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Quantifying the socio-economic value of CCUS: a review

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QUANTIFYING THE SOCIO-ECONOMIC VALUE OF CCS: A REVIEW

Key Messages

- As policymakers consider options at their disposal to achieve the goals of the Paris Agreement, understanding the socio-economic impacts on local communities and industrial regions is crucial.
- Integrated assessment models (IAMs), traditionally used to explore the feasibility of achieving climate targets and to inform global climate negotiations, often lack the economic, social and geographic detail to fully reveal the role CCS and BECCS can play in national economies.
- The three case studies presented in this report have previously been shared by the authors via published papers, conference presentations, workshops and seminars. Together, they provide insights regarding the impacts of CCS and CDR[1] deployment on regional economies and the relationship between industrial sectors and national strategic assets.
- Case study 1[2] shows that the goals of coal sector employment and climate change mitigation can be aligned, contrary to the way it is often portrayed. Together with a commitment to a net-zero target, the employment opportunities that may arise from CCS deployment should be carefully assessed.
- More broadly, this case study demonstrates that, if traditional industries were to embrace climate mitigation measures, rather than leading to the large-scale job losses considered inevitable by those industries, such outcomes might not actually be the case.
- Case study 2[3] shows that, when pursuing net-zero targets in energy systems, there is no "one size fits all" solution. The relative costs and opportunities associated with the transition to net zero are likely to be unevenly distributed between countries, with job losses concentrated among specific socio-economic groups and in some regions.
- Hence, carbon mitigation strategies that focus on cost and neglect social, geopolitical and macro-economic considerations are more likely to exacerbate labour market inequalities. Failing to address this can lead to deeper social divisions, with adverse implications for growth, productivity, well-being and social cohesion.
- Biomass can provide two main services for climate change mitigation. It can remove CO_2 from the atmosphere as it grows (CDR) and, by replacing fossil fuels, it can avoid the release of carbon emissions to the atmosphere (CO_2 avoidance). However, as generating bioenergy at scale from biomass for emission mitigation is expected to impact the amount of land available for food production, the sustainable use of biomass is important.

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[1] Carbon dioxide removal (CDR) technologies, also known as negative emissions technologies (NETs), are means by which CO_2 is removed from the atmosphere and stored/sequestered over geological time periods. Examples of CDR technologies include enhanced natural removal methods such as afforestation, reforestation, enhanced mineralisation and biochar, as well as advanced technologies such as direct air capture with CO_2 storage (DACCS) and bioenergy carbon capture and storage (BECCS). CDR technologies should not be confused with carbon capture and storage (CCS), a process in which the CO_2 is captured from large point-sources such as coal- or gas-fired power plants and heavy industry, following which it is compressed and stored/sequestered or used.

[2] Patrizio P, Leduc S, Kraxner F, Fuss S, Kindermann G, Mesfun S, Spokas K, Mendoza A, Mac Dowell N, Wetterlund E, Lundgren J, Dotzauer E, Yowargana P, Obersteiner M. Reducing US Coal Emissions Can Boost Employment, Joule, Volume 2, 2633-2648 2018.

[3] Patrizio P, Pratama YW, Mac Dowell N, Socially Equitable Energy System Transitions, Joule, Volume 4, 1700-1713, 2020.

- Case Study 3[4] shows that quantifying the socio-economic value of different BECCS pathways can inform policymakers of the optimal mix of CDR technologies to be deployed, while minimising biomass resource competition.
- Ultimately, the case studies illustrate that decarbonisation strategies that neglect social, geopolitical, and macro-economic considerations, are likely to widen existing economic imbalances, both at regional and national levels.
- While CCS is widely acknowledged as essential to reach net-zero targets within economies, its deployment has faced and will face challenges. Providing a multi-regional, technology agnostic and transparent quantification of the social value of CCS may help overcome some of these challenges.

Background to the study

The transformations needed to achieve the goals of the Paris Agreement require unprecedented rates of decarbonisation, along with the interconnected technical, economic, social and political changes that they entail. This places extraordinary demands on national and sub-national political systems, and the social feasibility of such transformations is often questioned.

Drivers such as socioeconomic development and the capabilities of individual member states, are judged to be particularly relevant for the implementation of effective decarbonisation strategies. As policymakers consider options at their disposal, understanding the socio-economic impacts of the transition on local communities and industrial regions is key. The deployment of CCS has continued to lag expectations, despite its acknowledged importance in achieving long-term climate targets and efforts by the scientific community to promote its early implementation – and, likewise, the implementation of sustainable BECCS for generating negative emissions.

Traditionally, climate scientists and economists have used integrated assessment models (IAMs) to explore the feasibility of achieving climate targets and to inform global climate negotiations. IAMs come in several different forms and vary greatly in their complexity. Computable general equilibrium models, for example, have a detailed representation of the economy with multiple sectors and often include higher resolution of energy technologies and regional content. These can consider the impacts of specific policies on economic, social and environmental parameters but, due to their complexity, economic growth is difficult to model. Similarly, macroeconomic models can be quite detailed in terms of energy technologies and geographic scope and may also be used to evaluate alternative climate policies.

Energy system models, a subcategory of partial equilibrium models, on the other hand, provide a detailed account of the energy sector, i.e., energy technologies and their associated costs. These are simpler and may be used to determine, say, the least-cost means to attain GHG emission reductions or the costs of alternative climate policies. Emission stabilisation pathways arising from these models highlight the key role of CCS and CDR technologies to achieve the 1.5°C target set out by the Paris Agreement. However, the lack of economic and geographic detail incorporated in these models provide limited information on the role that these technologies can play in national economies.

[4] Patrizio P, Fajardy M, Bui M and Mac Dowell N, iScience, 24, 102765 July 23, 2021.

The transition towards a net-zero economy implies profound structural changes for national and regional economies. The 'transition policies' adopted by nations include a portfolio of energy, industrial, climate and trade policies required to enable the transition to net zero. These changes and the upheaval brought by the decarbonisation of national energy systems will be particularly evident in the labour markets as carbon intensive industries and their associated labour forces become less competitive and decline while, on the other hand, low-carbon activities grow and their associated employment increases. These activities will not be evenly distributed as different regions not only have different levels of industrial and economic activity, but also possess different skill sets and natural resources. Hence the socio-economic impacts of decarbonisation, including those of CCS and CDR technologies, will depend on a portfolio of regional, physical, human and social capitals.

Scope of Work

The transition towards a net-zero economy will bring deep structural changes for national and regional economies, with changes most evident in the labour markets as traditional carbon intensive industries and their associated labour forces become less competitive and decline but, on the other hand, new low-carbon activities increase. Translating net-zero commitments into effective decarbonisation pathways requires a sound understanding of the intertwined techno-economic, social and policy dimensions of the transition. This is particularly the case for CCS and CDR, for which deployment still lags expectation despite its perceived key role in achieving meaningful emission reductions in the decades ahead.

The study reviews three case studies that have already been published in the scientific literature and shared via conference presentations, workshops and seminars. They centre on the socio-economic impacts of achieving ambitious climate targets via the deployment of CCS and CDR technologies in different economic circumstances, each focusing on specific CCS and CDR applications. In compiling and discussing them in a single document, findings on the impacts of CCS and CDR deployment on regional economies and the relationship between industrial sectors and national strategic assets are discussed.

Existing analytical tools for quantifying the socio-economic impacts associated with CCS and CDR deployment are examined, allowing the energy community to gain insights into their socio-economic value, as well as knowledge of the risks and opportunities associated with the transition to net zero.

Findings of the Study

Three case studies are employed to quantify the socio-economic impacts of achieving ambitious climate targets in the energy sector, viz:

Case study 1: Employment opportunities of deploying CCS in the US coal sector
In this first case study, the impacts on employment of reducing emissions from the coal sector in the United States by deploying a mix of decarbonisation options, including the deployment of CCS and BECCS, are explored and quantified.

Historically, the knock-on effects of environmental regulation on employment have played a central role in the political debate in the United States. Of particular concern has been that phasing out coal and investing in CO_2 mitigation will come at the expense of unemployment and lost competitiveness. On the other hand, investors and businesses are becoming aware of the risk that assets may become stranded if their investments do not include emission-reduction technologies.

Such contradictory perspectives emphasise the need for a quantitative assessment of the real opportunities (and risks) that the US economy could face when working towards carbon mitigation goals, particularly when mitigation is associated with CCS/CDR deployment.

A techno-economic study was conducted of the US coal sector that aimed to capture the socioeconomic effects of a technology transition initiated by climate policies, i.e., achieving 2050 emission reductions in the US coal sector that are consistent with the 2°C target.

Entering results on mitigation pathways from the BeWhere model[5] into the JEDI tool[6] allowed employment variations to be quantified within the 2015-2050 timeframe associated with the adoption of mitigation technologies. To this end, the introduction of a range of technology options to mitigate the carbon emissions of the existing coal units were considered:

- **Biomass co-firing**: Given that many coal plants are ageing and nearing replacement, blending coal with biomass could be a "bridging" strategy to quickly reduce CO_2 emissions, regardless of the future status of coal use. The average abatement cost of 10% biomass co-firing was estimated to be US$30/t$CO_2$ and relied on site-specific factors such as the purchasing cost of biomass and its availability, as well as the generating capacity of the existing coal plants.
- **CCS and BECCS retrofit**: Although retrofitting existing power plants with CCS inevitably results in a derating of the power output (up to 40% derating assumed for this study), such retrofits offer an opportunity to avoid the long-term "lock-in" of emissions from these facilities. The emission savings can be even higher if CCS is coupled with the co-firing of biomass (BECCS), i.e., with a CDR technology, provided the biomass feedstock is grown sustainably.
- **Replacement with natural gas**: As around half of ageing coal plants would need to be retired before 2050, the option of replacing coal with less carbon-intensive fuels was also considered. Natural gas-fired power plants are flexible and their output can quickly and easily be adjusted to accommodate fluctuations in demand. For these reasons, the assumption was that natural gas combined cycle (NGCC) technology would be the preferred replacement option for existing coal boilers in the short term.

An important finding was that employment in the coal sector experiences a much softer landing if CCS could be deployed by 2050 compared to a scenario where no climate action is undertaken. This is because, when more stringent emission reduction targets are implemented, fewer coal units are immediately retired as they are eligible for climate mitigation retrofits, such as BECCS, that keep some plants active and create additional jobs in manufacturing.

The introduction of BECCS may also lead to regional variations in coal sector employment. It was observed that regions characterised by the greatest emissions reductions by mid-century saw the highest number of jobs retained, i.e., local jobs that would have been lost due to the phase-out of coal plants. For instance, almost 50% of the coal plants in Illinois were retrofitted

[5] BeWhere is a techno-economic model developed and maintained by the International Institute for Applied Systems Analysis (IIASA).

