Inefficient investments as a key to narrowing regional economic imbalances
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SUMMARY
Policy led decisions aiming at decarbonizing the economy may well exacerbate existing regional economic imbalances. These effects are seldom recognized in spatially aggregated, top-down, and techno-economic decarbonization strategies. Here, we present a spatial economic framework that quantifies the gross value added associated with low carbon hydrogen investments while accounting for region-specific factors, such as the industrial specialization of regions, their relative size, and their economic interdependencies. In our case study, which uses low carbon hydrogen produced via autothermal reforming combined with carbon capture and storage to decarbonize the energy intensive industries in Europe and in the UK, we demonstrate that interregional economic interdependencies drive the overall economic benefits of the decarbonization. Policies intended to concurrently transition to net zero and address existing regional imbalances, as in the case of the UK Industrial Decarbonization Challenge, should take these local factors into account.

INTRODUCTION
The concept of simultaneously satisfying the imperative to grow the economy whilst also meeting environmental objectives lays at the heart of the ‘sustainable development’ discourse, first popularized by the 1987 Brundtland Report and subsequently institutionalized by the 1992 UN Conference on Environment and Development – the so-called “Rio Earth Summit”. More recently, the concept of green growth has been promoted by policymakers and academics (Bowen and Hepburn, 2014; Mealy and Teytelboym, 2020) as a mechanism for advancing prosperity while meeting environmental objectives. In this sense, a green policy attempts to break the historical link between economic growth and carbon emissions by directing investments in the decarbonization of energy and industrial products (Hanna et al., 2020).

Almost all countries which introduced fiscal stimulus packages in the aftermath of the 2008-2009 global economic recession included significant green programs. Almost a third of China’s stimulus package, a total of $219bn, was directed toward infrastructure projects to support green transport and energy efficiency initiatives, while for the US this was around 12% ($118bn). While the figures for individual European states varied, as much as 60% ($23bn) of the European Union’s collective stimulus package could be considered in this light (Barbier, 2010). The core argument used to justify these sums was Keynesian in nature; that in a slump, governments should sustain aggregate demand in the economy by replacing lost private sector demand with public expenditure (Jacobs, 2012). This in turn creates a multiplier effect which generates further income and employment growth. However, ambitious announcements by governments after the financial crisis did not materialize, and funding for large, complex engineering projects tended to produce disappointing results. In most cases the competitiveness of the industrial value chain was misjudged, deployment targets and policy support were applied too early, and hopes for a manufacturing value chain did not materialize (IEA, 2020).

Analogously, to tackle the pressuring issues associated with climate change while initiating the economic recovery following the COVID pandemic, numerous countries have recently proposed Net Zero roadmaps aligned with the green growth paradigm. The Industrial decarbonization challenge in the UK (BEIS, 2021), the European Green Deal (European Commission, 2019), and the recent American Jobs Plan (White House, 2021), are notable examples of how national governments are proposing to decarbonize their energy systems, while simultaneously delivering jobs and economic growth. In the European context, hydrogen is identified as one of the key sectors to receive support under the EU Green Deal, in particular owing to...
its ability to bolster the longer-term climate-neutrality, and strategic autonomy objectives of the European Union. According to the European Commission, installing 40 GW of renewable hydrogen by 2030 could create up to one million jobs in the EU (European Commission, 2020). Similarly, the UK government has recently set a medium-term plan for the roll-out of low carbon hydrogen targeting the deployment of 5 GW of production capacity by 2030 (BEIS, 2021). Thus far, UK government policy on low carbon hydrogen has been related to the proposed development of decarbonized industrial clusters where, *inter alia*, carbon capture and usage/storage (CCUS) and hydrogen are anticipated to be integral. Importantly, along with their financial viability, these regional investments will be prioritized based on their potential for delivering positive socioeconomic outcomes across the UK (BEIS, 2020).

As frequently pointed out in the literature, the political economy of growth differs markedly across countries, depending on the national manufacturing base, endowment of natural resources, and the extent of competition in markets, among other factors (Hepburn et al., 2020; Jewell and Cherp, 2020; Patrizio et al., 2020). In this sense, decarbonization policies have the potential to lead to regional differences and uneven economic development (Bridge et al., 2013; Coyle and Sensier, 2020; Olner et al., 2020; Arsova et al., 2021). These differences will be overlaid upon existing socioeconomic structures which are far from homogeneous. Therefore, identifying decarbonization measures that simultaneously achieve environmental aims and narrow existing imbalances, rather than widening them, emerges as an important policy challenge.

