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Summary

Carbon Capture Utilization and Storage (CCUS) stands as a pivotal technology crucial for achieving the most ambitious climate objectives. Despite its prominent inclusion in energy mix projections, its current deployment falls short of the requisite level. Additionally, uncertainties surrounding future developments pose potential obstacles to its optimal diffusion. This study addresses two primary shortcomings that could impede the widespread adoption of CCUS. Firstly, it investigates how investments in CCUS technologies either compete with or complement other green research and development (R&D) activities. Secondly, it explores how the heterogeneity among different economies and the factors influencing the technology might lead to alternative configurations compared to the current trajectory. To address these issues, this study introduces CCUS into a regional Integrated Assessment Model (IAM) incorporating endogenous green R&D and heterogeneous cost functions. The model generates optimal pathways for both CCUS and green R&D, revealing a significant challenge: an insufficient valuation of R&D costs could potentially displace all investment in CCUS. Furthermore, the distribution of CCUS capital across regions by the end of the century necessitates substantial investments from regions with currently lower values, such as Europe and lower-income countries. This research underscores the imperative need for policies that mitigate uncertainties surrounding future technologies and coordinate contemporary state investments. Such policies are essential for CCUS to attain the envisaged contributions to emission reduction targets.

Keywords: Carbon Capture Utilization and Storage (CCUS), Integrated Assessment Model (IAM), Green Research and Development (R&D), Climate Objectives, Technological Uncertainties, Regional Disparities, Emission Reduction Targets

JEL classification: Q53, Q54, O32

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Gotta Catch 'Em All: CCUS with endogenous technical change

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Abstract

Carbon Capture Utilization and Storage (CCUS) stands as a pivotal technology crucial for achieving the most ambitious climate objectives. Despite its prominent inclusion in energy mix projections, its current deployment falls short of the requisite level. Additionally, uncertainties surrounding future developments pose potential obstacles to its optimal diffusion. This study addresses two primary shortcomings that could impede the widespread adoption of CCUS. Firstly, it investigates how investments in CCUS technologies either compete with or complement other green research and development (R&D) activities. Secondly, it explores how the heterogeneity among different economies and the factors influencing the technology might lead to alternative configurations compared to the current trajectory. To address these issues, this study introduces CCUS into a regional Integrated Assessment Model (IAM) incorporating endogenous green R&D and heterogeneous cost functions. The model generates optimal pathways for both CCUS and green R&D, revealing a significant challenge: an insufficient valuation of R&D costs could potentially displace all investment in CCUS. Furthermore, the distribution of CCUS capital across regions by the end of the century necessitates substantial investments from regions with currently lower values, such as Europe and lower-income countries. This research underscores the imperative need for policies that mitigate uncertainties surrounding future technologies and coordinate contemporary state investments. Such policies are essential for CCUS to attain the envisaged contributions to emission reduction targets.

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1 Introduction

Carbon Capture and Storage (CCS) or Carbon Capture Utilization and Storage (CCUS, henceforward) are technologies aiming to capture carbon dioxide (CO_2) emissions from industrial processes, e.g. power plants or factories, and secure them in long-term storage locations instead releasing into the atmosphere. . The aim of CCUS therefore is to reduce greenhouse gas emissions to mitigate climate change by preventing the release of large amounts of CO_2. This process, which can take place at different stages of the emissions formation (Wilberforce et al., 2021), may be particularly complex, especially in the so-called "hard-to-abate" sectors (Chen et al., 2022). This is relevant, as even in a context ofgreen energy transition scenarios, fossil fuel will still be the main primary energy source for the foreseeable future (Huisingh et al., 2015). The International Energy Agency (IEA)estimates that, to achieve net zero emissions (NZE)by 2050, the global scale of CCUS should grow by factor 100 from today's level of 40 Mta^{-1} (Ma et al., 2022), and should account for 15% of emission reductions in 2050 (Bouckaert et al., 2021). Despite an upsurge in interest, the deployment of this technology is however still lacking (Chen et al., 2022).

Although this technology is often included in modelling attempts related to the energy transition and climate change, the study of its behaviour and impacts in future scenarios deserves some further enrichment. In particular, some works might introduce very detailed modelling at the cost of not being able to consider their setting in general and global manner, like focusing on single countries and/or industries.

Conversely, global models might lose the impacts that the heterogeneity of the relevant components of the technology (e.g. costs structure) could entail. To fill this gap, we extend a global IAM already including multiple regions and able to represent a process of endogenous technical change: the FEEM-RICE model (Bosetti et al., 2006). For this purpose, we disaggregate the endogenous energy R&D investment process in order to isolate the investment needed to develop a proper CCUS sector. Moreover, the regional CCUS cost structure is calibrated to follow empirical evidence, providing a test ground for regional heterogeneity within the model. This study therefore aims to contribute to scientific literature with a twofold exploration.