[6] The Jobs and Economic Development Impact (JEDI) models are user-friendly screening tools that estimate the economic impacts of constructing and operating power plants, fuel production facilities, and other projects. They were initially developed in 2004 to quantify the macro-economic impacts associated with energy projects development in the United States.

with BECCS by 2040. According to the model, this would allow around 4,000 jobs to be saved and 155 Mt less CO_2 emitted than if the entire capacity had been converted to natural gas. Furthermore, it is interesting to note that the number of jobs lost is higher in regions where BECCS is not part of the local energy mix, e.g., Montana and Oregon lose around 400 and 200 jobs, respectively. This strongly suggests that the retrofit of BECCS technology to existing coal plant saves more jobs and produces greater reductions in emissions of CO_2 than the replacement of coal generation by natural gas.

Moreover, findings highlight that the forestry industry benefits most from mitigation actions. BECCS facilities generate around 15,000 additional jobs in the forestry sector by 2050 with a further 2,500 jobs relating to logistics, while the job retention impact of BECCS is more pronounced in the mining sector, as around 12,000 mining jobs would otherwise be disrupted with the phase-out of coal.

While recognising the findings are dependent on the models deployed and the assumptions therein, combining these insights with regional employment analysis, can be useful for understanding how jobs might be preserved (in the mining sector) and expanded (in the forestry sector) according to region-specific factors. Mining and transport jobs may be preserved in areas that generate less electricity but where most of the coal is produced, e.g., in Wyoming, where 40% of coal in the United States is produced, while elsewhere jobs in electricity generation may be preserved due to early BECCS adoption, e.g., in States neighbouring the Great Lakes region.

Case study 2: The value of CCS in shaping socially equitable energy system transitions

Most current models for determining the best mix of strategies for a country to meet climate imperatives take the conventional least-cost and technology-focused approach. However, this 'one-size-fits-all' approach ignores the shape of a country's energy economy and its industrial strengths and could thereby lead to social inequalities. As a result, alongside the conventional approach, a novel, technology agnostic and welfare-focused approach is investigated.

Gross Value Added (GVA) is a widely recognised macroeconomic metric that measures the contribution to Gross Domestic Product (GDP) made by individual producers, industries or sectors to a country or region, i.e., it quantifies the *value* that each industrial activity adds to the domestic economy. However, as the JEDI tool alone could not present a complete picture of the supply or demand-side of the economy, sector specific GVA values descending from JEDI within the energy systems optimisation[7] (ESO) framework were incorporated. This allowed low-carbon deployment strategies that maximise social value in the different economies to be identified.

Scenarios were considered for decarbonising the electricity systems of Poland, Spain and the United Kingdom by 2050. The scenarios considered were:

- **Business As Usual** (BAU): Here, all existing policies are retained and all existing technologies are deployed according to historical build rates. No carbon target is imposed and the system is developed purely to minimise the total system cost.

[7] ESO is a model built for planning power-generation expansion, taking into account grid-level requirements such as hourly electricity demand and renewables availability, reserve, inertia, and emissions target requirements. It also incorporates constraints for considering the key technical capabilities and limitations of each power generation and storage technology.

- **All technologies** (AllTech): all technologies, including CCS and BECCS can be deployed, with system expansion planned to minimise the total system cost, subject to a target of net zero CO_2 emissions by 2050.
- **Renewables and Storage** (ReStor): as the European Green Deal aims at meeting the deep decarbonisation target using predominantly renewable and storage technologies, this scenario was constructed whereby only renewables and storage technologies could be deployed.
- **Social Equity** (EQ): this is similar to the AllTech scenario, except the system is designed to maximise the system's GVA during the transition as opposed to focusing exclusively on minimising the total system cost.

Considering the least-cost energy generation mix under the **ReStor** scenario, Poland initially replaces coal with natural gas and completely phases-out coal by 2035. With increasingly tighter carbon emission constraints, power generation from wind rapidly expands until it reaches a share of 60% in 2050. A similar trend is observed in Spain and the UK, where nuclear and natural gas rapidly give way to renewable power, especially from wind.

The **EQ** scenario, however, favours a more diverse energy generation mix within each country with shares of local resources varying according to the services provided to the system. In Poland, abated coal supplies more than 50% of the power output, owing to the ramp-up of CCS which lengthens the lifetime of existing plant and allows for new coal capacity addition. In Spain, nuclear provides more than 70 MWh of power output in 2050 in sharp contrast with that observed in the **ReStor** scenario. This, together with the adoption of indigenous biomass resources (with or without BECCS) allows the use of natural gas to be minimised (and entirely outsourced) and supports a forestry sector that experiences a 40% growth in GVA compared to the **BAU**.

Compared to Spain, which has negligible gas reserves, the UK can rely on domestic natural gas resources as well as on local expertise in CCS projects. Hence, the UK can utilise its CCGT-CCS capacity to provide firm, low-carbon capacity to the grid while boosting its manufacturing and mining sectors.

As well as the overall preference to enhance energy security by deploying domestic resources, all scenarios maximise value by deploying a large volume of CCS, which emerges as both a least-cost and socially valuable technology for a net zero energy transition.

Further analysis compares each country’s net-zero scenario against the following SDG indicators: the ratio of GVA to total system cost; employment growth (in the national economy and in the manufacturing sector); value added in the manufacturing sector (MVA); and shares of labour earnings in the total system cost. For this analysis, the value of pursuing a value maximisation strategy (**EQ** scenario) is compared to a cost minimisation one (**Alltech** scenario), when deploying CCS at scale.

Results reveal that efforts to decarbonise the power sector in Poland lead to GVA losses due to the diminishing role of domestic coal in the 2050 energy mix compared to the **BAU** scenario. Such trade-offs, which translate into 48% jobs reduction in the **ReStor** scenario, are lower in both **EQ** and **AllTech** scenarios, as the adoption of CCS allows for a greater utilisation of abated coal for power production.

Job disruptions projected in **ReStor** are unevenly distributed across the Polish economy. The mining sector bears the heaviest burden of the energy transition, while manufacturing industry experiences a 5% growth in employment resulting from the deployment of additional renewable capacity – these are primarily maintenance jobs associated with the routine operation of imported wind turbines and solar PV, increasing the exposure of the local labour market to further disruption arising from greater automation. Moreover, the share of investment migrating to employees is reduced by 50% in the **ReStor** scenario, with the energy transition outsourced, economic valuable assets replaced and a stagnated demand for a skilled workforce.

In contrast to that observed for Poland, transitioning to net-zero power in Spain brings economic growth and employment opportunities, especially in the **EQ** scenario. Gains are evident in the manufacturing sector, with growth of 23-26% in employment and around 40% in GVA within each scenario, as the country can rely on the domestic solar, wind and nuclear industries. In the **EQ** scenario, these benefits are experienced across all sectors of the economy, particularly the agricultural sector, where the expansion of bioenergy and BECCS capacity translates into an 18% growth in cumulative employment by 2050. As a result, high shares of low-carbon investments are retained in the economy in the form of employees' salaries and benefits, *e.g.*, social security contributions and welfare services, as the country can lean on local industries (wind and solar in **ReStor**, and nuclear and bioenergy in the other scenarios), and on its domestic labour pool to conduct the energy transition.

The UK falls behind on all indicators in the **ReStor** scenario, with larger trade-offs observed in the manufacturing industry. This is because the three-fold increase in installed capacity by 2050, required to meet the power demand from renewable energy sources, leads to higher investments having lower local value and displaces local workers in CCGT plants. The **AllTech** and **EQ** scenarios show no significant differences in socio-economic performance as their technology deployment pathways are almost identical. Overall, both scenarios forecast mild additional co-benefits compared to the **BAU**. Under the current carbon price floor, therefore, and assuming a rapid scale-up of the local CCS industry from 2030, the UK power system would 'naturally' evolve into a socially equitable energy system, where welfare is maximised, and domestic assets are favoured.

The results from Case study 2 imply that, when pursuing net-zero targets, there is no "one size fits all" solution, with the relative costs and opportunities associated with the transition unevenly distributed between countries. Cost-focused carbon mitigation strategies that neglect any social, geopolitical and macro-economic considerations may very likely exacerbate labour market inequalities.

Case study 3: The removal and avoidance value of BECCS

In Case Study 3, socio-economic analysis is extended to a suite of CDR pathways with the aim of quantifying the economic value of deploying biomass-based CDR technology in the UK.

Biomass-based CDR technologies provide two main services to climate change mitigation: **carbon removal**, since biomass sequesters carbon dioxide from the atmosphere, and **carbon avoidance**, associated with the displacement of fossil fuels by biomass.

An inherent advantage of CDR is its potential to integrate with different conversion processes, such as combustion, gasification and fermentation, thereby providing a wide range of low-carbon energy vectors, including electricity, liquid fuel, heat and hydrogen, while providing long-term CO_2 removal.

The main CDR pathways represented in IAMs are biomass conversion to electricity in large-scale combustion plants and biomass conversion to liquid fuels. The production of liquid fuels via BECCS (i.e., biofuels) can provide a substantial contribution to mid-century stabilisation scenarios by decarbonising transport. Hydrogen can contribute to decarbonisation of, for example, the industry, transport and heating sectors. The potential integration of biomass and/or CCS in hard-to-abate fossil intensive industries such as iron and steel, cement and chemicals is also gaining increasing attention as an industrial decarbonisation option.

The mitigation potential of each CDR pathway depends on biophysical factors, process specifications, regional factors and the counterfactual scenario considered. Understanding the best uses of CDR as a function of the regional context and of the pace of decarbonising the energy system is key. By combining its potential for the removal and avoidance of CO_2 with the socio-economic impacts associated with its deployment, it is possible to quantify the removal and avoidance value of various mitigation pathways. This is because each unit of GVA created within the CDR supply chain will result in the avoidance and removal of a certain amount of carbon.

The macroeconomic impact resulting from the deployment of BECCS and its associated value chain has been quantified. This was done within JEDI by applying a carbon accounting framework to quantify the net amount of CO_2 removed and avoided within each technology pathway. The BECCS applications considered include:

- BECCS in the power sector (biopower-CCS)
- Retrofit of integrated steel mills with BECCS (bio-steel)
- Adoption of tail-end calcium looping technology in cement plants (bio-cement)
- BECCS to biofuels (biohydrogen, Fischer-Tropsch diesel and bioethanol)
- Slow-pyrolysis technologies for biochar production

For this, JEDI was populated with socio-economic data from the main industrial sectors in the UK and extended to accommodate the techno-economic features of the BECCS applications.

GVA is created from the deployment of BECCS in the iron and steel sector (per tonne of crude steel) and in the cement sector (per tonne of clinker). In bio-steel pathways, around 23% of the value is attributed to the utility sector, such as the natural gas and electricity providers, and is associated with the additional energy required by the steel mill following the retrofit of CCS. In bio-cement pathways, the agroforestry industry is a significant beneficiary.

