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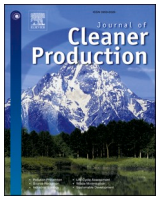

Industrial carbon capture utilisation and storage in the UK: The importance of wage responses in conditioning the outcomes of a new UK CO_2 transport and storage industry emerging in a labour supply constrained economy

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ABSTRACT

Carbon capture usage and storage (CCUS) is emerging as an important solution in delivering deep emissions reductions in energy-intensive industries, enabling hydrogen production, and possibly directly capturing existing carbon dioxide (CO_2) from the atmosphere. The potential for associated new industry activity – for example in CO_2 Transport and Storage (T&S) – could also be important in transitioning economies with legacy investment in oil and gas extraction. This paper addresses the question of how introducing a nascent T&S industry may impact the wider UK economy in the presence of persisting national labour supply constraints. It does so by refining a multi-sector economy-wide computable general equilibrium (CGE) model of the UK to run scenarios focussed on the emergence of a nascent sector, involving identification of benchmark activity – here, the existing oil and gas industry – where that nascent sector is not currently represented in national accounting data. Crucially, the CGE model embeds a theoretically and empirically tested wage bargaining function to consider how cost and price pressures triggered will condition dynamic outcomes for producers, consumers and government budgets. Results suggest that emergence of a new T&S industry is likely to deliver sustained net gains in UK employment and GDP. However, maximising T&S-linked jobs gains while minimising displacement of employment and price pressures elsewhere in the economy requires policy action to alleviate labour supply and skills constraints. This reinforces policy and industry recommendations around the need for net zero workforce planning and attention to the potential fiscal implications of taking action, or not/in different timeframes.

1. Introduction

The transition to net zero economies will involve emergence of several currently nascent sectors. For example, in decarbonising energy-intensive industries, there may be a need for the production, transportation and supply of new low carbon fuels, like hydrogen, and/or clustering and networking of activities required to capture and sequester persisting emissions to offshore storage sites. Thus, there is a need to understand how such nascent activities and industries will integrate into the economy, and how their emergence may be affected by prevailing and evolving economic conditions, such as persisting labour supply constraints and skills shortages.

This paper identifies CO_2 Transport and Storage (T&S) as a core nascent activity within the wider emerging carbon capture utilisation and storage (CCUS) solution that nations like the UK, Norway, the Netherlands, China and the USA are increasingly looking to, not only to decarbonise industry, but to help transition current oil and gas extraction industry and supply chain jobs, infrastructure and other capacity. That is, in reversing flows, with CO_2 generated by burning fossil fuels going back out to geological reservoirs where hydrocarbons have been taken from. The central research question emerges: how will introducing a T&S industry impact the wider UK economy in the presence of persisting national labour supply constraints?

In the UK, government estimates of gross value added (GVA or GDP) and employment associated with T&S and other CCUS activities have been put as high as £4.3 million per annum and 50,000 supported jobs (BEIS, 2019, 2021). However, it is not entirely clear how such figures are arrived at, and little attention seems to be given to labour market conditions and responses, where any increase in wage rates, as labour demand increases in the face of persisting worker and skills shortages,

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could trigger a range of price pressures and displace employment in other sectors.

An overarching aim of the research reported here is to help address this gap in policy intelligence, by considering the question of how emergence of a T&S industry may impact a labour supply constrained economy like the UK, focussing on the potential importance of wage responses. This is achieved by utilising the economy-wide computable general equilibrium (CGE) approach that is commonly applied to consider the impacts of changes activity or policy conditions (see Babatunde et al., 2017, for a climate policy focussed survey of CGE applications).

However, where CGE studies incorporate consideration of CCUS, this is generally limited to broader socio-economic analyses of the investment on and operation of CCUS (see e.g. Chen and Jiang, 2022, for China), the impact on production requirements of industries capturing CO_2 (e.g., see Xiao et al., 2022) and/or with CCUS considered amongst a range of decarbonisation options in considering wider climate policy issues, including carbon pricing (e.g., Pradhan and Ghosh, 2022) and in easing the transition away from fossil fuels (e.g., Hu and Wu, 2023). There is, however, little attention to the impacts of new industry activity associated with CCUS delivery, suggesting the gap in policy intelligence is underpinned by a knowledge gap in the research literature.

Here, in considering CCUS and more generally across the climate and wider public policy space, challenges involved in introducing nascent sectors – i.e., activities not currently represented in economy-wide input-output accounts informing the structural databases of most CGE models – have had limited coverage in CGE studies. Where new, often low carbon, industry emergence is considered (e.g., Phimister and Roberts, 2017), this generally does not extend to consider challenges such as the need to potentially oversize new industry capacity, both due to challenges around the nature of often indivisible infrastructure and an absence of market demand. However, both latter issues are likely to be relevant in the case of CO_2 T&S where, for example, the consequent need to subsidise users and/or guarantee utilisation/demand for suppliers has been the focus of UK policy development (BEIS 2022).

Thus, the objective of this paper is to make a useful contribution to both policy and scientific understanding by setting dynamic CGE scenario simulation analysis of the emergence of a CO_2 T&S industry in the context of various nascent sector challenges. These include the initial policy intervention to ensure capacity creation and utilisation that is likely required and being planned in the case example of the UK considered here, but with more generic lessons emerging both in this regard and in terms of the potential impacts of labour supply constraints as part of the wider economic landscape in many nations.

The remainder of the paper is structured as follows. Section 2 provides a fuller background and context to the UK case and the literature base to which this new study contributes. Section 3 outlines the CGE method before the simulation strategy is set out in Section 4. Results are presented in Section 5 informing the discussion in Section 6. Conclusions and policy recommendations are offered in Section 7.

2. Further background and context

CCUS involves the sequestration of CO_2 emissions captured during the use (or conversion) of fossil fuels in industrial or energy production (including hydrogen) with transport to storage sites, generally involving offshore reservoirs that previously held hydrocarbons (Serin, 2023). The International Energy Agency (IEA, 2020) presents evidence indicating the impossibility of delivering on the net-zero objectives globally by 2050 without CCUS.

Thus, CCUS plays some role in the net zero and economic transition plans of many nations, not least those with CO_2 sequestration capability and capacity developed in hosting oil and gas industries (e.g., see Chen and Jiang, 2022, for China). In Europe, this includes Denmark, Norway, the Netherlands and the UK, with potential for development of cross-country CCUS networks and emergence of international trade in CO_2 T&S services (see e.g., European Commission, 2022).

In the UK, between the Prime Minister's 'Ten Points Plan for a Green Industrial Revolution (HM Government, 2020) and subsequent Net Zero Strategy (HM Government, 2021), the policy objective has emerged to have four operational CCUS clusters (i.e., clustered capture industries linked to T&S networks) capturing and sequestering around 20-30MtCO_2 by 2030. 2021 saw initial steps taken with the announcement of two Track 1 CCUS clusters, in Merseyside (HyNet) and Teesside/North Humber (the East Coast Cluster). See DESNZ (2021). Early in 2023, the UK Government renewed its commitment to CCUS through the announcement of £20 billion funding for early deployment of CCUS in the UK Government's spring 2023 'Powering Up Britain' announcement (DESNZ, 2023a). In July 2023 the UK Government announced the selection of the Scottish Acorn project (a reserve cluster on Track 1) and South Humber Viking CO_2 T&S systems as the Track 2 CCUS clusters, subject to final decisions, due to their ability to meet the Track 2 criteria (DESNZ, 2023b).

