The Political Economy of Carbon Capture and Storage Technology Adoption

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Abstract

Carbon sequestration through capture and storage in subsurface porous geologic formations is one potential method for mitigating the problem of climate change due to emission of anthropogenic CO_2. In fact, in a world highly dependent on energy derived from hydrocarbons and coal, carbon capture and storage may represent the most promising approach to maintaining industrial development in the present period, while implementing other solutions that will deliver sustainable reductions in CO_2 emissions in the long run. Some countries have initiated pilot and large-scale projects to develop and improve carbon capture and storage technology, while others are slow to follow. What explains this variation? We develop a theory of the political economy of technology adoption to explore conditions under which countries are more likely to implement carbon capture and storage projects. We find that the likelihood of such projects depends on governments' policy positions and industries' research and development capacity. Data analysis of carbon capture and storage projects provides evidence in support of our theoretical expectations.

Global efforts to address climate change focus on reducing consumption of oil, gas, and coal—major sources of anthropogenic CO_2 in the atmosphere. Multilateral climate negotiations reflect objectives of such efforts in the form of emission reduction targets, which can be achieved through a combination of methods, including increased reliance on renewable energy, greater energy efficiency, and transition from more polluting to cleaner fuels, such as natural gas. Yet recent data indicate that major industrial nations fall short of these targets. Victor et al. (2017) show that results of enacted and pledged policies will be insufficient to reach emission targets agreed under the Paris framework of 2015. One of the key reasons why countries are failing in their efforts is the cost of deploying new technologies to reduce hydrocarbon consumption. Hence, among other recommendations, the study suggests that "particular attention must be paid to what governments are doing to stimulate private investment in new technologies" (26).

A fundamental question, we argue, is *when* governments are willing to adopt measures to stimulate private-sector investments in new technologies that would lead to reduced carbon dioxide emissions. Equally important is the

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private sector's ability to respond to such government incentives: even if governments are willing to provide investment incentives, companies should be in a position to respond and deliver meaningful outcomes in relevant technological areas. Therefore the greatest potential for developing technology to address climate change can only result from the interaction of governments and relevant industries under specific conditions.

This study investigates what conditions are conducive to such technological development and when they are likely to be present. Our argument focuses on the government's interest in supporting technological improvement and the industry's ability to deliver such improvement. To make our analysis more tractable, we focus on one area of innovation—geological carbon sequestration. We attribute the difference in the likelihood of technology development and adoption to the government's willingness to adopt policies incentivizing innovation with global environmental benefits, on the one hand, and the industry's research and development (R&D) capacity, on the other. This study identifies the oil and gas exploration and production (E&P) industry as a key industrial actor in this process.

To test our theoretical expectations, we focus on implementation of large-scale industrial and pilot projects to capture and store carbon. Our statistical analyses offer a novel insight into conditions that make such initiatives most likely: carbon capture and storage projects have the highest predicted implementation probability in countries with technologically advanced oil and gas E&P industry and left-wing governments, when they are highly supportive of technological and industrial innovation. Importantly, when these conditions are not met, technology adoption becomes highly unlikely. In the absence of the oil and gas industry's R&D capacity, countries do not deploy carbon sequestration technology, regardless of governments' policy preferences. At the same time, governments' reluctance to support technological innovation has a chilling effect even when the industry possesses high R&D capacity: we find the lowest probability of technology adoption in the case of right-wing governments that are the least committed to technology and infrastructure development, regardless of the industry's R&D activities. These findings present strong evidence of the critical role that public–private cooperation plays in the adoption of carbon capture and storage technology.

Carbon Capture and Storage Technology and its Potential as a Climate Change Abatement Instrument

Existing research and policy recommendations identify three primary methods of countering the rise of CO_2 concentration in the atmosphere. Countries can increase their energy efficiency and use less energy; transition to sources of energy that do not increase the amount of CO_2 in the atmosphere, such as solar, wind, or nuclear energy; or capture CO_2 and store it, thereby decreasing greenhouse gas emissions. All approaches require developing and adopting new

technologies and involve significant (but varying) costs. In practice, countries tend to adopt a combination of these strategies (Grimston et al. 2001).

The focus of this article is on the third approach—that is, carbon capture and storage (CCS)—because only recently has it become accepted as a viable mitigation option that can be part of countries' emission reduction strategies. A key document that provided a detailed description of the potential of this technology as an instrument to address climate change is the 2005 *Special Report of the Intergovernmental Panel on Climate Change*. This report and its favorable assessment of CCS as a method of emission reduction resulted in countries' increased interest in implementing CCS projects.

Conceptualization and development of CCS, however, took place before the Intergovernmental Panel on Climate Change (IPCC) considered its emission reduction potential. About two decades ago, permanent sequestration of industrial volumes of CO_2 became an engineering technology after Statoil injected one million tons of the greenhouse gas into an aquifer at a depth of 800 m under the North Sea (Benson and Cole 2008). Since then, multiple pilot and industrial sequestration projects have been initiated, targeting onshore geologic systems favorable for permanent storage of large volumes of the supercritical gas. Carbon sequestration projects require a suitable geologic setting and highly advanced technologies for capturing, transporting, storing, injecting, and monitoring subsurface movement of the greenhouse gas.

Such technologies became available as a result of R&D investments and experience of the oil and gas E&P industry. Specifically, the technique of using CO_2 for enhanced oil recovery (EOR) has been widely adopted and accounts for about 80 percent of commercially recovered CO_2 use in the United States and Canada (US Department of Energy [USDOE] 1999b). This industry's expertise in dealing with underground reservoirs and the injection of CO_2 to increase the productivity of mature wells made it one of the key actors in the recent development of CCS technology as a method of reducing CO_2 emissions (Stephens 2009; Tjernshaugen 2012; Vormedal 2008).