In general, the distribution of GVA created in the agroforestry and transport sectors is assumed to be a reliable proxy for the CO_2 removal efficiency achieved by each CDR technology. With BECCS to power, around 30% of the GVA is associated with CO_2 transport and storage, and 17% with agriculture activities. Almost 85% of the economic value created with biochar production is in biomass supply. For bio-steel pathways, the GVA associated with CO_2 storage is even higher than for the forestry sector as this CCS configuration maximises CO_2 capture from the various steel mill off-streams.

Combining these findings with carbon accounting analysis, it is possible to quantify the amount of CO_2 emissions that can be avoided and removed by deploying CDR technologies within the

UK economy. It provides an indication of the removal and avoidance efficiency of government spending as each unit of GVA created within the CDR technologies' supply chains results in the avoidance and removal of a certain amount of carbon.

The analysis points towards each CDR product having a distinctive removal and avoidance value for the UK economy. Among biofuels, the production of Fischer-Tropsch diesel has the highest avoidance value as higher biofuel yields are achievable compared to bioethanol production and, as a result, higher amounts of fossil gasoline are being displaced. The cost of a GJ of Fischer-Tropsch diesel is also lower than that of a GJ of biohydrogen, hence higher amounts of CO_2 can be avoided with the same level of investment for their production. However, when it comes to the value of carbon removal, producing bioethanol represents the most efficient investment.

Thus, large-scale power plants that deploy BECCS may represent a valid investment in terms of the mitigation and removal services provided as each unit of GVA created within the economy removes 10 kg CO_2 and avoids 3 kg CO_2. Indications were that biochar would represent the best investment for mitigation, mainly because of the small investment associated with slow-pyrolysis plants compared to large-scale BECCS power plants. However, as already observed, these benefits would be disproportionally concentrated in the agricultural sectors, while the value created in other industries, such as manufacturing and construction, would be minimal.

Expert Review Comments

Few substantive comments were picked up by the external reviewers. There had been some confusion in the text differentiating between CCS and CDR technologies, but this and other minor amendments to spelling and grammar were addressed by the authors in the final report.

Conclusions and Recommendations

Case study 1 indicates that the goals of coal sector employment and climate change mitigation could be aligned, contrary to the way it is often portrayed. Therefore, together with a commitment to a net-zero target, the employment opportunities that might arise with CCS deployment should be carefully assessed and promoted.

Case study 2 indicates that, when pursuing net-zero targets in the energy systems, there is no "one size fits all" solution, with the relative costs and opportunities associated with the transition unevenly distributed between countries. Hence, cost-focused carbon mitigation strategies that neglected any social, geopolitical, and macro-economic considerations were likely to exacerbate labour market inequalities, with job losses concentrated among specific socio-economic groups and in particular regions.

Case Study 3 indicates that quantifying the socio-economic value of different BECCS pathways could inform policy makers of the optimal mix of CDR technologies to be deployed while minimising biomass resource competition.

In total, findings from the three case studies strongly imply that decarbonisation strategies that neglect social, geopolitical, and macro-economic considerations were likely to widen existing economic imbalances, both at regional and national levels. While CCS is widely acknowledged as essential to reach net-zero targets within economies, its deployment has faced numerous challenges. Providing a multi-regional, technology agnostic and transparent quantification of the social value of CCS may be key to greater success moving forward.

Suggestions for further work

Decarbonising society presents complex structural changes to economies and communities. Further research is required to understand the sectoral and skill-based influences in the labour market associated with the deployment of CCS technologies at scale, as well as the social implications in the regions and communities involved.

To ensure a sustained structural transition of global economies, the socio-economic impacts of decarbonisation pathways must be explored using appropriate quantitative methodologies such as those discussed in this report. This will open a window on the levels of investment required in education and training for transitioning the existing labour force into the low-carbon society of the future.

Quantifying the socio-economic value of CCUS: a review

Report for IEAGHG

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Contents

Executive Summary

The transition towards a net-zero economy will imply profound structural changes for national and regional economies. These changes will be most evident in the labour markets as carbon intensive industries and their associated labour forces become less competitive and decline, and on the other hand low carbon activities increase.

Therefore, translating net-zero emissions commitments into effective energy decarbonization pathways requires further understanding of the intertwined techno-economic, social and policy dimensions of the transition. In this way, the social, economic, and mitigation value of low carbon technologies can be translated into meaningful metrics for energy modelers and analysts. This is particularly the case of Carbon Capture Utilization and Storage (CCUS), which deployment is still lagging expectation, despite its key role in achieving meaningful emission reductions in the decades to come.

To this end, this study presents a collection of case studies that quantify the socio-economic impacts of achieving ambitious climate targets in the energy sector for different economic archetypes. In particular:

- *Case study 1* quantifies the employment impacts of reducing the emission of the coal sector in the US by deploying a mix of decarbonization option, including Carbon Capture and Storage (CCS) and bioenergy with Carbon Capture and Storage (BECCS)
- *Case study 2* considers two potential approaches for decarbonizing the electricity systems of selected EU countries, *i.e.,* Poland, Spain and the UK: the conventional, least-cost and technology-focused approach, and a novel, technology agnostic and welfare-focused one
- *Case study 3* extends the socio-economic analysis to a suite of CO_2 removal pathways with the aim of quantifying the economic value of deploying biomass-based CDR technologies in the UK.

These case studies will show that the relative social costs and opportunities associated with the energy systems transition will be unevenly distributed between countries and that together with the commitment to net zero targets, the employment opportunities that might arise with CCS deployment should be carefully assessed and promoted. Hence, decarbonisation strategies that neglect any social, geopolitical, and macro-economic considerations, are likely to widen existing economic imbalances, both at regional and national levels.

Further research is required to understand the sectoral and skill-based impacts in the labour market associated with the deployment of CCS technologies at scale, as well as the social implications in the regions and communities involved. This will also allow to quantify the required level of investment in education and training for transitioning the existing labour force into the low-carbon society of the future.

1. Introduction

Historically, climate scientists and economists have used Integrated Assessment Models (IAMs) to explore the feasibility of achieving climate targets and to inform global climate negotiations. Emission stabilization pathways arising from these models highlight the key role of CCUS technologies to achieve the 1.5 ^{o}C target set out by the Paris Agreement (1). Under different transition scenarios, the removal capacity requirement of CCS can range from 150-1200 $GtCO_2$ over the next 80 years (2). However, the lack of technological detail incorporated in IAMs provide limited information on the role that these technologies will play in national energy systems.

Moreover, as frequently argued by energy transition scholars (3), the transition towards a net-zero economy implies profound structural changes for national and regional economies. The 'transition policies' adopted by nations include a portfolio of energy, industrial, climate, and trade policies required to enable the transition to a net zero paradigm. These changes and upheaval brought by the decarbonization of national energy systems will be particularly evident in the labour markets (4,5) as carbon intensive industries and their associated labour forces become less competitive and decline, and on the other hand low carbon activities growth and their associated employment increases (6). These activities will not be evenly distributed as different regions have different levels of industrial and economic activity. Hence the socio-economic aftermath of decarbonization will depend on regional portfolio of physical, human, social, and intangible capitals.

Translating net-zero emissions commitments into effective energy decarbonization pathways hence requires further understanding of the intertwined dimensions of the transition. In this way, the social, economic, and mitigation value of CCS, CCUS and BECCS technologies can be identified and subsequently translated into meaningful metrics for energy modelers and analysts. Local and regional areas will be an important unit of analysis to capture the socio-economic impacts of deploying these technologies. Rather than just using pure cost-based metrics (7), we believe that accounting for socio-economic factors is also necessary for the timely deployment of CCS at scale, despite the difficulty in doing so.

This study presents a collection of case studies on the socio-economic impacts of achieving ambitious climate targets *via* the deployment of CCS and Carbon Dioxide Removal (CDR) technologies in different economic archetypes. The starting point of the analysis will be the identification of key metrics available in the literature that allow the social value of CDR technologies to be quantified. A detailed description of the approach adopted within the different case studies will be proposed in section 2.2., with a special focus on how the trade in manufacturing of low carbon technologies can be accounted for. Section 3 introduces the context and motivation around the selected case studies and presents main results. Section 4 identifies gaps in existing approaches and suggest areas for future work.

2. Approach

2.1 Key socio-techno-economic impacts

` Developed in 2015, the United Nations Sustainability Development Goals (UN SDGs) is a blueprint by the UN General Assembly, demonstrating the intertwining relationship of the components in sustainable growth and development. Importantly, the indicators embedded within the SDGs framework (United Nations 2020) could be mapped onto broader potential implications of deploying CCUS concepts at scale. Nations were encouraged to adopt the global SDG indicators along with their individually set national indicators.

While there are increasing efforts in the energy modelling community to quantify the impact of GGR on natural resources such as land, biomass, and water use (8–10), the potential effects of deploying and upscaling these technologies across other SDGs are scarce notably regarding social, institutional, or policy dimensions. Consideration of regional socio-economic impacts such as employment creation (SDG 8), economic growth (SDG 9) and distributional effects (SDG 10) of CDR deployment is scarce in literature, despite indications that regional, cultural, socio-economic, and political differences and their influence on policy design could strongly affect progress towards sustainable development.

Although the UN SDG framework is widely referred to as a standard for sustainable development in international negotiations, the aggregate nature of these indicators hinders the ability to trace status, progress, and cross-national comparison. Within this context, the Organization for Economic Cooperation and Development (OECD) has developed a set of Green Growth Indicators (OECD 2017) which can be adopted at national level to assess the progress towards decarbonization and economic growth. Some relevant indicators include the percentage of R&D expenditure in green growth and GDP per unit of CO_2 emitted. Whilst these indicators do not account for regional-specific circumstances and need improvement when comparing progress in developing countries, they represent a useful set of metrics to address the socio-economic impacts of national decarbonization strategies.

A list of all relevant SDGs and OECD indicators for evaluating the socio-economic impacts of CCS adoption is summarized in Table 1.

Regional specialization

In addition to the equitable distribution of climate targets, much of the regionally initiated commitment towards low carbon transition has been found contingent on the political will and the socio-economic resources of the respective areas. As demonstrated by Jewell et al, nations that committed to the Powering Past Coal Alliance have also shown inherently small dependence on, and existing natural resources of, coal (11). As case study 2 will show, the socio-economic impacts associated with transitioning to net zero are likely to be unequally distributed among European countries, depending on regional economic strengths and geopolitical factors. Due to its land-use requirement and potential competition with agricultural needs, bioenergy with carbon capture and storage (BECCS) especially presents region-specific challenges through its deployment (12). Furthermore, the technological availability of CDR technologies such as Direct Air Capture with Carbon Capture and Storage (DACCS) can impact the regional capability for deployment. Hence, the dependency of regional resources, availability of geological constraints, and the structure of the local economy should be fully accounted for during the planning and deployment of these technologies.

