



Without mandated demand for greenhouse gas removal – High integrity GtCO₂-scale global deployment will be jeopardized: Insight from US economic policy 2020–23

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HIGHLIGHTS

- Greenhouse gas removals will be essential at GtCO₂-scale to achieve global net zero by 2050.
- While the US has expanded GGR RD&D efforts, demand-side incentives are largely lacking.
- To spur GGR deployment, policies should address systemic risks perceived by the private sector.
- These risks include uncertainty of offtake and clarity on subsidy eligibility and allocation.

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ABSTRACT

Greenhouse gas removals (GGRs) will be essential at GtCO₂-scale to offset residual emissions and achieve global net zero by 2050. Engineered GGRs have the greatest long-term, large-scale CO₂ storage potential and, therefore, offer opportunities to realize high-integrity removals. However, the most prominent engineered solutions are capital-intensive, generate expensive offset credits, and have achieved minimal market penetration. The United States has established policies subsidizing GGR deployment value chains which generate high-integrity removals to bring down engineered GGR costs. The US regime has the potential to result in substantial GGR cost reductions which will likely have implications on the policy frameworks for global GGR technology deployment. To date, research addressing the impact of US policies on the commercial imperatives and investment uncertainties for the global GGR sector is limited. Using a mixed methods approach, this contribution unpacked the motivations of early private sector actors. It did this by identifying characteristics of the most investable GGR business models and policy implementation requirements to establish the nascent sector, which will be critical to the GGR sector becoming a global multi-trillion-dollar, self-sustaining market. The analysis reveals that cost reduction alone will be insufficient to establish a high-integrity global GtCO₂-scale sector. Systemic market risks, especially certainty of offtake through demand-side incentives, need to be addressed. Therefore, the development of a stable and sustainable GGR sector, both in the US and globally, will remain problematic due to the inability to attract large-scale private capital investment.

1. Introduction

According to the Intergovernmental Panel on Climate Change's (IPCC) 6th assessment report (AR), the scale of the challenge of limiting warming to 1.5 °C translates to around 6 GtCO₂ of Greenhouse Gas Removal (GGR) per year by 2050 [1]. The remaining budget for a 50%

chance of limiting warming to this degree is only 500 GtCO₂, representing a significant gap between the current state of the GGR sector and where it needs to be by 2030 [2]. Augmenting carbon mitigation through carbon capture and storage (CCS) technologies, engineered GGR solutions have the greatest long-term, large-scale CO₂ storage potential and, therefore, generate high-integrity removals [3,4]. With only

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~2 GtCO₂ of global emissions removed annually today – 99% of which is via land-based sinks (e.g., reforestation) – engineered GGR solutions will need to scale up 30 times from current levels by 2030 and 1300 times by 2050 to keep global warming in check [5].

Currently, the market for GGRs from bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) is relatively nascent with sparse, voluntary demand from early corporate entrants and a limited project supply pipeline. Nonetheless, demand for engineered removals is projected to reach 31–623 MtCO₂ per year by 2030, equating to a total market size of \$3.6–56 billion [2]. To satisfy this projected demand and sustain the GGR market long-term, a consistent supply of high-integrity, durable removals supported by public policy and private investment will be essential in the near-term.

Despite being the most prominent engineered GGR solutions, DAC and BECCS are still expensive (DAC: \$515/tCO₂; BECCS: \$693/tCO₂) and have achieved minimal penetration in the negative emissions offset market [6,7,8]. Accordingly, the United States (US) has established policy measures to subsidize GGR technology development and expand the supply of high-integrity removals. It is anticipated that subsidies will substantially reduce the cost of GGRs making them more attractive for hard-to-abate actors and that demand for high-integrity removal offsets will be at a price that will sustain supply-side growth by crowding in capital from the private sector.¹ Private capital investment and public policy implementation will be required to maintain supply and demand in equilibrium as the market for negative emissions expands beyond first movers and government subsidies to a fully-fledged market. As GGR technologies accelerate down the cost curve, they will become more commercially viable such that more supply-side actors should enter the market. However, the majority of GGR policy intervention is supply-centric with demand-side incentives largely lacking, impacting the willingness of the private sector to invest [9]. As the extent of the US subsidies has the potential to result in substantial GGR cost reductions being realized there are likely insight and implications as to the policy and market frameworks required for GGR roll-out globally. To date, research addressing the impact of US policies on the commercial imperatives and investment uncertainties for the global GGR sector is limited.

Using a mixed methods approach, this contribution unpacked the motivations of early private sector actors by identifying characteristics of the most investable GGR business models and policy implementation requirements to establish the nascent sector, which will be critical to the GGR sector becoming a global multi-trillion-dollar, self-sustaining market. Section 2 provides a literature review and background on uncertainty in GGR technology deployment pathways, US GGR policy, and global GGR initiatives. Section 3 describes the research methods applied in the quantitative analysis and qualitative assessment to comply with the extent of uncertainty pervasive in the realization of the global GGR sector. Section 4 reviews the results of the modelling and interviews with early US GGR sector stakeholders. A discussion of the key themes and barriers to US GGR market development, the measures public and private sector actors can take to address them, and recommendations for GGR policy frameworks globally are presented in Section 5. Section 6

¹ In the context of GGR deployment, supply-side policies are those that result in the establishment of assets which generate negative emissions. Negative emissions credits generated from these assets can be sold to offset a tCO₂ that is emitted by demand-side actors (e.g., offtakers) in hard-to-abate sectors such as aviation and cement manufacturing. If the cost of negative emissions is not subsidized, demand-side offtakers will purchase fewer credits which will prevent the market from growing and GGR assets will struggle to attract capital investment. Reducing the cost of GGR and therefore the price of negative emissions credits through government subsidies – according to Keynesian economic theory – would allow more credits to be purchased and result in larger markets. Realizing economies of scale and regulating credit prices will attract more capital at a cheaper cost resulting in a virtuous circle of cheaper capital, cheaper negative emissions credits, and therefore greater demand.

concludes the work with recommendations for public and private sector actors to help realize a high-integrity GGR sector at GtCO₂-scale globally.

2. GGR technology uncertainty & policy

Net zero requires the rapid development of CCS and GGR technology [3,4]. CCS reduces CO₂ emissions at the source, thereby reducing levels of CO₂ emitted into the atmosphere. GGR technologies generate negative emissions by removing CO₂ from the atmosphere and sequestering it underground in geological storage – often via CO₂ transport networks. Both technologies are needed at GtCO₂-scale by 2050. At present there is 40 MtCO₂ per year sequestered by CCS technologies whereby the risk level is such that several of these projects having been supported by project finance [10]. In contrast to the GGR sector, all pilot plants to date have been funded off balance sheet as a function of the market being unable to accommodate the level of risk associated with these GGR projects.

This section outlines the characteristics of the GGR sector and the state of current policy to support the establishment and scaling of the sector. This has important implications on the selection of study approach as the extent of uncertainty characterized in the literature is often underestimated with the consequential implications on the policy and insight generated more broadly.

2.1. Uncertainty in GGR technology deployment pathways

Net zero pathways involve GGRs scale-up in later decades due to the extended timeline required for novel technologies to achieve learning effects and economies of scale [1]. Since 2020, the US GGR subsidy regime has sought to stimulate these learning effects – analogous to the impacts that government subsidies have stimulated across other technologies including renewables [11] and other capital-intensive energy technologies such as CCGT [12] and nuclear² [13] in order to reduce the cost of capital.