Firstly, it delves into the dynamics of investments in CCUS technologies, scrutinizing how they may either enter into competitive relationships or synergistically align with other green R&D endeavors.Secondly, it investigates the complex interplay of diverse economies and the factors influencing CCUS technology, considering how this heterogeneity might engender alternative developmental trajectories distinct from the current course. The resulting model not only delineates optimal pathways for both CCUS and green R&D but also highlights a substantial challenge: an inadequate assessment of R&D costs could potentially displace all investment in CCUS, in line with other theoretical applications such as Durmaz and Schroyen (2013). If the costs associated with R&D are undervalued or underestimated, there is a substantial risk that they might overshadow and divert funding away from crucial investments in CCUS.

This could hinder the advancement and deployment of CCUS technologies, potentially impeding progress toward achieving climate objectives and emission reduction targets. Thus, an accurate and thorough assessment of R&D costs is imperative to ensure a balanced and effective allocation of resources between. Moreover, the geographical distribution of CCUS capital toward the close of the century underscores the imperative for significant investments from regions currently possessing lower values, notably Europe and lower-income countries.

This work develops as follow: in Section 2 we briefly describe the ratio of CCUS technology, its main benefits and limitations, as well as how it has been considered so far by the modelling literature, in order to highlight the motivation of our application. In section 3 , we describe in detail the extension of the FEEM-RICE model, as well as the experiments carried out in our analysis. Section 4 provides information on the calibration and the choice of the main parameters values. In section 5 we present the results of the experiments, and discuss their main implications and policy implications. Section 6 finally draws a summary of the work, recalling the main limitations of this approach from which further research will begin.

2 Motivation

From a technical point of view, the captured CO_2 travels via pipeline or other means to a storage site, where it is injected into deep underground formations, typically geological formations such as depleted oil and gas reservoirs or saline aquifers. The stored CO_2 is then monitored to ensure it remains safely underground. Herzog (2011) identifies four main components of the technology: capture (separation and compression of CO_2), transport (the most economical form is through pipelines, possibly already existing), injection (depositing into the chosen geological site), and monitoring (to prevent leaks). Related technologies include Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture with Carbon Storage (DACCS). BECCS involves the use of bioenergy (e.g., from crops or forestry) to generate electricity or heat, with emissions captured and stored underground.

The idea behind BECCS is that theCO_2 emissions from the combustion of biomass are offset by the CO_2 that is captured and stored, resulting in a net reduction of CO_2 in the atmosphere. DACCS involves capturing CO_2 directly from the air using chemical or physical processes and then storing the CO_2 underground. It is also being explored as a way to achieve negative emissions. However, both BECCS and DACCS are still relatively new technologies and face a number of challenges, including high costs and the need for large-scale deployment to achieve significant emissions reductions. The first large-scale demonstration of CCUS technology occurred in the 1970s in the United States and was not related to climate change. Indeed, CO_2 was injected into oil reservoirs to enhance oil recovery. However, it was not until the late 1990s and early 2000s that CCUS began to be seriously considered as a way to reduce greenhouse gas emissions. Since then, several large-scale CCUS projects have been developed around the world, including in the United States, Canada, Australia, and Norway. One example of the largest CCUS projects to date is the Sleipner Project, which began in 1996 and is located in the North Sea (Torp and Gale, 2004). The Sleipner Project captures and stores approximately one million metric tons of CO_2 per year from a natural gas field and has been successful in demonstrating the feasibility of large-scale CCUS.

While CCUS has shown promise as a way to mitigate greenhouse gas emissions, it still faces significant challenges, such as high costs, public acceptance, and technological limitations. The cost of CCUS technology can vary widely depending on several factors, such as the size and complexity of the project, the type of industry, and the location. The cost of a large-scale CCUS plant can range from tens to hundreds of millions of dollars, and the cost per tonne of CO_2 captured can vary depending on the specific project. Estimates of the cost of CCS vary widely, but they are generally in the range of $50–100 per tonne of CO_2 captured, although some estimates are higher. Overall, CCS is generally considered a relatively expensive technology compared to other forms of greenhouse gas mitigation; nonetheless, the IPCC estimates that without an adoption of CCUS, mitigation costs will rise to 138% in 2100 (Ma et al., 2022). (Budinis et al., 2020) report that plants with CCUS have higher costs due to the immaturity of the technology; nonetheless these could be decreasing at a rate of 2.5% per year up to 2030. Another set of issues regards the availability of storage sites and the uncertainty surrounding their permeability.

(Wei et al., 2021) identify 432 sinks in 85 countries, but substantial technological and financial transfers should be needed to employ them all. (Lane et al., 2021) argue that deep uncertainty over the sustainable injection rate for selected sites might hinder the deployment of the technology. Indeed, the deployment of this technology in developing countries unclear (Huisingh et al., 2015). Including the process of exploration and availability of new sinks is also seen as a primary direction of research (Chen et al., 2022). Many institutes have produced studies that consider the potential role of CCUS as a means of reducing greenhouse gas emissions. Examples include the IPCC reports, the Stern Review on the Economics of Climate Change, and reports by McKinsey. Also, many Integrated Assessment Models (IAMs) that are used to project future climate change and evaluate different policy scenarios include CCS as one of the mitigation options. As an example of modelling, the Witch model (Emmerling et al., 2016) includes a module of CCS.The quantity of carbon captured is the sum of different capture technologies multiplied by specific capture rates. Cumulating these values provides the amount of storage needed. The costs for transport and storage are then a convex function of the cumulated sequestered emissions, and the total cost is the product of unit costs times the quantity of sequestered carbon. To model CCUS in socioeconomic applications, (Dooley et al., 2002) suggest disaggregating the CCS into components and considering their costs. As a typical taxonomy, they propose the energy cost of capture, capital costs for capture and separation units, and the cost of CO_2 transport and storage.