Sectoral heterogeneity

Besides region-specific drivers such as the geopolitical setting and natural resources involved, the heterogeneity of national economic structure, including national industrial strength and labor market composition, play a major role in the successful implementation of energy transition strategies. The potential socio-economic gains associated with low-carbon technologies will depend on the extent to which economies can rely on domestic industries and expertise for their implementation. In addition, the commercialization of low-carbon technologies and the diffusion of particular CDR practices will bring unequal socio-economic impacts across different sectors of the economy. In quantifying the employment effects of the decarbonization of the US coal sector, Patrizio et al. had shown that the deployment of BECCS would mitigate significant job losses in the mining industry while job creation would be predominantly observed in the forestry and transport sectors (13). The structural changes through the decarbonization of our society will also lead to skill- and innovation-based transitions in the job market. As more renewable energy technology gets deployed, the long-term improvements in efficiency and automation could lead to the displacement of manual labor activities. The re-skilling and re-training of labor forces from high carbon intensity sectors towards low carbon intensity ones present a nontrivial challenge for policymakers.

Framework	Goal	Example Indicator
SDG Framework (14)	7: Affordable and Clean Energy	Proportion of population with primary reliance clean fuels and technology
	8: Decent Work and Economic Growth	Unemployment rate, by sex, age and persons with disabilities
	9: Industry, Innovation and Infrastructure	CO_2 emission per unit of value added, Proportio of medium and high-tech industry value added total value added
	10: Reduced Inequalities	Labour share of GDP
	12: Responsible Consumption and Production	Amount of fossil-fuel subsidies per unit of GDP (production and consumption)
	13: Climate Action	Total greenhouse gas emissions per year
	15: Life on Land	Progress towards sustainable forest manageme
OECD Green Growth Indicators (15)	*The socio-economic characteristic of growth*	
	Productivity and trade	Relative importance of trade: (exports + import / GDP
	Labour markets	Labour force participation
	The environmental and resource productivity of the economy	
	1 - CO_2 productivity	GDP per unit of energy-related CO_2 emitted
	2 - Energy productivity	GDP per unit of Total Primary Energy Supply (TPES)
	The environmental dimension of quality of life	
	14 - Environmentally induced health problems and related costs	Population exposure to air pollution and the related health risks
	15 - Exposure to natural or industrial risks and related economic losses	N/A
	Economic opportunities and policy responses	
	17 - Research and development expenditure of importance to green growth	Environmental technology (% of total R&D)
	18 - Patent of importance to green growth	Environment-related patents (% of a country's patent families worldwide)
	20 - Production of environmental goods and services (EGS)	Gross value added in the EGS sector (% of GDP), Employment in the EGS sector

Table 1: Sustainable development and economic growth indicators relevant to CCS deployment

2.2 The Job and Economic Development Impact modelling approach

The Job and Economic Development Impact (JEDI) modelling approach was initially developed in 2004 from a collaboration between the National Renewable Energy laboratory (NREL) and MRG & Associates, to quantify the macro-economic impacts associated with energy projects development in the US. The portfolio of low carbon technologies covered in JEDI included conventional hydropower, geothermal, wind, bioenergy, coal- and natural gas power plants.

The underlying approach of JEDI is to couple macro-economic data from national I/O databases, with techno-economic details of selected energy technologies.

JEDI models have been used in many high-profile studies such as the U.S. Department of Energy (DOE) Wind Vision study and the DOE Hydropower Vision study (14) as well as in peer-reviewed journal articles (13,15,16). JEDI results in the United States typically conform to employment figures reported in press releases by developers and operators, and impact estimates are consistent with those found by other researchers (17).

Existing and freely available versions of JEDI have included only state and national data for the United States. Model users can include their own economic multipliers, but knowledge about I/O models is needed to use the model outside of the United States. Importantly, the JEDI suite of models maintained by NREL does not include key technologies such as CCS or BECCS. The balance of this report will focus on the JEDI version developed by Patrizio et al. which has been applied in the case studies presented in section 3 (16,18).

2.2.1 Modelling framework

A synthetic framework of JEDI is provided in

Figure *1* . The overall approach is to combine cost data of a specific energy project with socio-economic indicators from the database for structural analysis (STAN)[1] maintained by the Organization for Economic Development (OECD). The STAN database is a comprehensive tool for analyzing industrial performance at a relatively detailed level of activity across countries. It includes annual measures of output, value added and its components, labor input, investment and capital stock, from 1970 onwards, which allow users to construct a wide range of indicators to focus on areas such as productivity growth, competitiveness and general structural change. STAN is primarily based on member countries annual national accounts[2], while data from other sources, such as results from national business surveys/censuses (maintained by OECD, Eurostat or compiled directly from national sources) are adopted to estimate any missing detail. Many of

[1] For more information about the STAN database, please refer to www.oecd.org

[2] National accounts are reported here: http://www.oecd.org/sdd/na/

the data points in STAN are estimated and therefore do not represent official member country submissions.

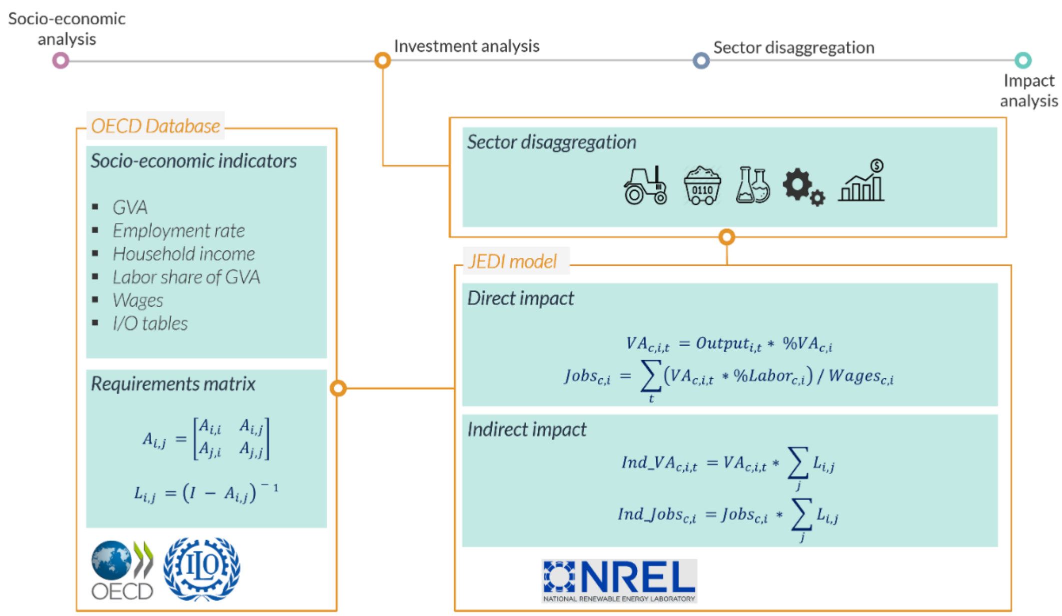

Figure 1: The JEDI framework, combining an investment analysis with a socio-economic analysis. The latter adopts national or regional socio-economic databases and quantifies the direct and indirect impacts associated with low-carbon investments

Within the model, it is possible to differentiate between *direct* (project expenditures themselves), *indirect* (resulting economic activity among other industries) and *induced* impacts (increased household spending induced by direct and indirect impacts). An example of these impacts is provided in Figure 2.

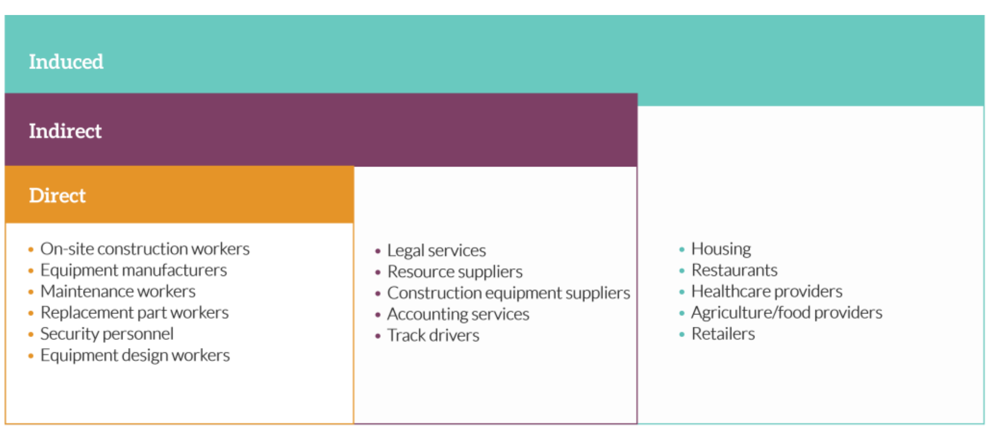

Figure 2 Type of impacts considered in JEDI

Key outputs of JEDI are *gross value added (GVA)*, the value of an industry's production to the country of analysis, and *employment creation.* These metrics are calculated for different industrial activities and economic sectors, based on the sectoral indexing of the International Standard Industrial Classification (ISIC)[3].The following indicators are extracted from STAN for the calculation of ***direct impacts***:

- $\%VA_i$ Value added share of production: this indicator shows the value added contributed by each sector *i* relative to total production. The GVA is a widely recognized macroeconomic variable that measures the contribution to the Gross Domestic Product (GDP) made by individual producers, industries, or sectors in a country. It provides an indication of the production structure of a given sector.

- $\%Labour_i$ Labor share of value added: Amount of labor compensation within the value added created by a given industry. It is used to calculate the total earnings generated within a certain economic activity.

- Wages: this indicator is used to calculate the number of jobs created by a given industry.

Value added and jobs created in each industry *i* are proportional to the output produced by technology *t* in that sector[4].

$$VA_{i,t} = Output_{i,t} * \%VA_i$$

$$Jobs_i = \sum_t \left(VA_{i,t} * \%Labour_i\right) /_{Wages_{i_i}}$$

Indirect and Induced impacts are calculated using the I-O methodology (19). The I-O models are based on social accounting matrices that contain sales and purchases made by sectors of the economy such as industries, households, investors, governments, and the rest of the world (via imports and exports). Each sector contains a "basket of goods" that includes either expenditures or inputs for production.
The calculation of ***indirect impacts*** requires Leontief inverse matrix L_1, calculated from a social accounting matrix A, a country specific I-O table showing the transactions and transfers among all the different industries and institutions within a certain country.