Within this context, it is worth noting that the EU currently spends about 34% of its budget on cohesion policy objectives with the aim of tackling regional development disparities. These funds are split between the European Regional Development Fund (ERDF, 55%), the European Social Fund (ESF, 23%) and the Cohesion Fund (CF, 20%), and are used to co-finance economic development projects drawn up by region. However, empirical studies have found a positive, albeit small, impact of EU funds on growth convergence (Becker et al., 2018; Bruegel, 2018), while a recent meta-analysis on the impacts of EU cohesion policy have questioned the effectiveness of such measures in addressing underlying disparity issues (European Parliament, 2019).

More generally, there is a gap in the literature around how national and regional economic strengths may inform the design of equitable policy outcomes (Balta-Ozkan et al., 2015). Whilst the economic multipliers associated with decarbonization investments have received ample scrutiny, and several analyses have quantified the socioeconomic value of low carbon investments (Wei et al., 2010; Barbose et al., 2016; Louie and Pearce, 2016), important local economic factors remain unaccounted for. The fact that regional economies are interdependent, i.e., they often rely on imported goods and services for their industrial activities, has fundamental consequences on the distribution of the socioeconomic impacts of green policies. By neglecting these factors, current approaches to investment appraisals might, in fact, exacerbate existing regional economic imbalances.

This study addresses these gaps and proposes a spatially explicit modeling framework which quantifies the socioeconomic benefits arising from low-carbon investments while accounting for region-specific features, such as the industrial specialization of regions, their relative size, and their economic interdependencies.

Given the prominent role assigned to hydrogen both in the EU and in the UK, the study considers the deployment of two complementary technologies, i.e., Autothermal Reforming and Carbon Capture and storage (ATR-CCS), as key investments to decarbonize the main industrial clusters in the European countries. To understand the economic trade-offs between these regions, the first section in the Results and Discussion applies the framework to the individual EU member countries. The subsequent sections present a case study for the NUTS1 regions of the UK to explore the impacts of 1) the economic structure, 2) the manufacturing base and 3) the geographic connectivity of regional economies, on the cost and value of hydrogen investments.

### RESULTS

Approximately 860 Mt of CO₂ (EEA, 2019) or about 20% of total EU CO₂ emissions in 2017, results from the generation of over 8.4 EJ of thermal energy (CIEP, 2017). The combustion of three fuels— coal, natural gas, and oil—generates most of this heat and its associated CO₂ emissions. The heat is then used directly — in furnaces, ovens, cement kilns, and other unit operations — or indirectly, to drive numerous processes like fluid heating, distillation, drying, and chemical reactions (Thiel and Stark, 2021). Natural gas is used in all the
industrial subsectors in Europe, covering almost half of the energy needs in ‘textile and leather’ (49%), ‘food and tobacco’ (47%), and more than a third in nonmetallic minerals (38%), machinery (36%), and chemical and petrochemicals (34%) (Anouk, 2019). In this context, a H₂-based heating supply may provide an attractive opportunity for “low-carbon” infrastructural transitions in these industries, because of its ability to reutilise the existing gas infrastructure.

Prominent technologies to produce low carbon hydrogen include methane reformation with CCS, and water electrolysis (WE). Whilst the European Commission’s hydrogen strategy identifies WE as the preferred route for low carbon H₂ production, its deployment at scale is contingent on the availability of low-cost and deeply decarbonized electricity. At the time of writing, the carbon intensity of EU grid power varies between 770 and 13.3 kg $\text{MWh}^{-1}$ with an average of 262 kg $\text{MWh}^{-1}$, and thus the conditions for large scale WE deployment remain some way off. Note that, extension of the WE infrastructure to include a dedicated renewable energy supply and associated storage is, of course, possible, but is deemed out of scope for this study. For these reasons and given the widespread availability of natural gas infrastructure in Europe, we adopt ATR-CCS as the archetypal hydrogen production technology in the near-to-medium term. Figure S1 presents a schematic overview of the ATR processes adopted in the analysis, techno-economic parameters for the reference ATR-CCS plants are taken from Sunny et al., and are summarized in Table S1 (Sunny et al., 2020).

In this study, the direct and indirect economic impacts of hydrogen investments are measured in terms of Gross Value Added (GVA), i.e., the contribution to the Gross Domestic Product (GDP) made by each sector of the economy. Specifically, the GVA associated with deployment ATR-CCS capacity in a certain region has been quantified with the Jobs and Economic Development Impact tool (JEDI), which combines an investment analysis with country specific Input-Output tables (IO) (Patrizio et al., 2018; Patrizio et al., 2020). As a first process step, the capital and operational costs of ATR-CCS have been allocated to the different industrial sectors, considering main physical equipment as well as technical and support activities required for the installment and operation of these facilities, Table S3 details the results of the investment analysis included in the JEDI database. Note that these costs have been scaled up based on the level of hydrogen production capacity that satisfies the demand for industrial heat within each region.