In addition to advanced technology, CCS requires suitable geological conditions, which may restrict the application of this technology to certain regions of the world. In particular, the geologic aspect of carbon sequestration includes the presence of a large sedimentary basin with a reservoir-quality rock (i.e., high porosity, high permeability, and relatively low salinity of connate reservoir water) in the subsurface of a country's territory and a shale seal on top of the reservoir rock. High-porosity and -permeability sedimentary rock (such as sandstone) is an optimal storage reservoir because it has high storage capacity (due to porosity) and high injection and volumetric extent potential (due to high permeability). Relatively low salinity is necessary for better mixing and dissolution of reservoir connate water and the supercritical CO_2 gas. To contain large volumes of injected CO_2 inside the reservoir rock, it is essential to have an extra-low permeability seal rock (such as shale) that acts as a barrier between the reservoir and upper freshwater aquifers and does not allow the gas

plume to come to the surface, causing extinction of animal life in the vicinity (Benson et al. 2002; Gale 2002; Krumhansl 2002; Marchetti 1977; Metz et al. 2005).

Conditional on geologic requirements being satisfied, advanced technology becomes a critical factor: carbon sequestration can only be performed successfully with up-to-date carbon capturing, storing, transporting, injecting, and monitoring technologies. CO_2 capturing can be accomplished at an oil-, gas-, or coal-fired power plant if this plant is equipped with capturing equipment. If such equipment is not available, a carbon sequestration operator might resort to capturing atmospheric CO_2 (so-called direct air capturing), which can be accomplished using chemical CO_2 adsorbing substances, such as zeolites (Hasan et al. 2013). Zeolites, however, require building surface infrastructure with towers and an additional power plant to increase concentration of CO_2 from the air, which further increases the cost of sequestration. Storing and injecting large volumes of CO_2 requires pumps and compressors capable of compressing the CO_2 gas to 73 atm (or 7.39 MPa or 1,071 psi) to change the gas phase into a supercritical state that behaves similarly to a fluid that can be easily transported and injected. The final technological aspect of CO_2 sequestration is monitoring. Once the supercritical gas is injected into the subsurface reservoir, it tends to form a plume underneath the seal rock due to high buoyancy of the gas. A high-pressure plume can cause damage to and fracturing of the seal rock and leakage of the gas to the surface. To avoid this hazard, all carbon sequestration projects must model the maximum safe volume of CO_2 to be sequestered in a given reservoir using reservoir simulation tools, and then monitor movement of the plume using 4D seismic over several decades.

This shows that the critical factor in the decision to adopt CCS technology is its cost, which can vary dramatically. Rubin et al. (2015) show that the cost of CO_2 utilization is highly dependent on the source of emission. Specifically, this research considers the four most common plan designs with CO_2 capturing features and provides cost estimates of a captured ton of CO_2 and the cost of an avoided ton of CO_2. The cost of CO_2 avoided is the cost of reducing CO_2 emissions into the atmosphere while still producing the same amount of product from a given plant. The cost of CO_2 avoided is usually expressed as US$/ton of CO_2 not emitted with respect to a given process. For example, a ton of CO_2 captured at a supercritical pulverized coal (SCPC) plant is in the range between US$ 36–53/ton with an average value of US$ 46, while the cost of an avoided ton of CO_2 is approximately US$ 63. For pulverized coal and natural gas combined cycle plants, the costs are higher: US$ 58–121/ton captured (with US$ 87/ton as a representative value) and US$ 48–111/ton avoided (with an average value of US$ 74/ton). Plants with integrated coal gasification combined cycle design can capture and avoid CO_2 emissions with lower costs. Specifically, the cost of CO_2 capture is in the range between US$ 28 and 41/ton (with an average value of US$ 34), and the cost of CO_2 avoided is between US$ 37 and 58/ton (with an average of US$ 46).

Because the cost of CCS technology plays a critical role in the industry's decision to adopt it, the industry's partnership with the public sector can provide incentives that may counter some of the costs and, hence, make technology adoption more likely. Previous studies provide evidence that such partnerships indeed take place as both public and private actors demonstrate their interest in pursuing CCS technology. The United States has been one of the first to invest in CCS activities: in the late 1990s, the US Department of Energy, for instance, provided approximately US$ 1.6 million for research in this area (USDOE 1999a). The European Union (EU) and its member nations sought to catch up later by establishing their own research initiatives, such as the European Potential for Geologic Storage of Carbon Dioxide from Fossil Fuel Combustion (GESTCO), and the EU Fifth Framework R&D Programme is supporting the project with 1.9 million euro, half of the overall budget (Grimston et al. 2001, 167). The private sector has also engaged in R&D activities to develop CCS technology. However, these efforts have been limited to large companies primarily in the oil and gas E&P sector. For example, BP had several projects in Texas, Alaska, and Canada. The company also participated in Pan Canadian Petroleum's Weyburn field project, which received support and funding from the US and Canadian governments (Grimston et al. 2001, 168). The Weyburn field example indicates that even large companies with significant R&D resources may need government support to implement CCS technology. The question that arises from this discussion is, under what conditions do such partnerships arise? We turn to this question in the next section. Our focus is not only on the conditions leading to public–private cooperation but also on the mechanism through which such cooperation between government and industry affects the development and adoption of CCS technology.

A Theory of CCS Technology Development

Our theoretical argument focuses on variation in timing of CCS technology development and its adoption in different countries. Specifically, we differentiate between adopters and nonadopters and evaluate the mechanism that results in observable variation in CCS adoption among different countries. Two types of actors and their interactions are critical to modeling and understanding such differences: national governments and industries.

When we refer to industries, we mean any of the companies or sectors that can be involved in the CCS process. As explained in the previous section, CCS technology requires cooperation of different companies for carbon capture, transportation, and storage. Moreover, costs of CCS vary across different sources of emissions. However, the leading sector in the development and implementation of CCS technology has been the oil and gas E&P industry. Therefore, for the purposes of our theoretical discussion, we will focus on this industry and treat it as one group with coherent preferences.