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[3] More information about International Standard Industrial Classification codes can be found at https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf

[4] Therefore, I-O methodology assumes that all estimates are linear and proportional. Value added, earnings, and jobs, are then simply proportional to certain output.

$$A = \begin{bmatrix} A_{i,i} & A_{i,j} \\ A_{j,i} & A_{j,j} \end{bmatrix}$$

Leontief inverse coefficients $L_{i,J}$ show how many units of intermediate production of sector *i* are needed to produce one unit of final demand for goods of sector *j* and are calculated as follow:

$$L_{i,J} = \left(I - A_{i,J}\right)^{-1}$$

The calculation of ***induced impacts*** follows the same methodology and is based on the total requirements matrix L_2 which also includes labor payments and household expenditures. Induced value added and jobs:

$$Ind\_VA_{i,t} = VA_{i,t} * \sum_j L_{i,j}$$
$$Ind\_Jobs_i = Jobs_i * \sum_j L_{i,j}$$

2.2.2 Trade In manufacturing

Within our approach is possible to specify how much of the value in service and manufacturing products are generated in a certain country as a percentage of the capital expenditure of low carbon technologies. In making the assessment, the lifetime costs of energy projects are disaggregated across main manufacturing and downstream activities. The cost breakdown is allocated to the corresponding industrial sectors, considering only the share of expenditure contributing to the creation of national economic output.

The production structure of energy technologies varies significantly. Conventional thermal power capacities such as that of coal fired plants and Combined Cycle Gas Turbine (CCGT) as well as utility scale bioenergy projects, are based on quite simple production value chain configurations and mostly local sourcing. Value chains in the more dynamic sectors of wind and solar are far more complex and geographically extended: 50% of the global wind industry value-chain is in South-East Asia, while China alone controls 70% of the global solar PV industry (20) .To capture the status of local supply within these industries, three criteria are utilized:

I. The presence of energy technology manufacturing companies, or multinational branches, in the country.
II. Local supply track record considers how much local companies have supplied to the industry (e.g., wind offshore, solar PV), following global manufacturing trade statistics obtained from the UN International Statistics database COMTRADE[5]. We describe

[5] For more information see: https://comtrade.un.org/

those companies that are proven suppliers, defined has having supplied greater than 200 MW equivalent of products (21).

III. The availability of local expertise considers the synergies with the parallel industries where the national economy has strengths, as this would facilitate a smooth transition of the local manufacturing sector into novel industrial activities. For example, most UK companies have made the transition to offshore wind because of the UK's position as a market leader and its long-standing strength in engineering, and marine and offshore services.

This latter criterion is particularly relevant for emerging power generation technologies such as CCS and BECCS, which have proved themselves on a demonstration-scale level but are not yet commercially deployed. In the UK, two competitive CCS procurement programs for power generation have been run by the government since 2007. Despite being abandoned without success, these efforts, and the creation of the CCS roadmap in 2013, demonstrates the country's leading position in early-stage CCS commercialization strategies.

CCS-equipped power capacity faces the additional challenge of being infrastructurally intensive, with the CO_2 transport being an over-designed element of the CCS value chain. The UK oil and gas industry has strong underpinning expertise in upstream processing of the CCS chain including high-pressure transport and injection, geological site operation and licensing. Moreover, detailed development plans for CO_2 injection in saline aquifers, including simulations, have been already investigated by the UK led study for early CO_2 storage development sites.

For these reasons, we include the deployment of CCS value chain among the list of available local expertise in the UK. With an understanding of the total expenditure in the manufacturing sector and of the status of the local supply, the domestic value of each energy technology can be generated.

In calculating the domestic value of power plants operation, we distinguish between imported and domestic fuels (natural gas, coal, biomass, and nuclear fuel) so that fuel procurement activities are allocated to the mining sector following national energy trade statistics. For imported biomass, only transportation activities (from seaport and inland ports to the bioenergy facilities) are assumed to generate economic value.

3 Case studies

This section proposes a collection of case studies in which JEDI has been combined with various modelling frameworks to quantify the socio-economic impacts of deploying CCS, BECCS and other CDR technologies. These case studies are:

- BeWhere-JEDI: here the JEDI tool has been combined with a techno-economic model to quantify the employment opportunities associated with CCS deployment in the US coal sector

- ESO-JEDI: This configuration has been used to identify net-zero energy systems transitions that maximize the socio-economic benefits for the UK, Poland and Spain economies
- CDRs-JEDI: In this case the results from a CO_2 emission balance has been combined with JEDI to quantify the removal and avoidance value of a portfolio of CDR technologies

3.1 Employment opportunities of deploying CCS in the US coal sector

3.1.1 Context and motivation

Historically, the knock-on effects of environmental regulation on employment have played a central role in the political debate in the US. Of particular concern, is that the coal phase-out and investment in mitigation come at the cost of unemployment, lost competitiveness, and a resultant loss of welfare for local communities. On the other hand, investors and businesses are becoming aware of the risk that assets might be stranded if their investments are not directed toward emission-reduction technologies.

Such contradictory perspectives emphasize the need for a quantitative assessment of the real opportunities (and risks) that the US economy could face when working toward carbon mitigation goals, particularly when mitigation is associated with CCS deployment.

In this work, we conducted a techno-economic study of the US coal sector that aims to capture the socioeconomic effects of technology transition initiated by climate policies, *i.e.* achieving 2050 emission reductions in the US coal sectors that are consistent with the 2C target.

To do so, the results descending from the mitigation pathways identified with the BeWhere model[6] have been included in the JEDI tool. This allowed to quantify the employment variations within the 2015-2050 timeframe associated with the adoption of mitigation technologies in the coal sector. To this end, the introduction of a range of technology options to mitigate the carbon emissions of the existing coal units have been considered:

- Biomass co-firing: Given that many coal plants are aging and near replacement, blending coal with biomass could be a "bridging" strategy to quickly reduce CO_2 emissions, regardless of the future status of coal use. The average abatement cost of 10% biomass co-firing is estimated to be US$30 per tCO_2 and relies on site-specific factors such as the purchasing cost of biomass and its availability, as well as the size of the existing coal plants.
- CCS and BECCS retrofit: Although retrofitting existing power plants with CCS inevitably results in a derating of up to 40% of the power output, such retrofits offer an opportunity to avoid the long-term "lock-in" of emissions from these facilities. The emission savings

[6] The BeWhere is a techno-economic model developed and maintained by the International Institute for Applied Systems Analysis (IIASA). More information can be found at: www.iiasa.ac.at/BeWhere

can be even higher if CCS is coupled with the co-firing of biomass (BECCS), provided that the feedstock is grown sustainably. Thus, we considered only biomass deriving from sustainably managed and certified forests across the US territory.

- Replacement with natural gas: As around half of the aging plants would need to be retired before 2050, we also considered the option of replacing coal with less carbon-intensive fuels. Among other alternative choices, natural gas-fired power plants are flexible, and their output can quickly and easily be adjusted to accommodate fluctuations in demand. For these reasons, we assumed that the natural gas combined cycle (NGCC) technology would be the preferred replacement option for existing coal boilers in the short run.

3.1.2 Main results

An important finding of this study is that coal sector employment experiences a much softer landing if CCS can be deployed by 2050 compared to a scenario where no climate action is undertaken. This is because when emission reduction targets are implemented, fewer coal units are immediately retired as they are eligible for climate mitigation retrofits, such as BECCS, that keep some plants active and create additional jobs in manufacturing. The introduction of BECCS might also lead to regional variations in coal sector employment, as emphasized by Figure 3

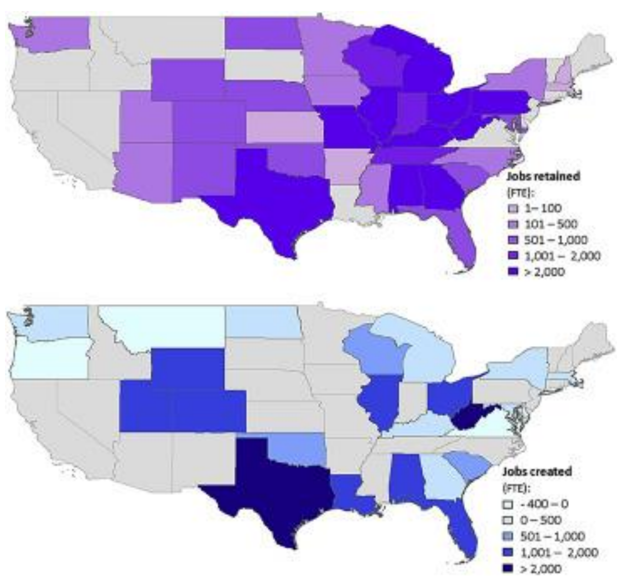

Figure 3: Jobs created and retained across the US by 2050 *via* CCS and BECCS deployment

It is in regions characterized by the greatest emission reductions by mid-century that we obviously observe the highest number of jobs retained (local jobs that would be lost due to the phase-out of the plants). For instance, almost 50% of the coal plants located in Illinois are retrofitted with BECCS by 2040. This allows about 4,000 jobs to be saved and 155 $MtCO_2$ lower emissions than if the entire capacity had been converted to natural gas. It is also interesting to note that the early replacement of coal in this scenario has a negative impact on the job market in six states: the number of jobs lost is higher in regions where BECCS is not part of the local energy mix (e.g., Montana and Oregon lose around 400 and 200 jobs, respectively). This shows that the retrofit of BECCS technology to existing coal plant saves more jobs and produces grater Co2 emission reductions that the replacement of coal generation by natural gas.

Moreover, the employment sectoral breakdown in

Figure *4* highlights that the forestry industry and the transport sector benefit the most from the emission mitigation actions: BECCS facilities generate 15,000 additional jobs in the forestry sector by 2050 and create 2,500 jobs connected to logistics activities, while the retaining effect of BECCS is more pronounced in the mining sector, as around 12,000 mining jobs would otherwise be disrupted with the phase-out of coal.

