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Assessment of CCS Technology in a Climate Mitigation Portfolio

Howard Herzog, Jennifer Morris, Sergey Paltsev

Massachusetts Institute of Technology

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/

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This document reports on activities for the project on the Assessment of CCS Technology in a Climate Mitigation Portfolio.

1. Project Summary

1.1 Overview

The objective of this project is to assess the future role for CO_2 Capture and Storage (CCS) in a portfolio of mitigation options as a basis for strategies to advance the CCS option. To achieve this goal, we used the MIT Economic Prediction and Policy Analysis (EPPA) model, a global energy-economy model, to examine different long term scenarios to estimate the importance of factors influencing CCS deployment and its role in mitigating carbon emissions. However, global energy-economy models in general need improvement in their representation of CCS and other mitigation technologies. So, we sought to improve model realism by incorporating recent experience, literature, and data. Specifically, we choose four key areas as the focus of this effort:

- Developing a consistent database for regional geologic CO_2 storage capacity worldwide
- Representing intermittent power generators (e.g., wind and solar) on a consistent basis with dispatchable power generators
- Incorporating industrial CCS into the model (most models only consider CCS in the power sector)
- Representing the costs of the various low-carbon power generators on a consistent basis

These changes allowed us to assess CCS issues across regions and applications.

This rest of this section summarizes the key findings of the project up to this point. The following section summarizes the four focus areas described above as well as the scenario analysis conducted with the updated model. More detailed documentation of this project are contained in four papers and two Master of Science theses that resulted from this work.

1.2 Key Findings

Base Case Scenario

The base case scenario (see **Figure 1**) shows that in 2100, CCS is responsible for almost 40% of world electricity production, with a third of that production from coal with CCS and the other two-thirds from gas with CCS. The total cumulative amount of CO_2 stored from 2015 through 2100 is about 420 Gt.

For the base case and all subsequent cases:

- the rise of global mean temperature is limited to 2°C
- we did not include the possibility of offsets like afforestation
- we did not include biomass with CCS (BECCS)

The costs used for the various power generators are described in the section 2.4. We included two options available for CCS – from coal-fired power plants or from gas-fired

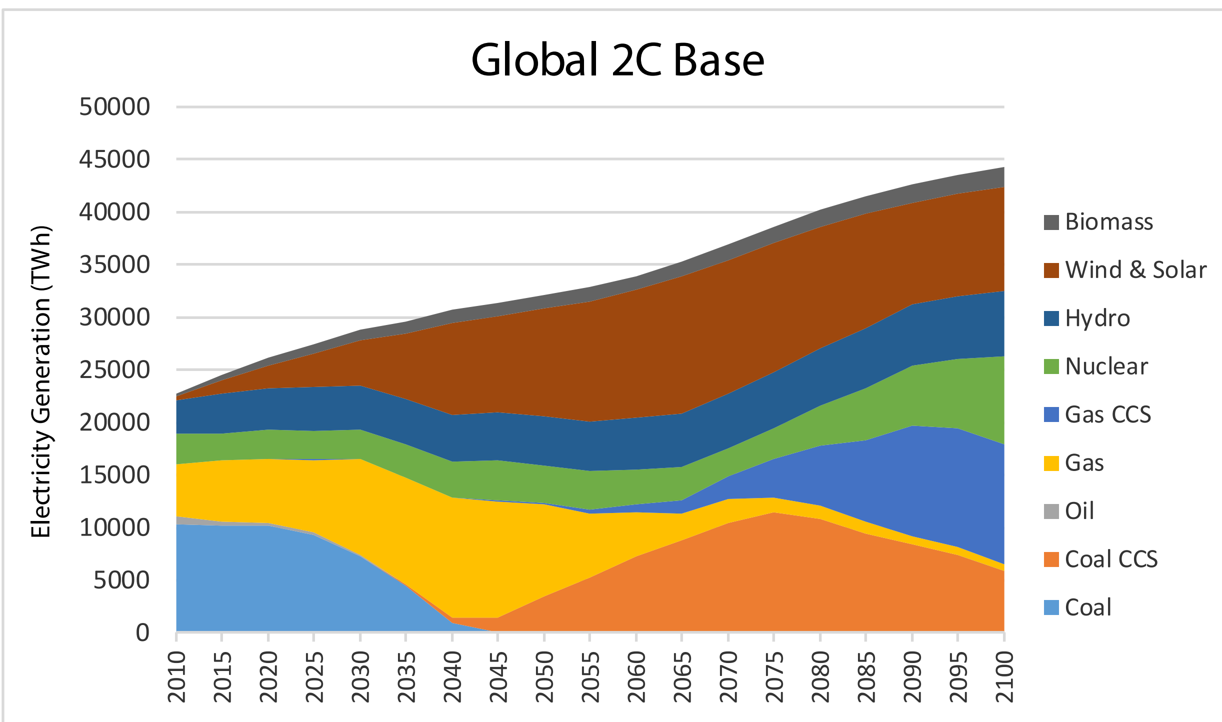

Figure 1. Base Case Scenario results for electricity generation.

power plants. For nuclear, we assumed that political constraints increase the cost above that estimated based on engineering data. For intermittent renewables, above a certain level of penetration (20%), we required backup in the form of natural gas (carbon producing) or biomass (carbon-free). The backup requirement is 1 kW of backup for each kW of new renewable capacity. The modeling of intermittent renewables was informed by the research described in section 2.2.