A common assumption in the literature is that these costs will decline over time. The cost of storage can be assumed to be homogeneous over regions and time, but the latter assumption is quite strong. Moreover, the finiteness of the storage space could also be considered. (Yu et al., 2019) study China's mitigation strategy through the GCAM-China model, using provincially estimated CCS cost curves. This work provides links to the literature on cost curve estimations, most notably Dahowski et al. (2005) and Dahowski et al. (2009). Smith et al. (2021) estimate levels of costs for transportation and storage, finding that the commonly held assumption in IAMs of 10 dollars per tCO2 could underestimate the figure for given regions finding their underestimation very likely. (Durmaz and Schroyen, 2013) extend the Acemoglu model of green endogenous technical change to include a CCUS sector, finding that a green energy regime is more plausible. There exist a number of applications in partial equilibrium detailed agent-based models. For instance, Budinis et al. (2020) develop an agent-based model to characterize the investment choice of heterogeneous firms in the coal-intensive sector of ammonia production in China. With a carbon price in place firms tend to adopt a carbon capture and storage solution rather than just switching to natural gas. Han et al. (2023) study the diffusion of CCUS in a network of heterogeneous firms depicting thermal plants. This concise literature review emphasizes the need for an application capable of incorporating the significant uncertainty and diversity that various regional factors may introduce. In our research, we develop a regional IAM by incorporating CCUS technology in addition to the conventional energy transition research and development (R&D) process, by extending the FEEM-RICE model (Bosetti et al., 2006), . By introducing a versatile CCUS cost function, we can effectively account for regional variations, while differentiating CCUS from other transition technologies allows us to identify fundamental trade-offs and synergies.

3 Methodology

In order to study the development of CCUS investments alongside other competing practices, we aim at extending an already established yet parsimonious depiction of a regional IAM. We select the FEEM-RICE model (Bosetti et al., 2006). Starting by RICE 99 ((Nordhaus and Boyer, 2000)), FEEM-RICE studies endogenous technical change in climate models, focusing on four pivotal factors—R&D investments, Learning by Doing, energy-saving, and fuel switching. Its specification features an energy technical change index dependent on Learning by Researching and Learning by Doing, impacting on energy and carbon intensity.We depart from this structure by explicitly including a CCUS technology separated from green or simply the remainder R&D.

3.1 CCUS investment

To best present the way through CCUS is introduced, it is valuable to report how the endogenous technical change is originally included in the FEEM-RICE model (Bosetti et al., 2006). An Endogenous Technical Change Index (ETCI) for region n and time t is described as:

$$ETCI(n,t) = K_R(n,t)^a ABAT_S(n,t)^b \quad (1)$$

Where $K_R(n,t)$ is the stock of knowledge, $ABAT_S(n,t)$ is the stock of cumulated emission abatement, and a, b are parameters governing their relative weight. The stock of knowledge evolve as:

$$K_R(n,t+1) = R\&D(n,t) + (1-\delta_R)K_R(n,t) \quad (2)$$

Where $R\&D(n,t)$ represent investment in energy $R\&D$ and δ_R is the depreciation rate of the knowledge stock. Moreover, the stock of abatement is described as:

$$ABAT_S(n,t+1) = \delta_A ABAT_F(n,t) + (1-\delta_B)ABAT_S(n,t) \quad (3)$$

Where $ABAT_F$ is the abatement flow, δ_A is the learning factor and δ_B is the depreciation rate of cumulated experience. The variable $ETCI(n,t)$ affects energy intensity by replacing the elasticity of inputs substitution within the original production function from RICE-99 model, which was described as :

$$Q(n,t) = \Omega(n,t)A(n,t)[K(n,t)^{1-\alpha_n-\gamma}L(n,t)^{\gamma}CE(n,t)^{\alpha_n}] - c^E(n,t)CE(n,t) \quad (4)$$

With the following equation:

$$Q(n,t) = \Omega(n,t)A(n,t)[K(n,t)^{1-\alpha_n(ETCI)-\gamma}L(n,t)^{\gamma}CE(n,t)^{\alpha_n(ETCI)}] - c^E(n,t)CE(n,t) \quad (4')$$

Where:

$$\alpha(ETCI(n,t)) = \frac{\theta_n}{2-exp[\beta_n ETCI(n,t)]} \quad (5)$$

Where the parameters θ_n,β_n are calibrated to reach the original α_n value for a given region.. In the RICE-99 model, the FEEM-RICE baseline model, effective energy results from both fossil fuel use and the exogenous technical change in the energy sector. This relation is described as:

$$E(n,t) = \varsigma(n,t)CE(n,t) \quad (6)$$

In FEEM-RICE this relation is modified as

$$E(n,t) = \varsigma(n,t)\left(\frac{1}{2-exp[\psi_n ETCI(n,t)]}\right)CE(n,t) \quad (6')$$

Where $ETCI(n,t)$ affects carbon intensity, reducing, ceteris paribus, the level of carbon emissions.