Our argument builds on a few key assumptions. First, developing CCS technology is costly for industries. Therefore industries will only invest in its development and implementation when they can receive market benefits from CCS (i.e., increased profits) or when governments incentivize industries financially (e.g., through subsidies) or otherwise (e.g., by imposing more stringent emissions standards). Second, investments in CCS technology are associated with significant uncertainty over the end result. Uncertainty stems from the ease (or difficulty) of implementation, varying costs of technology, and governments' future environmental policies, among other things. Higher levels of uncertainty should make industries more reluctant to invest in CCS technology because of increased investment risks. Therefore governments that value adoption and implementation of this technology may seek to counter greater risks through various incentives. Third, industries care not only about current profits but also about future profits (albeit at a discounted rate). Hence, under certain conditions, they should be willing to use some of their current resources to secure higher profitability in the future. In addition, companies may undertake investments if they expect to benefit through lower expenses due to greater efficiency or improved compliance with government regulations and, hence, lower government fines.

When industrial decision makers consider whether to invest in CCS development and implementation, one of the primary criteria they evaluate is how this new technology may increase their profits. For example, CO_2 injection, which is one of the steps in the CCS process, is used extensively by the oil and gas sector for EOR purposes. The choice to invest in the technology is driven by the industry's ability to extract more oil (in economic terms, to move probable and possible oil reserves into the category of proved reserves), which makes existing oil wells more profitable and increases the net worth of the asset owner. Therefore industries' R&D spending signals that industries estimated that this investment would likely increase their assets (or reduce their costs) and thus enhance future profitability. Increased R&D spending also shows that industries have resources for such activities. In sum, industries' investment in new technology shows that they are able and willing to use some of their resources today for enhanced profitability in the future.

Industries' willingness to spend on technology innovation can be dampened if there are significant risks associated with future returns on this technology investment. Hence industry decision makers evaluate available evidence to estimate whether this new technology is easy to adopt and use, how much it will affect companies' profitability, and how successful other companies may be in developing and deploying this technology and increasing their competitiveness. Industries also need to consider how likely they are to experience an exogenous shock, such as a change in market conditions or government policies. For example, such exogenous shocks can come in the form of sudden energy price drops or governments' adoption of stringent emissions standards.

Industries' approaches to dealing with these two types of risks may vary. In particular, technology-specific risks can be reduced by initiating pilot projects,

which allow companies to evaluate technology and work out problems prior to large-scale implementation. Other types of investment risks, such as shifting market or policy conditions, are harder to control. Therefore industry decision makers have to evaluate available information and form estimates of investment risks, which then affect expected future profits. With regard to government policy, the industry can rely on governments' policy positions as indicators of governments' preferences with regard to CCS technology.

First, we evaluate factors that can affect the industry's cost–benefit calculations regarding CCS technology development and adoption. We expect the industry to invest in CCS technology when expected benefits of innovation are at least as high as the cost of investment. This independent investment condition applies to the scenario without government support. If the government does contribute to the industry's innovative efforts, CCS technology is adopted when the sum of expected commercial benefits and government assistance exceeds the industry's cost of technology development and implementation.

Now we turn to the government's decision to contribute to the industry's innovation. First, suppose the industry's innovation costs are so low that the industry is willing to pursue CCS technology without government assistance. The government's best response is to remain uninvolved. Second, suppose the industry's innovation costs are so high that even government support would not convince the industry to invest. The government's best response is, again, to remain uninvolved. Finally, the industry's investment costs may be in the middle range: that is, they are too high to meet the independent investment condition but are low enough to make investment possible with some assistance. In this case, government assistance can sway the industry's decision. The government will choose to contribute when the expected environmental benefits of CCS technology are greater than the government's cost of supporting the industry.[1] The government support, in turn, incentivizes the industry to invest, which results in CCS technology development and implementation.

Given the government's and industry's strategies, we can identify conditions when we are likely to observe CCS technology adoption in a given country and state these conditions as testable hypotheses. The difference in adoption likelihood is due to the government's utility from technological improvements and its willingness to transfer resources to incentivize innovation, as well as the industry's ability to allocate resources toward R&D activities and expected profits from technological improvements. We expect these political and economic factors to have additive effects on technology adoption, but we also expect some interaction effects.

First, consider the industry's ability to fund R&D activities. We expect industries with well-funded ongoing programs to be in a better position to develop and implement CCS technology, all else being equal. The cost of

1. The government could also receive additional benefits from higher industry profits, such as increased tax revenues or greater electoral support. This would increase the government's likelihood of offering support to the industry.

investment is a determinant of the industry's investment decision. As the size of this cost increases, technology adoption becomes less likely. However, in industries with ongoing R&D activities that have already absorbed costs of technological development, additional investment CCS-related costs will likely be much lower than in industries with limited previous innovation. Therefore we expect a positive relationship between the industry's R&D activities and CCS project implementation:

> **Hypothesis 1 (R&D Capacity).** *The likelihood of CCS project implementation is higher in countries where industries invest higher amounts in R&D activities.*

Now consider the role of government policy positions. When it comes to governments' preferences with regard to CCS technology, two aspects are particularly relevant: a government's views on its role in the economy (more or less interventionist) and on modernization and technological development (more or less favorable). Following our argument, governments can increase the probability of CCS adoption when adoption costs are not too high by offering government support. Conservative, or right-wing, governments tend to be more reluctant to intervene in markets and increase government spending: previous research shows that levels of government transfers, taxes, and regulations are lower under conservative governments (Benoit and Laver 2006; Perotti and Kontopoulos 2002). Because conservative governments are more reluctant to increase government spending or use regulations, the cost of government support is higher for these governments. When it comes to CCS projects, conservative governments may be particularly hesitant to get involved because large-scale integrated CCS projects (LSIPs) require "a substantial commitment from both government and the industrial actors that will build and operate the facilities," since these projects are expensive both in the short and long terms (Kern et al. 2016, 251). Thus we expect countries with right-wing governments to be less likely to implement CCS projects compared to left-wing governments. In addition, we expect a positive association between governments' favorable view of technological innovation and CCS adoption. Such governments may seek to promote modernization and adoption of new technology because it contributes to greater social welfare and provides economic benefits. Therefore we formulate two testable hypotheses for governments' policy preferences:

> **Hypothesis 2 (Government Ideological Position).** *The likelihood of CCS project implementation is higher in countries with left-wing governments.*

> **Hypothesis 3 (Government Technology Position).** *The likelihood of CCS project implementation is higher in countries with governments that are more supportive of technological development.*

In addition, we consider interaction effects of the government's policy preferences and the industry's R&D capacity. CCS technology adoption and implementation should be most likely in countries with public–private cooperation in

this area; that is, we expect to see a stronger positive relationship between the government's ideology and technology positions and CCS adoption when the industry's R&D activities increase. We summarize this expectation in the following hypothesis:

> **Hypothesis 4 (Interaction Effects).** *The positive effect of a government's left-wing ideology and support for technological innovation grows as the industry's R&D capacity increases.*

Data and Variables

To test our theoretical expectations presented in the previous section, we created a data set by combining information from different data sources. First, we collected data on large-scale CCS facilities and pilot/demonstration projects available from the Global CCS Institute's database.[2] Second, we used the Seki–Williams Government Partisanship data set to obtain measures of governments' right–left positions and their technology/infrastructure views (Seki and Williams 2014). Third, we turned to the World Bank's World Development Indicators to construct the following variables: *Land Area (ln)*, *CO2 per Capita (ln)*, and *R&D Spending (ln)*. Fourth, the BP Statistical Review of World Energy served as the source of information on oil prices and annual oil production by country.[3] Fifth, we used Polity IV data to construct a democracy dummy, which takes the value of 1 for countries, with Polity2 scores of at least 7, and 0 otherwise.[4] Finally, we constructed dummies for EU members and countries that ratified the Kyoto Protocol.[5]

Our analysis focuses on implementation of large-scale CCS projects as well as pilot and demonstration projects. According to the Global CCS Institute (2017),

> large-scale integrated CCS projects (LSIPs) are defined as projects involving the capture, transport, and storage of CO_2 at a scale of: at least 800,000 tonnes of CO_2 annually for a coal-based power plant, or at least 400,000 tonnes of CO_2 annually for other emissions-intensive industrial facilities (including natural gas-based power generation). The thresholds listed above correspond to the minimum amounts of CO_2 typically emitted by commercial-scale power plants and other industrial facilities. Projects at this scale must inject anthropogenic CO_2 into either dedicated geological storage sites and/or enhanced oil recovery (CO_2-EOR) operations, to be categorized by the institute as LSIPs. EOR may result in partial (incidental) or complete storage of

2. The database is available at http://www.globalccsinstitute.com/, last accessed March 12, 2019.
3. The statistical report is available at http://www.bp.com/statisticalreview, last accessed March 12, 2019.
4. The Polity IV data set is available at http://www.systemicpeace.org/inscrdata.html, last accessed March 12, 2019.
5. EU membership information is available at https://europa.eu/european-union/about-eu/countries/member-countries_en; information on the Kyoto Protocol parties is available at http://unfccc.int/kyoto_protocol/status_of_ratification/items/2613.php.

> injected CO_2 in oil reservoirs, subject to technical and economic factors. The institute acknowledges that in some cases and jurisdictions, CO_2-EOR operators and/or regulatory authorities may not operate or permit CO_2-EOR sites for greenhouse gas mitigation purposes. Nevertheless, such EOR projects can demonstrate both the successful operation of full-chain CCS projects and the secure underground injection of CO_2 at industrial scale.

In contrast, pilot and demonstration projects lack at least some of these characteristics. In other words, they lack either full integration or the scale of larger projects. Pilots tend to serve as a way of gathering information on facility operations or economic outcomes, testing alternative designs and their technical feasibility, or facilitating public outreach. Many of these projects receive government cofunding.

Our models use the following dependent variables. *LSIP Count* represents a count of large-scale CCS projects ongoing in a given year. *LSIP Binary* is an indicator derived from *LSIP Count* and takes the value of 1 if there is at least one ongoing large-scale project in a given country in a given year, and 0 otherwise. We also count the number of large-scale and pilot projects implemented in a given country as of 2016: the resulting variables are *Total LSIPs* and *Total Pilots*, respectively.

We use three main explanatory variables to test our theoretical expectations. The first is *R&D Spending (ln)*, which is a (logged) amount of R&D spending by oil and gas companies in a given country, measured in million euros in 2015–2016. This variable gauges the industry's ability and willingness to invest resources in advanced technology. The other two variables capture the government's characteristics. *Government's Right–Left Position* captures the government's general ideological position, ranging from positive values, which represent right-wing, or conservative, governments, to negative values, which represent left-wing, or liberal, governments. Existing research suggests that left-wing parties are more likely to adopt green taxes (Daugsberg and Svendsen 2001) and implement measures to reduce pollution (Jahn 1998; Neumayer 2003). *Government's Technology Support* reflects a second relevant dimension of governments' policy preferences: specifically, this measure indicates how much a government values technological modernization and advances in industry, infrastructure, and other areas of the economy. According to the codebook of the Party Manifesto Project, several indicators combine to constitute a government's level of technology support: "Importance of science and technological developments in industry; Need for training and research within the economy … ; Calls for public spending on infrastructure such as roads and bridges; Support for public spending on technological infrastructure" (Lehmann et al. 2017). Values of *Government's Technology Support* range in our data set from 0 when a government does not support technological advances to 29 when a government shows high levels of technology support. Figure 1 illustrates one country's (Canada's) distribution of government positions on this dimension over time. In the early 2000s, the country's government was very supportive of

