Measuring the Welfare and Distributional Effects of Co-Benefits of Carbon Capture, Utilization and Storage Technology

Andrew R. Waxman and Sheila Olmstead, UT Austin

Introduction & Motivation

President Joe Biden's climate plan calls for net-zero carbon pollution from the U.S. electricity sector by 2035. Because coal and natural gas currently account for 60% of U.S. power generation, a key component of this (and other net-zero carbon plans) is incentivizing expansion of carbon capture, utilization and storage (CCUS) technologies through new research funding and tax incentives (Magill 2020).[1] There is a clear economic rationale for this strategy. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report suggests that excluding CCUS from the global portfolio of emissions-reducing technologies would more than double the cost of avoiding a 2-degree C increase in global mean temperature (IPCC 2014).

There are three reasons for this economic and practical importance of CCUS to climate policy: one, as distinct from alternative large-scale mitigation technologies, such as hydrogen fuel cells, "geologic sequestration is ready for large-scale deployment" as stated by a recent National Academies report (National Academies 2019, p. 8).[2] Two, the technology is potentially well-suited to recover carbon dioxide (CO_2) from industrial emissions, where complete substitution for low- or zero-carbon technologies may be cost-prohibitive. Industrial sources emitted 22% of U.S. greenhouse gases in 2018 (EPA 2019), and just over 30% of GHGs worldwide in 2010 (IPCC 2014). Greenhouse gas (GHG) mitigation in the industrial sector is difficult to obtain through electrification because returns to scale in the most carbon-intensive sectors (steel, cement and petrochemicals) limit the cost-effectiveness of electrified systems (Mikunda 2014). Three, power-sector CCUS would contribute to ongoing decarbonization in electricity generation and also indirectly contribute to decarbonization in transportation, via an increasing share of electric vehicles in the fleet. Four, as shown in Kuby, et al. (2011) and Waxman et al. (2020b), due to industrial clustering of major CO_2 sources and potentially large cost savings from coordination in CO_2 pipeline networks, CCUS development is likely to be characterized by substantial economies of scale, which has important implications for the research proposed.

An important unconsidered aspect of CCUS deployment is its effect on the local air pollution (LAP) impacts of CO_2 abatement, so-called climate co-benefits. The potential local air pollution impacts of CCUS are

[1] CCUS involves either the re-use of CO_2 (for example, through enhanced oil recovery) or store it in deep geological formations so that it will not enter the atmosphere and generate climate damages.

[2] Although questions remain about the physical science of storage, large-scale injection has been practiced for 50 years, and decades of studies support the assertion that it is sufficient to advance.

heterogeneous. For example, sulfur dioxide (SO_2) emissions may decline with carbon capture (Harmelen et al. 2011), while ammonia emissions may increase (Heo et al. 2015). Allam cycle natural gas electricity generation, which provides relatively pure streams of CO_2 that make CCUS more cost-effective than for other technologies, also produces lower levels of particulate matter (PM) (NETL 2019). Local air pollution can create larger damages than GHG externalities, given impacts of PM and other local pollutants on human health (Buonocore et al. 2016, Aldy et al. 2020a). Moreover, given policy concerns about racial and socioeconomic disparities in U.S. pollution exposure and the fact that industrial and power facilities are often located in communities of color (Depro et al. 2015, Muller et al. 2018), increased CCUS deployment may have important distributional implications. Finally, given the aforementioned large scale economies in CCUS deployment, there is reason to believe that potential LAP effects of CCUS could be heavily concentrated in areas with substantial power generation or industrial build-up, creating the potential for mitigation or aggravation of pollution "hot spots" that have been an important focus of recent research in this area (Shapiro and Walker 2021).

Despite the fact that CCUS has been highlighted as a critical area for future research for some time, there is limited direct treatment of CCUS in the economics literature (Anderson and Newell 2004, Heutel et al. 2016).[3] Prior work describes the role of CCUS in the portfolio of mitigation technologies for effective decarbonization (Heal 2009, Barrett 2008, 2009, Barrett and Moreno-Cruz 2015). Additional work has thought more broadly about policies to decarbonize industrial emissions (Löfgren et al. 2020, Rissman 2020). CCUS has also been incorporated into some integrated assessment models and computable general equilibrium models used to estimate climate change damages and the impacts and cost-effectiveness of policy approaches to climate mitigation (McFarland and Herzog 2006, Gerlagh and van der Zwaan 2006, Kalkuhl et al. 2015, Durmaz and Schroyen 2019). At the global level, for example, Kalkuhl et al. (2015) find that in the presence of lower-than-optimal and/or delayed carbon pricing, a combination of CCUS subsidies and renewable energy subsidies is more cost-effective than approaches relying solely on either of these two second-best policy instruments. Recent theoretical work has focused on the importance of learning-by-doing in reducing CCUS costs over time, and in determining the optimal intertemporal deployment of renewables and fossil energy generation with CCUS (Amigues et al. 2016). The potential for CCUS paired with enhanced oil recovery (EOR) has also been explored (Leach et al. 2011, van 't Veld et al. 2013). We know of no prior work in the economics literature examining the local air pollution tradeoffs from policies that incentivize CCUS compared to other approaches to GHG emissions mitigation.