Starting from the standard FEEM-RICE model, we separate CCUS from the Energy Technical Change Index variable, defining the CCUS Technical change index,$CTCI$. For region n at time t it is defined as:

$$CTCI(t,n) = CCUS(n,t)^c ABAT_{CCUS}(n,t)^d \tag{7}$$

where CCUS is the stock of capital dedicated to capture activities, while $ABAT_{CCUS}$ is its amount of captured emissions. The two variables capture the amount of invested resources, and the learning-by-doing in capture technology. These follows two law of motions:

$$ABAT_{CCUS}(n,t+1) = \delta_{CCUS_A} ABAT_f(n,t) + (1-\delta_{CCUS_A}) ABAT_{CCUS}(n,t) \tag{8}$$

$$CCUS(n,t+1) = CCUS_f(n,t) + (1-\delta_{CCUS}) CCUS(n,t) \tag{9}$$

where the current period flows update the stocks, while a part of the stocks is lost due to depreciation. The $CTCI$ index, combining both the stock of CCUS capital and its effectiveness through the learning by doing part, reduces the emissions of carbon energy CE(n,t), extending equation 6':

$$E(n,t) = \varsigma(n,t)(\frac{1}{2 - exp[\psi_n ETCI(n,t) - \omega_n CTCI(n,t)]}) CE(n,t) \tag{10}$$

where again, the parameters are set to provide the same initial conditions for a given region.

3.2 Specific CCUS investment costs

Finally, the CCUS technology investment affects the accumulation of capital as it was the case with energy R&D, therefore its law of motion is described as

$$K(n,t+1) = K(n,t)(1-\delta) + I(n,t) - \lambda R\&D(n,t) \tag{11}$$

with the following :

$$K(n,t+1) = K(n,t)(1-\delta) + I(n,t) - \lambda R\&D(n,t) - (1+CCUS_{cost}(n,t)) * CCUS_f(n,t) - \mu(1-U)(CCUS(n,t)) \tag{12}$$

Here $K(t,n)$ is the current (depreciating) stock of capital, $I(t,n)$ is investment, $\lambda R\&D$ is the crowding-out externality following the investment in energy R&D (with $\lambda > 0$). In the remainder of the equation, notice that the original capital accumulation is here reduced by two components: the invested amount $CCUS_f(n,t)$, and the operating costs of the existing CCUS stock, CCUS(n,t). These two are further characterized by additional factors. Regarding the investment, the impact of CCUS differs in each region according to the regional-specific cost component $CCUS_{cost}(n,t)$:

$$CCUS_{cost}(n,t) = (1 - \frac{\frac{CE(n,t)}{Q(n,t)}}{100}) + \bar{D}_{n,ccsite} + (1 - \frac{ABAT_{CCUS}(n,t)}{E(n,t)}) \tag{13}$$

Here the term $\frac{CE(n,t)}{Q(n,t)}$ captures the relative weight of the fossil fuel sector over the economy GDP, such that already existing infrastructure and competences in the exploration and transportation of fossil fuels can mitigate the costs. The term $\bar{D}_{n,ccsite}$ captures the cost component to send captured carbon to selected stocking sites, with $\bar{D}_{n,ccsite}$ being the normalized average distance in kilometers between a regions's population center (or centroids) and potential sites. The position of population centroids is the GDP-weighted average of the position of each region's population centers, estimated using data retrieved from the Gridded Population of the World Version 3 (GPWv3).[1] The coordinates of potential active storage sites is then obtained by the US National Energy Technology Laboratory (NETL), providing a global collection of planned, pilot and active CCUS projects.[2] The distance is thus computed by means of the Haversine formula.Finally, $\frac{ABAT_{CCUS}(t,n)}{E(n,t)}$ captures the learning-by-doing aspect of the operations, lowering the costs as long that new carbon is captured over the total emissions. Indeed, a decrease in CCUS costs due to improved maturity in the technology is to be expected (Budinis et al., 2020). Therefore, in an extreme unrealistic case where an economy is fully dedicated to the production of carbon energy ($CE = Q$), the distance from a storage site is zero, and all the emissions are captured, the term $CCUS_{cost}(n,t)$ would collapse to zero, implying that just the invested amount would subtract from capital accumulation, without additional crowding out externalities. Vice-versa, $CCUS_{cost}(n,t)>0$ amplifies the externality. Regarding the stock of CCUS, the use, monitoring and maintenance of the plants requires additional resources. Compared to standard R&D, the whole CCUS stock affects the accumulation due to the relevance of operating and maintenance costs share, µ. Nonetheless, this cost figure depends also negatively on the parameter U, which depicts the fraction of captured carbon which falls into utilization .