To translate these expenditures into sector specific measures of GVA, JEDI adopts IO tables descending from national accounts and containing measures of GVA and its components for 36 sectors of the economy. Specifically, with the aim of accounting for the economic interdependencies within and between national economies, our analysis adopts intercountry input-output tables (ICIO), where national accounts are combined with international trade statistics to describe supply and demand relationships between industries within and between economies, as well as the uses in different final demand components, i.e., consumption, investment, and government spending.

The rationale to adopt ICIO tables, rather than individual national account statistics, is that in developed economies industrial activities are likely to be internationally fragmented to varying degrees (Reich, 2018). As shown in Table S3, a large share of industrial value added in EU economies originates from imports: on average, 37% of total manufacturing GVA is domestic, and almost 40% originates from trade between EU economies. By accounting for these intermediate imports, it is possible to understand the links between the country where the value is created and the market where it is absorbed as final demand. This, in turn, provides a more accurate quantification of the spillover effects associated with hydrogen investments in a given economy.

Whilst there are several ICIO databases currently available, the OECD-WTO database (OECD, 2018) was used in our analysis as it provides data on economic flows for 64 countries, i.e. 36 OECD and 28 non-OECD economies, and the rest of the world (RoW). Moreover, since its publication, the OECD-WTO database has been widely adopted in the analysis of global supply chain trades, offshoring on labor demand and numerous policy-oriented studies.

The direct economic impacts of ATR-CCS investments show a great variation across EU countries, ranging between 140 and 300 €/kW. As Figure 1 shows, these benefits are largely contingent on the national manufacturing base: greater economic impacts can be observed in countries such as Germany (DEU), Hungary (HUN) and Check Republic (CZE), owing to their relatively higher-value manufacturing sectors, responsible for more than 22% of the annual GVA. Moreover, as shown in the case of service economies,
i.e., countries that realize most of their national output via tertiary activities, the R&D intensity of manufacturing activities matters. In fact, despite the size of the manufacturing sector which is below the European average of 15%, the direct economic impacts in Denmark (DNK), the Netherlands (NLD) and France (FRA) range between 200 and 214 €/kW, higher than what is observed in Poland (POL) and Bulgaria (BGR) at 188 and 152 €/kW, respectively. This is quite intuitive, as the majority of the value associated with hydrogen investments is expected to be created in knowledge intensive sectors, such as chemicals, machinery and electrical equipment. Countries with such industrial infrastructure in place may therefore be expected to benefit from the deployment of low carbon hydrogen technologies.

Whilst the direct impacts depend on the structure of the national manufacturing sectors, and determine the regional benefits of hydrogen investments, the indirect effects of these investments across the industrial sectors depends on whether each country can satisfy its internal demand with domestic production. In this sense, the trade in manufacturing value added (TiVa), represents a reliable indicator of the degree of economic interdependence of the EU countries (OECD, 2016, 2021). The underlying concept of TiVa is that domestic industries often rely on intermediate inputs of goods and services purchased from international suppliers.

As shown in Table S4, EU countries show a high degree of economic interdependence. Whilst countries such as Germany, Italy and France rely primarily on their national industrial infrastructure to satisfy their internal demand, between 41% and 51% of the manufacturing GVA in Hungary, Slovenia, Czech Republic, and Estonia is realized in other EU countries. As shown in Figure 2, the largest portion is supplied by Germany (around 32%), followed by Italy (10%) and Poland (7%), while the remaining is distributed among neighboring countries. These economic interdependencies explain the fall in indirect economic impacts observable in Figure 1. Thus, whilst Central European economies may benefit the most from the deployment of ATR-CCS capacity, under the existing paradigm, these countries are likely to outsource most products and services required for their manufacturing sector. Hence, the indirect impacts for Hungary, Czech Republic, Slovakia, and Estonia, are 40%–63% lower than the economic growth projected by their corresponding direct impacts. These facts have important implications for the successful implementation of green policies, especially those seeking to stimulate economic convergence between regions. Rather than simply supporting green investments in lagging regions, cohesion policies should seek to direct investments in countries specialized in high-tech manufacturing, while simultaneously supporting strategic sectors associated with these industrial activities. In this way, greater economic value can be retained within the domestic economy rather than being outsourced to already high-performing regions.
The UK industrial decarbonization challenge

With the aim of decarbonizing its industrial sector, the UK Government has recently set out an ambition to deploy 5 GW of low carbon hydrogen production capacity by 2030, while targeting the roll-out of two CCUS industrial clusters in the mid-2020s, and further two clusters by 2030. Together with their financial viability, the proposed CCUS projects will be evaluated against their value for money, i.e., their potential for delivering jobs and economic growth across the different regions of the UK. This would, in turn, contribute to the government’s leveling up agenda, i.e., narrowing existing regional economic imbalances by delivering high-skilled jobs and growth across the different regions of the UK. Within this context, it is essential to understand both the scale of the financial efforts required to decarbonize the national industrial sector and the economic benefits created by these investments across the entire country.