Research Plan & Data

[3] In contrast, there is a larger economics literature on terrestrial carbon sequestration via forests and agriculture.

The proposed work will examine the potential co-benefits and/or co-damages of local air pollution exposure (Aldy et al. 2020b) from increased reliance on CCUS, including environmental justice outcomes. First, we will build on existing inventories of the local air pollution footprint of U.S. fossil fuel generation and industrial production (EPA. 2019). To measure co-benefits, we will evaluate both exposure and impact via potential health effects. To calculate baseline exposure, we will use EPA Constant Emission Monitoring System data augmented by EPA Greenhouse Gas Reporting data. We will then input these data into EPA source-receptor matrices to translate NOx and SO_2, emission rates into pollution concentrations. We will validate this exercise and extend the analysis to other pollutants such as PM and ozone using Aerosol Optical Depth (AOD) satellite data and EPA ground monitor observations (NASA, 2021; EPA, 2021).

Next, we will inventory the emissions profile of existing U.S. CCUS projects, mapped in Figure 1, below. This exercise will help us characterize potential changes in emission profiles on a facility-by-facility basis. For CCUS conversions we will use an event-study approach to characterize changes in emission profiles, while for new or pilot facilities, we will rely on engineering estimates to characterize likely changes in emissions.[4] While it is possible to do this for all U.S. gas- and coal-fired power plants and industrial facilities, many are unlikely to be economically and/or technologically viable for CCUS. As such, we will use an approach piloted in prior work (Waxman et al. 2020b), approximating a CCUS supply curve to identify the set of facilities for which CCUS at scale is likely to be cost-effective given current federal incentives (the so-called 45Q tax credit).

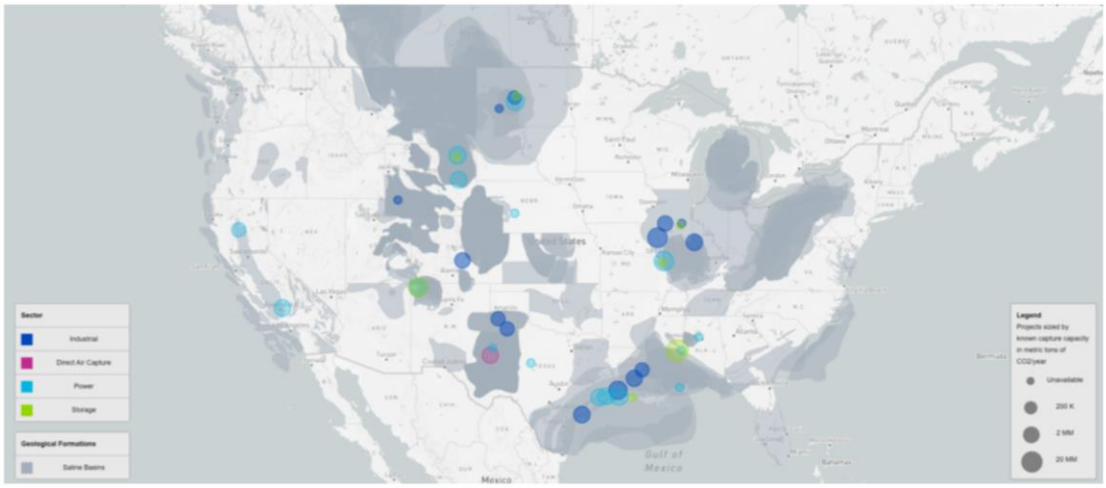


Figure 1. CCUS Projects in the United States. *Source*: Clean Air Task Force

[4] In principle, we could estimate counterfactual pre-CCUS emission levels by matching them to similar non-CCUS facilities, but it is not clear that this exercise would yield credible hypothetical conversion estimates.