The nascent GGR sector is characterized by: (1) deep uncertainty³ as to how the GGR technology portfolio will develop & [14]; (2) the fact that CDR innovation is market led [15]; (3) that public acceptance of the large-scale deployment of these technologies is largely untested [16]; (4) that it is a highly fragmented sector whereby academia, policy makers, and market participants have little systemic visibility to enable holistic insights required to design systemic interventions [17]; and (5) that there is a need to incentivize incumbent actors to support GGR innovation who through their financial, physical, human, organisational, informational, and relational resources can be a barrier to systems change [18].

The consolidative⁴ Integrated Assessment Models that are used to

² For example, in the UK, EDF – the French utility responsible for developing both Hinkley Point C and Sizewell C – advocate that making construction more predictable cuts the cost of financing – which at Hinkley accounted for 60% of total project costs.

³ Deep uncertainty is defined as a situation where analysts do not know, or the parties to a decision cannot agree on: (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future; (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models; and/or (3) how to value the desirability of alternative outcomes. In particular, the long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences.

⁴ Consolidative models gather all relevant knowledge into a single package which projects needs based on pre-defined outcomes [32].

generate these insights assume the market operates at equilibrium to maximize utility at each point in time, neglecting the extent of uncertainty which some characterise as deep [19]. Alternatively, exploratory approaches⁵ integrate fundamental detail on scenario underpinnings defined by “large-scale (non-marginal) changes in technologies, systems, and industrial and institutional structures” [20]. Developing robust climate mitigation strategies requires exploratory approaches that integrate various values-based stakeholder perspectives. They consider several possible futures for GGR technology deployment, focusing specifically on the high dimensionality of the decision space in order to provide participants with the insight to navigate the rapidly evolving industry. It will therefore be important to apply exploratory strategic foresight principles that can manage the extent of uncertainty in different possible future system outcomes.

Value pool mapping is particularly powerful in rapidly evolving industries where new regulation and business model innovation is expected to shift the distribution of profit along value chains. The UK government was the first to employ business models as a mechanism of assessing and addressing key barriers to investment, thereby supporting a diverse range of GGR technologies [21]. Determining value pool size and business model profit potential across possible futures can assist in shaping GGR policy development, presenting a pathway for policies that effectively unlock the full potential of existing GGR business models (BM) and pave the way for the creation of new ones [22]. [23] built upon this bottom-up approach for quantifying potential opportunities for value capture among BMs in the UK, integrating the concept of deep uncertainty in technology deployment modelling.

Workman et al. [18] further applied the value pool approach to GGR development for the aviation sector in the UK, prioritizing first-mover needs and their role in realizing new CO₂ removal value chains. This work emphasized that the existing regulatory environment poses too much risk to the sector as a function of the substantive capital commitment for GGR solutions. Four measures for addressing first-mover dilemmas were presented: (1) Ensure better coordination in UK GGR policy implementation; (2) Develop monitoring, reporting, and verification (MRV) standards for negative emissions technologies; (3) Get hard-to-abate sectors on track to achieve net zero by 2050; and (4) Establish a balanced portfolio of GGR technologies in the UK.

McKinsey & Company [24] also employed the value pool approach in the Global Energy Perspective 2022 to quantify the value capture of GGR solutions, projecting new technologies will capture 65% of global investment in the energy sector to 2035. The work also recognizes deep uncertainty in the energy transition, affirming that GGR business models will likely be impacted by the shifting regulatory environment. Though strong demand is expected for GGRs due to cost reductions and mounting net zero commitments, revenue streams and policy support mechanisms to incentivize private investment in the sector will remain uncertain. In terms of EBIT growth, McKinsey & Company projects the total size of GGR value pools to quadruple by 2050, emphasizing the importance of policies that address existing business model risks, stimulate investment in various net zero solutions, and ensure a successful decarbonization strategy.

Therefore, GGR policy implementation and private investment require strategic decision-making approaches that can capture a range of future outcomes and potential trade-offs in removing atmospheric emissions. Incentivizing business model innovation and unlocking niche markets for CO₂ removal projects will be critical to accelerating GGR technology deployment. However, it is difficult to anticipate which business models will be the most desirable to investors in the future

given deep uncertainty and systemic, sector-wide risk. Considering the deep uncertainty which prevails in commercialization pathways for novel technologies as well as the compressed timeline for achieving net zero, this research will combine a quantitative business model analysis with a qualitative survey of early private sector stakeholders that will expand the GGR industry at the outset.

2.2. US GGR policy

The US has been selected as the country of focus due to its recent substantive investment in national decarbonization efforts with \$369 billion committed to energy and climate-related programs in the Inflation Reduction Act (IRA), more than any other country in the world [25]. Despite substantial oscillation in the national political landscape in recent decades, under the current administration President Joe Biden has made a strong push for national climate action.

The US took a major step towards nationwide GGR policy integration with the publication of *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* – hereto forth referred to as the US LTS – a comprehensive, long-term mitigation plan for achieving net zero by 2050 [26]. Scaling up CO₂ removal is projected to account for ~10% of projected greenhouse gas (GHG) emissions reductions with a focus on building out both land carbon sinks and engineered GGR solutions. The report is highly focused on supply-side factors for GGR scale-up and proposes investment in demonstrations of several engineered GGRs including BECCS, DACCS, enhanced mineralization, and ocean-based approaches.

The US federal government has focused more on DAC than BECCS in GGR policy implementation, allocating \$8 million and \$9 million from congressional budgets to DAC research in FY2020 and FY2021, respectively [27]. Policy intervention for DAC is well underway, yet there remains a major gap in demand-side policy intervention without any carbon pricing regulation or federal procurement program. Meanwhile, there have been no federal policies specifically focused on BECCS enacted in the US as of mid-2023 according to the Carbon180 Policy Tracker.

At the state level, the California Air Resources Board Cap-and-Trade Program [28] has established offset credits for removals that entities may purchase to meet up to 4% of their emissions compliance [29]. California also has a low-carbon fuel standard (LCFS) that sets annual carbon intensity benchmarks based on lifecycle emissions of transport fuels supplied or offered for sale in the state, allowing DAC projects to generate LCFS credits to sell to buyers that exceed the benchmark [30]. In New York, the state government has nearly passed the Carbon Dioxide Removal Leadership Act which would seek to procure an amount of removals equivalent to 10,000 tCO₂ per year, doubling every year for five years [31]. Other states in the process of developing GGR policies include New Jersey, Maryland, and Colorado – all historically liberal US states paving the way for advancing CO₂ removals at the regional level.

Together, federal and state policy mechanisms will help scale-up removals by distributing costs between the public and private sector and fostering ‘supply pull’ and ‘demand push’ dynamics for US GGR BMs. Adapted from Harvey, Workman, & Heap [32], a summary of key US policy mechanisms implemented at both the state and federal level is provided in Table 1.

Despite positive momentum in recent US GGR policy, current federal GGR investment is considered insufficient to effectively scale the sector [33]. This research will explore several possible futures for the US GGR sector that will impact the invest-ability of GGR BMs and realizability of negative emissions targets in the US leading up to the 2050 net zero target. Furthermore, the limited literature focused on US GGR sector development does not address the deep uncertainty that could alter business model profitability and investor sentiment. This research will fill the gaps in the literature by quantifying value pools for BECCS and DAC BMs in the US in several possible futures and qualitatively assessing the desirability of GGR BMs and systemic market risks perceived by

⁵ Exploratory models map assumptions onto consequences, accounting for deep uncertainty in possible policy design. Exploratory approaches accommodate that some uncertainty and actor biases need to be addressed in the decision-making process rather than defaulting to market-based, economically rational allocations which are often opaquely endogenized within a model [58].