Here, we present the results of a techno-economic assessment of adopting ATR-CCS to decarbonize the manufacturing industries of the six main industrial regions of the UK. As in the previous section, it is assumed that low carbon hydrogen replaces the existing fuel mix of energy-intensive industries (see Figure S2 for a detailed fuel mix composition for these clusters), thus significantly reducing their heating-related emissions.

As illustrated in Figure 3, delivering low-carbon heat within these clusters could avoid up to 28 MtCO₂ per year, corresponding to 57% of their cumulative emissions. For the reasons discussed above, lowest avoidance costs are observable for industries specialized in aluminum and cement production activities: there, the avoidance factor of low carbon hydrogen is in the range of 230 - 240 tCO₂/GWh, assuming ATR-CCS
plants operating at 80% capacity. Hence, the Merseyside region can achieve 78% emission reductions by switching to H2-based heat at an average avoidance cost of 182 £/tCO2, because of its specialization in such manufacturing processes. Conversely, fewer mitigation benefits are achievable in the iron and steel sector in South Wales, Teesside and Humber regions. Because these are predominantly integrated steel mills adopting metallurgical coal and other carbon-rich raw materials for the production of iron, the role of hydrogen is limited to the supply of around 1.6 MWh/tsteel of thermal energy to the blast furnace (Mandova et al., 2019), otherwise provided by pulverized coal injection (PCI) or natural gas-fired boiler. Unless the process emissions are also abated via CCS, fuel switching with hydrogen would only lead to 10% emission reduction, explaining the avoidance cost of more than 230 £/tCO2 observable for this sector. Given that ironmaking accounts for more than 70 and 50% of cumulative annual emissions in the Humber and South Wales regions, respectively, investing in blue hydrogen in these clusters would only lead to marginal emission benefits, and considerably high costs.

The leveling up value of decarbonization

In this section, we use the JEDI tool to first quantify the direct socioeconomic impacts associated with the deployment of ATR-CCS within each industrial cluster. Subsequently, by constructing regional IO tables for the NUTS1 statistical region of the UK, we quantify the indirect effects of these investments on the UK regional economies.

As shown in Table 1, the overall direct economic benefits of decarbonization are in the range of 14.3 - 26.5 £/MWhH2, with South Wales and Scotland capturing most of the growth. For all regions considered the largest benefits are realized in the utility sector, supplying 2.5 £/MWhH2 of energy services, i.e., natural gas and electricity, for the continuous operation of ATR-CCS plants. However, the magnitude of these impacts in the other economic sectors is largely dependent on local factors. The sectoral GVA analysis in Table 1 shows that the Humber and Merseyside clusters retain the highest GVA contribution in the machinery sector, while the largest economic gains in the chemical sector are observable in North East and North West regions, where the majority of their manufacturing activity is concentrated.

To account for these regional factors in the computation of the indirect effects of industrial decarbonization, we constructed regional IO tables describing the flow of nonfinancial economic sectors of the NUTS1 regions of the UK. We simultaneously accounted for the industrial specialization of the regions, their relative size, and their economic interdependencies (see section 3.2 of the SI). As illustrated in Figure 4, the interregional trade that connects the various regions of the UK plays a significantly different role in each cluster. In particular, the North West exhibits important economic links with both the eastern and central regions of the UK. As a result, every kWh of hydrogen produced in the Merseyside cluster results in indirect economic benefits across almost all UK regions, particularly in East England and the Humber regions, at 217 £/MWh and 150 £/MWh, respectively. With an export value equal to around 20% of its annual GDP, the North East region is characterized by the strongest manufacturing exports among the UK regions, mainly
in chemical related products (37%) and machinery equipment (35%) (Tees Valley Combined Authority, 2019). Consequently, the area is relatively disconnected to the other parts of the country with trade links limited to the neighboring Humber and the North West regions. These facts explain the low indirect economic multipliers associated with ATR-CCS investments in Teesside (Figure 4). Finally, the socioeconomic benefits of decarbonizing the Grangemouth and South Wales clusters are largely retained within the domestic economy, with milder effects, in the range of 47-96 £/MWh and 49-112 £/MWh, respectively, in the other parts of the country.

