -0.387 | -0.661 | -0.914 | -0.342 | -0.505 | -0.650 |
| Imports (% change) | 515,334.82 | 0.312 | 0.149 | -0.014 | 0.279 | 0.122 | -0.013 |
| Household consumption (% change) | 1,185,745 | 0.023 | -0.055 | -0.127 | 0.021 | -0.038 | -0.083 |
| Total investment (% change) | 310,036 | -0.054 | -0.181 | -0.302 | -0.019 | -0.070 | -0.120 |

The first point to take from Table 3 is that even where export elasticities are low (1.1), the impact of introducing the T&S sector on the aggregate variables GDP, employment, exports and investment, is negative. There is a small increase household consumption but because wage income falls, this is likely to be accompanied by negative distributional effects (not addressed here) across households. As the export elasticities are raised, the change in household consumption becomes negative and the fall in the other aggregate activity measures is increased. From the data column seven in Table 3, with the bargained real wage and export elasticities equal to 3.0, exports now fall by 0.65%. This generates reductions of 0.12% in investment, around 0.085% in GDP and household consumption and nearly 0.069% in employment.

With the fixed real wage labour market closure, much more extreme results are observed. This is clearly reflected in the time path of employment outcomes shown in Figure 3. Here,

where the export elasticity is 3.0, not only is the total employment decline large, but by 2040 it is only around 75% of its full long-run negative change.

**Figure 3. Employment impacts of introducing the new T&S industry - polluter pays case under alternative wage setting and trade response assumptions**

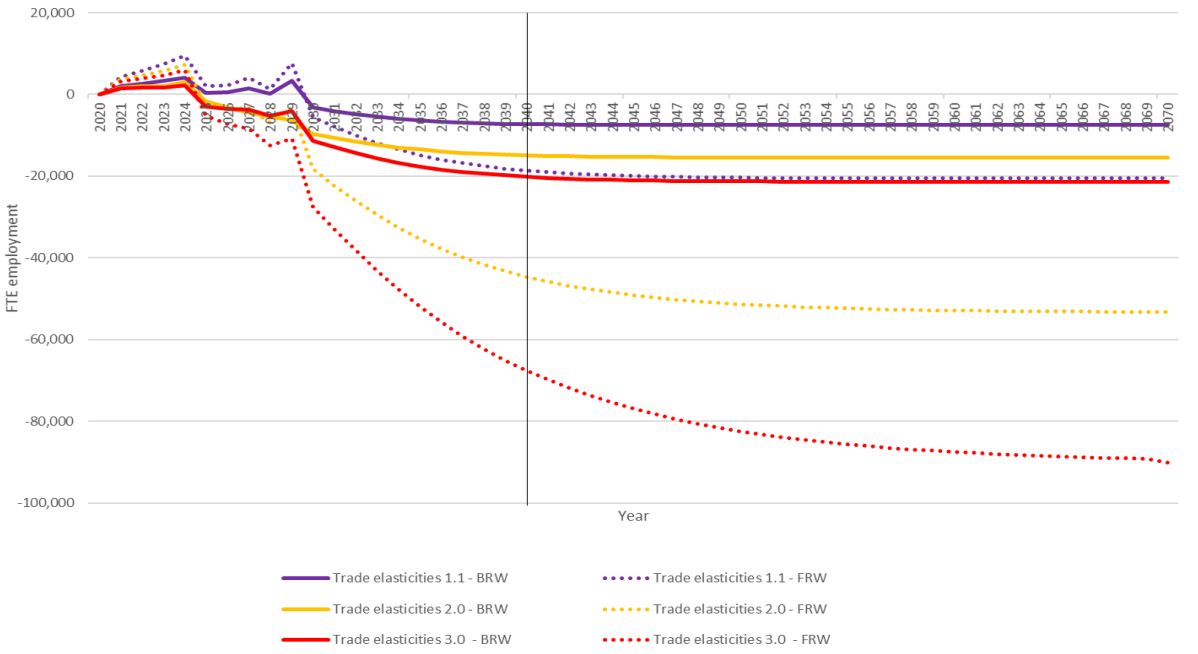
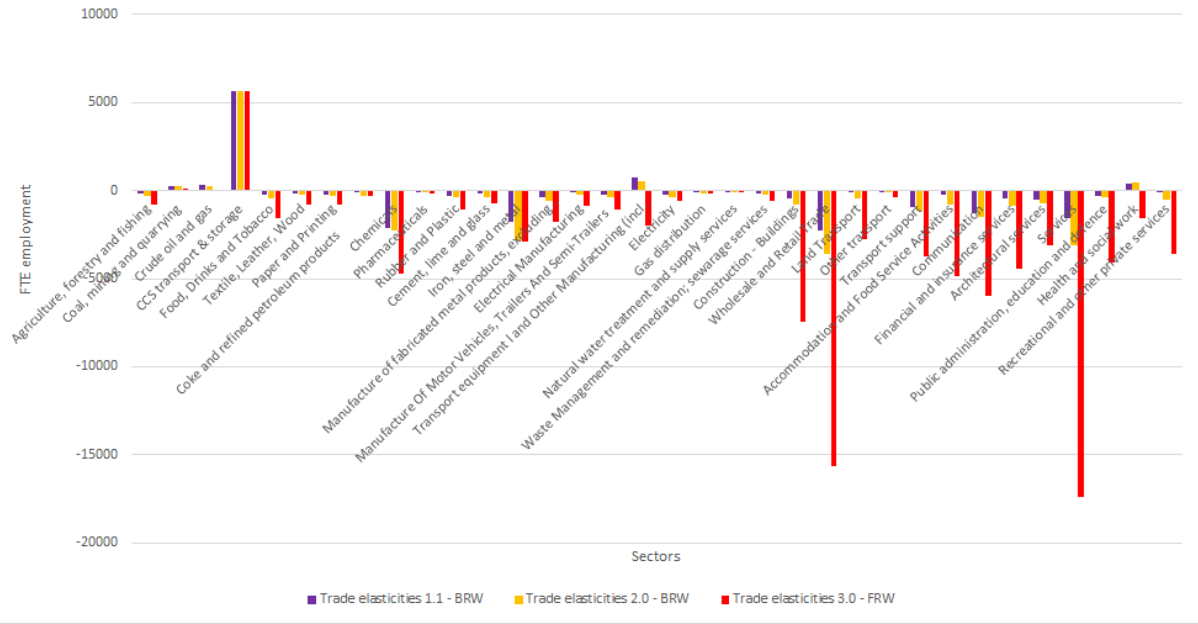



