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A policy agenda for gigaton-scale carbon management

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1. The need for a comprehensive carbon management agenda

The scale of the climate challenge is monumental. Today's global economy still relies on fossil fuels for 84 % of its energy needs[1]; these fuels are extracted, transported, processed, and consumed through large, intricate, and often interconnected systems that developed over more than a century and reflect trillions of dollars of invested capital. In 2019, the United States accounted for 6 billion of the 40 billion tons of greenhouse gases emitted globally. In the span of a few decades, we must transition to an economy with net-zero emissions. The scale of this challenge—technologically, financially, logistically, and politically—is difficult to overstate. And success will not be possible unless critical clean energy and climate mitigation technologies, several of which are still in the nascent stages of commercialization and deployment, are scaled by several orders of magnitude within the next two decades. Technologies for managing carbon emissions, including technologies that can capture carbon dioxide (CO_2) from large point sources or remove CO_2 from the atmosphere, are among these high priority solutions, and must be scaled to the gigaton level by 2050.

Climate change, for all its complexities, is fundamentally a problem of too much carbon in the wrong place. Managing carbon flows – the basis of fossil fuel energy – is central to the challenge of climate protection. Technologies that avoid emissions in the first place, such as renewable and nuclear energy, will play a crucial role by making the transition to net-zero more achievable. On a broader scale, the task at hand is to transition from an economy that regularly releases carbon into the atmosphere, to one that actively manages carbon by *reducing* existing emissions, *displacing* unavoidable emissions, and *removing* carbon that is already in the atmosphere as a result of historic emissions.

This broad view requires a coherent set of market and policy signals to support emissions mitigation and carbon capture or removal methods under a general framework of "carbon management" that encompasses the portfolio of technologies, applications, and infrastructure necessary to capture, remove, transport, store, and make use of CO_2.[2] Carbon management also requires the development of robust accounting frameworks to accurately measure, track, and distinguish between the climate effects of different activities. These strategies and accounting systems must be developed holistically and concurrently. A piecemeal approach will produce suboptimal outcomes, as individual project investments and emerging policy priorities are likely to be incomplete or misaligned—problems that characterized past efforts by the U.S. government to develop carbon capture and sequestration (CCS) technology for concentrated emissions sources such as power plants.

The components of a carbon management agenda are as follows:

(1) Point-Source CO_2 Capture – technologies that capture CO_2 emissions from large, concentrated point sources such as power plants and industrial facilities. The concentrated CO_2 captured by these systems must then be stored responsibly and, ideally, permanently. While much of the initial policy focus and public investment in carbon capture systems in the U.S. reflected an assumption that coal-fired power plants would be a major source of electricity for decades to come, future domestic applications of CCS technology will more likely focus on capturing emissions from natural gas or biomass-fueled facilities and from hard-to-decarbonize industrial processes.

(2) CO_2 Removal – technologies and strategies that remove CO_2 from ambient air, where CO_2 concentrations are far more dilute than in the emissions streams encountered in point-source capture. It is worth clarifying that the act of removing CO_2 already present in the atmosphere is a different tool for addressing climate than reducing new CO_2 emissions from being introduced into the atmosphere (as with point source capture). Carbon removal can be achieved through natural, engineered, or hybrid means.

Engineered carbon removal – Engineered removal has some technology overlap with point-source capture but lacks the advantage of higher CO_2 concentrations associated with flue gases from point sources. The term "direct air capture" (DAC)

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[1] Hannah Ritchie and Max Roser (2017) "Fossil Fuels." *Published online at OurWorldInData.org.* (accessed 14 July 2021) Retrieved from: https://ourworldindata.org/fossil-fuels

[2] We note that carbon management can also refer to the management of methane, a potent greenhouse gas, but the financial opportunities for curbing methane are substantially higher than CO_2 and are not the focus of this article. The authors wish to emphasize that actively managing all greenhouse gases – including CO_2, methane, nitrous oxide, and fluorinated gases – are crucial components to meeting net-zero goals.