Regional Variations

Results are available for all 18 geographic regions in EPPA. We focused on four key regions: United States, Europe, China, and India. **Table 1** summarizes the results.

Table 1. Share of CCS generation and cumulative emissions captured in USA, Europe, China, and India.

Region	% of electricity generation in 2100		CO_2 Emissions (Cumulative, Gt)
	Coal with CCS	Gas with CCS	
USA	5%	63%	27
Europe	0%	33%	16
China	18%	0%	175
India	25%	27%	71

Graphical results for these regions are documented in the research summarized in section 2.5.

Results are very sensitive to capture efficiency for CCS

We assumed that gas with CCS has a 90% capture efficiency, while coal with CCS has a 95% capture efficiency. In the model, as we approach the 2°C limit, the carbon price rises to large values. This makes even the relatively small emissions from a CCS plant very expensive, resulting in CCS becoming less economic. In comparing this to reality, one can question whether there will be a hard cap on CO_2 emissions. Stated another way, would policy really allow carbon prices to grow to 100s or even 1000s of dollars per ton of CO_2?

Because we want to eventually get to "net-zero" emissions, not absolute zero emissions, incorporating offsets can alleviate some of the problems caused by a hard cap. However, the scenarios run in this project did not have an offset option. We plan to incorporate offsets in future work.

For this project, we did add a CCS option that qualifies as net-zero CO_2 emissions, specifically a coal-fired CCS plant co-fired with 8% biomass (by heating value) and a 95% capture efficiency. The negative emissions generated by capturing the CO_2 from the biomass used for co-firing offset the 5% of the CO_2 generated by the coal that is emitted to the atmosphere. The results (**Figure 2**) show that coal-fired power with CCS jumped from 13% to 42% of global electricity generation in 2100 when biomass co-fir-

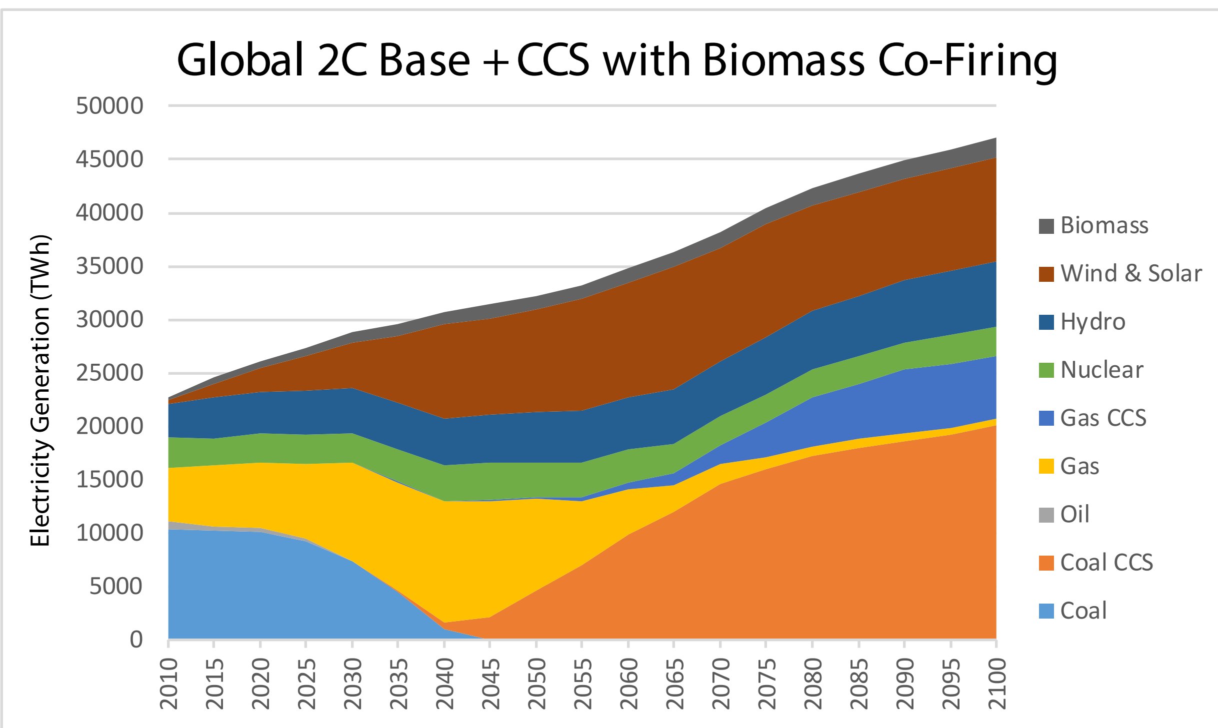

Figure 2. Coal with biomass co-firing and CCS scenario results for electricity generation.

ing is included. Gas-fired power with CCS was cut in half from 26% to 13%, and total generation increased by 5%. The total cumulative amount of CO_2 stored from 2015 through 2100 rose from 420 Gt in the base case to 1030 Gt when biomass co-firing is included.