With this analysis it is also possible to appreciate how the GVA growth is distributed among the different industrial sectors of the UK, depending on local industrial strengths (Figure 5). For instance, mining and extraction activities in the North West would be expanded by directing investments in the Humber and Grangemouth areas, while the ICT sector in the South West would be boosted by prioritizing the decarbonization of Southampton and South Wales regions. In comparison, given their similar economic structures, the East and West Midlands exhibit similar results: regardless of which cluster is being decarbonized, the greatest indirect effects are observed in Low-Tech manufacturing sectors, and in service-related activities. Hence, one can use analysis such as this to guide investment in one sector so that other strategically important economic activities around the country are supported.

**DISCUSSION**

Policy aimed at decarbonizing existing industrialized regions in Europe is likely to create winners and losers, with local factors dictating the relative size of economic benefits generated by low carbon investments. Given the existing regional economic imbalances across the EU and the UK, place-based strategies, tailoring their mix of policies to local conditions, offer a novel approach to regional economic development.

Using the example of blue hydrogen as a low carbon fuel to mitigate the emissions originating from the EU industrial sector, we show that regions specialized in high value manufacturing activities are well placed to benefit from a domestic hydrogen economy. However, the extent to which these effects are perceived in other economic sectors within and between regions, is largely affected by cross-sector dependencies. By considering the trade in manufacturing value added (TiVa) between EU countries, we show that, whilst countries such as Hungary, Czech Republic, Slovakia, and Estonia foresee high economic multipliers from hydrogen investments, these economic benefits are likely to be redirected to already high performing regions such as Germany, unless other strategic sectors are concurrently supported.

Moreover, as demonstrated for the UK, directing investments in the North West and Humberside regions, will likely produce spillover effects across almost all other parts of the country. Hence, when aiming at

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**Table 1. Summary of results obtained from the techno-economic analysis**

| Cluster ID  | Humberside | Southampton | Merseyside | Teesside | South Wales | Grangemouth |
|------------|------------|-------------|------------|----------|------------|-------------|
| NUTS1 region | Yorkshire and the Humber | South East | North West | North East | Wales | Scotland |
| Installed capacity (GW) | 3.7 | 1.72 | 2.7 | 4.32 | 2.37 | 1.91 |
| Emission reduction (%) | 48 | 76 | 76 | 56 | 37 | 78 |
| Direct impact (£/MWh) | 14.48 | 14.35 | 16.65 | 17.36 | 26.36 | 25.94 |

**Sectoral breakdown (%GVA)**

- **Utilities**: 0.21, 0.21, 0.24, 0.29, 0.49, 0.49
- **Construction**: 0.36, 0.35, 0.36, 0.39, 0.41, 0.39
- **Chemicals products**: 0.13, 0.16, 0.19, 0.2, 0.15, 0.18
- **Machinery/electrical equipment**: 0.4, 0.32, 0.46, 0.27, 0.37, 0.34
- **Maintenance**: 0.43, 0.41, 0.42, 0.41, 0.32, 0.46
- **Transport**: 0.48, 0.39, 0.42, 0.46, 0.46, 0.44
- **Professional activities**: 0.62, 0.56, 0.56, 0.66, 0.6, 0.62
- **Support service activities**: 0.5, 0.57, 0.55, 0.59, 0.7, 0.61

The sectoral breakdown represents the share of GVA directed in the regional economic sectors.
narrowing existing economic imbalances between countries and regions, it is the connections between places and sectors that matters (Balta-Ozkan et al., 2015). In this sense, strategically astute investment in one region can act to support the leveling up agenda in other regions, whilst concurrently supporting strategically important sectors that are ostensibly unrelated to the initial investment. As manufacturing becomes more sophisticated, supply chains become more complex and thus highly fragmented. Domestic industries increasingly rely on significant intermediate imports, i.e., in value added by industries in upstream countries. Neglecting these national and region-specific factors in green policies design will exacerbate existing socioeconomic disparities; the opposite of what is intended.

Finally, in the context of delivering the hydrogen economy there are important environmental and techno-economic trade-offs that need to be addressed, especially considering the ambitious targets set out by the EU and the UK. Firstly, for blue hydrogen to be a viable low carbon option, the management of the natural gas supply chain is vital, so that methane leakage, currently in the range of 2.9–35.75 kg CO₂ eq/GJ LHV are minimized (Mac Dowell et al., 2021). At the same time, the deployment of blue hydrogen at the pace and scale indicated by national and international policy strategies, is contingent on the availability of CCS transport and storage infrastructure, which deployment within the European context, is highly controversial. Moreover, whilst the EU Hydrogen Strategy has indicated an overall preference for renewable hydrogen, current electrolyzer production capacity in Europe is well under 1GW per year. Achieving 40 GW by 2030 will require a very rapid scale up in electrolyzer production capacity and strong reliance on imported electrolyzers (Oxford Institute for Energy Studies, 2021), which would substantially reduce the potential socioeconomic benefits associated with the hydrogen economy.