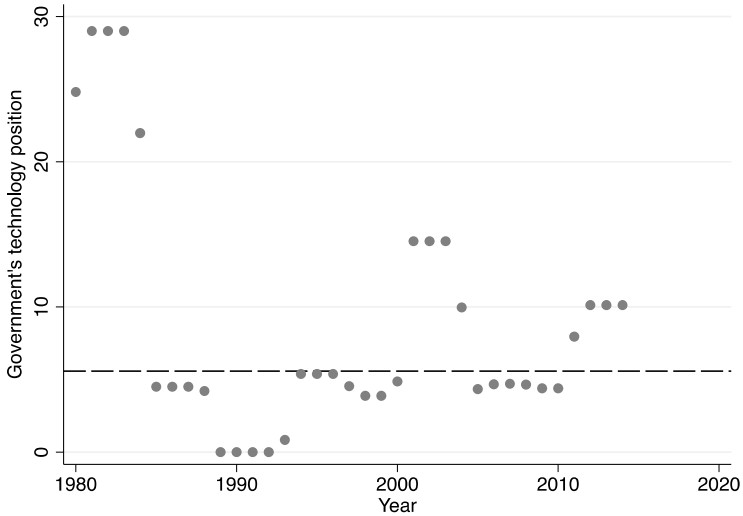

Figure 1
Canadian Government's Technology Support Positions

The dashed line corresponds to the mean value of the variable.

technological improvements, as values of *Government's Technology Support* are well above the mean, whereas in the late 2000s, the government was much less supportive (values are below the mean).

Finally, we use several control variables to consider various political and economic factors that can affect the likelihood of CCS technology development and deployment. We include measures like *Democracy*, *EU Member*, and *Kyoto Ratification* following previous research that indicates that democratic countries, EU members, and parties to the Kyoto Protocol are more likely to adopt more ambitious climate change policies (Bättig and Bernauer 2009; McLean and Stone 2012; Neumayer 2002; Schreurs and Tiberghien 2007; Von Stein 2008). The EU also showed its interest in CCS by supporting its use as a mitigation option under the Kyoto Protocol and the Clean Development Mechanism (Vormedal 2008). Larger countries are more likely to have suitable geological settings within their borders, while economies with greater CO_2 emissions offer greater opportunities for CCS technology implementation (Intergovernmental Panel on Climate Change [IPCC] 2005, 351). In addition, there is more international pressure on these countries to reduce CO_2 emissions (Jaccard and Tu 2011). Therefore we control for *Land Area (ln)* and *CO2 per Capita (ln)* with the expectation of a positive association between these variables and CCS project implementation. At the same time, potential benefits from CCS deployment may decline as oil prices and countries' oil production increase, thereby dissuading companies from adopting this technology; hence *Annual Oil Production (ln)* and *Oil Price* should have a negative effect on CCS project implementation.

Discussion of Results

Before presenting our statistical results, we turn to a scatterplot of governments' policy positions on two dimensions to illustrate the importance of including two measures in our analyses. If one dimension, that is, the general ideological position, reflected governments' preferences over support for technological modernization, we would see our observations cluster in two quadrants of the figure. If, for example, more conservative governments also tended to be more supportive of infrastructure and industry advancements, we would see most of the observations in the upper-right and lower-left quadrants. Yet Figure 2 shows that this is not the case. There is clearly no strong correlation between governments' preference for more (or less) conservative policies and their support for technological advancement. The correlation coefficient between the two measures is also close to zero ($r = -0.13$). This suggests that governments have complex policy positions that cannot be collapsed into a unidimensional measure without loss of information. Specifically, some left-wing governments that tend to favor social spending rather than business support pursue policies favorable to industries' technological advancement. On the flip side, some right-wing governments that are generally pro-business adopt conservative policies in the area of technological modernization, leaving it up to industries to allocate resources for R&D and to deploy new technologies.

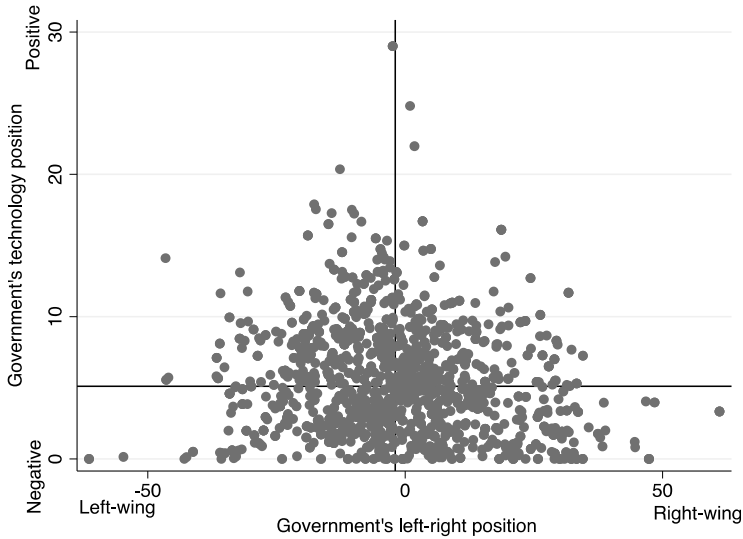

Figure 2
Governments' Policy Positions on the Right–Left and Technology Support Dimensions

The lines correspond to the median values of the variables.