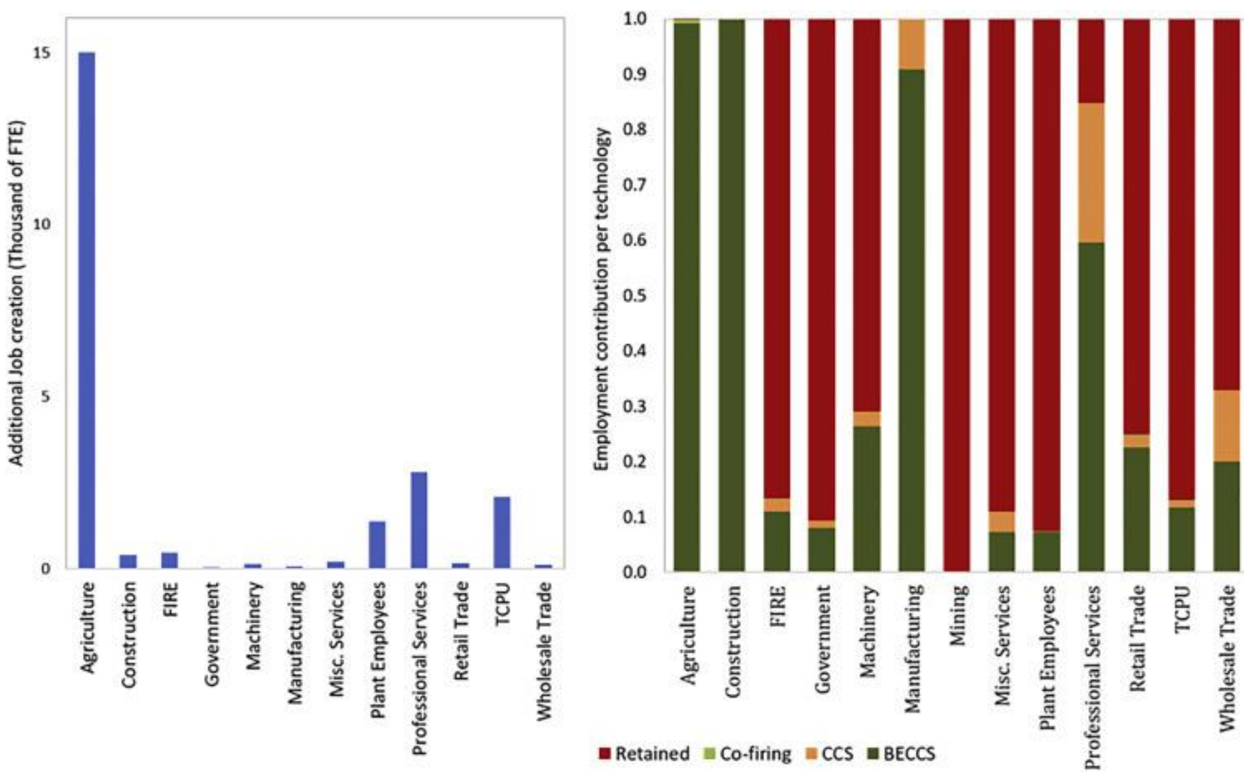

Figure 4: Sectoral breakdown of employment creation by deploying bioenergy, CCS and BECCS in the US

Combining such insights with the regional employment analysis proposed in Figure 3, can be useful for understanding how jobs are preserved (in the mining sector) and expanded (in the forestry sector) according to region-specific factors: mining and transport jobs are preserved in areas with less generation but where the majority of coal is produced (e.g., Wyoming, producing 40% of coal in the US), while elsewhere energy generation jobs are preserved due to early BECCS adoption (e.g., the states of the Great Lakes region).

3.2 The value of CCS in shaping socially equitable energy system transitions

3.2.1 Context and motivation

The Gross Value Added (GVA) is a widely recognized macroeconomic variable that measures the contribution to the Gross Domestic Product (GDP) made by individual producers, industries, or sectors in a country. The expression is profound as it consists of measuring the *value* that each industrial activity adds to the domestic economy. Whilst being able to take fully account of country-specific industrial inter-dependencies, the JEDI tool alone cannot present a complete picture of the supply or of the demand side of the economy, in that it does not envision optimizing behavior of economic agents faced with alternative courses of action. Importantly, choices about the proportions in which inputs, *e.g.,* energy technologies, are to be combined in the production of a given output, *e.g.,* power supply, are excluded from the analysis.

To overcome these limitations, the case study presented here incorporates sector specific GVA values descending from JEDI within the energy systems optimization (ESO) framework, which allow to identify low carbon deployment strategies that maximize social value in different economy archetypes. More details can be found in Patrizio et al. (16)

The study aims at investigating the potential of societal value as an orienting principle for shaping effective decarbonization trajectories featuring the large-scale deployment of CDR technologies. This is done by contrasting two opposite approaches to energy transition: the conventional, least-cost and technology-focused approach, and a novel, technology agnostic and welfare-focused one.

Hence, this case study considers three different scenarios for decarbonizing the electricity systems of selected countries, *i.e.,* Poland, Spain and the UK, by 2050. These scenarios are:

- Business As Usual (BAU): Here, existing policies, for example, the current carbon tax, and technology banning are maintained and all existing technologies, namely, nuclear, unabated fossil, and renewables. No carbon target is imposed, and the system is developed purely to minimize the total system cost.
- All technologies (AllTech): all technologies, including CCS and BECCS can be deployed and the system expansion is planned to minimize the total system cost, subject to a target of net zero CO_2 emissions by 2050.
- Renewables and Storage (ReStor): as the European Green Deal aims at meeting the deep decarbonization target using predominantly renewable and storage technologies, we construct a scenario in which only renewables and storage technologies can be deployed.
- Social Equity (EQ): this is like the AllTech scenario, but the system is designed to maximize the system's gross value added (GVA) during the transition as opposed to focusing exclusively on minimizing the total system cost.

3.2.2 Main Results

The left-hand side of Figure 5 presents the least cost energy generation mix in each country, under the ReStor scenario. In Poland, natural gas initially replaces coal, which is completely phased-out by 2035. with increasingly tighter carbon emission constraints, power generation from wind is rapidly expanded until it reaches a share 60% in the national energy generation mix in 2050. A similar trend is observed in Spain and in the UK, where nuclear and natural gas rapidly give way to renewable power especially from wind, producing more than 300 MWh and 260 MWh respectively.

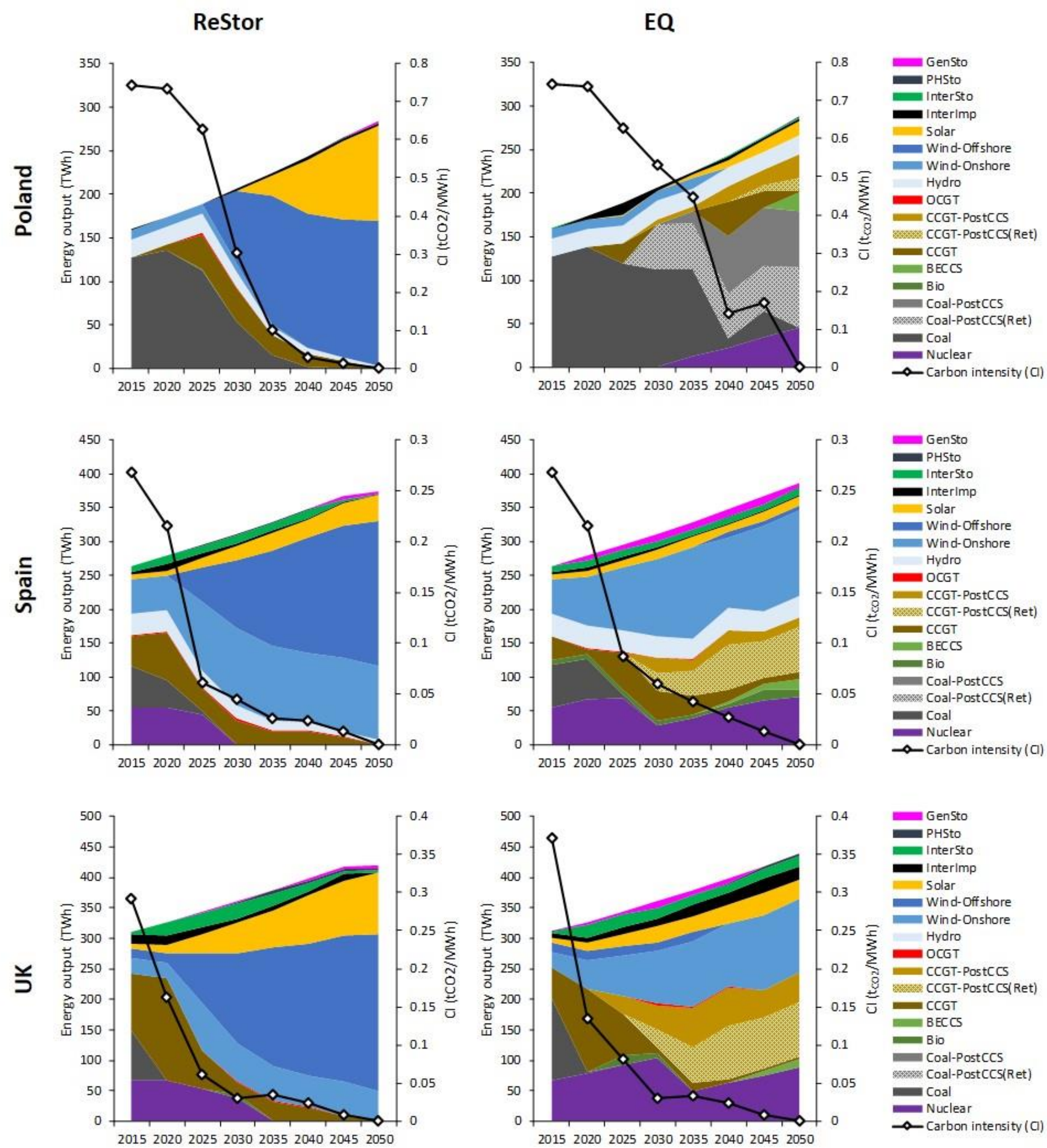

Figure 5: 2050 net zero energy generation mix for Poland, Spain and the UK based on 100% renewables cost minimization scenario (ReStor) and a value maximization scenario (EQ) featuring CCS deployment

The social equity (EQ) scenario favors a more diverse energy generation mix within each country with shares of local resources varying according to the services provided to the system. In Poland abated coal supplies more than 50% of the power output, owing to the ramp-up of CCS which lengthens the lifetime of existing plant and allows for new coal capacity addition. In Spain, nuclear provides more than 70 MWh of power output in 2050 in sharp contrast with what observed in the ReStor scenario. This, together with the adoption of indigenous biomass resources (with or without BECCS) allow to minimize the use of natural gas, which is entirely outsourced in the country, and to support the forestry sector which experience a 40% growth in GVA compared to the BAU.

Compared to Spain, which gas reserves are negligible, UK can rely on domestic natural gas resources as well on local expertise in CCS projects. Hence, UK can utilize its CCGT-CCS capacity to provide firm, low-carbon capacity to the system while boosting its manufacture and mining sectors.

Beside the overall preference for domestic resources, a common feature of all value maximization scenarios is the large deployment of CCS, emerging as both a least cost and socially valuable technology for a net zero energy transition.

For the remaining on the analysis, the net-zero scenarios for the selected countries are compared against the following SDGs indicators: GVA to TSC ratio; employment growth (in the national economy and in the manufacturing sector); value added in the manufacturing sector (MVA); and shares of labor earnings in TSC. Beside the scenarios proposed in Figure 5, the Alltech scenario is also presented, to quantify the value of pursuing a value maximization strategy (EQ scenario) against a cost minimization one (Alltech scenario) when deploying CCS at scale.