While emphasising the need for delivery of economic benefits in the Track 1 (DESNZ, 2023c, p.2) and Track 2 (DESNZ, 2023d, p.4) calls, the UK Government has not updated on the (BEIS, 2019, 2021) work that generated the £4.3 million GDP p. a./50,000 supported jobs figures cited in the introduction to this paper. Some more recent studies have been published in the grey literature, largely relying on demand-drive and simple economic 'multiplier' approaches, such as that commissioned by TUC & CCSA (2013).

In terms of the research literature, the most common focus of CCUS studies is on carbon reduction potential (e.g., Fan et al., 2021), plant-level abatement costs (e.g., Fan et al., 2022) and/or barriers to uptake (e.g., Budinis et al., 2018). Studies are also prevalent on the importance of uncertainty analyses in techno-economic assessment of CCUS uptake (e.g., Van der Spek et al., 2020) and firm-level issues around the importance of capture readiness to ease retrofitting processes (e.g., Ding et al., 2020).

CGE modelling tends to be the dominant methodology for economy-wide scenario simulation analysis around new or emerging activities. Here, as explained in the introduction, there is limited attention to CCUS in the literature beyond its role as an emissions reduction solution. This is a crucial gap where one expectation of CCUS, particularly in those nations with capability and capacity developed through oil and gas extraction, is to generate new supply chain activity and jobs associated with the emergence of domestic and traded activity as this decarbonisation solution is more widely adopted (BEIS, 2021). It is this gap the current paper aims to contribute to addressing, with specific focus on the potential contribution of new CO_2 T&S activity developing from the foundations of the existing oil and gas industry in the case of the UK, and with particular attention to how supply constraints in the national labour market may condition outcomes.

3. Materials and methods – the UKENVI CGE model of the UK economy

As noted above, CGE models are the most common approach adopted in conducting scenario simulations of changes affecting the wider economy. Here, one of the main benefits of CGE is enabling users to capture the impacts of price changes across the wider economy. Given the focus here on labour market conditions in determining wider economy outcomes, where wages are among the key determinants of prices across all economies, CGE modelling is ideally placed to investigate the effects this study aims to capture.

The UK CGE model, UKENVI, is calibrated on a social accounting matrix (SAM) that incorporates the most recent (at the time of undertaking the applied work), and sectorally detailed 2018 industry-by-industry (IxI) input-output (IO) data published by the UK Office for National Statistics (ONS) aggregated to 33 domestic sectors (and corresponding imports), but retaining original reported data on key sectors/activities driving and experiencing outcomes (see Appendix A for a

listing). In the absence of more recent IO publications – a problem inherent to most CGE studies given the time lag in producing complex IO data for any nation - the 2018 SAM[1] is taken to represent the real economy structure in the pre-CCUS base year of 2022. This is accompanied by the necessary 'health warning' that this requires abstraction from subsequent changes in the structure of key sectors, and across the wider of the UK economy (particularly but not limited to the COVID pandemic, Brexit and war in Ukraine). The CGE modelling approach adopted involves simulating and focussing only on the impacts of introducing the T&S sector. This is important to build new understanding that isolates and explains causal effects and the transmission mechanisms thereof, with all results reported in terms of changes relative to an otherwise unchanging real baseline.

One challenge in modelling the impacts of a nascent sector like CO_2 T&S activity is that it is not present in the base year IO and SAM data. Until such a time as T&S actors can be surveyed in the way all UK producers are surveyed to build the national IO tables, the most transparent approach is to select a proxy industry and take the supply chain structure of that as the destination of investment in the new (34th) industry. The proxy selected here is the existing UK oil and gas extraction industry, on the basis that it currently extracts fossil fuels from the offshore reservoirs that CO_2 will be sequestered to. Using the proxy essentially means that the upstream supply structure is carried over to T&S, but with a minimal starting level of activity (as small as the CGE model will pick up – here 0.2% of the oil and gas proxy) that builds to a projected scale based on the estimated investment required to create sufficient capacity to sequester emissions generated in the Track 1 and 2 CCUS cluster areas identified.

The following is a high-level description of the key features of UKENVI for the application presented here to facilitate the readers' understanding. Turner (2021, 2022a,b) provide more detailed descriptions of UKENVI with the former two focussing specifically on earlier T&S applications, based on earlier stage datasets and without the in-depth attention to labour market responses developed here.

3.1. Production and investment

The output of all sectors is determined using a nested CES production function, as is standard in CGE models, involving substitution between domestically produced and imported intermediates, including different types of energy supply, and labour and capital. In terms of the latter, the existing 33 sectors all use a recursive dynamic process to adjust their capital stock on a year-by-year basis. Investment is endogenous, covering depreciation and a fraction between the actual and desired capital stock. Investment in the nascent T&S industry (the 34th sector) is determined exogenously, simulating an initially oversized industry prior to its operational phases. One of the long-run equilibrium conditions across all sectors is that the actual matches the desired capital stock, with investment being sufficiently large to cover capital depreciation.

3.2. Labour market

The central assumption for the UK economy is of a fixed total labour supply, abstracting from any natural population changes, which (as with factors such as technological progress) would require a full analysis of potential counter-factual scenarios involving a range of potential economic and policy developments. This would distract from identifying and understanding the drivers and outcomes associated with the T&S industry rollout itself.

In the absence of sectoral data on skills/occupations, the labour supply is assumed fully mobile across sectors. However, given the importance of the overall labour supply constraint, an imperfectly competitive labour market is specified. Here, workers move in and out of a pool of unemployed labour in response to changes in labour demand and the UK average real wage rate, through specification of a bargained real wage (BRW) function based on the work of Blanchflower and Oswald (2009):

$$ln[w_R] = \omega - \varepsilon\, ln(u_t) \tag{1}$$

The base year (full-time equivalent, FTE) unemployment rate is 4.1% (in line with ONS data[2]). Workers have greater bargaining power as the unemployment rate falls and vice versa, with this effect determined by ε, the elasticity of wages relative to the unemployment rate. As in all UKENVI applications, the central value of ε is set at 0.113 based on the work of Layard et al. (1991). This is consistent with more recent analyses by Blanchflower and Oswald (2005), who find a persistent universal long-run value of this parameter of 0.1 across more than 40 nations, including the UK, where Allan et al. (2021) confirms the persistence of the 0.1 value.

However, in the interest of understanding the implications of potential changes in the value of ε, in the context of policy responses to changing labour market conditions, sensitivity analyses are conducted involving consideration of (relatively) low (0.05) and high (0.2) values for ε. This permits consideration of the importance of the unemployment-wage bargaining relationship in the context of potential policy action on skills development and/or otherwise inducing increased participation in labour supply activity. The analysis includes consideration of an extreme case with zero bargaining power (ε = 0.000001), effectively replicating a fixed real wage (FRW) specification.

To more fully understand how the influence of real wage bargaining on long-run equilibrium outcomes may be reduced alternative scenarios regarding the labour supply are also considered. The first involves assuming a flow migration process, following the approach developed by Layard et al. (1991) and Treyz et al. (1993) that is more generally applied in sub-national or regional contexts, taking the form:

$$nim_t = \varsigma - v^u\left[ln(u_t) - ln\left(\overline{u}^{ROW}\right)\right] + v^w\left[ln\left(\frac{w_t}{cpi_t}\right) - ln\left(\frac{\overline{w}^{ROW}}{\overline{cpi}^{ROW}}\right)\right] \tag{2}$$

Here, migration in each year is negatively related to the gap between the log of national (here UK) and international (ROW) unemployment rates and positively to the log of real wages. Two elasticities measure the impact of the unemployment (v^u) and real wages (v^w), respectively set at -the 0.08 and 0.06 values estimated by Layard et al. (1991). Basically, this enables an updating of the UK labour supply in response to changing labour demand where, over time, any increase in the real wage rate will be negated by the response of an increasing labour supply.