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is often used to describe systems for engineered removal; development of DAC technology has recently advanced to a point where the advantages of these systems—in terms of scalability and cost-effectiveness, verifiability of CO_2 benefits, siting flexibility, and reduced land requirements—could support expanded deployment in the near future.

Natural carbon removal – Natural removal strategies, such as forestry and agricultural practices that enhance the uptake of carbon in forests and soils, will be an important part of a successful climate strategy, but will need to address concerns surrounding land-use and permanence of associated CO_2 reductions in order to be responsibly scaled-up.

Hybrid systems – Biomass energy with carbon capture and storage (BECCS) is a prototypical example that leverages a combination of natural (atmospheric removal through the natural process of photosynthesis) and engineered (point source capture upon combustion of biomass) methods. BECCS has the added benefit of generating revenues from energy production, but faces similar concerns as natural carbon removal regarding land-use with scale-up. Given the inherent value as a removal technology, some have suggested rebranding this class of removal techniques as “biomass carbon removal and storage” (BiCRS) to emphasize the utility of net negative emissions.[3]

(3) CO_2 Transport – the coordinated transport of captured or removed CO_2 to locations where it can be stored and/or used. While there is a role for vehicle transport, the most cost-effective means to move high volumes of CO_2 is through pipelines.[4] In some cases, the need for transport infrastructure can be minimized—for example by building DAC facilities adjacent to injection sites for geological storage. In other cases, the need for transportation infrastructure may be unavoidable—for example, to connect existing industrial hubs with extensive CCS deployment to areas that offer suitable geologic storage potential.

(4) CO_2 Storage – technologies and practices for removing CO_2 from the carbon cycle on a time scale that has positive climate impacts. This can be performed through geologic storage in saline aquifers, through enhanced oil recovery (EOR), or through natural (biogenic) storage. Pragmatic, scalable regulatory regimes for accessing storage sites and certifying the safety, transparency, and permanence/risk-of-reversal of storage conditions must be developed.

Geologic storage – Permanent storage of CO_2 away from the atmosphere is a foundational component of a long-term carbon management agenda. In general, geologically suitable sites for storing CO_2 in underground saline formations are plentiful—more than 12,000 gigatons of saline storage potential have been identified in the United States alone[5] (equivalent to more than 2000 years of annual U.S. emissions at current emissions rates)—and the technology for injecting CO_2 and sealing it underground is well developed. An efficient and well-regulated leasing and permitting regime, including increased clarity on pore space and mineral ownership among the many different actors involved in underground injection, will be needed and successful siting will require thoughtful community engagement to address potential concerns.

Enhanced oil recovery (EOR) – The oil and gas industry has been injecting CO_2 into depleted reservoirs to boost hydrocarbon production for decades, developing an infrastructure and technical base of knowledge that can be leveraged for carbon management. Regulatory systems to oversee these injection practices are in place at the state and federal levels. Because the use of captured CO_2 for EOR does result in oil production, properly accounting for the net carbon impacts of this approach, in isolation and compared to other industry practices, is an issue that warrants careful consideration.

Natural (biogenic) storage – The time scale of storage for CO_2 sequestered in trees or soils is an important consideration within the carbon management agenda. As mentioned earlier, these forms of storage are subject to uncertainty about future conditions, including the risk of wildfires and the impacts of future land management decisions.[6] Regardless, it is important to recognize that these low-cost, decade-scale storage options will be an essential component for meeting climate goals this century.

(5) Carbon Utilization – revenue-generating technologies and opportunities that make use of captured CO_2 are key to the continued technological advancement and deployment of engineered CO_2 capture and removal. While EOR has already been mentioned as an example for storage, the revenues produced by a barrel of oil make EOR both a use and storage technology. Other uses of CO_2 include as a feedstock for concrete, as a component of steel, and in new products such as carbon nanotubes. Each of these productive uses of CO_2 has the potential to reduce net emissions while creating revenue streams and supporting business models that can help advance critical carbon management technologies and associated infrastructure.

