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Evaluating technology options to mitigate greenhouse gas emissions

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Defining the Value of Carbon Capture, Utilisation and Storage for a Low-Carbon Future

IEA GREENHOUSE GAS R&D PROGRAMME

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DEFINING THE VALUE OF CARBON CAPTURE, UTILISATION AND STORAGE FOR A LOW-CARBON FUTURE

Key Messages

1. To limit global warming to well below 2°C countries must achieve net-zero emissions by around mid-century. Integrated assessment models (IAMs) are used to help inform this complex and daunting energy transition by identifying the lowest-cost mitigation pathways for countries to achieve economy-wide, net-zero emissions.
2. CCUS is an available mitigation option to support these energy transitions and has been highlighted by global IAMs as a necessary technology to limit anthropogenic warming to well below 2°C.
3. Moreover, there is much evidence in the literature on the value of CCUS in reducing the costs of energy transitions, in providing value beyond cost-competitiveness, in enhancing low-carbon energy security - particularly in the context of increased wind and solar electricity penetration - and in providing a mitigation option for hard-to-abate sources. In modelling by the IEA, CCUS is also used in the production of low-carbon hydrogen and to achieve negative emissions, primarily through BECCS.
4. Despite this, there continues to be dissent and misinformation in some quarters regarding the role CCUS can or should play in a low-carbon future. In addition, the identification of cost-optimal pathways reveals little about the feasibility of their implementation or their economy-wide impact for individual countries. To achieve this, a broader, deeper, multi-disciplinary understanding of the value of mitigation options is needed. This is what this study sets out to achieve.
5. Globally, IAMs have highlighted the role of CCUS, an available mitigation option to support energy transitions, as a necessary technology to limit anthropogenic warming to well below 2°C. There is much evidence in the literature on the value of CCUS in reducing the costs of energy transitions, in providing value beyond cost-competitiveness, in enhancing low-carbon energy security – particularly in the context of increased wind and solar electricity penetration – and in providing a mitigation option for hard-to-abate sources.
6. Despite dissent and misinformation from some quarters regarding the role it can play in a low-carbon future, CCUS was found to create value from techno-economic, socio-technical and environmental standpoints and, in many cases, was found highly likely to enhance the robustness of long-term mitigation strategies and portfolios. Notably, compared to other low-carbon mitigation options, CCUS deployment has the potential to help overcome real-world deployment challenges related to energy transitions, e.g., issues of land availability, siting restrictions, social acceptance and the potential for negative environmental impact.
7. As a tool to inform policymakers, a 2x2 decision framework was introduced in this study for use in making ‘high-level’ assessments regarding the option value of CCUS. As with all such tools, users need to be educated in its application, with its findings reflective of the level of detail employed.

8. Under the current paradigm, there is a severe risk that mitigation plans will be based entirely around techno-economic assessments and aim to support single-pathway options only. Given this, it is recommended that value-based assessments such as those explored in this study be extended to other countries and mitigation options, with increased rigour and subjected to peer-review.
9. Although multi-disciplinary value-based assessments could be significant for helping to identify robust mitigation options and pathways, climate change will always be subject to deep uncertainty. For this reason, there is an additional value proposition associated with investing in RD&D to keep open the option for CCUS to be commercially deployed at scale within a short-term time period. Due to the long lead times involved in developing all the elements of CCUS, even if CCUS is not ultimately needed in a particular country application, it nevertheless provides a valuable hedging strategy in case other options fail or underachieve given the carbon budget involved. This risk-based approach to address the climate challenge is another area that warrants wider recognition and further research.

Background to the study

To limit global warming to well below 2°C, countries must achieve net-zero emissions by around mid-century. The necessary energy transition to achieve this goal presents a daunting task for most countries. To help inform energy transitions, IAMs have been used to identify the lowest-cost mitigation pathways for countries to achieve economy-wide, net-zero emissions. However, the identification of cost-optimal pathways reveals little about the feasibility of their implementation or their economy-wide impact. To achieve this, a deeper, wider, multi-disciplinary understanding of the value of mitigation options is needed.

Climate change is a complex, global problem that may be approached at different levels. While some may focus on a specific mitigation technology or industry, others may take a broader approach and, for example, consider the interaction between energy and the environment and reflect on how this interaction may contribute to global warming. In setting the goal of “well below 2°C”, the Paris Agreement marked a watershed moment in terms of perception of the climate problem. To achieve net-zero emissions by around mid-century, robust mitigation strategies will be required that work not only from a techno-economic or cost perspective but also from social, political and environmental perspectives. They will also need to work at different levels, from the global level right down to the company level. Developing a broader and deeper understanding of the potential ‘value’ of different mitigation options is one way to assess their robustness.

Typically, the value of mitigation options has been limited to consideration of their techno-economics (or cost-competitiveness) only. However, in isolation, this reveals little about the feasibility of deploying a mitigation option. For example:

- Renewables-heavy pathways may in general be low-cost but they may also result in significant land-use impacts, creating a risk that these pathways could be rejected by local communities; and
- Expansion of solar PV power generation may be an extremely low-cost mitigation option but its feasibility and scale may be constrained in a given jurisdiction by non-

economic factors, such as solar energy resource availability, grid reliability, availability of suitable sites, potential impacts on biodiversity and other natural resources, potential resistance from local communities to new transmission line corridors, and potential backlash from an incumbent fossil fuels industry.

Without a more comprehensive, holistic assessment of the potential value of different mitigation options, the best-laid net-zero energy transitions strategies may be vulnerable to unanticipated (but avoidable) setbacks. In this study, a more comprehensive assessment of the value of CO_2 capture, utilisation and storage (CCUS) technology is investigated.

Scope of Work

A key objective of the study was to explore the concept of ‘value’, when applied to a technology deployed in a low-carbon energy system. CCUS is an available mitigation option to support energy transitions and has been highlighted by global IAMs as a necessary technology to limit anthropogenic warming to well below 2°C. Despite this, there continues to be dissent among academics, business leaders and policymakers regarding the role CCUS can or should play in a low-carbon future. This opposition appears to stem not only from a narrow and incomplete focus on cost, and the perception that CCUS is a high-cost mitigation option under all circumstances, but also a failure to recognise the value of CCUS from other perspectives, such as human, social and environmental, to support the energy transition to net zero. As a result, a wider, deeper, and multi-disciplinary review of the ‘value’ of CCUS is explored.

Recent literature spanning sector-specific techno-economic models, global and regional IAMs, and social studies to explore the diverse value of CCUS is reviewed. Results from Princeton University’s *Net-Zero America* study[1] are summarised, where five alternate modelled pathways to net-zero emissions in the United States provided an exceptional level of sectoral, temporal and spatial granularity to highlight the value of CCUS in these pathways. Finally, a semi-quantitative, 2x2 decision framework was introduced to help policymakers screen the relative competitiveness of CCUS as a mitigation option across multiple domains. This framework was applied across a number of case studies, including the United States, the UK, Indonesia, Australia and Japan, to highlight under what circumstances CCUS might prove to be a valuable mitigation option to help these jurisdictions achieve time-bound mitigation goals.

Findings of the Study

There is much evidence in the literature highlighting the value of CCUS in reducing the costs of the overall energy system and of the energy transition. Recent studies are reviewed that illustrate circumstances under which CCUS can drive cost reductions in the decarbonisation of both electricity generation and industrial processes and, as IAMs reveal, its value in reducing costs globally. Examples are also highlighted where CCUS provides value beyond just cost-competitiveness, where it offers low-carbon energy security as well as providing a mitigation option for hard-to-abate sources.

Electricity generation. Traditionally, in energy systems analysis, the levelised cost of electricity (LCOE) has been the key metric used to assess the techno-economic value of

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[1] E. Larson, et al. Net-Zero America: Potential Pathways, Infrastructure, and Impacts (interim report) (Princeton University). (2020). Report, annexes, and data downloadable at https://netzeroamerica.princeton.edu.

generation technologies. Implicit in the use of this metric was the fact that the available generation options – namely, thermal generation technologies – could all provide reliable generation (albeit with different degrees of capacity, cost and flexibility). More recently, rapid declines in the capital costs of wind and solar power have, in many cases, made these the cheapest new generation technologies. However, as wind and solar are inherently variable in supply, a focus on LCOE does not guarantee energy security or service reliability – their contribution must be considered in a broader system context. As a result, contemporary energy systems analysis has evolved to sub-divide generation technologies across additional categories, as follows:

- **firm generation** technologies are able to guarantee their availability at any time and with reasonable notice;
- **flexible generation** technologies are able to guarantee their availability, to vary the capacity delivered and to do so at short notice; and
- **variable generation** technologies are unable to guarantee their availability at any time.

Studies[2,3] have demonstrated that the generation mix with the lowest system cost included a significant tranche of firm generation capacity, even more so in regions with less consistent renewable resources – noting that, in the latter case, the differential value could also be provided by increasing interregional transmission capacity. They showed that, while decarbonising the grid consistently resulted in a higher total system cost, irrespective of the combination of low-carbon technologies, inclusion of firm generation capacity was key to obtaining the lowest cost near-zero emissions system.

Studies[4,5] focusing on the UK's electricity system explored the value of different types of CO_2 capture (post-combustion capture and oxy-combustion) and also compared the impact of capture-equipped and flexible capture-equipped thermal power plants. They found that the inclusion of CCS-equipped thermal power plants resulted in a significant reduction in total system cost under all combinations of future demand and emissions intensity targets. These studies also demonstrated that flexible CCS technologies offer additional value as they are able to accommodate higher levels of variable renewable capacity, which given the very low operational costs of renewables, results in a lower total system cost.

While studies have shown that firm, low-carbon generation capacity reduces future low-emissions electricity system costs, it is worth noting that modelling studies often make assumptions about the trajectory of future costs of technology and fossil fuels, both of which are uncertain, and which may have a significant effect on findings.

Industrial processes. Considerable advocacy for CCUS comes from certain hard-to-abate materials production sectors, including cement, iron and steel, and fertilizers and other petrochemicals, especially in fast-growing developing countries. A lack of like-for-like substitutes (of feedstock or products), an inability to scale, or unintended consequences of

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[2] Sepulveda, N. A., Jenkins J.D., de Sisternes, F.J, Lestor, R. K. The role of firm low-carbon electricity resources in deep decarbonization of power generation. Joule 2, 2403-2420. (2018).

[3] Boston, A., Bongers, G., Byrom, S. and Bongers, N. The Lowest Total System Cost NEM – the impact of constraints (Gamma Energy Technology P/L). (2020).

[4] Heuberger, C.F., Staffell, I. Shah, N., and Mac Dowell, N. Quantifying the value of CCS for the future electricity system. Energy Environ. Sci. 8, 2497-2510 (2016).

[5] IEAGHG, "Valuing Flexibility in CCS Power Plants", 2017/09, November 2017.

scaling-up substitutes makes such substitutes impractical and CCUS the most cost-effective technology option for decarbonising these emissions sources.

A recent study[6] exploring the challenges for decarbonising Germany's iron and steel industry investigated three pathways the German steel industry could take, each adopting different production outlooks and technologies. It was found that all pathways struggled to meet Germany's 2035 emissions reductions commitments, in part because refurbishment decisions needed to be taken by asset owners now, which, in the absence of commercially available alternative technologies, would lock in the emissions-intensive technologies for decades to come. Significantly, much of the iron and steel production asset base has been commissioned this century and is likely, under business-as-usual, to continue to operate beyond mid-century.

Similarly, while new low-carbon alternatives to traditional ordinary portland cement (OPC) have been identified, several challenges exist which hinder their widespread adoption.

Collectively, the examples presented illustrate the value that CCUS offers as a mitigation option for transitioning hard-to-abate heavy industry sectors to zero-carbon processes. The fact that CCUS may be the only reliable option to decarbonise some sectors underscores its technical value to limiting global warming to well below 2°C.

Global decarbonisation. Arguably the main analytical tools used to inform climate and energy policies are IAMs, global models that determine the cost-optimal combination of actions that achieve certain mitigation goals over time. It is notable that virtually all scenarios that comply with the goals of the Paris Agreement tend to rely on substantial amounts of CCUS for both emissions reductions and negative emissions.

The IEA's recent net-zero roadmap[7] to achieve net-zero emissions from the energy and industrial systems by 2050, for example, indicates the need for large-scale deployment of CCUS globally. CCUS is deployed to mitigate emissions from existing fossil energy assets and from hard-to-abate, emissions-intensive industries. It is also used in the production of low-carbon hydrogen and for negative emissions, primarily BECCS. In cases where the carbon budget overshoots, reliance on CCUS for negative emissions increases.

Human and social value of CCUS. In a recent IEAGHG study,[8] three case studies were explored to exemplify the perils of relying on techno-economic feasibility and cost-optimal approaches alone in planning energy transitions. Specific emphasis was placed on socio-economic and geopolitical considerations, and the broader sustainable development goals. In one of the case studies, it was found that the total system cost to decarbonise the grid was marginal for technology agnostic scenarios, whereas it increased markedly in a renewables-only scenario.

Notably, in technology agnostic scenarios, despite significant renewable expansion, a significant tranche of thermal power capacity remained (and was abated with CCS). It was also found that, in technology agnostic decarbonisation transition pathways, the value of existing assets was respected and social equity ensured by minimising job losses. In so doing, value

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[6] Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A. & Zhang, Q. Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. Journal of Cleaner Production 163, 84-98 (2017).
[7] IEA, 'Net-zero by 2050: A roadmap for the global energy sector', International Energy Agency (2021).
[8] IEAGHG, 'Quantifying the socio-economic value of CCUS: a review', 2022/TR03, June 2022.

was maximised by finding an appropriate balance between economic growth, social wellbeing and system costs.

In contrast, pathways that were technology prescriptive and neglected socio-economic considerations resulted in sub-regional labour market inequalities and social divisions and, because of those socio-economic costs, erosion of value (GVA). In general, CCUS was found to be a valuable mitigation option to support national and sub-national efforts to achieve economy-wide net-zero emissions goals. Broadly speaking, CCUS deployment can:

- Reduce energy costs;
- Provide energy security;
- Mitigate hard-to-abate emissions sources;
- Enable a just transition for workers in incumbent fossil fuels industries; and
- Help overcome 'real-world' deployment challenges that are likely to impede the scale and pace demands of energy transitions.

Real-world deployment challenges may include:

- Limitations in supply chains, human or institutional capacities, or financial capital;
- Siting restrictions arising from community opposition to some projects;
- Legal and regulatory hurdles;
- Impacts on food production, water resources, and biodiversity; and
- Potential for influential political coalitions to undermine certain mitigation technology pathways.

The value of CCUS for economy-wide transition to net-zero. A review of Princeton University's *Net-Zero America* study provided a broader exploration of the value of CCUS, a more comprehensive understanding of how CCUS could enhance the feasibility of the transition to net-zero emissions. Five technologically diverse mitigation pathways to net-zero were modelled across all economic sectors and covering all GHGs for the lower 48 states. The study indicated that, when compared with a 100% renewables scenario, i.e., where CCUS was disallowed, CCUS deployment was found to enhance the feasibility of the energy transition in the following ways:

- **Techno-economic:** CCUS deployment could reduce the net present value of supply-side transition costs by 50%, the fraction of GDP estimated to be spent on energy services in 2050 by a full one percent, and reduce markedly the cumulative amount of supply-side capital invested by 2050;
- **Human and social:** CCUS deployment could halve the amount of job losses, which were anticipated to be disproportionately concentrated in Middle America; and
- **Environmental:** CCUS deployment could maintain a substantial area of land (approximately 5% of the United States) for alternative use, including biodiversity protection, visual amenity or other climate adaptation infrastructure expenditure.

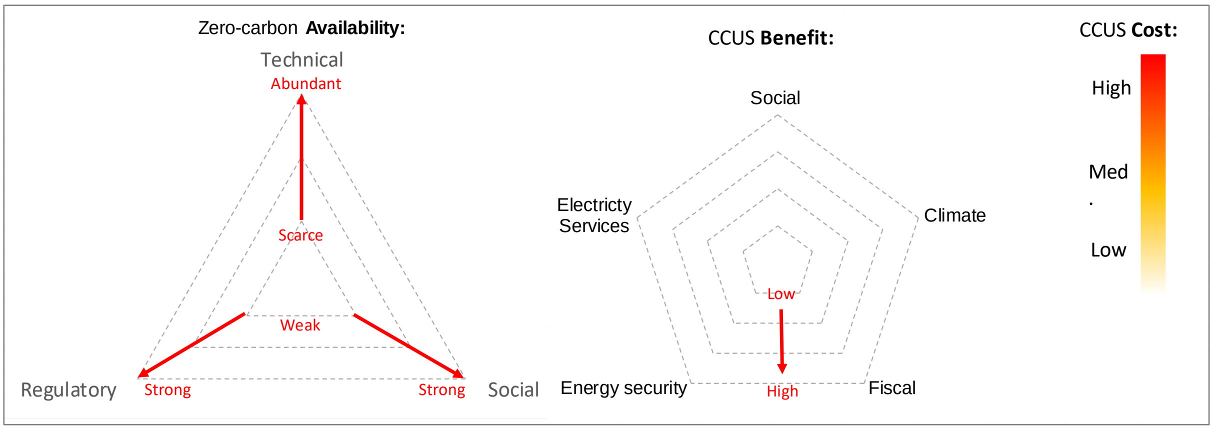
This interdisciplinary, multi-stakeholder, energy transitions approach offers a helpful context to assess the efficacy and robustness of alternative mitigation technology options. It showed that, under various circumstances, CCUS was likely to be highly valuable in helping jurisdictions achieve ambitious net-zero emissions pledges.

2x2 decision framework for assessing the option value of CCUS

Some of the analysis described above, particularly the *Net-Zero America* study, involved person-years of sophisticated work and the application of complex models and algorithms. Policymakers, however, are often in search of higher level ‘scoping’ assessments that can inform policy objectives, and support decisions related to RD&D investments, clean energy- and climate-related laws, regulations and incentives. These objectives often do not have a solid technical foundation as they aim to support incremental policy (and political) progress.

The 2x2 decision framework, which has previously been applied by the authors to CO_2 removal technologies, was introduced into this study as a tool to assist policymakers make such high-level assessments at national or sub-national scales. The framework offers a methodological approach for screening the potential value of CCUS in achieving mitigation goals, applying a broad cross-section of semi-quantitative metrics. The decision framework was applied in this study to the United States, the UK, Indonesia, Australia and Japan. For illustration purposes, just two of these (Japan and the United States) are described in this Overview.

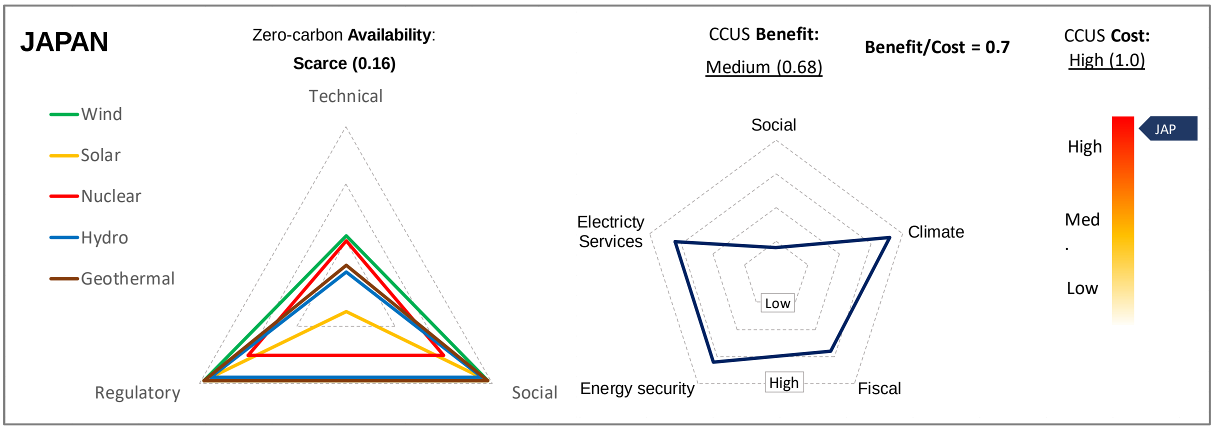
For each country, zero-carbon resource availability and CCUS benefit-cost are represented graphically using radar charts



Japan. Japan has a high mitigation ambition, having pledged net-zero emissions by 2050 but has limited socio-technical zero-carbon mitigation options. Although nuclear power is a clear option, social opposition in the wake of the Fukushima disaster in 2011 greatly stifled the potential for new nuclear deployment. Japan has limited solar and onshore wind potential. Offshore wind may be expensive due to the deep near-shore ocean floor in the Pacific Ocean.

CCUS deployment is anticipated to generate a relatively neutral benefit-cost for Japan. Benefits could be extensive, with a significant scale of hard-to-abate industrial capacity (steel, cement and petrochemicals), as well as a relatively young coal and natural gas generation fleet. However, CCUS also faces higher costs due limited local CO_2 geologic storage potential, with the likelihood of having to ship CO_2 to more prospective jurisdictions further afield.

Representation of zero-carbon resource availability and CCUS benefit-cost for Japan



At present, Japan is unique in that it has limited socio-technically feasible mitigation options to achieve its goals despite its ambitions pledge to reach net-zero emissions by 2050. CCUS deployment is likely to be an important mitigation strategy in Japan despite its high cost.

The zero-carbon availability assessment in the radar chart shows that Japan has scarce alternative zero-carbon resources to meet its energy services demands vis-à-vis the technical potential, the level of regulatory ease/support and level of social acceptance.