4 Calibration

To identify a solution to the model, a number of parameters need to be set to numerical values. If not indicated, the parameters follow the values of the original calibration in Bosetti et al. (2006). Some values, e.g. emissions, for which more recent series became available, are updated accordingly. Table 1 reports the values of the parameter employed in the baseline version. Most of the parameters referring to the CCUS part required new values. These are elaborated from empirical data when available, or according to the capital good sector as a reference. Table 2 presents the regionalization employed in the model[3], and the initial CCUS capital stock. The latter figures are calculated

[1]For further details, see: hhttp://sedac.ciesin.columbia.edu/gpw.

[2]For further details, see: https://netl.doe.gov.

[3]Countries are divided between the regions following the original regionalization of the RICE 99 model (Nordhaus and Boyer, 2000).

Parameters	Description	Value
c, d	Investment and learning-by-doing weight	0.50
δ_{ccus}	Depreciation rate for CCUS stock	0.05
δ_{ccusa}	Depreciation rate for CCUS LbD	0.05
μ	Share of operating costs for CCUS stock	0.01
U	Utilization rate of captured $CO2$	0.03

Table 1: New parameters values.

Region	Initial CCUS stock (USD trillions)
China	0.028307635
Eastern Europe (EE)	0.001377839
Europe	0.071630975
Lower Income (LI)	0
Lower-Middle Income (LMI)	0.0027
Middle Income (MI)	0.000183478
Other High Income (OHI)	0.140287193
USA	0.064204846

Table 2: Regionalization of the model and initial CCUS stock capital allocation in trillions USD.

from the IEA CCUS Project Database[4] , by aggregating active and planned plants costs by region. Figure 1 display the global map of the storage sites employed to calculate the normalized distance in equation 13. Parameter $\varphi_n$and the new parameter ω_n associated to $CTCI$ in equation 10 have been calibrated in order to replicate the base year in the original model.

5 Results & Discussion

5.1 Optimal solution of the benchmark scenario

The model is solved providing the optimal path for all control variables until 2100. These results, are thencompared with a benchmark scenario where technical change and investment includes only green R&D, namely, where CCUS is again abstracted back in that part.

Figure 2 shows the emission intensity path in both models, for all the regions. In the benchmark model this variable is decreasing, following the endogenous evolution of technological change, which result in a decrease of emissions. Extrapolating the CCUS technology decreases emission intensities. This indicates a favorable environmental trend when compared to the benchmark scenario. There is nonetheless an heterogeneity when comparing the different regions. For instance, certain regions, such as the United States, demonstrate a more

[4]IEA (2023), CCUS Projects Database, IEA, Paris, http://www.iea.org/data-and-statistics/data-product/ccus-projects-database

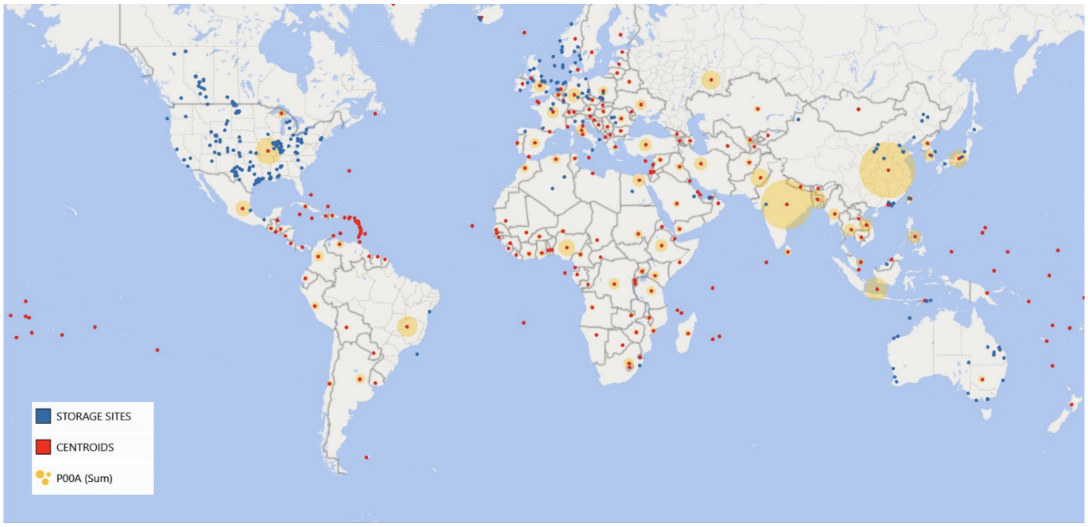

Figure 1: Map of the storage sites and the centroids of countries employed to define the average distance costs part.

significant decline. the MI and OHI region display for the initial years a better performance by the benchmark model, but in later periods this allineates to the other regions. Therefore, it seems that enhancing the pathway of improved efficiency, as opposed to relying solely on input substitution, leads to more favorable outcomes in terms of emission reduction and economic performance for optimal investments in CCUS, at least according to this model.

Table 3 shows the average GDP % variation between the original model and the one with the CCUS. The introduction of the new technology enable every region of the model, to a different extent, a gain in term of GDP, allowing to produce more energy services per unit of carbon inputs.