Our proposed work requires the estimation of marginal CCUS costs for each U.S. industrial facility and power plant suitable for CCUS. We will follow an approach used by Waxman et al. (2020b) to estimate marginal CCUS costs for industrial facilities in the Texas and Louisiana Gulf Coast region. In that work, currently under review, our approach to calculating costs is bottom-up, based on cost parameterization and CCUS network analysis for the Gulf performed by Tutton (2018), and depends on appropriate technology for each industrial process in our facility inventory. From these aggregate cost estimates, we construct supply curves for CCUS which reflect the marginal cost of abatement using this approach. CO_2 storage location options we examine include onshore depleted oil and gas reservoirs, and nearshore saline aquifers. We also allow cost estimates to vary based on the spatial configurations of pipeline networks. Because heavily-emitting industrial facilities in the Gulf region are geographically concentrated in clusters, we compare a CO_2 transport system that would connect each individual facility directly to a storage location with a networked system with intra-cluster distribution lines connected to common, long-distance transmission pipelines to leverage economies of scale in the pipeline network. We also allow for a range of marginal abatement costs corresponding to variation in estimates of the capital cost of carbon capture technology, which comprises the lion's share of marginal abatement costs. Figure 2 illustrates the estimated supply curves from this prior work, which we plan to replicate for industrial and power plant facilities nationwide.

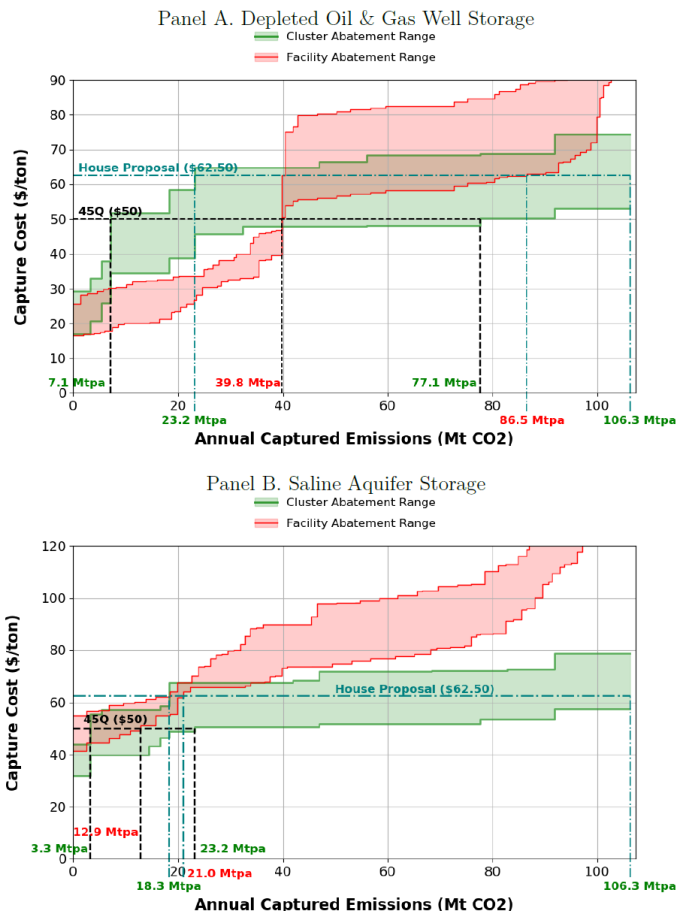


Figure 2. Marginal Abatement Cost Curves for Gulf Coast Industrial CCUS.

Notes: This figure illustrates the range of unit costs of Gulf Coast industrial CCUS relative to total abatement, where unit costs are sorted by facility (or cluster) from left to right by lowest to highest. Panel A calculates costs based on storage in depleted oil and gas wells, while Panel B calculates costs based on storage in deep saline aquifers. The red area corresponds to the range of cost values where CO2 transport is done independently by each facility, while the green area describes the range of values when transport is provided in cluster-level pipeline networks. Black dashed lines show the credit level and cost-effective abatement level under the current level of 45Q by 2026, while dashed blue lines indicate the same values under the higher credit level proposed in the U.S. House of Representatives in February 2020. Green quantities on the horizontal axis indicate cost-effective abatement levels under clustered transport, and red quantities are for facility-level transport. *Source*: Waxman et al. (2020b).

