PNAS OPINION

How to design better incentives for carbon capture and storage in the United States

Sheila M. Olmstead[a,b,c,1], Benjamin D. Leibowicz[d], Charles F. Mason[c,e], Andrew R. Waxman[f], Emily Grubert[g], HR Huber-Rodriguez[h], and Joseph Stemmler[i]

Affiliations are included on p. 4.

The current Carbon Capture, utilization, and Storage (CCS) tax credit in the United States is unlikely to incentivize emissions reduction at a reasonable cost. Incentives for CCS should be redesigned to address counterproductive CO_2 emissions incentives in the short run and the long run, as well as potential impacts on local pollutants that affect human health. Image credit: Science Source/Victor de Schwanberg

Carbon capture, utilization, and storage (CCS) technologies trap carbon dioxide (CO_2) from power plants and industrial facilities and either use or store it underground.* Subsidies to support these technologies were an important component of the Biden Administration's strategy to reach net-zero emissions by 2050 and offer a path for power plants to comply with US greenhouse gas (GHG) emission standards.

Even if Biden-era GHG standards for power plants are repealed by the current administration, generous federal tax incentives may lead some power plants to deploy CCS anyway—and use at industrial plants in multiple sectors is already under way. Moreover, the staying power of federal support for CCS through multiple administrations with very different views on climate policy suggests that continued support is likely (note that at the time of this writing, the budget bills in both the US House of Representatives and the US Senate retain or even enrich subsidies for CCS, even while they cut those for most other clean energy technologies). Although deployed CCS capacity is small, the United States currently has more than any other nation (1). Fifteen US CCS projects already operate at commercial scale, and another eight are under construction.† Nearly all this new deployment is supported by a

*We use the term CCS instead of the broader carbon capture, utilization, and storage (CCUS) for brevity, though we include an important type of utilization—enhanced oil recovery (EOR)—in our discussion.

†See the Global CCS Institute, CO_2RE Facilities Database at: https://co2re.co/FacilityData (accessed 13 February 2024).

Author contributions: S.M.O., B.D.L., C.F.M., A.R.W., E.G., H.R.H.-R., and J.S. designed research; performed research; analyzed data; and wrote the paper.

The authors declare no competing interest.

[1]To whom correspondence may be addressed. Email: solmstead@cornell.edu.

Published July 16, 2025.