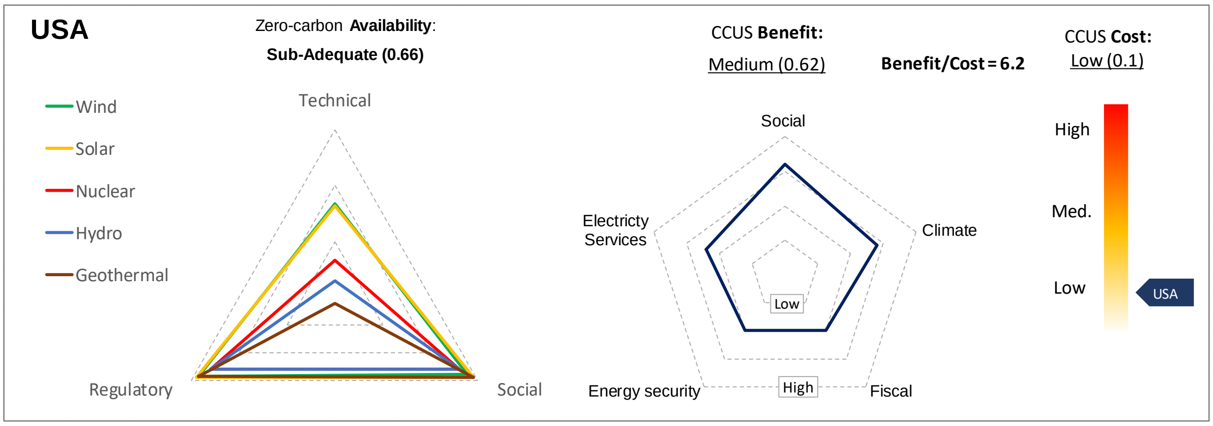
The CCUS benefit-cost assessment shows that CCUS deployment in Japan could create some key benefits (notably energy security, firm electricity service provision and mitigation in its hard-to-abate industry sectors) at high cost (Japan has limited CO_2 storage potential). Overall, CCUS deployment in Japan is considered to offer a net-cost.

United States. While the United States has indicated high ambition to achieve mitigation goals under the Biden-Harris administration, it also faces some socio-technical challenges that limit zero-carbon deployment capability. These include a low potential for new hydro power, high social opposition to new nuclear, medium social opposition to onshore and offshore wind power, and concerns over social opposition to large-scale new transmission line corridors to support large-scale renewables deployment.

In terms of benefit-cost, it is anticipated that CCUS deployment could generate a net-benefit for the United States. This is driven in part by offering a just transition for a substantial oil and gas industry workforce, as well as the low cost of deploying CCUS, which is supported by federal 45Q tax credit incentives and large CO_2 geological storage potential.

The zero-carbon availability assessment shows the United States has sub-adequate alternative zero-carbon availability to meet its energy service demands vis-à-vis the technical potential, level of regulatory ease/support and level of social acceptance.

Representation of zero-carbon resource availability and CCUS benefit-cost for the United States



The CCUS benefit-cost assessment shows that CCUS deployment in the United States could create medium benefits (notably an equitable transition for its large O&G industry, high mitigation given the prevalence of hard-to-abate industrial, non-CO_2 animal agriculture and aviation sources) at low-cost (given the ample, high-quality CO_2 geologic storage potential). Overall, CCUS deployment in the United States is considered to offer a high net-benefit.

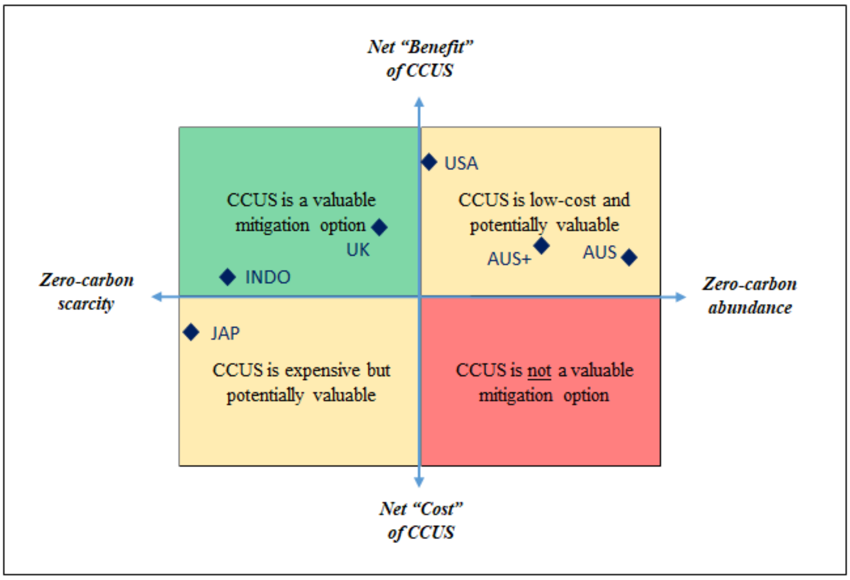
This assessment shows that the United States has medium capability to deploy alternative zero-carbon options based on their technical potential, level of regulatory ease/support and level of social acceptance. However, the United States has high ambition to achieve mitigation goals.

In summary, zero-carbon capability coupled with a high net-benefit makes CCUS deployment a potentially valuable mitigation strategy in the United States.

2x2 decision framework. The horizontal ‘zero-carbon availability’ axis measures the relative availability of socio-technically feasible mitigation options to meet zero-carbon goals. Options include wind, solar, hydro, nuclear and geothermal power. The relative availability of these options depends on a combination of both the political ambition and the socio-technical capability to deploy these technologies. The horizontal axis ranges from scarcity to abundance, with scarcity signalling the potential for CCUS deployment to be a robust, valuable mitigation option for achieving stated goals.

The vertical ‘benefit-cost’ axis measures the relative benefits versus costs of CCUS deployment on the environment. Benefits are determined by the anticipated effect of CCUS deployment criteria including energy security, electricity service performance, social and equity outcomes, mitigation impact and fiscal revenue. Costs are determined by the estimated overall CCUS value chain costs and proximity to, and quality of, geological storage resources.

Graphical representation of the 2x2 decision framework



It is not necessary for the country to have proven and prospective CO_2 storage reserves. For the analysis, the absence of CO_2 storage simply confers high-cost transport and storage via international shipping or pipeline transfers of CO_2 to regions with abundant storage. The vertical axis ranges from net benefit to net cost, with net benefit signalling the potential for CCUS to offer a valuable, economically beneficial and socially-just option for achieving mitigation goals.

Overall, the framework is intended only as a screening methodology to provide policymakers with an impression as to whether CCUS deployment could be a valuable option to achieve mitigation goals. It is recognised that the underlying metrics could be defined with further rigour, as desired.

The applications shown in the main report – for Australia, Indonesia, Japan, the UK and the United States – are illustrative only. The matrix suggests that each of the United States, the UK, Indonesia and Japan could enhance the feasibility of clean energy transitions by deploying CCUS. CCUS deployment may also be valuable in Australia where, coupled with zero carbon abundance. it would generate a net-benefit to society.

The authors note that this matrix could also be applied at different scales (e.g., at the sub-national scale).

Expert Review Comments

Addressing 'value', which is usually considered somewhat of a subjective concept, has often solicited strong views. So, it was unsurprising that comments varied widely, from "… *thought it was great. The authors have done an awesome job, ….*" to "… *not impressed with the report. … too qualitative.*" On balance, however, comments from other reviewers were closer in tone to the former quote than the latter.

One feature of the report that raised some concern was the 2x2 decision framework. For example, for a country that might already be invested in deploying CCUS, the implication, from a benefit-cost perspective, that CCUS was not the best option could prove problematic. In another example, one of the reviewers felt the 2x2 case study relating to Japan was limiting as, not allowing for the import into Japan of low-emissions fuels such as hydrogen and ammonia produced from fossil fuels with CCUS occurring in another country, the full picture was not being considered. In response, the authors emphasised its application lay in providing a high-level snapshot of ‘value’ where, undoubtedly, the output was strongly dependent on the level of detail employed. It was intended simply to be one tool in a policymaker’s toolbox.

It was felt by one reviewer that, as the bulk of the report focused on the value of CCUS to provide low-carbon electricity generation while, in contrast, its value in decarbonising hard-to-abate industry was less well addressed, the report’s title might be misleading. As other reviewers were broadly satisfied that the content was consistent with the title, the title was not amended.

Several other points and comments were raised by reviewers. In response, the authors made every effort to address them and, where helpful, provided additional clarification and explanation in the text.

The study was genuinely appreciated by most reviewers as a welcome contribution to the CCUS oeuvre.

Conclusions and Recommendations

Adoption of the Paris Agreement in 2015 served as the main catalyst behind a series of net-zero emission pledges made by countries at both the national and sub-national level, and by businesses around the world. The scale and pace of the energy transition necessary to achieve this goal and to avoid the most severe impacts of climate change presents one of the most daunting challenges of the twenty-first century.

While complex, the energy transition challenge is, in some ways, reasonably well-defined. There were only a handful of supply-side zero-carbon options available (i.e., wind, solar, hydro, nuclear, geothermal, bioenergy and CCUS) for deployment to satisfy future energy demand. The challenge is to identify the combinations of these options that would reliably achieve the net-zero goals by mid-century. Traditionally, the main approaches have been techno-economic in nature, aiming to identify the lowest-cost combinations of options, often for a single sector. However – and importantly –cost-optimal combinations (especially in one sector) may not necessarily be the most effective way to achieve economy-wide, net-zero goals. This is because success depends on more than just favourable techno-economics, but also the human and social, political, and environmental impacts. Therefore, it is essential to develop a wider and deeper understanding of the potential value of mitigation options to assess their ability to achieve the energy transition.

Multi-disciplinary, value-based assessments of mitigation options and pathways is an underexplored area of the academic literature on climate change. Yet, it is increasingly important that these assessments are undertaken, as governments commit to policies and develop long-term investment agendas related to energy transitions. Under the current paradigm, there is a significant risk that these plans will be based entirely around techno-economic assessments and a commitment made to support single-pathway options only (often relying heavily on renewable power). Without considering the potential value of alternative mitigation pathways, countries (at the national and sub-national levels) will be exposed to the risk of failing to achieve their mitigation goals because of unforeseen socio-technical challenges.

Such a broader, deeper exploration of the potential value of CCUS is undertaken in this study. Despite some dissent from academics, businesses, and policymakers, CCUS was found to create value across multiple socio-technical domains and, in some cases, was likely to enhance the robustness of long-term mitigation strategies and portfolios. Notably, in a recent paper,[9] it was found that in some jurisdictions (e.g. the USA), CCUS holds 'threshold value' – meaning that it is an essential mitigation technology without which achieving net-zero is not possible.

CCUS deployment has the potential to help overcome several real-world deployment challenges related to the energy transition, including issues of land availability, siting restrictions, social acceptance and the potential for negative environmental impacts.

A 2x2 decision framework was introduced that produces a high-level assessment (or snapshot) of the value of CCUS and which could prove a helpful instrument in the policymaker' toolbox.

It was recommended that value-based assessments similar to those explored in this study be extended to other countries and mitigation options, with increased rigour, and subjected to peer-review.

Suggestions for further work

Although multi-disciplinary value-based assessments could be significant for helping to identify robust mitigation options and pathways, they are by no means a panacea. The threat of both known and unknown unknowns will always afflict complex problems that are subject to deep uncertainty like climate change.

Recent initiatives adopted by many to ratchet up deployment rates of low-carbon technologies underscores an additional value proposition associated with investment strategies that seek to expand the portfolio of mitigation options. That is, CCUS can offer value as a real option, even if it is not ultimately needed to achieve mitigation goals. In this context, a real option is one that is ready to be deployed commercially, at scale, and within a short time period. That might mean investing in storage resource characterisation and RD&D to assure its readiness. In such a case, CCUS has value as part of hedging strategy to be deployed should other options fall short of expectations or should a nation wish to upscale its level of mitigation ambition. This risk-based, decision-making approach to address the climate problem is an area that warrants further research.

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[9] Greig, C. and Uden, S. The value of CCUS in transitions to net-zero emissions. The Electricity Journal, Volume 34, Issue 7, August–September 2021 (https://doi.org/10.1016/j.tej.2021.107004).

Defining the value of carbon capture, utilization and storage (CCUS) for a low-carbon future[1]

Abstract

To limit global warming to well below 2^{o}C, countries must achieve net-zero emissions (NZE) by around mid-century. The necessary *energy transition* to achieve this goal presents a daunting task for most countries. To help inform energy transitions, the literature is replete with quantitative models that identify the lowest-cost mitigation pathways for countries to achieve economy-wide, NZE. However, the identification of cost-optimal pathways does not necessarily reveal much about the *feasibility* of their implementation. For example, while renewables-heavy pathways may in general be low-cost, they also result in significant land-use impacts; creating a risk that these pathways could be rejected by local communities. As countries and states begin to turn their attention to 'how' they can achieve their NZE pledges, we argue that a deep, wide, and multi-disciplinary understanding of mitigation option *value* is necessary.

In this report, we aim to initiate such an exploration for carbon capture, utilization and storage (CCUS) technology. We review recent literature spanning sectoral-specific and global techno-economic assessments, jobs and social impact research, as well as Princeton University's recent *Net-Zero America* study, to explore the diverse value of CCUS. Building on this review, we introduce a 2x2 decision-making framework for policymakers to make high-level 'scoping' assessments regarding whether CCUS could provide value as a mitigation option at jurisdictional scales. We apply this framework to case studies, including the US, UK, Indonesia, Australia, and Japan.

Overall, we find that CCUS is likely to be a valuable mitigation option across multiple domains to support net-zero emission energy transitions, and is potentially valuable even in circumstances where a region is endowed with renewable energy abundance, or where CCUS is expected to be very expensive as a result of a lack of accessible geologic storage resources. Only when the combination of zero-carbon energy abundance, and CCUS costs with limited socio-economic benefits is CCUS unlikely to offer value for a nation transitioning to net-zero emissions.

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1 Executive Summary

Complex, global problems like climate change can be viewed through a number of different lenses. Some lenses are narrow, such as applying focus on a specific mitigation technology or industry, while others are broader, such as considering the interaction between energy and environmental systems, and how this interaction may contribute to global warming. Adoption of the Paris Agreement in 2015 marked a watershed moment in terms of perception of the climate problem, as it set a concrete resource management goal of “well below 2°C”. The natural question of ‘how’ we can achieve this goal elevated the emergent and integrated *energy transitions* lens to viewing the climate problem, and the need to develop robust mitigation strategies that work across multiple domains to steward economies towards NZE by around mid-century. Such domains may include: techno-economic; human and social; political; and environmental; which exist in different forms at multiple scales, including: global; regional; national; sectoral; local; and at the firm-level.

An energy transitions lens requires that we develop a broader and deeper understanding of the potential *value* of different mitigation options, as this is one way we can assess their robustness across the various domains. Typically, the value of mitigation options is limited to the techno-economic (or cost-competitiveness) domain only. However, this domain in isolation reveals little about the *feasibility* of deploying a mitigation option. For example, while expansion of solar PV power generation may be an extremely low-cost mitigation option, its feasibility and scale may be constrained in a given jurisdiction by non-economic factors, such as (but not limited to): solar energy resource availability; grid reliability; availability of suitable sites; potential impacts on biodiversity and other natural resources; potential resistance from local communities to new transmission line corridors; and potential backlash from an incumbent fossil fuels industry. Without a more comprehensive, holistic assessment of the potential value of different mitigation options, the best-laid net-zero energy transitions strategies may be vulnerable to unanticipated (but avoidable) setbacks.

In this report, we seek to initiate this more comprehensive assessment of the value of CO_2 capture, utilization and storage (CCUS) technology. CCUS is an available mitigation option to support energy transitions and has been highlighted by global energy-emissions models as a necessary technology to limit anthropogenic warming to well below 2^oC. Despite this, there continues to be dissent amongst academics, businesses, and policymakers regarding the role CCUS can or should play in a low-carbon future. We think that this opposition stems from not only a narrow and incomplete focus on cost, and the perception that CCUS is a high-cost mitigation option under all circumstances, but also a failure to recognize the value of CCUS in other domains, such as human and social and environmental, to support energy transitions. As a result, we explore a wider, deeper, and multi-disciplinary review of the value of CCUS.

We review recent literature spanning sector-specific and regional techno-economic models, global Integrated Assessment Models, and social studies to explore the diverse value of CCUS (Sections 3 and 4). In addition, we draw on Princeton University's recent *Net-Zero America* study, which downscaled five alternate modelled pathways to NZE in the US to an unprecedented level of sectoral, temporal, and spatial granularity, and highlight the value of CCUS in these pathways (Section 5). Finally, we introduce a semi-quantitative, 2x2 decision-making framework to help policymakers determine the circumstances under which CCUS could provide value as a mitigation option at jurisdictional scales (Section 6). We apply this framework to a number of case studies, namely, the US, UK, Indonesia, Australia, and Japan.

Overall, and in general, we find that CCUS is likely to be a valuable mitigation option to support many national and subnational efforts to achieve economy-wide NZE goals. CCUS deployment can: reduce energy costs; provide energy security; mitigate hard-to-abate emissions sources; enable an equitable transition for workers in incumbent fossil fuels industries; and help overcome 'real-world' project execution challenges that are likely to impede the scale and pace demands of energy transitions. These challenges may include: limitations in supply chains, human or institutional capacities, or financial capital; siting restrictions arising from community opposition to some projects; legal and regulatory hurdles; impacts on food production, water resources, and biodiversity; and the potential for influential political coalitions to undermine certain mitigation technology pathways. We find that CCUS is a valuable mitigation technology for USA, UK and Indonesia and maybe a valuable option for Japan and Australia.

Princeton University's Net-Zero America study offered a further more quantitative and granular examination of the vale of CCUS. CCUS deployment in pathways that allowed continued fossil fuel utilization was found to create value (and enhance the feasibility of energy transitions to NZE) relative to a 100% renewable pathway, for the United States in the following ways:

- **Techno-economic**: CCUS deployment could reduce the Net Present Value of supply-side transition costs by almost $2 trillion (or 50%), reduce the fraction of GDP estimated to be spent on energy services in 2050 by a full one percentage point, and lower the cumulative requirements for supply-side investment capital by approximately $3-4 trillion to 2050;
- **Human and social**: CCUS deployment could halve the amount of job losses, which are anticipated to be disproportionately concentrated in key fossil fuel producing regions like the US Gulf Coast and Appalachia; and

- **Environmental**: CCUS deployment could allow upwards of 0.48 *million* km^2 of US landscapes (i.e. approximately the size of Spain) to be preserved for alternative use, including biodiversity protection, preserving visual amenity, or other climate adaptation infrastructure expenditure.

The interdisciplinary, multi-stakeholder, energy transitions lens offers a helpful context to assess the efficacy and robustness of alternative mitigation technology options. CCUS is one such option that, under various circumstances, is likely to hold a high option value for helping jurisdictions achieve ambitious NZE pledges. Further research can help more comprehensively explore the potential value of CCUS and other mitigation options across multiple domains. Such research can also serve as building blocks for the development of conceptual, integrated decision-making frameworks based upon a broad understanding of the value of mitigation options for facilitating NZE transitions.

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[2] This includes the full spatial extent of the additional wind (mostly) and solar farms in the 100% renewables scenario (which disallows CCUS) versus the unconstrained scenario. It is acknowledged that the *direct* footprint of the wind turbines is a fraction of the aerial extent of the farm.

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2 Context

The Paris Agreement, adopted in December 2015, signaled a global consensus around the ambition to limit anthropogenic global warming to “well below 2°C and to pursue efforts towards 1.5°C”. [1] This ambition will require deep decarbonisation of the energy and industrial sectors to around NZE by mid-century. Indeed, recent analytical updates have emphasized the urgency of accelerating all decarbonisation efforts, including CO_2 capture, utilization and storage (CCUS). [2-12]. CCUS refers to techniques which either capture CO_2 flue gas from stationary point sources or engineer the direct removal of CO_2 from the atmosphere, before then either recycling this CO_2 into products (e.g. low-carbon fuels; building materials) or geologically storing it in deep reservoirs underground. CCUS achieves mitigation via emissions reductions or in some bioenergy coupled with CCS (BECCS) and/or direct air CCS (DACCS) applications can result in net-drawdown from the atmosphere.

CCUS is expected to play an important role in helping nations, states, and corporations achieve NZE pledges, which have been growing in momentum following the Paris Agreement. [13-20] Indeed, the majority of global Integrated Assessment Model (IAM) studies and similar energy transition scenarios indicate that a widespread and large-scale rollout of CO_2 capture and geological storage (CCS) is crucial to reduce cost and increase feasibility of constraining global average temperature rise to well below 2°C. [21-28]

Despite this virtual consensus among the global energy-emissions modelling community of the *expected* role that CCUS plays in a low-carbon future, there is still some dissent among academics, businesses, and policymakers over the value that CCUS offers, and the role the technology can or should play in a deeply decarbonized future. Arguments against CCUS range from its perceived high cost [29-31] and potential to act as a prop for the fossil fuel industry, to concerns about the integrity of subsurface storage of CO_2 and other concerns about environmental or public health risks. [32-34]

The purpose of this paper is to initiate a wider and deeper assessment of the potential value of CCUS in limiting anthropogenic global warming to well below 2°C. This includes an assessment of value beyond just a techno-economic (or cost-competitiveness) domain, and into alternate domains, including human and social, environmental, political, and more. It also includes an assessment of value at different scales, including global, national, and local scales. Such a multi-dimensional perspective is vital for identifying robust mitigation strategies [35-37] capable of facilitating NZE transitions. We view this work, among similar assessments, as building blocks that could help inform the development of conceptual, integrated frameworks that support decision- and policy-making processes.

This paper considers five critical issues related to the definition of *value*, including:

(a) Value extends beyond the traditional techno-economic domain to multiple domains, at multiple scales, and may vary across time.

(b) Value is realized in relation to a *goal or objective*. For the purpose of this analysis, CCUS value is realized when CCUS deployment is likely to help *enhance the feasibility* of economywide, NZE transitions.[3]

(c) Value is realized under *certain conditions*. For example, CCUS may reduce electricity sector total system cost when deployed in conjunction with a large-scale renewable energy rollout, while not necessarily so when deployed exclusively (e.g. a 100% CCUS decarbonization strategy). CCUS may also reduce the cost of low-carbon energy systems in scenarios where the cost of fossil fuels is very low.

(d) Value is created even if the mitigation option in question is not deployed. For example, taking steps to ready CCUS as a *real option*[4] for near-term commercial deployment at-scale (e.g. performing feasibility studies; investing in research, development, CO_2 storage appraisal, and demonstration projects) can serve to hedge against the risk that a desired pathway (e.g. 100% renewables) succumbs to unanticipated setbacks.