This exercise will help to identify a set of CCUS facilities and pollution streams with corresponding locations. Finally, to understand the impact of the changes and translate them into estimated premature mortality rates, we will use Cox proportional-hazard models following Krewski et al. (2009) and Lepeule et al. (2012). The recent literature on air pollution exposure focuses on its disproportionate effect on low-income and non-white communities (Colmer et al. 2020; Ma 2020). Given the higher relative exposure of these communities to pollution, any reductions (or increases) in local air pollution from CCUS may have a meaningful impact on health disparities and be of critical importance in understanding the environmental

justice implications of CCUS policy. Since CCUS may induce changes in the composition of local air pollution, not just the level, one concern would be so-called "hidden pollution" (i.e., pollution that is harmful to human health but is less noticeable in terms of smog or smell as shown by Bickerstaff & Walker (2001)) that may not be observed by local homeowners and therefore may further exacerbate environmental justice issues (Hausman & Stolper, 2020).

Finally, we will explore the consequences of a set of policy alternatives for CCUS, weighing CO_2 abatement potential relative to local air pollution mitigation. Facility-level estimates of the potential non-GHG emission effects of CCUS will be an important input to any analysis of incentives like 45Q as a component of a decarbonization goal, because the literature demonstrates that market-based incentives that do not account for heterogeneous impact across pollutants can undermine a policy's desired effect (Auffhammer and Kellogg, 2014). Our policy analysis will compare the local air pollution effects from what one might expect with existing CCUS incentives, to what one might expect with a carbon tax, or from pairing CCUS incentives with more stringent regulations of NOx, VOC or SO_2 emissions to reduce local air pollution exposure.

Major Contributions

The proposed work has the potential for several significant contributions to our understanding of the impact of CCUS technology on disparate health outcomes. As described, it would allow us to benchmark the economic benefits of CCUS from GHG emissions relative to reductions in local air pollution, net of expected adoption costs. Second, given the spatial concentration of carbon-intensive facilities for which CCUS is feasible, it would provide the first estimates of the environmental justice implications of CCUS, a key component of any mid-century net-zero carbon target. Lastly, the estimates could provide a guide for potential future modifications to the National Ambient Air Quality Standards (NAAQs) to account for pollution hot spots and the effects of CCUS on pollution concentrations.

Research Team and Qualifications

Andrew Waxman is an Assistant Professor at the Lyndon B. Johnson School of Public Affairs at the University of Texas at Austin. Waxman is an urban and environmental economist whose research uses structural, theoretical and reduced form methods to recover the value of infrastructure in transportation, housing and energy sectors. His previous research has been published in the *Journal of Urban Economics*, *Environmental Research Letters* and others. He received his PhD from Cornell University in 2016.

Sheila Olmstead is a Professor of Public Affairs at the Lyndon B. Johnson School of Public Affairs at the University of Texas at Austin, a University Fellow at Resource for the Future, and a Senior Fellow at the Property and Environment Research Center. Her research studies the economics of water and the energy

sector and has been published widely including the *Journal of the Association of Environmental and Resource Economics, Proceedings of the National Academy of Sciences,* and others.

References

Aldy, Joseph, Matthew Kotchen, Mary Evans, Meredith Fowlie, Arik Levinson, and Karen Palmer. 2020a. "Deep flaws in a mercury regulatory analysis." *Science* 368(6488): 247-248.

Aldy, Joseph, Matthew Kotchen, Mary Evans, Meredith Fowlie, Arik Levinson, and Karen Palmer. 2020b. "Co-benefits and regulatory impact analysis: theory and evidence from federal air quality regulations." *RFF Working Paper* 20-12, Resources for the Future, Washington, DC.

Amigues, Jean-Pierre, Gilles Lafforgue, and Michel Moreaux. 2016. "Optimal timing of carbon capture policies under learning-by-doing." *Journal of Environmental Economics and Management* 78: 20-37.

Anderson, Soren and Richard Newell. 2004. "Prospects for carbon capture and storage technologies." *Annual Review of Environment and Resources* 29(1): 109-142.

Auffhammer, Maximilian, and Ryan Kellogg. "Clearing the air? The effects of gasoline content regulation on air quality." *American Economic Review* 101, no. 6 (2011): 2687-2722.

Barrett, Scott. 2008. "The incredible economics of geoengineering." *Environmental and Resource Economics* 39: 45-54.

Barrett, Scott. 2009. "The coming global climate-technology revolution*." Journal of Economic Perspectives* 23(2): 53-75.