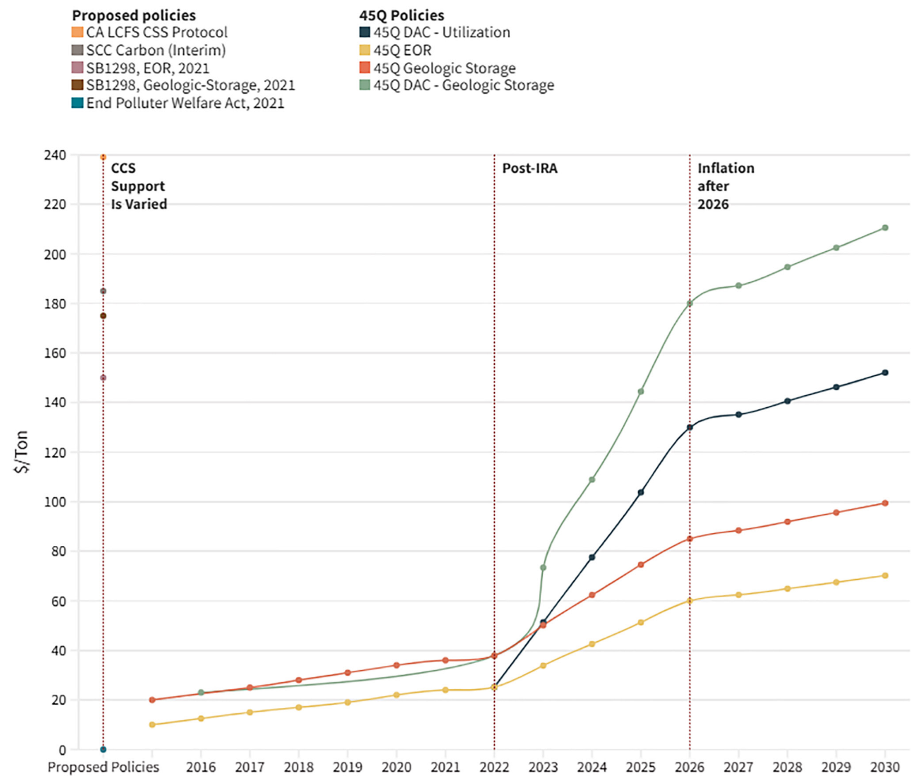

Fig. 1. **Section 45Q CCS subsidy history and alternative proposals. Per-tonne subsidies (in dollars) for carbon capture under Section 45Q of the US Internal Revenue Code are plotted over time from 2015-2030, with the subsidy for pre-and post-combustion CO_2 capture for enhanced oil recovery (EOR) in yellow, geologic storage in orange, direct air capture (DAC) for utilization in blue, and DAC for geologic storage in green. Incentives for all four types of carbon capture increase with the 2022 Inflation Reduction Act (IRA) and then increase at the rate of inflation after 2026. At left, plotted points identify per-tonne subsidies for CCS in pre-IRA legislative proposals that did not become law.**

federal subsidy—the tax credit for CO_2 sequestration under Section 45Q of the Internal Revenue Code—which was significantly increased in 2022 via the Inflation Reduction Act (IRA) (Fig. 1).

This tax credit has received bipartisan support—a rarity for climate-focused policy in the United States. Recently, however, legislators on both sides of the aisle have questioned whether it should continue. We argue that the 45Q tax credit is unlikely to incentivize emissions reduction at a reasonable cost and that incentives for CCS in the United States should be redesigned. A redesign of 45Q should address three problems: counterproductive CO_2 emissions incentives in the short run and the long run; and potential impacts on local pollutants that affect human health.

A CCS Subsidy

Decarbonization "carrots"—subsidies for emissions-reducing technologies and behaviors—play a greater role in US climate policy than "sticks" such as carbon pricing (2, 3) that are more common in Canada, China, and the European Union (EU). Why carrots in the United States? Three primary reasons: failed attempts at pricing carbon at the national level, several empirical studies suggesting that carrots offer a more feasible path to deep emissions reductions (4–7), and a polarized Congress that has prioritized taking action via the federal budget reconciliation process rather than direct lawmaking.

Subsidies are attractive because CCS is costly and generates no direct revenue in most applications. Some types of subsidies for CCS have strong economic justification. For example, governments can justify subsidies for research and development because the benefits of CCS innovations spill over within the industry through patents and research publications, a shared labor force, and informal communication. In addition, when firms cooperate to build CO_2 collection infrastructure (as ethanol producers are proposing in the Midwest, for example), this reduces costs. Markets don't tend to incentivize an efficient level of such cooperation, offering justification for government support.

The 45Q tax credit is not for research and development or networked infrastructure, however; instead, it pays firms to reduce emissions. Fig. 1 shows the evolution of the 45Q tax credit over time and compares 45Q to other recent US legislative proposals. The US Congress established the 45Q tax credit in 2008, starting at \$20/tonne of CO_2 for geologic sequestration.[‡] The Bipartisan Budget Act of 2018 ramped up the 45Q incentive to \$50/tonne. In 2022, the IRA further increased the tax credit to \$85/tonne.

What does that mean in practice? Recent estimates suggest a total fiscal cost of the IRA's increase in 45Q exceeding \$100 billion through 2031 (8). For a single 500-megawatt, coal-fired power station, payments would amount to \$3 billion to \$4 billion over 12 years (9).

At its current level of \$85/tonne, the 45Q tax credit could certainly lead to much more rapid US deployment of CCS (10, 11). Multiple models suggest that the increased 45Q subsidy is sufficient to incentivize retrofits of power plants and industrial facilities with CCS, with total predicted CO_2 storage ranging from 200 to 800 million tonnes annually (9, 12, 13). Suitable

[‡]Technically the subsidy is per tonne of "qualified carbon oxide," though we refer to CO_2 throughout the paper.

storage locations roughly track with the presence of saline aquifers and depleted oil and gas reservoirs, especially along the Gulf Coast and in the Midwest and California.

However, CCS differs from other decarbonization technologies in some critical respects relevant to the design of 45Q. First, ongoing market intervention of some kind (subsidies, CO_2 prices, or emissions standards) will be required to make CCS economically rational for most emitting firms. CCS is expensive both to build and to operate. Unlike subsidies for capital deployment that support a marketable commodity with low operational costs (e.g., wind farms producing electricity), CO_2 subsidies are unlikely either to be replaced by private demand for a product or to become unnecessary once the capital investment is paid off. Small, private CCS incentives exist in California and in the Regional Greenhouse Gas Initiative states in the form of carbon prices and where firms use CO_2 for enhanced oil recovery (14). The marginal cost of CCS is higher than CO_2 prices in these areas, however (11).

