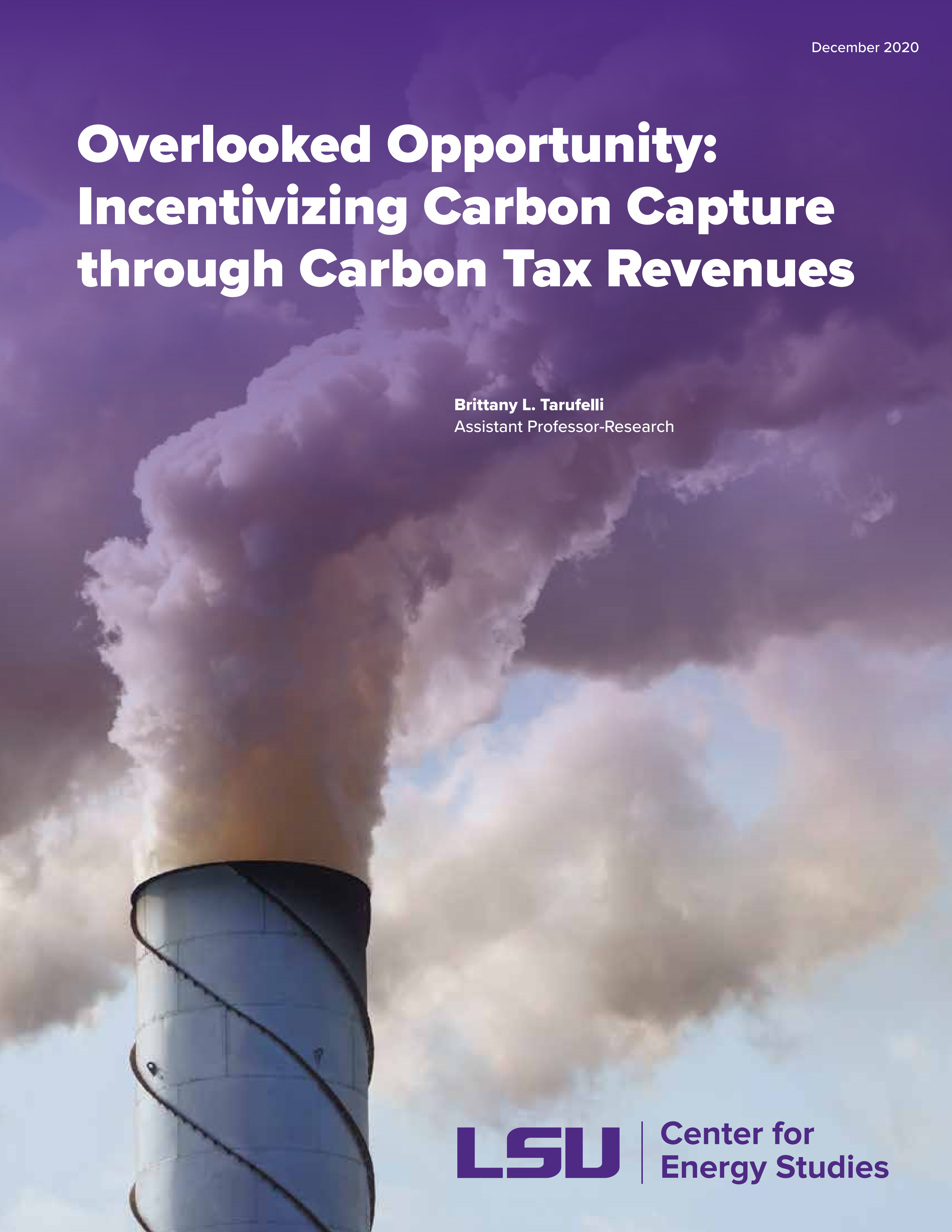
December 2020

Overlooked Opportunity: Incentivizing Carbon Capture through Carbon Tax Revenues

Brittany L. Tarufelli
Assistant Professor-Research



LSU | Center for Energy Studies

Overlooked Opportunity: Incentivizing Carbon Capture through Carbon Tax Revenues

December 2020

Brittany L. Tarufelli
Assistant Professor-Research
Louisiana State University
Center for Energy Studies

Executive Summary

This literature review systematically evaluates potential climate policy outcomes when a carbon tax and carbon capture utilization and storage (CCUS) are jointly utilized to lower the cost of CO_2 emissions reductions for the CO_2 emissions-intensive industrial sector.

Relevant studies suggest that carbon tax revenues can cost-effectively subsidize CCUS research, development and implementation, and coordinate with CCUS subsidies to reduce the burden of a carbon tax on affected firms.

Near-term CCUS investment can assist firms in achieving CO_2 emissions reduction goals and smooth the transition from a fossil fuel-based energy system to a reduced carbon energy system.

Table of Contents

List of Figures

List of Tables

1 | Strategic Responses to Climate Change

Amid burgeoning climate concerns, industries and governments worldwide are increasingly adopting strategies to decrease their environmental impacts and avoid climate-related operational disruptions. Concurrently, with global energy consumption forecast to grow by 50 percent from 2018 to 2050, and the industrial sector making up over half of forecasted end-use energy consumption (EIA, 2019), industry and policymakers face the problem of how to meet growing energy demand while reducing CO_2 emissions.

Nations and firms are taking many approaches to this challenge, including reducing energy demand through energy efficiency, decarbonizing fossil fuels and electricity through switching to less emissions-intensive fuels such as natural gas and carbon-free alternatives, and enhanced deployment of CO_2 removal measures. Receiving extensive analysis and deliberation worldwide, two of the leading climate response policies and technologies used to meet those policies are carbon capture utilization and storage (CCUS), and revenue-neutral carbon taxes.

CCUS is a process that captures CO_2 emissions from industrial sources and transports and stores the emissions in geological formations or utilizes the emissions for enhanced oil recovery (EOR). Revenue-neutral carbon taxes are taxes exacted on the carbon content of emissions to account for environmental damages and revenues are returned to households and firms.

CCUS and revenue-neutral carbon taxes have been utilized independently with success, but an approach that pairs the two—recycling carbon tax revenues to incentivize and reduce the cost of CCUS — remains largely overlooked.

This targeted literature review provides a background on the costs of carbon taxes, including their potential fiscal interactions, distributional impacts, and how they compare to other pollution control instruments. Next follows a brief overview of the current state of CCUS with a focus on the costs of CCUS and how existing barriers to large-scale adoption of CCUS can be ameliorated with a carbon tax. Last is an in-depth review of current themes from the literature on combining a carbon tax with CCUS, providing policymakers with research-backed evidence of the efficacy of a revenue-neutral carbon tax combined with CCUS to cost-effectively address climate policy goals.

2 | Climate Policies Cost

While beneficial for society, carbon taxes can be trying for emissions-intensive industry. That is why economists advocate for a revenue-neutral carbon tax, which can reduce CO_2 emissions at a lower cost than other climate policies (Goulder, 1995; Tietenberg, 2013). Carbon taxes provide a unique set of challenges that need to be considered: carbon taxes can interact with other distortionary taxes in the fiscal system, and carbon taxes can disproportionately affect CO_2 emissions-intensive firms and energy consumers. The choice of a carbon tax or other pollution control instrument, as well as other policy design choices, can affect the extent of these challenges and the ultimate cost of climate policies.

2.1 Fiscal Interactions Affect the Cost of Climate Policies

A robust literature demonstrates that revenue-neutral carbon taxes can promote economic growth and provide climate benefits while lowering costs from existing taxes. Nonetheless, two fiscal interactions—the revenue-recycling effect and the tax-interaction effect—can significantly impact the cost of a carbon tax policy.

In related literature, there are two predominant options to return revenues from a carbon tax to the economy: lump-sum transfers to households or cuts to existing distortionary tax rates (typically, cuts to income/corporate income tax rates).[1] Using carbon tax revenues to reduce distortionary costs of existing taxes is known as the revenue-recycling effect of a carbon tax policy.[2] Revenue-recycling reduces the costs of a carbon tax more than lump-sum rebates because it lowers distortionary costs from existing taxes (Parry and Williams, 2010).

However, because carbon taxes raise the cost of producing fossil fuel-intensive goods, they also reduce employment and investment—reducing economic growth. In this sense, a carbon tax is an implicit tax on labor and capital, which interacts with pre-existing taxes, ultimately raising the costs of the carbon tax (Bovenberg and de Mooij, 1994; Parry, 1995). This effect is known as the tax-interaction effect of the carbon tax policy.

Both the revenue-recycling and tax-interaction effects determine the overall cost of the policy to society. While the revenue-recycling effect can reduce the cost of the carbon tax, the tax-interaction effect tends to outweigh the revenue-recycling effect, ultimately increasing policies' costs (Bovenberg and de Mooij, 1994; Goulder, 1995; Parry, 1995).

2.2 Distributional Impacts of Climate Policies

Carbon taxes cause disproportionate losses to CO_2 emissions-intensive firms. Concessions can be made to address this distributional impact, but come at an increased cost for the carbon tax policy.

While both the revenue-recycling and tax-interaction effects are important considerations for the overall costs of a carbon tax policy, also substantial are how the costs are distributed across society.

[1] Cuts to income/corporate income taxes reduce the efficiency costs of carbon taxes by more than other revenue-recycling mechanisms as these taxes are more distortionary in the U.S. economy (Pearce, 1991; Jorgenson and Yun, 1991).

[2] For a selection of early work on this subject see Oates and Schwab (1988), Pearce (1991), Poterba (1991), Repetto et al. (1992), Poterba (1993).