Limitations of the study
To quantify the socioeconomic impacts associated with ATR-CCS projects our analysis relies on IO methodology which is not without limitations. In general, IO models can be described as static linear models describing the economy through sets of relationships between industries which do not change over time. This includes any optimizing from the supply side, because it excludes all choice about the proportions in which inputs are to be combined in the production of a given output. As such, adopting IO methodology to produce long-term estimates of economic growth, might produce misleading or inaccurate results (because the production

Figure 4. Regionally disaggregated socio-economic impacts of blue hydrogen investments
(A) Spatial economic interdependencies of UK regions and (B) Interregional indirect effects of decarbonizing UK industrial clusters. In (B) values are expressed in terms of £ of indirect GVA created within the local economy for each kWh of hydrogen produced.
function remains constant over time). However, a recent study on the economic effects of green policies for four selected countries (both, developed and emerging economies) note that the median average annual changes in output multipliers over the 1995–2007 period was between 0.1 and 0.3 percent (Pollin, 2016). This suggests that, in general, production relationships between the domestic sectors in the IO tables do not change significantly if the time frame of analysis is sufficiently short.

An additional limitation stems from the boundaries of our analysis, which excluded the transport and storage activities associated with supplying hydrogen to the industrial facilities. To quantify the investment associated with hydrogen infrastructure, an in-depth spatial analysis accounting for place specific conditions would be required. Therefore, further analysis could leverage the results of this study and investigate place-specific conditions that would hinder or favor the adoption of hydrogen technologies.

**STAR+ METHODS**

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  - Socio-economic analysis
  - Investment analysis
Input output tables (IO)
OECD inter-country (ICIO) system
UK sub-regional IO tables

SUPPLEMENTAL INFORMATION
Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.103911.

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AUTHOR CONTRIBUTIONS
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DECLARATION OF INTERESTS
P.P. is currently an editorial board member of the journal.

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STAR METHODS

KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| Deposited data | This paper (supplemental information) | |
| Techno-economic parameters of ATR-CCS processes | This paper (supplemental information) | |
| Co2 emissions from heating processes for key industries in the UK | This paper (supplemental information) | |
| Heating requirements for key UK industrial sectors | This paper (supplemental information) | |
| CAPEX and OPEX breakdown for ATR-CCS plants | This paper (supplemental information) | |

RESOURCE AVAILABILITY

Lead contact
Further information and requests for resources should be directed to and will be fulfilled by Prof Niall Mac Dowell (niall@imperial.ac.uk)

Materials availability
Not applicable

Data and code availability
- The attached Supplemental Information file includes all dataset generated or analysed during this study
- This paper does not report original code
- Any additional information is available from the lead contact upon request

METHOD DETAILS

Low carbon hydrogen production technology: ATR-CCS

Hydrogen is currently being produced on a large scale via natural gas reforming. The state-of-the-art technology is steam methane reforming (SMR), where methane reacts with steam to produce a hydrogen-rich syngas. Autothermal reforming (ATR) combines SMR with the partial oxidation process inside a single reactor unit. It consists of a thermal zone where partial oxidation of the feedstock is used to generate the heat needed to drive the downstream steam reforming reaction. Hence, contrary to a SMR plant, no external furnace is required (Antonini et al., 2020). Natural gas is first converted into a syngas mixture (CO and H2) in a catalytic furnace, which subsequently reacts in the presence of water to form CO2 and H2 in a shift reaction. A significant advantage of this process is that it can be operated flexibly whilst producing higher quantities of H2 than in a partial oxidation process alone. In order to control the reaction temperature, pressure and product gas composition, the ratio of O2 to fuel and steam to carbon ratio should be tightly controlled around 2 – 3. Figure S1 shows a schematic overview of the ATR process.

The process can be operated at greater pressures than SMR and produces a syngas mixture with a higher concentration of CO2/H2 from the O2-fired process. This reduces the cost of CO2 capture, thereby allowing an economical capture rate of up to 95 - 98%. This notwithstanding, our analysis assumes a lower bound capture rate of 90%, in line with similar techno-economic assessments (Antonini et al., 2020; Sunny et al., 2020).