Table 1
US GGR policy mechanisms and programs. Adapted from [32].

Program / Mechanism	Year	Department / State	Description
<i>Federal Acts</i>			
Carbon Dioxide Removal (CDR) Purchase Pilot Prize	2023	Department of Energy (DOE)	Up to \$35 million to advance technologies that reduce emissions from hard-to-abate sectors and legacy CO ₂ pollution by removing it directly from the atmosphere.
Inflation Reduction Act (IRA)	2022	–	Includes updates to the 45Q/45 V tax credit, increases credits for bioenergy (impacting BECCS) and increases spending on rural areas (impacting nature-based GGR).
CHIPS Act	2022	–	Industrial and manufacturing funding package, focused on bolstering semiconductor leadership, includes \$1 billion for GGR research, development, and demonstration (RD&D).
Infrastructure Investment and Jobs Act (IIJA)	2021	–	\$3.5 billion to develop 4 DAC hubs, \$7 billion for 7 regional clean hydrogen hubs, and additional funding for infrastructure development, such as CO ₂ transportation pipelines or injection wells.
Agriculture Improvement Act (Farm Act)	2018	–	Key mechanism for agriculture and food policy that is updated every 5 years, allocating RD&D funding through the USDA, relevant to biological GGR.
<i>Federal Policies</i>			
Carbon Negative Shot	2021	DOE	Mission to accelerate breakthroughs for GGR through RD&D support, specifically engineered methods, with a goal to achieve \$100/tCO ₂ by 2030.
Conservation Stewardship Program	2021	US Department of Agriculture (USDA)	Provides technical and financial assistance to improve grazing conditions, increase crop resiliency, and develop wildlife habitats, increasing nature-based GGR.
Environmental Quality Incentives Program	2019	USDA	Provides technical and financial assistance to agriculture producers and forest landowners. Land conservation incentives that support Afforestation and Soil Carbon Sequestration.
CarbonSAFE Initiative	2016	DOE	Initiative aims to address feasibility gaps in CCS, to identify safe storage and facilitate permitting, impacting BECCS and DAC.
45Q Carbon Tax Credit (Internal Revenue Code)	2008	Treasury	Tax credit first developed in 2008 for enhanced oil recovery (EOR) and CCS, updated in the IRA. Raised from \$50 to \$180

Table 1 (continued)

Program / Mechanism	Year	Department / State	Description
Renewable Fuel Standard	2007	Environmental Protection Agency (EPA)	per tonne for DAC and a new minimum capacity of 1000 tCO ₂ , down from 100,000 tCO ₂ , allowing small-scale developers to qualify. Created to boost renewable fuel sector with minimum standards on bio-based blends in transportation fuel. This supports biofuel and bioenergy industry, indirectly advancing BECCS and biochar.
<i>State Policies</i>			
Carbon Dioxide Removal Market Development Act	2022	California	Aims to develop and support GGR technologies. State created a combined GGR and CCS target of 20 MtCO ₂ by 2030 and 100 MtCO ₂ by 2045.
Low Carbon Fuel Standard (LCFS)	2021	California	A regional regulated market with up to \$200 per tonne available for DAC, BECCS and CCS across the country.

early private sector stakeholders.

2.3. The implications of US policy on global GGR deployment

There are 3 main geographic foci for global GGR sector establishment and scaling: the United States, United Kingdom, and European Union. The UK has invested over £20 billion over 10 years, including CCS initiatives [32] and the EU an equivalent amount in the next five years & [34]. These sums pale in comparison to recent initiatives in the US, which are almost two orders of magnitude greater, resulting in calls for the UK and EU to compete on a subsidy basis [35].

More enlightened thinking suggests that that this would be misguided for a number of reasons [36]. Firstly, the US has a large domestic market and therefore is an ideal place for technology innovation as it can sell into a largely homogenous market and therefore realize economies of scale with minimal transaction costs. Though the EU is an equivalently large market, it is much more fragmented. Secondly, expenditures on domestic innovation do not lock-in benefits to the subsidizing nation. In a globalised world, '*global innovation leads to national growth, and national innovation leads to global growth*' – i.e., GGR innovation in the US will lead to spill-over and network effects [37]; and therefore, the third consideration for the EU and UK is not how to compete on a subsidy basis but rather how to respond to the implications of the US policy interventions on the global GGR market in order to realize the global multi-GtCO₂ sector that is needed to 2050. An important question for other global actors that the analysis seeks to consider is whether the massive intervention of the US, and the likely substantial global cost reductions in GGR technology, will be sufficient to establish a high-integrity GtCO₂-scale sector, and if not what else would be required. This has not been addressed in the GGR literature, so far.

Accommodating the collective insights generated in Section 2, Table 2 summarizes the novelty of the approach that is being undertaken in this contribution and how it addresses a substantive gap in the GGR sector development literature.

Table 2

Novelty of insights being generated from this research contribution through the application of an exploratory approach relative to consolidative modelling approaches which dominate the orthodoxy.

Consolidative whole system energy modelling approaches are *not* in a position to manage the extent of deep uncertainty nor assess: (1) the role of market incentive structures, commercial imperatives, and investment uncertainties created in the development of GGR technology BMs and instead default to a least-cost optimisation convention; (2) the geopolitical and political dimensions to which net zero is subjected [38]; and (3) non-parameterizable dimensions integral to how firms respond to market signals such as investor risk appetite and market confidence, which are fundamental to GGR sector establishment and scaling which are frequently relegated to simple generic surveys (e.g., [39]). Consolidative approaches to market development tend to therefore:

- Defer to a cost-centric approach resulting in analytical underreach relative to what is likely important to technology development;
- Predict technology costs which is inherently difficult and hidden; and
- Lack systemic, bottom-up insight including the extent of investor sentiment.

The exploratory approach in this research contribution will seek to accommodate for these factors by: (1) addressing deep uncertainty, the fact that market actors lead innovation in the sector, and the lack of systemic perspective by the co-production of insight through engagement with investment and GGR actors; (2) the financialization of policy and market incentive interventions to augment engagement with market actors and investors to identify financial and non-financial barriers to GGR market development in the US including geopolitical, political implications, and the potential for global spill-overs; and (3) these in turn can be used to understand and identify the appropriate targeted innovation policy instruments such as fiscal, regulatory, or statutory interventions required to incentivize actors along the value chains to realize an economically functioning GGR market. Exploratory approaches to market development tend to therefore:

- Create decision-centric data, quantifying revenue opportunities and value capture in different possible futures including co-benefits;
- Highlight the innovation, policy, and regulatory environment required to ensure the resilience of different revenue streams and maintain investor confidence; and
- Unpack technology development uncertainty without need to understand technology/business models.

3. Methodology

This research seeks to evaluate and assess the motivations of early private market participants in the US. It does this by quantifying the profit potential of BECCS and DAC BMs in the US in three scenarios and qualitatively assessing the desirability of GGR BMs and systemic market risks perceived by early private sector stakeholders. The aim of this research is to assess the role of public policy and private capital in catalyzing the realization of high-integrity GGR projects as well as the implications and lessons for GGR roll-out globally. The research objectives are as follows:

1. Quantifying revenue potential of seven BECCS and DAC BMs across three possible scenarios in a value pool model – Sections 3.1 and 3.2;
2. Qualifying desirable BM characteristics and key market risks via interviews ($n = 12$) with early US GGR sector stakeholders and private market participants – Section 3.3; and
3. Synthesizing the findings to define risks and opportunities for both public and private sector actors to realize GGR technology scale-up to attain a multi-GtCO₂ sector globally by 2050 – Sections 4 and 5.