Two types of distributional impacts are of concern to policymakers: fairness, in terms of a carbon tax's regressive impact on lower income households,[3] and—a key focus of this analysis—a carbon tax's disproportionate impact to energy-intensive industries.

Carbon taxes reduce the price fossil fuel producers receive on their output[4] and raise costs in industries that use fossil fuels as inputs. Both of these impacts act to disproportionately reduce firm profits in these industries. Standard revenue-recycling approaches, such as economy-wide reductions in personal or corporate income taxes, will not substantially reduce the impact of the carbon tax on fossil fuel industries (Bovenberg and Goulder, 2001).

In related literature, recommendations for policy mechanisms that can preserve profits of key industrial stakeholders and reduce the impact of the carbon tax on the fossil fuel sector include: differential tax rates (for example, granting industry-specific cuts in corporate tax rates), exempting a portion of emissions from affected firms, and exempting emissions from firms that are covered by other policies (Tietenberg, 2013).[5] However, these mechanisms are not a panacea.

Industry-specific cuts in corporate tax rates reduce the impact of a carbon tax by reducing a firm's overall tax burden; however, if firms can shift the burden of the carbon tax to consumers while profiting from reduced corporate tax rates, they will be overcompensated—making the policy less efficient and more regressive (Tietenberg, 2013). Instead, a better policy design is to exempt a small fraction of emissions from the carbon tax, which reduces costs for the affected fossil fuel industry, but increases emissions (Farrow, 1999; Bovenberg and Goulder, 2001).[6] In practice, targeted tax exemptions in carbon tax programs have led to either increased emissions or little impact in emissions reductions due to extensive tax exemptions (Tietenberg, 2013).[7]

Still, there are other climate policy instruments available to policymakers that can reduce the distributional impacts of a carbon tax on fossil fuel-intensive industries while reducing emissions.

2.3 Pollution Control Instruments

Carbon taxes are more effective pollution control instruments than subsidies, technology mandates, and performance standards. Carbon taxes also provide more stable price incentives than carbon cap-and-trade programs with tradeable permits. If a policymaker needs to address more than one market failure, such as pollution and innovation market failures, additional pollution control instruments may be needed.

[3] While the focus of this paper is on the impact to the fossil fuel intensive industrial sector, distributional equity is also a significant concern as a carbon tax raises the price of energy-intensive goods, which are a larger share of the budget for lower income households (Poterba, 1991; Poterba, 1993; Bull, Hassett, and Metcalf 1994; and Metcalf; 1998). These concerns can also be addressed by specific rebates to lower income households, but come at a cost of efficiency for the policy (Goulder, 2013). See Parry et al. (2006) and Parry (2015) for further discussion on regressive impacts of carbon taxes and potential policy options.

[4] Producers receive the price net of the carbon tax for their output.

[5] Industry-specific revenue-recycling policies may also not address the risk that carbon taxes put a nation's carbon-intensive firms at a disadvantage relative to their global competitors. In this case, border adjustments— carbon taxes applied to carbon-intensive imports, or carbon tax exemptions applied to exports—may be necessary to preserve global competitiveness. This concern can be remedied by a carbon tax that is placed on downstream firms—at the point of fuel combustion—which reduces demand for both domestic and foreign fuels alike, but increases administrative costs (Goulder and Schein, 2013).

[6] Bovenberg and Goulder (2001) find that exempting 15 percent of emissions from the oil and gas industry and 4.3 percent of emissions in the coal industry are sufficient to preserve profits in these industries. These findings are based on a simulation of the economy, and are specific to the underlying assumptions and parameters of their model, which include highly elastic supply of and inelastic demand for fossil fuels, which allows firms to shift the burden of the tax onto consumers.

[7] Bruvoll and Larsen (2004) found emissions increased in Norway due to excessive exemptions from the carbon tax. Johansson (2000) found that while emissions were reduced in the residential and transport sectors in Sweden, industry impacts were small due to many tax exemptions. Skou Anderson (2008) found that specific industries and target groups have tended to obtain special arrangements in countries with carbon tax policies, leading to sectoral differences in the impacts of carbon taxes. For a survey of the empirical literature on carbon taxes applied in practice see Skou Anderson (2008), Sumner et al. (2011), Tietenberg, (2013).

Pollution control instruments can help policymakers deal with common problems faced in environmental policy design—such as uncertainty in environmental damages, monitoring and enforcement costs, how benefits and costs are distributed across firms, and how technological progress influences cost-effectiveness. These nuanced issues affect a policy's overall costs.

Options for pollution control instruments include carbon taxes, tradeable permits (cap-and-trade),[8] subsidies for CO_2 emissions reductions, performance standards, mandates for the adoption of specific technologies, and subsidies for research for new clean technologies. Although there isn't a particular instrument that is superior for pollution control for all climate policy objectives, there are some key takeaways in the literature.

Carbon taxes and tradeable permits are more cost-effective than subsidies, technology mandates, and performance standards.

Through providing a subsidy for CO_2 emissions reductions,[9] subsidies lower firms' average costs (which can attract additional firms to enter the industry), resulting in increased industry CO_2 emissions even if emissions are reduced for an individual firm (Baumol and Oates, 1988). To correct for these misaligned incentives, subsidy rates need to be higher than taxes or tradeable permit prices to achieve the same level of CO_2 emissions reductions, raising overall policy costs (Goulder and Parry, 2008).

Technology mandates—which require firms to change some aspect of the production process, such as installing pollution abatement technology—do not provide an incentive for firms to find the most cost-effective way to reduce pollution, which raises policy costs compared to a carbon tax or tradeable permit (Newell and Stavins, 2003). Further, because firms do not face a price for each additional unit of CO_2 emissions, mandates may result in less pollution reduction overall (Spulber, 1985; Goulder and Parry, 2008).

Performance standards—which require a firm's output to meet certain standards, such as Corporate Average Fuel Economy (CAFE) standards—allow more flexibility than technology mandates in how the standards are met, which provide better cost-reduction incentives. However, firms again do not face a CO_2 emissions price for each additional unit of CO_2 emissions, which can lead to less pollution reduction than under a carbon tax or carbon cap-and-trade with tradeable permits program, raising the policy's costs (Austin and Dinan, 2005).

Carbon taxes and tradeable permits provide incentives for firms to find the most cost-effective way to reduce CO_2 emissions and encourage consumers to reduce energy use. Their revenues can be used to offset costly fiscal interactions.

Market-based instruments like carbon taxes and tradeable permits[10] provide incentives for fossil fuel intensive producers to reduce CO_2 emissions, pursue knowledge-enhancing investments to reduce the costs of CO_2 emissions abatement, and encourage consumers to conserve energy (Milliman and Prince, 1989; Fischer and Newell, 2008). Although other factors, such as monitoring costs and impacts from other fiscal interactions also influence cost-effectiveness, revenue-raising policies such

[8] Cap-and-trade sets a cap for the maximum allowable amount of carbon emissions. Carbon emissions permits are then allocated or auctioned to firms. Firms can buy or sell permits in a marketplace, and the market determines the carbon emissions price.

[9] As an example, subsidies can include grants, low-interest loans, and favorable tax treatment such as the 45Q tax credit.

[10] U.S. carbon cap-and-trade programs include the Regional Greenhouse Gas Initiative and California's Cap-and-Trade Program.

as a carbon tax or tradeable permits have an advantage as their revenues can be used to offset costly fiscal interactions (Goulder et al., 1997).

Carbon taxes provide more stable prices, which encourage investment in new emission reduction technologies.

Carbon taxes and tradeable permits are very similar along several dimensions, but academic researchers continue to debate whether taxes or tradeable permits are more effective policy instruments.[11] To differentiate between emissions taxation and cap-and-trade: under emissions taxation, policies set the taxation price for emissions, but the market determines the volume of emissions reduced under the policy; with cap-and-trade, a "cap" is placed on the maximum allowable amount of emissions, permits are auctioned or allocated, and the market determines the CO_2 emissions price (Tietenberg, 2013). In short, carbon taxes will have less price volatility,[12] providing more stable investment incentives (Goulder and Schein, 2013). A stable investment environment encourages innovation in CO_2 emissions reduction activities, such as investing in R&D for new abatement technologies; however, under a carbon tax, CO_2 emissions reductions will be uncertain, which can be problematic for climate policies.

Carbon taxes alone are not enough to address emissions targets and climate-related economic impacts. Other market failures may exist, which require additional policy instruments.

Another concern for policymakers is that climate initiatives and policies may involve multiple market failures. For example, carbon taxes alone may not be sufficient to spur technological improvement in CO_2 emissions reduction technologies if there are innovation market failures—which occur when society benefits from the research and development (R&D) efforts of a private investor, but the investor is not fully compensated for the social returns their investment generates (Fischer and Newell, 2008). This market failure results in underinvestment in R&D due to the difference in the private and social returns on investment. In this case, more than one policy instrument—such as a carbon tax plus an R&D subsidy—may be needed to correct the problem.

Further, if innovation occurs via learning through production with new technologies—known as 'learning-by-doing'—subsidies may be desirable to counter the production-reducing effect of carbon taxes (Fischer and Newell, 2008); however, when more than one policy instrument is used to correct a climate problem, instruments can interact, which is also a matter of concern and requires in-depth analysis.