**Figure 4. Long run sectoral distribution of total economy FTE employment impacts of introducing the new T&S industry - polluter pays, central case compared with 'best' and 'worse' cases determined by wage setting and trade response assumptions**



Crucially, Figure 4 highlights the outcome that negative impacts across both capture industries and local service sectors increase both with international trade response to losses in UK competitiveness, which would be expected, and with downward wage rigidity. This latter point is important, given that policymakers might consider falling wage rates as much of a problem as falling employment in regions of concern under the stated 'levelling up' agenda. But this downward flexibility in the real wage stems activity loss in our scenarios, particularly in cluster regions.

## 5. Conclusions

The wider economy implications of supporting the deployment of the $CO_2$ transport and storage element of CCS have been commonly measured by employment and other 'multiplier' metrics. However, while generated through widely accepted modelling methods, such metrics are likely to be a poor measure of the economy-wide response to a demand shock (here, introduction of an entirely new sector to the economy) that requires financing and/or evolves in the presence of supply-side constraints. Our analysis is very much early stage and focusses on identifying the nature of trade-offs involved in different broad funding approaches for T&S rather than the detail of potential CCS policy instruments. Crucially, it demonstrates that the presence of a national labour supply constraint - here in the form of a fixed UK labour force - coupled with the UK Government's preferred 'polluter pays' funding option, has important macroeconomic and distributional implications.

In particular, the UK Government has cited CCS as an integral part of its 'green growth' and 'levelling up' agendas. Our results challenge such a view. If a T&S industry is introduced

under a ‘polluter pays’ scenario, positive impacts are only assured in the initial periods of infrastructure construction. Subsequently, costs to emitting industries are likely to generate substantial activity loss and ‘off-shoring’ of production and the resulting wider economy losses are likely to be largely concentrated in host regions. This constitutes a key policy challenge. CCS may well be necessary in order to deliver the deep decarbonisation required to meet the UK’s ‘net zero’ and other climate change commitments, and to do so in ways that help transition Oil and Gas industry capacity and jobs. However, our analysis suggests that ultimately adopting a ‘polluter pays’ approach to guaranteeing demand for T&S industry output is likely to generate negative outcomes in the very regional cluster activity that Government aims to safeguard. Moreover, Turner et al. (2021) suggest such outcomes will be exacerbated by capture costs. Thus, it is not necessarily the case that either ‘green growth’ or ‘levelling up’ outcomes will follow from supporting T&S industry development to service deep decarbonisation of regional industry clusters.