3.1. Value pool model

DAC and BECCS value chains and business models are of current interest to early-stage GGR technology investors. Therefore, the value pool model was constructed as a quantitative method for stress-testing business model profitability and revenue capture across three possible futures for the US GGR sector.

Projecting scenarios in decade-long intervals, the value pool model is comprised of three key components: value pools (VPs), BMs, and scenarios. Inputs to the model include scenario assumptions based on the defined narrative for the future political environment; assessed market size and carbon offset projections unique to each VP and BM; and cost estimations (i.e., revenue and expense inputs for assessing business model profit). The modelling process consisted of three steps:

1. Defining narratives for scenario development including assumptions and their justifications;
2. Sizing of value pools to quantify revenue capture and costs avoided in all scenarios using market and technology-related data compiled for scenario and cost inputs; and
3. Estimating revenues and costs for business models to project profitability through 2060 across all scenarios.

3.2. Scenario definition

The first step of value pool modelling is to define several narratives that represent a range of possible future scenarios for the GGR policy landscape in the US. The three scenarios considered in the value pool model serve to prescribe supply-side dynamics that could shape deployment schedules of the selected GGR technologies and delimit market penetration of certain GGR co-products (e.g., low-carbon concrete, biochar, etc.) as well as the size of the carbon credit market for negative emissions in the US – see ‘Policy Scenarios’ tab of value pool model in supplementary information in Appendix A.

3.2.1. Value pool & business model creation

The second step in constructing the value pool model involved defining seven VPs for six GGR BMs in the US, representing a host of potential opportunities for revenue capture. Value pools considered in the model are characterized briefly as follows:

VP 1: Tax Credit is assumed to be a cost avoided from the Section 45Q and 45 V tax credits for CO₂ utilization from DAC and BECCS BMs; permanent CO₂ storage from DAC and BECCS BMs; and clean H₂ production [40]. GGR business models analyzed will only be eligible for the Section 45Q/45 V tax credits if they involve DAC technology or point-source carbon capture.

VP 2: Carbon Credit consists of revenue captured from CO₂ removal credits sold in voluntary markets for carbon permanently sequestered in all GGR BMs analyzed.

VP 3: Enhanced Oil Recovery consists of revenue captured from injecting captured carbon into Class II wells (i.e., depleted oil and gas reservoirs for increased oil production in EOR) and selling additional oil recovered to oil refineries as well as cost avoided from the Section 45Q tax credit for utilization from industrial and power generation carbon capture.

VP 4: Concrete entails revenue captured from producing low-carbon concrete and revenue from selling carbon removal credits for permanent CO₂ sequestered in the final product.

VP 5: Electricity Generation consists of revenue captured from generating biomass-based power and cost avoided from the Section 45Q tax credit for point-source carbon capture.

VP 6: Biofuel consists of revenue captured from selling bioethanol to the transport industry and cost avoided from the Section 45Q tax credit for point-source carbon capture.

VP 7: Hydrogen (H₂) consists of revenue captured from selling clean hydrogen to utilizers in industry and cost avoided from the Section 45 V tax credit for hydrogen production.

The third step in the value pool modelling approach encompasses business model creation and profit analysis. Six BMs were defined based on feasible combinations of the selected GGR technologies and one or more of the value pools analyzed. It was assumed that “carbon plus” businesses – i.e., BMs that involve carbon removal and one or more other activities or production processes – are more likely to be successful due to the diversification of the business value chain.

It is noteworthy that the technological maturity of the components of these BMs is highly variable with some as low as TRL 4. The approach used allows these aspects to be assessed in other facets of the process though not undertaken in this research [23]. Business models analyzed in the research are parameterized as follows:

BM 1: BECCS & Biofuel involves the conversion of biomass feedstock to bioethanol via fermentation with carbon capture, the sale of bioethanol to utilizers in the transport industry, and the transfer of captured carbon to transport and storage (T&S) entities responsible for either permanently storing or utilizing the CO₂ in products (e.g., carbonated beverages, greenhouses, etc.).

BM 2: BECCS & Hydrogen has been defined as biomass processing via anaerobic digestion and biogas upgrading with carbon capture followed by steam methane reforming for hydrogen production. The business model includes carbon capture units at both the biomass processing and hydrogen production phases with the transfer of captured carbon to T&S entities.

BM 3: BECCS entails the processing of biomass feedstock to generate carbon-neutral electricity, carbon capture and permanent storage, and the sale of renewable energy generated to power suppliers – i.e., regional utility companies [41].

BM 4: DACCS has been defined as pure-play direct air capture via either high temperature liquid sorbent (HTLS) or low temperature solid sorbent (LTSS) – the two most common chemical filtration processes used in DAC – with transport and permanent CO₂ storage [42].

BM 5: DAC & EOR entails direct air capture for use in enhanced oil recovery via CO₂ flooding – injecting carbon into deep geologic reservoirs to increase the volume of oil extracted from the production well [43].

BM 6: DAC & Concrete is comprised of direct air capture and the licensing of accelerated carbonation technology for low-carbon concrete production via blending a primary stockpile of cement with liquified CO₂ in an enclosed rotating carbonation chamber [44].

It is noteworthy that the technological maturity of the components of these BMs is highly variable with some as low as TRL 4. The approach used allows these aspects to be assessed in other facets of the process though this is not undertaken in the research presented⁶ [23]. Once the value pool model was complete, quantitative insights were collected including Total Addressable Market (TAM) of the different value pools and impact of future scenarios on business model profitability. Business model value capture at each timescale, as well as the decade-over-decade trend, was noted and compared to other business models in order to form pertinent conclusions about the commercial viability of selected GGR technologies individually and in combination with specific value pools and co-products. Particular attention was paid to the effect of different scenarios on business model profit. This would inform the realizability of certain GGR business models and help derive questions to be posed in subsequent interviews on the outlook for investing in GGR technology businesses given deep uncertainty impacting future market

fundamentals.

3.3. Interview process

As a supplementary, qualitative assessment of the prospects for US GGR sector scale-up, an interview-based method was adopted whereby model outputs were presented to early US GGR sector stakeholders and a series of related questions was posed. The objective of the interviews is two-fold: (1) to synthesize the rationale for private investment and public policy intervention to propel early-stage GGR solutions and (2) to collect insights on the desirability of certain VPs and BMs as well as a general outlook on market fundamentals for sector scale-up. This qualitative approach serves to complement the quantitative analysis by providing context on the perspectives of active private sector participants on the range of possible futures for the US GGR sector.

The overarching focus of this research as to whether the US GGR market interventions are sufficient to establish the global market fundamentals allows for a broader cohort of interviewees. While early-stage venture capital (VC) investors ($n = 7$) were the target of the interviews and make up the majority of those included, with the aim of deriving the viewpoint of private capital sources, it was determined that policy experts ($n = 3$) and startup founders ($n = 2$) – i.e., the recipients of private capital – would be equally valuable to include in the research to improve the diversity of perspectives incorporated into the analysis. Interviewees were selected based on their current level of involvement in the US GGR landscape.

All interviews were semi-structured and conducted after the value pool model was completely developed. The selected interview format allows for interviewees to express feedback as they see fit and gives them the opportunity to confer information that the interviewer may not have considered [45]. The inquiry delved into the desirability of certain GGR business models, the interviewees' outlook on US GGR policy support, and the interviewee firm's approach to investing – either capital or time and effort – in GGR technology businesses.