An overarching requirement to support all five aspects of a gigaton-scale carbon management strategy is a clear, transparent, and credible accounting framework that looks across the many different processes for and approaches to capturing or removing, storing, and utilizing CO_2. A comprehensive and universally accepted accounting framework can provide a foundation for better analyzing project effectiveness and for implementing effective incentive structures that inform investment decisions and policy design. This framework must factor in the permanence and verifiability of various carbon management pathways and help ensure that projects are scored in a manner that accurately reflects their climate impact. The overlapping components of the carbon management agenda are displayed in Fig. 1.

It is useful to look back to the rise of utility scale solar energy when thinking about how to construct a policy agenda for carbon management. After decades of R&D, the first utility-scale solar projects were all launched shortly after several different policy tools were enacted: (1) a cash-convertible Investment Tax Credit, (2) new loan guarantees authorized in the 2009 stimulus bill through DOE’s Loan Program Office, and (3) state level Renewable Portfolio Standards. Being able to “stack” the tax credit and attractive financing with a power-purchase agreement created the right conditions to bring the technology to scale. Similarly, no single policy on its own will put us on a path to gigaton-scale carbon management. We will need a comprehensive

3 David Sandalow et al. (2021) “Biomass Carbon Removal and Storage (BiCRS) Roadmap.” (accessed 14 July 2021) Retrieved from: https://www.icef-forum.org/pdf/2020/roadmap/roadmap.pdf?0128

4 Victor Onyebuchi et al. (2018) "A systematic review of key challenges of CO2 transport via pipelines." Renewable and Sustainable Energy Reviews 81: 2563–2583. https://doi.org/10.1016/j.rser.2017.06.064

5 Carbon Storage R&D, Office of Fossil Energy, Department of Energy. (accessed 14 July 2021) Retrieved from: https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-storage-rd

6 Sabine Fuss et al. (2018) "Negative emissions—Part 2: Costs, potentials and side effects." *Environmental Research Letters* 13.6: 063002. https://doi.org/10.1088/1748-9326/aabf9f

Fig. 1. Graphical representation of the core components of a comprehensive carbon management agenda.

agenda with a suite of policy tools and options.[7]

2. The current state of play

Considering the scale of the challenge, existing policies to enable a carbon managed economy fall far short of what is needed. In part, this is due to the U.S. government's historic focus on abating CO_2 emissions from coal-fired power plants, which were seen as a high priority due to their large size, substantial emissions, and low operating costs. Thus, most CCS policies, funding, and political support over the last two decades targeted the development of point-source capture technologies for coal facilities. In recent years, however, coal has accounted for a diminishing share of the U.S. electricity mix, thanks to an influx of cheaper and cleaner alternatives such as wind, solar, and natural gas generators. Thus, foundational CCS development efforts and the political base of support for CCS research have been out of sync with what is needed.

The carbon managed economy of the future will build on capabilities and industries that are in place today. Gas-separation technologies for feedstock flue gas streams that have been used by industrial firms for decades have already been demonstrated to work effectively in large-scale applications for capturing high volumes of CO_2.[8],[9] Likewise, the domestic oil and gas industry has utilized CO_2 for EOR for nearly half a century and now moves millions of tons of CO_2 through a well-regulated pipeline and injection network on an annual basis (most of this CO_2 is currently sourced from natural deposits underground, not captured from the atmosphere).[10]

Current policies to support carbon capture, however, are too modest and piecemeal to leverage this experience base and drive new business models for large-scale deployment. The federal policy agenda to date has largely consisted of a strong DOE-based research and development program combined with a federal tax credit, the 45Q program, for CO_2 capture and storage. DOE has had some special programs in the last 20 years to support commercial-scale CCS demonstration projects, most notably FutureGen and the Clean Coal Power Initiative. Finally, the DOE Loan Programs Office (LPO) is authorized to provide financial backing