(e) A variety of quantitative and qualitative approaches can be used to assess value.

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[3] We emphasize that enhancing feasibility depends not just on reducing cost, but also: increasing social acceptance; reducing or avoiding environmental impacts; increasing political viability; reducing scale and pace demands (i.e. increasing technical potential); etc.

[4] We define *real* options as alternative mitigation options that, crucially, can be deployed without substantial delay could provide a hedge against the risk that countries fail to achieve their mitigation targets. In this context 'real' not only reflects the physical infrastructure aspect (i.e., consistent with the typical definition of a real option), but in this case, also the relatively high execution readiness of these mitigation options for rapid deployment at scale.

3 Review of previous studies on techno-economic value of CCUS

CCUS is often perceived as a high-cost mitigation option. However, there is a vast literature that highlights the value of CCUS in terms of its ability to reduce overall energy system and transition costs. In this section, we review recent techno-economic studies applied in both the electricity generation and industrial sectors to illustrate the circumstances under which CCUS can drive cost reductions. In addition, we review the value of CCUS as identified in global cost-optimizing IAMs. Finally, we begin to highlight examples of where CCUS provides value beyond just cost-competitiveness, such as by offering low-emissions energy security as well as a mitigation option for hard-to-abate sources.

3.1 Electricity generation decarbonization

Historical energy systems analysis leaned heavily on the metric of *Levelized Cost of Electricity (LCOE)* to assess the techno-economic value of alternative generation technologies. LCOE measures the nominal cost of generating electricity over the economic life of the generation asset that would provide an acceptable return on total invested capital after meeting operating and fuel costs. Implicit in the use of this metric was the fact that the available generation options – namely, thermal generation technologies – could all provide reliable generation (albeit at different levels of capacity, cost and flexibility). Rapid declines in the capital costs of wind and solar power have made these the cheapest new generation technologies. However, as wind and solar are inherently weather dependent, and hence *variable* in supply, a focus on LCOE does not guarantee energy security and service reliability unless considered in a broader system context with transmission and storage. As a result, contemporary energy systems analysis evolved to distinguish generation technologies across additional categories, including:

- *firm* generation technologies that are able to guarantee the availability of their capacity to the system at any time, with reasonable notice;
- *flexible* generation technologies that are able to guarantee the availability of their capacity and to vary the capacity delivered to the system at any time, at very short notice; and
- *variable* generation technologies that are dependent on the weather and so unable to guarantee the availability of their capacity to the system at any time.

A number of studies have shown that firm, low-carbon generation capacity reduces future low-emissions electricity system costs. [38-41] It is worth noting however that the modeling studies reviewed here make assumptions about the trajectory of future costs of technology and fossil fuels, both of which are uncertain, and which have a significant effect on findings.

One of the first comprehensive studies [38] exploring the feasibility of deeply decarbonizing the electricity sector, including the case of zero-CO_2 electricity production, examined the economic and operational performance of different mixes of low-carbon technologies which allowed or disallowed firm generation options such as natural gas with CCS, nuclear, biogas and biomass. The study used GENx, a power system investment and operations model. The authors modeled hourly variability in both renewable energy output and electricity demand, along with the detailed operational constraints and costs of thermal plant start-up and shut-down, minimum generation and ramp rates. This study also considered uncertainties in future technology cost (including very optimistic, low-cost projections for wind, solar and batteries) and the impact of regional variation in renewable resources.

The authors reported that the average cost of electricity escalates as emissions intensity is reduced and that the rate of escalation increases dramatically when firm low-carbon technologies are disallowed (Figure 1). Across a range of system conditions and assumptions regarding the future capital cost of wind, solar and batteries, the generation mix with the lowest cost system included in order of 20% to more than 50% firm generation capacity with the percentage of firm generation increasing as the assumed future cost of renewables increased. They also found that the beneficial value of firm low-carbon generation increases in regions with less consistent renewable resources, but that differential value can also be provided through increasing interregional transmission capacity.

Another recent example [39] provided a case study for decarbonizing Australia's National Electricity Market (NEM), a system currently reliant of fossil fuels for more than 70% of annual generation. Their model (MEGS) uses linear optimization with an objective function of minimizing the short run cost each day of using transmission, generation and storage assets. For each interconnected region it must meet demand and provide a minimum level of upwards reserve, either from within the region or via transmission links. It must also meet a minimum level of inertia from within each region. Each day typically consists of 5-10 scheduling points and a year will consist of all 365 days which are scheduled chronologically so storage levels can be tracked. MEGS can be run for a single year, or for many years with stochastic variation of fuel prices, weather, and/or plant capacities. Key outputs are total system cost (TSC) and emissions. It also has a goal seeking algorithm that runs single years and attempts to find the portfolio of generation that gives the lowest TSC for a given emissions reduction target. Running the model many times using different weather patterns from a database with over a decade of historic weather data ensures the modelled systems satisfy demand and grid service constraints in favorable and unfavorable weather conditions across all timescales. These authors report that decarbonizing the system always results in a higher TSC irrespective of the combination of low-carbon technologies and that the increase in TSC increases as the emissions constraint is increased (Figure 2). In addition, their findings also suggest that constraining access to one or more low-carbon technology options results in a higher TSC, than if all technology options are allowed to participate. Consistent with the US study reviewed above, they find that the lowest cost near-zero emissions system includes approximately 20% firm generation.

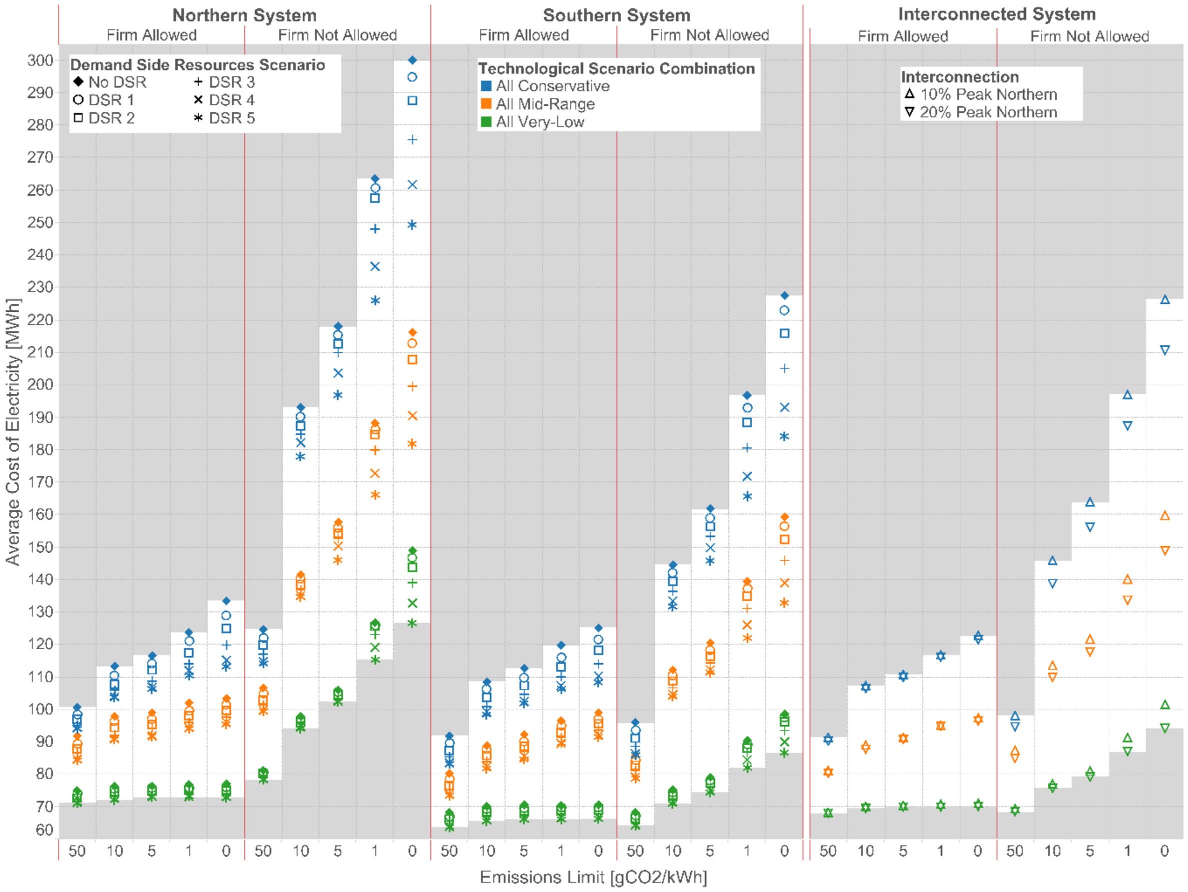

Figure 1 Illustration of the value of firm low-carbon electricity resources in deep decarbonization of power generation. [38].

The three panels, representing two different electriciy network systems – unconneted and connected - show the increase in averge cost of electricity ($/MWh) as the level of carbon intensity is reduced from 50 gCO_2/kWh to 0 gCO_2/kWh, with and without the participation of firm (dispatchable) generation. Irrespective of the network system the authors show that the availbality of firm generation offers a material benefit in reducing the cost of electricity, with the benefit increasing rapidly as the level of decarbonization increases. The third panel shows increased network interconnectedness reduces electricity cost but the benefits are marginal compared with the those offered by firm generation resources . [Figure 4 from Sepulveda, N. A., Jenkins J.D., de Sisternes, F.J, Lestor, R. K. "The role of firm low-carbon electricity resources in deep decarbonization of power generation" Joule 2, 2403-2420]

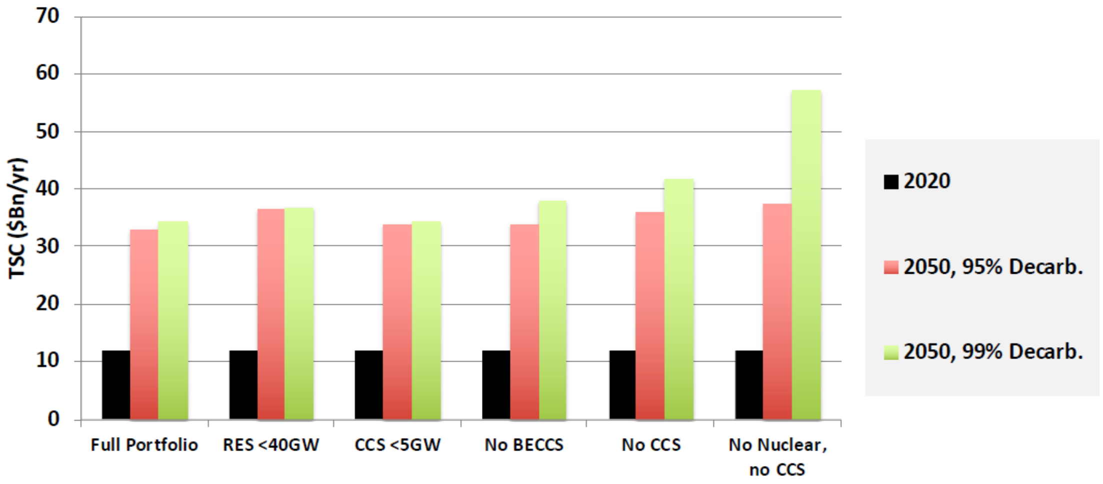

Figure 2 Annualized Total System Cost for the Australian National Electricity Market with Different Constraints on available resources.[39]

Annualized Total System Cost for the Australian National Electricity Market with Different Constraints on available resources. If no low emissions, firm generation such as CCS and nuclear, are available, very deep decarbonisation becomes a significant cost issue. Note that Australian Radiation Protection and Nuclear Safety Act of 1998 prohibits nuclear power from being deployed in Australia, so the "No Nuclear, No CCS case" is essentially a no CCS Case, and the No CCS case (which includes nuclear) is not currently a real option. [Figure 25 from Boston, A., Bongers, G., Byrom, S. and Bongers, N., (2020). The Lowest Total System Cost NEM – the impact of constraints. Gamma Energy Technology P/L, Brisbane Australia.]

Finally, two more recent studies considered the value of different types of CCS (post-combustion capture and oxy-combustion) and also compared CCS-equipped and *flexible* CCS equipped thermal power plants in the UK's electricity system [40, 41]. Like the Australian study, they find the inclusion of CCS-equipped thermal power plants results in a significant reduction in TSC under all combinations of future demand and emissions intensity targets.

These studies employed an optimization-based electricity systems model, tailored to represent the UK, to simultaneously determine the cost-optimal capacity mix and dispatch schedule for given service reliability and annual emissions intensity. These studies also defined a system value metric (SV) as the reduction in TSC that results from the integration of one capacity unit of that technology (in £/kW), and changes as a function of the level of penetration of that technology and the system conditions.

The UK studies also demonstrated that flexible CCS technologies offer additional value as they are able to accommodate higher levels of variable renewable capacity and electricity generation, which given the very low operational costs of renewables, results in a lower TSC (Figure 3). The SV of flexible CCS technologies is a function of the technology capacity mix, and declines as the installed capacity of CCS increases, resulting in a TSC benefit as high as £800/kW to as low as £200/kW.

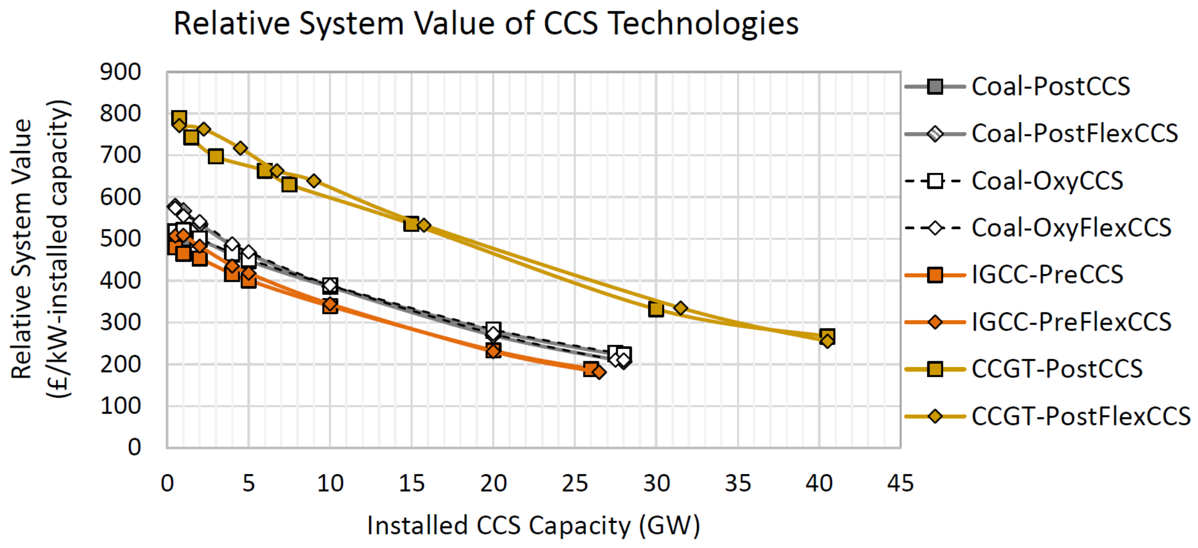

Figure 3 Graphical summary of the relative System value of non-flexible and flexible CCS technologies in the UK electricity system. [41].

CCS-equipped coal generation offers between £200 -600 /kW-installed value, with marginal differences between generation technologies or benefit from flexibility. Flexible CCS-equipped natural gas combined cycle plants offer between £275 -800 /kW-installed value to the system. [Figure 9.16 from Mac Dowell, N., Heuberger, C.F., Staffell, I., Shah, N., "IEAGHG, Valuing Flexibility of CCS Power Plants" 2017/09, December 2017.]

3.2 Industrial process decarbonization

Considerable advocacy for CCUS comes from certain hard-to-abate materials production sectors, including cement, iron and steel, and fertilizers and other petrochemicals, especially in fast-growing developing countries. A lack of like-for-like substitutes (both feedstock or products), inability to scale, or unintended consequences of scaling-up substitutes makes such substitutes infeasible and CCUS the most cost-effective technology option for decarbonizing these emissions sources. [42-47]

One recent case study explored the challenges for decarbonizing Germany's iron and steel industry. [48] The study explores 3 different pathways the German steel industry could take with different production outlooks and technologies adopted, and finds that all pathways struggle to meet Germany's 2035 emissions reductions commitments. These challenges reflect the fact that despite an increasing trend to more recycling of steel using electric arc furnace technology, and emerging iron reduction technologies which utilize hydrogen instead of coking coal especially in developed economies, the prospects for these technologies to scale rapidly enough to materially reduce the emissions from blast furnace iron-making at the rate need to deliver adequate, timely emissions reductions are highly uncertain. This is in part because refurbishment decisions need to be taken by asset owners now, which, in the absence of commercially available alternative technologies, will lock in the emissions-intensive technologies for decades to come.

This challenge is exacerbated in fast growing Asian nations where 70% of global production currently takes place. [49] Much of the iron and steel production asset base has been commissioned this century and is likely, under business-as-usual, to continue to operate beyond mid-century.

Similarly, while new low-carbon alternatives to traditional Ordinary Portland Cement (OPC) have been identified, a number of challenges exist which retard their widespread adoption. [50] These include:

(a) The uncertain supply of alternative materials;
(b) The incremental nature of the way innovation is applied in traditional incumbent industries;
(c) The need for intense cooperation of a multitude of diverse partners from basic research organizations to technology vendors, manufacturers and regulators; and
(d) The existence of prescriptive standards by regulators who, unsurprisingly, are risk-averse in assuring the safety performance and longevity of capital-intensive public infrastructure.

Collectively, these examples illustrate the value that CCUS offers to industrialized nations as a mitigation option for transitioning hard-to-abate heavy industry sectors to zero-carbon processes. The fact that CCUS may be the only reliable option to decarbonize some sectors underscores its technical value to limiting global warming to well below 2°C.

3.3 Global-scale decarbonization

Arguably the main analytical tools used to inform climate and energy policies are IAMs. In contrast to sectoral-specific, cost-optimizing decarbonization models, IAMs are global models that ‘integrate’ energy, land, ocean, and atmospheric systems to determine the cost-optimal combination of mitigation actions that achieve certain mitigation goals over time.

To provide this output, IAMs first forecast how emissions may change overtime, most commonly to 2100, under a range of input assumptions, such as anticipated population and economic growth rates, resources availability, technology costs, and more. [2] This forecast is often defined as the ‘business-as-usual’ scenario, which describes an emissions outcome without any outside mitigation influence. Modelers then determine the cost-optimal combination of mitigations actions (i.e. shift to low-carbon energy resources across various sectors of the economy over time) that would achieve a desired mitigation goal.

At this alternate scale of techno-economic assessment, IAMs highlight the cost-competitive value of CCUS. In particular, we note that virtually all scenarios that comply with the Paris Agreement goals tend to rely on substantial amounts of CCS for both emissions reductions and negative emissions. Figure 4 summarizes projected annual CCS rates across various IAM ‘Shared Socio-economic Pathway’ scenarios resulting in a 66% chance of limiting global average temperature increases to 1.5°C. [55] Figure 4 also includes results from the International Energy Agency’s (IEA) recent net-zero ‘roadmap’ to achieve NZE from the energy and industrial systems by 2050. [56] The roadmap aims to optimize for multiple objectives, including technical feasibility, cost-effectiveness and social acceptance. Both studies indicate the need for large-scale (i.e. multi-gigatonne/year) deployment of CCUS globally, with results generally centralizing around 5-20 Gt/year by 2050. These models deploy CCUS variously to mitigate emissions from existing fossil energy assets, and hard-to mitigate emissions-intensive industries like cement production, as well as 'blue' hydrogen production, and for CDR through negative emissions technologies (i.e. primarily BECCS). The share of CCS for emissions reductions compared to negative emissions (i.e. BECCS) is anticipated to vary over time. One paper that summarizes a collection of recent IAMs estimates that, at 2050, negative emissions could comprise anywhere between 10% and 80% of total CCS. [57] In general, the share of CCS for negative emissions is anticipated to increase over time to 2100. [28] In cases where the carbon budget is allowed to overshoot to 2°C, reliance on CCS for negative emissions increases. Recent IAM literature has focused on exploring scenarios that limit or disallow 2°C overshoot, which was a somewhat arbitrary modelling design convention of previous generation IAMs. [58,59]

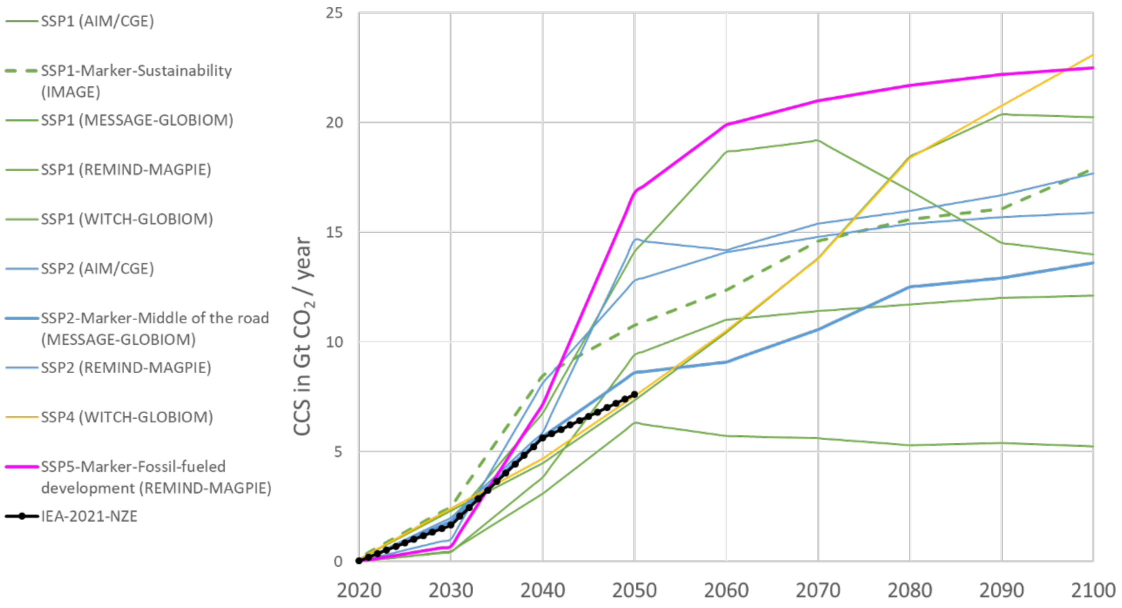

Figure 4 Summary of global-scale modeling results for energy transitions consistent with keeping global average temperature rise to 1.5°C; and net-zero emissions by mid-century.[55,56]

Pathways include IAM's under the various SSPs under RCP1.9 resulting in a 66% chance of limiting global average temperature increases to 1.5°C[55]; and the International Energy Agency projection in its 2021 Global NZE by 2050 Roadmap[56]. *Pathways which indicated large scale CCUS deployment (Gt/year+) prior to 2020 have been omitted.*

We note that CCUS for negative emissions provides added technical value in a similar manner to the way CCUS can help support decarbonization of hard-to-abate sources. For example, there are dispersed sources of emissions (e.g. animal agriculture) as well as some non-stationary point sources (e.g. aviation) that may be impossible to reliably decarbonize within the anticipated available time frame to limit global warming to well below 2°C.