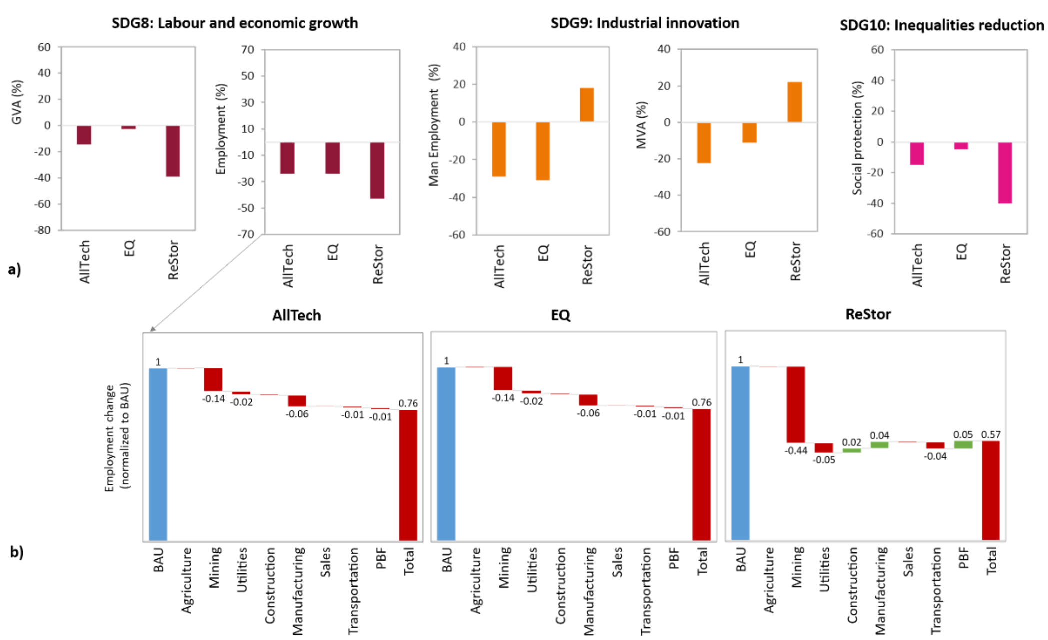

Figure 6: Socio-economic impacts of net-zero transition in Poland across SDGs 8,9 and 10

As Figure 6a reveals, any effort to decarbonize the power sector in Poland leads to GVA losses, due to the diminishing role of domestic coal in the 2050 energy mix compared to the BAU scenario. Such trade-offs, which translate into 48% jobs reduction in the ReStor scenario, are lower in the EQ and AllTech scenarios, as the adoption of CCS allows for a greater utilization of abated coal for power production.

As be observed from Figure 6b, showing the sectoral contributions to changes in local employment within each scenario, the job disruptions foreseen in the ReStor are unevenly distributed across the Polish economy. The mining sector bears the heaviest burden of the energy transition, while the manufacturing industry experiences 5% employment growth, resulting from the deployment of additional renewable capacity. However, these are primarily maintenance jobs associated with the routine operation of imported wind turbines and solar PV, increasing the exposure of the local labor market to further disruption arising from greater automation[49]. Moreover, as illustrated in Figure 6a, the share of investment translating into compensation of employees is reduced by 50% in the ReStor scenario, as the energy transition is outsourced, economic valuable assets are being replaced and the demand for skilled workforce stagnates.

In contrast to what observed for Poland, transitioning to a net-zero power system brings economic growth and employment opportunities in Spain, especially in the EQ scenario (Figure 7). The gains are quite evident in the manufacturing sector, which foresees a growth of 23-26% in employment and of around 40% in value added within each scenario, as the country can rely on domestic solar, wind and nuclear industries. In the EQ scenario, these benefits are perceived across all sectors of the economy, particularly in the agricultural sector, where the expansion of bioenergy and BECCS capacity translates into an 18% growth in cumulative employment by 2050. As a result, high shares of low-carbon investments are retained in the economy in the form of employees' salaries and benefits, *e.g.,* social security contributions and welfare services, as the country can lean on local industries (wind and solar in the ReStor, nuclear and bioenergy in the other scenarios), and on its domestic labor pool to conduct the energy transition.

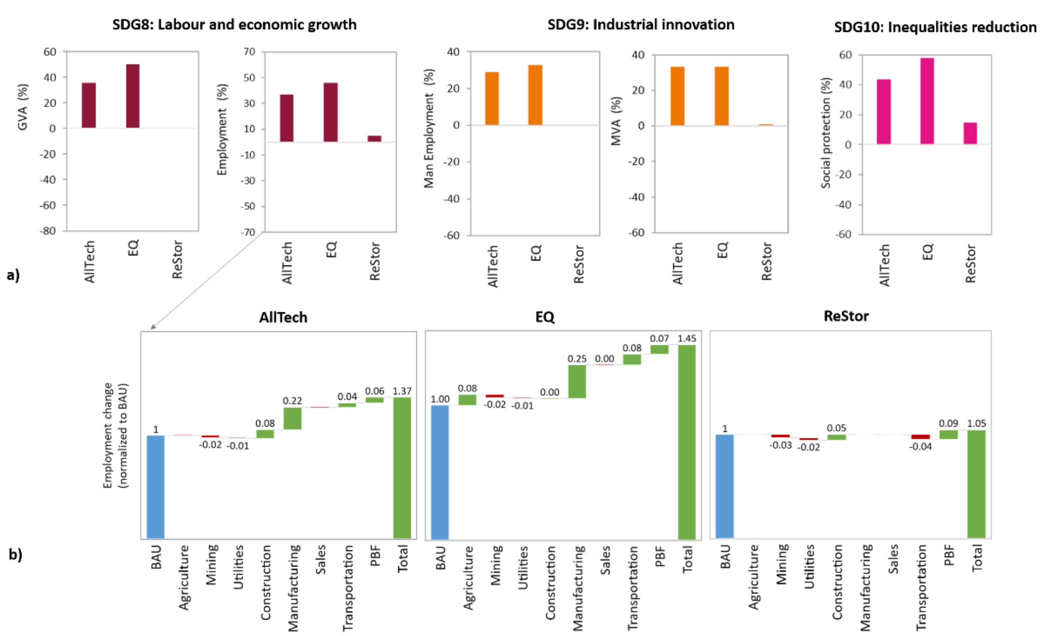

Figure 7: Socio-economic impacts of net-zero transition in Spain across SDGs 8,9 and 10

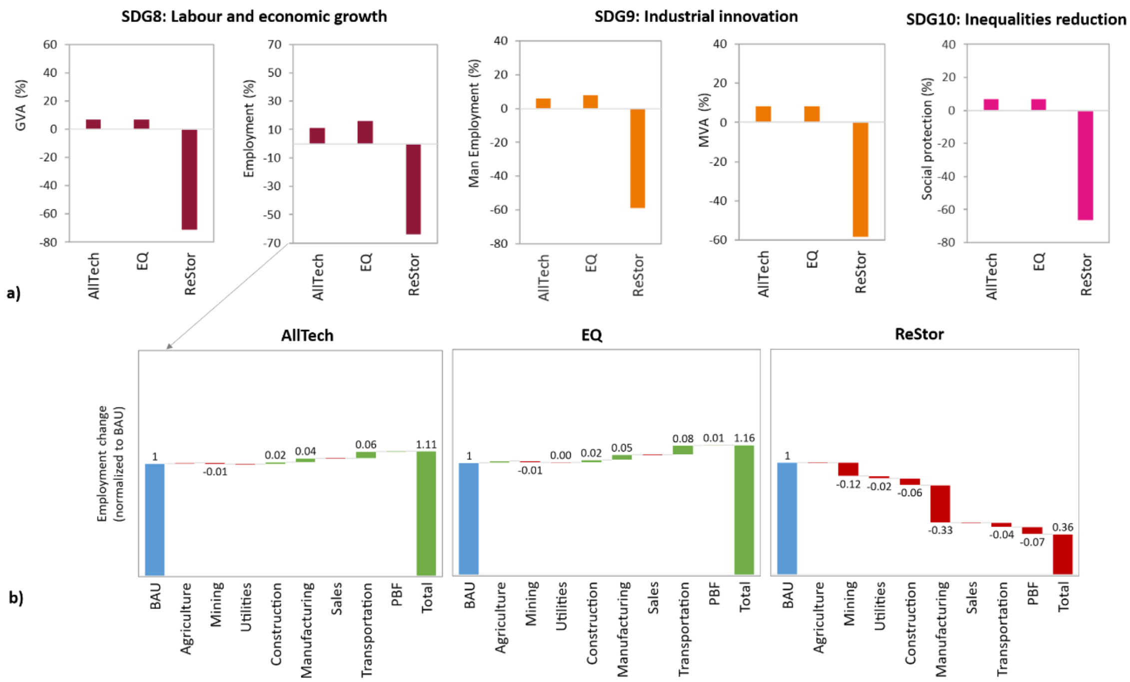

Figure 8: Socio-economic impacts of net-zero transition in the UK across SDGs 8,9 and 10

The ReStor scenario falls behind on all indicators in the UK, with larger trade-offs observed in the manufacturing industry (Figure 8). This is because, the 3-fold increase in installed capacity by 2050 required to meet the power demand from renewable energy sources alone, i) leads to higher investments having lower local value and ii) displaces local workers in CCGT plants. The socio-economic performance the AllTech and EQ scenarios show no considerable differences, as their technology deployment pathways are almost identical. Overall, both scenarios forecast mild additional co-benefits compared to the BAU: 7-8% growth in GVA and 5-7% growth in employment in the AllTech and EQ scenario, respectively. Under the current carbon price floor, therefore, and assuming a rapid scale-up of the local CCS industry from 2030, the UK power system will "naturally" evolve into a socially equitable energy system, where welfare is maximized, and domestic assets are favored.

3.3 The removal and avoidance value of biomass-based CDR technologies

3.3.1 Context and motivation

Biomass-based CDR technologies can provide two main services for climate change mitigation: *carbon removal*, since biomass sequesters carbon dioxide from the atmosphere, and *carbon avoidance*, associated with the replacement of fossil fuels or high carbon materials with bioenergy or products.

An inherent advantage of biomass with CO_2 capture and storage (BECCS) relies on its potential integration within different conversion processes, such as combustion, gasification, and fermentation-based routes, thereby providing a wide range of low carbon energy vectors, including electricity, liquid fuel, heat and hydrogen, while providing long-term CO_2 removal.

The main BECCS pathways represented in IAMs are typically biomass conversion to electricity in large scale combustion plants, and biomass conversion to liquid fuels. The production of liquid fuels via BECCS (i.e., biofuels) can provide a substantial contribution to transport decarbonisation in the mid-century stabilisation scenarios. Hydrogen can be used to decarbonise multiple sectors at a national level, e.g., industry, transport and heating. The potential integration of biomass and/or CCS in hard-to-abate fossil intensive industries such as cement, chemicals and iron and steel is also gaining increasing attention and is foreseen as a key industrial decarbonisation option at the national scale.

