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CARBON CAPTURE AND STORAGE:
AN ASSESSMENT OF REQUIRED TECHNOLOGICAL GROWTH RATES AND CAPITAL INVESTMENTS

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About the Climate Change Research Platform

In November 2005 diplomats from around the world met in Montreal to begin negotiations on a successor agreement to the Kyoto Protocol. While the Kyoto agreement runs through 2012, governments are already focused on the period after 2012 because effective limits on the emissions that cause global warming require a long-term approach. Most of these gases are emitted from the energy sector, where capital investments last for decades. Private firms are unlikely to invest adequately in advanced technologies to cut their emissions unless they believe that limits will become sufficiently strict as governments get serious about slowing global warming.

There is no clear plan for Kyoto's successor. The Kyoto agreement, itself, does not offer an effective framework. The U.S. has pulled out and has yet to offer an alternative strategy for slowing global warming. Canada and Japan have formally joined the Kyoto treaty, but neither nation has yet offered a workable plan for meeting its Kyoto commitments. Only the European Union is implementing a scheme that will yield compliance with its Kyoto obligations. But a system that attracts only Europe is unlikely to exert much leverage on global emissions, as the EU accounts for only 15% of the world's total emissions. Moreover, the limits on emissions enshrined in the Kyoto agreement exclude developing countries, which account for nearly half of the world's GHG emissions. (China alone is responsible for 12%.) Because they are more populous, these countries' per-capita emissions remain much lower than that of the industrialized world. Nonetheless, any viable strategy for taming global warming must include a vision the eventual engagement of developing countries.

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About the Author

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Prior to starting graduate school, Danny worked for the Program on Energy and Sustainable Development, the Natural Resources Defense Council, and MAP Royalty Inc., an energy investment firm. His work has appeared in Climatic Change, Nature, and Scientific American; he has reviewed papers for Climatic Change, Ecological Economics, the Journal of Geophysical Research, and the Stanford Environmental Law Journal. He holds degrees in Earth Systems (BS) and Management Science & Engineering (MS), both from Stanford.

1. Introduction

Carbon dioxide capture and storage ("CCS") technologies present one possibility for reducing greenhouse gas emissions associated with fossil fuel use.[1] Among the many options for carbon mitigation, CCS stands out because of its relationship to contemporary patterns of energy use around the world. Fossil fuels dominate the global energy mix, and are projected to do so for years to come (e.g. IEA, 2008).

To date, many studies have described the engineering and geologic aspects of CCS. Some have projected the technical potential for sequestration as a climate mitigation option. Most notably, the Intergovernmental Panel on Climate Change released its Special Report on Carbon Dioxide Capture and Storage (2005), synthesizing the available literature. In particular, the Special Report discussed the contribution of CCS to the results of the IPCC Third Assessment Report mitigation scenarios (IPCC, 2001). As I discuss in the next section, the IPCC suggests a large and important role for CCS in controlling anthropogenic CO_2 emissions, with the scale depending on the economic, technological, and demographic path global society takes.

However, there are only a small handful of carbon dioxide storage projects operating at present, totaling about 7 $MtCO_2$ per year (Rai et al., 2008). Furthermore, most projects operate for the purpose of enhanced oil recovery, rather than climate mitigation; there is not a single, commercial-scale power plant in operation that sequesters its emissions. Hence, all studies on

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[1] As discussed in this paper, CCS refers to a two-part system: first, a technology that captures carbon dioxide from an emissions source (or, in the future, directly from the atmosphere); and second, a means by which the carbon dioxide is stored outside the atmosphere. Typically, CCS projects seek to sequester carbon dioxide in geologic formations, such as active or depleted oil and gas wells, or in saline aquifers. Alternatively, one could also consider storing carbon dioxide in the oceans, or via mineral carbonation.

future costs and deployment of commercial CCS systems are either based on limited inference, or purely theoretical constructs.

Now, with the release of a database of publicly known CCS projects under development (Rai et al., 2008), it is possible to gauge the short-term potential for CCS. Based on this database, I create four empirically grounded scenarios about the development of the CCS industry to 2020. I then calculate the sustained growth needed to meet the sequestration estimates reported by the IPCC over the course of this century from these possible starting points.[2]

The paper is organized as follows: Section 2 discusses the current expectations for CCS as a climate mitigation option. Section 3 describes the data and methods used to analyze the potential for CCS in this study. Section 4 reports the results of my analysis. Finally, Section 5 discusses the implications of these results for the energy modeling and climate policy communities.

2. CCS in climate mitigation and energy models

CCS plays a large role in the integrated assessment modeling literature. This section briefly describes the scale at which CCS is expected to contribute to future climate mitigation strategy, in order to demonstrate the importance of benchmarking the required rates of growth that follow.

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[2] A note on the scope of this paper: rather than assess the full costs and benefits of a CCS strategy, the purpose of this study is to benchmark the required rates of growth needed to meet various long-term projections for CCS. Serious consequences to human and natural systems could arise from CCS projects. This study is agnostic with respect to the environmental impacts of storage. It will be similarly agnostic about the specific technologies employed to deliver the final output of CCS technologies, total metric tons of carbon dioxide sequestered.

2.1 CCS in the IPCC TAR mitigation scenarios

In its 2005 Special Report on CCS, the IPCC included a summary of the estimated economic potential for CCS, based on the mitigation scenarios of the Third Assessment Report (IPCC, 2001). These numbers, reported in Table 1, are the result of a series of modeling runs over common emissions scenarios (known as the "SRES"; see IPCC, 2000), combined with a target for the atmospheric concentration of CO_2. Scenarios with higher economic growth or use of fossil fuels increase the expected contribution of CCS; similarly, stricter atmospheric targets for CO_2 lead to more CCS.

Beyond the scale of expected sequestration, the split between developed and developing nations is notable. For most scenarios and CO_2 concentration targets, the developing world (non-OECD) is expected to host two thirds to three quarters of total sequestration. This implies that in addition to the development of a mature, workable set of CCS technologies, the models assume that CCS will be widely available at the international level.