However, following Brexit, UK Government policy is more focussed on targeted (often sector-specific and likely transitory) migration. Thus, a stock migration process is also considered, where the labour supply is exogenously determined as follows:

$$LS_t = LS_0 \times (1 + u_0) + stckmig_t \tag{3}$$

where $stckmig_t$ determines the variation of the labour supply in time period t (year). This will similarly alleviate the national constraint and consequent wage pressure, but not as extensively as with open flow migration as in (2).

3.3. Household consumption

An aggregate household group/single representative household is identified, where the main components of income are earnings from employment, capital income and government transfers (the latter is

[1] The SAM used here is publicly available at: https://doi.org/10.15129/67521ce7-3184-47bf-8d63-4764ae5d1951

[2] Data on the UK's annual unemployment rate can be sourced at https://www.ons.gov.uk/employmentandlabourmarket/peoplenotinwork/unemployment/timeseries/mgsx/lms.

assumed fixed in real terms). Total net income (excluding taxes and savings) determines household consumption, while the SAM gives the initial consumption distribution. However, the level and composition of household spending responds to changes in income and relative prices.

3.4. Trade

The UK trades with a single external rest of the world (ROW) region, where the prices of goods and services are fixed but the volume of imports and exports responds to relative price changes between domestic and external goods and services (Armington, 1969).

3.5. Government

The government budget (*GB*) is given by:

$$GB_t = GY_t - GEXP_t \quad (4)$$

GY is government revenue, composed of income tax (the largest component), other taxes (e.g., the indirect business tax), capital revenue and foreign remittances at a fixed exchange rate. *GEXP* reflects the government expenditure:

$$GEXP_t = GQ_t \bullet Pg_t + TRG_{hh} \bullet CPI_t + TRG_{firm} \bullet CPI_t \quad (5)$$

GQ is real government spending on goods and services, which is exogenously determined but adjusts for changes in the government price index *Pg*. Government transfers to households (TRG_{hh}) and firms (TRG_{firms}) similarly adjust for changes in the consumer price index (*CPI*). A balanced budget is not imposed, with the implication that the value of *GB* is impacted via *GQ* where the UK Government acts to guarantee demand for T&S output.

4. Calculation - CGE simulation strategy

4.1. Introducing an initially oversized T&S sector

The simulation strategy comprises two main components. The first focuses on the dynamic adjustment of the capital stock of the new T&S sector, with a view to establishing the necessary infrastructure and production capacity ahead of the sector becoming operational and market demand emerging. There are two Investment Stages, enabling a sustained Operational Phase.

Investment Stage 1 involves developing T&S capacity to sequester CO_2 emissions generated in the Track 1 CCUS clusters. These are the North England Hynet and East Coast clusters in Merseyside and Teesside/North Humber regions. In the absence of publicly available information on the size of the investment and how it is spread over time, capital requirement estimates are drawn from Calvillo et al. (2022), adjusting for the subsequent identification of the Track 1 and 2 clusters. The outcome is the scenario specification that £1,599 million of new capital needs to be introduced for the new T&S industry to service the sequestration needs of Track 1 clusters. Based on the capital intensity of the oil and gas benchmark, this requires a total investment spend of £2,007 million over the 4 years to 2026, with this element of the T&S industry entering the Operational Phase in 2027.

Investment Stage 2 of T&S capacity creation begins in 2027 for the Track 2 clusters, which are now identified as the Scottish Cluster and the Viking cluster in the South Humber region.[3] Integrating the Track 2 clusters in a full-scale T&S industry (with ongoing additional investment requirement to maintain Track 1 capacity) requires £1,448 million additional capital and a total investment of £2,202 million spread over 3 years. Track 2 is operational from 2030 so that the T&S industry fully moves into the Operational Phase from 2030, in alignment with HM Government (2020) goals.

In total, for the T&S industry to service both Track 1 and 2 clusters, a £3,047 million capital requirement by 2030 requires a total investment of £4,210 million and subsequent ongoing annual investment of £431 million to offset depreciation. The capital introduced for Track 1 clusters supports £553 million of new industry output, which increases to £994 million when both Track 1 and 2 clusters are operational, enabling the sequestration of 53.84MtCO_2e of domestic industry emissions only. Note that this total volume exceeds the UK Government's targets for 2030 (HM Government, 2021), with Calvillo et al.'s (2022) T&S investment requirements and capacity calculated based on the total emissions of each cluster in the absence of detailed information on which industrial units will utilise T&S services.

Crucially, in line with the UK Government's current CCUS Business Models (BEIS, 2022) demand for this output is assumed to be guaranteed (paid for) by the UK Government. In practice this is likely to involve subsiding users (BEIS, 2022, p.12). In the absence of specific information at this stage as to how such an intervention will be funded, a deficit funding approach is assumed and, thus, reflected in the government budget balance, at least for the mid-term timeframe to 2045 focussed on here. This may align with government commitments as currently stated for a 10–15-year timeframe once T&S is fully operational (see BEIS, 2022, p.48). However, where the model is run on to consider the properties of long-run equilibria beyond that point, results should be considered with caution.

Thus, the first component of the simulation strategy involves two distinct types of exogenous shocks: (1) investment in the T&S sector, with both the transitory upfront spending to 2030 and subsequent annual spending to offset depreciation; (2) government guaranteeing demand for the capacity created through the subsequent Operational Phase at least until 2045.

4.2. Considering the implications of labour market constraints

The second component of the simulation strategy focusses on the implications of workers having bargaining power in negotiating real wage rates and, crucially, how outcomes are affected by varying the unemployment-wage elasticity governing the extent of this bargaining power under the central BRW closure. The hypothesis is that this may reflect changes in the importance of real wage bargaining (and therefore the unemployment-wage elasticity) due to government action (or not) in supporting the training of new workers and/or retraining/upskilling the existing domestic labour force. This is considered against the potential to ease international migration constraints.

The first four scenarios (Sc1-4) reported focus on understanding the importance of wage bargaining pressure. A further two (Sc5-6) consider the potential impacts of easing the labour supply constraint itself. In all cases, the model is run forward over the two Investment Stages and the Operational Phase, with focus on reporting of results on both long-run outcomes and the dynamic adjustment of key employment-related variables. The scenarios are summarised as follows:

- **Sc1 (central case)**: Bargained real wage with the unemployment-wage elasticity set at 0.113 (base value) and fixed labour supply.
- **Sc2**: Adjust Sc1 for higher (0.2) unemployment-wage elasticity only (i.e., increasing wage bargaining power where there is little/no action on skills).
- **Sc3**: Adjust Sc 1 for lower (0.05) unemployment-wage elasticity only (i.e., reducing wage bargaining power where non-wage actions to increase labour supply are enacted).
- **Sc4**: Adjust Sc 1 for effectively zero (0.000001) unemployment-wage elasticity only, to replicate a fixed real wage closure to identify long-

[3] The analyses detailed here were conducted prior to the announcement of the Track 2 clusters. Subsequent information suggests that the size of the Viking cluster may be overestimated here. Generally, applied policy analyses building on the research presented here will likely require updating as more information emerges.

run outcomes where labour supply constraints and associated wage pressures do not persist.