This leads to two important implications. First, government policy literally creates the market for CCS, so any deployment incentivized by a temporary subsidy will eventually cease to generate climate benefits. Firms that deploy CCS due to the subsidy are likely to stop capturing carbon when the subsidy expires (similar to the way in which a large coal-fired power plant in Texas that captures CO_2 for enhanced oil recovery shut down its capture unit when the price of oil fell during the COVID-19 pandemic). Second, the need for an ongoing government CCS incentive represents a fiscal challenge that becomes steeper as more firms take up the incentive (15). Thus, policymakers now face an unpleasant trade-off with CCS subsidies: extend them beyond the planned 12 years and risk fiscally unsustainable payments or eliminate them on schedule and see facilities revert to releasing CO_2 into the atmosphere.

The most important difference between 45Q and other US federal decarbonization subsidies is the fact that the government pays the tax credit to emitting firms on a dollar-per-tonne basis. Thus, the firms with the highest emissions are eligible for the largest government support. For example, under the \$85/tonne incentive, 45Q currently awards about \$100 per megawatt hour for coal generation and about \$40 per megawatt hour for gas generation, rewarding coal's greater carbon intensity. Even without an extension of the current 12 years of availability, most of the US coal-fired power plants with the highest potential 45Q values could receive payments between \$10 billion and \$20 billion (13). There's no other major US pollution control policy that's designed this way.

Perversely, the subsidies disincentivize development of technologies to reduce the carbon intensity of electricity or industrial production because facilities will receive fewer dollars for reducing CO_2 emissions that can be stored—with the added complexity that carbon capture is easier for higher CO_2 concentrations. Based on this analysis, we argue that the current system has three major design flaws.

Serious Drawbacks

The first flaw is that fossil power and other CCS retrofits may increase emissions under 45Q. This may seem counterintuitive, because firms installing CCS may capture most of their CO_2 emissions. For example, a common capture technology for power plants and many industrial facilities, aqueous amine absorption, has a unit cost that is approximately constant between 80% and 95% removal (16), so adopting firms are likely to meet or exceed 45Q's required 75% capture design capacity requirement. However, once a polluting facility installs CCS, the tax credit earned under 45Q reduces the facility's average cost of production, which will tend to increase its output and thus its CO_2 emissions. That's because firms make output choices based on their own costs, as well as market prices (17, 18).

For example, a coal-fired power plant that has installed CCS and obtains the tax credit would likely produce more electricity over the course of a year than it would without CCS; even during hours with low electricity prices, the 45Q subsidy could make it profitable for the plant to generate. Moreover, carbon capture requires energy, which creates additional CO_2 that can be stored and subsidized, without linking subsidized emissions to a pre-IRA baseline. Thus, in theory, facilities can increase emissions to maximize storage and 45Q payments, with no incentive to continue capture after the 12-year tax credit expires (13).

The second flaw is that 45Q will alter the entry and exit incentives for power plants and industrial facilities in a way that favors carbon intensity. Polluting facilities that would've been unprofitable with a price on carbon will actually earn a profit with an equivalent 45Q subsidy that covers CCS costs, thus keeping them in an industry they would otherwise exit (17, 19). It's too early to evaluate this impact of 45Q on industry dynamics with observational data—few US CCS facilities are currently operating, the 45Q incentive has only recently been high enough to make CCS a viable enterprise, and CCS projects are major capital investments that take years to develop. But if, for example, 45Q incentivizes coal plants to stay in the generation mix rather than retire, this could increase emissions. Indeed, 45Q uptake is more highly incentivized for coal-fired than for gas-fired power plants, in part because of higher emissions and higher flue gas CO_2 concentrations (13). A recent analysis of IRA's impacts projects significant induced coal generation with CCS, but little induced natural gas generation with CCS (9).

The third design flaw is that 45Q may generate human health damages from local air pollution. Carbon-intensive facilities often emit other air pollutants as well. CCS can reduce direct emissions of sulfur dioxide, nitrogen oxides, and particulate matter, but when facilities adopt postcombustion carbon capture technology, ammonia emissions may rise (20). The result: an uptick in the secondary formation of fine particulate matter (21). Due to this phenomenon, a particular concern for industrial facilities and natural gas power plants (22), the global climate benefits from 45Q may be offset by localized human health costs. And even though coal-fired power plants that deploy CCS may reduce their impact on human health (22), 45Q could provide sufficient support to keep them open and stop them from being replaced by cleaner generation.