[7] Varun Sivaram (2020) "The American Recovery & Reinvestment Act and the Rise of Utility-Scale Solar Photovoltaics: How U.S. Public Policy During the Great Recession Launched a Decade-Long Solar Boom." *American Energy Innovation Council and the Bipartisan Policy Center*. (accessed 14 July 2021) Retrieved from: http://americanenergyinnovation.org/wp-content/uploads/2020/06/The-Successful-Demonstration-of-Utility-Scale-PV.pdf

[8] Álvaro A. Ramírez-Santos et al. (2018) "A review of gas separation technologies within emission reduction programs in the iron and steel sector: Current application and development perspectives." *Separation and Purification Technology* 194: 425–442. https://doi.org/10.1016/j.seppur.2017.11.063

[9] Magda Kárászová et al. (2020) "Post-combustion carbon capture by membrane separation, Review." *Separation and purification technology* 238: 116448. https://doi.org/10.1016/j.seppur.2019.116448

[10] Xiaohu Dong et al. (2019) "Enhanced oil recovery techniques for heavy oil and oilsands reservoirs after steam injection." *Applied energy* 239: 1190–1211. https://doi.org/10.1016/j.apenergy.2019.01.244

for some CCS projects and could be an important source of support going forward. However, the current combination of policies and programs has so far failed to deliver a scalable, commercially vibrant CCS industry.[11]

For now, the clear lynchpin of policy support for CCS is the federal tax credit. Known by its section of the tax code, the 45Q credit offers a tiered credit of up to $50 per ton for CO_2 capture with geological storage and up to $35 per ton for CO_2 capture and utilization, including incidental storage through EOR operations. At these levels, the credit has not been sufficient to incentivize new, large-scale capture projects in the more expensive applications such as power generation or certain industrial processes that vent less-concentrated CO_2 streams. Additionally, the design of the 45Q credit limits its usability in practice: minimum CO_2 capture requirements make many demonstration projects and CCS applications in small industrial operations ineligible; the lack of a direct pay mechanism forces project development to rely on complex and expensive tax equity markets; and a requirement that projects must commence construction by January 1, 2026 to be eligible, especially in light of time lost to the COVID-19 pandemic and the years required to bring new projects online, have all served to undercut the effectiveness of the program, particularly in the context of current uncertainty about future policies for carbon management.

Absent a program to cap or price economy-wide carbon emissions, clean technologies will need tailored policy support to penetrate and scale in existing energy markets. As mentioned earlier, the success of wind and solar provides encouragement and a template for carbon management. These renewable technologies benefitted from a combination of sustained policies and programs that worked together over decades to drive down costs and increase deployment, bringing wind and solar to the point where they can now compete with established energy options in many market applications.[12] The next section of this article outlines a policy framework that builds on existing programs to create the incentives needed to bring emerging carbon management solutions to gigaton scale.

3. The way forward

America is entering a new moment for energy and climate policy. Policy makers,[13] corporate leaders,[14] and the broader public are increasingly aware of climate change and receptive to the view that a serious response is needed.[15] The Republican party, historically averse to climate action, has begun to engage in a serious policy agenda. With greater agreement that there is a problem, the focus of debate has shifted to potential policy interventions and their impacts on jobs, businesses, and energy costs. It is evident that any broadly supported program for transitioning to a net-zero economy must ensure that Americans continue to have access to affordable, reliable energy, while also creating new employment and investment opportunities—particularly in the most affected industries and regions. Carbon management sits at the center of any path to success, facilitating political and substantive progress by helping to reconcile the need for rapid carbon reductions with the imperative to protect consumers, workers, and the economy.

Corporate players are beginning to shift their climate strategies, increasing transparency around their carbon footprint and making new financial commitments. Growing numbers of businesses have publicly adopted the goal of achieving net-zero emissions and innovative projects are being considered and announced. For example, Schlumberger, Chevron, and Microsoft have announced a joint project to generate power with net-negative emissions using biomass energy with CCS in California.[16] Summit Agriculture group has announced an initiative, Summit Carbon Solutions, to decarbonize biofuels and certain applications in the agriculture industry.[17] Occidental, through its Oxy Low Carbon Ventures unit, is developing a new business platform focused on investing in DAC.[18] ExxonMobil recently outlined its vision for a large-scale, public-private CCS innovation hub that would implement CCS with permanent CO_2 storage in an offshore saline formation in the Houston ship channel—the goal is to store 50 megatons of CO_2 annually by 2030.[19] Supporting these business models and projects and building momentum for further commitments will be an important test of whether America's carbon management policy agenda is effective.