[60,61] Negative emissions can compensate for these residual sources, and in this way provide technical value for the purpose of supporting economywide, NZE transitions. [62] NETs applied to non-electricity applications also offers the advantage of higher utilization factors relative to CCS coupled to power plants, which can be subject to declining load factors with increasing penetration of wind and solar. As mentioned above, IAMs typically only model BECCS as the available engineered carbon removal solution. However, due to recent research highlighting potential limits to BECCS, notably in the form of land availability and biodiversity impacts, we expect that future IAMs are likely to explore alternative engineered removal options, such as DACCS. [63] While currently more expensive, DACCS tends to have a smaller geographic footprint compared to large-scale BECCS, which often requires the use of energy crops. [64] DACCS also has the potential to see significant future cost reductions through materials innovation and modularization.

In summary, CCUS deployment is highlighted in IAM and IEA modelled pathways on the basis that it enables the lowest-cost combination of mitigation actions which limit global warming to well below 2^{o}C. This underscores the techno-economic value of CCUS at the global-scale.

4 Review of previous studies on human and social value of CCUS

In this section, we depart from the typical techno-economic domain for assessing mitigation option value and begin to explore the social domain. Several studies have highlighted the perils of relying on techno-economic feasibility and cost-optimal approaches alone in planning energy transitions, with specific emphasis on socio-technical considerations, [65] political feasibility in the context of social justice [66] and the broader sustainable development goals. [67]

A number of studies have sought to demonstrate the benefits of low-carbon transitions on employment at a national level, but such studies generally do not consider localized impacts or barriers to the transfer of skills across industries or geographically. For example, studies have used economic models to demonstrate the relative employment benefits of ‘green’ energy transitions over ‘brown’ energy transitions. [68] Another study sought to demonstrate how efforts to reduce coal US coal emissions by repurposing existing coal generation assets to BECCS and natural gas CCGT would preserve and indeed grow jobs, [69] although this would not deal with the decline in coal mining jobs. A recent report [70] described how the US 45Q legislation which incentivizes CO_2 capture and permanent geologic storage may stand to create substantial new jobs in the development and operation of CO_2 capture facilities.

Very few academic studies have explored the social value of CCUS specifically, considering for example the perspectives of equity and social justice. We review one recent study here, which set about defining value in energy transitions within a framework combining techno-economic benefits, social wellbeing and broader economic benefits. [71] The authors combine an energy systems optimization model with a country-specific socioeconomic Jobs and Economic Development Impact (JEDI) tool to measure the gross value added (GVA) and direct employment impacts considering local industry capabilities across the full value chain, resulting from the transition. Applying the framework to case studies in the UK, Poland and Spain, the study examined three policy approaches to decarbonization pathways with a reference (business-as-usual pathway):

(a) A *technology agnostic* scenario in which all technologies compete to decarbonize the system at minimum total system cost;
(b) A *renewables-only* scenario in which only renewable resources and electricity storage are allow to compete to decarbonize the grid at minimum total system cost; and
(c) A *technology agnostic* and *socially equitable* scenario in which all technologies compete to decarbonize the system while maximizing the system's GVA.

As shown in Figure 5, the study finds that the total system cost to decarbonize the grid is marginal (increases 1-11%) for technology agnostic scenarios, but increases between 160% and 450% in a renewables-only scenario. Notably, in technology agnostic scenarios, the required capacity of thermal power remains reasonably uniform, despite significant renewable expansion, and is abated with CCS in these scenarios.

The study also found that decarbonization transition pathways that are technology agnostic (in other words retain optionality among low-carbon technologies), respect the value in existing assets and ensure social equity by minimizing job losses. In doing so they maximize value by finding an appropriate balance between economic growth, social wellbeing and system costs. In contrast, pathways which were technology prescriptive, e.g. renewables-only, and neglected socioeconomic considerations resulted in sub-regional labor market inequalities and social divisions, and erosion of value (GVA) as a result of those socio-economic costs. The erosion of GVA was regionally variable being greatest in the UK and least in Spain.

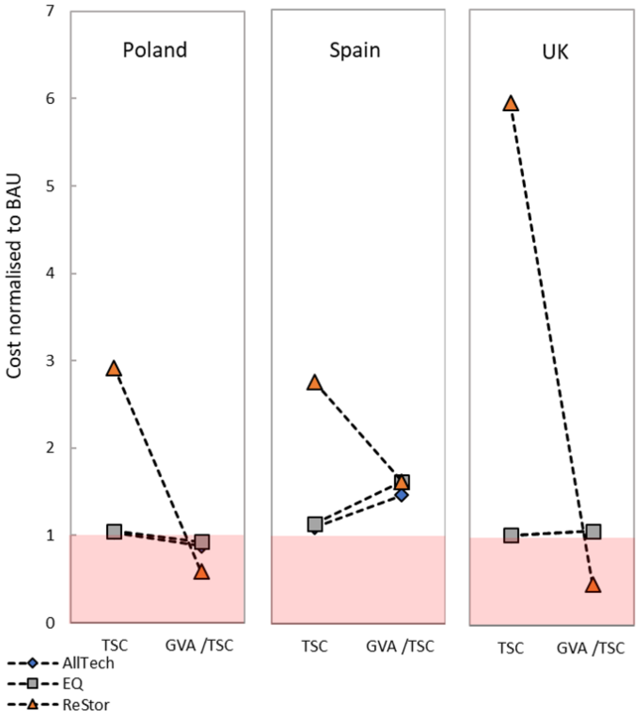

Figure 5 Total System Cost and Gross Value Added of alternative (electricity system) energy transition scenarios in cases studies of Poland, Spain and U.K. [71].*

*Employing the full portfolio of technologies results in the lowest system cost and maximizes Gross Value Added. Systems restricted to rely entirely on renewable resources and storage generates negative socioeconomic value in Poland and the UK. * Scenario descriptions:* ***AllTEch*** *allows all technologies to be deployed and the system expansion is planned to minimize the TSC, subject to a target of net-zero CO_2 emissions by 2050.* ***ReStor*** *is constrained to use only renewables and storage technologies.* ***EQ*** *is similar to the AllTech scenario, but the system is designed to maximize the system's GVA during the transition as opposed to focusing exclusively on minimizing the TSC. Note that AllTech results are obscured by EQ results in the UK and Poland cases. [Figure 4 from Patrizio, P., Pratama, Y.W. Mac Dowell, N. (2020) "Socially Equitable Energy System Transitions' Joule 4, https://doi.org/10/1016/j.joule.2020.07.010]*

5 The value of CCUS for economy-wide transitions to net-zero emissions

In the previous sections, we explored studies which offered a deep focus on a specific domain value of CCUS, including its techno-economic and socio-economic value, expressed in terms of jobs and economic development. In this section, we pursue an equally deep but also *wider* exploration of the value of CCUS – across all domains – in an effort to more comprehensively understand how CCUS could enhance the feasibility of NZE transitions. To do so, we review Princeton University's recent *Net-Zero America* study. [72] The Net-Zero America study modelled five technologically diverse mitigation pathways to NZE across all economic sectors and covering all GHGs for the U.S, lower 48 states, and *downscaled* these pathways to an unprecedented level of sectoral, temporal and spatial granularity. This downscaling revealed a number of under-appreciated but highly plausible 'real-world' execution challenges that could stymie NZE transitions, including the significant scale and pace demands for new infrastructure development, as well as a host of sector- and location-specific barriers and bottlenecks related to: land availability; siting restrictions; legal and regulatory issues; and environmental impacts on food production, water resources, and biodiversity protection. By reviewing this study, we aim to understand how and where CCUS can provide value to enhance the feasibility of NZE transitions.

5.1. Overview of Princeton Net-Zero America Study

The Net-Zero America study was motivated by the growing number of pledges that are being made by major corporations, municipalities, states, and national governments to reach NZE by 2050 or sooner. It sought to reveal deep insights into plausible pathways under which the U.S. economy would emit no more greenhouse gases into the atmosphere than are permanently removed and stored each year, and to provide granular guidance on what getting to net-zero really requires, and on the actions needed to translate ambition of NZE to execution reality.

The study outlines five distinct technological pathways to net-zero. It is agnostic as to pathway preference, and acknowledges that none of the modelled pathways is likely to evolve as described. Rather, the authors' intention was to frame a set of pathways that could span the range of pathways that might be plausible over the next three decades, given status of current and emerging technologies.

The original and distinguishing feature of the Net-Zero America study is its comprehensive cataloguing of energy infrastructure deployments and related capital expenditures at high geospatial and temporal resolution, across all major supply and demand sectors, needed for the transition to a net-zero economy. That granularity helps reveal the true scale and pace of development and associated impacts including plant and infrastructure; impacts on landscapes and other natural capital; impacts on communities and incumbent industries, human capital requirements; financial capital; and key risks and uncertainties that are likely to confront investors, and potentially retard progress on emissions reductions. As a result, the study provides important insights as to the *real option* value of key mitigation technologies, including CCUS, as part of a mitigation technology portfolio for NZE transitions.

5.2. The five pathways in Net-Zero America

The five pathways build on combinations of *six pillars of deep decarbonization*:

(i) Improving energy productivity through end-use electrification and efficiency;
(ii) Clean electricity, including weather dependent renewables, transmission, storage and firm generation;
(iii) Clean (liquid and gaseous) fuels and feedstocks, derived from biomass, electrolysis, or fossil resources (coupled with CCS and/or offset with engineered CO_2 removal);
(iv) CO_2 capture, utilization and storage;

(v) Reducing non-CO_2 emissions; and
(vi) Increasing land sinks.

The study utilized the modelling framework of Evolved Energy Resources LLC (EER) which couples their Energy PATHWAYS demand-side model and RIO supply-side model. Pathways begin with demand side projections, including service demands (taken from the EIA's 2019 Annual Energy Outlook [73]), end-use technology, and energy efficiency. Energy supply portfolios are selected to meet energy demand and economy-wide emissions constraints at least cost across 14 energy zones. All pathways assume straight-line emissions trajectory from 2020 to 2050. The objective function reflecting 'least cost' is net present value (NPV) over the transition period (i.e. 2020-2050). All scenarios are underpinned by assumptions about future technology performance and costs, both of which become increasingly favorable over time, as each technology follows its respective learning curve. The model also relies on assumptions about future fuel costs. In the NZA pathways we adopted the EIA's low-cost oil and gas price scenarios[5].

Like many such modelling frameworks, RIO benefits from high levels of foresight and seamless cross-sectoral integration. Acknowledging the inability of such models to anticipate and account for the many and varied socio-technical uncertainties that could compromise minimum cost pathways, the study defined a variety of alternate pathways by imposing notional constraints on the deployment of certain technologies that might result in the event that such uncertainties translated to binding risks and bottlenecks. The defining characteristics of the five core scenarios are described in Table 1.

Table 1 Overview of five core scenarios in Net-Zero America study [72]

Scenario	Sector	Pillar	Scenario characteristic
E+	Demand	Electrification	High rate electrification
E-	Demand	Electrification	Reduced rate of electrification
E-B+	Supply	Clean fuels/electricity	Expanded biomass supply
E+RE-	Supply	Clean electricity	Wind and solar deployment constrained to peak historical US deployment rates.
E+RE+	Supply	Clean electricity	Nuclear and CCUS disallowed

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[5] However, it is worth noting that in a transition to net-zero emissions, oil and gas prices could be very much lower again as demand reduces. In that case, the model would likely select more fossil fuel generation, blue hydrogen (and derivatives) and potentially greater long-run consumption fossil fuels in multiple sectors, offset with negative emissions technologies like BECCS. This suggests that a future with very low-cost fossil fuels would likely feature more CCUS deployment.

The final stage of the modelling framework involves *downscaling* analysis. Downscaling essentially involved the development and application of algorithms which takes the demand- and supply-side technology expansion projections and makes individual siting decisions. The decision algorithms identify lowest-cost locations to site individual energy supply assets from available candidate sites considering both resource quality and more than 50 exclusion criteria ranging from demographic, economic, environmental, and cultural restrictions, competing land use, and buffer zones around strategic assets, e.g. airports and military bases.

The overall approach to generating scenarios in the Net-Zero America Study in illustrated in Figure 6.

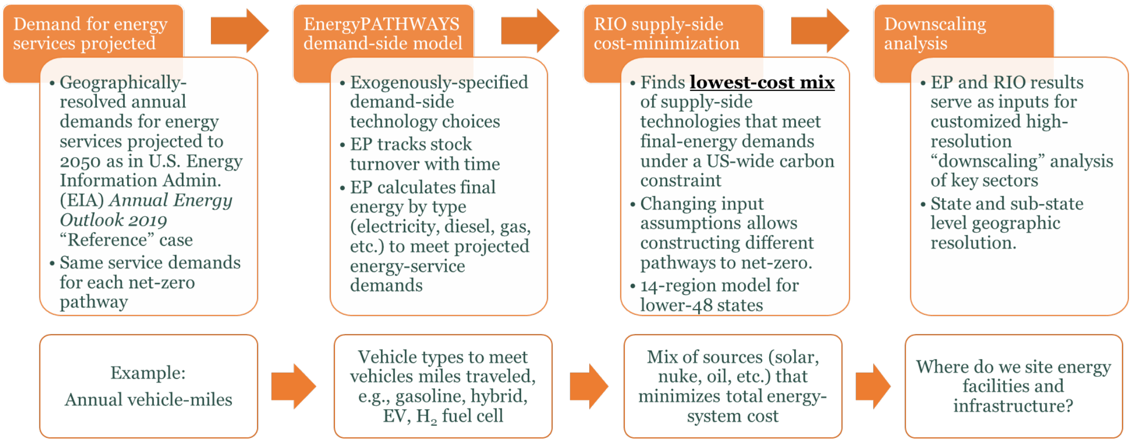

Figure 6 Schematic illustration of modelling and analytic framework adopted for the Net-Zero America study. [72]

Downscaling is critical to elucidate potential risks to different pathways and the value of retaining technology options to maximize value by considering the broader impacts on natural, social, human, manufactured and financial capital.

5.3. Insights for valuing CCUS is NZE transitions

In this section we draw insights from the Net-Zero America study across multiple domains, by contrasting the impacts of different scenarios on environmental, human and social, and techno-economic domains.

We focus on three scenarios which involve significant differences in the role that CCUS plays in the emissions reductions to net-zero, as illustrated in

Table 2.

Table 2 Description of three Net-Zero America scenarios chosen to illustrate the impact of CCUS across different domains of value. [72]

Scenario	Scenario characteristic	Role of CCUS[6] in 2050
E+RE-	Wind and solar deployment constrained to peak historical US deployment rates.	1.67 Gt/year captured 1.65 Gt/year stored
E+	Energy supply options largely unconstrained	1.06 Gt/year captured 0.93 Gt/year stored
E+RE+	100% renewable energy (wind; solar; biomass; hydro; and energy storage), fossil fuels, nuclear and geologic storage disallowed	0.69 Gt/year captured Nil stored

5.3.1 Techno-economic domain

As shown in Figure 7, large-scale CO_2 capture featured in all of NZA's cost-optimal pathways to NZE, expanding from about 2025 and reaching at least 690 million tonnes/per year to as much as 1,760 million tonnes per year in 2050. Notably, in a sensitivity that excluded any CO_2 capture, the model was unable to solve for a pathway to NZE in 2050.

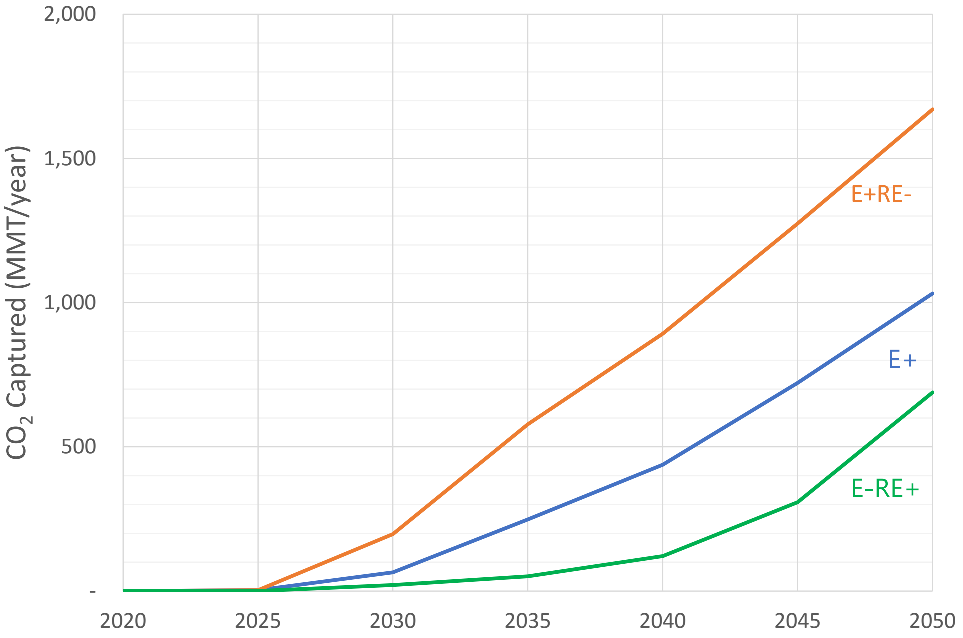

Figure 7 CO_2 capture rates in E+, E+RE+, and E+RE- in Princeton's NZA study in 2050.[72].

CO_2 capture featured in all pathways ranging from 690 million tonnes per year in E+RE- to 1,760 million tonnes per year in 2050 in E-B+.[72]

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[6] Table separately indicates the ongoing rates of CO_2 being captured and geologically stored in 2050. The difference is the amount being utilized in the synthesis of liquid or gaseous fuels and feedstocks.

Across the scenarios, CO_2 is variously captured at cement plants, bioenergy plants for power, hydrogen and fuels production, natural gas power and hydrogen plants and via DAC (Figure 8). BECCS and DAC, generally considered CDR technologies, are treated as a core mitigation or offset technologies in the NZA pathways that compete among the low-carbon energy options to meet the mutual objectives of supplying energy service demands and a declining annual emissions budget consistent with the linear path to NZE.

Figure 9 shows the destination of the captured CO_2 in 2050, with the majority being geologically stored and a minority utilized in the production of synthetic (liquid and gaseous) fuels. However, in the 100% renewables pathway which disallowed geologic storage, all of the captured CO_2 is utilized.

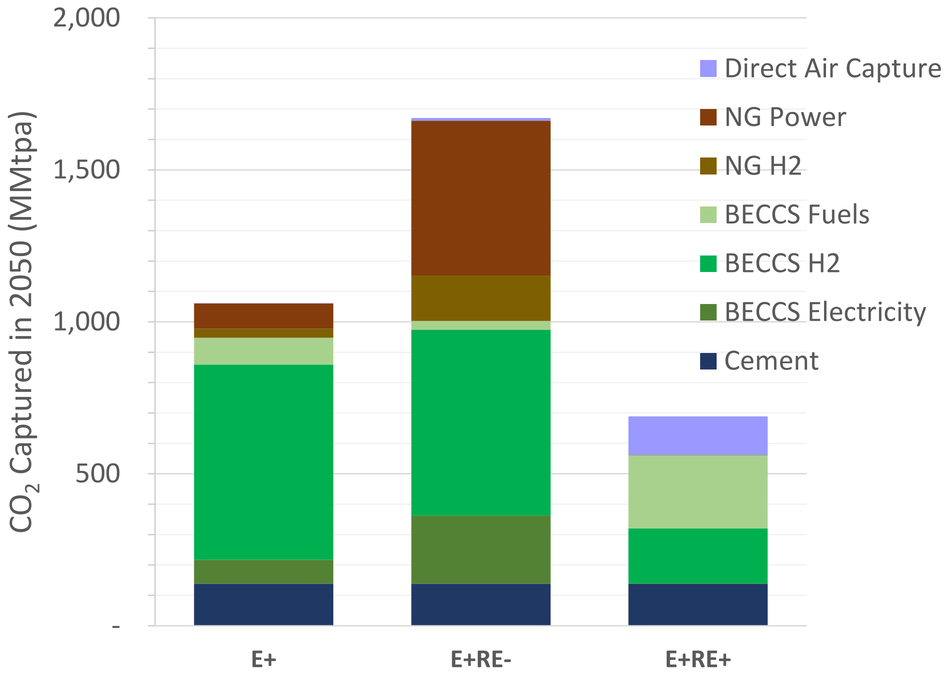

Figure 8 CO_2 sources captured for utilization and/or geologic storage in E+, E+RE+, and E+RE- in Princeton's NZA study in 2050.[72].