Taken together, these three design flaws mean that the 45Q subsidy will have an uncertain, and potentially undesirable, effect on US CO_2 emissions. It may also lead to new public health worries.

Capturing Viable Solutions

How, then, can these challenges be addressed? An obvious fix from an economic, if not political, perspective would be to tax CO_2, which would prompt CCS deployment where it is cost-effective, without the counterproductive dynamic effects on industry composition and (possibly) emissions. Although not likely to be politically feasible, such a tax would likely increase CCS deployment in the industrial sector (though perhaps not in the power sector, where renewables are often cheaper alternatives). A CCS mandate could also reduce emissions (23, 24), but this would be more costly and seems no more likely politically than a tax.

A more viable policy fix would correct the most significant downside to 45Q: the fact that it rewards carbon-intensive production. To correct this, 45Q could be paid per unit of production, meeting strict emissions standards (for example, per megawatt hour for fossil-fired power plants), rather than per unit of captured emissions. This approach is consistent with the 45V hydrogen tax credit, which determines subsidy eligibility based on life-cycle emissions.

Hybrid approaches to policy redesign may also work. For example, policymakers could adjust the 45Q structure so that it does not favor carbon-intensive production and *also* price uncaptured CO_2 emissions. This would provide carrots to CCS-adopting facilities (perhaps retaining political support compared to a carbon price alone) and would reduce emissions. (However, this pair of policies would be more expensive for taxpayers than a carbon price alone.)

Another hybrid approach would reduce the level of the 45Q incentive to soften the subsidy's counterproductive dynamic effects and better contain fiscal costs and would pair this change with an investment tax credit to reduce the costs of installing CCS. This would enable projects to recoup more of their costs upfront and make them less exposed to future policy risk, though ongoing 45Q payments would still have to cover the operating costs of capture.

Finally, to avoid local air pollution trade-offs, policymakers would need to directly address the potential for CCS technologies to increase ammonia emissions and worsen human health. Secondary water washes and other treatment options are available but are not currently mandated for this purpose. And they're costly, so firms are unlikely to employ them unless required.

Clearly, the ambiguous impacts of the unusual environmental subsidy embodied in 45Q require urgent attention from policymakers. If the 45Q incentive is retained and enriched over time as it has been through successive administrations of both parties, it will almost certainly increase US CCS deployment. Unfortunately, it won't do so in a cost-effective manner and may encourage counterproductive emissions increases of CO_2 and local air pollution. We need a rethink and redesign that reduces CO_2 emissions with fewer unintended negative consequences.

ACKNOWLEDGMENTS. Financial support was provided by Alfred P. Sloan Foundation Grant G-2021-14150. We are grateful to Daniel Steinberg for comments and to Chris Deranian for excellent research assistance.

Author affiliations: [a]Jeb E. Brooks School of Public Policy, Cornell University, Ithaca, NY 14853; [b]Atkinson Center for Sustainability, Cornell University, Ithaca, NY 14853; [c]Resources for the Future, Washington, DC 20036; [d]Operations Research and Industrial Engineering, Cockrell School of Engineering, University of Texas at Austin, Austin, TX 78712; [e]Department of Economics, College of Business, University of Wyoming, Laramie, WY 82071; [f]LBJ School of Public Affairs, University of Texas at Austin, Austin, TX 78712; [g]Keough School of Global Affairs, University of Notre Dame, Notre Dame, IN 46556; [h]Beveridge & Diamond PC, Austin, TX 78701; and [i]CO_2RE Hub, Smith School of Enterprise & Environment, Oxford University, Oxford OX1 3QY, United Kingdom