To better understand the sensitivity to capture efficiency, we ran a series of cases with a specified carbon price. The results are shown in **Figure 3**. As the carbon tax rises, the difference between CCS use in the coal-biomass case compared to the base case increases, as does the share of CCS utilizing the "net-zero" coal-biomass option.

Sensitivity analysis

Sensitivity analyses were run by making favorable assumptions for the three key generating technologies—CCS, nuclear, and renewables—as follows:

- For CCS, we assumed an advanced gas turbine technology inspired by the Allam Cycle technology, which is currently under development (see https://www.netpower.com/). We represented this technology as achieving 100% capture efficiency at costs about 10% greater than standard gas turbines.
- For nuclear, we removed the additional cost multiplier associated with political constraints, and used the cost derived from engineering data (see section 2.4).
- For renewables, we relaxed the requirement for backup capacity. Specifically, the amount backup required is endogenously determined based on the share of intermittent renewables in total generation. Above the share of 20%, 22% backup is required (i.e. for every kW of wind capacity, 0.22 kW of backup capacity is required). The backup requirement gradually increases to 100% (i.e. 1-for1 kW backup required) once the share of renewables hits 80% of total generation.

The results of this analysis are presented in **Figures 4 a-c**.

As expected, the favorable assumption about a technology increased its market share, but the results are somewhat uneven:

- For the advanced gas CCS case, the new turbine is a real game changer. Gas CCS dominates at 57% of global generation in 2100, essentially eliminating coal CCS and gas without CCS. Nuclear declines from 19% in the base case to 5% in 2100. Renewable market share in 2100 holds steady (dropping from 22% to 21%), but actual generation from renewables increases by 8%. This is because overall generation increases by 15% in 2100, due to the availability of a cheap carbon-free technology (the advanced gas CCS) which results in more electricity generation. The total cumulative amount of CO_2 stored from 2015 through 2100 rose from 420 Gt in the base case to 450 Gt.
- For cheap nuclear, the global share of nuclear generation in 2100 jumped to 56%, up from 19% in the base case. Overall generation in 2100 increased 18% from the base case. Coal CCS was eliminated and gas CCS

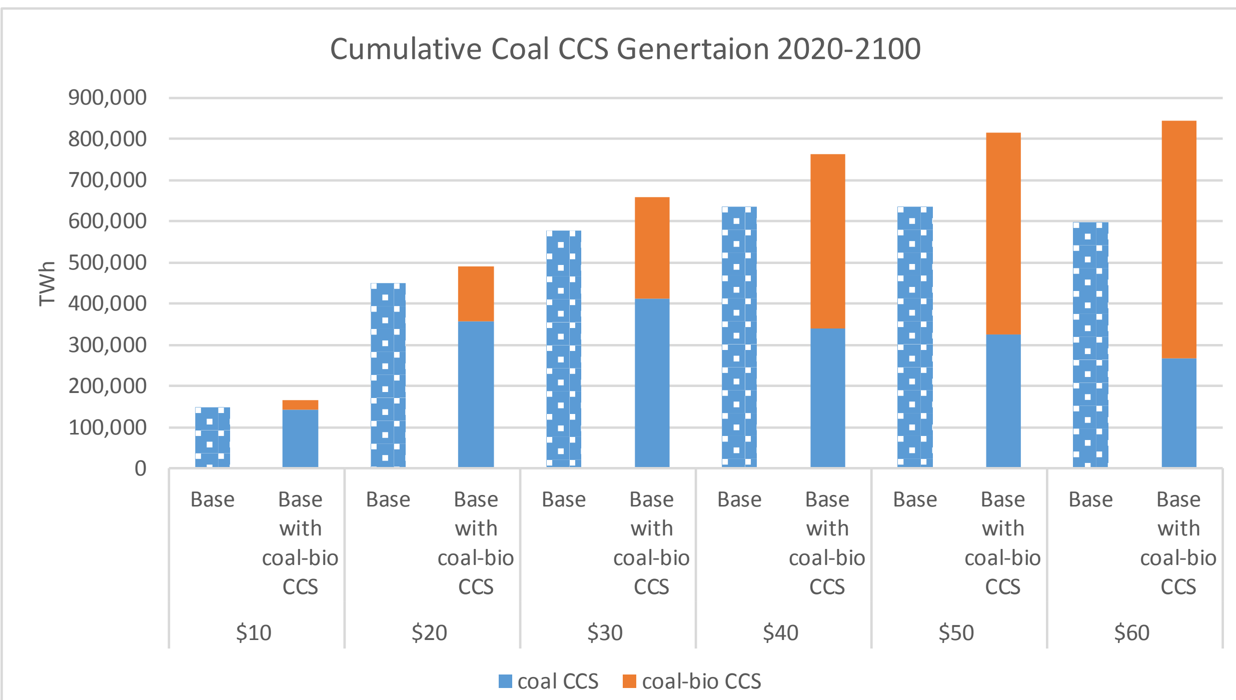

Figure 3. Comparison of base case with no "net-zero" CCS options to a case with a "net-zero" CCS option (coal co-fired with biomass) for various specified carbon prices.