While the literature indicates that a carbon tax performs better than other policy instruments when achieving cost-effective emissions reductions, the carbon tax is not a faultless response to negative impacts stemming from climate change. In addition to the noted issue that a carbon tax alone cannot cope with multiple market failures are multiple other drawbacks, including the heavy burden that the carbon tax would place on the fossil fuel industry.

[11] See Keohane (2009) and Stavins (2007) for pro cap-and-trade arguments, Metcalf (2007) for pro carbon tax arguments. See Goulder and Schein (2013) for a review of the literature.

[12] As an example, California's Regional Clean Air Incentives Market (RECLAIM), a cap and trade program, had allowance prices rise from $400/ton to over $40,000/ton during the California electric power crisis which required some older power generators to be brought online and buy allowances from the fixed allowance pool (Goulder and Schein, 2013).

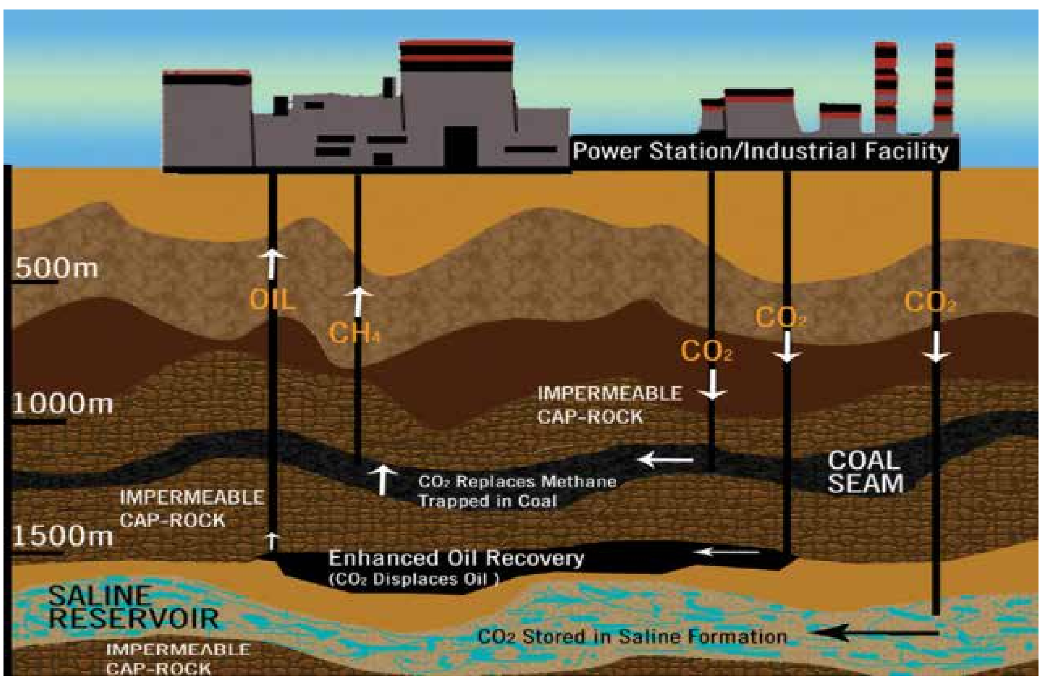
3 | Overlooked Opportunity: CCUS + A Revenue-Neutral Carbon Tax

Though empirical research has given great scrutiny to the carbon tax itself, largely passed over is the promise of pairing a revenue-neutral carbon tax with another policy tool: carbon capture utilization and storage. Under such an arrangement, carbon tax revenues would be "recycled" and applied towards R&D, implementation and incentivization of CCUS.[13]

3.1 CCUS: The Basics

As shown in Figure 1, CCUS is a process that captures CO_2 emissions from industrial sources, transports the emissions from point of capture, and either stores them in geological formations or reuses them for enhanced oil recovery (EOR). CCUS costs consist of capture costs, transport costs, and—if emissions are not reused for EOR—storage costs. While CCUS is not the only option available to policymakers to reduce CO_2 emissions,[14] it has the potential to cost-effectively mitigate CO_2 emissions while providing fossil fuel-intensive firms increased flexibility in achieving CO_2 emissions reductions (IPCC, 2005).

Figure 1: Carbon Capture Utilization and Storage Flow Chart



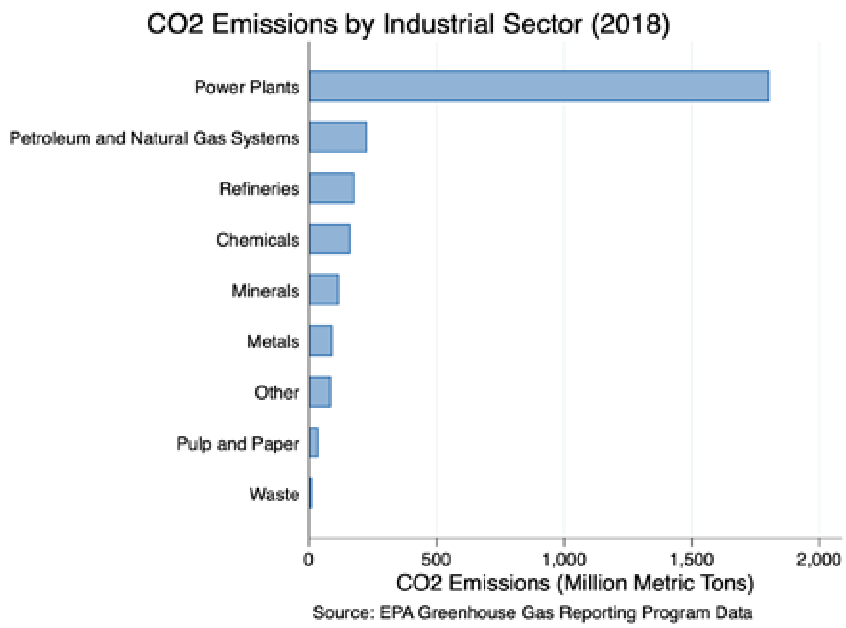
Source: The World Resources Institute

[13] Carbon capture and storage will always require an input of energy as CO_2 requires compression for storage, necessitating a carbon price or subsidy (House et al., 2011).

[14] Other CO_2 emissions mitigation options include energy efficiency improvements, fuel switching to less carbon-intensive fuels (nuclear or natural gas), renewable energy deployments, and enhancing biological sinks (IPCC, 2005).

Probable candidates for CCUS are stationary sources in the industrial and power sectors that have large volumes of CO_2 emissions. These include fossil fuel-fired power plants, as well as fossil fuel-intensive industrial facilities in the natural gas processing, cement, refineries, ethanol, hydrogen, ammonia, steel and other metals, and petrochemical sectors. Not all stationary sources are equally amenable to CCUS. Several factors, including the purity and pressure of the CO_2 exhaust stream that needs to be captured and compressed, as well as access to affordable transportation and storage options affect the economic feasibility of CCUS. Figure 2 displays CO_2 emissions by industrial sector as reported to the EPA's Greenhouse Gas Reporting Program. While there are some options to decarbonize the power sector without CCUS, all other industries represented in Figure 2 will require CCUS for decarbonization.

Figure 2: CO_2 Emissions by Industrial Sector, 2018.



Current policy incentives for CCUS in the U.S. are tax credits from Section 45Q of the U.S. tax code. In 2018, the 45Q tax credit was revised to increase tax credits from $20/metric tonne to $50/tonne for CO_2 emissions captured and stored in secure geologic storage, and from $10/tonne to $35/tonne for CO_2 emissions captured and utilized for EOR.[15] Although the 45Q tax credit provides necessary financial incentives for CCUS, the costs of CCUS typically outweigh its potential revenues (Tarufelli et al., 2020). At present, there are several bills in Congress to extend 45Q's tax credits.

Because CCUS has limited deployment, projects face "first-of-its-kind" risks where costs can be higher because technological progress through "learning-by-doing" is still in its early stages (IEA, 2015). For this reason, incentives are necessary to increase deployment of CCUS. With increased deployment of CCUS, key technologies can be refined and cost reductions can be achieved (IEA, 2015). However, without a certain stream of revenue for carbon capture, CCUS investments are

[15] The tax credit reaches its full value in 2026, and will track inflation thereafter. The tax credit applies to carbon capture equipment placed in service on or after February 9, 2018, and currently has a 12 year sunset provision.

difficult to justify. One potential way to generate a certain stream of revenue for carbon capture projects is with a carbon tax.

3.2 CCUS Associated Costs

Industrial processes that combust fossil fuels produce CO_2 in combination with other gases. In order to capture CO_2, it must be separated from these other gases. This can be achieved pre-combustion by separating CO_2 from hydrogen, or post-combustion, by separating CO_2 from other flue gases (Simbolotti, 2010). Most commonly, CO_2 is separated post-combustion by scrubbing the CO_2 from the flue gas, where the CO_2 is captured by chemical absorption using amine solvents.[16] Up to 85-99 percent of CO_2 emissions can be captured by pre- or post-combustion systems (IEA, 2020). The CO_2 is then typically dehydrated and compressed, to make it behave more like a liquid for transport (IEA, 2011).

The capture component of a CCUS project is typically the largest individual cost item, accounting for 70 – 80 percent[17] of a CCUS system's expenses. Costs depend on the purity (concentration) of the CO_2 exhaust stream and its pressure, and more pure and pressurized exhaust streams lower capital and operating costs for capture systems (Summers et al. 2014).[18] Because industrial plants emit varying volumes of CO_2 emissions from multiple exhaust stacks that differ in CO_2 concentrations and pressures, carbon capture costs range widely, and depend on a firm's unique production processes and configuration.[19]

Summers et al. (2014) established a baseline cost of carbon capture (price for CO_2 emissions in dollars per tonne) required for high and low purity industrial sources to recover costs of CO_2 separation, purification, and compression. The National Petroleum Council provided a more recent update on the costs of carbon capture (NPC, 2019). These estimates are shown in Table 1.