2.2 Technical potential for CCS

Toth and Rogner (2006) offer some detail that helps explain why integrated assessment models reviewed by the IPCC are so optimistic about CCS. Toth and Rogner describe the technical potential for CCS, which is defined as anthropogenic emissions suitable (from an engineering point of view) for applying CCS technologies.[3]

Toth and Rogner begin by reporting total CO_2 emissions for each scenario and model. They then calculate the technical potential for CCS using a set of common estimators for what types of emissions sources could be addressed by CCS technologies. Combining these two

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[3] Toth and Rogner limit this definition further, isolating those CCS opportunities estimated to cost less than \$300/tCO_2. While not a purely "technical" estimate–by including cost parameters, their definition doesn't strictly match the conventional definition–this is an attempt to focus on the main applications of CCS (large, stationary emissions sources) that would be suitable for a broad-scale mitigation effort.

metrics, I show the percentage of emissions in each sector that could be captured and sequestered in Table 2. In addition, Table 2 also shows the contribution of each sector to the total CCS potential.

In 2020, most model/scenario pairs are in rough agreement with respect to the technical potential for CCS. Toth and Rogner assume that transportation sector emissions are not generally suitable for CCS, due to their extremely dispersed nature; hence, Table 2 shows no potential in that sector. Similarly, the models agree on the limited potential for CCS in the residential and commercial sectors, where typical energy consumption patterns do not include centralized emissions sources suitable for capture.

With two exceptions, the models achieve similar CCS potentials for the power and industrial sectors in 2020 (about 20% and 10%, respectively). The two exceptions are for the A1T scenario, which examines the impact of rapid technological change. In the MESSAGE version of A1T, the power sector potential is significantly higher than all other model/scenario pairs, but the total CCS potential is not much different than the others. In the MiniCAM version of A1T, the model presumes the development of a hydrogen fuel system for transportation. Hydrogen production is considered readily available for CCS, and included in the industrial sector numbers, leading to the high potential estimated for that sector. All of the other models agree across scenarios that 9-12% of emissions in 2020 are suitable for CCS. A1T-MiniCAM, with its centralized hydrogen production, shows about double the potential, at 22%.

In 2050, similar patterns hold. Once again, the models agree on the transportation, residential and commercial sectors. In the power sector, all models show that at least half, and up to two thirds of emissions are suitable for CCS. Industrial sector potentials vary more than in 2020, with a range of estimates of 31% to 79%. At the aggregate level in 2050, CCS potential varies from 21% to 67% of total emissions, suggesting an immense opportunity to control emissions if the technology could be scaled at a reasonable cost.

To summarize, most energy models show a large potential for CCS technologies, as most forecast a significant use of large, centralized emissions sources. These results help explain why the IPCC (2005) is so optimistic about the scale at which CCS could be deployed over the next century. The question to which I now turn is: how fast does the CCS industry have to grow, in order to reach the levels implied by the IPCC?

3.0 Data and methods

In order to analyze the feasibility of the IPCC results, I rely on newly released data describing the near-term development of the CCS industry. From these data, I construct four scenarios through 2020–empirically grounded stories about how the CCS industry might grow over the next few years. For each scenario, I estimate the total sequestration to date in 2020 and the annual rate of sequestration in 2020. From these numbers, I back-calculate the required growth needed to meet the previously mentioned IPCC estimates.

3.1 CCS project data

A previous working paper from Stanford University's Program on Energy and Sustainable Development tracks publicly documented carbon sequestration project announcements (Rai et al., 2008). Sixty-five projects are drawn from several sources, including projects listed in the IPCC Special Report on Carbon Capture and Storage (2005), the International Energy Agency's Energy Technology Perspectives (2008), the Carbon Capture and Sequestration Technologies Program at MIT (2008), and a J.P. Morgan industry report (Levinson, 2007). The full data set is available online in the original working paper, and is not reproduced here.

The projects Rai et al. track are planned to begin sequestration at various points over the next few years, up until the year 2020. While there are a small handful of sequestration projects already in operation (about 7 $MtCO_2$ per year in 2008), the vast majority of tracked projects are in the planning stage, with a minority under construction as of this writing. Figure 1 shows the annual additions to the rate of global sequestration, as tracked by Rai et al. (2008).

Because most projects are in the planning stage, one cannot precisely estimate the likelihood that an individual project will actually occur. Based on interviews with industry experts and project documentation, Rai et al. classify planned projects into two categories. "Possible" projects are those the authors assign a subjective probability of completion between 50% and 90%. "Speculative" projects are those the authors assign a subjective probability of completion lower than 50%. While these categories are not meant to give a specific estimate of exactly which projects will succeed and which will fail, they do account for the qualitative differences in viability that can be observed at present.

3.2 Four scenarios to 2020

Based on these data, I construct four scenarios that offer alternative forecasts for the growth of CCS technologies through 2020. Two are drawn directly from the classifications used by Rai et al. (2008), without modification:

- **Possible**. Publicly announced projects, estimated by Rai et al. to have a probability of completion between 50% and 90%.
- **Speculative.** Publicly announced projects, estimated by Rai et al. to have a probability of completion less than 50%.

There are several reasons why Rai et al. are likely to have comprehensively tracked near-term CCS projects. Most projects are planned for the US, EU, or Australia, where laws typically require public participation in the regulatory process. Regulatory approval for normal power plants can take years in these markets; the additional complications of regulating CCS suggest approval for CCS projects could take even longer (Wilson et al., 2007), increasing the foresight of public awareness into corporate planning. In many cases, projects seek government subsidies; this further increases the likelihood of public documentation. Finally, business has taken an explicit interest in CCS, resulting in publicly available corporate analyses from industry leaders like McKinsey & Company (Nauclér et al., 2008) and J.P. Morgan Global Corporate Research (Levinson, 2007).