CO_2 capture rates range from 690 MMt/year to 1,760 MMt/year in 2050. CO2 is captured at cement plants and bioenergy plants in all scenarios and variously from natural gas power and hydrogen plants, and direct air capture in others.[72]

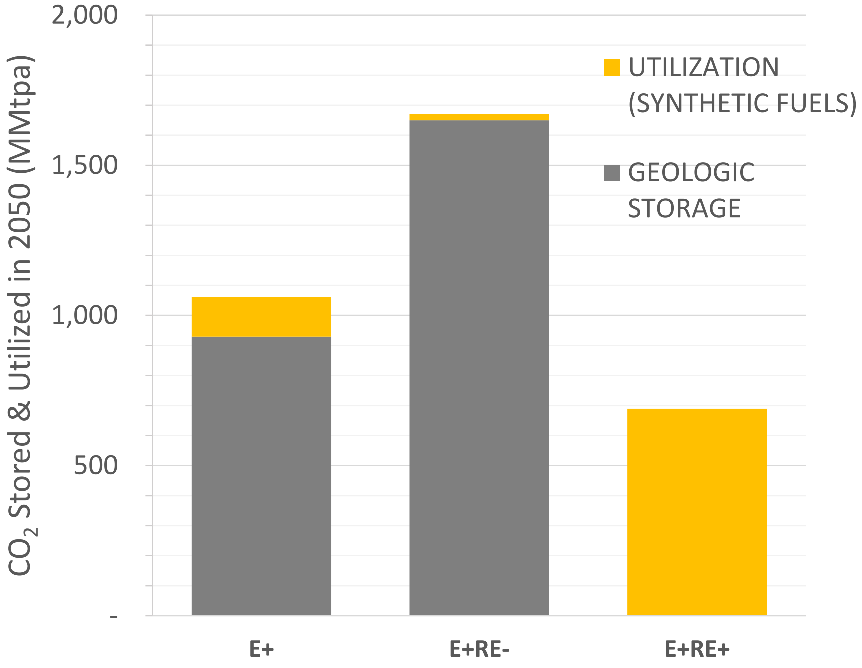

Figure 9 Destination (geologic storage or utilization) of captured CO_2 in E+, E+RE+, and E+RE- in Princeton's NZA study in 2050.[72]

These findings underscore value of CCUS, and that it may be a *necessary* technology option for at least some major economies (e.g. the United States) and hence the global economy to achieve NZE by 2050.

5.3.2 Techno-economic domain

The Net-Zero America study also reported a number of economic measures for each of the NZE pathways. By way of disclaimer, all of these economic metrics must be considered in light of the underlying assumptions regarding current and future technology costs, fuel costs and costs of capital, all of which are uncertain, but transparent and available with the study. The metrics we explore below will be more or less sensitive to any significant departure from these assumptions, for different scenarios.

The first metric is Net Present Value of future supply side costs, which we illustrate in Figure 10. This graph shows that the Net Present Cost of the 100% renewable energy pathway is almost $2 trillion (or 50%) more than that for the E+ and E+RE- scenarios. This reflects the capital intensity of the scenario and the need to deploy expensive fuels synthesis technologies which utilize captured CO_2 including direct air capture.

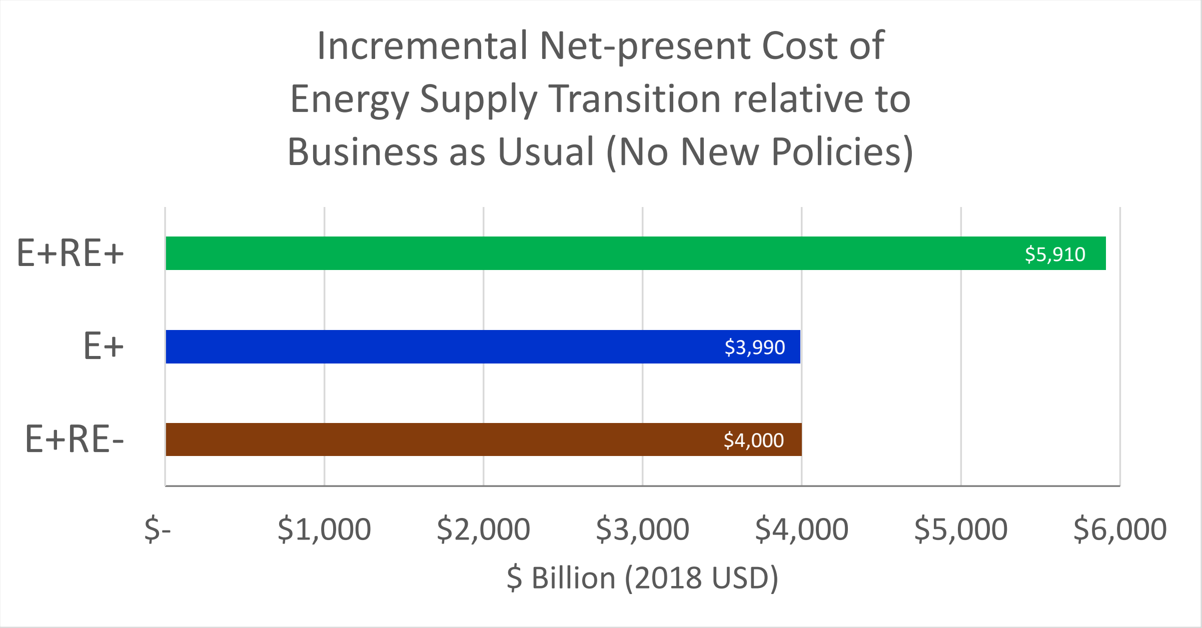

Figure 10 The net-present cost of future energy supplies including capital investments, operating, maintenance, and fuel costs in E+RE+, E+ and E+RE- over and above a no-new-policies reference case from Princeton's NZA study. [72]

A second economic metric that is reported in this study is the annualized cost of energy services over time, represented as a percentage of GDP. Figure 11 shows the scenarios tracking quite closely through 2035 and then beginning to diverge, with the 100% renewable energy pathway diverging quite significantly during the last decade, with annual costs of that scenario being more than a full one percent of GDP higher than the other two cases in 2050.

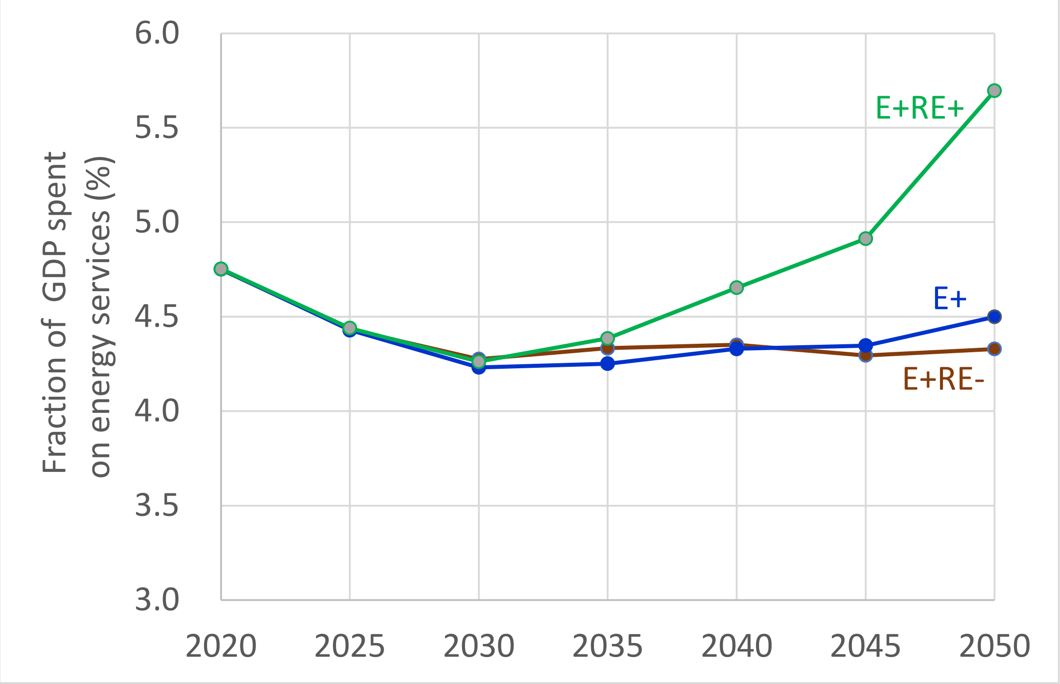

Figure 11 Annual expenditure on energy services as a percentage of GDP for the E+RE+, E+ and E+RE- pathways from Princeton's Net-Zero America study. [72]

Finally, in Figure 12, we illustrate a third economic metric extracted from the Net-Zero America study being the mobilization of capital. Deep decarbonization pathways (especially those that involve increased renewables) are fundamentally capital intensive, with fuel and operating costs being traded for higher (upfront) system capital costs over time. Accordingly, a key benefit of most deep decarbonization pathways is a shift away from a dependence on fossil fuels and their ongoing costs (and historical price volatility), to essentially zero marginal cost renewable resources. Notwithstanding such benefits, the challenges associated with the rapid mobilization of large sums of risk-capital implied in net-zero transitions, should not be taken for granted.

Error! Reference source not found. shows the very significant differences in capital intensity and in particular the much larger capital demands for the 100% renewables scenario being 3.5 to 4.1 trillion USD higher in 2050, compared to the two NZE scenarios which allow CCS.

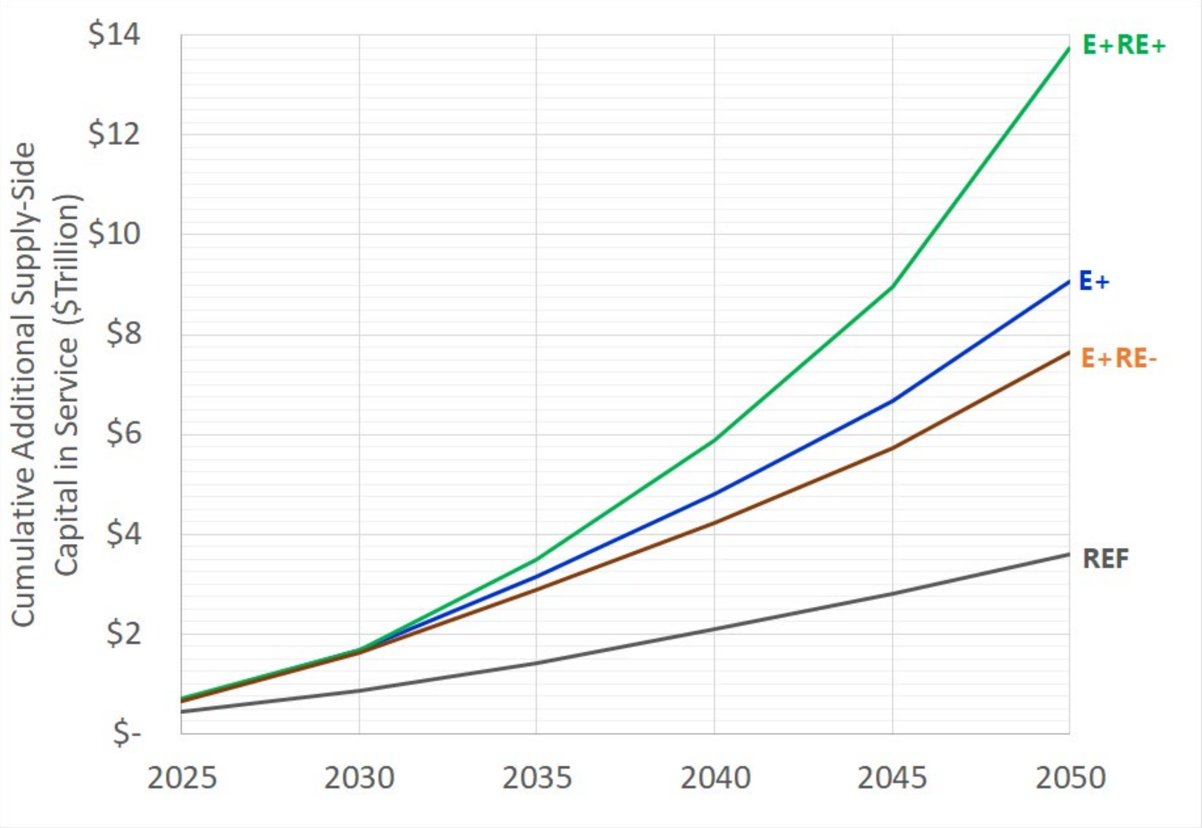

Figure 12 Cumulative supply-side investment capital in service over time for the E+RE+, E+ and E+RE- pathways relative to a reference (no new policies) case from Princeton's Net-Zero America study. [72]

Note: Supply-side capital includes plant and infrastructure investments in electricity generation, transmission & distribution; fuels production; and CO_2 capture utilization and storage. Excludes investments in demand-side transport, buildings and industry; fuels distribution infrastructure; biomass crop establishment; and land sink enhancements. Capital costs also exclude the at-risk pre-investment expenditure on feasibility studies, contract formation, permitting and financing.

5.3.3 Environmental domain

A key characteristic of all Net-Zero America scenarios is an increase in land-use intensity with increasing dependence on resources having a lower energy density than fossil fuels or uranium. Unsurprisingly all of the net-zero scenarios involve the deployment of wind and solar generation along with transmission at sustained annual build rates ranging from the national historical maximum in E+RE-, to as much as 10 times that historical maximum in E+RE+.

Figure 13 illustrates the sharp contrast in the spatial extent of wind and solar electricity generation and transmission assets in the three pathways to NZE.

The implications of NZE energy transitions in respect of the erosion of natural capital values could span, without limitation: land and ocean resources; visual amenity; biodiversity; and potential impacts on migratory birds. [74] Beyond these somewhat obvious impacts are a range of other impacts on natural resources which typically receive much less attention, e.g.:

(i) Extraction of minerals and impacts of secondary processing of such minerals to produce the metals needed for renewables-heavy transitions of such grand scale; and

(ii) Increased requirements for end-of-life disposal and recycling of materials resulting from the deployment of solar PV and wind technologies which have lower capacity factors by virtue of their weather dependence, and shorter operating lives than traditional thermal energy technologies.

Our purpose is not to suggest that CCUS technologies are themselves without potential adverse environmental impacts. For example, in the case of CCUS there is a risk that CO_2 leakage from geologic storage could contaminate adjacent aquifers[7], [75] or that continuing injection under pressure could induce micro-seismicity. [77] Indeed, all energy generation and utilization assets come with their own specific impacts. Such is the nature of trade-offs in tackling climate change. Our purpose here, is to draw attention to the need for a broader and deeper consideration of the environmental domain when valuing alternative mitigation technology options, as impacts in this domain could compromise the feasibility of those lowest-cost energy transition pathways.

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[7] Notwithstanding these risks, the likelihood of significant consequential leakage is estimated to be low for sites that have been properly characterized and for which injection operations and monitoring are well regulated. [76]

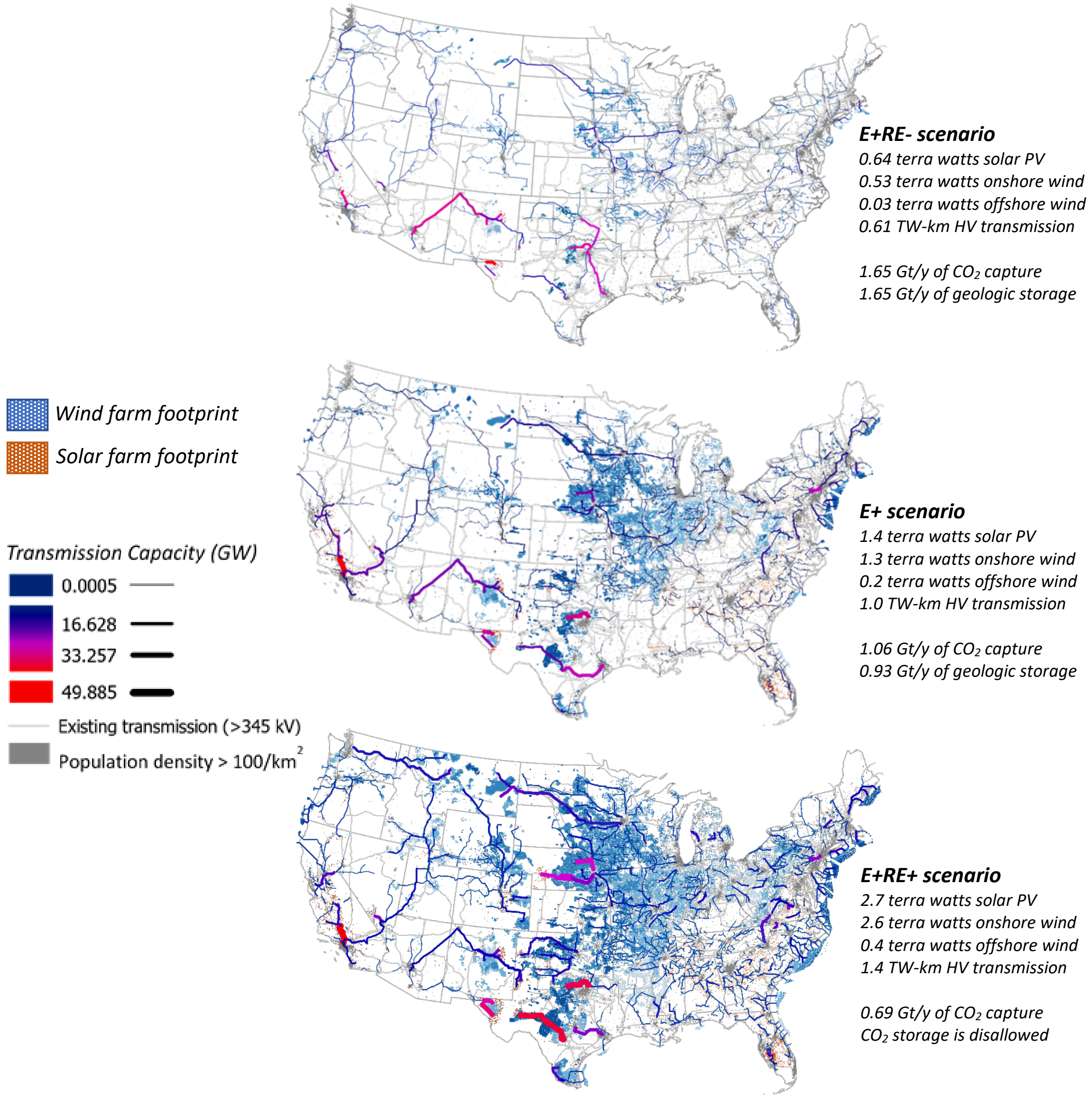

Figure 13 Spatial representation of cumulative wind and solar generation assets and long-distance high-voltage transmission infrastructure in 2050 in three Net-Zero America [72] pathways.

From top to bottom the scenarios represented are E+RE-, E+ and E+RE+.

5.3.4 Human and social domain

The study estimated direct labor requirements across the value chain including manufacturing, engineering, construction and installation, and ongoing operations and maintenance. A key characteristic of all Net-Zero America scenarios is an increase in energy sector employment relative to business as usual. At face value this is good news from a human and social perspective, but when examined at a greater level of sectoral, spatial and temporal resolution, the human and social benefits and costs and the scale of the labor mobilization challenge are found to be quite heterogenous.

Figure 14 illustrates the variation in employment across the same three scenarios considered in section 5.3.1. The graph clearly illustrates the differential job gains and losses across different sectors, with very strong demand for new employment in the all-renewable scenario, but more than twice as many jobs being lost in the fossil fuel sectors in that same scenario.

This graph also illustrates the scale of the differential challenge to mobilize talent in the all-renewables scenario, a challenge that could potentially represent a bottleneck which slows progress and delays the achievement of emissions reduction commitments.

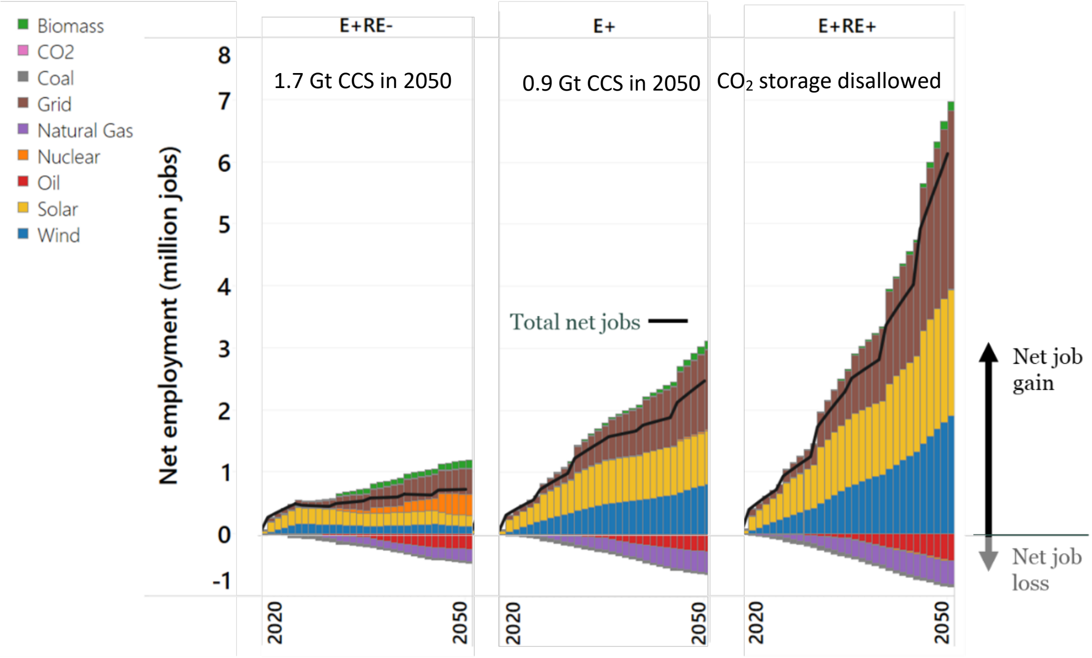

Figure 14 Sectoral disaggregation of increase and decrease in jobs for E+RE-, E+ and E+RE+ scenarios in the Net-Zero America study [72].

The graphs indicate twice as many jobs lost in the fossil fuel sectors for E+RE+ versus E+RE-.