Table 1: Carbon Capture Costs in $/Tonne CO_2 Emissions

Industrial Process	Total Estimated Capture Cost ($/tonne) for Reference Plants	
	NETL Cost of Capturing CO_2 from Industrial Sources (Summers et al., 2014)	NPC Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of CCUS (NPC, 2019)
Natural Gas Processing	$18	$23 - 35
Ammonia	$27	$21 - 30
Ethanol	$30	$24 - 34
Steel/Iron	$99	$75 - 113
Cement	$100	$64 - 95
Coal Power Plants	$77	$83 -124
Natural Gas Power Plants	Not provided.	$93 - 140

Source: Summers et al., 2014; NPC, 2019

[16] Other CO_2 separation technologies may be utilized depending on the purification needs.

[17] See Blomen et al. (2009).

[18] For example, ethanol, natural gas processing, ammonia production, and ethylene oxide production have high purity (nearly 100 percent by volume) CO_2 flue gas concentrations, whereas coal-fired power plants have CO_2 flue gas concentration of around 13.5 percent (Summers et al., 2014).

[19] In addition, carbon capture technology can be installed on new "greenfield" plants or on existing "retrofitted" plants, which also have cost implications.

Although the capture cost for each facility depends on the specific financing assumptions and reference firm size (in emissions), an important takeaway is that carbon capture from high purity sources (natural gas processing, ammonia, ethanol production) is much more cost-effective than carbon capture from low purity sources (steel/iron, cement, power plants). Low purity sources have higher capital costs due to the need for separation and purification equipment.[20]

Capture technologies are well understood but expensive (IEA, 2013)—Table 1 communicates that carbon capture of high purity sources may be financially feasible for some facilities at current 45Q tax credit levels; however, capture is just one piece of the supply chain necessary to capture, transport, and store emissions. Because costs of capture are expected to improve with research and development and learning-by-doing effects generated as carbon capture technology capacity increases, there is a need for increased government support in deploying large-scale projects that incorporate CCS technology (IEA, 2013; IEA, 2020).[21]

3.3 Carbon Transport Costs

Once captured, carbon dioxide needs to be transported from its capture location (source) to a suitable location where it will be used for EOR or injected deep underground for permanent storage—known as "the sink." The cost of transport depends on the method of transport used and the source's proximity to the sink. Although truck or rail transport is possible for small quantities of CO_2, pipelines are the most common method for transporting large quantities of CO_2. Compressed CO_2 requires a pipeline that can operate at sufficient pressure to keep the CO_2 in its dense (supercritical) form.[22] Fossil fuel prices and weather conditions influence the cost of a pipeline, as do other factors, including a pipeline's length and diameter, geographical region, average annual utilization, and maximum pressure (Dismukes et al., 2019).[23]

Typically, costs of CO_2 pipeline infrastructure are based on existing data from oil and natural gas pipelines, as there is limited research available on actual pipelines that have been converted to transport CO_2. For the cost of new pipelines, the National Petroleum Council estimates the cost of new construction by region, based on historical construction costs.[24] These cost estimates are shown in Table 2. At these estimated costs, transport costs range from \$2 to \$38 per tonne avoided CO_2 emissions (NPC, 2019).

---

[20] Summers et al. (2014) and NPC (2019) results are similar to those found in Leeson et al.'s (2017) academic literature survey, in which costs of capture ranged from 20-120 \$/tonne for low purity sources, and from 4 – 74 \$/tonne for high purity sources.

[21] In particular, financial support mechanisms are recommended to encourage private financing of projects (IEA, 2013).

[22] The National Energy Technology Laboratory (NETL) offers an Excel-based mathematical model that estimates the cost of transporting dense phase CO_2 using a pipeline in its FE/NETL CO_2 Transport Cost Model. https://www.netl.doe.gov/projects/files/FENETLCO2TransportCostModel2018ModelOverview_050818.pdf (accessed 9/24/2020). For other industry standard costing methods for CO_2 pipelines see Onyebuchi et al. (2018).

[23] Although repurposing natural gas pipelines for CO_2 transport is an often discussed idea to lower transport costs (Rabindran et al., 2011; Noothout et al., 2014; Onyebuchi et al., 2018), Dismukes et al. (2019) found that because CO_2 is usually compressed at very high pressures (2,200 pounds per square inch gauge), very few natural gas pipelines are viable options for conversion to CO_2 transportation. When available, converting existing pipelines does save costs. Dismukes et al. (2019) point to one example in the U.S. where Denbury repurposed the West Gwinville natural gas pipeline for CO_2 transport at a cost of \$5.2 million, compared to the NETL model estimate of \$41 million for a new 50-mile, 16-inch diameter pipeline; however, limited data availability on converted pipelines points out a need for more research. Currently in the U.S. there are 5,200 miles of CO_2 pipelines, compared to 200,000 miles of natural gas pipelines (Dooley et al., 2006).

[24] To determine the cost per mile of a pipeline requires multiplying the diameter of the pipe (in inches) by the distance of the pipe (in miles), which is why the pipeline cost is provided in inch-miles.

Table 2: Estimated CO_2 Pipeline Costs by Region

Region	Pipeline Cost (Thousand Dollars/Inch-Mile)
Western	120
Rockies	150
Central	80
Eastern	100

Source: NPC, 2019

The cost of a new CO_2 pipeline can be excessive for an individual facility (Onyebuchi et al., 2018), but with regional cooperation there are economies of scale to be gained for pipeline capacity, as unit costs significantly decrease while CO_2 quantities increase (IEA, 2020). The IEA recommends several operations to reduce pipeline costs: clustering sources and sinks, planning pipeline networks similar to natural gas pipeline infrastructure, and improving pipeline materials and CO_2 compression technologies (IEA, 2013).

3.4 Carbon Storage Costs

The storage component of the CCUS supply chain involves injecting the CO_2 into a subsurface geological formation. Saline reservoirs, depleted oil and natural gas fields, and unmineable coal seams are the best candidates (Simbolotti, 2010; IEA, 2020). The storage component of the CCUS system requires drilling a well, CO_2 compression and injection, operation and maintenance, and long-term monitoring (Simbolotti, 2010). Various economic factors affect the cost of storage including: the sink-to-source distance, storage capacity, and the expense of accessing the storage facility.[25] Storage sites must also meet various underground injection control regulations required by the EPA (Dismukes et al., 2019).

Current costs of CO_2 storage are largely based on oil and gas experience. The National Petroleum Council (2019) estimates the storage volume-weighted average cost by region in the United States. These cost estimates are provided in Table 3.[26]

[25] The costs to access the storage facility include the number of wells required to achieve the desired injection rate, maximum allowable pressure, and how effective the storage facility is at storing the emissions permanently.

[26] The NPC 2019 study estimates storage costs using the National Energy Technology Laboratory (NETL) 2017 storage cost model. The NETL storage cost model is an Excel-based mathematical model for the cost of storing CO_2, based on geo-engineering equations that calculate reservoir values needed to determine injection well costs, monitoring costs, and financial responsibility costs. This model is available at https://edx.netl.doe.gov/dataset/fe-netl-co2-saline-storage-cost-model-2017 (accessed 9/24/2020). Note that the NPC 2019 study assumes less monitoring wells than in the NETL 2017 storage cost model, which has the effect of reducing storage costs by approximately 50 percent (NPC, 2019).

Table 3: Volume-Weighted Storage Costs by Region

Region	Average Cost ($/tonne)	Storage Volumes (gigatonnes)
California	$7	11
Midwest	$7	54
North Central	$11	85
Gulf Coast	$7	135
South Central	$8	129
Overall Average/Total	$8	413

Source: NPC, 2019

Currently, the technical storage capacity for underground CO_2 storage is uncertain, and more site characterization and exploration, as well as definitive demonstration that CO_2 storage is safe and permanent are needed (Simbolotti, 2010; IEA, 2020). Even with existing uncertainties, potential storage capacity is very large (IEA, 2020) and existing storage projects have confirmed expectations about underground behavior of CO_2 (Simbolotti, 2010), with the possibility for leaks found to be generally low (IEA, 2020); however, evaluating new storage capacity is similar to that required for oil and gas, necessitating exploration and appraisal, which can incur significant costs and time (IEA, 2020).