Although these reasons imply that an impending CCS project is likely to have public documentation, the likelihood that the data set "sees" all realistic projects decreases as one looks further out into the future. As Figure 1 shows, the Rai et al. database contains very few projects projected to begin between 2016 and 2020. It is possible—and indeed probable—that this absence does not reflect the full growth potential of CCS; there are many reasons why companies interested in pursuing projects in this timeframe have not released public information to that effect. Most obviously, one does not necessarily expect to hear specific proposals seven to twelve years in advance. Furthermore, regulatory uncertainty in energy or carbon policy could delay private planning, or result in corporate reticence with respect to long-term, low-carbon technology strategies (Victor and Cullenward, 2007). Many companies are waiting for developments in the US on climate policy, and on the successor to the Kyoto regime post-2012. Therefore, it seems plausible to consider an additional scenario about the development of CCS from 2016 to 2020:

- **Hypothetical.** This scenario attempts to account for the "missing" projects in the period 2016 to 2020. It follows the "Speculative" scenario through 2015. Over the period 2016 to 2020, a constant rate of new carbon sequestration is added each year, so that the annual rate of sequestration in 2020 is double that of the "Speculative" scenario.

This choice, while arbitrary in some respects, is meant to be a simple and transparent way to consider an expanded CCS development pathway. Finally, because many analysts have called for a significant demonstration phase for CCS technology (e.g. Wilson et al., 2008), I consider a final scenario in which the CCS industry experiences considerable growth through 2020:

- **Aggressive.** This scenario is the most optimistic with respect to CCS, and presumes massive government and business support of CCS. It follows the "Speculative" scenario through 2015. From 2016 to 2020, the annual rate of carbon sequestration grows exponentially at the compound average growth rate of the "Speculative" scenario over the period 2008 to 2015 (49%).

To reiterate, the first two scenarios ("Possible" and "Speculative") are directly based on empirical evidence about actual CCS projects. The third scenario ("Hypothetical") attempts to account for presumed deficiencies with the empirical evidence to date. The fourth scenario ("Aggressive") explores the effect of a large-scale effort to demonstrate and expand the first generation of CCS technologies.

Figure 2 describes the yearly carbon sequestration capacity expansions for all four scenarios. Figure 3 shows the resulting annual rate of carbon sequestration, again for all four scenarios. Table 3 shows the annual rate of sequestration for each scenario. The "Aggressive" scenario, for example, yields an annual storage of 889 $MtCO_2$ by 2020. In comparison, Toth and Rogner (2006) estimate that technical potential for CCS in 2020 is between 2,584 and 7,790 $MtCO_2$ per year.

3.3 Analytical approach

As discussed earlier, Table 1 reports the estimated global economic potential for CCS as reviewed by the IPCC (2005). Each estimate, which I will call $X_{j,k}$, is produced using the average of several energy model results, driven by a common atmospheric CO_2 concentration target, j, and a specific SRES scenario for global economic activity, k (Table 8.5 in IPCC, 2005). For the analysis in this paper, I decompose the total sequestered carbon dioxide estimate (in $MtCO_2$) as follows:

$$X_{j,k} = A_i + B_i + C_{i,j,k} \tag{1}$$

Where A_i is the total sequestered carbon dioxide (in $MtCO_2$) from 2000 to 2020; B_i is the total sequestered carbon dioxide (in $MtCO_2$) from projects that exist in 2020 and continue to operate to 2100; and $C_{i,j,k}$ is the total sequestered carbon dioxide (in $MtCO_2$) that is needed from new projects during the period 2021 through 2100 to meet the IPCC sequestration estimate $X_{j,k}$; and i is the scenario representing CCS activity from 2000 to 2020, based on Rai et al. (2008). Figure 4 depicts this decomposition graphically.

The amount of carbon dioxide sequestered from 2000 to 2020, A_i, is determined by the four CCS scenarios. In this period, for each scenario i and year t, the rate of sequestration is $s_{i,t}$ (in $MtCO_2$):

$$A_i = \sum_{t=0}^{20} s_{i,t} \tag{2}$$

Similarly, the amount of carbon dioxide sequestered from 2021 to 2100 is comprised, in part, of the contribution from projects already operating in 2020:

$$B_i = 80 \times s_{i,2020} \tag{3}$$

Where $s_{i,2020}$ is the rate of sequestration in the year 2020, for each scenario i.

Equations (2) and (3) are determined by the four scenarios described in the previous section. The remaining sequestration needed to meet a given IPCC estimate $X_{i,j,k}$ will determine what projects emerge in the period 2021 to 2100. I will model two possible pathways: first, a linear growth model, where a constant, additional amount of sequestration is developed each year; and second, an exponential growth model, where the rate of sequestration grows by a fixed percentage over the previous year.

The linear growth model is:

$$C_{i,j,k} = \sum_{t=21}^{100} \Delta_{i,j,k} \times (t-20) \tag{4}$$

Where $\Delta_{i,j,k}$ is the constant growth of new sequestration capacity each year (in $MtCO_2$ per year).

The exponential growth model is:

$$C_{i,j,k} = \sum_{t=21}^{100} s_{i,2020} \times (1+r_{i,j,k})^{(t-20)} \tag{5}$$

Where $r_{i,j,k}$ is the rate of growth occurring each year.

Operational lifetimes for mature, commercial CCS projects are estimated to be on the order of decades, rather than a century (IRGC, 2007; Wilson et al., 2008). It is therefore likely that many of the CCS projects completed during the period 2000 through 2020 will not continue for the remainder of the century. Assuming, as I do, that these projects will all continue is optimistic with respect to the cumulative CO_2 storage from CCS. The growth in the period 2020 to 2100 ($C_{i,j,k}$) required to meet a given IPCC sequestration estimate ($X_{j,k}$) is therefore a lower bound estimate, and will likely be higher in practice. Although it would be desirable to forecast some form of capital vintage model,[4] there is no available data by which to estimate the appropriate parameters.

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[4] A capital vintage model tracks the stock of equipment, differentiated by age, and calculates the aggregate performance resulting from changes to the equipment stock. A capital vintage model for CCS would incorporate the effect of having individual sites close injection operations after a specified length of time. Lacking these effects, my results likely underestimate $C_{i,j,k}$ and therefore $r_{i,j,k}$.

In addition, I assume that there is zero leakage from CCS projects. The IPCC is only slightly less optimistic: over 100 years, for an appropriately selected project site, the IPCC has 90% to 99% confidence that over 99% of sequestered CO_2 will remain in place; over 1000 years, the IPCC has 67% to 90% confidence (page 14 in IPCC, 2005).