Figure 15 illustrates the regional variation in employment across the central scenario (E+) illustrated in Figure 14. The diagram shows the potential for social inequities with significant job losses possible in at least one decade in multiple states. The decadal timesteps are color coded red to reflect a >15% decline in energy sector jobs; green to reflect a >15% increase on energy sector jobs; and yellow to reflect a change in either direction of ≤15%. The representation is coarse across time scales and spatial dimensions with the result that this graphical representation may obscure quite serious and short-term local concerns.

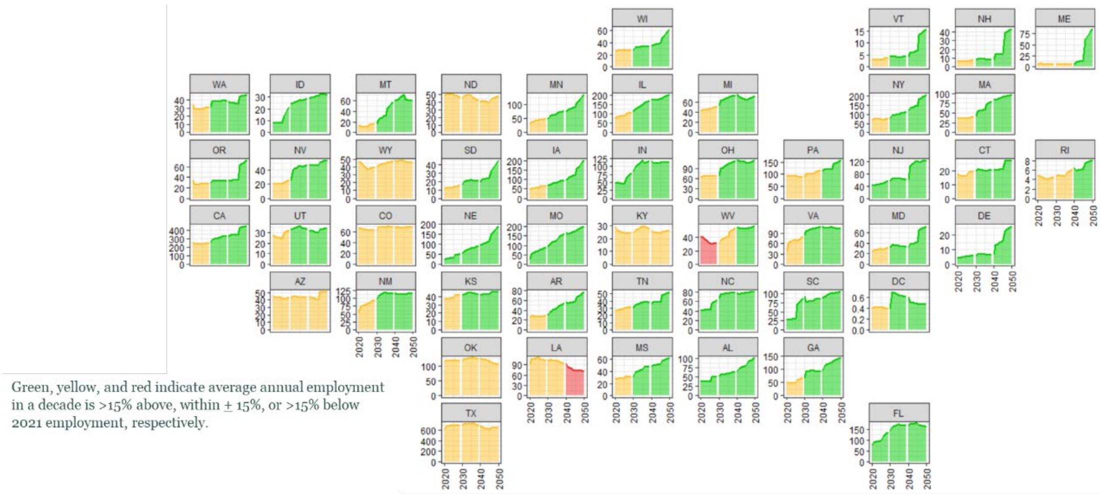

Figure 15 Spatial disaggregation of employment across different states highlights the challenges for states with historical dependence on fossil fuels which don't benefit from growth in renewable energy related activities such as Louisana, Wyoming, West Virgina, and North Dakota, in the Net-Zero America study [72].

6 Decision framework for assessing the value of CCUS

The Net-Zero America study provided a comprehensive, quantitative analysis of energy transitions, revealing new insights about scale and pace demands, ‘real-world’ execution challenges, and the potential for CCUS to enhance energy transition feasibility across multiple domains. The kind of analysis represented in (notably) that study – but also the previous sectoral-specific techno-economic and global IAM research – typically involves many person-years of sophisticated work and the application of complex models and algorithms. Policymakers, however, are often in search of higher level ‘scoping’ assessments which can inform policy objectives and support decisions related to research, development and demonstration investments, as well as new clean energy- and climate-related laws, regulations, and incentives. These objectives are often not built on a solid technical foundation, as they aim to achieve incremental policy (and political) progress.

In this section, we introduce a decision framework to assist policymakers make such high-level assessments at national or subnational scales. A similar version of this framework has previously been applied by the authors to CO_2 removal technologies. [**Error! Reference source not found.**] The framework offers a methodological approach for screening the potential value of CCUS in achieving mitigation goals across multiple domains, represented by a broad cross-section of semi-quantitative metrics. We apply the framework to case studies, including the US, UK, Indonesia, Australia, and Japan.

6.1 Overview of the framework

The 2x2 framework is presented in Figure 16, below. The horizontal “zero-carbon availability” axis indicates the relative availability of socio-technically feasible zero-carbon mitigation options to satisfy energy demands and achieve ambitious mitigation goals. Zero-carbon options include: wind; solar; hydro; nuclear; and geothermal power. The horizontal axis ranges (left-to-right) from scarcity (0.1) to adequacy (1) to abundance (10), with scarcity signaling the potential for CCUS deployment to be a robust, valuable mitigation option across multiple domains for achieving stated mitigation goals.

The vertical “benefit-cost” axis indicates the relative benefits versus costs of CCUS deployment in the specific country or subnational location of interest. Benefits are determined by the anticipated effect of CCUS deployment on a number of criteria, including: energy (both electricity and fuels) security; electricity service performance; social and equity outcomes connected with declining employment in fossil-fuel reliant sectors, and in fossil fuel producing regions; mitigation needs including the existence of limited-age carbon-intensive assets and/or the hard-to-mitigate emissions from industrial production for which CCUS is currently considered the only technically feasible mitigation option; and fiscal revenue linked, for example, to declining exports of fossil fuels. The cost metric represents an assessment of the overall CCS value chain costs especially around the proximity to, and quality of, geologic storage resources.[8] In our analysis it is not necessary for the country to have proven and prospective CO_2 storage reserves in close proximity to emissions sources. Rather, the absence of proximal CO_2 storage means the CCS value chain is characterized by high cost transport and storage options involving international shipping or pipeline transfers of CO_2 to regions with abundant storage, or CO_2 utilization to store the carbon in long-lived products. The vertical axis ranges (top-to-bottom) from net benefit (10) to neutral (1) to net cost (0.1): with net-benefit signaling the potential for CCUS to offer a valuable, economically beneficial, and socially just option for achieving mitigation goals combined with lower costs of implementing CCUS; and net-cost signaling limited benefits offered by CCUS combined with higher costs of implementing CCUS.

Overall, the framework offers a high-level screening methodology for policymakers to assess whether CCUS deployment *could* be a valuable option to deploy to achieve mitigation goals. Below, we apply this framework to a variety of case studies. These applications are illustrative only; and we note that the underlying metrics could be defined with more rigor if desired.

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[8] For the purpose of this framework we assume that CCUS siting and CO_2 geologic storage are well-vetted and meet high environmental standards, and so direct environmental impacts from projects would be minimal. We note that, in the case of BECCS, this assumption would need to be revised (and the potential for environmental impacts incorporated into the framework), given the potential for land, water, and biodiversity impacts from large-scale energy crops. For further information on incorporating BECCS into the framework, see [78].

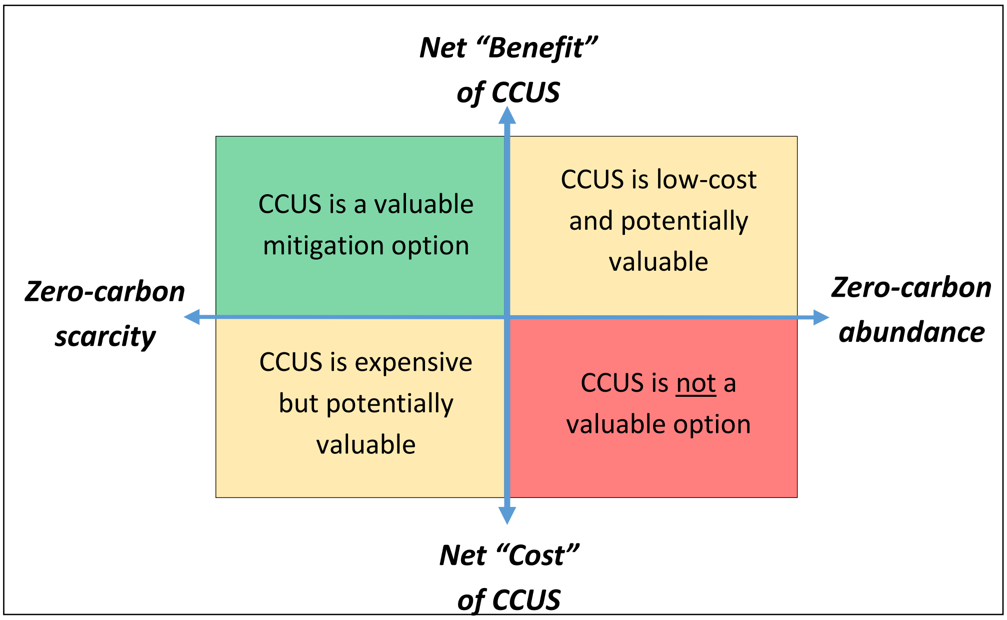


Figure 16: 2x2 decision matrix for assessing CCUS value.

Assessments are made on a jurisdictional basis. In the event that a jurisdiction has zero-carbon scarcity (i.e. low socio-technical capability to deploy the alternative zero-carbon mitigation options, including wind; solar; nuclear; hydro; and geothermal power), and that CCUS deployment would likely result in a net benefit (i.e. combination of high benefits: e.g. avoided job losses/job creation; mitigation; fiscal revenue; and low deployment costs), then CCUS is screened as a valuable mitigation option to help achieve time-bound mitigation goals.

The horizontal zero-carbon availability axis is plotted on a logarithmic scale ranging (left-to-right) from 0.1 (scarcity), 1 (adequacy), and 10 (abundance) of socio-technically feasible zero-carbon mitigation options.

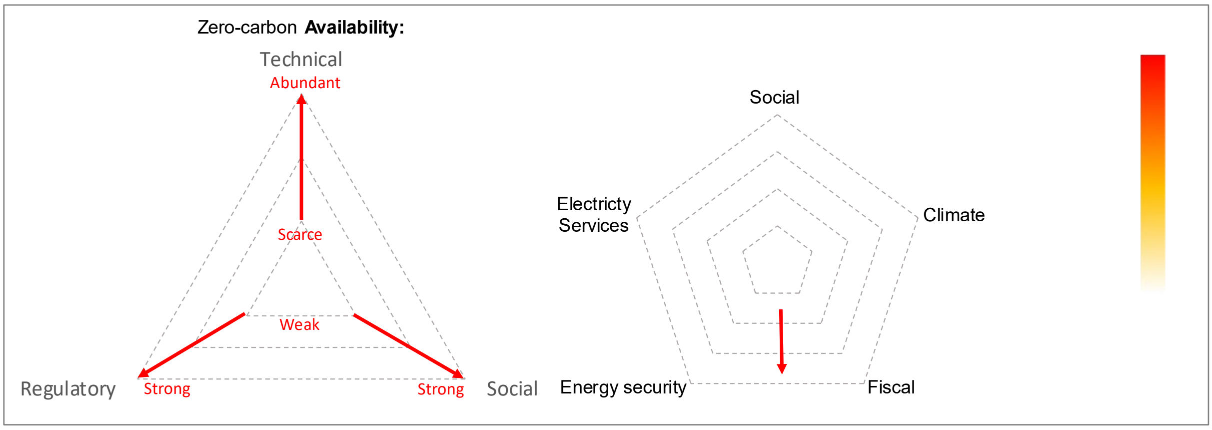
The vertical CCUS benefits/cost axis: Benefits are determined using a qualitative judgement/expert elicitation of by the anticipated effect of CCUS deployment on a number of variables, including: energy security; electricity service performance; social outcomes; mitigation potential; and fiscal measures (stranded assets & export industries). Each of the five characteristics are ranked from 0 to 1 and then added together to indicate aggregate benefits. CCUS costs are also ranked on a scale of 0.1 to 1 using expert judgement of CO_2 transport and storage cost i.e. high if low availability of suitable storage reservoirs and associated institutional capability to develop storage options which then demands very expensive CO_2 utilization or cross-border transfers (by pipe or ship) to storage sites.

The vertical CCUS benefit/cost (ratio) axis is plotted on a logarithmic scale ranging (bottom to top) from 0.1 - 1 (net cost), and 1-10 (net benefit) of deploying CCUS in the region.

6.2 Case study applications of the framework

Throughout the following sections statements are made around potential resource availability and feasibility of expansion in different countries. For details on how these assessments and judgements are made, including references to underlying source data, see Appendices A and B and the Supplementary Material.

In general, the zero-carbon availability are graphically summarized by country using radar charts in the following sections.



6.2.1 USA

Figure 17 illustrates the zero-carbon deployment capability and relative benefits/costs of CCUS for the USA. It has good renewable energy potential and the world's largest nuclear fleet, but also faces some socio-technical challenges that might limit future zero-carbon deployment capability to meet its very high national energy demand. These include but are not limited to: low new hydro power potential; high and medium social opposition respectively to new nuclear and wind power (onshore and offshore); and concerns about social opposition to new transmission line corridors to support large-scale renewables. [72] In terms of benefit-cost, it is anticipated that CCUS dep could generate a net-benefit for the US. This is driven in part by offering a just transition for a substantial oil and gas industry workforce, as well as the relatively low cost of deploying CCUS, which is supported by federal 45Q tax credit incentives and large amount of CO_2 geologic storage potential. In summary, *sub-adequate zero-carbon* options coupled with a high *net-benefit* suggests that CCUS deployment is *a valuable mitigation strategy* in the US.

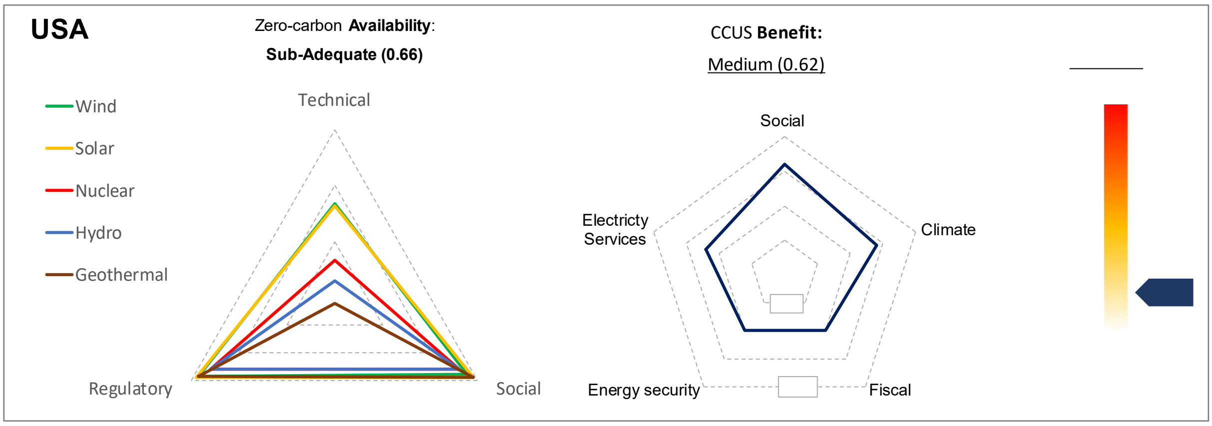


Figure 17 Representation of zero-carbon resource availability and CCUS Benefit-Cost for the USA.

Left panel: US zero-carbon availability assessment. This assessment shows that the US has sub-adequate alternative zero-carbon availability to meet their energy services demands; considering technical potential; level of regulatory ease/support; and level of social acceptance.

Right Panel: USA CCUS benefit-cost assessment. This assessment shows that CCUS deployment in the US could create medium benefits (notably: equitable transition for large oil and gas industry; high mitigation given the prevalence of hard-to-abate industrial, non-CO_2 animal agriculture, and aviation sources) at very low-cost (i.e. the US has ample, high-quality CO_2 geologic storage potential). Overall, CCUS deployment in the US is considered to offer a high net-benefit.

6.2.2 UK

Figure 18 illustrates the zero-carbon deployment capability and relative benefits/costs of CCUS for the UK. The UK has good offshore wind prospects and nuclear capabilities but faces socio-technical challenges that limit the ability zero-carbon options to meet service demands. These include: negligible new solar and hydro power potential; and only moderate social and regulatory support for these nuclear and wind technologies. Meanwhile, it is anticipated that CCUS deployment could generate a net-benefit for the UK. Again, and similar to the US this is driven in part by offering a just transition for a substantial oil and gas industry workforce, as well as the moderate cost of deploying CCUS, with significant CO_2 geologic storage potential in the North Sea. In summary, *sub-adequate zero-carbon* potential coupled with a CCUS *net-benefit* makes CCUS deployment a *valuable mitigation strategy* in the UK.

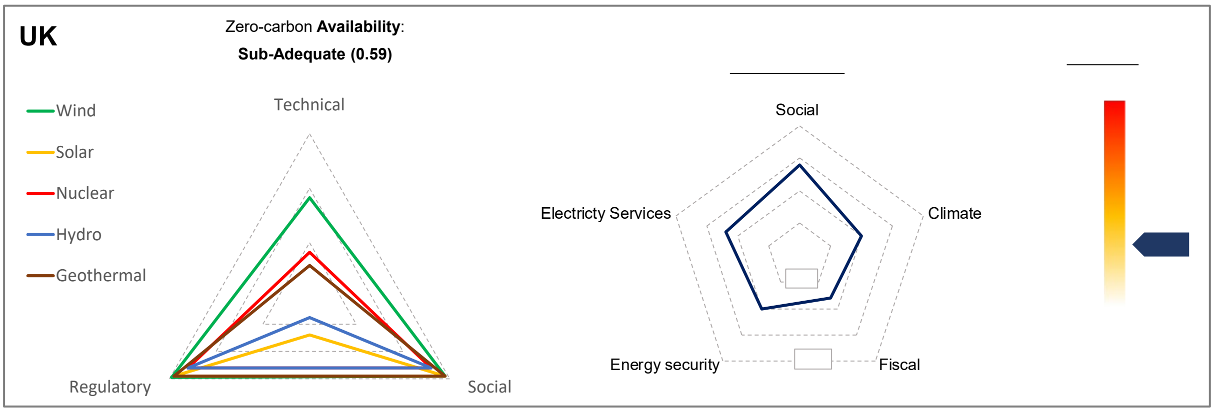


Figure 18 Representation of zero-carbon resource availability and CCUS Benefit-Cost for the UK.

Left panel: UK zero-carbon availability assessment. This assessment shows that the UK has sub-adequate alternative zero-carbon availability to meet their energy services demands; considering technical potential; level of regulatory ease/support; and level of social acceptance.

Right panel: UK CCUS benefit-cost assessment. This assessment shows that CCUS deployment in the UK could create medium benefits (notably: equitable transition for large oil and gas industry) at relatively low-cost (i.e. the UK has a decent amount high-quality CO_2 storage potential). Overall, CCUS deployment in the UK is considered to offer a net-benefit.

6.2.3 Indonesia

Figure 19 illustrates the zero-carbon deployment capability and relative benefits/costs of CCUS for Indonesia. Indonesia also faces some socio-technical challenges that create zero-carbon scarcity, including: low-to-medium wind, hydro, and nuclear power technical potential and support; low solar PV potential; and moderate geothermal potential. Indonesia could potentially benefit substantially from CCUS deployment. As a developing country with high dependence on coal production and exports, and a significant but declining oil and gas industry, CCUS could sustain and create jobs, energy security, and offer positive fiscal consequences. This benefit is partly offset by a medium cost of deploying CCUS, as Indonesia has uncertain CO_2 geologic storage potential. In summary, *zero-carbon* *scarcity* coupled with a net-benefit makes CCUS deployment *likely to be a valuable strategy* in Indonesia.

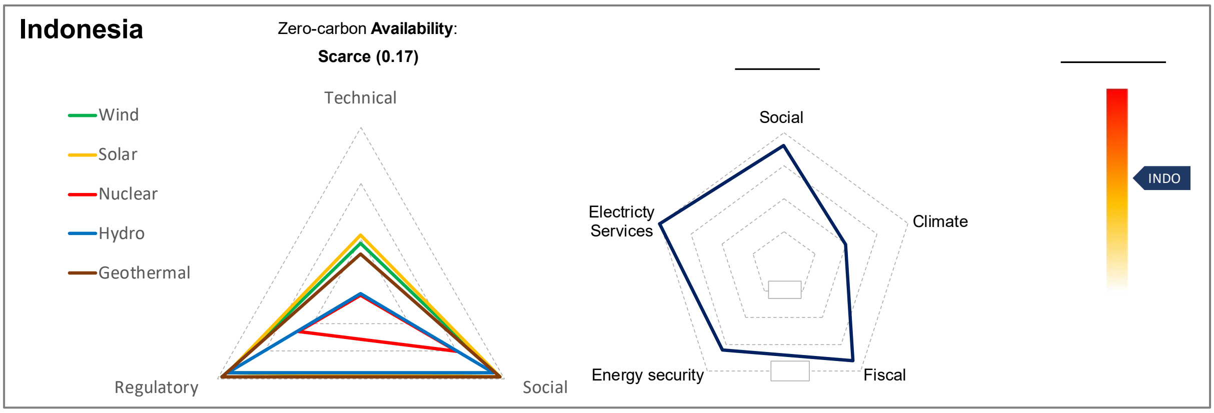


Figure 19 Representation of zero-carbon resource availability and CCUS Benefit-Cost for Indonesia.

Left panel: Indonesia zero-carbon availability assessment. This assessment shows that Indonesia has scarce alternative zero-carbon resources to meet their energy services demands; considering technical potential; level of regulatory ease/support; and level of social acceptance.

Right panel: Indonesia CCUS benefit-cost assessment. This assessment shows that CCUS deployment in Indonesia could create substantial benefits (notably equitable transition for large existing coal producing areas; fiscal benefits owing to the preservation of a primary export-base and improved energy service reliability) at medium cost (i.e. Indonesia has uncertain CO geologic storage potential). Overall, CCUS deployment in Indonesia is considered to offer a net-benefit.

6.2.4 Australia

Figure 20 illustrates the zero-carbon deployment capability and relative benefits/costs of CCUS for Australia. Australia has relatively low domestic energy demand, some of the highest solar and wind power potential in the world, and substantial land availability, creating zero-carbon abundance. In terms of benefit-cost, it is anticipated that CCUS deployment could generate a net-benefit for Australia. Similar to the US, this is driven in part by CCUS offering a just transition for the coal and gas industry, as well as fiscal benefits that could continue to accrue to Australia, owing to a large fossil fuels export-base into the Asia-Pacific region. In summary, *zero-carbon abundance* coupled with a *net-benefit* means CCUS deployment *may be a valuable* mitigation strategy in Australia.