That agenda must be tailored to support the full innovation cycle for carbon management technologies, bridge commercial gaps, and resolve lingering regulatory and market barriers. The costs of carbon capture projects remain high relative to conventional energy options,[20] especially absent broader national climate policies that would shift the economic incentives for avoiding and reducing emissions. In addition, first movers must manage complex engineering and regulatory risks. Investments to build out supporting infrastructure can reduce barriers to entry for a broad range of projects and benefit all players. Meanwhile, establishing long-term market signals for low-carbon solutions will be important to pull new investors and innovators into the nascent carbon management sector. To address all of these issues, coordinated and targeted policy solutions are needed in several key areas: (1) technology development and demonstration, (2) tax credits, (3) early markets, (4)

[11] Eric Redman (2020) "A review of Federal efforts to demonstrate carbon capture and storage with commercial-scale coal-based power plants (2003–2016)." *American Energy Innovation Council and the Bipartisan Policy Center*. (accessed 14 July 2021) Retrieved from: http://americanenergyinnovation.org/wp-content/uploads/2020/06/The-Mixed-Success-of-the-Carbon-Capture-Demonstrations.pdf

[12] Varun Sivaram (2020) "The American Recovery & Reinvestment Act and the Rise of Utility-Scale Solar Photovoltaics: How U.S. Public Policy During the Great Recession Launched a Decade-Long Solar Boom." *American Energy Innovation Council and the Bipartisan Policy Center*. (accessed 14 July 2021) Retrieved from: http://americanenergyinnovation.org/wp-content/uploads/2020/06/The-Successful-Demonstration-of-Utility-Scale-PV.pdf

[13] Scott Waldman (2021) "Republicans to unveil a GOP-only climate caucus." *E&E News.* (accessed 14 July 2021) Retrieved from: https://www.eenews.net/stories/1063734621

[14] Business Roundtable. (2020) "Addressing Climate Change: Principles and Policies." (accessed 14 July 2021) Retrieved from: https://s3.amazonaws.com/brt.org/Business-RoundtableAddressingClimateChangeReport.September2020.pdf

[15] Jon Krosnick and Bo MacInnis (2020) "Climate Insights 2020: Overall Trends. Surveying American Public Opinion on Climate Change and the Environment." *Resources for the Future.* (accessed 14 July 2021) Retrieved from: https://www.rff.org/publications/reports/climateinsights2020/

[16] Reuters. (2021) "Chevron to build California carbon capture plant with Microsoft, Schlumberger." (accessed 14 July 2021) Retrieved from: https://www.reuters.com/article/us-chevron-renewables-mendota/chevron-to-build-california-carbon-capture-plant-with-microsoft-schlumberger-idUSKBN2AW1UB

[17] GlobeNewswire. (2021) "Green Plains Announces Carbon Sequestration Partnership with Summit Carbon Solutions." (accessed 14 July 2021) Retrieved from: https://www.globenewswire.com/news-release/2021/02/18/2178062/0/en/Green-Plains-Announces-Carbon-Sequestration-Partnership-with-Summit-Carbon-Solutions.html

[18] GlobeNewswire. (2020) "Oxy Low Carbon Ventures, Rusheen Capital Management create development company 1PointFive to deploy Carbon Engineering's Direct Air Capture technology." (accessed 14 July 2021) Retrieved from: https://www.globenewswire.com/en/news-release/2020/08/19/2080502/0/en/Oxy-Low-Carbon-Ventures-Rusheen-Capital-Management-create-development-company-1PointFive-to-deploy-Carbon-Engineering-s-Direct-Air-Capture-technology.html