Finally, as a simple exercise in benchmarking the required investment in CCS projects, I calculate the annual costs for the linear growth model. To do so, I need a way to create a price per unit of sequestration capacity. Using cost and performance estimates from the IPCC, along with an assumed capacity factor of 0.85, I estimate the cost of sequestration capacity for each of three technologies: natural gas combined cycle post-combustion capture, pulverized coal post-combustion capture, and integrated gasification combined cycle pre-combustion capture. I then take the average of the three costs. Details are shown in Table 4.

4. Results and discussion

4.1 Linear Model

Table 5 reports the results of the linear growth model, the average sequestration capacity expansion ($\Delta_{i,j,k}$) needed each year from 2021 to 2100 (Equation 4). To give context, I also show the ratio of the yearly capacity expansion to the existing sequestration capacity in 2020.

Although the four scenarios through 2020 imply very different levels of effort and success with respect to the early demonstration of CCS, they do not significantly affect the average long-term level of growth needed to reach the estimated economic potential of sequestration. This is because the average long-term growth is strongly dependent on the choice of SRES scenario and CO_2 concentration target, but largely unresponsive to the starting point in 2020. Even the “Aggressive” scenario is only an early beginning for CCS, relative to what is needed if it is to take hold in the long run.

Using performance and cost estimates provided by the IPCC, I calculate the annual investment needed to sustain a linear growth trend in Table 6. As before, the scale of growth depends on the SRES scenario and the CO_2 concentration target, but is largely unresponsive to the development of CCS to 2020. Tens (if not hundreds) of billions of dollars a year will be required to finance the average annual CCS capacity expansion, sustained over 80 years.

4.2 Exponential Model

While the choice of a 2020 scenario does not have a large impact on the average growth rate of CCS from 2021 to 2100, it could have benefits in terms of the operational experience and lessons learned from a first generation of CCS technologies. One means of examining this effect is to use the exponential model (Equation 5) to look at the compound average growth rate needed to meet the IPCC estimates, reported in Table 7. Here again the choice of SRES scenario and the atmospheric CO_2 concentration target are both important drivers of the required CCS growth rate, although the role of development through 2020 is important, too. As listed in the "Avg." column of Table 7, in order to reach 750 ppmv CO_2, CCS must grow 3.0 to 7.3% per year, over 80 years. For 650 ppmv CO_2, the range is 4.1 to 8.1%; for 550 ppmv CO_2, the range is 4.8 to 8.7%; and for 450 ppmv CO_2, the range is 6.4 to 10.1%. Lower growth rates will be required if CCS follows the "Hypothetical" or "Aggressive" scenarios; the technology will then have a better base on which to build future efforts. Higher growth rates will be required if CCS follows the "Possible" or "Speculative" scenarios, in which relatively few CCS projects are developed by 2020.

In all cases, because of the exponential nature of the growth function, the majority of sequestration occurs in the later years of the period 2000 to 2100. To give context for the policy implications of the exponential growth model, I calculated the percentage of sequestration that occurs over 2076 to 2100, relative to the total sequestration from 2001 to 2100. Due to the long periods over which CCS capacity compounds, more than 80% of sequestration occurs during the period 2076 to 2100, in almost every case. Hence, if the global CCS industry follows an exponential growth pattern in order to reach the IPCC Mitigation Scenario levels, it will not contribute significantly to climate mitigation for decades to come.

It is possible to quantify the effect of early action on the required growth rates. Table 8 shows the reduction in compound annual growth rates that follows from achieving higher near-term CCS levels. Compared to the "Possible" scenario, which has the lowest CCS growth by 2020, the "Speculative" scenario lowers the required growth rates by about 1%, on average. The "Hypothetical" scenario lowers the rate by about 2%, compared to the "Possible" scenario. Finally, the "Aggressive" scenario lowers the rate by about 4%, relative to the "Possible" scenario.

5. Conclusions

It is not an easy to task to say whether or not a technology will succeed over the course of a century. Still, the magnitude of the expectations for CCS as a technology deserves closer scrutiny. According to the IPCC mitigation scenarios and the calculations of the exponential model presented in this study (Equation 5; Table 7), meeting 550 ppmv CO_2 requires CCS capacity to grow at 4.8 to 8.7% per year, over 80 years; meeting 450 ppmv CO_2 requires 6.4 to 10.1% per year. This suggests two possible interpretations. The first is that today's expectations for the contributions from CCS are overstated, because these sorts of growth rates are implausible. This would mean a larger role for other technologies, population choices, and behavioral changes to reduce carbon dioxide emissions. Here, too, one must project and estimate technical and economic potentials, which I have not attempted to do in this paper. It is an area requiring much more work, in order to make proper comparisons between alternative strategies.

A second possibility is that we really do need to accomplish CCS on this level. Whether because alternative mitigation options prove similarly difficult to scale, or because the sheer magnitude of the carbon challenge requires every possible solution, we might need as much CCS as is currently projected.

5.1 Implications for the representation of CCS technologies in energy models

Most studies of the long-term application of CCS technologies incorporate one or more CCS options into a global economic model (e.g., Akimoto et al., 2004; Edmonds et al., 2004; Kurosawa, 2004; McFarland et al., 2004; McFarland and Herzog, 2006; Riahi et al., 2004a, 2004b). In these models, assumptions about the cost of CCS technologies may be static, or in some cases, the models account for technological change with a variety of techniques (for an overview, see Weyant, 2004).

In order to determine the future deployment of technologies, most models rely on representative technology performance and cost estimates, coupled with an endogenous carbon price. One advantage of this modeling approach is that it allows analysts to be technology neutral–that is to say, the models do not explicitly prefer one technology over another, and can be based on independent assessments of technology costs.

With respect to commercially mature technologies, this approach can work well. In such cases, details about the costs and operating parameters of the technologies are derived from years of experience. However, with CCS, only a handful of carbon dioxide sequestration projects are operational at present. Moreover, most of these projects are done for the purpose of enhanced oil recovery, with a few gas separation projects at industrial facilities. There is not yet a single operating power plant that captures carbon dioxide and sequesters it outside the atmosphere.