3.5 Effects of Economies of Scale

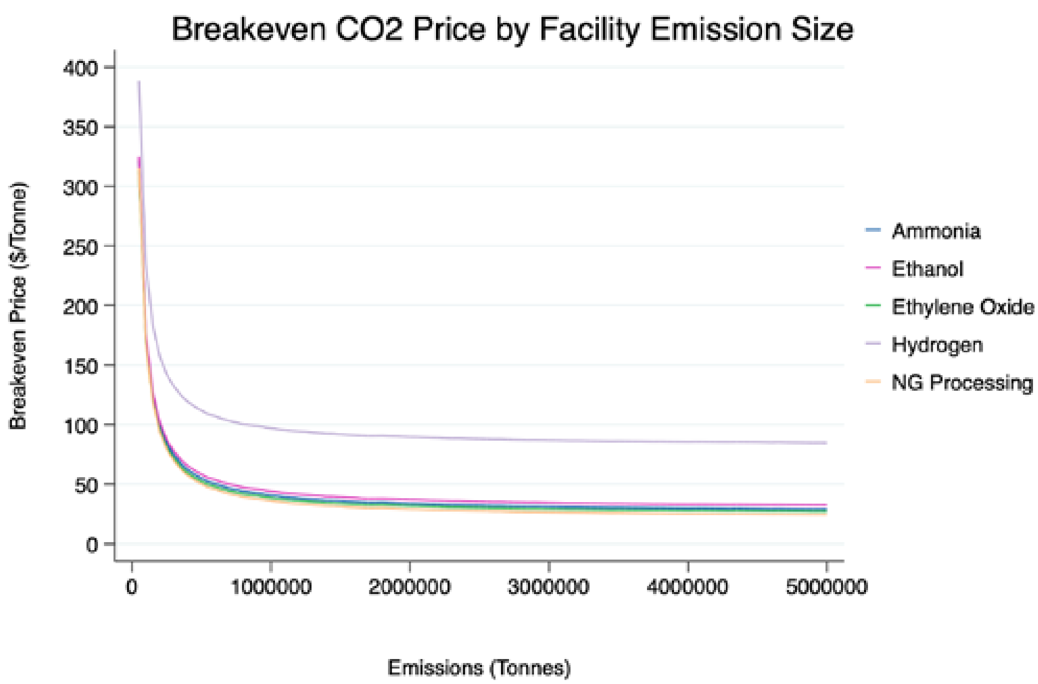
Economies of scale reduce overall CCUS costs and can be achieved through the creation of industrial hubs that share transport and storage infrastructure.

At current costs of CO_2 capture, transport, and storage, Tarufelli et al. (2020) find that few large industrial plants with high-purity CO_2 exhaust streams will profitably employ CCUS at the expanded Section 45Q tax credit levels. To address this incentive shortfall, the National Petroleum Council recommends economic incentives of $110 per tonne of avoided CO_2 emissions to spur large-scale CCUS development (NPC, 2019).

Another option is to create industrial hubs that share transport and storage infrastructure. These can reduce the costs of CCUS through fostering economies of scale, which can be achieved with large industrial emitters or by capturing emissions from clusters of facilities before transport and storage to reduce overall costs. Figure 3 shows the necessary carbon price to cover the cost of carbon capture, transport, and storage—the breakeven price—at different levels of CO_2 emissions (Tarufelli et al., 2020). As captured CO_2 emissions increase, the breakeven price decreases.

Economies of scale can be aided by policy mechanisms such as placing a value on carbon through a carbon tax, lowering risks to investment through financial support, and facilitating the development of CO_2 transport and storage infrastructure (Global CCS Institute; IEA, 2020). Costs can be further reduced through R&D, leading to spillover effects and large-scale CCUS development that facilitates learning-by-doing (IEA, 2020).

Figure 3: Breakeven CO_2 Price by Facility Emission Size



Note: Assumes a 50-mile transportation system and Lower Tuscaloosa dome storage geology.
Reproduced from Tarufelli et al. (2020).

3.6 Necessary Conditions for Deploying CCUS at Industrial Scale

In order to realize wide-scale deployment of CCUS, policy incentives are needed.[27] Three primary actions improve the feasibility of wide-scale CCUS deployment: placing a value on CO_2 through a carbon tax or other policy instrument, lowering risks to investment through financial support from grant funding or other provisions from federal and state government,[28] and facilitating the development of CO_2 transport and storage infrastructure (Global CCS Institute, 2019; IEA, 2020).

Because fossil fuels are forecast to continue to dominate primary energy supplies, and strong demand for industrial goods requiring high-temperature heat (including cement, steel, and chemicals) persists, CCUS remains an effective tool for policymakers to address climate change problems. To foster industrial scale CCUS development, a carbon tax could be utilized to incentivize CCUS, using its revenues to reduce CCUS costs.

[27] In 2019, 19 active CCS projects (10 of which are in the U.S.) permanently stored 25 million tonnes of CO_2 from power and industrial sectors (Global CCS Institute, 2019). This represents less than one percent of the nearly three billion tonnes of CO_2 emissions from stationary sources in the U.S. alone (based on facility-level greenhouse gas data from major industrial sources as reported to the EPA's Greenhouse Gas Reporting Program in 2018 https://www.epa.gov/ghgreporting/key-facts-and-figures (accessed 9/23/2020)). See Stigson et al. (2012) for a survey of CCS stakeholder perceptions.

[28] Access to debt financing from banks is currently difficult as projects risks are perceived by banks as too high, a risk that is expected to lower as more projects come online (Global CCS Institute, 2019). CCUS requires a stable investment environment because it requires significant capital investment and has a long life span (Van den Broek, 2011).

4 | Revenue-Neutral Carbon Tax: The Basics

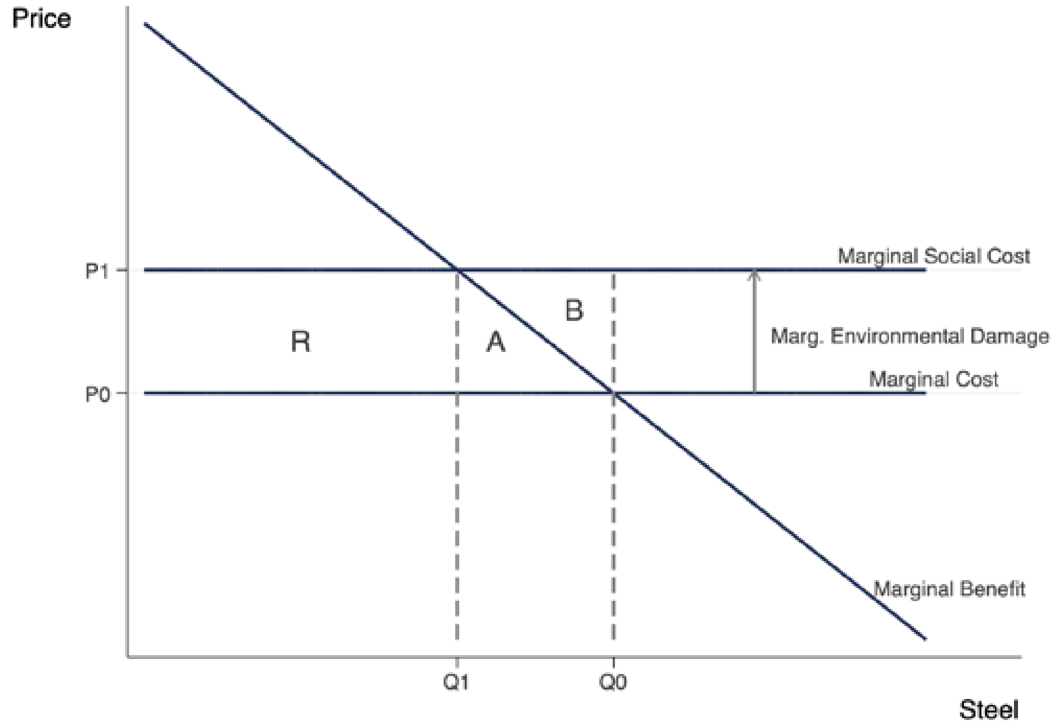
A revenue-neutral carbon tax affixes a price to carbon emissions, then returns those revenues to society—typically through lump-sum tax credits or cuts in distortionary tax rates. Revenues can also be used to reduce the distributional burden of the carbon tax, make the policy less regressive, or improve the policy's political feasibility or stability (Tietenberg, 2013). A revenue-neutral carbon tax using revenues to promote CCUS is a promising but largely unexplored policy option to reduce the tax's distributional burden on emissions-intensive firms while still achieving deep emissions cuts.

To understand why economists advocate for a revenue-neutral carbon tax, it is useful to examine the benefits and costs of a carbon tax—shown in Figure 4 for steel production. Producing steel requires the combustion of fossil fuels, which generate environmental damages in the form of CO_2 emissions. Without a carbon tax, the quantity of steel produced in a competitive market is *Q0*, where the marginal benefit of steel production equals a firm's private marginal cost; however, at *Q0*, the true cost of steel production to society, the marginal social cost—which includes the marginal environmental damages generated from CO_2 emissions—exceeds the marginal benefit from using steel. In short, too much steel is produced and excessive environmental damages are incurred.

To correct for this market failure, a carbon tax equal to the marginal environmental damages generated from CO_2 emissions can be applied to steel production. With the carbon tax, the quantity of steel produced will be *Q1*, where the marginal social cost equals the marginal benefit of steel production. By raising the price of carbon-intensive steel, the carbon tax acts as an incentive to reduce CO_2 emissions through reducing the production of steel.

The carbon tax policy will generate environmental benefits of *A* + *B*, due to avoided environmental damages from CO_2 emissions. However, the policy is not costless. Consumers will also have to pay more for steel, leading to a loss in consumer surplus of *A* + *R*. But if policymakers adopt a revenue-neutral stance on the carbon tax policy, meaning revenues, *R*, from the carbon tax are returned to the economy, the overall cost of the policy is *A*. The net benefits of the policy—its economic efficiency—are equal to *B*, which are the environmental benefits (*A* + *B*), less the cost of the policy, *A*. The revenue-neutral carbon tax policy is more cost-effective than a carbon tax policy that does not return revenues to the economy, because it reduces CO_2 emissions at a lower cost (*A*, instead of *A*+*R*) (Goulder, 2005; Goulder, 2013).