## References

Alabi O, Turner K, Figus G, Katris A and Calvillo C (2020) Can spending to upgrade electricity networks to support electric vehicles (EVs) roll-outs unlock value in the wider economy? *Energy Policy* 138: 111117.

Armington P (1969) A theory of demand for products distinguished by place of production, *IMF Staff Papers*, 16, 157–178.

Balta-Ozkan N, Watson T and Mocca E (2015) Spatially uneven development and low carbon transitions: Insights from urban and regional planning. *Energy Policy* 85:500-510

Blanchflower DG, and Oswald AJ (2009). The wage curve. Europe *Revue Litteraire Mensuelle*, 92, 215–235.

Budinis S, Krevo, S, MacDowell N, Brandon N and Hawkes A (2018) An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews* 22: 61-81.

Business Energy & Industrial Strategy (BEIS) (Department for) (2017) Industrial Strategy: Building a Britain fit for the future. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf (accessed 24 February 2021).

Business Energy & Industrial Strategy (BEIS) (Department for) (2018) The UK carbon capture, usage and storage (CCUS) deployment pathway: an action plan. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759637/beis-ccus-action-plan.pdf (accessed 17 February 2021).

Business Energy & Industrial Strategy (BEIS) (Department for) (2019) What is the Industrial Clusters mission? Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/803086/industrial-clusters-mission-infographic-2019.pdf (accessed 26 July 2021).

Business Energy & Industrial Strategy (BEIS) (Department for) (2021a) Cluster Sequencing for Carbon Capture Usage and Storage Deployment: Phase-1. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/983961/ccus-cluster-sequencing-phase-1-guidance.pdf (accessed 11 May 2021).

Business Energy & Industrial Strategy (BEIS) (Department for) (2021b) Industrial decarbonisation strategy. Available at: https://www.gov.uk/government/publications/industrial-decarbonisation-strategy (accessed 14 April 2021).

Business Energy & Industrial Strategy (BEIS) (Department for) (2021c) The Carbon Capture and Storage Infrastructure Fund: An Update on the Design of the CCS Infrastructure Fund. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984001/ccs-infrastructure-fund-cif-design.pdf (accessed 11 May 2021).

Business Energy & Industrial Strategy (BEIS) (Department for) (2021d) CCUS Supply Chains: a roadmap to maximise the UK's potential. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984308/ccus-supply-chains-roadmap.pdf (accessed 11 May 2021).

Calvillo C, Race J, Chang E, Turner K and Katris A (2021) Characterisation of Industrial Clusters in the UK and Techno-Economic Cost Assessment for CCTS Implementation. Working paper. https://doi.org/10.17868/77310

Cuppen E, Brunsting S, Pesch U and Feenstra Y (2015) How stakeholder interactions can reduce space for moral considerations in decision making: A contested CCS project in the Netherlands. *Environment and Planning A* 47(9): 1963-1978.

European Commission (2018). Preliminary Carbon Leakage List, 2021-2030. Official Journal of the European Union C 162. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:C:2018:162:FULL&from=EN (accessed 23 June 2021).

European Commission (2021) Candidate PCI projects in cross-border carbon dioxide (CO2) transport networks. Available at: https://ec.europa.eu/energy/sites/default/files/detailed_information_regarding_the_candidate_projects_in_co2_network.pdf (accessed 14 April 2021).

Gillespie G, McGregor PG, Swales JK, and Yin YP (2001) The displacement and multiplier effects of regional selective assistance: a computable general equilibrium analysis. *Regional Studies* 35(2): 125-139.

HM Government (2020) The Ten Point Plan for a Green Industrial Revolution. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf (accessed 17 February 2021).

HM Treasury (2021), Build Back Better: Our Plan for Growth, March 2021. Available at: https://www.gov.uk/government/publications/build-back-better-our-plan-for-growth (accessed 17 February 2021).

HM Treasury/UK Debt Management Office, HMT/DMO (2021), UK Government Green Financing Framework. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/998127/20210630_UK_Government_Green_Financing_Framework_Final.pdf (accessed 2 July 2021).