- **Sc5**: Building on Sc 3 as key policy scenario where government eases the unemployment-wage link by focussing on skills development and other non-wage adjustments, but also allows temporary stock migration to address transitory peaks in wage-cost pressure (here linking to construction sector activity in the Investment Stages).
- **Sc6**: Also building on Sc3, but with labour supply adjusting in response to changes in the UK real wage and unemployment rates, to indicate the maximum dynamic adjustment in the UK labour supply (and its sectoral composition) required to maximise employment and other wider economy gains from introducing the new T&S industry.

5. Results

5.1. The importance of real wage bargaining power in driving economy-wide outcomes

Table 1 summarises the key economic characteristics of the new UK CO_2 Transport and Storage industry that emerges through the Track 1 and 2 developments captured in the Investment Stages. Once the T&S industry fully enters the Operational Phase from 2030, sequestering just under 54 Mt of industrial CO_2 emissions per annum, the total direct contribution to UK GDP is £627 million per annum and direct T&S employment is 432 full-time equivalent (FTE) jobs. As explained in Section 4.1, the initial stimulus to the wider economy emerges through the £4.2 billion of investment to create T&S industry capacity involving a £3 billion capital stock. Once the industry is fully operational, there are two sources of sustained stimulus via annual investment spending of £431 million per annum to maintain the T&S capital stock and the £994 million of demand per annum (guaranteed by the UK government) for the industry's output.

The CGE scenario simulations involve isolating the economy-wide impacts of these combined transitory and sustained stimuli. Crucially, once in the Operational Phase, economy-wide impacts are driven through indirect stimulus of the type of domestic supply chains and import requirements traditionally associated with the UK oil and gas industry, but now with the 'greener' focus of supporting the sequestration of industrial CO_2 emissions. However, an additional wider economy stimulus emerges as income from employment rises, due to a combination of rising employment and real wage rates where the 'green' credentials of associated economic activity - including GDP and jobs gains - may be questionable.

Referring to the central case (Sc1 – with the default wage bargaining closure and unemployment-wage elasticity) the first data column of Table 2 reports the long run impact on key macroeconomic indicators, mainly in terms of percentage impacts relative to the model's 2018 base year (assumed to apply in 2022 with no other real changes to the economy). The corresponding Sc1 trendlines in Fig. 1 show the evolution of total GDP and employment, where these variables settle on their long-run values quite rapidly (by the mid-2030s). The first bar of Fig. 2 (reported for 2045 as a key timeframe by which government is likely to move towards an alternative funding model, and where Sc1-3 reach long-run equilibrium) reports the sectoral distribution of the employment impact, in terms of the number of FTE jobs.

Table 1
Key economic characteristics of the UK CO_2 Transport and Storage industry.

Key T&S industry investment and operational characteristics	Track 1 clusters only	Track 1 & 2 clusters
Total capital stock created (£m)	1,599	3,047
Pre-operation investment (£m) - Evenly distributed over the investment period	2,007	4,210
Ongoing additional annual investment (£m)	240	431
Total output/demand serviced (£m)	553	994
Direct employment (FTE)	241	432
Value added (GDP) (£m)	349	627
Total industrial emissions serviced (Mt, millions of tonnes of CO_2)	30.60	53.84

Table 2
Key long-run macroeconomic impacts in the UK of introducing the T & S industry in Track 1 and Track 2 clusters (alternative bargained real wage assumptions).

	Scenario 1: Central BRW case (0.113 U–W)	Scenario 2: BRW (0.2 U–W) High bargaining power	Scenario 3: BRW (0.05 U–W) Low bargaining power	Scenario 4: BRW (0.000001 U–W) No bargaining power
Net public deficit impact (£million), composed of:	−762	−786	−715	−565
Net additional government revenues (£million)	557	573	526	429
Direct spending on T & S (£million)	−994	−994	−994	−994
Nominal adjustments to meet real spending commitments (£million)	−326	−365	−248	0
GDP (£million)	960	862	1,151	1,762
GDP (% change)	0.050%	0.045%	0.060%	0.092%
Employment (FTE)	4,395	2,788	7,547	17,578
Employment (% change)	0.015%	0.009%	0.026%	0.060%
Unemployment (% change)	−0.349%	−0.221%	−0.599%	−1.395%
Nominal wage - index to 1 (% change)	0.075%	0.084%	0.057%	0.000%
Real wage - index to 1 (% change)	0.039%	0.044%	0.030%	0.000%
CPI - index to 1 (% change)	0.036%	0.040%	0.027%	0.000%
Exports (% change)	−0.068%	−0.076%	−0.052%	0.000%
Imports (% change)	0.087%	0.088%	0.083%	0.071%
Real household consumption (% change)	0.055%	0.054%	0.057%	0.064%
Total investment (% change)	0.089%	0.085%	0.098%	0.127%

Basically, this is a picture where the combined investment and demand stimulus of introducing and publicly supporting the new T&S industry triggers a marginal but sustained increase in UK GDP of £960 million per annum (2018 prices - an uplift of 0.5% relative to what it would otherwise be), with a gross increase in total employment of 4,395 jobs (including 432 direct T&S industry jobs). There is also a net increase in total government revenues per annum (p/a) (£557 million) that partially offsets the public spending requirement (£994 million) of guaranteeing demand for T&S output.

Note that the sustained increase in UK employment (0.015%, 4,395 jobs) is less than proportionate to the GDP uplift. This is a compositional effect, driven by the relatively high capital intensity of the T&S industry and its supply chain. However, with an uplift in total household consumption of 0.055%, there is a small but sustained stimulus to more

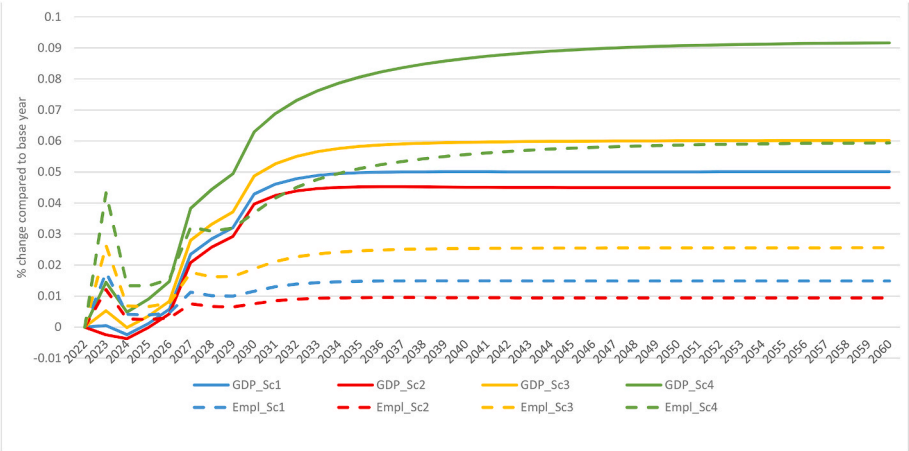

Fig. 1. Adjustment path of UK GDP and total employment of introducing the CO_2 T&S industry (Scenarios 1–4, % changes).