Figure 4: Benefits and Costs of a Carbon Tax



Source: Based on Goulder (2005) and Goulder (2013).

How the carbon tax revenue is returned to the economy is critical to determining the policy's economic impact. If the carbon tax revenues are used to reduce marginal tax rates of existing incentive-distorting taxes—for example, corporate income or personal income taxes—rather than returned to society as a lump sum rebate, there is the potential that additional cost savings can be made, reducing policy costs below A, and increasing net benefits. Another option is to use the revenues to promote economic activities that generate economic growth or other societal benefits, such as incentivizing research and development in clean energy technologies.

Because carbon taxes disproportionately affect the fossil fuel-intensive sector of the economy—raising prices on and reducing output of energy-intensive consumer goods—policymakers have a prime opportunity to reduce this burden by recycling revenues from the carbon tax to incentivize CCUS.

5 | Recycling Carbon Tax Revenue to Promote CCUS

The economic literature provides two primary approaches to analyzing the cost-effectiveness and net benefits of a carbon tax or other climate change policies: ex ante analyses using computer simulations to determine potential outcomes, or ex post analyses to examine actual outcomes from the implemented policy. Because climate change policies have multi-faceted impacts and limited deployment within the U.S., ex ante simulations to determine potential policy outcomes constitute the majority of this line of research.[29]

If the goal of a climate policy is to minimize the cost of reaching an emissions reduction target, firms need to use the lowest cost combination of decreasing their emissions (including fuel-switching to lower carbon fuels, and reducing output), and installing and using abatement technology such as CCUS (Goulder and Mathai, 2000). In the literature, researchers typically consider how various policy instruments, or combinations of policy instruments (such as a carbon taxes, fossil fuel taxes, non-carbon/renewable energy subsidies, and fossil fuel decarbonization through CCUS) perform at achieving cost-effective emissions reductions.

Studies converge on several themes about the incorporation of a carbon tax with CCUS affecting climate policy outcomes, revenue-neutral carbon taxes incentivizing and subsidizing CCUS, and the efficiency and cost-effectiveness of climate policies that utilize both instruments.

5.1 A Carbon Tax Is More Cost-Effective than a Fossil Fuel Tax

In studies that allow for the use of CCUS technology, a carbon tax economically outperforms a fossil fuel tax.

While both taxes provide incentives to decrease fossil fuel-intensive output and CO_2 emissions, because a fossil fuel tax focuses on fuel rather than emissions, it does not provide incentives for firms to invest in CCUS. Alternatively, a carbon tax raises the cost of CO_2 emissions by incentivizing the use of CCUS technologies up to the point when the marginal cost of CCUS emissions abatement equals the marginal value of the tax (Gerlagh and Van der Zwaan, 2006; Ricci, 2012; Duan et al., 2013; Grimaud and Rouge, 2014).

Without CCUS investment, output is reduced more under the fossil fuel tax to meet the same emissions goals, and at a higher cost than the carbon tax (Gerlagh and van der Zwaan, 2006; Ricci, 2012; Grimaud and Rouge 2014). As a case-in-point, Gerlagh and Van der Zwaan (2006) found that the fossil fuel tax was 20 percent more expensive than the carbon tax for the same emissions reductions—because the fossil fuel tax did not encourage CCUS investment. Further, carbon taxes administered in conjunction with CCUS perform stronger under increasingly stringent emission targets (Gerlagh and Van der Zwaan, 2006).

[29] Outcomes from ex ante simulations are sensitive to both structural and parametric assumptions made in the model.

5.2 Subsidies Alone Don't Work

Promoting CCUS through subsidies alone is never the most cost-effective policy option, but CCUS subsidies used in union with a carbon tax can be the most cost-effective option. Revenue-neutrality (using carbon tax revenues to fund CCUS subsidies) lowers the policy's cost even more.

A CCUS subsidy reduces emissions by abating them with CCUS technology. A carbon tax reduces emissions through output reduction and emission abatement, while encouraging the use of CCUS technology (to the point that the marginal cost of CCUS emissions abatement equals the marginal value of the tax). Because of this dynamic, the CCUS subsidy costs more than a carbon tax for the same level of emissions reduction (Ricci 2012; Duan et al. 2013; Grimaud and Rouge, 2014).

CCUS subsidization policies provide adequate incentives for capturing CO_2 emissions, but also increase the extraction and use of fossil fuels (Ricci, 2012; Grimaud and Rouge, 2014). Worth noting is that CCUS subsidies send the wrong incentives for the level of energy produced, causing fossil fuel output and consumption to increase.[30]

As shown in Figure 4, a carbon tax has the opposite effect. A carbon tax sends the correct incentives for the level of energy produced, reducing output and consumption, creating a burden for emissions-intensive firms and their products' consumers.

However, CCUS used in conjunction with a carbon tax requires less of a decrease in final output and consumption (than the carbon tax alone) to achieve the same emissions reduction, and will also temper the tax's output- and consumption-shrinking effects—ultimately abating the economic strain (Ricci, 2012; Grimaud and Rouge, 2014).[31] The carbon tax's economic burden to the industrial sector is further reduced when revenues are recycled from the tax to a CCUS subsidy (Ricci, 2012).

5.3 Subsidizing Research and Development for CCUS Can Address Barriers to CCUS Adoption

When paired with a carbon tax, CCUS R&D subsidies can help realize deep emissions cuts, and address innovation market failures that discourage CCUS adoption.

Because CCUS has limited deployment, some CCUS projects face "first-of-its-kind" risks where costs can be higher (IEA, 2020).[32] Even with a dedicated revenue stream from a carbon tax, high-cost CCUS investments may be difficult to justify, despite the societal benefits from increased CCUS deployment. This situation is known as an innovation market failure. Because private investors may not be fully compensated for the social returns on their CCUS investment, there is potential for underinvestment in CCUS R&D (Grimaud et al., 2011).[33] A solution for policymakers is to use a carbon tax in conjunction with a CCUS R&D subsidy to encourage CCUS adoption and technological progress.

[30] This dynamic also occurs if a carbon tax is set inefficiently low; however, Kalkuhl et al. (2015) found that a policy that subsidizes both CCUS and renewables can achieve emissions reductions at a lower cost than only subsidizing renewables when a carbon tax is below its optimal level.

[31] Subsidizing CCUS also promotes learning by doing from increased production, which reduces future CCS costs (Keller et al., 2008).

[32] Although CCUS facilities have been operating for decades in some industries, such as natural gas processing, in others—such as cement or steel—CCUS is less developed (IEA, 2020).

[33] Empirical evidence has shown that there is a 60-80 percent discrepancy between private and social returns on innovation investments (Jones and Williams, 1998; Popp, 2006; Grimaud et al., 2011).

Through increased CCUS deployment, key technologies can be refined and cost reductions can be achieved (IEA, 2015).

Subsidies for CCUS R&D work better when paired with a carbon tax. Although a carbon price alone will incentivize CCUS R&D, it takes time to realize gains from technological improvements (Otto and Reilly, 2008). Combining a CCUS R&D subsidy with a carbon tax allows for CCUS to immediately overcome cost hurdles and substitute for conventional technologies in energy intensive sectors, allowing for more cost-effective emissions reductions than a carbon price alone (Otto and Reilly, 2008).

Grimaud et al. (2011) also found that a revenue-neutral carbon tax policy using revenues to subsidize CCUS R&D strengthened the role of CCUS and achieved greater emissions reductions than a carbon tax alone. Further, deep emissions cuts were observed without significantly-reduced energy consumption only through the dual implementation of a carbon tax and a CCUS R&D subsidy (Grimaud et al., 2011).

5.4 Delayed CCUS Investment Delays Rewards

Carbon taxes increase the price of fossil fuel intensive goods and reduce consumption of these goods, but CCUS alleviates this burden. Because of this effect, immediate CCUS investment reaps prompt returns.

Investing in CCUS in the near term[34] decreases the burden of the carbon tax on the current generation and spares ensuing generations this expenditure (Gerlagh, 2006; Grimaud and Rouge, 2014). Although long-run economic growth remains higher under carbon taxes, they reduce output and consumption of emissions-intensive goods in the short-run, causing short- and mid-term losses in economic growth (Grimaud et al., 2011; Grimaud and Rouge, 2014). Pairing a carbon tax with CCUS subsidies or CCUS R&D preserves the long-term growth benefits of the carbon tax while helping offset short- and mid-term losses (Grimaud et al., 2011; Grimaud and Rouge, 2014).[35]

Delaying the implementation of comprehensive climate policies can adversely affect the incentives of CO_2 emissions-intensive firms. When firms expect future regulations of CO_2 emissions, it can spur firms to behave differently in the present. That's why climate policies encouraging future proliferation of inexpensive renewable resources can prompt increased fossil fuel extraction today, and climate policies stimulating cheap CCUS technology in the future can make fossil fuel resources more attractive in the future, discouraging fossil fuel extraction in the present (Sinn, 2008; Hoel and Jensen, 2012). Because of this dynamic, investments made to lower CCUS technology costs may be more desirable than equivalent reductions in renewable energy costs (Hoel and Jensen, 2012).[36] Further, because technological progress accumulates over time, investing in CCUS in the near term maximizes gains from innovation (Keller et al., 2008; Grimaud et al., 2011).[37]

[34] Studies often differentiate between short-run (near-term) and long-run (long-term) effects. Although timescales can vary across studies, a general definition of short run or near term is the current period and the near future, whereas the long-run or long-term refers to the period during which fossil-fuel resources decrease, that is, the distant future (Grimaud and Rouge, 2014).