International Energy Agency (IEA) (2016) 20 Years of Carbon Capture and Storage: Accelerating Future Development. Available at: https://iea.blob.core.windows.net/assets/24c3d26b-aa44-4b54-b9c0-5201d4d86a04/20YearsofCarbonCaptureandStorage_WEB.pdf (accessed 7 May 2021).

International Energy Agency Greenhouse Gas (IEAGHG) R&D Programme (2020). Carbon Capture and Storage and the Sustainable Development Goals: IEAGHG Technical Report 2020-14. Available at: https://ieaghg.org/ccs-resources/blog/new-ieaghg-report-ccs-and-the-sustainable-development-goals-sdgs (accessed 14 April 2021).

Leontief W (1970) Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics* 52(3): 262-271.

Liang X, Reiner D, Gibbins J and Li J (2010) Getting ready for carbon capture and storage by issuing capture option. *Environment and Planning A* 42(6): 1286-1307.

McGregor PG, Swales JK and Yin YP (1996). A long-run interpretation of regional input-output analysis. *Journal of Regional Science* 36(3): 479-501.

Miller R and Blair P (2009) *Input-Output Analysis: Foundations and Extensions*: Cambridge University Press, Cambridge.

Nestor, DV and Pasurka, CA (1995) CGE model of pollution abatement processes for assessing the economic effects of environmental policy, *Economic Modelling* 12(1): 53–59.

Phimister E and Roberts D (2017) Allowing for uncertainty in exogenous shocks to CGE models: the case of a new renewable energy sector. *Economic Systems Research* 29(4):509-527.

Prime Minister's Office (PMO) (2021) The Queen's Speech 2021. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data

/file/986770/Queen_s_Speech_2021_-_Background_Briefing_Notes..pdf (accessed 18 June 2021).

Porthos (2019). Porthos project $CO_2$ reduction through storage beneath the North Sea. Published by Port of Rotterdam Authority, Energie Beheer Nederland B.V. (EBN) and N.V. Nederlandse Gasunie. Available at: https://www.rotterdamccus.nl/wp-content/uploads/2019/07/Brochure-Rotterdam-CCUS-Porthos-EN-3.pdf (accessed 17 February 2021).

Schäfer D and Stahmer, C (1989) Input Output Model for the Analysis of Environmental Protection Activities. *Economic Systems Research* 1: 203–228.

Shove E (2010) Beyond the ABC: Climate Change Policy and Theories of Social Change, *Environment and Planning A* 42(6): 1273-1285.

SINTEF (2018) Industrial opportunities and employment prospects in large-scale CO2 management in Norway, Report 2018:0594, ISBN 978-82-14-6865-8. Available at https://www.nho.no/contentassets/e41282b08ceb49f18b63d0f4cc9c5270/industrial-opportunities-ccs_english.pdf (accessed 17 February 2021).

Stern, N. (2021) G7 leadership for sustainable, resilient and inclusive economic recovery and growth: An independent report requested by the UK Prime Minister for the G7. London School of Economics. Available at https://www.lse.ac.uk/granthaminstitute/publication/g7-leadership-for-sustainable-resilient-and-inclusive-economic-recovery-and-growth-summary-report/ (accessed 11 June 2021).

Turner K, Race J and Sweeney G. (2019) The economic opportunity for a large-scale CO2 management industry in Scotland. Report produced for Scottish Enterprise. Available at: https://www.evaluationsonline.org.uk/evaluations/Search.do?ui=basic&action=showPromoted&id=689 (accessed 8 June 2021).

Turner K, Race J, Alabi O, Katris A and Swales JK (2021) Policy options for funding carbon capture in regional industrial clusters: What are the impacts and trade-offs involved in compensating industry competitiveness loss? *Ecological Economics* 184: 106978.

UK Legislation (2019). UK Climate Change Act 2050 Amendment (2019). Available at: https://www.legislation.gov.uk/ukdsi/2019/9780111187654/pdfs/ukdsiem_9780111187654_en.pdf (accessed 17 February 2021).

Zero Emissions Platform, ZEP (2018) Role of CCUS in a below 2 degrees Scenario. Report published by ZEP (European Technology and Innovation Platform adviser to the EU on deployment of CCS/CCUS). Available at: https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-Role-of-CCUS-in-below-2c-report.pdf (accessed 2 July 2021).