In Table 1, we present four models of CCS project implementation.[6] Here we focus on large-scale projects. We specify models 1 and 3 as additive models, whereas models 2 and 4 rely on the same specifications as models 1 and 3, respectively, but add interactions between our indicators of governments' policy positions and industries' R&D spending. The dependent variable in models 1 and 2 is *LSIP Binary*; therefore we use logit to estimate these models.[7] The dependent variable in models 3 and 4 is *LSIP Count*; thus the corresponding columns report negative binomial estimates.[8]

In the two additive models (models 1 and 3), one of our key explanatory variables, *Government's Right–Left Position*, has a negative and statistically significant coefficient. This suggests that countries with conservative governments are less likely to implement CCS projects, all else being equal. This result lends support to Hypothesis 2 (i.e., the Government Ideology Hypothesis). The other policy dimension, the government's support for technology, does not have a significant effect on project implementation in these additive specifications. The third key explanatory variable, *R&D Spending (ln)*, is positively and significantly associated with large-scale CCS projects. The positive relationship suggests that such projects are more likely when the oil and gas E&P industry has the resources and incentives to increase its spending on R&D activities, all else being equal. This empirical evidence is consistent with Hypothesis 1 (i.e., the R&D Capacity Hypothesis).

Two other models, models 2 and 4, provide further support for our theoretical expectations. While the key findings from models 1 and 3 remain unaffected, we also find interaction effects as stated in Hypothesis 4 (i.e., the Interaction Effects Hypothesis). Specifically, when we include interaction terms for two dimensions of government policy preferences and the industry's R&D spending, we find a positive relationship between *R&D Spending × Government's Technology Support* and the likelihood of LSIP implementation in models 2 and 4. Furthermore, we find a negative relationship between *R&D Spending × Government's Right-Left Position* and the likelihood of LSIP implementation; however, in model 4, the result does not reach conventional levels of statistical significance. Because these are interaction models, we generate predicted probability plots to illustrate effects identified in the models.

Figure 3 uses results in model 2 to illustrate the probability of a large-scale CCS project for different combinations of government policy positions, on the one hand, and a full range of the industry's R&D spending, on the other, while holding controls fixed at their mean values. When the industry does not provide significant resources for R&D activities, governments are virtually indistinguishable as the expected probability of an LSIP remains low for all combinations of

6. The results hold if we use lagged explanatory variables.
7. Postestimation classification tables indicate that model 1 correctly predicts 97.45 percent of outcomes, while model 2 correctly predicts 97.66 percent of outcomes.
8. We conducted robustness checks with cumulative CCS capacity of LSIPs as the dependent variable. Our main findings remain largely unchanged.

Table 1
Determinants of Large-Scale Carbon Capture and Storage Project Implementation

	Model 1: LSIP Binary	*Model 2: LSIP Binary*	*Model 3: LSIP Count*	*Model 4: LSIP Count*
Land Area (ln)	9.19**	20.53**	2.59**	2.89**
	(3.04)	(6.97)	(0.50)	(0.51)
Kyoto Ratification	1.74**	2.41**	0.54	0.69
	(0.18)	(1.08)	(0.61)	(0.66)
CO_2 per Capita (ln)	9.49*	20.75**	1.09	1.29
	(5.10)	(9.67)	(0.84)	(0.85)
Annual Oil Production (ln)	−3.24	−4.24**	−1.49**	−1.55**
	(2.10)	(1.34)	(0.35)	(0.37)
R&D Spending (ln)	2.29**	4.71**	0.48**	0.37**
	(0.79)	(1.91)	(0.11)	(0.07)
Government's Technology Support	0.06	0.44**	0.06	0.06
	(0.06)	(0.17)	(0.07)	(0.05)
Government's Right-Left Position	−0.05**	−0.15**	−0.02**	−0.03**
	(0.02)	(0.04)	(0.01)	(0.01)
R&D Spending * Government's Technology Support		0.10**		0.02**
		(0.04)		(0.01)
R&D Spending * Government's Right-Left Position		−0.01**		−0.00
		(0.01)		(0.00)
Oil Price	0.00	−0.02*	−0.00	−0.01**
	(0.01)	(0.01)	(0.00)	(0.00)
Time	−0.12	0.07	0.04**	0.04**
	(0.22)	(0.14)	(0.01)	(0.01)
Constant	94.52	−468.42**	−123.37**	−121.01**
	(423.88)	(175.66)	(28.04)	(24.13)
Pseudo R2	0.78	0.83	0.61	0.62
Observations	470	470	470	470

Note. M1, M2: logit models; M3, M4: negative binomial models. Unit of analysis: country-year. Period: 1996–2016. Standard errors clustered by country, in parentheses.
*$p < 0.10$. **$p < 0.05$.

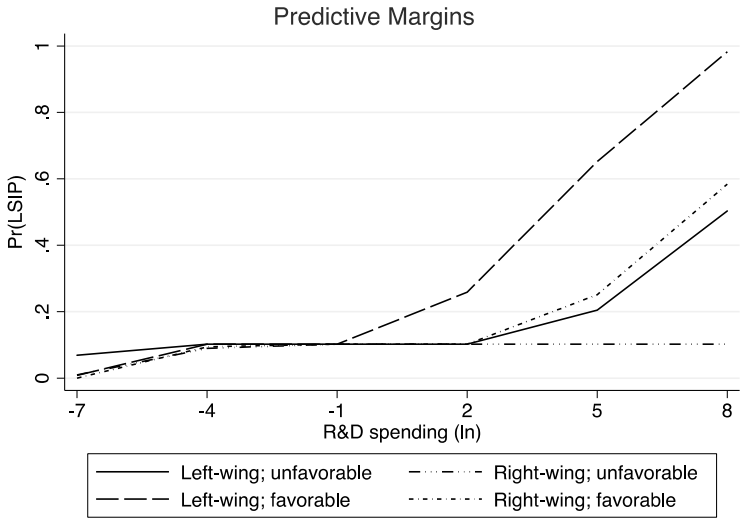

Figure 3
Predicted Probability of LSIP Implementation

policy positions. However, the situation changes when R&D spending grows. The likelihood of LSIP implementation shows the highest increase in R&D spending under left-wing governments that are committed to investing in technology and infrastructure: the predicted probability of LSIP implementation for countries with these governments equals 0.98 when R&D spending is at its maximum. The lowest level of increase is observed in the case of right-wing governments that are the least committed to technology and infrastructure development. Even when the industry spends the largest amounts on R&D activities, countries under such governments are predicted to implement a CCS project with a probability of only 0.1. The other two government types (right-wing governments with favorable technology positions and left-wing governments with unfavorable technology positions) display a similar rate of increase in the predicted LSIP probability, which is in the middle between the first two government types. When R&D spending reaches its maximum level, countries with these types of governments implement LSIPs with predicted probabilities of 0.58 and 0.50, respectively. Our results also emphasize the key role of the industry in CCS technology adoption: if we fix all other regressors at their means and reduce R&D spending from its maximum (8) by 1 standard deviation (3.6), we calculate that the probability of an LSIP decreases from 0.42 to 0.11, which represents a substantial decline in LSIP likelihood.