[35] Implementing CCUS subsidies without a carbon tax has the opposite effect on long-run economic growth, because subsidies encourage more resource extraction in the short-run, they stifle long-run growth.

[36] Narita (2009) finds the opposite effect: scarcity in storage capacity can eventually drive up the price of CCUS, making renewable energy the more favorable technology to incentivize; however, recent research points to the potential capacity for storage capacity being very large (IEA, 2020).

[37] Goulder and Mathai (2000) also point out that technological progress lowers marginal abatement costs, which implies a lower carbon tax is necessary to incentivize CCUS investment.

5.5 CCUS is a Medium-Term Solution for Climate Change Mitigation

Without CCUS, fossil fuels have to be phased out earlier to reach emission reduction targets. Even with CCUS, additional policy initiatives are required to meet climate objectives.

If CCUS is not utilized to decarbonize fossil fuels, emission reduction necessitates decreasing fossil fuel usage; however, increasing CCUS investment can make for a smoother transition from a fossil fuel-based energy system to a renewables-based energy system, as CCUS postpones the shift to renewables (Edenhoffer et al., 2005). Gerlagh and Van der Zwaan (2006) estimate that without CCUS, meeting climate stabilization goals[38] will require 80 percent of the energy system to be sourced from renewable resources. They forecast that with CCUS, only 50 percent of the energy system will need to be sourced renewably, reducing the need for renewable energy by about 30 percent.[39]

Emissions reductions achieved through the use of a carbon tax and CCUS do not reduce long-term emissions enough to meet climate stabilization goals on their own. Gerlagh and Van der Zwaan (2006) found that even with large-scale CCUS deployment (where 30 – 50 percent of new fossil fuel based capacity was outfitted with CCUS), renewable resources will need to supply half of energy needs to realize emissions cuts necessary to stabilize the climate. Similar to Gerlagh and Van der Zwaan (2006), Grimaud et al. (2011) found that large-scale CCUS deployment is a medium-term option for reducing emissions—as in the long-term, significant amounts of renewable resources are necessary for stabilizing the climate.[40]

The dynamics behind these findings are that a carbon tax initially raises demand for CCUS technology, causing CCUS innovations to increase in value and CCUS deployment to achieve greater scale. However, CCUS deployment is limited over time, restricted to servicing finite fossil fuel operations while renewable resources continue to grow in scale. This same pattern, where CCUS deployment initially grows quickly, peaks, and then tapers off, is also found by Kalkuhl et al. (2015), and Duan et al. (2013).[41]

---

[38] Gerlagh and Van der Zwaan (2006) climate stabilization goals cap emissions at 450 parts per million volume of CO_2 equivalent (ppmv) to limit global warming to 2° Celsius.

[39] These findings are sensitive to the assumptions about renewable energy and CCS costs, which are both higher than current costs, as well as other parameter and structural assumptions of the model. Nevertheless, this finding is found across several studies with varying parameterization and structural assumptions.

[40] These results are sensitive to the relative marginal costs of abatement from renewables vs. CCS. Iverson (2015) found that CCS is a near to medium-term solution only if it is more cost-effective at abating CO_2 than renewables. However, there is an argument to be made that emissions abatement from renewables leaves unexploited fossil fuel deposits that could give rise to future environmental liabilities if future generations exploit those resources. CCS eliminates this risk, which creates additional value (Iverson, 2015).

[41] Kalkuhl et al. (2015) find this relationship in the optimal long-term growth of CCUS subsidies, which initially increase for several decades, but ultimately decline, due to the eventual displacement of CCUS by more competitive renewable energy. Duan et al. (2013) find this relationship in the ratio of emissions reduced by CCUS technology, where the ratio of emissions reduced by CCUS grows initially, but shrinks as carbon-free technologies replace CCUS technologies in later years.

6 | Conclusions / Next Steps

In the creation of this literature review, several key themes emerged:

Carbon taxes alone cost-effectively encourage CCUS investment. Putting a price on CO_2 emissions causes firms to seek the most affordable abatement technologies; among them is CCUS.

Subsidizing CCUS (the current U.S. approach) is not the most cost-effective policy option. Subsidies encourage excessive production, causing subsidy policies to cost more than carbon tax policies for the same amount of emissions reductions; however, when paired with a carbon tax, CCUS subsidies can offset the burden of the carbon tax for energy-intensive industries and consumers.

Subsidizing CCUS research and development (R&D) can help overcome barriers to CCUS adoption. Because CCUS projects face "first-of-its-kind" risks which increase costs, private investors may be discouraged from investing in CCUS. Pairing CCUS R&D subsidies with carbon taxes can encourage deeper emissions cuts than a carbon tax alone.

Pairing CCUS subsidies with a carbon tax reduces the social cost of the carbon tax. While carbon taxes reduce output and consumption of emission-intensive goods in the short run, CCUS encourages more production and consumption of the same goods. Pairing a carbon tax with a subsidy for CCUS reduces the initial burden of a carbon tax for society.

CCUS is a mid-term solution for reducing emissions. Without CCUS, fossil fuels have to be phased out earlier to meet CO_2 emissions reduction goals. Even with CCUS, more emissions reductions are needed to meet carbon emission targets.

Although the literature has thoroughly explored the potential for carbon taxes and CCUS subsidies to expand the role of CCUS in climate policies, additional research is necessary to understand other policy mechanisms or government support that can aid in reducing cost and investment uncertainty for CCUS—including options for facilitating the development of transport and storage infrastructure.

While current literature focuses on the economics of permanently storing CO2 emissions, another avenue for future research is to further explore how carbon taxes incentivize the utilization of captured CO2 emissions for EOR and other economic purposes. Additional economic uses for CO2 emissions can provide new revenue streams to further incentivize the use of CCUS technology.

Because CCUS has currently experienced limited deployment, much of the findings in the literature on pairing a carbon tax with CCUS are based on ex-ante computer simulation models. As carbon taxes and CCUS gain more prominence worldwide, additional research is needed to verify the ex post outcomes of carbon tax and CCUS policies.

References

Austin, D. and Dinan, T.2005. Clearing the air: The costs and consequences of higher CAFE standards and increased gasoline taxes. *Journal of Environmental Economics and Management*, 50(3), pp. 562-582.

Baumol, W.J. and Oates, W.E., 1971. The use of standards and prices for protection of the environment. In *The Economics of Environment* (pp. 53-65). Palgrave Macmillan, London.

Baumol, W.J. and Oates, W.E., 1988. *The Theory of Environmental Policy*. Cambridge University Press.

Blomen, E., Hendriks, C. and Neele, F., 2009. Capture technologies: improvements and promising developments. *Energy Procedia*, 1(1), pp. 1505-1512.

Bovenberg, A.L. and De Mooij, R.A., 1994. Environmental taxes and labor-market distortions. European *Journal of Political Economy*, 10(4), pp. 655-683.

Bovenberg, A. and Goulder, L.H., 2001. Neutralizing the adverse industry impacts of CO_2 abatement policies: What does it cost? In *Behavioral and Distributional Effects of Environmental Policy* (pp. 45-90). University of Chicago Press.

Bruvoll, A. and Larsen, B.M., 2004. Greenhouse gas emissions in Norway: do carbon taxes work? *Energy Policy*, 32(4), pp. 493-505.

Bull, N., Hassett, K.A. and Metcalf, G.E., 1994. Who pays broad-based energy taxes? Computing lifetime and regional incidence. *The Energy Journal*, 15(3).

Dismukes, D.E., Layne, M. and Snyder, B.F., 2019. Understanding the challenges of industrial carbon capture and storage: An example in a U.S. petrochemical corridor. *International Journal of Sustainable Energy*, 38(1), pp. 13-23.

Dooley, J.J., Dahowski, R.T., Davidson, C.L., Wise, M.A., Gupta, N., Kim, S.H., Malone, E.L., 2006. Carbon dioxide capture and geologic storage. A Technology Report from the Second Phase of the Global Technology Strategy Program. Available from: http://www.globalchange.umd.edu/data/gtsp/workshops/2006/ccs_report.pdf.

Duan, H.B., Fan, Y. and Zhu, L., 2013. What's the most cost-effective policy of CO_2 targeted reduction: An application of aggregated economic technological model with CCS?. *Applied Energy*, 112, pp. 866-875.

Edenhofer, O., Bauer, N. and Kriegler, E., 2005. The impact of technological change on climate protection and welfare: Insights from the model MIND. *Ecological Economics*, 54(2-3), pp. 277-292.

EIA (U.S. Energy Information Administration) 2019. International Energy Outlook 2019. U.S. Energy Information Administration https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf

Farrow, S., 1999. The duality of taxes and tradable permits: A survey with applications in Central and Eastern Europe. *Environment and Development Economics*, pp. 519-536.

Fischer, C. and Newell, R.G., 2008. Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, 55(2), pp. 142-162.

Gerlagh, R., 2006. ITC in a Global Growth-Climate Model with CCS: The Value of Induced Technical Change for Climate Stabilization. *The Energy Journal*, pp.223-240.

Gerlagh, R. and Van der Zwaan, B., 2006. Options and instruments for a deep cut in CO_2 emissions: Carbon dioxide capture or renewables, taxes or subsidies?. *The Energy Journal*, 27(3).

Global CCS Institute, 2019. The Global Status of CCS: 2019. Australia.

Goulder, L.H., 1995. Environmental taxation and the double dividend: a reader's guide. *International Tax and Public Finance*, 2(2), pp. 157-183.