Variability in the CCUS cost component in the capital accumulation equa-

Region	Average GDP % variation
China	0.57
Eastern Europe (EE)	0.89
Europe	0.12
Lower Income (LI)	0.41
Lower-Middle Income (LMI)	0.28
Middle Income (MI)	0.43
Other High Income (OHI)	0.03
USA	3.05

Table 3: Economic impacts by regions. Average GDP % variation compared to benchmark

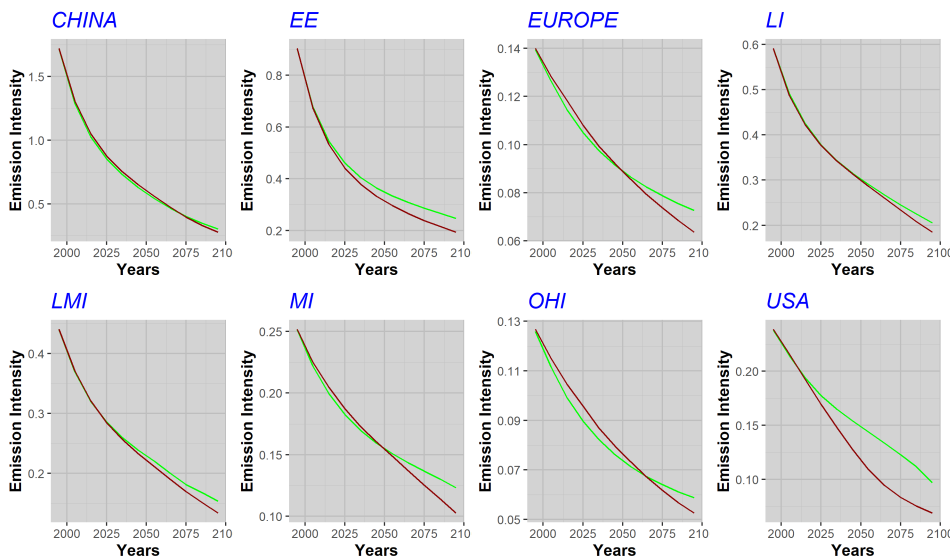

Figure 2: Emission Intensity ration in the original model (green) and in the reference scenario (red)

tion yields distinct regional pathways, with certain country groups positioned to end up with more investments than others. Figure 3 shows the share of initial CCUS capital and share of CCUS capital at the and of the century. The optimal trajectory for CCUS in the reference scenario indicates that all regional groups are inclined to invest in this technology. A high final share is necessary by the end of the simulation for Europe, as well as for OHI and LI countries. The question that arises is whether these regions will have the necessary resources to pursue these investments.

5.2 Sensitivity experiments

A series of sensitivity analysis simulations is conducted using varying parameter values. Notably, green energy R&D competes with CCUS since both require ongoing investments, which both acts as control variables in the optimal allocation of intertemporal resources by the social planner. Externalities, represented by markups stemming from crowding out effects and CCUS investment and operating costs, influence how regions allocate their resources among different mitigation choices. Variations in these parameters, as well as in the parameters values of the efficiency in the two technical indexes, might result in different scenarios, where it is possible that the economy selects only one of the two as the optimal choice, completely crowding out the other.

Figure 4 shows the evolution of the R&D investment for different values of the cost externality markup parameter λ in equation 12. It is evident that discount-

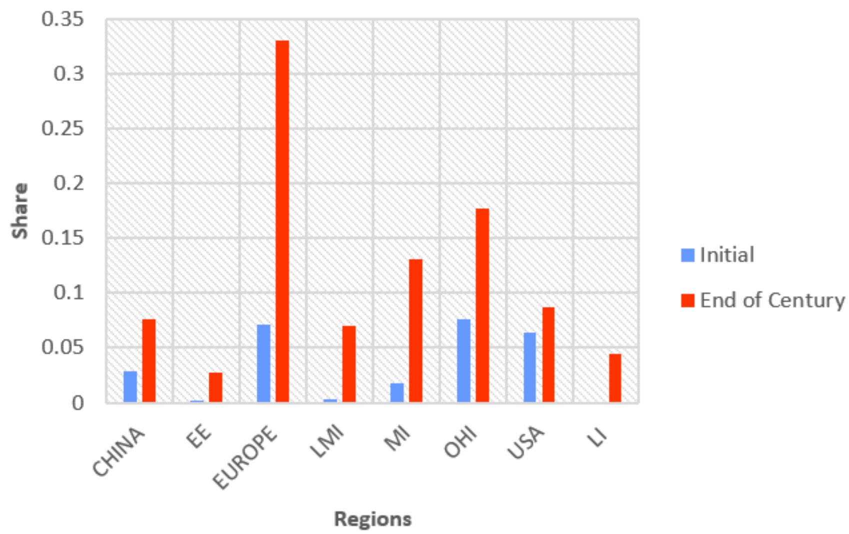

Figure 3: Share of initial CCUS capital and share of CCUS capital at the and of the century .

ing some regional variations, R&D investment decreases when the crowding-out externalities is higher.