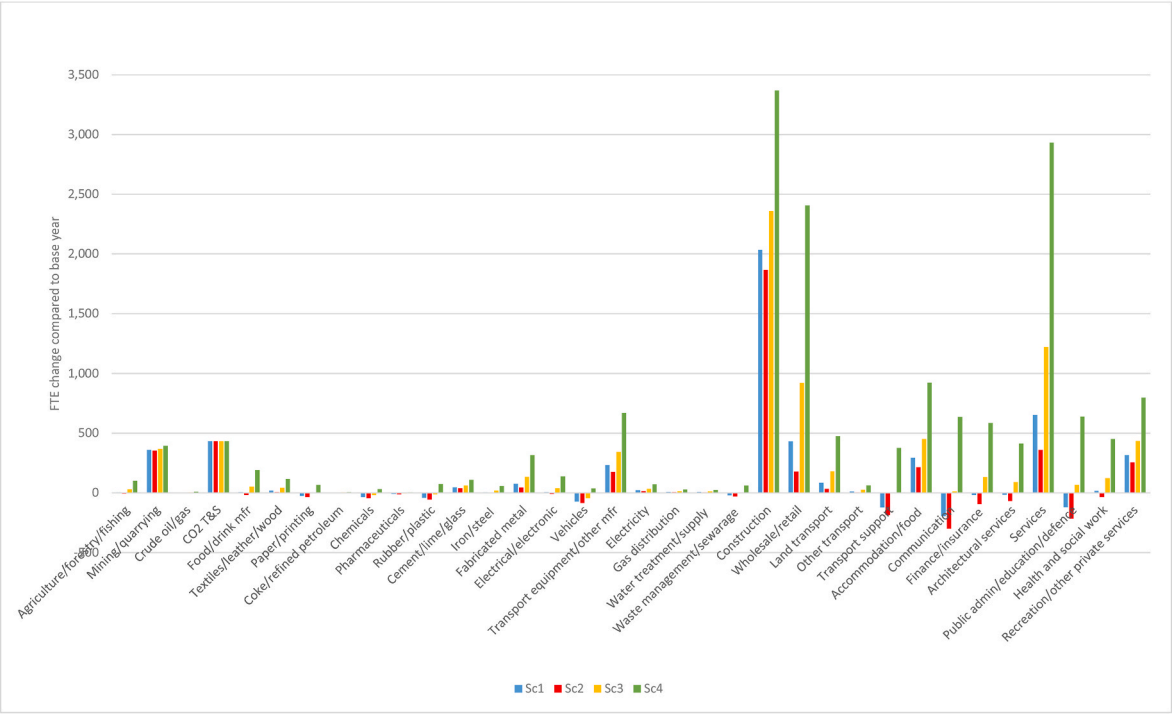

Fig. 2. Impacts on sectoral (full-time equivalent, FTE) employment by 2045 of introducing the CO_2 T&S industry.

consumer-facing sectors. Fig. 2 shows that (by 2045) some sectors suffer marginal net losses in employment as wage rates and price levels increase as the economy expands in the presence of the persisting UK labour supply constraint. These include those manufacturing industries where the 0.068% contraction in export demand is concentrated and several more labour-intensive service sectors that benefit less, if at all, from increased T&S supply chain and consumer demand.

The crucial constraint on expansion is the impact of increased labour demand (where the national labour supply is fixed) on nominal wage costs and price levels more generally, reflected in the CPI dynamics in Fig. 3 for nominal price dynamics. The trigger for price pressure is bargaining between workers and employers over real wage rates. In Sc1, the average real wage rate across the UK labour economy is bid up from the outset, settling on the sustained increase of 0.039% (first column of Table 2). This combines with the sustained 0.015% increase in employment to raise household incomes and power the 0.055% increase in real household consumption.

However, the sustained impact on the nominal wage faced by producers is greater (0.075%), reflecting the 0.036% increase in the CPI as the impact of constrained expansion on all prices filters through all costs and prices in the economy. The CPI increase also has implications for the public budget, assuming the UK Government is committed to maintaining the real value of spending, with the requirement for an additional £326 million in nominal spending partially offsetting the positive impact of increased revenues on the net annual public budget outcome (-£762 million).

The extent to which real wage pressure constrains the expansion can be understood through consideration of Sc2-4, reported in the second, third and fourth data columns of Table 2 and the GDP/employment trendlines in Fig. 1. Examining the Sc2 results, where the wage rate response to any reduction in unemployment (rise in labour demand) is increased (almost doubled), reflects a situation where worker bargaining power increases. This could potentially happen if government is not seen to act on skills development or any other route to ease the national

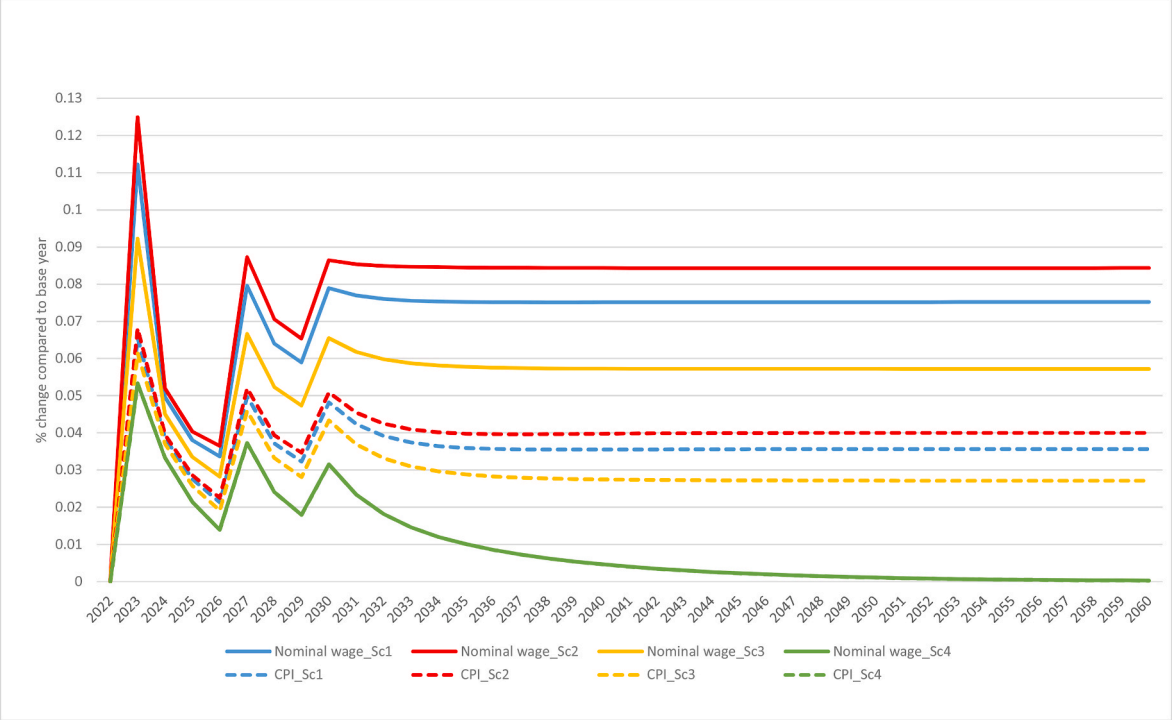

Fig. 3. Impacts (% change) over time on UK CPI and nominal wage rate of introducing the CO_2 T&S industry.

labour supply constraint, particularly in a wider transitionary context where multiple competing demands for labour are likely to compound beyond the T&S element of industrial CCUS considered here.