After each interview concluded, recordings and transcripts were reviewed for significant observations and opinions stated by interviewees. Summarized by exemplary quotes in Table 4, these insights were categorized into several key themes that aligned with the aforementioned system market risks: 1) Capital (i.e., investment opportunity and funding needs); 2) Market (i.e., supply and demand factors); 3) Political (i.e., regulation and policy intervention); and 4) Technological (i.e., technology advancement and feasibility).

4. Analysis

The value pool model and interviews with early US GGR sector stakeholders generated relevant data and results that will be presented and analyzed in the following section. The results and analysis will feed into the discussion and suggestions for further research on how risks and opportunities perceived by the private sector can be addressed by public policy intervention.

4.1. Business model profit & scenario Results

Total profit by 2060 for each business model across the three scenarios analyzed in the value pool model is depicted in Fig. 1. See key insights gathered from the value pool model and interviews in Fig. 2.

4.1.1. Scenario 1: Right Wing Shift

In Scenario 1, conservative fiscal policy leads to a curtailment of government backing for several early-stage GGR technologies and co-products. The Section 45Q/45 V tax credits (VP 1) are assumed to be cut in half from the base values in Sc. 2, largely disincentivizing investment in various GGR business models. Additionally, the price for carbon removals in the voluntary market would decline in this possible future due to federal deprioritization of GGR technology research,

⁶ Other aspects of the Integrated Strategic Foresight and Human Centred Design approach developed in [23] include the following components: (1) Feasibility – the extent to which technology development is able to realize the business models and revenue streams, process and product standards, regulation, etc.; (2) Desirability – the willingness of customers to take up services and/or co-products; and (3) Realizability – the structural changes required in the sector in order to realize the value or desired outcome of constructive, specific interventions.

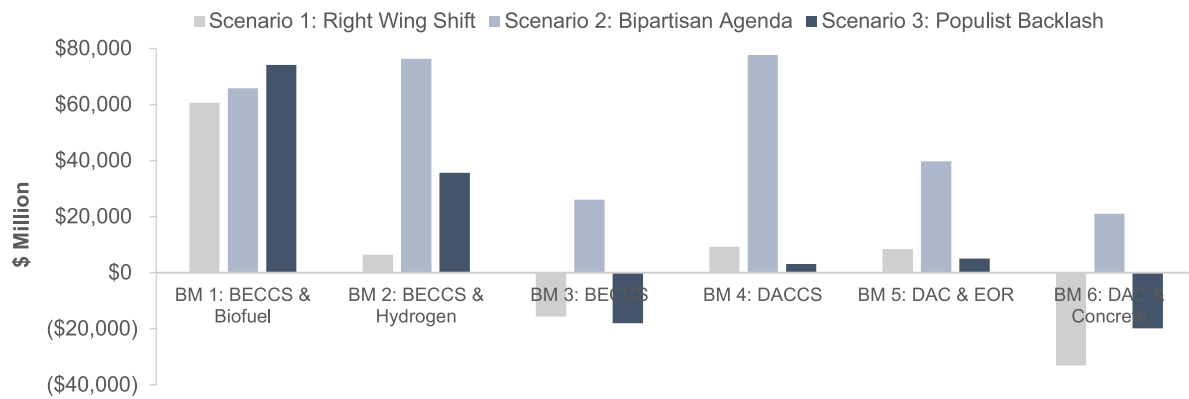


Fig. 1. Total business model revenue accessible in 2060 in all scenarios.

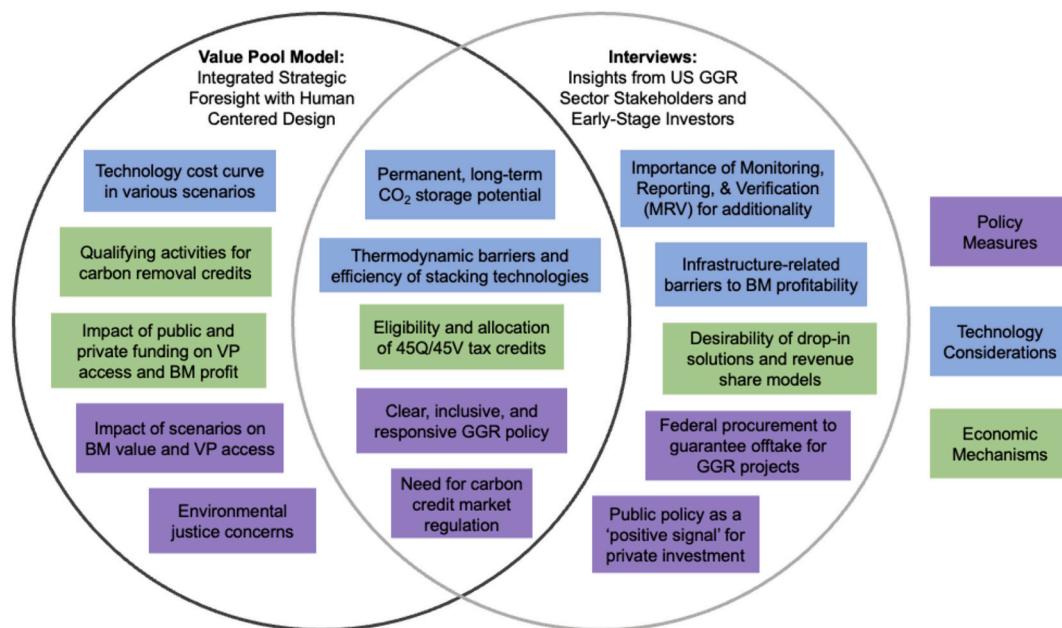


Fig. 2. Key insights gathered from the value pool model and interviews.

demonstration, and development, reducing the total amount of CO₂ captured from DAC and BECCS BMs over time. Relative to Sc. 2, the impact of the lower cost avoided from VP 1 in Sc. 1 significantly reduces total profit potential across all six business models analyzed.

Accordingly, BM 3 does not achieve breakeven by 2060 in Sc. 1 due to the combined effect of the Section 45Q tax credit for point-source carbon capture with storage at half-value, a lower assumed share of CCS power consumption attributed to biomass – in favour of fossil fuel-based CCS power from the oil and gas industry – and a lower carbon credit price, resulting in revenue capture (\$96 billion) that is insufficient to offset total costs associated with BECCS technology (\$112 billion).

A hard right-wing shift, Sc. 1 represents the possible future with the lowest potential for value capture from green hydrogen production (VP 7) which is viewed by conservative legislators as an expensive technology that could detract from the profits of legacy oil and gas companies. Therefore, BM 2 generates minimal profit in Sc. 1 by 2060 as a result of the lower Section 45 V production tax credit value and higher cost of H₂ production with CCS due to the deprioritization of green hydrogen and BECCS technology investment by a government with a conservative majority.

BM 6 is projected to generate the least total profit of all business models analyzed in Sc. 1 as it is assumed that this business model would not break even due to the high cost of DAC technology and less market

share for low-carbon concrete as GGR co-products are deprioritized under a right-wing agenda. Sc. 1 represents a possible future in which sufficient policy incentives are lacking – and thus learning effects are not generated – such that DAC does not accelerate down the cost curve as it would in Sc. 2 and revenue capture (\$23 billion) is insufficient to offset total costs (\$56 billion) in BM 6.

Considering a conservative majority would continue to support federal policies that boost infrastructure spending and sustain fossil fuel reliance, the GGR sector would be propped up slightly by CO₂ removals that support the oil and gas industry or could be framed as an investment in US infrastructure. While EOR represents a relatively small value pool for GGR projects, VP 3 exhibits the greatest potential for value capture in Sc. 1 compared to other modelled scenarios. Accordingly, BM 5 generates \$3 billion more profit by 2060 than in Sc. 3 due to a greater volume of additional oil recovered and CO₂ captured from DAC units under a right-wing shift.