In contrast to SMRs, the requirement for an Air Separation Unit (ASU) increases its power requirements. The reference ATR plant with CCS operates at a pressure of 40 bar, with an efficiency of 78% HHV (Walker et al., 2018). ATRs can also be combined with gas-heated reforming to exploit the high temperatures from the gaseous streams downstream of the reforming process to convert more natural gas to H2. However, there
is limited commercial experience in its use and further technology appraisals are needed before deployment. Table S1 summarized main techno-economic data adopted in our analysis. Note that, for the EU case study, cost data have been converted to €2018.

Industrial emissions and energy intensity data
Figure S2 in the supplementary information, shows the location of the six industrial clusters considered in this study and the industrial breakdown of cumulative emissions in each region. These are process derived and heating emissions descending from the combustion of a specific fuel mix, as indicated in Figure S2. Our analysis considers the replacement of fossil-based energy mix with low carbon hydrogen. Hence, the fuel requirement and associated ATR-CCS capacity to be deployed within each cluster has been modelled based on the heating demand of each industrial process. (See Table S2 for a detailed breakdown).

Socio-economic analysis
Our socio-economic analysis adopts the Job and Economic Development Impact (JEDI) model, described in Patrizio et al. (Patrizio et al., 2020). The overall approach is to combine cost data of a specific energy project with socio-economic indicators from publicly available macroeconomic databases. JEDI adopts country or region-specific measures of output, gross value added (GVA) and its components, labour cost, and wages for each of the 36 sectors of the economy (based on the International Standard Industry Classification -ISIC-).

Investment analysis
To quantify the socio-economic impacts associated with the deployment of ATR-CCS within a certain country or region, it is necessary to disaggregate the project cost in its main cost divers. Here, the lifetime costs of ATR-CCS have been disaggregated across main manufacturing and downstream activities, based on recent industrial analysis (H21, 2019). Subsequently, these expenditures are allocated to each industrial sector, according to the ISIC classification (UNIDO, 2018).

With an understanding of the total expenditure across these industrial sectors, JEDI calculates the corresponding GVA generated at sector level. The GVA generated by any unit engaged in production activity can be calculated as the residual of the units’ total output less intermediate consumption, goods and services used up in the process of producing the output (output approach), or as the sum of the factor incomes, i.e. Labour costs, Consumption of fixed capital, taxes less subsidies and Net operating surplus and mixed income, generated by the production process (income approach). In this study, the output and income measures of GVA by industry have been compared at sector level to validate the analysis.

Input output tables (IO)
The quantification of the indirect economic effects descends from national and regional IO tables, described in this section. IO tables are constructed from observed economic data for a specific geographic region, generally obtained from national statistics. They describe the activity of a group of industries that both produce goods (outputs) and consume goods from other industries (inputs) in the process of producing each industry’s own output. The fundamental information used in IO analysis concerns the flows of products from each industrial sector, considered as a producer, to each of the sectors, considered as consumers. This basic information from which an IO model is developed is contained in an interindustry transactions table. The rows of such a table describe the distribution of a producer’s output throughout the economy. The columns describe the composition of inputs required by a particular industry to produce its output, i.e. intermediate consumption. Hence, an essential set of data registered in IO tables are monetary values of the transactions between pairs of sectors (from each sector i to each sector j). A detailed overview of IO conceptual framework, underlying assumptions and main applications, can be found in Miller and Blair (2009).

OECD inter-country (ICIO) system
The OECD ICIO system consists of a set of annual symmetric industry by industry input output tables describing the annual monetary flows across 36 industrial sectors within and between EU countries (OECD, 2018). The latest version of the database contains 2018 data and formed the basis of our analysis. The database also contains Trade in Value Added (TiVa) indicators, a set of measures that aims to provide insights into production networks and on the degree of fragmentation of manufacturing supply chains.
The basic concept of TiVa is that the production of a certain manufactured good requires intermediate inputs from both domestic industries as well as industries from outside the country. As such, much of the revenue (or value added) from selling that good may accrue abroad to reflect purchases of intermediate imports used in production, leaving only marginal benefits in the exporting economy. In other words, the TiVa reveals how the value of final demand goods and services consumed within a country, is an accumulation of value generated in many industries and many countries.

Table S3 shows the origin of manufacturing value added embedded in the final demand of EU economies. It can be noticed that on average, only 38% of the intermediate inputs used in manufacturing activities is domestic, reflecting how EU economies are highly interconnected: for Hungary, more than 50% of these inputs originates from other EU countries, while Germany mainly relies on its domestic industries. By accounting for these trades, it is possible to understand where GVA originates and, in turn, which country foresee a growth in economic output and employment due to an increase in demand from a given sector in a given country. In this way, the indirect effects originating from a certain economic activity, can be allocated between industrial sectors within and between countries.