Figure 21 the zero-carbon deployment capability and relative benefits/costs of CCUS for Australia, with four-times the final energy demand. This reflects the opportunity for Australia to help meet future clean energy needs of some of its trading partners that are anticipated to be facing zero-carbon scarcity (e.g. Japan). Even after expanding energy demand in this way, Australia's substantial wind and solar resource potential still results in zero-carbon abundance under the assessment framework, and CCUS deployment *may be a valuable* mitigation strategy in Australia.

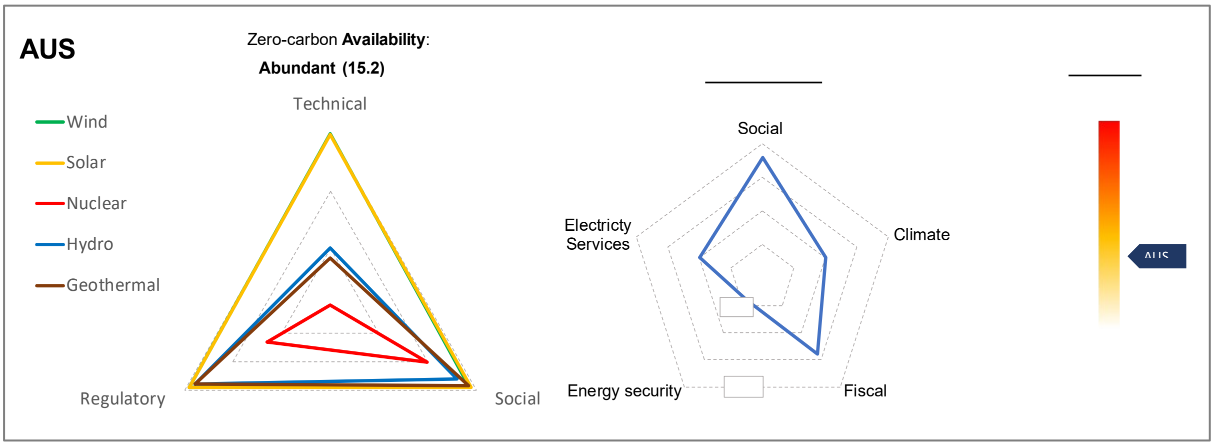


Figure 20 Representation of zero-carbon resource availability and CCUS Benefit-Cost for Australia (domestic energy services)

Left panel: Australia zero-carbon availability assessment This assessment shows that Australia has abundant alternative zero-carbon resources to meet their energy services demands; considering technical potential; level of regulatory ease/support; and level of social acceptance.

Right panel: Australia CCUS benefit-cost assessment. This assessment shows that CCUS deployment in Australia could create medium benefits (notably: equitable transition for large existing coal, oil and gas industries; fiscal benefits owing to the preservation of a primary export-base) at low-medium cost (i.e. Australia has decent CO_2 geologic storage potential). Overall, CCUS deployment in Australia is considered to offer a net-benefit.

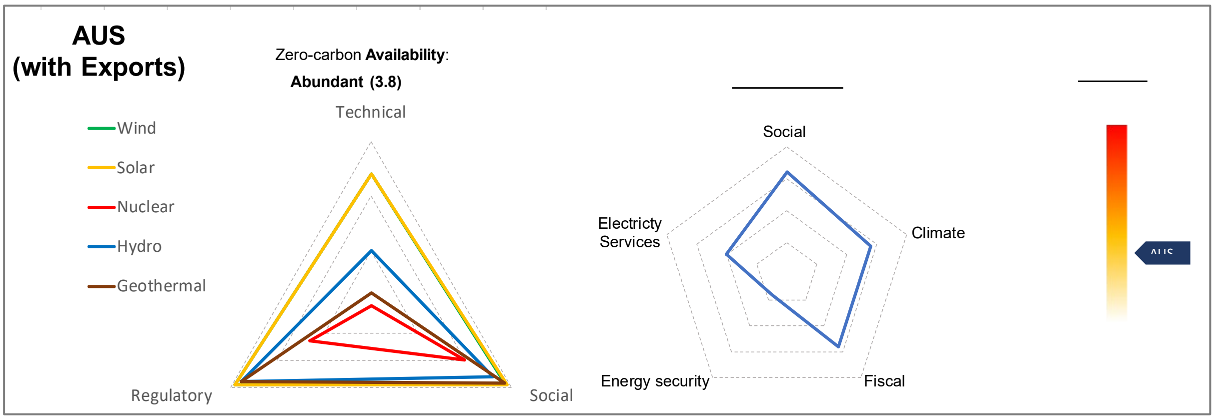


Figure 21 Representation of zero-carbon resource availability and CCUS Benefit-Cost for Australia (including low-carbon exports to substitute existing fossil energy exports)

Left panel: Australia zero-carbon availability assessment This assessment shows that Australia still has (albeit less) abundant alternative zero-carbon resources to meet their energy services demands and produce low-carbon substitutes for its fossil energy exports; considering technical potential; level of regulatory ease/support; and level of social acceptance.

Right panel: Australia CCUS benefit-cost assessment. This assessment shows that CCUS deployment in Australia could create medium benefits (notably: equitable transition for large existing coal, oil and gas industries; fiscal benefits owing to the preservation of a primary export-base) at low-medium cost (i.e. Australia has decent CO_2 geologic storage potential). Overall, CCUS deployment in Australia is considered to offer a net-benefit.

6.2.5 Japan

Figure 22 illustrates the zero-carbon deployment capability and relative benefits/costs of CCUS for Japan. Japan has high mitigation ambition, having pledged NZE by 2050, but has very limited socio-technically feasible zero-carbon mitigation options. Although nuclear power was a clear option, social opposition in the wake of the Fukushima disaster in 2011 has greatly stifled the potential of new nuclear deployment, and even the restart of much of its existing fleet. Japan also has limited solar and onshore wind potential. Offshore wind may also be expensive due to the deep near-shore ocean floor in the Pacific Ocean. CCUS deployment is anticipated to generate a relative net-cost for Japan. Benefits could be extensive, with a significant scale of hard-to-abate industrial capacity (steel; cement; petrochemicals), as well as a relatively young coal and natural gas generation fleet. However, CCUS also faces much higher costs due to limited, easily -accessible local CO_2 geologic storage potential, with the likelihood of having to ship CO_2 to more prospective jurisdictions like the Middle East or Australia, or adopt expensive utilization in long-lived products. Overall, Japan is a unique global case study in that it has very limited socio-technically feasible mitigation options to achieve its goals despite its ambitious pledge to reach NZE by 2050. CCUS deployment *may still offer a valuable mitigation strategy* in Japan despite its high cost.

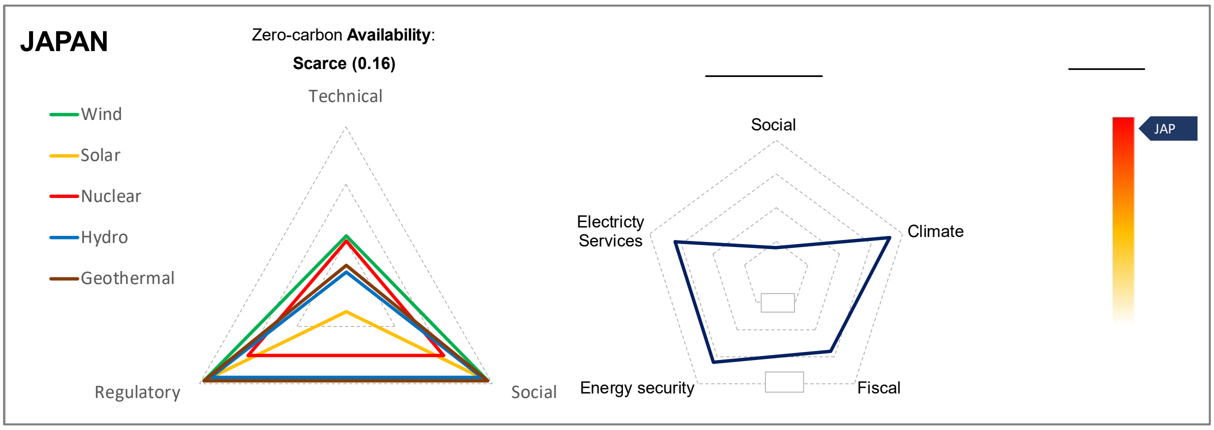


Figure 22 Representation of zero-carbon resource availability and CCUS Benefit-Cost for Japan

Left panel: Japan zero-carbon availability assessment. This assessment shows that Japan has scarce alternative zero-carbon resources to meet their energy services demands; considering technical potential; level of regulatory ease/support; and level of social acceptance.

Right panel: Japan CCUS benefit-cost assessment. This assessment shows that CCUS deployment in Japan could create some key benefits (notably: energy security and firm electricity service provision; mitigation due to large hard-to-abate industrial sectors) at very high cost (Japan has limited CO_2 geologic storage potential which is proximal to suitable storage reservoirs). Overall, CCUS deployment in Japan is considered to offer a net-cost.

6.3 Value of CCS for case-study countries

The assessments described in this section are summarized in the 2X2 CCUS value matrix in Figure 23 for the US, UK, Indonesia, Australia, and Japan. The matrix suggests that CCUS offers value as a mitigation option to each of the US, UK and Indonesia. because despite being assessed to have sub-adequate (scarce in the case of Indonesia) zero-carbon energy resources, the energy security and service, social and climate mitigation benefits coupled with low or moderate cost of CCUS presents value in the opportunity. CCUS deployment *may* also offer value as mitigation option in Australia, where it would generate a net socio-economic benefit. However, due to an abundance of alternative zero-carbon mitigation options, CCUS deployment in Australia may not be required. In Japan, a scarcity of zero-carbon energy resources means that CCUS may provide value as a mitigation option because of energy security, social and climate mitigation benefits, despite its relatively high cost.

Finally, we reiterate that the framework offers a screening methodology for policymakers to assess whether CCUS deployment *could* be a valuable option to deploy to achieve mitigation goals. The applications we have chosen are illustrative only; and we note that the underlying metrics and data analysis are somewhat subjective and could be defined and assessed with more rigor if desired.

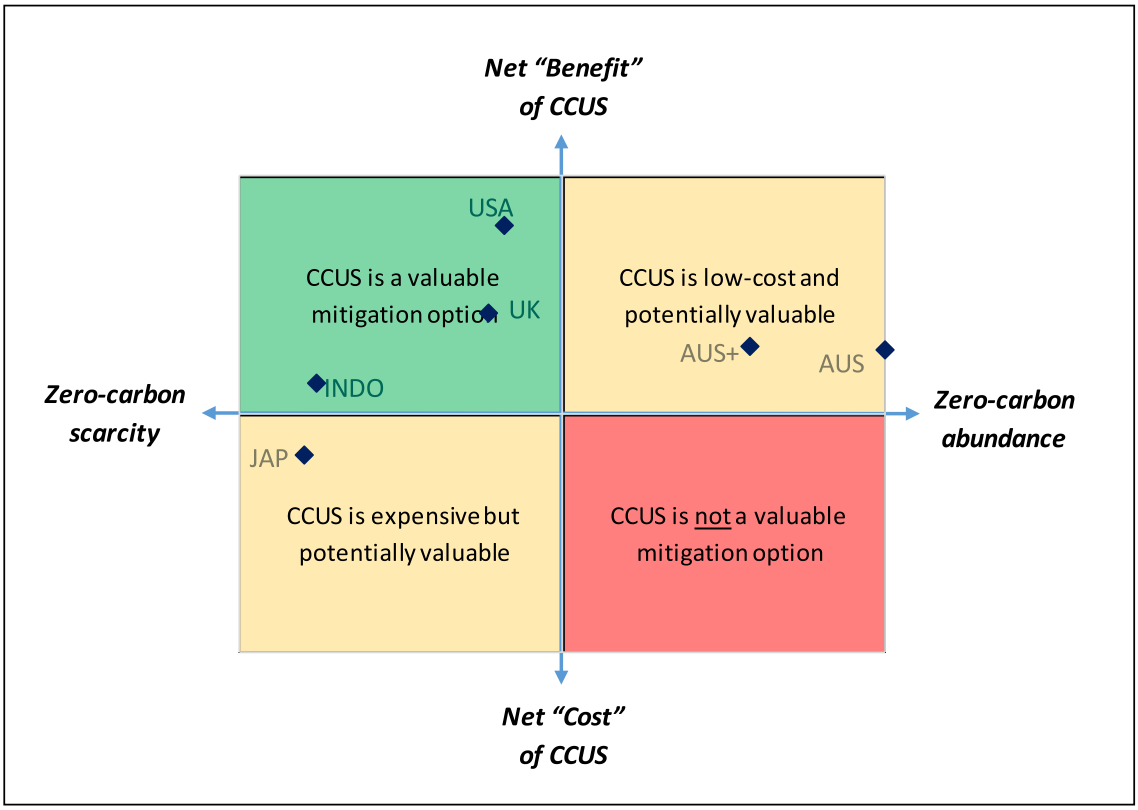


Figure 23: CCUS value matrix applied to the US, UK, Indonesia, Australia, and Japan.

The matrix suggests that each of the US, UK, and Indonesia would enhance the feasibility of clean energy transitions by deploying CCUS, which exhibits value across multiple domains. CCUS deployment may also be valuable in Australia, where it would generate a net-benefit to society. However, due to an abundance of alternative zero-carbon mitigation options, CCUS deployment in Australia may not be necessary. In Japan, notwithstanding very high costs of CCUS, CCUS may offer value to their clean energy transition, due to the scarcity of zero-carbon alternatives.

7 Conclusion and recommendations

Adoption of the Paris Agreement in 2015 served as the key catalyst behind a series of NZE pledges made by countries, states, and businesses around the world. The scale and pace of the energy transition necessary to achieve such a goal, and avoid severe climate damages, presents one of the most daunting challenges of the twenty-first century.

The energy transition problem is, while complex, in some ways a reasonably well-defined problem: there are only a handful of supply-side zero-carbon options available (i.e. wind; solar; hydro; nuclear; geothermal; bioenergy and CCUS) that can be deployed to meet future energy demand. Our interest lies in identifying the combinations of these options that can reliably achieve NZE goals by mid-century. The current main approaches to identifying these combinations have been techno-economic in nature, and aim to identify the lowest-cost combinations of options, often just for one sector. However – and one of key points we seek to communicate in this report – is that cost-optimal combinations (especially in one sector) *may not necessarily be the most feasible* for achieving economy-wide, net-zero goals. This is because feasibility depends on more than just the techno-economic domain, but also the human and social, political, and environmental domains. Therefore, it is important that we have a wider and deeper understanding of the potential *value* of mitigation options, spanning each of these domains, as a means to assess their ability to enhance energy transition feasibility.

Multi-disciplinary, value-based assessments of mitigation options and pathways is an underexplored area of the academic literature on climate change. Yet, it is increasingly important that these assessments are undertaken, as governments commit to policies and develop long-term investment agendas related to energy transitions. Under the current paradigm, there is a significant risk that these plans will be based entirely around techno-economic assessments, and aim to support single-pathway (usually relying almost exclusively on renewable power) options only. Without considering the potential value of alternative mitigation pathways across multiple domains, countries and states will be exposed to the risk of failing to achieve their mitigation goals because of unforeseen socio-technical challenges.

In this report, we explored the potential value of CCUS through this lens. Despite some dissent from academics, businesses, and policymakers, we find that CCUS does create value across multiple domains, and in some cases is likely to enhance the robustness of long-term mitigation strategies and portfolios. Notably, a recent paper by the authors [79] found that in some jurisdictions (e.g. the USA), CCS holds “threshold value” – meaning that it is an *essential mitigation technology*, without which NZE is not possible.

CCUS deployment has the potential to help overcome a number of (otherwise forthcoming) real-world execution challenges related to energy transitions, including issues of land availability; siting restrictions; social acceptance; and the potential for negative environmental impacts in the event of large-scale, 100% renewable energy deployment scenarios. We introduced a 2x2 decision framework to assist policymakers make high-level assessments regarding the value of CCUS.

We recommend that similar value-based assessments as explored in this report be extended to other countries and mitigation options, with increased rigor, and subjected to peer-review.

Although multi-disciplinary value-based assessments could be significant for helping to identify robust mitigation options and pathways, they are by no means a panacea. The threat of both known and unknown unknowns will always afflict complex problems like climate change, which are subject to deep uncertainty. For example, in the space of one-year the US evolved from being a major climate laggard into a potential global leader, and with that shift came a sudden need to ratchet up deployment rates of zero-carbon technologies. This underscores an additional value proposition associated with mitigation investment strategies that seek to expand the portfolio of mitigation options. That is, CCUS can offer value as a *real option*, even if it is not ultimately needed to achieve mitigation goals. In this context, real option means being ready for commercial deploy CCUS at scale in a short time period. That might mean investing in storage resource characterization and research, development, and demonstration to assure its readiness. In this case, CCUS has value as part of hedging strategy to expand mitigation options in the event that other options fall short of expectations, or that a nation wishes to ratchet up its level of mitigation ambition. This risk-based, decision-making under deep uncertainty approach to addressing the climate problem is another area of the academic literature that warrants further research.

8 References

1. United Nations Framework Convention on Climate Change (UNFCCC). *FCCC/CP/2015/L.9/Rev.1: Adoption of the Paris Agreement.* UNFCCC (2015).
2. Clarke, L. et al. in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer, O. et al.) Ch. 6, 413-510 (Cambridge Univ. Press, 2014).
3. Luderer, G. et al. Residual fossil CO2 emissions in 1.5-2 degrees C pathways. *Nat. Clim. Chang*. 8, 626–633 (2018).
4. Kriegler, E. et al. Short-term policies to keep the door open for Paris climate goals. *Environ. Res. Lett*. 13, 074022 (2018).
5. Minx, J. C. et al. Negative Emissions-Part 1: Research landscape and synthesis. *Environ. Res. Lett*. 13, 063001 (2018).
6. Hilaire, J. et al. Negative emissions and international climate goals-learning from and about mitigation scenarios. *Clim. Chang.* 157, 189-219 (2019).
7. Liu, P. R. & Raftery, A. E. Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 °C target. *Communications Earth & Environment* 2, 1–10 (2021).
8. Larkin, A., Kuriakose, J., Sharmina, M. & Anderson, K. What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Clim. Policy* 18, 690–714 (2018).
9. Marcucci, A., Panos, E., Kypreos, S. & Fragkos, P. Probabilistic assessment of realizing the 1.5 degrees C climate target. *Appl. Energy* 239, 239–251 (2019).
10. Holz, C., Siegel, L. S., Johnston, E., Jones, A. P. & Sterman, J. Ratcheting ambition to limit warming to 1.5 degrees C-trade-offs between emission reductions and carbon dioxide removal. *Environ. Res. Lett*. 13, 064028 (2018).
11. Benveniste, H., Boucher, O., Guivarch, C., Le Treut, H. & Criqui, P. Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: uncertainty analysis and distribution of emissions. *Environ. Res. Lett*. 13, 014022 (2018).
12. Hepburn, C. et al. The technological and economic prospects for CO_2 utilization and removal. *Nature* 575, 87-97 (2019).
13. In law: Denmark, France, New Zealand, Norway (2030), Sweden (2045), UK (2050).
14. Podesta, J., Goldfuss, C., Higgins, T. Bhattacharyya, B., Yu, A., & Costa, K. *A 100 per cent clean future* (Center for American Progress). (2019).
15. https://www.americanprogress.org/issues/green/reports/2019/10/10/475651/fact-sheet-100-percent-clean-future/.3. (2019).
16. European Commission. Climate action: 2050 long-term strategy. https://ec.europa.eu/clima/policies/strategies/2050_en.4 (2020).

17. Podesta, J. & Stern, T. A Foreign Policy for the Climate. *Foreign Affairs* (2020).
18. Krup, F., Keohane, N., & Pooley, E. Less than Zero. *Foreign Affairs* https://www.foreignaffairs.com/articles/2019-02-12/less-zero/ (2019).
19. World Economic Forum. World economic forum asks all Davos participants to set a NZE target. https://www.weforum.org/agenda/2020/01/davos-ceos-to-set-net-zero-target-2050-climate/ (2020).
20. UNFCCC. Commitments to net zero double in less than a year. https://unfccc.int/news/commitments-to-net-zero-double-in-less-than-a-year (2020).
21. Global CCS Institute. *The Value of Carbon Capture and Storage (CCS)*. (2020).
22. Rogelj, J., McCollum, D. L., Reisinger, A., Meinshausen, M. & Riahi, K. Probabilistic cost estimates for climate change mitigation. *Nature* 493, 79–83 (2013).
23. Davidson, C. L. et al. The value of CCS under current policy scenarios: NDCs and beyond. *Energy Procedia* 114, 7521–7527 (2017).
24. Vinca, A., Rottoli, M., Marangoni, G. & Tavoni, M. The role of carbon capture and storage electricity in attaining 1.5 and 2^{o}C. *Int. J. Greenh. Gas Control* 78, 148–159 (2018).
25. IEA. *Exploring Clean Energy Pathways: The role of CO2 storage*. (2019).
26. Luderer, G. et al. Residual fossil CO2 emissions in 1.5-2^{o}C pathways. *Nat. Clim. Chang.* 8, 626–633 (2018).
27. Gambhir, A., Rogelj, J., Luderer, G., Few, S. & Napp, T. Energy system changes in 1.5^{o}C, well below 2^{o}C and 2^{o}C scenarios. *Energy Strateg. Rev*. 23, 69–80 (2019).
28. IEAGHG. *CCS in Energy and Climate Scenarios*. (2019).

29. Climate Council. What is carbon capture and storage? https://www.climatecouncil.org.au/resources/what-is-carbon-capture-and-storage/ (2021).

30. IEEFA. It all comes down to costs, analysts argue: Carbon capture is simply too expensive. https://ieefa.org/it-all-comes-down-to-cost-analysts-argue-carbon-capture-simply-too-expensive/ (2019).