4.1.2. Scenario 2: Bipartisan Agenda

Scenario 2 represents a possible future that broadly encourages GGR sector development and upholds the Section 45Q tax credits for CO₂ sequestration and utilization from DAC and point-source capture at the base values published in the Inflation Reduction Act, increasing each decade, in-line with historical inflation [5]. The total cost avoided from

the Section 45Q/45 V tax credits and revenue capture from selling carbon removal credits drives business model profitability in Sc. 2 across all six business models analyzed.

By 2060, BM 4 is projected to generate a profit of \$77 billion primarily due to the Section 45Q tax credit for DAC storage – the highest value tax credit available – exceeding the total cost of DAC plant installation and T&S of captured carbon.⁷ Similarly, BM 3 total profit is buoyed by both the cost avoided from the Section 45Q tax credit for point-source capture and revenue capture from carbon removal credits, reflecting the supportive policy environment in Sc. 2 for businesses incorporating both carbon capture and permanent, geological storage.

The market for additional oil recovery is assumed to constrict by over half in Sc. 2 as the fossil fuel industry is disincentivized by a bipartisan agenda and the bulk of CO₂ captured by GGR projects (73%) is dedicated to permanent, long-duration storage as opposed to use in EOR. Given the proportional impact of the Section 45Q tax credit for DAC with utilization on total profit of BM 5 by 2060 is significantly greater than that of EOR sales revenue, it is important to note that fiscal incentives are critical to the economic viability of GGR business models – more so than sales revenue from co-products.

Electricity generation (VP 5) is projected to generate maximum revenue capture in Sc. 2 which represents a possible future wherein biomass-based power production paired with carbon capture is strongly incentivized by a government with a majority favouring Mt-scale GGR technology deployment. Among all possible futures analyzed in the value pool model, BM 3 only achieves breakeven in Sc. 2 because the cost avoided from the Section 45Q tax credit for point-source capture with CO₂ storage is sufficient to offset the costs associated with BECCS technology.

Hydrogen (VP 7) also achieves peak revenue capture in Sc. 2 under a bipartisan agenda that incentivizes investment in a breadth of novel clean energy solutions, resulting in a total value pool size of \$83 billion by 2060. In the same decade, BM 2 is projected to generate a profit of \$76 billion – more than double the business model profit projected in Sc. 3 – due to the substantial cost avoided from claiming both the Section 45 V production tax credit for green hydrogen, Section 45Q tax credit for point-source capture, and revenue capture from sales to H₂ utilizers in industry.⁸

Similarly, low-carbon concrete (VP 4) production in BM 6 is profitable in Sc. 2 due to the cost avoided from claiming the DAC with CO₂ storage tax credit and the greater volume of CO₂ capture from DAC plants in the possible future characterized by a political agenda supporting both GGR technologies and their co-products. With the Section 45Q tax credit (VP 1) making the greatest contribution to total profit of BM 6 by 2060, it implies that a possible future in which the tax credits are devalued would likely jeopardize the success of this business model.

4.1.3. Scenario 3: Populist Backlash

In Scenario 3, a populist backlash significantly reduces the potential cost avoided from the Section 45Q/45 V tax credits and revenue capture from carbon removal credits with dwindling demand for CO₂ removals in this possible future leading to a significant reduction in the volume of

CO₂ capture from GGR BMs. With carbon capture and storage seen a “false solution” for climate action (i.e., reducing emissions), public policy that props up proceduralism [46] and reflects the “anti-removals” viewpoint of specific communities, would necessarily hinder the profitability of several GGR BMs in the long-term.

BM 3 is the least profitable among all business models analyzed in Sc. 3 due to the combined negative effect of the half-value Section 45Q tax credit for point-source capture and reduced carbon credit pricing as incentives for GGR technology are rolled back in a possible future. Revenue capture from BECCS power generation (VP 5) is limited under a populist backlash as it is assumed policy intervention would be dictated by Environmental Justice (EJ) groups opposed to bioenergy for reasons related to land use competition and “Not In My Backyard” factions concerned about the impact of CCS projects on local communities.

Despite populist political headwinds, biofuel (VP 6) production is projected to generate the greatest revenue capture in Sc. 3 as it is viewed positively as an alternative energy source that supports rural economies dependent on agriculture. Despite less policy support for BECCS technology in this possible future, BM 1 achieves peak profit in Sc. 3 due to strong incentives for emissions-curtailling renewables, modelled as a 33% increase in both the total volume of bioethanol produced and net CO₂ capture of this business model by 2060. BM 2 total profit is also bolstered by the assumption that green hydrogen (VP 7) is a strong alternative fuel source for heavy emitters in industry, resulting in declining technology costs and higher H₂ prices that industrial utilizers are willing to pay in Sc. 3. However, H₂ production methods using CCS are widely deprioritized across policy intervention driven by an “anti-GGR” populist backlash such that BM 2 profit in Sc. 3 (\$36 billion) is less than half of that in Sc. 2.

Compared to a possible future with a bipartisan agenda, value capture from EOR (VP 3) is constrained by half in Sc. 3 with EJ advocates strongly opposed to both continued reliance on fossil fuels and investment in CCS technology. Accordingly, BM 5 hardly breaks even by 2060 due to the assumed reduction in the Section 45Q tax credit values for DAC with CO₂ utilization and lower volume of carbon capture from DAC units in this scenario. Market demand for low-carbon concrete (VP 4) is also assumed to be limited in a possible future where GGR co-products and DAC technology are not sufficiently incentivized such that BM 6 does not achieve breakeven by 2060.

Table 3 summarizes the ranking and performance of each business model in all three scenarios based on key measurements and scenario resilience. Scenario resilience of a BM refers its ability to access revenue across scenarios whereby it would be able to realize more than \$50 billion profit, achieve breakeven (less than \$50 billion), or not – as per the color coding in the figure annotation.

4.2. Interviews with early US GGR sector stakeholders

The following section will involve a discussion of insights emerging from the interviews related to the role of public policy and private capital in stabilizing supply and demand fundamentals in the emerging GGR sector. The interviews revealed four main categories of systemic risk perceived by investors as follows:

- **Capital Risk:** Potential loss of part or all of an investment (i.e., low profit potential);
- **Market Risk:** Potential for insufficient supply or demand to create a surplus or deficit in the market for GGRs;
- **Political Risk:** Possible political instability or shifts that may negatively impact investment returns and BM desirability; and
- **Technology Risk:** Potential that the technology is not feasible, when one or more function(s) fails to achieve the desired result.

Within each of these categories of risk, investors identified actions that can be taken by policymakers and the private sector to minimize these risks. Exemplary evidence for each of these categories is

⁷ While a well-designed investment tax credit policy would be periodically adjusted with respect to changes in technology cost, value pool model projections are a result of semi-arbitrary growth assumptions reflected in scenario and cost inputs. In reality, responsive fiscal policy would ensure that tax credit values track the individual costs of GGR technologies to always be approximately at parity in order to adequately incentivize technology developers.

⁸ It is assumed that BM 2 would be eligible to claim both the Section 45 V and 45Q tax credits for fulfilling two components of the value chain – point-source CO₂ capture and H₂ production. However, the current regulation is ambiguous as stated and project eligibility for the incentives remains to be proven, highlighting a need for clarification around eligibility and allocation of the fiscal benefits on a per project basis.

Table 3

Summary of business model profit analysis, including rank and profitability in 2060 for each scenario, SWOT analysis, and scenario resilience. Green = Top-tier result. Yellow = Profit less than \$50 billion or minimal viability. Red = Negative result.