[19] William Fleeson (2021) "ExxonMobil unveils vision for $100-bil Texas carbon capture hub." *IHS Markit.* (accessed 14 July 2021) Retrieved from: https://ihsmarkit.com/research-analysis/exxonmobil-unveils-vision-for-100billion-carbon-capture-hub.html

[20] Peter Psarras et al. (2020) "Cost Analysis of Carbon Capture and Sequestration from US Natural Gas-Fired Power Plants." *Environmental science & technology* 54.10: 6272–6280. https://doi.org/10.1021/acs.est.9b06147

financing options, (5) enabling infrastructure, and (6) carbon accounting (Fig. 2).

(1) Invest in technology development and demonstration

Increased R&D – The United States has fallen behind in energy R&D investments. According to a recent report, it no longer makes the list of top 10 countries for energy innovation.[21] Though still a global leader in the carbon management arena, capitalizing on this position will require expanded investments to advance low-carbon technologies. By spurring innovations in materials science, chemistry, systems engineering, and other critical areas, such investments can lower costs and unlock entirely new methods for managing carbon and reaching net zero.

Demonstration Projects – Bridging the gap from earlier stage development to broader commercial adoption requires a risk-tolerant approach to scaling advanced technologies. Pilot projects and first-of-a-kind commercial demonstrations of novel carbon management technologies are essential to create a track record, drive down costs, and mobilize private-sector investments and broader deployment efforts. The Energy Act of 2020, which was incorporated in end-of-year omnibus budget legislation in 2020, authorized several robust carbon management programs at DOE, including a prize competition for commercial- and pilot-scale DAC demonstrations. A similar focus on demonstrating and deploying carbon management solutions is reflected in the current administration's American Jobs Plan, which Congress will consider in the coming months.

(2) Enhance the 45Q tax credit

As discussed earlier, the 45Q tax credit is the federal government's primary policy tool for incentivizing CCS deployment today. Absent a broader policy to create market value for avoided carbon emissions, the 45Q program needs to be reformed.

Higher credit values – While some applications of point-source carbon capture are cost-competitive at the level of the current 45Q credit (examples typically involve high-concentration settings, such as ethanol production, natural gas processing, ammonia production, and some chemical processes), the current credit is insufficient to overcome cost barriers to most point-source capture methods, especially at facilities that emit CO_2 at lower concentrations. The Great Plains Institute has calculated these lower-concentration facilities account for about 84 % of the point-source CO_2 emissions that are potentially capturable in the United States over the near and medium term (about 300 million metric tons per year).[22] Raising the value of the 45Q credit would go a long way to support these forms of point-source capture. More generally, higher credit values for all forms of CO_2 storage and utilization—including EOR—should be prioritized at this early stage in the development of a carbon management industry.

Direct Air Capture, in contrast to point-source capture, involves pulling CO_2 from the lowest-concentration reservoir of all: the atmosphere. DAC costs have declined significantly over the last decade but remain well out of range of the existing 45Q tax credit. Establishing a higher credit value for Direct Air Capture based on its capture costs and unique value to carbon mitigation is also important and justified.

Expand Eligibility – Currently power plants have to capture at least 500,000 tons of CO_2 per year to be eligible for the 45Q tax credit (a capture requirement of 100,000 tons per year applies to industrial facilities, DAC projects, and EOR applications). This requirement excludes smaller-scale capture and removal operations and thus dampens incentives for innovation and experimentation. Eliminating current capture requirements will make the credit far more effective.

Extend credit – The current credit is available only to projects that commence construction by January 1, 2026. Extending this window of availability and allowing project developers to claim the credit over a longer period of time would help resolve some of the main development and financing obstacles that face new projects.

Direct Pay – Currently, most CCS developers must turn to tax equity markets to monetize the value of the 45Q tax credit. This has proved complex and expensive, because tax equity providers often extract a significant portion of the credit value in exchange for providing cash to projects while using the credits to offset their own tax liabilities.[23] To remove this hurdle, Congress should allow project developers to opt for a "direct payment" in lieu of the tax credit (this has been done in the case of tax credits for renewable energy projects).