The central impact is a larger increase (0.044% in Sc2 compared to 0.039% in Sc1) in the real wage rate, which feeds through to the CPI and nominal labour costs. However, this cost-price impact is constrained by the negative effect it has on the boost to total domestic activity, where the sustained uplift to GDP falls from £960 million per annum to £862 million. Comparing the first and second data columns of Table 2, observe that this is due to the combination of reduced domestic investment and consumption activity, where the greater real wage uplift is more than offset by a smaller increase in employment. However, higher wage rates do support a larger increase in government revenues (which rise by £16 million relative to Sc1), but with the nominal public spending implications of the CPI increase more than offsetting this so that the net public budget outcome worsens (to £786 million p/a, where the £994 million commitment to guaranteeing demand for T&S output is constant).

The loss in employment gains, which Fig. 1 shows takes effect from the outset, ultimately settles at a loss of just under 37% relative to what is reported in Sc1 (falling from 4,395 FTE job gains to 2,788), which is substantial relative to the reduction in GDP gains (just over 10%). This reflects the importance of wage cost and consumer price pressure in constraining the expansion beyond the highly capital-intensive new T&S industry, where the exogenous imposition of the scaled industry (as reflected in Table 1) is unaffected by increased real wage pressure.

This is a key policy consideration in a broader net zero/just transition context. The operation of the new T&S industry should sustain previous oil and gas industry jobs and create other greener supply chain employment and increases in wage incomes, fuelling further final demand and spending. This is positive for economic welfare – including through creation of jobs accessible to unskilled workers across the wider economy - but will limit overall emissions reductions (not modelled here but implied by increased activity). However, where the combination of the persisting labour supply constraint and wage bargaining trigger cost and price pressures across the economy, wider job creation will be limited, particularly in more labour-intensive sectors where the impact on wage costs, associated with even lower paid jobs, limits expansion.

However, consider Sc3, where the key wage-unemployment elasticity in the wage bargaining function is reduced (by more than half). All the cost-price pressures are reversed relative to Sc1-2 considerations above, and the wider economy expansion is less constrained. This may reflect a situation where government acts, for example through investment in skills development and/or to otherwise enable workers to move out of unemployment (or other forms of economic inactivity) through inducements not confined to wage rates. Here, comparison of the results in the third data column of Table 2 - and the Sc3 GDP and employment trendlines in Fig. 1 - with the Sc1 results shows that the real wage and price pressure is reduced by around a quarter, which limits the contraction in export demand.

Here, the overall impact on the economy is reflected in an increase in the GDP uplift of about 20% (from £960 million in Sc1 to £1,151 million to Sc3). However, again, the most substantial impact is on total employment, where the FTE gain across the economy increases by 72%, from 4,395 to 7,547. This offsets the lower rise in real wage rates to deliver a slightly larger boost to total household consumption (0.57%). On the other hand, there is a slight reduction in government revenues due to reduced income tax take when the wage rate is lower. Nonetheless, this is more than offset by the reduced pressure on nominal spending so that the overall public deficit outcome improves, from -£762 million p. a. in Sc1 to -£715 million p. a. in Sc3. Moreover, Fig. 2 shows that net losses in sectoral employment by 2045 are almost entirely negated in Sc3, with only the manufacture of paper, rubber/plastic and vehicles still suffering some sustained net loss.

However, some wage and price pressures do persist, with the implication that the positive activity and employment outcomes emerging in Sc3 do not equate to the type of demand-driven 'multiplier' outcome that is likely to underpin the types of employment outcomes being considered for the UK in BEIS (2019, 2021). Particularly in the presence of a persisting labour supply constraint such as that characterising the UK economy, such outcomes could only emerge if sustained wage pressures in the system were substantially limited. This is tested in Sc4 by effectively collapsing the BRW function by setting the wage-unemployment elasticity close to zero. This represents an extreme

illustrative scenario where the key feature of the results in the fourth data column of Table 2 is the absence of real wage pressure (from the outset).

The long-run implication (with full economy-wide adjustment not achieved until the early 2050s in this more expansionary case), is that, once short-term capital constraints ease through dynamic investment processes, there is no sustained nominal price pressure in the system at all (see Fig. 3). Thus, sustained GDP and employment gains are maximised – at 0.092%/£1,762 million per annum and 17,578 FTE jobs respectively – with no losses in export demand or any sectoral displacement of activity or employment, even by 2045 (see Fig. 2).

Note that the model configuration underlying and long-run outcomes (see Table 2) emerging from Sc4 effectively replicates a case where the real wage is fixed (tested by re-running Sc4 substituting the bargained real wage labour market closure in equation [1] with a fixed real wage closure). However, such an absence of any real wage response is unlikely, particularly in the context of a persisting labour supply constraint, even where unemployment is low. Thus, it is useful to consider the impacts of potentially relaxing the labour supply constraint.

5.2. The impacts of relaxing the labour supply constraint

The results of Sc3 show that wage-driven cost-price pressures may be reduced if policy action can be taken to induce unemployed workers to re-join the labour supply through non-wage drivers - for example training and other action on skills development. However, action to otherwise increase the labour supply, for example through attracting skilled workers from overseas, could also play a role. Moreover, initial bidding up of UK wage rates could play a key role in ultimately alleviating wage-cost pressure where the outcome is the attraction of additional workers.

Since leaving the European Union, UK policy no longer allows for unconstrained in-migration. However, targeted in-migration is possible through a new 'points based' system (House of Commons Library, 2022), not least as a means of addressing specific labour supply constraints and associated wage cost pressures, even if only on a transitory basis. Thus, one informed use of the results reported in Section 5.1 may be to consider where spikes in labour costs occur (e.g., 2023 and 2027, during the two Investment Phases) and what sector(s) are demanding the most labour (the construction sector in these two cases) and direct targeted migration to such sectors during these periods of most acute need during the Investment Stage.

Sc5 focusses on such an example, combining the more optimistic assumption regarding a reduced domestic unemployment-wage elasticity (i.e., as in Sc3, assuming there is enhanced action on skills development and/or other non-wage drivers to incentivise domestic participation in the labour force) with some transitory stock migration set equal to the additional annual construction industry labour demand in the Investment Phase. Here, this peaks at 11,499 migrants in 2023, reducing to an average of 4,298 migrants until 2029 prior to Operational Phase activity.

Considering Fig. 4, a key outcome of Sc5 is that the domestic labour supply constraint is relaxed to the extent that the full potential UK-wide employment gains observed in Sc4 (the fixed labour supply case where workers have no real wage bargaining power, or the real wage is fixed) can be fairly closely replicated between 2023 and 2026. That is, in those years where only upfront investment activity takes place. This is achieved under Sc5 with only a marginal uplift in the real wage rate in all years except 2024, when, indeed, it is driven down by the relatively substantial in-migration of labour (4,822 workers) in response to the spike in the 2023. From 2027, when Track 1 moves into the Operational Phase, the gap starts to open between Sc4 and Sc5 employment impacts and from 2030, when Investment Phase 2 ends, the employment trajectory under Sc5 falls back down to converge with that in Sc3, and real wage growth gains pace, again converging with that under Sc3. However, the temporary uplift does put the economy on a slightly quicker trajectory to achieve the Sc3 long run employment and other outcomes.