Business Model	Rank & Profitability			Strengths / Opportunities	Weaknesses / Threats	Scenario Resilience
	Scenario 1: Right-Wing Shift	Scenario 2: Bipartisan Agenda	Scenario 3: Populist Backlash			
BM 1: BECCS & Biofuel	1	3	1	Relatively mature technology, diverse revenue stream	Biofuel market exposure, required coordination	
BM 2: BECCS & Hydrogen	4	2	2	Niche market, diverse network of US offtakers	Biomass supply constraints, required coordination, technology maturity	
BM 3: BECCS	5	5	5	High VP access, diversification of energy mix, distributed gen.	Biomass supply constraints, storage site co-location, technology maturity	
BM 4: DACCS	2	1	4	High measurability, long-duration GGR	Technology cost and maturity, storage site co-location	
BM 5: DAC & EOR	3	4	3	Diverse revenue stream, higher likelihood of bipartisan support	Continued fossil fuel reliance, technology maturity, storage site co-location	
BM 6: DAC & Concrete	6	6	6	Niche market, high VP access, measurability	Technology cost and maturity, concrete sequestration potential	

summarized in Table 4. For example, capital risk can be mitigated by investors targeting flexible business models that can evolve with the market and by policy intervention that treats carbon removal as a public service with increased RD&D funding and procurement programs at the federal and state-level.

Investors (I1 and I5) proposed that market risk could be addressed by market stabilizing measures that generate certainty of future offtake and carbon pricing as well as transparent policy that explicitly states forms of carbon removal (i.e., including permanent, durable sequestration) that are eligible for government support.

Investors also noted that public policy will be crucial to help them identify the market winners and losers based on understanding how technologies will be supported by different types of government funding. Nonetheless, several investors remained steadfast in their approach, claiming that policy is a positive signal for their funds but that they invest in carbon removal and CO₂ co-products due to their intrinsic value that will provide future returns.

Technology risk was acknowledged by policy experts calling attention to the need for increased emphasis of GGR policy on expanding transport and storage (T&S) capacity to encourage permanent sequestration methods. Additionally, given that capital-intensive GGR business models can be ill-suited for early-stage VC fund strategies, investors proposed that first movers in the private sector should focus on businesses working on technology breakthroughs that have the potential to shape the entire market.

In summary, there are several actions that early market participants in both the public and private sector can take to mitigate various systemic risks. Accordingly, over time, market fundamentals will become increasingly stable and the US GGR sector will become more investable. These insights have significant implications on the policy and market frameworks for generating a global GGR sector at GtCO₂ scale by 2050 which are explored in the next section.

5. Implications on US and global GGR GtCO₂ sector development

5.1. Key themes & barriers to GGR market expansion

The value pool model and interviews revealed several key themes related to policy measures, technology considerations, and economic

mechanisms that will be critical to scaling the US GGR sector – see Fig. 2. There are three key insights related to policy measures that particularly stand out. First, despite the Section 45Q/45 V tax credits and carbon removal credits being essential to value capture of GGR BMs in the value pool model, several interviewees clarified that their firms view existing federal incentives as a “positive signal” for their investment strategy rather than a critical component of their underwriting. Second, the results of the value pool model and interviewee insights were consistent in acknowledging a critical need for responsive and inclusive GGR policy with a stronger emphasis on permanent, long-term CO₂ storage methods. Third, if selling carbon credits is to become a durable source of revenue for GGR BMs by 2050 as the value pool model presumes, it will be essential to enact legislation for participants in voluntary carbon markets and GGR project suppliers in the US focused on certifying high-integrity projects to stabilize carbon removal credit prices.

5.2. Addressing the gap in demand-side policy measures

Given the strong focus of existing US GGR policy intervention on RD&D and supply-side factors, which will nonetheless be important for encouraging global innovation and bringing down technology costs, a fundamental insight for both US and global GGR market establishment and stabilization is the need for demand-side policy implementation for accelerated GGR sector scale-up. Though the US government has committed billions of dollars to research efforts and demonstration projects, existing regulation has been supply-side dominant. This is replicated in the EU and UK which exposes a need for concurrent demand-pull measures such as government procurement programs and carbon pricing regulation. In order to address systemic risks perceived by the private sector, as represented in Table 4, it will be essential to establish policy measures that stimulate demand in lockstep with supply development.

Though the US is partially addressing this with the federal CDR Purchase Pilot Prize and LCFS in California, these interventions will be insufficient on their own to achieve a GtCO₂-scale sector in the US – see

Table 4

Exemplary evidence from interviews overlapping with the key themes of GGR sector development. Early-stage investors = I. Policy experts = P. Startup founders = F.

Theme	Public Policy Intervention	Private Sector Action
Capital	“Money has to go into making sure that carbon gets removed from the atmosphere to the public good rather than to the pockets of investors. I don’t quite see how we’re going to move from the current moment in the US, which is Silicon Valley-inflicted into something that looks much more public goods-focused.” [P2]	“[The] ideal business model is a combination [of] capture with utilization, all on site...If you’re a corporate client, there is the potential for additional revenue streams that utilization opens up...especially if they’re able to do a drop-in. A pure carbon credit play is not as exciting for a partner. They also want the integration of...the actual product they’re able to create with the carbon for revenue share.” [I7]
Market	“[I would like to see] clarity on permanence and what actually constitutes a removal...but [policy] still has to be dynamic enough that it can grow with an industry that is still learning things today. Among removal options, how do we define what is actually removal and disposal of that waste in the same way that we do with the waste industry? There’s not actual scientific rigor around geological sequestration and what that means. That clarity is very necessary right now.” [I5]	“...Everything that generates a certain stability and certainty of future offtake. That is the most important policy measure for us as investors because it is a sign that the market will be stable. That would trigger follow-on funding – project finance and bank finance – investors for our exits. This ‘positive signaling effect’ is very important...early signs of offtake, early signs of certain prices. If you have more certainty of prices, then businesses can calculate where they should end up on their unit economics.” [I1]
Political	“As we continue to see rules written that specify who is eligible for what types of subsidies and why, and who’s going to be able to access the one-time big injections of capital to help move technologies down the cost curve, those are pieces that will help bring into focus where there are going to be winners and losers in the market.” [I3]	“Having third-party verifiers is really important...whether that is a government entity or just another company...I think that could really help voluntary carbon markets as well as with corporate buyers. A lot of corporate buyers want to buy carbon credits and they’re not as tuned into the fact that not all carbon credits are the same and you can get really screwed over by purchasing credits that are not actually what they say they are.” [I7]
Technological	“The transport and storage piece is number one for me [for de-risking business models] ...It’s expensive, takes expertise that often lives with oil and gas companies, and is under-valued in the policy space...” [P1]	“These [capital intense] business models aren’t friendly to the VC model, which is built off of the idea that you have 10× returns on one company...and then a lot that barely return your investment...So, we’ve looked at technology breakthroughs that could catalyze rapid expansion...that might provide those massive returns because it’s 10× better than the existing technology.” [I5]

Table 1. The value pool model assumes that carbon prices will ramp down to stabilization around \$100–150/tCO₂⁹ across all three scenarios by 2050; however, this price trajectory will not be achieved without policy that creates a demand curve for CO₂ removals via a removal obligation and/or a price on emissions. Additionally, the interviews

⁹ The 2050 carbon removal credit price in the value pool model is conservatively assumed to be approx. in-line with the US DOE’s Carbon Negative Shot target of \$100/tCO₂ [59].

revealed the most important market intervention for investors is one that will generate stability and a certainty of future offtake, either in the form of an advance market commitment (AMC) from the private sector or public procurement – see Table 5. Indeed, UK policy instruments will not function efficiently to stimulate the sector without a clear demand curve and reference price for CO₂ [21,47,48].