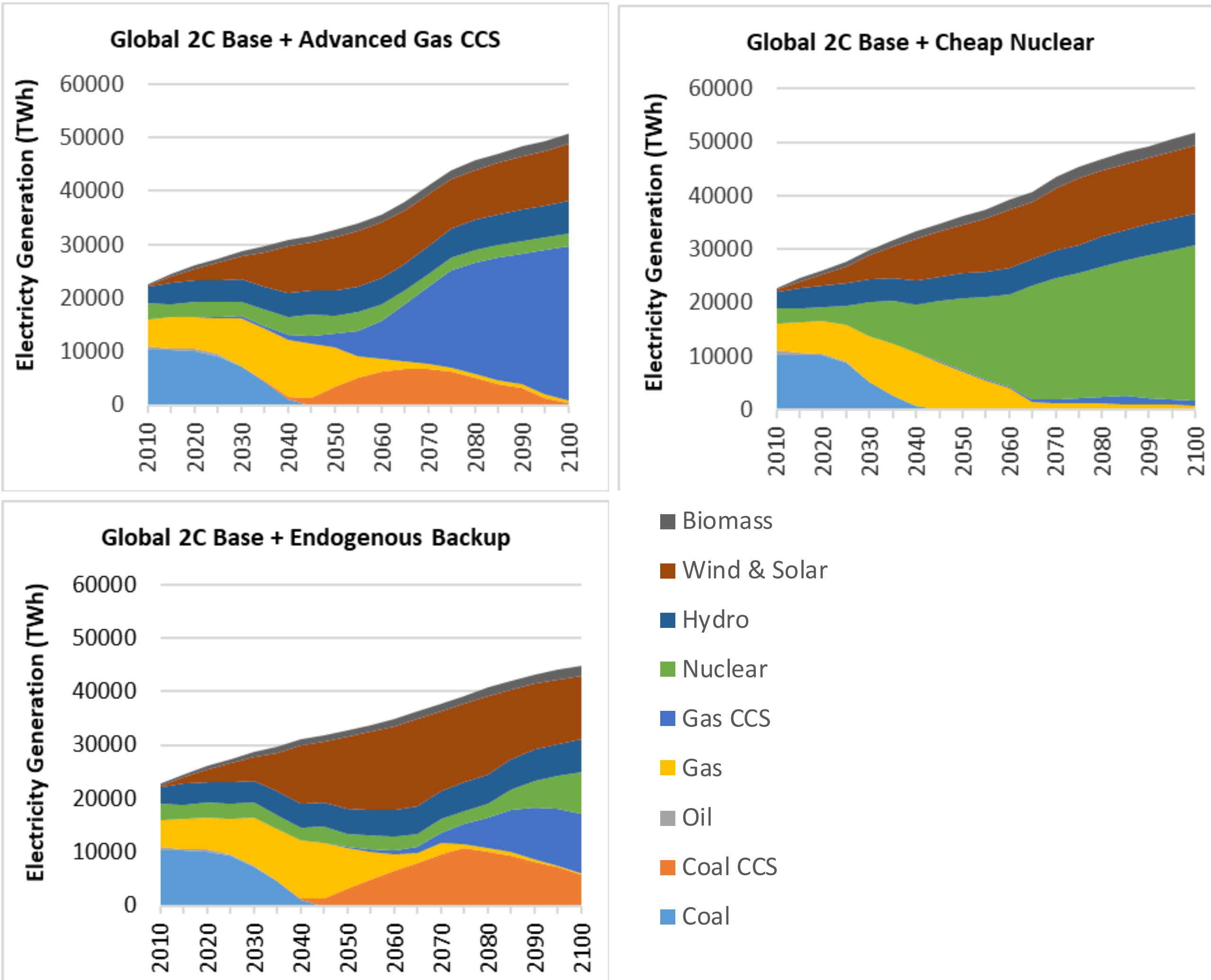

Figure 4. Sensitivity analysis results: (a) advanced gas CCS available, (b) cheap nuclear and (c) endogenous backup requirement for wind.