As a result, it is extremely difficult to estimate the levelized costs of a power plant that sequesters carbon dioxide, because analysts can draw only on limited experience with industrial (non-power plant) analogs. Because these two sectors (power and industry) are expected to host the primary climate mitigation applications of CCS technologies (see Table 2), specific assumptions about CCS costs have almost no empirical backing, and modelers are forced to rely on theoretical estimates.

Furthermore, making static assumptions about technology costs over a one hundred year period may be unwise. The most common modeling extension is to include learning-by-doing effects, which reduce the costs of new instances of the technology based on cumulative production to date (Arrow, 1962). The magnitude of learning-by-doing effects can be quite large for energy technologies (Grubler et al., 1999), and is especially important when considering long-term climate scenarios (Goulder and Mathai, 2000). But the rates studied vary from technology to technology, and it is not possible to predict, *a priori*, what the learning rate will be for a specific case. Such a prediction would require even more data than a static cost estimate.

This is not meant to say that energy models do not give us important insight into climate policy questions. Rather, the dominant modeling paradigm does not appear to be an appropriate means to analyze the emergence of novel technologies. Some other technique is needed to assess technology strategy, with more detail on the challenges of technological change.

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Global Carbon Sequestration in the IPCC Mitigation Scenarios

Cumulative GtCO2 sequestered

		Scenario						
Region	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
World	450 ppmv	5628	2614	1003	1298	1512	918	2162
	550 ppmv	3462	740	225	505	324	133	898
	650 ppmv	2709	430	99	299	149	0	614
	750 ppmv	1986	0	0	277	0	0	377
OECD (1990)	450 ppmv	1060	637	270	256	603	483	551
	550 ppmv	800	202	82	174	115	80	242
	650 ppmv	654	166	54	103	55	0	172
	750 ppmv	497	0	0	104	0	0	100
Non-OECD (1990)	450 ppmv	4568	1977	733	1042	909	435	1611
	550 ppmv	2662	538	143	331	209	53	656
	650 ppmv	2055	264	45	196	94	0	442
	750 ppmv	1489	0	0	173	0	0	277

Regional distribution as percentage total sequestered CO2

		Scenario						
Region	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
OECD (1990)	450 ppmv	19%	24%	27%	20%	40%	53%	25%
	550 ppmv	23%	27%	36%	34%	35%	60%	27%
	650 ppmv	24%	39%	55%	34%	37%	n/a	28%
	750 ppmv	25%	n/a	n/a	38%	n/a	n/a	27%
Non-OECD (1990)	450 ppmv	81%	76%	73%	80%	60%	47%	75%
	550 ppmv	77%	73%	64%	66%	65%	40%	73%
	650 ppmv	76%	61%	45%	66%	63%	n/a	72%
	750 ppmv	75%	n/a	n/a	62%	n/a	n/a	73%

NOTE: Results averaged across different modeling teams, as compiled in IPCC, 2000.
SOURCE: IPCC, 2005, Table 8.5.

OECD membership in 1990: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Republic of Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweeden, Switzerland, Turkey, United Kingdom, and the United States (IPCC, 2000).

Table 1: Estimated global carbon sequestration, 2000 to 2100

Estimated Technical Potential for CCS

Percentage of total emissions suitable for CCS

		Capture potential by sector in 2020					Capture potential by sector in 2050					
Scenario	Model	Power	Industry	Res. & Comm.	Trans.	Total	Power	Industry	Res. & Comm.	Trans.	Total	Notes
A1B	AIM	18%	10%	3%	0%	9%	63%	40%	18%	0%	28%	
	IMAGE	21%	9%	4%	0%	10%	63%	35%	19%	0%	35%	
A1T	MESSAGE	33%	10%	2%	0%	12%	66%	61%	17%	0%	33%	(1)
	MiniCAM	21%	37%	4%	0%	22%	63%	79%	21%	0%	67%	(2)
A1FI	MiniCAM	22%	11%	4%	0%	12%	65%	54%	21%	0%	45%	(2)
	MESSAGE	24%	17%	3%	0%	12%	66%	62%	18%	0%	38%	(1)
A2	IMAGE	22%	9%	4%	0%	10%	64%	36%	20%	0%	36%	
	AIM	20%	10%	3%	0%	11%	65%	40%	22%	0%	39%	
B1	IMAGE	21%	8%	4%	0%	9%	56%	31%	18%	0%	21%	
	MiniCAM	21%	10%	3%	0%	11%	60%	42%	19%	0%	35%	(2)
B2	MESSAGE	23%	19%	2%	0%	12%	65%	57%	16%	0%	38%	(1)
	AIM	20%	10%	3%	0%	10%	62%	38%	21%	0%	35%	

Contribution of each sector to the total CCS potential

		Capture potential in 2020					Capture potential in 2050					
Scenario	Model	Power	Industry	Res. & Comm.	Trans.	Total	Power	Industry	Res. & Comm.	Trans.	Total	Notes
A1B	AIM	65%	30%	5%	0%	100%	54%	34%	12%	0%	100%	
	IMAGE	79%	16%	4%	0%	100%	78%	17%	5%	0%	100%	
A1T	MESSAGE	70%	27%	3%	0%	100%	35%	55%	9%	0%	100%	(1)
	MiniCAM	32%	66%	2%	0%	100%	27%	71%	3%	0%	100%	(2)
A1FI	MiniCAM	70%	27%	3%	0%	100%	63%	33%	4%	0%	100%	(2)
	MESSAGE	55%	42%	4%	0%	100%	48%	45%	7%	0%	100%	(1)
A2	IMAGE	80%	16%	4%	0%	100%	76%	17%	6%	0%	100%	
	AIM	71%	25%	4%	0%	100%	69%	23%	8%	0%	100%	
B1	IMAGE	79%	16%	5%	0%	100%	57%	31%	13%	0%	100%	
	MiniCAM	67%	29%	4%	0%	100%	62%	33%	5%	0%	100%	(2)
B2	MESSAGE	48%	48%	4%	0%	100%	38%	55%	7%	0%	100%	(1)
	AIM	69%	27%	4%	0%	100%	65%	25%	10%	0%	100%	

SOURCE: Table A1 and Table A2, Toth and Rogner, 2006

NOTES: (1) "Industry" includes refineries, synfuels, hydrogen.
(2) "Industry" includes synfuels, hydrogen.