Goulder, L.H., 2013. Climate change policy's interactions with the tax system. *Energy Economics*, 40, pp. S3-S11.

Goulder, L.H., Mathai, K., 2000. Optimal CO_2 abatement in the presence of induced technological change. *Journal of Environmental Economics and Management* 39 (1), 1–38.Goulder, L.H. and Parry, I.W., 2008. Instrument choice in environmental policy. *Review of Environmental Economics and Policy*, 2(2), pp. 152-174.

Goulder, L.H., Parry, I.W., and Dallas Burtraw, 1997. "Revenue-Raising vs. Other Approaches to Environmental Protection: The Critical Significance of Pre-Existing Tax Distortions." *RAND Journal of Economics*, 284, pp.708-73.

Goulder, L.H. and Schein, A.R., 2013. Carbon taxes versus cap and trade: a critical review. *Climate Change Economics*, 4(03), p.1350010.

Grimaud, A., Lafforgue, G. and Magné, B., 2011. Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics*, 33(4), pp. 938-962.

Grimaud, A. and Rouge, L., 2014. Carbon sequestration, economic policies and growth. *Resource and Energy Economics*, 36(2), pp. 307-331.

Hoel, M. and Jensen, S., 2012. Cutting costs of catching carbon—intertemporal effects under imperfect climate policy. *Resource and Energy Economics*, 34(4), pp. 680-695.

House, K.Z., Baclig, A.C., Ranjan, M., van Nierop, E.A., Wilcox, J. and Herzog, H.J., 2011. Economic and energetic analysis of capturing CO_2 from ambient air. *Proceedings of the National Academy of Sciences*, 108(51), pp. 20428-20433.

IEA, 2011. Technology Roadmap – Carbon Capture and Storage in Industrial Applications, 2011, IEA, Paris https://webstore.iea.org/download/direct/574

IEA, 2013. Technology Roadmap - Carbon Capture and Storage 2013, IEA, Paris https://www.iea.org/reports/technology-roadmap-carbon-capture-and-storage-2013

IEA, 2015. Carbon Capture and Storage 2015, International Energy Agency, Paris https://www.iea.org/reports/carbon-capture-and-storage-2015

IEA, 2020. CCUS in Clean Energy Transitions, International Energy Agency, Paris https://www.iea.org/reports/ccus-in-clean-energy-transitions

IPCC, 2005. Special Report on Carbon Dioxide Capture and Storage. In: Metz, B., Davidson, O., et al. (Eds.), *Intergovernmental Panel on Climate Change*. Cambridge University Press, Geneva, Switzerland.

IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment *Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

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.)]. IPCC, Geneva, Switzerland, 151 pp.

Iverson, T. and Belfiori, M.E., 2015. Burn coal? The supply-side case for carbon capture and storage.

Johansson, B., 2000. The carbon tax in Sweden. *Innovation and the Environment*, 85.

Jones, C.I. and Williams, J.C., 1998. Measuring the social return to R&D. *The Quarterly Journal of Economics*, 113(4), pp. 1119-1135.

Jorgenson, D.W. and Yun, K.Y., 1991. *Tax Reform and the Cost of Capital*. Oxford University Press.

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

Keller, K., McInerney, D. and Bradford, D.F., 2008. Carbon dioxide sequestration: how much and when?. *Climatic Change*, 88(3-4), p.267.

Keohane, Nathaniel, 2009. “Cap and Trade, Rehabilitated: Using Tradable Permits to Control U.S. Greenhouse Gases.” *Review of Environmental Economics and Policy* 3(1): 42-62.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C. and Fennell, P.S., 2017. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control*, 61, pp.71-84.

Metcalf, G.E., 1998. A distributional analysis of an environmental tax shift (No. w6546). National Bureau of Economic Research.

Metcalf, Gilbert E., 2007. A Proposal for a U.S. Carbon Tax Swap: An Equitable Tax Reform to Address Global Climate Change. Hamilton Project Discussion Paper 2007-12. Washington, DC: The Brookings Institution.

Milliman, S.R. and Prince, R., 1989. Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management*, 17(3), pp. 247-265.

Narita, D., 2009. Economic optimality of CCS use: a resource-economic model.

Newell, R.G. and Stavins, R.N., 2003. Cost heterogeneity and the potential savings from market-based policies. *Journal of Regulatory Economics*, 23(1), pp. 43-59.

Noothout, P., Wiersma, F., Hurtado, O., Macdonald, D., Kemper, J. and van Alphen, K., 2014. CO_2 Pipeline infrastructure– Noothout, P., Wiersma, F., Hurtado, O., Macdonald, D., Kemper, J. and van Alphen, K., 2014. CO_2 Pipeline infrastructure–lessons learnt. *Energy Procedia*, 63, pp. 2481-2492.

NPC (National Petroleum Council). 2019. Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage. National Petroleum Council Report.

Oates, W.E. and Schwab, R.M., 1988. Economic competition among jurisdictions: efficiency enhancing or distortion inducing? *Journal of Public Economics*, 35(3), pp. 333-354.

Onyebuchi, V.E., Kolios, A., Hanak, D.P., Biliyok, C. and Manovic, V., 2018. A systematic review of key challenges of CO_2 transport via pipelines. *Renewable and Sustainable Energy Reviews*, 81, pp. 2563-2583.

Otto, V.M. and Reilly, J., 2008. Directed technical change and the adoption of CO_2 abatement technology: the case of CO_2 capture and storage. *Energy Economics*, 30(6), pp. 2879-2898.

Parry, I.W., 1995. Pollution taxes and revenue recycling. *Journal of Environmental Economics and Management*, 29(3), pp. S64-S77.

Parry, I.W., Williams III, R.C. and Goulder, L.H., 1999. When can carbon abatement policies increase welfare? The fundamental role of distorted factor markets. *Journal of Environmental Economics and Management*, 37(1), pp. 52-84.

Parry, I.W., Sigman, H., Walls, M. and Williams III, R.C., 2006. The incidence of pollution control policies. International *Yearbook of Environmental and Resource Economics*, 2007, pp. 1-42.

Parry, I.W. and Williams, R.C., 2010. What are the costs of meeting distributional objectives for climate policy? *The BE Journal of Economic Analysis & Policy*, 10(2).

Parry, I., 2015. Carbon tax burdens on low-income households: a reason for delaying climate policy?. Working paper.

Pearce, D., 1991. The role of carbon taxes in adjusting to global warming. *The Economic Journal*, 101(407), pp. 938-948.

Popp, D., 2006. ENTICE-BR: The effects of backstop technology R&D on climate policy models. *Energy Economics*, 28(2), pp. 188-222.

Poterba, J.M., 1991. Tax policy to combat global warming: on designing a carbon tax (No. w3649). National Bureau of Economic Research.

Poterba, J.M., 1993. Global warming policy: a public finance perspective. *Journal of Economic Perspectives*, 7(4), pp. 47-63.

Rabindran, P., Cote, H. and Winning, I.G., 2011, April. Integrity management approach to reuse of oil and gas pipelines for CO_2 transportation. In Proceedings of the 6th pipeline technology conference. Hannover Messe, Hannover, Germany (pp. 04-05).

Ricci, O., 2012. Providing adequate economic incentives for bioenergies with CO_2 capture and geological storage. *Energy Policy*, 44, pp. 362-373.

Repetto, R., World Resources Institute WRI., Dower, R.C. and Jenkins, R., 1992. Green fees: how a tax shift can work for the environment and the economy. Washington: WRI.

Simbolotti, G., 2010. CO_2 Capture and Storage. Energy Technology Systems Analysis Programme, IEA Technology Network, International Energy Agency.

Sinn, H.W., 2008. Public policies against global warming: a supply side approach. *International Tax and Public Finance*, 15(4), pp. 360-394.

Skou Anderson, M., 2008. Environmental and economic implications of taxing and trading carbon: Some European experiences. Vt. J. Envt. L., 10, p.61.

Spulber, D.F., 1985. Effluent regulation and long-run optimality. *Journal of Environmental Economics and Management*, 12(2), pp. 103-116.

Stavins, Robert N., 2007. A US Cap-and-Trade System to Address Global Climate Change. Hamilton Project Discussion paper 2007-13. Washington, DC: The Brookings Institution.

Stigson, P., Hansson, A. and Lind, M., 2012. Obstacles for CCS deployment: an analysis of discrepancies of perceptions. *Mitigation and Adaptation Strategies for Global Change*, 17(6), pp. 601-619.

Summers, W.M., Herron, S.E. and Zoelle, A., 2014. Cost of Capturing CO_2 from Industrial Sources. NETL: Albany, OR, USA.

Sumner, J., Bird, L. and Dobos, H., 2011. Carbon taxes: a review of experience and policy design considerations. *Climate Policy*, 11(2), pp. 922-943.

Tarufelli, B., Snyder, B., and Dismukes, D., 2020. The Potential Impact of the U.S. Carbon Capture and Storage Tax Credit Expansion on the Economic Feasibility of Industrial Carbon Capture and Storage. *Energy Policy*, forthcoming.

Tietenberg, T.H., 2013. Reflections—carbon pricing in practice. *Review of Environmental Economics and Policy*, 7(2), pp. 313-329.

Van den Broek, M., Veenendaal, P., Koutstaal, P., Turkenburg, W. and Faaij, A., 2011. Impact of international climate policies on CO_2 capture and storage deployment: Illustrated in the Dutch energy system. *Energy Policy*, 39(4), pp. 2000-2019.

LSU | Center for Energy Studies