In order to more closely replicate the Sc4 trajectory for employment and wider economy adjustment, further relaxation of the absolute labour supply constraint is required. This could take the form of continued stock migration aimed at different sectors in subsequent timeframes or longer-term action on skills development and education of the evolving domestic workforce to meet projected sectoral needs. One way of identifying these needs is to run scenario simulations with an unconstrained labour supply and focus on the sectoral composition of the potential employment outcomes. Here, this is illustrated through Sc6, which involves turning on the flow migration labour market closure combined with the Sc3 real wage bargaining assumptions so that wage and unemployment responses are fully considered. The outcomes contrasts with those of Sc4 (where the real wage is fixed), though Fig. 4 shows that the employment trajectories of Sc4 and Sc6 do ultimately converge on the same long-run outcome, but with a different pathway of adjustment in the real wage rate under Sc6 until this is achieved.

However, the key point is that in considering a scenario simulation

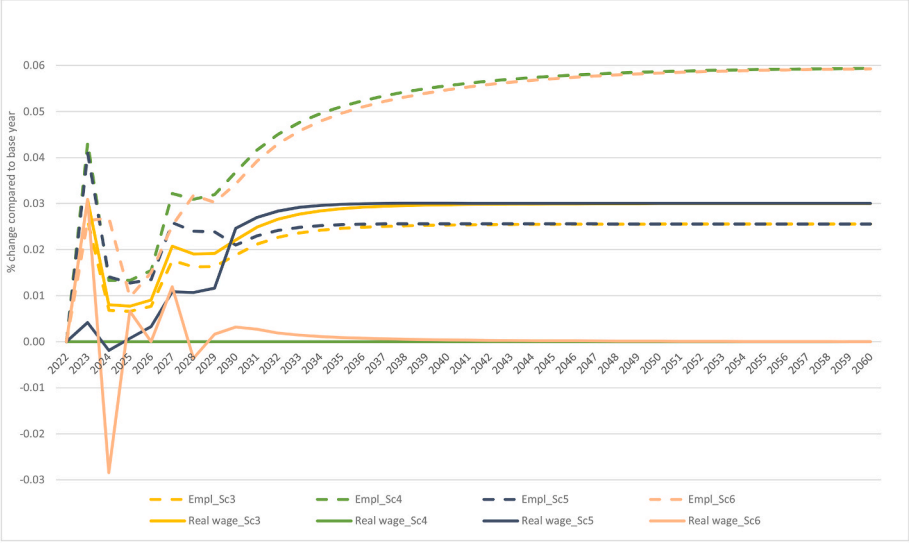

Fig. 4. Impacts (% change) over time on UK employment and average wage of introducing the CO_2 T&S industry under alternative wage bargaining and labour supply assumptions.

output like Fig. 5 (here shown for Construction and T&S and broad groupings like the 'T&S main supply chain', as well as the 'All Other Services' grouping, across which the largest employment impacts are observed across different timeframes), it is possible to identify how the sectoral composition of employment requirements shift over time as the introduction of the new UK T&S sector evolves. Fig. 5 shows that ultimately the T&S industry and its supply chain present most employment requirements in the Operational Phase. However, note that increased household consumption also contributes to gains in some of the key T&S supply chain sectors, such as 'Wholesale/retail'. Generally, the complexity of sectoral requirements is greater in the Operational Phase, not least due to the income and consumption driven element associated with increased earnings and household consumption.

6. Discussion

All nations face a challenge in rolling out major decarbonisation solutions in a landscape of multiple economic constraints. Given the importance of labour to all forms of production activity, and in determining the real income and spending power of citizens and their households, those nations facing persisting worker and skills shortages urgently need to give attention to how such constraints can be overcome. This is in terms not only of ensuring the delivery of decarbonisation projects, but in mitigating the cost and price pressures that may ripple throughout the wider economy. The current study does not extend to consider the challenges that potential competition between different decarbonisation actions may trigger. However, it does highlight how competition for scarce labour resources between even just one major industrial decarbonisation solution and other existing activities in the economy bring complex and challenging trade-offs for public policy decision makers.

The focus here is on the CO_2 Transport and Storage element of CCUS, which is rolling out in the UK in the context of both the nation's industrial strategy and net zero policy. It requires substantial upfront and ongoing investment in new infrastructure that enables existing UK oil and gas industry/supply chain capability and capacity to be repurposed to sequester emissions back to the reservoirs that hydrocarbons were previously extracted from. This arguably equates to 'greening' the existing oil and gas supply chain capacity in a way that supports new industrial activity going forward, with the implication that CCUS activity, which shifted into industry strategy space in the UK in 2018 (BEIS, 2017, 2018), is now being considered across a wider public policy space on green growth and jobs (see e.g., HM Government, 2020; BEIS, 2021).

The key and novel finding in the CCUS, and industrial decarbonisation context more generally, is that actions triggering an increase in labour demand where supply is constrained are likely to trigger real wage bargaining processes, which will in turn increase the costs of all producers and risk displacement of employment across multiple sectors of the economy. Moreover, cost increases feed through to price pressure affecting the wider cost-of-living and doing business, which will not only further exacerbate real wage demands in the labour market but also bring challenges for finance ministry actors (HM Treasury in the UK) concerned with managing public budgets and real spending commitments. These issues are of concern to a wider set of public policy actors in the UK, with HM Treasury's (2021) Net Zero Review having dedicated an entire chapter on what the fiscal implications of government intervention may be, and how these may be mitigated, while the much-cited Skidmore (2022) review focussed on the potential fiscal costs of delaying necessary actions.

At this stage it has not been possible to model skills, but it is hypothesised skills shortages may give workers greater wage bargaining power. This motivates consideration of how reducing the importance of wage rates in drawing domestic workers out of unemployment and/or economic inactivity - for example through action on skills development - could reduce cost and price pressures as the economy expands in response to, here, new CO_2 T&S industry activity. The key finding is that employment and other wider economy outcomes are highly sensitive to variations in the parameter that governs wage bargaining power in the UKENVI model. However, where any wage bargaining power remains, the employment gains that UK policymakers seek as a key political economy benefit are limited relative to what they would be if simulations were designed to mimic the type of demand-driven (passive supply) measures commonly cited in the grey literature.