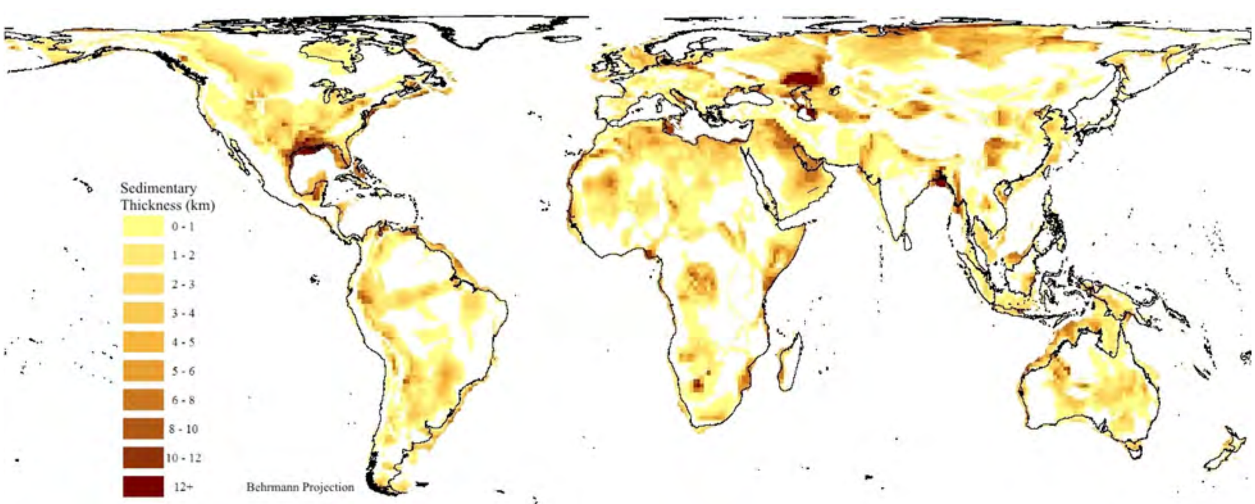

Figure 5. Worldwide capacity for geologic storage of CO_2. The darker the area, the greater the storage capacity.

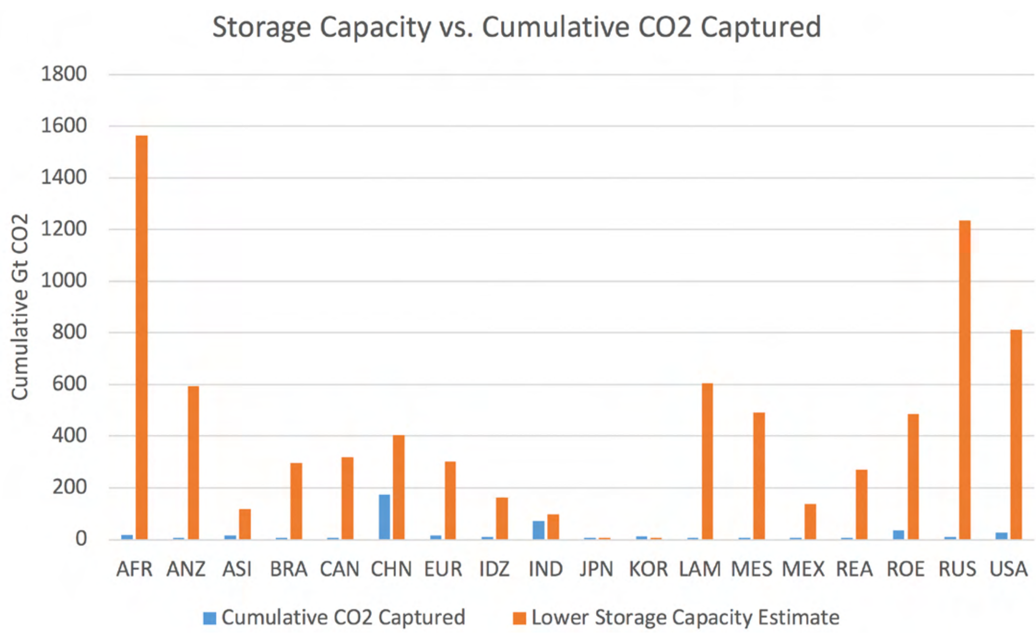

Figure 6. Regional capacity for geologic storage of CO_2 compared to the cumulative CO_2 captured in each region under the Base scenario.

dropped to 2% market share. Market share for renewables increased slightly to 24%, up from 22% in base case. This case clearly shows the strong competition between nuclear and CCS. That competition was also evident in the advanced gas CCS case.

- For the endogenous wind backup case, the renewable share of global generation in 2100 rose from 22% to 27%. Overall generation only increased 2%. Coal and gas CCS market share each dropped about 1% point from their values in the base case. This case indicates that even modest backup requirements that are explicitly charged to wind restrict its market share.