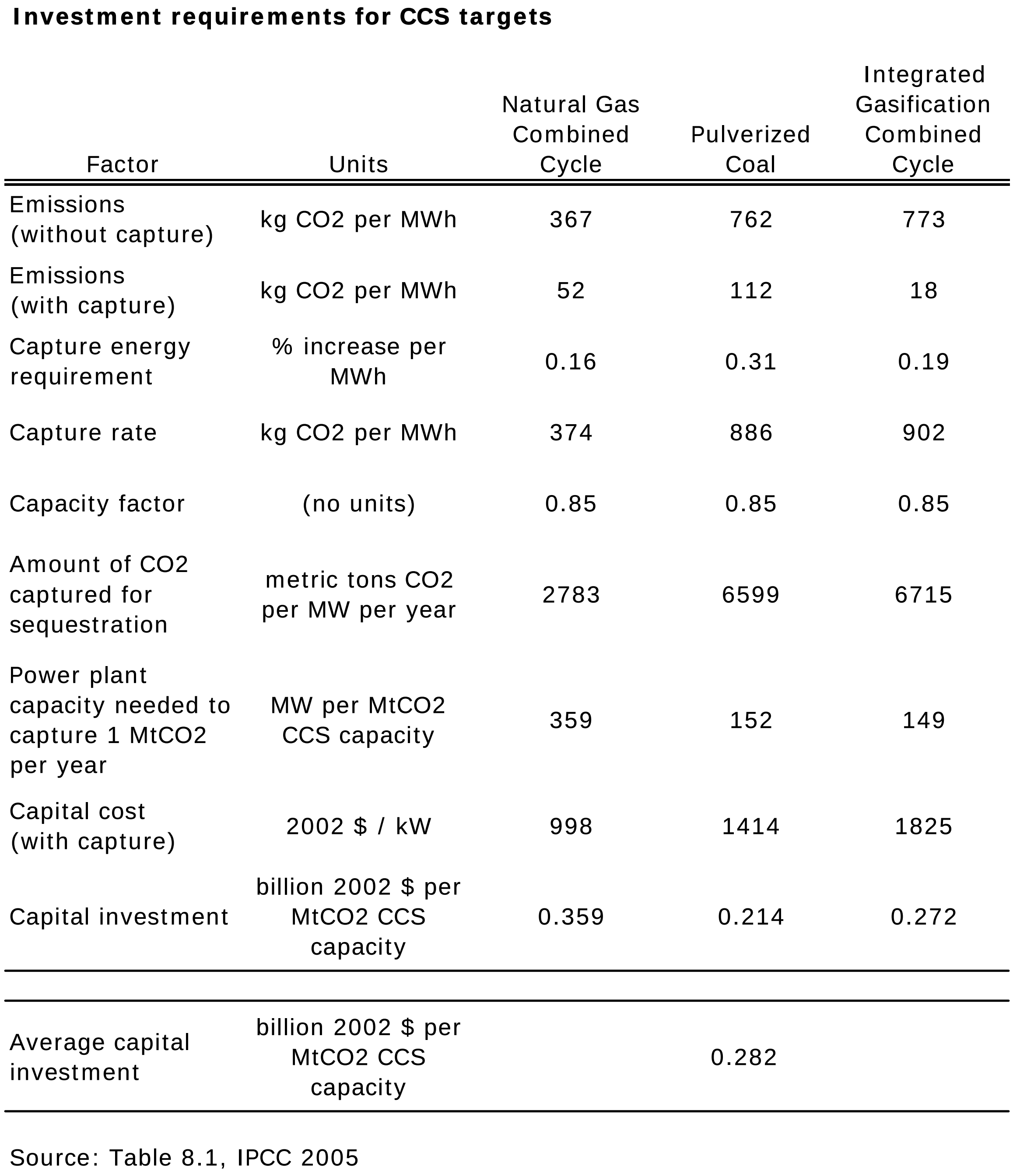
Table 2: Estimated technical potential for CCS

Four Scenarios for Global CCS Industry Development through 2020

MtCO2 sequestered per year

Scenario	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Possible	7	7	12	32	43	59	67	89	89	92	92	92	92
Speculative	7	8	16	39	51	68	82	121	124	131	131	131	158
Hypothetical	7	8	16	39	51	68	82	121	158	189	228	267	315
Aggressive	7	8	16	39	51	68	82	121	181	269	401	597	889

Table 3: Four scenarios for global CCS industry development through 2020



Investment requirements for CCS targets

Factor	Units	Natural Gas Combined Cycle	Pulverized Coal	Integrated Gasification Combined Cycle
Emissions (without capture)	kg CO2 per MWh	367	762	773
Emissions (with capture)	kg CO2 per MWh	52	112	18
Capture energy requirement	% increase per MWh	0.16	0.31	0.19
Capture rate	kg CO2 per MWh	374	886	902
Capacity factor	(no units)	0.85	0.85	0.85
Amount of CO2 captured for sequestration	metric tons CO2 per MW per year	2783	6599	6715
Power plant capacity needed to capture 1 MtCO2 per year	MW per MtCO2 CCS capacity	359	152	149
Capital cost (with capture)	2002 $ / kW	998	1414	1825
Capital investment	billion 2002 $ per MtCO2 CCS capacity	0.359	0.214	0.272
Average capital investment	billion 2002 $ per MtCO2 CCS capacity		0.282	