It is not as though demand-side policy for CO₂ removals that would generate stability in the establishment of the GGR sector is not available. There are several regulatory measures that would stimulate the market for CO₂ removals and buttress rapid technology deployment as outlined in Table 5. The open question is whether there is the political will to implement them and by extension provide economic coherence with the billions being invested in supply-side measures.

5.3. Broadening the global GGR technology portfolio and other market enablers

While DAC and BECCS are further along the TRL spectrum relative to other negative emissions technologies, making them favourable for investors and policymakers seeking to test hypotheses for accelerating GGR sector scale-up, there is a need for a broader perspective on supply- and demand-side measures that can help advance the entire spectrum of CO₂ removals [53]. As highlighted in **Error! Reference source not found.**, clear, responsive, and inclusive policy intervention will be critical to accelerating RD&D efforts in lockstep with expanding corporate procurement and other forms of advance market commitments.

In the US, there is currently a lack of coordination in the approach to GGR policy implementation that places certain GGR BMs at a disadvantage due to “winner-picking” inherent in the incentives for carbon capture set out in the IRA and ILJA. It will be essential to establish a more comprehensive suite of policies at both the federal and state level to balance supply and demand in the near-term and realize a GtCO₂-scale US GGR sector by mid-century. Two landmark federal policies announced in recent years: the CDR Purchase Pilot Prize, a novel federal procurement program, and the collective \$10.5 billion for developing DAC and clean hydrogen hubs will have a transformative effect on market fundamentals for US GGRs. The former will send a positive signal to potential carbon removal credit purchasers, serving as a stimulus for voluntary carbon markets in the US. The latter will accelerate the supply pipeline for DAC and green hydrogen projects and improve the economics of GGR BMs incorporating those technologies as they advance down the cost curve. Despite this regulation representing a step in the positive direction for the US GGR sector, it neglects to acknowledge the importance of balancing GGR pathway diversity and developing rigorous standards for quantifying GGR potential [54].

Policy incentives should seek to compose a diverse portfolio of GGR solutions, not over-indexing on any single technology, and feature inclusive language that does not immediately disqualify certain GGR business models that may have a strong net climate benefit. Additionally, there remains a need for a universal MRV framework to quantify net carbon removal with life-cycle analysis and uncertainty considerations both for existing scale of GGR deployment but also accommodating for future scale-up as emergent environmental and other systemic impacts are manifest [55]. For reference, the forthcoming European Carbon Removal Certification Framework (EU-CRCF) has the potential to set the standard for verifying high-integrity CO₂ removal practices, informing global governments of the approach to certifying durable GGRs [56]. These examples of all-encompassing policy intervention will be essential to accelerate a wide range of GGR technologies and co-products, including biochar and low-carbon concrete, in order to mobilize supply and demand in lockstep.

These initiatives all need to be considered within a broader governance framework which will accommodate the need to address broader systemic issues as well as enable GGR value chains to be integrated into existing industrial sectors whilst improving economic viability and CO₂

Table 5

Proposed demand-side policy intervention required for GGR sector scale-up both in the US and globally.

Emissions Trading Scheme Integration. The integration of GGR credits into the EU and/or other large-scale emissions trading schemes would provide demand albeit the mechanisms by which negative emissions credits were integrated would have implications on the extent of demand generated.
Public Procurement Schemes. Public sector procurement has the potential to reach \$1+ billion in the US. The CDR Purchase Pilot Prize announced in September 2023 made up to \$35 million available for GGR projects generating negative emissions credits [49]. The establishment of negative emissions product standards for items procured by governments and the public sector more broadly would potentially stimulate billions in the way of demand for negative emissions credits.
Adaptation of the European Climate Law. A legally-binding target for GGRs similar to the European Climate Law's broader goal of climate neutrality by 2050 [50] would compel heavy emitters in the private sector to participate in carbon removal markets and actively incorporate GGRs into their environmental, social, and governance (ESG) frameworks and net zero commitments.
Establish a Carbon Take Back-Obligation (CTBO). This is an enhanced producer responsibility policy which would require all fossil fuels extracted or imported into a region, nation or group of nations, to be offset by storing an equivalent amount of CO ₂ underground to that generated by the fuel. A CTBO, phased in over time, would reach the requirement of storing 100% of emissions by 2050, ensuring carbon clean-up and making the cost a part of the cost of fossil fuel production [51].
Expand the existing \$35 million US CDR Purchase Pilot Prize and \$23.5 million Danish initiative for GGR procurement to the multi-billion-dollar range, allocated across a diverse portfolio of GGR solutions. The US and Danish government-backed offtake agreements will accelerate deployment of Mt-scale GGR projects and signal to the private sector that investment in CO ₂ removals is crucial. Indeed, Google recently committed to matching the US government purchases in 2024 [52].

removal efficiency [57].

6. Conclusion

This research addressed a significant gap in the GGR literature by employing an exploratory approach to assess the state of US public policy and private capital in catalyzing the supply of high-integrity GGR projects and the implications that this would have on establishing and scaling a global GtCO₂-scale sector given the pervasive deep uncertainty to which the sector is subjected.

The quantitative analysis demonstrated that revenues from material policy incentives such as tax credits or carbon removal credits will catalyze BM innovation substantially in all future scenarios. As learning by doing is realized over time, GGR technologies will benefit greatly from scaled deployment and enhanced profit potential across possible futures. However, technologies with limited volume of permanent sequestration potential (e.g., low-carbon concrete production) will be less likely to achieve profitability in policy-dominated revenue schemes – where tax credit and carbon credit value pools are primary revenue streams. Additionally, businesses with a wider total addressable market will benefit financially in all future scenarios as evidenced by BM 1 and BM 2 that access the large US markets of biofuel for transport and hydrogen for industry, respectively – see Fig. 1. These business model characteristics will define future demand by early-stage private investors seeking both return on investment and verifiable net-negative emissions.

According to the interviewees, desirable business models will be resilient in various possible futures given deep uncertainty in the US GGR policy landscape. It was widely acknowledged, however, that achieving a large-scale US GGR sector will require steady supply of high-integrity removals *and* a guaranteed future demand curve for negative emissions. This is the single biggest take-away from this analysis for the establishment and stabilization of both a US and global GtCO₂-scale sector.

Without clearly defined policies to balance the incentivization of investment in GGR projects with mechanisms which stimulate offtake agreements, the ability to accelerate deployment of commercial-scale GGR projects would be problematic. Furthermore, demand-side policies would likely broaden the GGR technology portfolio when undertaken with other market enablers such as MRV. Early US GGR sector stakeholders also suggested there is a need for consistent direction from US policymakers to incentivize private investment, generate learning effects and technology cost declines, and boost public acceptance of CO₂ removals. Without this, investment by the US, EU and UK public sector will be out of lockstep with the much-needed private capital investment to realize both the multi-trillion-dollar GGR market and achieve global net zero by 2050.

CRedit authorship contribution statement

Madison Cuthbertson: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Mark Workman:** Writing – review & editing, Supervision, Conceptualization. **Aoife Brophy:** Supervision, Conceptualization.

Declaration of competing interest

On behalf of all the authors of this submission, I declare there is no competing interest in the form of financial or personal relationships with other people or organizations that might inappropriately influence or bias this piece of work.

Data availability

I have shared my data in the Attach File step (see .xlsx file).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2024.123806>.

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