Barrett, Scott, and Juan Moreno-Cruz. 2015. "The alternatives to unconstrained climate change: emission reduction versus carbon and solar geoengineering." In: *Towards a Workable and Effective Climate Regime*, ed. S. Barrett, C. Carraro, and J. de Melo, pp. 353-365. CEPR Press, London.

Bickerstaff, Karen, and Gordon Walker. 2001. "Public Understandings of Air Pollution: the `Localisation' of Environmental Risk." *Global Environmental Change*, 133-145.

Boomhower, Judson. 2019. "Drilling like there's no tomorrow: bankruptcy, insurance, and environmental risk." *American Economic Review* 109(2): 391-426.

Buonocore, Jonathan J., Kathleen F. Lambert, Dallas Burtraw, Samantha Sekar, and Charles T. Driscoll. 2016. "An analysis of costs and health co-benefits for a U.S. power plant carbon standard." *PLOS ONE* 11(6): e0158792. https://doi.org/10.1371/journal.pone.0158792.

Colmer, Jonathan, Ian Hardman, Jay Shimshack, and John Voorheis. "Disparities in PM2. 5 air pollution in the United States." *Science* 369, no. 6503 (2020): 575-578.

Depro, Brooks, Christopher Timmins, and Maggie O'Neill. 2015. "White flight and coming to the nuisance: can residential mobility explain environmental injustice?" *Journal of the Association of Environmental and Resource Economists* 2(3): 439-468.

Durmaz, T., and F. Schroyen. 2019. "Evaluating carbon capture and storage in a climate model with endogenous technological change." Working paper, Department of Economics, Yildiz Technical University, Istanbul, Turkey.

Gerlagh, R., and B. van der Zwaan. 2006. "Options and instruments for a deep cut in CO2 emissions: carbon dioxide capture or renewables, taxes or subsidies?" *Energy Journal* 32: 209-238.

Goulder, Lawrence H., and Ian W. H. Parry. 2008. "Instrument choice in environmental policy." *Review of Environmental Economics and Policy* 2(2): 152-174.

Harmelen, T. V., A. V. Horssen, M. Jozwicka, T. Pulles, N. Odeh, and M. Adams. 2011. "Air pollution impacts from carbon capture and storage." https://www.eea.europa.eu/publications/carbon-captureand-storage.

Hausman, Catherine, and Samuel Stolper. "Inequality, Information Failures, and Air Pollution." No. w26682. National Bureau of Economic Research, 2020.

Heal, G. 2009. "The economics of renewable energy." NBER Working Paper No. 15081, National Bureau of Economic Research, Cambridge, MA.

Heo, J., S. T. McCoy, and P. J. Adams. 2015. "Implications of ammonia emissions from post-combustion carbon capture for airborne particulate matter." *Environmental Science & Technology* 49(8): 5142-5150.

Heutel, G., J. Moreno-Cruz, and K. Ricke. 2016. "Climate engineering economics." *Annual Review of Resource Economics* 8(1): 99–118.

Intergovernmental Panel on Climate Change (IPCC). 2014. "Climate Change 2014: Synthesis Report." Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)].

Kalkuhl, M., O. Edenhofer, and K. Lessmann. 2015. "The role of carbon capture and sequestration policies for climate change mitigation." *Environmental and Resource Economics* 60(1): 55-80.

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., Turner, M. C., Pope III, C. A., Thurston, G., Calle, E. E., and Thun et al, M. J. (2009). "Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality." Health Effects Institute Boston, MA.

Kuby, M.J., Middleton, R.S., Bielicki, J.M. 2011. "Analysis of cost savings from networking pipelines in CCS infrastructure systems." *Energy Procedia* 4: 2808-2815.

Leach, A., C. F. Mason, and K. van 't Veld. 2011. "Co-optimization of enhanced oil recovery and carbon sequestration." *Resource and Energy Economics* 33: 893-912.

Lepeule, J., Laden, F., Dockery, D., and Schwartz, J. (2012). "Chronic exposure to airborne particles and mortality: an extended follow-up of the Harvard six cities study from 1974 to 2009." *Environmental health perspectives*, 120(7):965.

Löfgren, Åsa, Dallas Burtraw, and Amelia Keyes. 2020. "Decarbonizing the industrial sector: the potential for ambitious EU member states to use flexible performance standards to strengthen carbon price signals." RFF Report 20-03. Resources for the Future, Washington, DC.

Ma, Lala. "Mapping the clean air haves and have-nots." Science 369, no. 6503 (2020): 503-504.