Congress is currently considering adjustments to the 45Q tax credit in all of these areas.

(3) Support early markets for carbon management technologies

Procurement – Success in early deployment is best assured by developing a diverse portfolio of revenue streams for projects that capture and use or store CO_2. The government can also enhance market certainty by leveraging its purchasing power to increase demand for low-carbon products and carbon capture services. This can be done at the federal level through the General Services Administration (GSA); it can also be done at the state level (e.g. California's Buy Clean program).

Clean Electricity Standard – A clean energy standard could be designed to spur the deployment of CCS technologies as well as zero-carbon generation sources by recognizing carbon capture and storage as a compliance option for meeting low-carbon emissions requirements.

(4) Financial support

Deploying carbon management technologies on a meaningful scale will require more than a single federal tax credit with a limited time horizon. Beyond improving the 45Q program and leveraging government procurement, a broad array of "stackable" financing options is needed. Existing tools that could be tailored to support carbon capture and removal projects include *master limited partnerships*, which are favorable tax structures that have been used since the 1970s, mostly by oil and gas companies, and *private activity bonds*, which are administered by state and local governments. DOE's Loan Programs Office can also play a large role in helping to overcome financing hurdles.

Additional tax credits beyond 45Q should be explored – including the possibility of a separate tax credit for DAC projects or natural gas power plants with carbon capture and storage. The section 48 investment tax credit should also be expanded to support a broader range of carbon management approaches, including pre-combustion capture and removal technologies.

New and existing financing options should be viewed as complements, rather than substitutes. For many projects, combining or "stacking" multiple incentives and financing tools will be essential to create a viable business case. Thus, the introduction of new forms of financing assistance should not be viewed as a reason to let existing

[21] NewTechMag. (2021) "Bloomberg Innovation Index 2021: Brazil, the most innovator in LatAm." (accessed 14 July 2021) Retrieved from: http://newtechmag.net/2021/03/06/bloomberg-innovation-index-2021-brazil-the-most-innovator-in-latam/

[22] Elizabeth Abramson et al. (2020) "Transport Infrastructure for Carbon Capture and Storage." *Regional Carbon Capture Deployment Initiative and the Great Plains Institute*. (accessed 14 July 2021) Retrieved from: https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf

[23] Bipartisan Policy Center. (2011) "BPC Study Finds Opportunity for More Efficient Federal Renewable Energy Incentives; Treasury Cash Grants Twice as Effective as Tax Credits for Wind and Solar." (accessed 14 July 2021) Retrieved from: https://bipartisanpolicy.org/press-release/bpc-study-finds-opportunity-more-efficient-federal-renewable-energy/