On a similar note, figure 5 illustrate that the higher the modelled markup for green energy R&D, the greater the investment in CCUS, and vice versa. CCUS may struggle to reach a significant level or remain confined to the lower bound if the perceived costs of other green technologies are too low.

This leads to consider that each of the factor embedded in the CCUS structure might trigger one of these scenarios. In Figure 6, the baseline model is compared to one where the Utilization rate U is greater, showing that the greater the value of this parameter the greater the investment in CCUS technology will be.

5.3 Discussion

In the baseline model, where CCUS is actively pursued as an emission reduction strategy, emission intensities decrease for all regions at the end of the simulation, and for most of them, the reduction is even more pronounced.

This analysis unveils a crucial insight into the optimal trajectory of an economy that integrates CCUS investments. Specifically, it signals a shift in the final distribution of CCUS capital stock among diverse regions. Unique regional characteristics, including variations in economic structure and the location of sinks, introduce distinct development paths for this technology. Consequently, these deviations can lead to modifications in the initial distribution of capital shares. Notably, certain regions, particularly those classified as lower-middle-income or

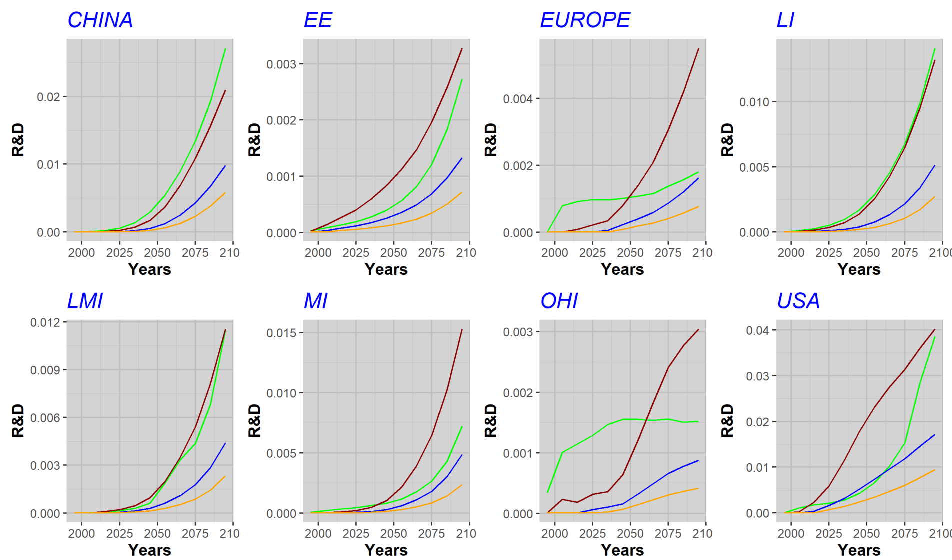

Figure 4: R&D investment with different value of crowding out parameter λ . Original FEEM-RICE model (green), reference scenario (red), λ=10 (blue), λ=15 (orange)

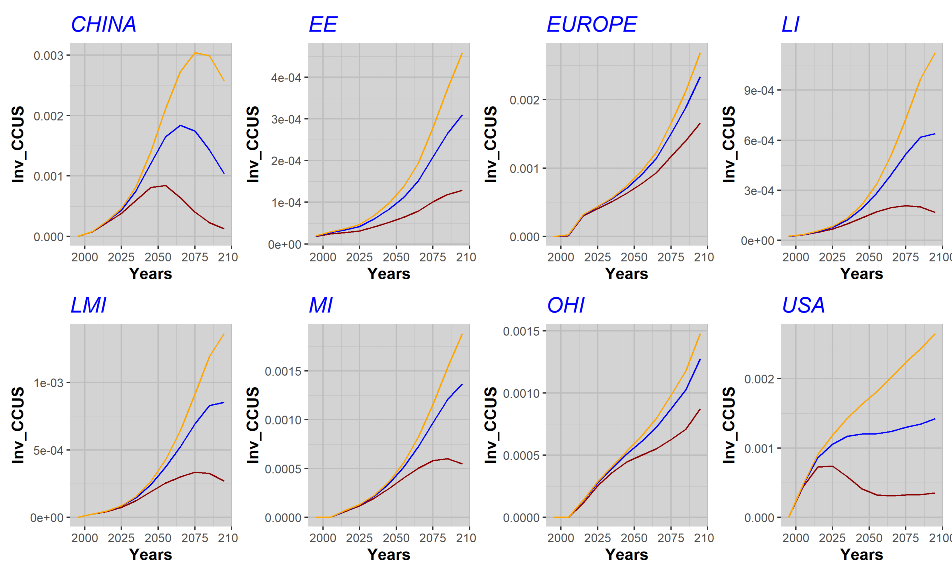

Figure 5: CCUS investment with different value of crowding out parameter λ. Reference scenario (red), λ=10 (blue), λ=15 (orange)