Source: Table 8.1, IPCC 2005

Table 4: Cost and performance estimates for CCS

Linear Growth Model Results

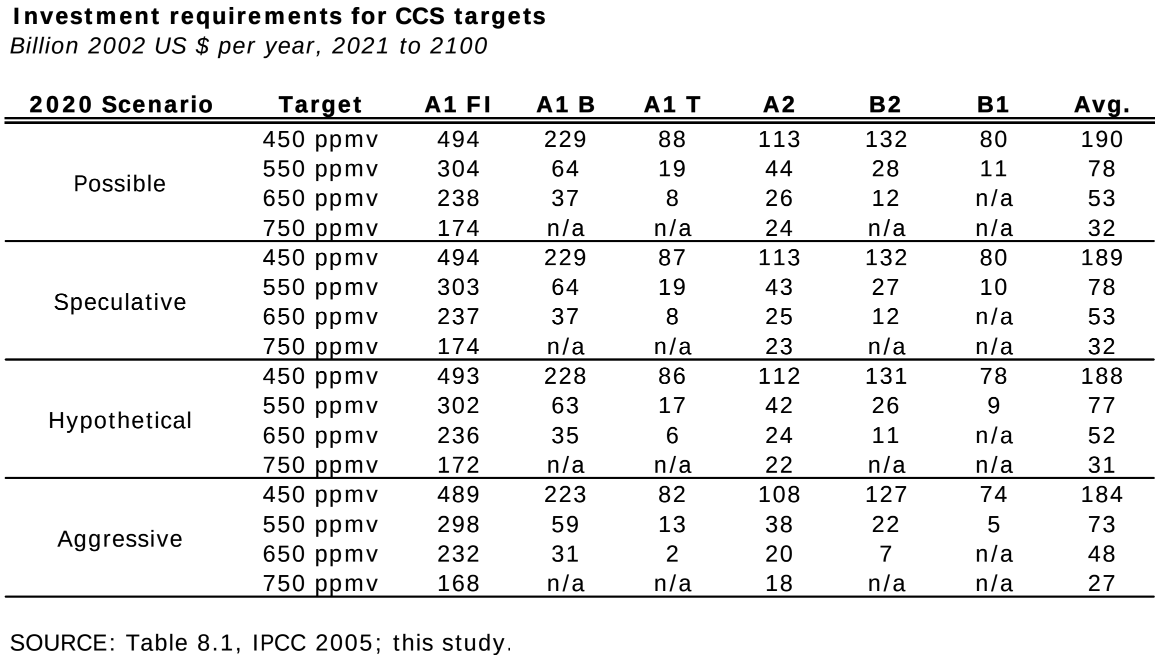
New CO2 sequestration capacity added per year, 2021 to 2100 (MtCO2/yr)

		Scenario						
2020 Scenario	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
Possible	450 ppmv	1,756	814	311	403	470	284	673
	550 ppmv	1,079	229	68	155	99	39	278
	650 ppmv	844	132	28	91	44	n/a	189
	750 ppmv	618	n/a	n/a	84	n/a	n/a	115
Speculative	450 ppmv	1,754	813	309	401	468	283	671
	550 ppmv	1,078	227	66	154	97	37	276
	650 ppmv	842	130	27	89	42	n/a	188
	750 ppmv	616	n/a	n/a	82	n/a	n/a	114
Hypothetical	450 ppmv	1,750	809	305	397	464	279	667
	550 ppmv	1,074	223	62	149	93	33	272
	650 ppmv	838	126	23	85	38	n/a	184
	750 ppmv	612	n/a	n/a	78	n/a	n/a	109
Aggressive	450 ppmv	1,736	794	290	383	449	264	653
	550 ppmv	1,059	208	47	135	78	18	258
	650 ppmv	823	111	8	70	23	n/a	169
	750 ppmv	598	n/a	n/a	63	n/a	n/a	95

Ratio of annual capacity growth to installed capacity in 2020

		Scenario						
2020 Scenario	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
Possible	450 ppmv	19.13	8.87	3.39	4.39	5.12	3.10	7.33
	550 ppmv	11.76	2.49	0.74	1.69	1.08	0.43	3.03
	650 ppmv	9.20	1.44	0.31	0.99	0.48	n/a	2.06
	750 ppmv	6.73	n/a	n/a	0.92	n/a	n/a	1.26
Speculative	450 ppmv	11.14	5.16	1.96	2.55	2.97	1.79	4.26
	550 ppmv	6.84	1.44	0.42	0.97	0.62	0.24	1.75
	650 ppmv	5.35	0.83	0.17	0.57	0.27	n/a	1.19
	750 ppmv	3.91	n/a	n/a	0.52	n/a	n/a	0.72
Hypothetical	450 ppmv	5.56	2.57	0.97	1.26	1.47	0.88	2.12
	550 ppmv	3.41	0.71	0.20	0.47	0.29	0.11	0.86
	650 ppmv	2.66	0.40	0.07	0.27	0.12	n/a	0.58
	750 ppmv	1.94	n/a	n/a	0.25	n/a	n/a	0.35
Aggressive	450 ppmv	1.95	0.89	0.33	0.43	0.51	0.30	0.73
	550 ppmv	1.19	0.23	0.05	0.15	0.09	0.02	0.29
	650 ppmv	0.93	0.13	0.01	0.08	0.03	n/a	0.19
	750 ppmv	0.67	n/a	n/a	0.07	n/a	n/a	0.11

Table 5: Linear growth model results



Investment requirements for CCS targets

Billion 2002 US $ per year, 2021 to 2100

2020 Scenario	Target	A1 FI	A1 B	A1 T	A2	B2	B1	Avg.
Possible	450 ppmv	494	229	88	113	132	80	190
	550 ppmv	304	64	19	44	28	11	78
	650 ppmv	238	37	8	26	12	n/a	53
	750 ppmv	174	n/a	n/a	24	n/a	n/a	32
Speculative	450 ppmv	494	229	87	113	132	80	189
	550 ppmv	303	64	19	43	27	10	78
	650 ppmv	237	37	8	25	12	n/a	53
	750 ppmv	174	n/a	n/a	23	n/a	n/a	32
Hypothetical	450 ppmv	493	228	86	112	131	78	188
	550 ppmv	302	63	17	42	26	9	77
	650 ppmv	236	35	6	24	11	n/a	52
	750 ppmv	172	n/a	n/a	22	n/a	n/a	31
Aggressive	450 ppmv	489	223	82	108	127	74	184
	550 ppmv	298	59	13	38	22	5	73
	650 ppmv	232	31	2	20	7	n/a	48
	750 ppmv	168	n/a	n/a	18	n/a	n/a	27

SOURCE: Table 8.1, IPCC 2005; this study.