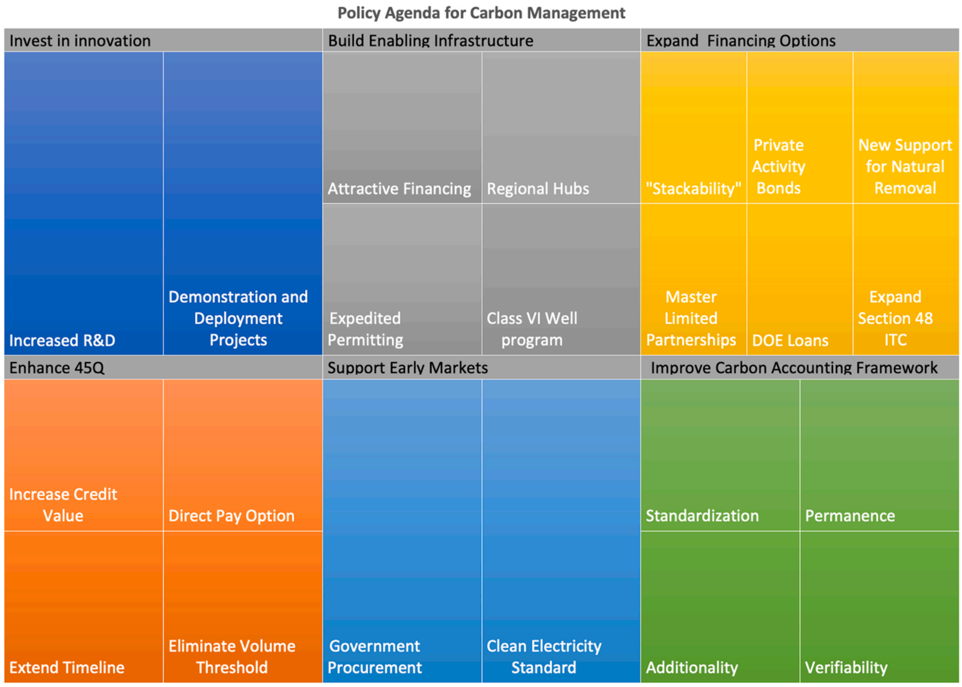

Fig. 2. A gigaton-scale carbon management policy agenda.

supports lapse.

Finally, incentive programs or other market frameworks are needed to encourage afforestation and agricultural practices that increase carbon uptake by natural systems. These biogenic carbon removal strategies have the added potential to support rural economies and improve local environmental conditions.

(5) Enabling infrastructure

An underappreciated component of building a net-zero economy is supporting the broad deployment of enabling infrastructure, including CO_2 pipelines and geologic storage hubs. Fortunately, early investments in this type of infrastructure will pay dividends for decades to come, by driving down costs for future carbon management projects. Durable policy solutions will be needed to motivate sustained infrastructure buildout over time, including the development of a modernized and efficient regulatory system. Beyond financing assistance, permitting improvements to accelerate deployment and efforts to resolve long-term liability uncertainties for onshore and offshore geologic sequestration will be needed. Additionally, a greater focus on (and funding for) EPA's Class VI well program is necessary to unlock saline sequestration at the necessary scale.

(6) Carbon Accounting

To create the right incentives and measure progress over time, a careful accounting of how different activities affect fluxes of carbon into and out of the atmosphere will be essential. Inconsistencies in the accounting frameworks applied to past offset projects and uncertainty around the actual impact of these projects on long-term emissions have been problematic.[24] Developing transparent, uniform standards for measuring the verifiability, permanence, and additionality of carbon management practices, and building public and stakeholder trust in those standards, is an integral part of the long-term climate agenda.

Implementing sound carbon accounting practices will require merging assessments of natural and engineered projects and integrating extensive expertise from the fields of land management, soil science, geology, and engineering. Frameworks and methodologies that have been developed for existing carbon markets have a role to play but consolidation across different carbon management practices is needed. A common, scalable accounting framework would provide greater investment certainty and help clarify differences in the climate mitigation benefits achieved by various engineered, hybrid, and natural carbon management solutions.

4. Conclusion

As a complement to the rapid scaleup of zero-emissions energy sources, the successful commercialization and large-scale deployment of an array of carbon capture and removal technologies is critical to meet national and international climate goals while growing the economy and protecting American workers and consumers. Leadership in developing these technologies will also open export opportunities for American companies. The policy agenda outlined here offers a roadmap for scaling carbon management systems. Its key elements include: (1) increased public investment to advance needed carbon management options and build out the necessary enabling infrastructure, (2) focused efforts to establish a trusted and verifiable regulatory framework; and (3) enhanced coordination among stakeholders and across relevant government agencies. The business community, for its part, has an important role to play in designing and building carbon management solutions, in advancing creative business models for carbon management projects, and in supporting well designed programs and policies. As the successful commercialization of other advanced technologies has frequently demonstrated, a combination of tailored policies and strong collaboration between the public and private sectors is likely to deliver the best results.

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[24] Grayson Badgley et al. (2021) "Systematic over-crediting of forest offsets." (accessed 14 July 2021) Retrieved from: https://carbonplan.org/research/forest-offsets-explainer

the public, commercial, or not-for-profit sectors.

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