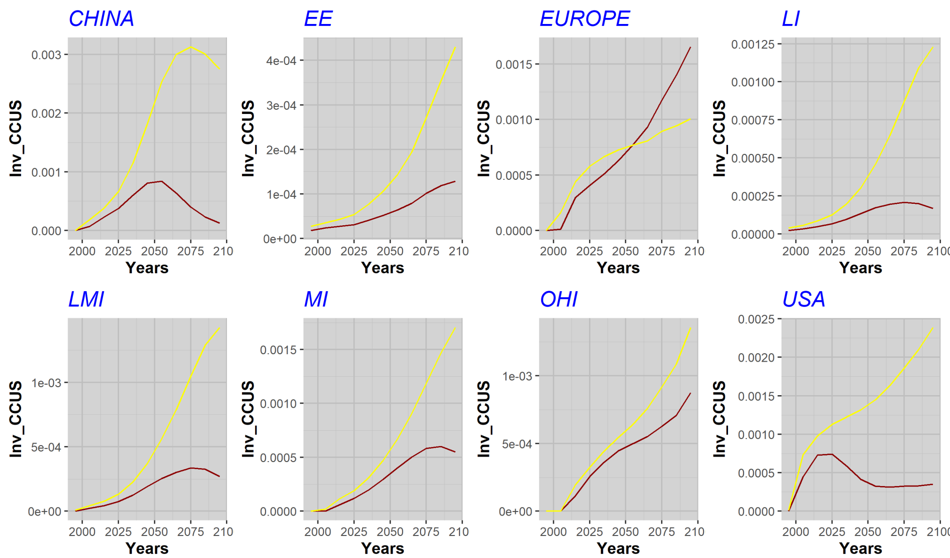

Figure 6: Parameter variation U: Reference scenario U=0.03 (red) and U=0.3 (yellow)

lower-income countries, will require substantial investments to align with this trajectory. This emphasizes the importance of recognizing regional nuances and directing targeted investments to ensure the equitable and effective deployment of CCUS technology.

Conducting a sensitivity analysis on the relative weight of the two different technology components' costs illustrates how the social planner might opt for a mix of the two. However, there could be instances where CCUS is not even considered. In this model, green R&D encompasses both fuel switching and efficiency gains, providing additional avenues to reduce emissions compared to capture alone. This is true even without explicitly factoring in the risks and uncertainties associated with CCUS. Consequently, the potential positive impact on emission intensities could be forfeited if stakeholders choose to delay or rely on alternative technologies for similar efficiency gains without initiating substantial investments promptly.

Variations in the parameters governing the CCUS cost equation can influence the investment path. Policies that reduce storage, monitoring, and verification costs and increase the utilization rate can likely prevent situations where CCUS investments fail to increase.

6 Concluding Remarks

In this study, we have extended the FEEM-RICE model originally presented by Bosetti et al. (2006) to account for an endogenous Carbon Capture, Utilization and Storage (CCUS) technology. To achieve this, we have disaggregated the general green technology Research and Development (R&D) sector to separate the investment in the two different components. As CCUS technology does not affect the substitutability of different production inputs, it is included only as a term capable of reducing emissions while using the same level of carbon energy. Similar to R&D, the planner sets the optimal level of investment for the technology in each region. The regions are endowed with heterogeneous CCUS investment costs, which depend on a variety of literature-highlighted features, such as the distance from storage sites. The latter are empirically calibrated according to the regional values.

The model's optimal solution indicates that Carbon Capture Utilization and Storage (CCUS) technologies have the potential to reduce emission intensity across all regions, offering an additional avenue for enhancing energy efficiency. However, the competition between the two investments is influenced by the relative weight of cost components in different technologies. Given that green Research and Development (R&D) also impacts the fuel-switching channel, it tends to overshadow investment in CCUS, potentially leading to scenarios where the investment remains at the lower bound. If this scenario were to unfold, it could impede the realization of the most ambitious climate goals, as explicit formulations of energy mix projections consistently require a positive and substantial share of CCUS in 2050 and beyond. Our analysis identifies two primary strategies to avert this situation: avoiding overestimation of the development of alternative green R&D measures and investing in reducing CCUS relative costs through either adopting less costly technology or increasing the utilization rate of captured carbon. Moreover, due to regional heterogeneities, the final distribution of CCUS capital shares diverges from the present one. Effective policy coordination on investment is crucial, especially for middle and lower-income countries to achieve optimal investment shares.

This work present some limitations. First, only the CCUS module is disaggregated from the energy R&D part. This means that the latter still appears as a broad category, losing possible features that the different technologies might bring in the interaction with the former. Second, the RICE model regions are also broad, which means that further segmentation might provide more precise values for the parameters governing the choice of CCUS investment. Additional factors might hinder the diffusion of the technology, such as public support (Chen et al., 2021). In conclusion, our extension of the FEEM-RICE model to incorporate an endogenous CCUS technology provides a more comprehensive framework for analyzing the potential role of this technology in achieving climate change mitigation goals. By considering the heterogeneity of CCUS investment costs across regions, we have highlighted the importance of addressing regional-specific factors in the development of CCUS technology. Our results provide valuable insights for policymakers and stakeholders as they seek to design effective policies and strategies to reduce greenhouse gas emissions and combat climate change.

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