Storage Capacity Constraints

Storage capacities for CCS have not been incorporated into EPPA, but we can compare EPPA results to capacity estimates we have generated. Section 2.1 summarizes the methodology we used and the storage capacity results for all of the EPPA geographic regions. Worldwide, our estimates were in the range of 8,000-55,000 Gt. **Figure 5** shows the geographic distribution. Regions with the tightest constraints include India, Japan, Korea, and Other East Asia.

Figure 6 compares the base case results to our lower storage capacity estimates. It shows that storage is not a limiting factor for CCS technology deployment. China and India are the regions using CCS to capture the most emissions—about 175 Gt in China and 71 Gt in India. The corresponding storage capacity estimates for China and India are about 400 Gt and 100 Gt for the lower estimates, respectively. India is the only region that approaches its lower storage capacity estimate. The upper storage capacity estimates are much higher, about 3000 Gt and 700 Gt for China and India (see section 2.1).

Industrial

The scenarios run here did not include industrial CCS. We did develop models for industrial CCS as described in section 2.3. Results show that allowing industrial CCS reduces the costs of meeting a stabilization target, as well as increases output from the industrial sector. Future work calls for incorporating the industrial sector CCS options along with the electricity sector CCS options.

2. Component Summaries

2.1 Developing a consistent database for regional geologic CO_2 storage capacity worldwide

Abstract:

Assessments of the geologic storage capacity of carbon dioxide in the current literature are incomplete and inconsistent, complicating efforts to assess the worldwide potential for carbon dioxide capture and storage (CCS). We developed a method for generating first-order estimates of storage capacity requiring minimal data to characterize a geologic formation. We show this simplified method accounts for the majority of the variance in storage capacity found in more detailed studies conducted in the United States. We apply our method to create a worldwide database of storage capacity, disaggregated into 18 regions, and compare this storage capacity to CCS deployment in the MIT Economic Prediction and Policy Analysis (EPPA) model. Globally, we estimate there are between 8,000 and 55,000 gigatonnes (Gt) of practically accessible geologic storage capacity for carbon dioxide. For most of the regions, our results indicate storage capacity is not a limiting factor for CCS deployment through the rest of this century even if stringent emissions reductions are required.

Publication:

Jordan Kearns, Jordan, Gary Teletzke, Jeffrey Palmer, Hans Thomann, Haroon Kheshgi, Yen-Heng Henry Chen, Sergey Paltsev, Howard Herzog, "Developing a consistent database for regional geologic CO_2 storage capacity worldwide," Energy Procedia 114: 4697–4709 (2017). https://globalchange.mit.edu/publication/16946

Presentations:

Jordan Kearns, "Developing a consistent database for regional CO_2 storage capacity worldwide," GHGT13, Lausanne, Switzerland, November 2016.

2.2 Effects of Intermittent Generation on the Economics and Operation of Prospective Baseload Power Plants

Abstract:

The electricity system is transitioning from a system comprised primarily of dispatchable generators to a system increasingly reliant on wind and solar power – intermittent sources of electricity with output dependent on meteorological conditions, adding both variability and uncertainty to the system. Dispatchable generators with a high ratio of fixed to variable costs have historically relied on operating at maximum output as often as possible to spread these fixed costs over as much electricity generation as possible. Higher penetrations of intermittent capacity create market conditions that lead to lower capacity factors for these generators, presenting an economic challenge. Increasing penetrations of intermittent capacity, however, also leads to more volatile electricity prices, with highest prices in hours that renewable sources are unavailable. The ability of dispatchable generators to provide energy during these high priced hours may counteract the loss of revenue from reduced operating hours. Given the disparate revenues received in this volatile market, the relative competitiveness of generation technologies cannot be informed by their cost alone; the value of generators based on their production profiles must also be considered. Consequently, comparisons of generator competitiveness based on traditional metrics such as the levelized cost of electricity are misleading, and power system models able to convey the relative value of generators should instead be used to compare generator competitiveness.

The purpose of this thesis is to assess the relative competitiveness of generation technologies in an efficient market under various penetrations of intermittent power. This work is specifically concerned with the relative competitiveness of power plants equipped with carbon capture and storage (CCS) technology, nuclear power plants, and renewable generation capacity. In order to assess relative competitiveness, this work presents an extensive literature review of the costs and technical flexibility of generators, with particular attention to CCS-equipped and nuclear capacity. These costs and flexibility parameters are integrated into a unit commitment model. The unit commitment model for co-optimized reserves and energy (UCCORE), developed as part of this thesis, is a mixed integer linear programming model with a focus on representing hourly price volatility and the intertemporal operational constraints of thermal generators. The model is parameterized to represent the ERCOT power system and is used to solve for generator dispatch and marginal prices at hourly intervals over characteristic weeks. Data from modeled characteristic weeks is interpolated to estimate generator profits over a year to allow for a comparison of generator competitiveness informed by both costs and revenues.

Scenario analysis conducted using the UCCORE model shows that the difference in energy prices captured by generators becomes an important driver of relative competitiveness at modest penetrations of intermittent power. Increasing the ratio of intermittent to dispatchable capacity causes intermittent generators to depress market prices during the hours they are available due to their coordinated output. Prices, however, rise in hours when intermittent capacity is unavailable because of scarcity of available capacity.