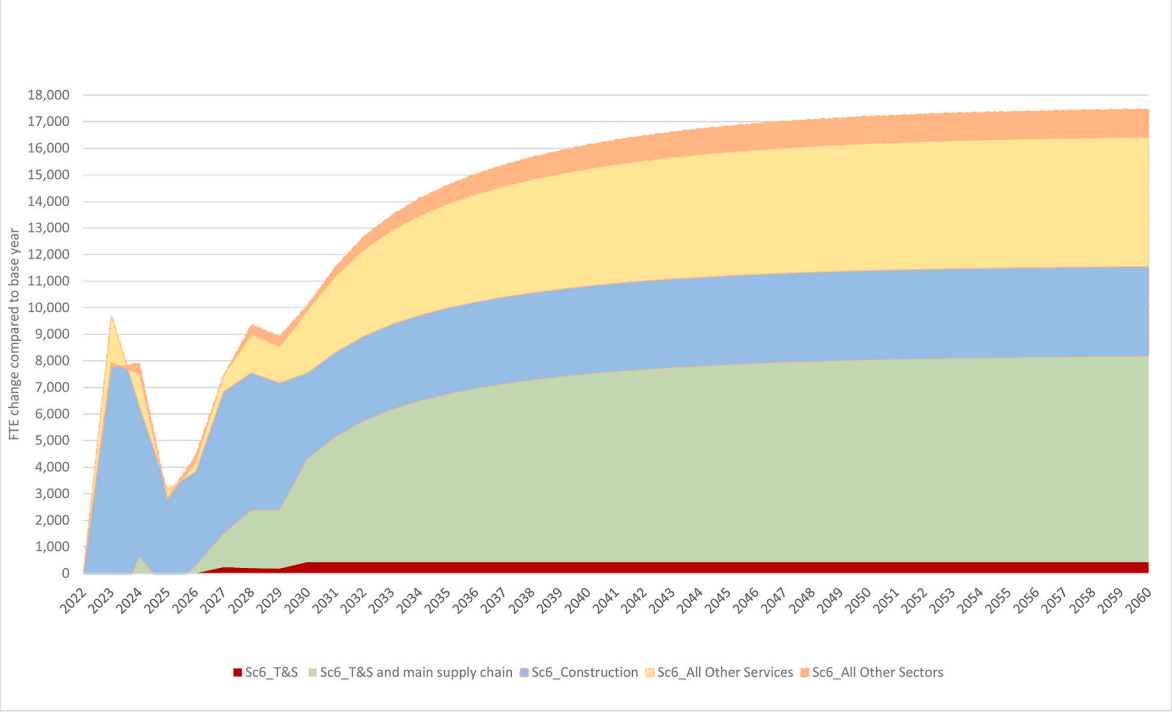

Fig. 5. Break down of UK sectoral employment impacts (FTE change) over time of introducing the CO_2 T&S industry under Scenario 6 (flow migration).

Thus, the final stage of the current analysis is to consider the impacts of potential policy action to increase the labour supply – the absolute number of workers. The final scenario considered shows that over time, even with real wage bargaining, allowing a full flow migration in response to changing UK wage and unemployment rates will maximise employment outcomes and relieve cost and price pressures on the economy. Note, however, that such an approach is unlikely in the context of post-Brexit UK migration policy and any consideration thereof implies that CCUS and wider net zero policy also cut across into the domain of migration policy, in addition to, and linked to the need for workforce planning, not least in the presence of persisting skills and other supply challenges characterising the UK labour market (e.g., see ONS, 2021, 2023).

Here, one of the main recommendations of the Skidmore (2022) review relates to the need for the UK Government to publish an action plan for net zero skills, including a comprehensive roadmap of when, where and in which sectors specific skills needs are likely to arise. This requirement is more recently reinforced in net zero workforce review by the statutory advisory body to the UK national and devolved governments, the Climate Change Committee (CCC, 2023). The main CCUS industry body, the Carbon Capture and Storage Association, CCSA (2023) has also published work relating specifically to workforce planning around CCUS, as have other industry actors operating in the net zero domain (e.g., see Offshore Energies UK, 2022).

The results and analysis presented in this paper reinforce and further elucidate the need for government leadership in such planning, with focus on the potential outcomes under different labour market circumstances, including the potential to ease labour and skills constraints via limited stock migration, consistent with the UK Government's current targeted approach (using points-based visas – see Home Office, 2020).

7. Conclusions and policy recommendations

This has been a preliminary analysis to consider the cross-cutting public policy challenges in introducing a new CO_2 Transport and Storage industry, which involves repurposing and arguably 'greening' of existing oil and gas industry and supply chain capacity and capability in a country like the UK. Initial focus is on a case where such a new industry only services domestic demand, focussing on the challenge of maximising wider economic gains in the presence of a persisting labour supply constraint and a labour market characterised by real wage bargaining.

The key policy insight emerging is that while introducing a new T&S industry is likely to generate sustained economic gains, outcomes will be constrained and conditioned, while worker and skills shortages persist, by a range of sustained cost and price pressures rooted in wage responses. The key implications are the risk of displacement of jobs in other sectors of the economy (CCC, 2023) and a combination of cost-of-living and related fiscal challenges combined with increased consumption activity, the latter likely offsetting the overall emissions reductions gains of deploying CCUS. Thus, the main policy recommendation, which is doubtless applicable in many national settings, is that there is an urgent need for Government to follow policy stakeholder calls in taking a leadership role in workforce planning, and to embed finance ministry focus on understanding the wider fiscal implications of action, and the timing thereof.

The main shortcomings of the analysis are the current lack of modelling of skills or emissions in different sectors of the economy. Going forward, it will be important to extend modelling capacity to enable fuller analyses in these regards, while retaining a detailed treatment of the UK labour market and further improving the specification and parameterisation of the core real wage bargaining function.

Moreover, this work assumes that the T&S sector will have a supply chain structure resembling the one of the current Oil & Gas industry. While this is supported by informal engagement with T&S stakeholders, the input structure of the nascent T&S sector may vary from the oil and gas benchmark in a range of ways. Thus, it will be important to revisit analyses as more reliable data and information emerge. Going forward, it will also be desirable to extend CCUS scenarios to include a full range of related activities (including capture activity requirements) and the potential for international trade in T&S, all set in the context of developments in uni- and multi-lateral developments in carbon pricing.

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CRediT authorship contribution statement

Karen Turner: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Antonios Katris:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Abdoul Karim Zanhouo:** Investigation, Data curation, Investigation, Resources, Writing – original draft, Visualization. **Christian Calvillo:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation. **Julia Race:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Karen Turner reports financial support was provided by UK Carbon Capture and Storage Research Community. Karen Turner reports financial support was provided by Industrial Decarbonisation Research and Innovation Centre.

Data availability

Data will be made available on request.

Appendix A. The sectors in the UKENVI CGE model

Table A.1
Sector aggregation in CGE model and link to SIC2007 codes

Sector Number	Sector Name	SIC code
S1	Agriculture, Forestry and Fishing	01–03
S2	Coal, Mining and Quarrying	05 & 08-09
S3	Crude Oil and Gas	06–07

(*continued on next page*)

Table A.1 (*continued*)

Sector Number	Sector Name	SIC code
S4	CO_2 Transport & Storage	new sector
S5	Food, Drinks and Tobacco	10–12
S6	Textile, Leather and Wood	13–16
S7	Paper and Printing	17–18
S8	Coke and Refined Petroleum Products	19
S9	Chemicals	20
S10	Pharmaceuticals	21
S11	Rubber and Plastic	22
S12	Cement, Lime and Glass	23
S13	Iron, Steel and Metal	24 & 25.4
S14	Manufacture of Fabricated Metal Products, excluding weapons & ammunition	25.1–3 & 25.5–9
S15	Electrical Manufacturing	26–28
S16	Manufacture Of Motor Vehicles, Trailers And Semi-Trailers	29
S17	Transport Equipment l and Other Manufacturing (incl Repair)	30–33
S18	Electricity	35.1
S19	Gas Distribution	35.2–3
S20	Natural Water Treatment and Supply Services	36
S21	Waste Management and remediation	37–39
S22	Construction - Buildings	41–43
S23	Wholesale and Retail Trade	45–47
S24	Land Transport	49
S25	Other transport	50–51
S26	Transport support	52–53
S27	Accommodation and Food Service Activities	55–56
S28	Communication	58–63
S29	Financial and Insurance Services	64–66
S30	Architectural Services	71
S31	Services	68-70 & 72-82
S32	Public administration, Education and Defence	84–85
S33	Health and Social Work	86–88
S34	Recreational and other private services	90–98

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