UK sub-regional IO tables

The greatest disadvantage of national level IO is that, since they consider the whole economy as an aspatial entity, they cannot represent regional differences. Importantly, national IO cannot account for the contribution of interregional trades to regional economic performances, which, undoubtedly, plays a significant role in periphery and central regions. Since most countries, including the UK, publish only national IO tables, there is no detailed information about interregional economic dependencies, which would serve as the basis of much regional research. However, the intensifying interest for regional economic analysis over the last decades has led to modifications and extensions of the original IO framework. At present, there are several well-known variations of regionalization methods in the literature, see Miller and Blair for a detailed discussion of main approaches (Miller and Blair, 2009). This section describes the main steps adopted in the creation of regional IO tables for the NUTS1 region of the UK. Underlying data are freely available and can be downloaded from various national statistical databases.

The starting point of the analysis is the national IO table, depicting the monetary flows between sectors of the economy. The first step is to account for region specific characteristics, which can be done by adopting cross industry location quotients (CIQL), expressing the size of each regional sector, in terms of total output (in monetary terms), compared to the size of the same sector at national level. In particular, CIQL coefficients consider the size of both purchaser and producers’ industries in a region \( r \). Mathematically, this can be expressed as follows:

\[
CIQL_{ij} = \left( \frac{x_{ri}}{x_{ri}} \right) \left( \frac{x_{nj}}{x_{nj}} \right)
\]

where \( x_{ri} \) and \( x_{nj} \) represent, respectively, the output of industry \( i \) (producer) in region \( r \) and in nation \( n \). Similarly, \( x_{nj} \) is the output of industry \( j \) (purchaser) in region \( r \).

Together with its relative specialization, the self-supplying ability of a region is affected by its relative size, which can be accounted for by adopting the Flegg location coefficients:

\[
FQL_{ij} = CIQL_{ij} \times \chi'
\]

where \( \chi' \) stands for the relative size of the region and can be calculated using the following:

\[
\chi' = \left( \log_2 \left( 1 + \frac{x_{jr}}{x_{jr}} \right) \right)^{\delta}
\]

where \( x_{jr}/x_{jr} \) represent the ratio of employment in region \( r \) to the national employment, and it is used as a proxy for the relative region size. The general idea is to reduce national coefficients less for larger regions, based on the assumption that larger regions import relatively less than smaller ones. Note that the size is not modified directly by the relative size, but by the logarithmic value of it. Thereby, the scaling is not so
intensive, and the whole expression is then raised to the power of $d$, which is a sensitivity parameter. Empirical work (Flegg and Webber, 2000) has suggested that $d = 0.3$ seems to work well in a variety of situations.

Finally, it is possible to obtain the intraregional $a_{ij}$ table as follows:

$$a_{ij}^{\prime} = \begin{cases} (FQL_{ij}^{\prime}) + a_{ij} & \text{when } FQL_{ij}^{\prime} < 1 \\ a_{ij} & \text{when } FQL_{ij}^{\prime} > 1 \end{cases}$$

The logic is that, if the share of industry $i$ (producer) in region $r$ (compared to the national level) is higher than the share of industry $j$ (purchaser) in the same region (again compared to the national level), then the region can satisfy industry $j$’s input requirements in industry $FQL_{ij}^{\prime} > 1$. Otherwise, if $FQL_{ij}^{\prime} < 1$, the region needs to import.

From this, it follows that the total amount of imports from the rest of the country, roc, to region $r$ can be defined as:

$$T_{ij}^{\text{roc}} = (1 - FLQ_{ij}^{\prime}) * a_{ij} * x_j$$

where $T_{ij}^{\text{roc}}$ is the net flow of imports entering the region from the rest of the country. These imports need to be distributed between regions, so that, beside the intraregional $a_{ij}^{\prime}$ table, interregional trade matrices can be estimated. In other words, considering an example consisting of three regions, $r$, $s$, $z$, then $T_{ij}^{\text{roc}}$ need to be allocated between $s$, $z$, so that interregional matrix $a_{ij}^{\prime}$ and $a_{ij}^{\prime'}$ can be estimated. If regional statistics are available, interregional trade data can be used to distribute these imports between regions. In our case, interregional trades are based on the 2018 Road Freight Statistic from the UK Department of Transport (UK Department for Transport, 2019), as Figure S3 illustrates.

**SUPPORTING CITATIONS**

The following references appear in the supplemental information: (ONS, 2018; Sunny et al., 2020; OECD, 2021)