Magill, Jim. 2020. "Biden's Plans For Carbon Capture Buildout Could Make Headway In Congress." *Forbes*. 24 November. https://www.forbes.com/sites/jimmagill/2020/11/24/bidens-plans-for-carbon-capturebuildout-could-make-headway-in-congress/?sh=7669653230e9.

Mason, Charles F., Lucija A. Muehlenbachs, and Sheila M. Olmstead. 2015. "The economics of shale gas development." *Annual Review of Resource Economics* 7: 269-289.

McFarland, J. R., and H. J. Herzog. 2006. "Incorporating carbon capture and storage technologies in integrated assessment models." *Energy Economics* 28(5): 632-652.

Méndez Ruiz, Andrés. 2020. "Coase on fire: regulation and adoption of natural gas flaring abatement technology in North Dakota." Job market paper, the University of Texas at Austin. Available at: https://www.andresmendezruiz.com/jmp.

Mikunda, T., Kober, T., De Coninck, H., Bazilian, M., Rosler, H., and Van Der Zwaan, B. 2014. "Designing policy for deployment of CCS in industry." *Climate Policy*, 14(5): 665–676.

Muller, Nicholas Z., Peter Hans Matthews, and Virginia Wiltshire-Gordon. 2018. "The distribution of income is worse than you think: including pollution impacts into measures of income inequality." *PLOS One* 13(3): e0192461.

National Academies of Science, Engineering and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* Washington, DC: National Academies Press.

National Aeronautics and Space Administration (NASA). 2021. "Health and Air Quality Data Pathfinder." https://earthdata.nasa.gov/learn/pathfinders/health-and-air-quality-data-pathfinder

National Energy Technology Laboratory (NETL). 2019. *Coal-based power plants of the future. U.S. Department of Energy*. Washington, DC. https://netl.doe.gov/sites/default/files/2019-10/Direct-fired-Supercritical-Carbon-Dioxide-Power-Plant-System-8-Rivers-Capital.pdf.

Shapiro, Joseph S., and Reed Walker. 2021. "Where is Pollution Moving? Environmental Markets and Environmental Justice." No. w28389. National Bureau of Economic Research.

Tutton, Peter .M. 2018. "Carbon Capture and Storage Network Optimization Under Uncertainty." Master's Thesis: The University of Texas at Austin.

U.S. Environmental Protection Agency (EPA). 2021. "Air Data: Air Quality Data Collected at Outdoor Monitors Across the US" https://www.epa.gov/outdoor-air-quality-data.

U.S. Environmental Protection Agency (EPA). 2019. "Inventory of us greenhouse gas emissions and sinks: 1990–2017." EPA 430-R-19-001. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gasemissions- and-sinks-1990-2017.

van 't Veld, K. 2006. "Hazardous-industry restructuring to avoid liability for accidents." *International Review of Law and Economics* 26(3): 297-322.

van 't Veld, K., C. F. Mason, and A. Leach. 2013. "The economics of CO2 sequestration through enhanced oil recovery." *Energy Procedia* 37: 6909-6919.

Waxman, Andrew, Achmad Khomaini, Benjamin Leibowicz, and Sheila M. Olmstead. 2020a. "Emissions in the stream: estimating the greenhouse gas impacts of an oil and gas boom." *Environmental Research Letters* 15: 014004.

Waxman, Andrew R., Sean Corcoran, Andrew Robison, Benjamin Leibowicz, and Sheila Olmstead. 2020b. "Leveraging returns to scale and policy incentives: carbon capture, utilization and storage in Gulf clusters." Working paper, University of Texas at Austin.

The White House. 2016. "United States Midcentury Strategy for Deep Decarbonization." Available at: https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_reportfinal_red.pdf.

Conflict of Interest Statement

Olmstead serves on the review committee for this RFP. Waxman and Olmstead both note that the proposed work has already been approved from the Sloan Foundation for support as part of a larger multi-year, multi-part project on the economics of CCUS with additional co-PI's Benjamin Leibowicz (UT-Austin), Charles Mason (Univ. of Wyoming), Susan Hovorka (UT-Austin) and Vanessa Nuñez-López (UT-Austin). We are submitting this proposal because we believe our proposed work would benefit from interactions with researchers supported by the "Energy Equity" initiative. If our proposal were accepted as part of the NBER program, we would waive the associated honoraria, since our project is already receiving support from a Sloan Foundation grant. Prior work by both authors on CCUS has been supported by the Cynthia and George Mitchell Foundation. The authors have no other conflicts of interest related to the proposed work.