31. Hughes, G. *The bottomless pit: The economics of CCS* (Global Warming Policy Foundation). (2017).

32. Stephens, J.C. Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels. *Wiley Interdiscip. Rev.-Clim. Chang*. 5, 169–173 (2014).
33. Corry, O. & Riesch, H. Beyond 'For or Against' - Environmental NGO-evaluations of CCS as a climate change solution. in The Social Dynamics of Carbon Capture and Storage: Understanding CCS Representations, Governance and Innovation (eds. Markusson, N., Shackley, S. & Evar, B.) 91–108 (Routledge, 2012).

34. Ulterino, M. CCS: Sitting on the Wrong Side of Innovation. *Energy & Environment* 23, 419–424 (2012).
35. Lempert, R.J. & Schlesinger, M.E. Robust strategies for abating climate change. *Clim. Chang.* 45, 387-401 (2000).
36. Lempert, R.J., Schlesinger, M.E. & Bankes, S.C. When we don't know the costs or the benefits: Adaptive strategies for abating climate change. *Clim. Chang.* 33, 235–274 (1996).
37. Haasnoot, M., Kwakkel, J.H., Walker, W.E. & ter Maat, J. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Glob. Env. Chang.* 23, 485-498 (2013).
38. Sepulveda, N. A., Jenkins J.D., de Sisternes, F.J, Lestor, R. K. The role of firm low-carbon electricity resources in deep decarbonization of power generation. *Joule* 2, 2403-2420. (2018).
39. Boston, A., Bongers, G., Byrom, S. and Bongers, N. *The Lowest Total System Cost NEM – the impact of constraints* (Gamma Energy Technology P/L). (2020).
40. Heuberger, C.F., Staffell, I. Shah, N., and Mac Dowell, N. Quantifying the value of CCS for the future electricity system. *Energy Environ. Sci.* 8, 2497-2510 (2016).
41. Mac Dowell, N., Heuberger, C.F., Staffell, I., Shah, N. *Valuing flexibility of CCS power plants* (IEAGHG). (2017).
42. Lipponen, J., McCulloch, S., Keeling, S., Stanley, T., Berghout, N. & Berly, T. The politics of large-scale CCS deployment. *Energy Procedia* 114, 7581-7595 (2017).
43. Andreas, J.-J., Serdoner, A. & Whiriskey, K. *An Industry's Guide to Climate Action* (Bellona Europa). (2018).
44. Rissman, J. et al. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *App. Energ.* 266, 114848 (2020).
45. Bataille, C.G.F. Physical and policy pathways to NZE industry. *Wiley Interdiscip. Rev.-Clim. Chang.* 11, e633 (2020).
46. IEA. *Transforming Industry through CCUS*. (2019).
47. Psarras, P.C., Comello, S., Bains, P., Charoensawadpong, P., Reichelstein, S. & Wilcox, J. Carbon Capture and Utilization in the Industrial Sector. *Env. Sci. & Tech.* 51, 11440-11449 (2017).
48. Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A. & Zhang, Q. Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. *Journal of Cleaner Production* 163, 84-98 (2017).
49. World Steel Association. *2020 World Steel in Figures*. (2020).
50. Dewald, U. & Achternbosch, M. Why more sustainable cements failed so far? Disruptive innovations and their barriers in a basic industry. *Environ. Innov. Soc. Trans.* 19, 15–30 (2016).

51. Krey, V., Luderer, G., Clarke, L. & Kriegler, E. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Clim. Chang.* 123, 369-382 (2014).
52. Riahi, K. et al. Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* 90, 8–23 (2015).
53. Muratori, M. et al. Carbon capture and storage across fuels and sectors in energy system transformation pathways. *Int. J. Greenh. Gas Control* 57, 34–41 (2015).
54. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change-Human Policy Dimens*. 42, 153–168 (2017).
55. Intergovernmental Panel on Climate Change (IPCC). *Special Report on Global Warming of 1.5°C.* (2018).
56. Bouckaert, S. et al. Net-zero by 2050: A roadmap for the global energy sector (International Energy Agency (IEA)). (2021).
57. Lane, J.L., Greig, C. and Garnett, A.J., Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nat. Clim. Chang.* https://doi.org/10.1038/s41558-021-01175-7.
58. Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* 573, 357-363 (2019).
59. Obsersteiner, M. et al. How to spend a dwindling greenhouse gas budget. *Nat. Clim. Change* 8, 7-10 (2018).
60. Davis, S.J. et al. Net-zero emissions energy systems. *Science* 360, eaas9793 (2018).
61. Ahmed, J. et al. *Agriculture and climate change* (McKinsey & Company). (2020).
62. Baker, S. et al. *Getting to neutral: options for negative carbon emissions in California* (Lawrence Livermore National Laboratory). (2020).
63. Fuhrman, J. et al. Food–energy–water implications of negative emissions technologies in a +1.5°C future. *Nat. Clim. Chang.* 10, 920–927 (2020)
64. Smith, P. et al. Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Chang.* 6, 42–50 (2016).
65. Geels, F.W., Sovacool, B.K., Schwanen, T. & Sorrell, S. Socio-technical transitions for deep decarbonization. *Science* 357, 1242-1244 (2017).
66. Patterson, J.J. et al. Political feasibility of 1.5°C societal transformations: the role of justice. *Current Opinion in Environmental Sustainability* 31, 1-9 (2018).
67. Griggs, D. et al. Sustainable development goals for people and planet. *Nature* 495, 305–307 (2013).
68. Garrett-Peltier, H. Green versus brown: Comparing employment impacts of energy efficiency, renewable energy and fossil fuels using an input-output model. *Economic Modelling* 61, 439-447 (2017).

69. Patrizio, P. et al. Reducing US coal emissions can boost employment. *Joule* 2, 2633-2648 (2018).
70. King, B., Herndon, W., Larsen, J., and Hiltbrand, G. *Opportunities for Advancing Industrial Carbon Capture* (Rhodium Group). (2020).
71. Patrizio, P., Pratama, Y. W. & Mac Dowell, N. Socially equitable energy system transitions. *Joule* 4, 1700-1713 (2020).
72. E. Larson, et al. *Net-Zero America: Potential Pathways, Infrastructure, and Impacts (interim report)* (Princeton University). (2020). Report, annexes, and data downloadable at https://netzeroamerica.princeton.edu/
73. EIA. https://www.eia.gov/outlooks/aeo/. (2019).
74. Rehbein, J.A. et al. Renewable energy development threatens many globally important biodiversity areas. *Global Change Biology* 26, 3040-3051 (2020).
75. Koornneef, J., Ramirez, A., Turkenburg, W. and Faaij, A. The environmental impact and risk assessment of CO_2 capture, transport and storage – An evaluation of the knowledge base. *Progress in Energy and Combustion Science* 38, 62-86 (2012).
76. Alcalde, J., Flude, S., Wilkinson, M. et al. Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications* 9, 2201 (2018).
77. Vilarrasa, V., Carrera, J., Olivella, S., Rutqvist, J., and Laloui, L.: Induced seismicity in geologic carbon storage, *Solid Earth*, 10, 871–892, https://doi.org/10.5194/se-10-871-2019, 2019. (2019)
78. Uden., Dargusch, P. & Greig, C. et al., Cutting through the noise on negative emissions, Joule, https://doi.org/10.1016/j.joule.2021.06.013, (2021)
79. Greig, C. and Uden, S. The value of CCUS in transitions to net-zero emissions. The Electricity Journal 34, https://doi.org/10.1016/j.tej.2021.107004 (2021)

Appendix A: Zero-carbon availability assessment[9]

Methodology Overview

see Supp. Info. for details: Greig 2021-IEAGHG-Value of CCUS-Supplementary Information

The zero-carbon availability was assessed as follows for each case study country.

Obtain final energy consumption

1. Final energy demand (for 2018) was extracted from IEA data. Final energy demand was selected as opposed to primary energy demand to reflect the significant reduction in combustion losses associated with zero-carbon alternatives.

Evaluate the practicable annual generation capacity

2. For wind and solar, using literature sources and adjusting for land-use conflict, typical siting restrictions, and comparing with Net-Zero America 100% Renewable scenario (E+RE+).
3. For nuclear, consider historic trends in installed capacity and generation plus a qualitative assessment of the current social and regulatory environment to assess the potential future role for nuclear. e.g. for the countries in this study, use maximum historical generation to define total potential, assuming that during the next 30 years, nations could potentially replace retiring assets, and/or for example, in the case of Japan, restart existing facilities that have been mothballed since Fukushima. In China, we would assume that there is the potential to expand the fleet at the current trend.
4. For hydro, historical maximum installed capacities and annual generation are assumed in view of growing socio-political opposition to the development of new large-scale hydro schemes.
5. For geothermal, a literature review yielded the 'measured' geothermal energy resource (or in some cases reserves) of different nations. This was translated to a potential installed capacity and annual generation potential.

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[9] This appendix contains a high-level summary description of methodology and results tables only. For underlying source data, see the Supplementary Materials excel spreadsheet: ***Greig 2021-IEAGHG-Value of CCUS-Supplementary Information***

Normalize zero-carbon generation potential to final energy demand

6. This provides a measure of the potential of a particular zero-carbon energy resource to meet the national demand. Note that a second case study was run for Australia in which existing fossil energy exports are displaced with clean hydrogen derived from zero-carbon energy sources (effectively multiplying the national demand times four.

Adjust normalized potential to account for social and regulatory support

7. Social acceptance was based on a qualitative rank from 0 (strong opposition) to 1 (strong acceptance), based on a combination of available literature, expert judgement and elicitation of the views of industry and academic peers, with knowledge of the country.
8. Regulatory ease was based on a qualitative rank from 0 (legislated prohibition) to 1 (highly supportive regulatory environment), based on a combination of available literature, expert judgement and elicitation of the views of industry and academic peers, with knowledge of the country.

Calculate Relative Abundance metric

9. The product of demand normalized generation potential x min(social acceptance factor, regulatory ease factor). We use the minimum of these factors to reflect that that likelihood that deployment might be constrained by the most binding constraint.
10. Rank from 0.1 (Scarcity) to 10 (Abundance) as per Table A1. Where a value is greater less than 0.1 it is given a rank of 0.1 and when more than 10, it is given a rank of 10.

Table A1: Metrics to assess zero-carbon availability and scale for ranking 'Abundance' (plotted on a logarithmic scale)

Resource	**Technical**	**Social Acceptance (Likert Scale 0-1)**	**Regulatory Support / Ease (Likert Scale 0-1)**
Wind	Gross potential generation / Final energy demand	Qualitative expert judgement	Qualitative expert judgement
Solar	Gross potential generation / Final energy demand	Qualitative expert judgement	Qualitative expert judgement
Nuclear	Maximum annual generation since 2000 / Final energy demand	Qualitative expert judgement	Qualitative expert judgement
Hydro	Maximum annual generation since 2000 / Final energy demand	Qualitative expert judgement	Qualitative expert judgement

Zero-Carbon Availability Rank	
10	**Abundance**
1	**Adequacy**
0.1	**Scarcity**

Table A2: Zero-carbon availability results per country

	Final Energy Demand (A)	Gross Technical Potential (B)	Normalized Technical Potential (B)/(A) = (C)	Social Acceptance (D)	Regulatory Support / Ease (E)	Availability (C) x min(D,E) = (F)
	PWh	PWh	PWh Potential/ Final Energy Demand	Likert	Likert	
United States	18.54					Scarcity
Wind		8.80	0.47	0.6	0.7	0.28
Solar		8.07	0.44	0.8	0.8	0.35
Nuclear		0.85	0.05	0.4	0.4	0.02
Hydro		0.36	0.02	0.4	0.4	0.01
Geothermal		0.14	0.01	0.8	0.7	0.01
Total (Sum)						**0.66**
United Kingdom	1.50					Scarcity
Wind		1.00	0.67	0.8	0.9	0.53
Solar		0.00	0.00	0.8	0.8	0.00
Nuclear		0.10	0.07	0.4	0.4	0.03
Hydro		0.01	0.00	0.4	0.4	0.00
Geothermal		0.06	0.04	0.8	0.8	0.03
Total (Sum)						**0.59**
Australia	0.97					Abundance
Wind		9.90	10.21	0.7	0.8	7.15
Solar		9.75	10.06	0.8	0.8	8.04
Nuclear		0.00	-	0.1	0.02	-
Hydro		0.02	0.02	0.4	0.6	0.01
Geothermal		0.07	0.07	0.7	0.6	0.04
Total (Sum)						**15.24**
Japan	3.29					Scarcity
Wind		0.40	0.12	0.8	0.8	0.10
Solar		0.02	0.01	0.8	0.8	0.00
Nuclear		0.33	0.10	0.1	0.1	0.01
Hydro		0.09	0.03	0.6	0.6	0.02
Geothermal		0.12	0.04	0.8	0.8	0.03
Total (Sum)						**0.16**
Indonesia	1.76					Scarcity
Wind		0.15	0.09	0.8	0.6	0.05
Solar		0.21	0.12	0.8	0.6	0.07
Nuclear		0.00	-	0.1	0.1	-
Hydro		0.02	0.01	0.6	0.6	0.01
Geothermal		0.10	0.06	0.8	0.8	0.04
Total (Sum)						**0.17**
Australia**	3.88					Abundance
Wind		9.90	2.55	0.7	0.8	1.79
Solar		9.75	2.51	0.8	0.8	2.01
Nuclear		0.00	-	0.1	0.02	-
Hydro		0.02	0.01	0.4	0.6	0.00
Geothermal		0.07	0.02	0.7	0.6	0.01
Total (Sum)						**3.81**

*** Including clean energy exports*

Appendix B: CCUS benefit-cost assessment[10]

Methodology

Benefit/Cost Ratio

Whether or not CCUS offers a nation relative net-benefit or relative net-cost is determined by the ratio of Benefits/Costs, which are individually defined further below. In the 2X2 matrix, CCUS Benefit/Cost is again plotted on a logarithmic scale with values less than 1 reflecting 'net-cost' and values greater than 1 reflecting 'net-benefit'. If a value is less than 0.1 it is given a rank of 0.1 and when more than 10, it is given a rank of 10.

Benefits offered by CCUS

CCUS is assumed to be beneficial to a nation in the following circumstances:

1. **Social:** Scale of the incumbent fossil fuel extraction industry in the host country across coal, gas and oil, reflecting the economic benefit to incumbent firms, and employment and services in communities that are dependent on those extractive industries. CCUS is more valuable for countries with a large incumbent fossil fuel extraction industry.
2. **Climate Mitigation:** Scale of production of hard-to-abate sources (e.g. heavy industry, non-CO_2 emissions in the agricultural sector and some transport, namely shipping, and aviation) which have limited alternate abatement options, or rely of negative emissions to allow them to continue. CCUS is more valuable for countries with high emissions in hard-to-abate sectors.
3. **Fiscal:** Economic value of carbon intensive exports which are vulnerable if CCUS is not available (export and extraction royalties to governments), and the age of existing carbon-intensive assets which reflects a high exposure to stranding or devaluation of assets. CCUS is more vulnerable for countries with high carbon intensive exports and young carbon-intensive operating assets.
4. **Energy Security:** Abundance of indigenous low-carbon energy options which results in an inability of maintain energy independence, and/or (in the case of Japan) the restrictions in energy import options. CCUS is more valuable when zero-carbon resources are scarce.

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[10] This appendix contains a description of methodology and results tables only. For underlying source data, see the Supplementary Materials excel spreadsheet. ***Greig 2021-IEAGHG-Value of CCUS-Supplementary Information***

5. **Electricity Service:** The ability to provide reliable generation on seasonal, daily and hourly timescales to meet demand. CCUS is more valuable when zero-carbon firm generation is scarce.

Table B1: Metrics to assess CCUS *benefit*

Variable	**Metric**
Social	Size of incumbent fossil fuel extraction industry (relative to other sectors) (i.e. avoided job loss/job creation indicator)
Climate	Amount of hard-to-abate sources (i.e. industrial sources; non-CO_2 agriculture; heavy-duty transport incl. aviation and shipping) indicator
Fiscal	Size of exports of carbon-intensive products / age of fleet of emissions intensive assets (i.e. risk of stranding indicator)
Energy security	Zero-carbon resource scarcity indicator
Electricity Services	Firm zero-carbon resource scarcity indicator

Benefit Rank	
1	Very High
0.75	High
0.5	Moderate
0.25	Low
0.1	Negligible

Table B2 CCUS benefit assessment results per country

	Benefit	***Qualitative expert assessment***
United States	**Med-High**	
Social	0.8	Large oil & gas sector including upstream and downstream
Climate	0.7	Large economy with hard-to-abate industries and high climate ambition
Fiscal	0.5	Much of the carbon-intensive assets are aging so limited risk of asset stranding; but recent considerable investment in new petrochemical production
Energy security	0.5	Moderate low-carbon availability (this analysis)
Electricty Services	0.6	Low firm zero-carbon resource availability
Average	**0.62**	
United Kingdom	**Med**	
Social	0.7	Medium oil & gas sector including upstream and downstream
Climate	0.5	Medium economy with some hard-to-abate industries and high climate ambition
Fiscal	0.4	Much of the carbon-intensive assets are aging so limited risk of asset stranding
Energy security	0.5	Moderate low-carbon availability (this analysis)
Electricty Services	0.6	Low firm zero-carbon resource availability
Average	**0.54**	
Australia	**Med**	
Social	0.9	Large coal and oil & gas sector including upstream and infrastructure for seaborne trade
Climate	0.5	Medium economy with limited hard-to-abate industries and modest climate ambition
Fiscal	0.7	Much of the carbon-intensive assets are aging so limited risk of asset stranding; but high economic dependence on fossil fuel exports
Energy security	0.2	High low-carbon availability (this analysis)
Electricty Services	0.5	Mod firm zero-carbon resource availability (Snowy)
Average	**0.56**	
Japan	**High**	
Social	0.2	Limited domestic coal and oil & gas sector including upstream and downstream
Climate	0.9	Large economy with extensive hard-to-abate industries and high climate ambition
Fiscal	0.7	Significant recent investment in new and refurbished carbon-intensive industries creating stranded asset risk
Energy security	0.80	Scarce low-carbon resources (this analysis)
Electricty Services	0.8	Scarce firm low-carbon resources
Average	**0.68**	
Indonesia	**High**	
Social	0.9	Large domestic coal and oil & gas sector including upstream and downstream
Climate	0.5	Medium economy with limited hard-to-abate industries and modest climate ambition
Fiscal	0.9	Current and recent investment in carbon-intensive assets creating major risk of asset stranding; high economic dependence on fossil fuel exports
Energy security	0.8	Scarce low-carbon resources (this analysis)
Electricty Services	1	Scarce firm low-carbon resources
Average	**0.82**	
Australia**	**Med**	
Social	0.8	Large coal and oil & gas sector including upstream and infratructure for seaborne trade
Climate	0.7	Medium domestic economy with limited hard-to-abate industries and modest climate ambition; but large challenge to substutite fossil export revenues with low-carbon substitutes
Fiscal	0.7	Much of the carbon-intensive assets are aging so limited risk of asset stranding; but high economic dependence on fossil fuel exports
Energy security	0.2	High low-carbon availability (this analysis)
Electricty Services	0.5	Mod firm zero-carbon resource availability (Snowy)
Average	**0.58**	

*** Including clean energy exports*

Costs of CCUS

We propose a simple metric for cost based on the likely abundance of suitable, cost-effective CO_2 storage capacity. Storage is considered the main differentiator between countries since the capture technologies and costs are likely to be largely similar across most countries.

This is derived from expert opinion and consideration of:

(i) Historical oil and gas production being indicative of the presence of scale and quality of formations (presence of seal, porosity and permeability) and institutional capacity to characterize, develop and operate efficiently and safely;

(ii) Documented evidence of characterization of formations hosting suitable saline aquifers; and

(iii) Documented evidence of exploration of potential CO_2 storage areas and appraisal of candidate injection sites.

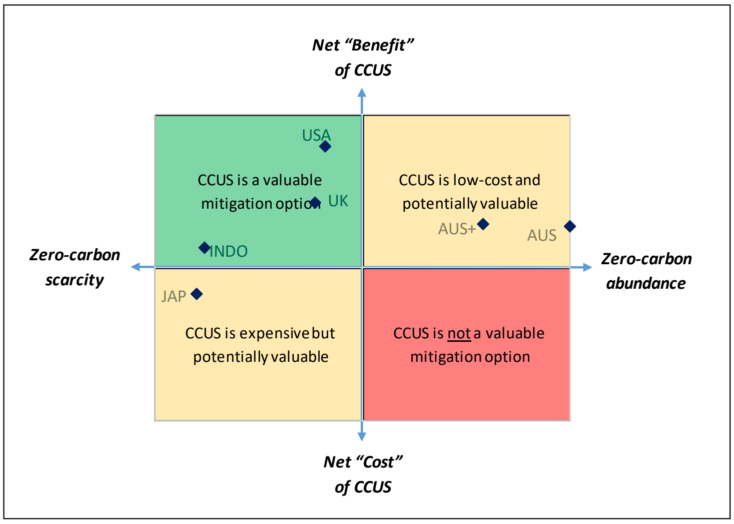
Table B3: Metrics to assess CCUS *cost*

Cost Rank		*Description*
Very Low	0.1	*Many suitable sedimentary basins across nation (onshore and offshore); high current production of conventional oil and gas; strong organizations and institutions; CO_2 characterization being advanced already*
Low	0.25	*Suitable sedimentary basins offshore or onshore; high current production of conventional oil and gas; strong organizations and institutions + CO_2 characterization underway*
Medium	0.5	*Some suitable basins; medium current production of conventional oil and gas; plus strong organizations and institutions; some CO_2 characterization*
High	0.75	*Limited knowledge of geologic formations; plus modest oil and gas production; no CO_2 characterization underway*
Very High	1	*Known to have major limitations for CO_2 storage*

Table B4 CCUS cost assessment results per country

	Cost	
United States	0.1	**Very Low**
United Kingdom	0.2	**Low**
Australia	0.3	**Low**
Japan	1	**Very High**
Indonesia	0.6	**Medium**

Appendix C: Summary of Results for Zero-Carbon Abundance and CCUS Benefit/Cost



	Zero-C Availability	CCUS Benefit/Cost
USA	0.66	6.20
UK	0.59	2.70
AU	10.00	1.87
AU+	3.81	1.93
JAP	0.16	0.68
INDO	0.17	1.37

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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