This work develops the weighted value factor to compare the revenues of intermittent and dispatchable generation capacity. The weighted value factor is the market value of a generators production profile relative to an ideal generator dispatched at full capacity for all hours. The results show that as the proportion of intermittent capacity increases, the relative value of dispatchable generators also increases and at an increasing rate. At high penetrations of intermittent capacity, the power system experiences increasing risk of generation shortages leading to exceptionally high prices. In these systems, dispatchable generators able to capture peak pricing become most profitable. At lower penetrations of intermittent capacity, peak pricing remains influential, but is less extreme and the relative importance of low capital and fixed costs increases. The sensitivity of generator profitability to assumed value of lost load, oil and gas price, and carbon price is also assessed.

The key implication of these results is that efficient price signals may lead to opportunities for investment in dispatchable generators as the proportion of intermittent capacity on a power system increases. Markets and models that do not capture the full hourly volatility of efficient energy prices, however, are missing critical signals. The importance of these signals on relative competitiveness increases with the penetration of intermittent power. Without accounting for price volatility, markets and models will undervalue dispatchable capacity and overvalue intermittent capacity.

Publication:

Kearns, Jordan, "Effects of Intermittent Generation on the Economics and Operation of Prospective Baseload Power Plants," M.I.T. Masters Thesis, September (2017). https://globalchange.mit.edu/publication/16783

2.3 The role of industrial carbon capture and storage (CCS) in emission mitigation

Abstract:

Carbon capture and storage (CCS) technology is an important option in the portfolio of emission mitigation technologies in scenarios that lead to deep reductions in greenhouse gas (GHG) emissions consistent with limiting increases in global average surface air temperature to 2 degrees Celsius (2C) above pre-industrial levels. Industrial CCS applications are more challenging to analyze than CCS in the power sector -- mainly due to the vast heterogeneity in industrial and fuel processes. Our study focuses on the cement industry and provides the estimated costs associated with several CCS options: coal-fired post-combustion capture (PCC), natural gas-fired PCC, and Cryogenic Carbon Capture (CCC). We explore regional cost estimates with variations in costs of capital and fuels to provide a basis for regional and global projections of industrial CCS deployment. We offer a methodology for incorporating the CCS cost information into energy-economic and integrated assessment models. Our methodology can be applied to other applications of CCS in the industrial sector. We illustrate our method by introducing the industrial CCS options into the MIT Economic Projection and Policy Analysis (EPPA) model, a global energy-economic model that provides a basis for the analysis of long-term energy deployment, and we discuss different scenarios for industrial CCS deployment in different parts of the world. We tested in the EPPA model the potential for industrial CCS under the assumptions that CCS is the only mitigation option for deep GHG emission reduction in industry and that negative emission options are not available for other sectors of the economy. When industrial CCS is not available, global costs of reaching the 2C target are higher by 12% in 2075 and 71% in 2100 relative to the cost of achieving the policy with CCS. Overall, industrial CCS enables the continued use of energy-intensive goods with large reductions in global and sectoral emissions. We find that in scenarios with stringent climate policy, CCS in the industry sector is a key mitigation option, and our approach provides a path to projecting the deployment of industrial CCS across industries and regions.

Publications:

Farrell, Jessica N., "The Role of Industrial Carbon Capture and Storage in Emissions Mitigation," MIT Masters Thesis, June (2018). https://globalchange.mit.edu/publication/17069

Farrell, Jessica, Jennifer Morris, Haroon Kheshgi, Hans Thomann, Sergey Paltsev, Howard Herzog, "The role of industrial carbon capture and storage (CCS) in emission mitigation," proceedings of the14th International Conference on Greenhouse Gas Control Technologies, October (2018). Available at SSRN: https://ssrn.com/abstract=3365585

Presentations:

Howard Herzog, "The Role of Industrial Carbon Capture and Storage in Emissions Mitigation," MITEI CCUS Low-carbon Center Workshop, Cambridge, MA, October, 2018.

Jessica Farrell, "The Role of Industrial Carbon Capture and Storage in Emissions Mitigation," GHGT14, Melbourne, Australia, October 2018.