The mitigation and removal potential of each CDR pathway depends on biophysical factors, process specifications, regional and the counterfactual scenario considered. Understanding the best uses of this scarce resource, as a function of the regional context and of the pace of the energy system decarbonization is key. Moreover, combining the removal and avoidance potential of CDR technologies with the socio-economic impacts associated with their deployment, it is possible to quantify the removal and avoidance value of various mitigation pathways. This is because each unit of value created within the supply chains of biomass-based CDR technologies will result in the avoidance and removal of certain amount of carbon.

This case study aims at quantifying the macroeconomic impact resulting from deployment of CDR technologies and their associated value chains. This is done by coupling a carbon accounting framework that quantifies the net amount of CO_2 removed and avoided within each CDR pathways, with the JEDI tool. The technologies considered include:

- BECCS in the power sector (Biopower-CCS)
- Retrofit of integrated steel mills with BECCS (Bio-steel)
- Adoption of tail-end calcium looping technology in cement plants (Bio-cement)
- BECCS to biofuels: biohydrogen, FT diesel and bioethanol
- Slow-pyrolysis technologies for biochar production

Here the JEDI has been implemented with socio-economic data of the main industrial sectors in the UK and extended to accommodate the techno-economic features of the CDR technologies portfolio.

3.3.2 Main results

As Figure 9 shows, the GVA created *via* the deployment of BECCS in industry amounts to 68 $/t$_{cs}$ (tonne of crude steel) for the iron and steel and to 47 $/t$_{clk}$ (ton of clinker) in the cement sectors. In bio-steel pathways, around 23% of this value is allocated to the utility sector, such as natural gas and electricity providers, and is associated with the supply of additional energy to the steel mill after the CCS retrofit. In Bio-cements configurations the agroforestry industry benefits for 20 $/t_{clk}$, corresponding to 20 M$/year for the reference cement kiln.

Among biofuels, the GVA is between 20-23 $/GJ, with high shares being generated in agriculture in the case of second-generation bioethanol, given the lower biofuel yields associated to this pathway. Since this configuration allows for grater CO_2 removal compared to other biofuel routes, larger economic value is also being allocated to the CO_2 transport and storage activities compared to the FT and biohydrogen options.

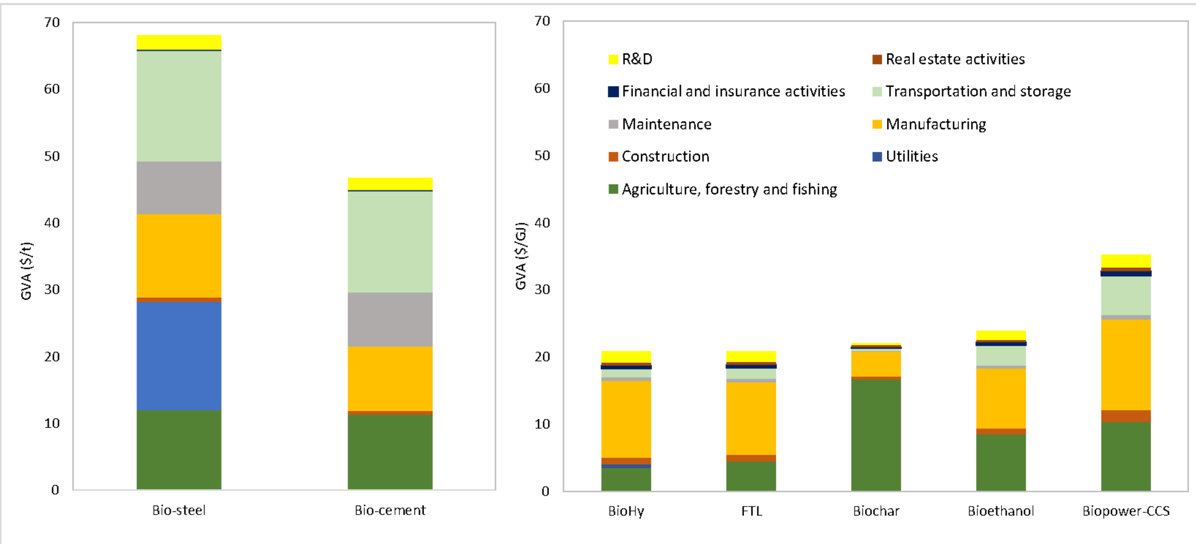

Figure 9: Economic impacts of NETs deployment within the UK industrial sectors

In general, the distribution of GVA created in the agroforestry and transport sectors respectively, is a reliable proxy of the CO_2 removal efficiency achieved within each CDR technology: while in BECCS to power around 30% and 17% of the GVA is associated with CO_2 T&S and agriculture activities respectively, almost 85% of the economic value created with biochar production is in biomass supply. Similarly, for bio-steel pathways the GVA associated with CO_2 storage is even higher than for the forestry sector since this CCS configuration maximizes the CO_2 capture from the different steel mill off-gases.

Combining these findings with the carbon accounting analysis, it is possible to quantify the amount of CO_2 emissions that can be avoided and removed by deploying NETs within the UK economy. This allows to provide an indication of the removal and avoidance efficiency of government spending, since each unit of value created within the NETs supply chains will results in the avoidance and removal of certain amount of carbon.

As shown in Figure 10, each CDR product has a distinctive removal and avoidance value for the UK economy. Among biofuels, the production of FT diesel has the highest avoidance value, since higher biofuels yields are achievable compared to bioethanol production, hence higher amounts of fossil gasoline are being displaced. The cost of one GJ of FT diesel is also lower than 1 GJ of biohydrogen, hence higher amounts of CO_2 can be avoided with the same level of investment for their production. However, when it comes to the value of carbon removal, producing bioethanol represent the most efficient investment since 9 $kgCO_2$ are being removed from the atmosphere for each $ retained in the UK economy.

Large combustion BECCS power plants represent a valid investment both in terms of mitigation and removal services provided, since each unit of GVA created within the economy removes 10 Kg and avoids 3 Kg of CO_2 emissions otherwise emitted by fossil electricity. At the end of the spectrum, we find biochar, representing the best investment for mitigation: this is mainly because of the small investment associated with slow-pyrolysis plants compared to large BECCS to power project, which allow to achieve higher CO_2 removal with the same amount of GVA. However, as already observed from the GVA breakdown in Figure *9*, these benefits are disproportionally concentrated in the agricultural sectors, while the value created in other industries, such as manufacturing and construction, is minimal.

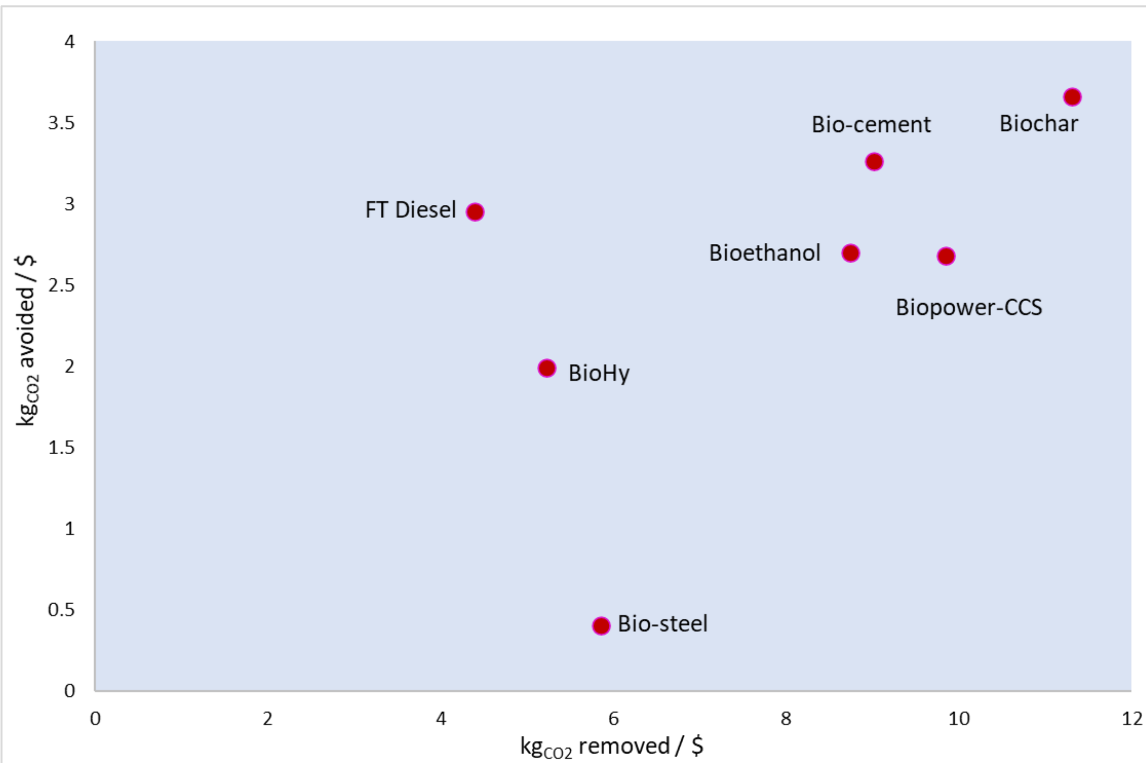

Figure 10: Amount of CO_2 emissions that can be avoided and removed by creating value for the UK economy

4 Conclusions

The essential deployment of existing CCS technologies to reach net-zero targets within our economies has historically faced numerous deployment challenges. Providing a multi-regional, technology agnostic and transparent quantification of the social value of CCS is hence key.

Case study 1 has shown that the goals of coal sector employment and climate change mitigation can be aligned, which is not how it is often portrayed in the public discourse. Therefore, together with the commitment to net zero targets, the employment opportunities that might arise with CCS deployment should be carefully assessed and promoted.

The results from Case study 2 showed that, when pursuing net-zero targets in the energy systems, there is no "one size fits all" solution, and that the relative costs and opportunities associated with the transition are unevenly distributed between countries. Hence, cost-focused carbon mitigation strategies that neglect any social, geopolitical, and macro-economic considerations, are likely to exacerbate labour market inequalities, as job losses are concentrated among specific socio-economic groups and in some regions.

Finally, Case study 3 has shown that quantifying the socio-economic value of different BECCS pathways could inform policy makers on the optimal mix of CDR technologies to be deployed, while minimizing biomass resource competition.

The decarbonization of our society will present complex structural changes in our economy and communities. Further research is required to understand the sectoral and skill-based impacts in the labour market associated with the deployment of CCS technologies at scale, as well as the social implications in the regions and communities involved. To ensure a sustained structural transition of our economies, the socio-economic impacts of the decarbonization pathways should be carefully studied using the appropriate quantitative method such as those discussed in this report.

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Evaluating technology options to mitigate greenhouse gas emissions

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