Figure 4 relies on results reported in model 4 of Table 1 to visualize the predicted probability of implementing at least one large-scale CCS project. The results are quite similar to those presented in Figure 3. Regardless of the government's policy positions, the probability of project implementation is low when

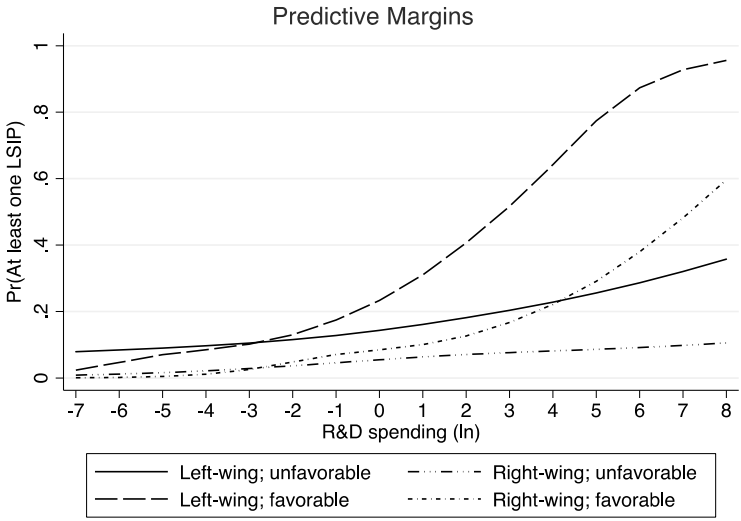

Figure 4
Predicted Probability of Implementing One or More LSIPs

R&D spending levels are low. As R&D spending grows, the most substantial increase in the predicted project probability is observed in the case of left-wing governments supportive of technological innovation. We find the smallest increase for right-wing governments with unfavorable technology positions, while the other two government types are in the middle in terms of the rate of increase of project probability.

Several control variables yield interesting insights. As expected, a country's territorial size is positively associated with large-scale CCS project implementation, as well as the number of such projects. These results suggest that the probability of identifying favorable geologic settings for CCS projects is higher in larger countries, which in turn leads to a greater likelihood of CCS project implementation. We also find that the likelihood of project implementation is higher in countries that have ratified the Kyoto Protocol, which indicates a positive effect of this international climate change agreement on countries' willingness to pursue CCS technology to reduce their greenhouse gas emissions. Emissions intensity, or CO_2 emissions per capita, also increases the likelihood of a CCS project. This relationship can be linked to greater opportunities for CCS projects. Two remaining results indicate that CCS technology adoption cannot be attributed to the strength and profits of the oil and gas industry: higher oil prices and increasing volumes of oil production lead to a decrease in the likelihood of CCS projects and their number. These findings strengthen one of our main conclusions: we attribute the adoption of CCS technology to the industry's R&D capacity rather than to the industry's size or profits. Our result emerges while we control for these two industry characteristics.

Because measures of government policy positions are only available for democracies, our conclusions apply to this group of countries. Historically, these countries were the first to develop and adopt CCS technology; therefore our measurement restrictions do not affect the interpretation of available data for past large-scale CCS projects. The first nondemocratic country to implement a large-scale CCS project was Saudi Arabia: the country's Uthmaniyah CO_2-EOR Demonstration Project became operational in 2015. More importantly, nondemocratic countries demonstrate their growing interest in the CCS technology and capability to pursue its adoption and implementation: even though few large-scale CCS projects are located in nondemocratic countries, these countries are implementing a rapidly increasing number of pilot projects. Therefore future research will need to consider determinants of CCS technology adoption in nondemocracies.

Another extension of this research needs to evaluate the relationship between availability of suitable geological formations for storage and adoption of CCS technology. Our main results use information for all countries, with or without known prospective storage areas. However, countries should be more likely to implement CCS projects when geological storage formations have already been identified. The quality of such information may vary across countries and over time; therefore we do not limit our main models to countries with known prospective sedimentary basins due to data quality and availability concerns.

As a first step in addressing these two aspects of CCS technology adoption, we estimate models of large-scale and pilot CCS project implementation in all countries, but only for the year of 2016 and without our measures of government policy positions. We then rerun these models after restricting the sample to countries with known prospective sedimentary basins. We obtain data on prospectivity from a report on carbon dioxide capture and storage prepared by the Intergovernmental Panel on Climate Change: the report provides a map of locations with suitable saline formations, coal beds, or oil and gas fields (IPCC 2005).

Table 2 summarizes these results. Models 1–3 report results for pilot project implementation and use the total number of pilot projects a country has initiated by 2016 as the dependent variable. Models 4–6 show results for large-scale projects; here the dependent variable is the total number of large-scale CCS projects a country has initiated by 2016. In models 3 and 6, the sample is restricted to countries with known prospective sedimentary basins. All the explanatory variables are lagged (i.e., their values are from 2015). The regressors included in these model specifications are mostly the same regressors used in Table 1: *Land Area (ln)*, *Kyoto Ratification*, *CO2 per Capita (ln)*, *R&D Spending (ln)*, and *Annual Oil Production (ln)*. We add two dummy variables: *Democracy* takes the value of 1 for countries with Polity2 scores of 7 or higher, and 0 otherwise; *EU Member* takes the value of 1 for countries that have joined the EU, and 0 otherwise.