2.4 Representing the Costs of Low-Carbon Power Generation in Energy-Economic Models

Abstract:

While energy-economic models are often used to analyze long-term scenarios of energy development, they usually rely on a simplified representation of technological details in power generation. We describe a method for modeling the economic competition between different advanced technologies in energy-economic models based on a markup approach, which represents the measure of the cost of a technology relative to the price received for electricity generation. The markup includes capital costs, fixed and variable operating and maintenance (O&M) costs, fuel costs, transmission and distribution (T&D) costs. For intermittent technologies it also includes a backup requirement to make these technologies effectively dispatchable. We provide a standardized markup calculation for generation technologies for different regions of the world, including USA, China, India, EU, Japan and others. Then we analyze the sensitivity of the calculation to critical inputs, including capital costs, fuel costs, carbon prices and capacity factors. We provide a detailed calculation of the relative costs of the following technologies: new pulverized coal, new pulverized coal with carbon capture and storage (CCS), natural gas combined cycle, natural gas with CCS, biomass-fueled plant, biomass with CCS, advanced nuclear, wind (for small and medium penetration levels), solar, wind with backup (for large penetration levels), co-firing of coal and biomass combined with CCS, and advanced CCS on natural gas. For illustration, we incorporate the markups into the MIT Economic Projection and Policy Analysis (EPPA) model, a global energy-economic model with a detailed representation of power generation technologies, and run several scenarios. Our analysis and results provide insight on the deployment of different low-carbon power generation technologies depending on assumptions about carbon policy stringency.

Publication:

Morris, Jennifer, Jessica Farrell, Haroon Kheshgi, Hans Thomann, Henry Chen, Sergey Paltsev, Howard Herzog, "Representing the Costs of Low-Carbon Power Generation in Multi-region Multi-sector Energy-Economic Models." *International Journal of Greenhouse Gas Control*, 87, 170–187.

Presentations:

Jessica Farrell, "Representing the Costs of Low-Carbon Power Generation in Energy-Economic Models," GHGT14, Melbourne, Australia, October 2018.

2.5 Scenarios for Deployment of Carbon Capture and Storage in a Portfolio of Mitigation Options (in preparation)

Abstract:

To transition to low-carbon energy at a global scale, a portfolio of options is required. Carbon capture and storage (CCS) could play an important role in providing low-carbon energy in many regions. Using the MIT Economic Projection and Policy Analysis (EPPA) model, we explore the factors influencing CCS deployment and its role in mitigating carbon emissions. We find that in the scenario with our base technology costs, CCS play an important role in the second half of the century. By 2100 CCS is responsible for almost 40% of world electricity production, with a third of that production from coal with CCS and the other two-thirds from gas with CCS. We also explore regional differences in the deployment of CCS, and focus on the United States, Europe, China, and India. In terms of CCS, the U.S. and Europe mostly rely on gas CCS, while China relies on coal CCS and India pursues both options. We find that capture efficiency affects CCS deployment. As emissions constraints get tighter and the carbon price rises, the penalty on uncaptured emissions can deter the use of CCS. We investigate the role of a "net zero" CCS technology, a coal-fired CCS plant co-fired with enough biomass to offset the uncaptured emissions. Finally, we provide a sensitivity analysis, by making favorable assumptions for the three key generating technologies—CCS, nuclear, and renewables. We find that under stringent mitigation scenarios the power sector relies on a mix of technological options. The conditions that favor a particular mix of technologies differ by region.

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3. Additional Activities

3.1 Bioenergy with carbon capture and storage: key issues and major challenges

Abstract

Projections of the pathways that reduce carbon emission to the levels consistent with limiting global average temperature increase to 1.5°C or 2°C above pre-industrial levels often require negative emission technologies like bioenergy with carbon capture and storage (BECCS). We review the global energy production potential and the ranges of costs of the BECCS technology. We find that BECCS can make a substantial contribution in the second half of the 21st century. The main uncertainties weighing on BECCS development are bioenergy availability at large scale, CCS development, policy incentives and social acceptance. The costs performance is expected to improve but some aspects of the BECCS chain are still unknown, such as CO_2 storage cost, maximum annual rate of CO_2 storage, the BECCS/CCS deployment rate. Careful modeling of BECCS technology constraints is required for an adequate assessment of its potential. We use a global energy economic model, the MIT Economic Projection and Policy Analysis (EPPA) model, to illustrate the challenges to capture the necessary details for assessing the long-term potential of the BECCS technology. Compared to previous studies, we provide a consistent approach to evaluate all of the components of the technology, from growing biomass to CO_2 storage assessment. Our results show that global economic costs and carbon prices are substantially higher when BECCS technology is not available. The efforts to improve public knowledge about CCS projects should be enhanced as in many cases the opposition is based on inaccuracy in understanding the nature of CO_2 properties and its storage. To overcome these challenges, policy makers might consider a support the accelerated development of BECCS, including the advanced methods to increase biomass productivity.

Publication:

Nicolas, Claire, Henry Chen, Jennifer Morris, Niven Winchester, Howard Herzog, Sergey Paltsev, "Bioenergy with carbon capture and storage: key issues and major challenges," proceedings of the 20th Annual Conference on Global Economic Analysis, June (2017), https://www.gtap.agecon.purdue.edu/resources/download/8757.pdf

Presentation:

Nicolas, Claire, Henry Chen, Jennifer Morris, Niven Winchester, Howard Herzog, Sergey Paltsev, "Bioenergy with carbon capture and storage: key issues and major challenges," proceedings of the 20th Annual Conference on Global Economic Analysis, West Lafayette, IN, USA, June 2017.