1. International Energy Agency (IEA), "Energy technology perspectives: Special report on carbon capture, utilisation and storage: CCUS in clean energy transitions (Tech. Rep., International Energy Agency, 2020).
2. E. Narassimhan, S. Koester, K. S. Gallagher, Carbon pricing in the US: Examining state-level policy support and federal resistance. *Polit. Gov.* **10**, 275–289 (2022).
3. R. G. Newell, W. A. Pizer, D. Raimi, U.S. federal government subsidies for clean energy: Design choices and implications. *Econ.* **80**, 831–841 (2019).
4. J. Meckling, N. Kelsey, E. Biber, J. Zysman, Winning coalitions for climate policy. *Science* **349**, 1170–1171 (2015).
5. J. Meckling, T. Sterner, G. Wagner, Policy sequencing toward decarbonization. *Nat. Energy* **2**, 918–922 (2017).
6. M. Pahle *et al.*, Safeguarding the energy transition against political backlash to carbon markets. *Nat. Energy* **7**, 290–296 (2022).
7. M. Mildenberger, *Carbon Captured: How Business and Labor Control Climate Politics* (MIT Press, Cambridge, MA, 2020).
8. W. Mathis, A. Rathi, US Climate Bill's Subsidy Bonanza Gives New Allure to Carbon Capture. Bloomberg Green, 23 August (2022). https://www.bloomberg.com/news/articles/2022-08-23/us-climate-bill-s-subsidy-bonanza-could-boost-investment-in-carbon-capture?embedded-checkout=true. Accessed 8 July 2025.
9. J. Bistline *et al.*, Emissions and energy impacts of the Inflation Reduction Act. *Science* **380**, 1324–1327 (2023).
10. J. Edmonds *et al.*, Could congressionally mandated incentives lead to deployment of large-scale CO_2 capture, facilities for enhanced oil recovery CO_2 markets and geologic CO_2 storage? *Energy Policy* **146**, 111775 (2020).
11. A. Waxman, S. Corcoran, A. Robison, B. Leibowicz, S. Olmstead, Leveraging scale economies and policy incentives: Carbon capture, utilization and storage in Gulf clusters. *Energy Policy* **156**, 112452. (2021).
12. U.S. Environmental Protection Agency (USEPA), Electricity sector emissions impacts of the Inflation Reduction Act. (September (2023). https://www.epa.gov/system/files/documents/2023-09/Electricity_Emissions_Impacts_Inflation_Reduction_Act_Report_EPA-FINAL.pdf. Accessed 9 February 2024.
13. E. Grubert, F. Sawyer, US power sector carbon capture and storage under the Inflation Reduction Act could be costly with limited or negative abatement potential. *Environ. Res. Infrastruct. Sustain.* **3** (150AD08).
14. S. Gao, C. Hou, L. Zhao, On the economics of CO_2 contracts in the enhanced oil recovery industry. *J. Appl. Econ.* **25**, 802–818 (2022).
15. J. Bistline, N. Mehrotra, C. Wolfram, Economic implications of the climate provisions of the Inflation Reduction Act. *Brook. Pap. Econ. Act.* **2023**, 77–157 (2024).
16. T. Gao, J. L. Selinger, G. T. Rochelle, Demonstration of 99% CO_2 removal from coal flue gas by amine scrubbing. *Int. J. Greenhouse Gas Control* **83**, 236–244 (2019).
17. W. J. Baumol, W. E. Oates, *The Theory of Environmental Policy* (Prentice-Hall, Englewood Cliffs, NJ, 1975).
18. M. I. Kamien, N. L. Schwartz, F. T. Dolbear, Asymmetry between bribes and charges. *Water Resour. Res.* **2**, 147–157 (1966).
19. D. F. Bramhall, E. S. Mills, A note on the asymmetry between fees and payments. *Water Resour. Res.* **2**, 615–616 (1967).
20. J. Koornneef *et al.*, The impact of CO_2 capture in the power and heat sector on the emission of SO_2, NOx, particulate matter, volatile organic compounds and NH_3 in the European Union. *Atmos. Environ.* **44**, 1369–1385 (2010).
21. K. M. Jablonka *et al.*, Machine learning for industrial processes: Forecasting amine emissions from a carbon capture plant. *Sci. Adv.* **9**, eadc957 (2023).
22. A. Waxman, H. R. Huber-Rodriguez, S. M. Olmstead, What are the likely air pollution impacts of carbon capture, utilization and storage? *J. Assoc. Environ. Resour. Econ.* **11** (S1), S111–S155 (2024).
23. C. Fischer, S. W. Salant, Alternative climate policies and intertemporal emissions leakage: Quantifying the green paradox. in *Resources for the Future Discussion Paper 12–16* Washington, DC (2012).
24. M. R. Allen, D. J. Frame, C. F. Mason, The case for mandatory sequestration. *Nat. Geosci.* **2**, 813–814 (2009).