Table 2
Determinants of the Number of Pilot and Large-Scale Carbon Capture and Storage Projects

	Model 1: Pilots	*Model 2: Pilots*	*Model 3: Pilots (basins)*	*Model 4: LSIPs*	*Model 5: LSIPs*	*Model 6: LSIPs (basins)*
Land Area (ln)	0.65**	0.21*	0.51**	0.61**	0.27	0.37**
	(0.16)	(0.11)	(0.15)	(0.20)	(0.20)	(0.14)
Democracy	1.49**	0.85*	3.54**	0.85	0.57	2.07**
	(0.65)	(0.44)	(1.11)	(0.78)	(0.75)	(0.81)
EU Member	1.35**	0.95**	1.20**	−0.45	−0.52	−0.27
	(0.56)	(0.36)	(0.45)	(0.97)	(0.87)	(0.77)
Kyoto Ratification	0.46	1.54**	0.32	−0.28	0.35	−0.46
	(1.00)	(0.57)	(0.73)	(1.17)	(1.17)	(0.66)
CO_2 per Capita (ln)	1.30**	0.92**	1.55**	2.12**	1.60**	1.81**
	(0.39)	(0.29)	(0.38)	(0.74)	(0.67)	(0.49)
R&D Spending (ln)	0.12**	−0.01	0.09**	0.20**	0.07	0.08**
	(0.03)	(0.03)	(0.03)	(0.06)	(0.07)	(0.03)
Annual Oil Production (ln)		0.89**			0.66**	
		(0.16)			(0.32)	
Constant	−13.44**	−10.01**	−13.87**	−14.05**	−10.64**	−11.10**
	(3.32)	(2.24)	(3.31)	(4.56)	(4.22)	(3.25)
Pseudo R2	0.36	0.41	0.41	0.43	0.39	0.46
Observations	195	83	128	195	83	128

Note. Negative binomial models. Unit of analysis: country. Standard errors in parentheses.
$^*p < 0.10$. $^{**}p < 0.05$.

Many of the results that we reported in Table 1 also hold in Table 2. R&D spending is positively and significantly associated with CCS project implementation in four out of six models. The variable loses statistical significance in models 2 and 5, when we control for annual oil production. Given that R&D spending and annual oil production are highly correlated in these models (at 0.54), we conclude that this correlation accounts for the change in the coefficient on R&D spending when annual oil production is included. We also find that *CO2 per Capita (ln)* and *Land Area (ln)* have a positive and statistically significant effect on large-scale and pilot project initiation, which is similar to results in Table 1. EU members and democratic countries appear to be more likely to initiate pilot projects. However, there is no statistically significant difference

between these and other countries' rates of large-scale project initiation. Countries that have ratified the Kyoto Protocol do not appear to be more (or less) likely to implement large-scale or pilot projects than other countries. We also find no difference between models with all countries and models restricted to countries with known prospective sedimentary basins.

Conclusions

There is little disagreement that climate change measures need to rely on a combination of approaches, and CCS is one promising method of reducing the amount of carbon in the atmosphere. Yet this technology still requires significant investments, which often impedes its development and adoption. Our study has examined conditions when countries can overcome these impediments and adopt CCS technology by initiating large-scale or pilot CCS projects. Our theoretical argument identifies cooperation between governments and the private sector as a condition conducive to technology adoption. Such cooperation, in turn, results from the government's support for technological innovation and willingness to provide resources to incentivize innovation, and the industry's advanced R&D capacity.

Our statistical results lend support to the theoretical expectations derived from this approach. Specifically, we find that countries with an oil and gas sector that engages in significant R&D activities are more likely to implement CCS projects. We also find evidence that governments' policy positions matter: specifically, CCS projects are less likely in countries with more conservative governments. Finally, we identify some interaction effects. Liberal governments display an even stronger positive relationship with CCS adoption when levels of R&D spending by the oil and gas sector increase. In addition, countries with governments supportive of technological innovation become much more likely to implement CCS projects as the industry's R&D capacity grows. However, when R&D spending is low, governments' policy positions do not appear to matter: for all combinations of policy positions, CCS technology adoption is highly unlikely.

Findings reported in this article suggest that, somewhat counterintuitively, large oil and gas companies may not always find measures to combat climate change to go completely against their economic interests. In fact, some countries demonstrate that it is possible to harness technological innovation produced by R&D activities in oil and gas companies and use these techniques to reduce CO_2 emissions in the atmosphere. An important challenge to this prospect is the difference in R&D investment levels across different energy industries. The coal sector, for example, lags behind oil and gas companies in this regard.

Future research is necessary to determine the effect of various types of government policies on the private sector's willingness to invest in CCS technology. In this study, we use broad indicators of governments' policy positions. The next step is to collect more nuanced data on individual measures, such as subsidies,

regulations, and tax credits, to evaluate governments' choices of specific policy instruments and their varying degrees of effectiveness in promoting technological innovation. Another direction of follow-up research should consider the fact that national governments are not the only actors that can incentivize companies to invest in CCS technology: previous research demonstrates that international organizations and subnational governments, such as municipalities or state-level governments in the United States, can implement a broad range of measures to protect the environment (Betsill and Bulkeley 2004; McLean 2015; Vogel 1997). This suggests that these political actors can play a role in the adoption and implementation of various stages of CCS. Finally, our findings raise the question of technology transfer. Given that CCS is now viewed as one method of reducing greenhouse gases and addressing the problem of global climate change, it may be necessary to transfer CCS technology from countries with high levels of company R&D capacity to those with low levels. However, companies may be reluctant to allow such transfers to take place due to concerns regarding potential loss of competitive advantage in the future (Bayer and Urpelainen 2013). Until these concerns can be resolved successfully, countries will continue relying on technological innovation generated by domestic companies and experiencing constraints on CCS technology development and adoption identified in our research.

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