Table 6: Investment requirements for CCS targets

Exponential Growth Model Results

Compound annual percentage growth, 2021 to 2100

		Scenario						
2020 Scenario	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
Possible	450 ppmv	11.6%	10.4%	8.8%	9.3%	9.5%	8.7%	10.1%
	550 ppmv	10.8%	8.4%	6.4%	7.7%	7.0%	5.5%	8.7%
	650 ppmv	10.4%	7.5%	4.9%	6.9%	5.7%	n/a	8.1%
	750 ppmv	9.9%	n/a	n/a	6.8%	n/a	n/a	7.3%
Speculative	450 ppmv	10.7%	9.5%	8.0%	8.4%	8.6%	7.8%	9.2%
	550 ppmv	10.0%	7.5%	5.5%	6.9%	6.1%	4.5%	7.8%
	650 ppmv	9.6%	6.6%	3.9%	6.0%	4.7%	n/a	7.2%
	750 ppmv	9.1%	n/a	n/a	5.8%	n/a	n/a	6.4%
Hypothetical	450 ppmv	9.6%	8.4%	6.8%	7.3%	7.5%	6.7%	8.1%
	550 ppmv	8.9%	6.3%	4.2%	5.7%	4.9%	3.0%	6.7%
	650 ppmv	8.5%	5.4%	2.3%	4.7%	3.3%	n/a	6.0%
	750 ppmv	8.0%	n/a	n/a	4.6%	n/a	n/a	5.1%
Aggressive	450 ppmv	8.0%	6.7%	5.0%	5.5%	5.8%	4.9%	6.4%
	550 ppmv	7.2%	4.5%	1.7%	3.7%	2.7%	-0.5%	4.8%
	650 ppmv	6.8%	3.3%	-3.3%	2.5%	0.1%	n/a	4.1%
	750 ppmv	6.2%	n/a	n/a	2.3%	n/a	n/a	3.0%

Fraction of CCS occurring during 2076-2100 in the exponential model

		Scenario						
2020 Scenario	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
Possible	450 ppmv	94%	92%	88%	89%	90%	88%	91%
	550 ppmv	92%	87%	79%	85%	82%	75%	88%
	650 ppmv	92%	84%	72%	81%	76%	n/a	86%
	750 ppmv	91%	n/a	n/a	81%	n/a	n/a	83%
Speculative	450 ppmv	92%	90%	86%	87%	88%	85%	89%
	550 ppmv	91%	84%	75%	81%	78%	69%	85%
	650 ppmv	90%	80%	64%	77%	70%	n/a	83%
	750 ppmv	89%	n/a	n/a	77%	n/a	n/a	79%
Hypothetical	450 ppmv	90%	87%	81%	83%	84%	81%	86%
	550 ppmv	88%	79%	66%	76%	71%	58%	80%
	650 ppmv	87%	74%	51%	70%	60%	n/a	77%
	750 ppmv	85%	n/a	n/a	69%	n/a	n/a	73%
Aggressive	450 ppmv	85%	81%	72%	75%	76%	71%	79%
	550 ppmv	83%	68%	46%	63%	55%	27%	71%
	650 ppmv	81%	60%	9%	53%	32%	n/a	66%
	750 ppmv	79%	n/a	n/a	51%	n/a	n/a	58%

Table 7: Exponential growth model results

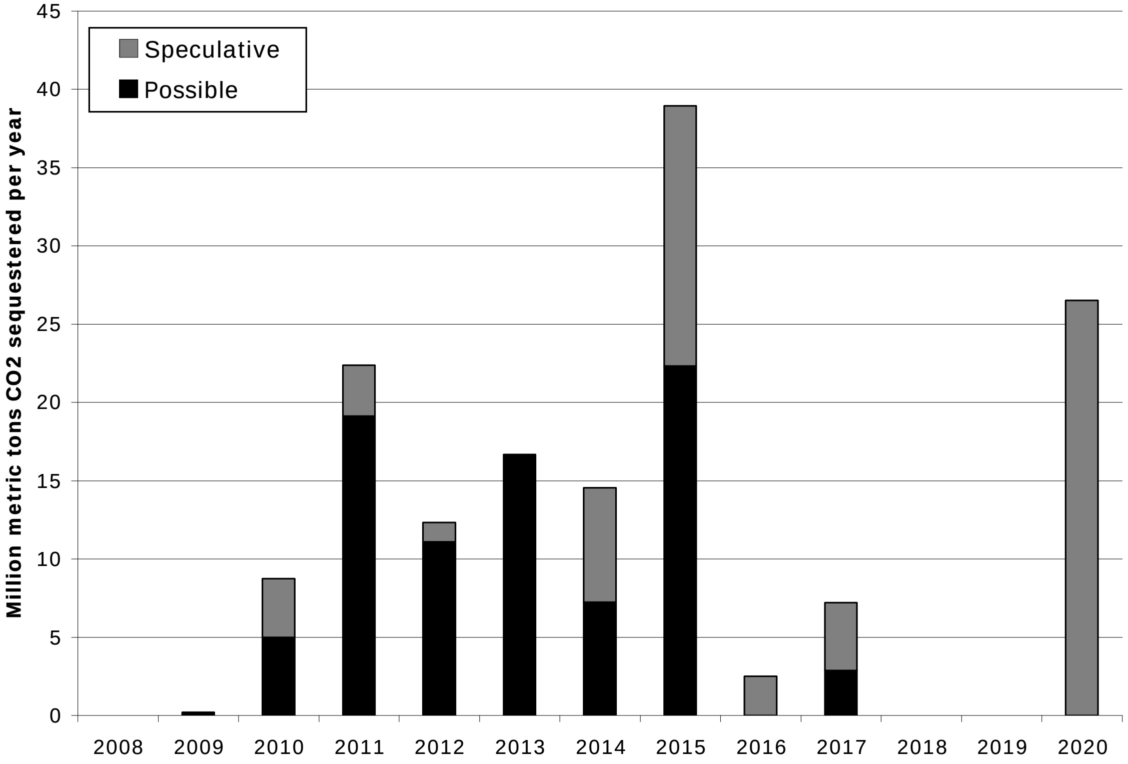
Effect of Near-Term CCS Development on the Required Long-Term Growth Rate

Reduction in compound annual percentage growth, 2021 to 2100
Measured for each 2020 Scenario relative to the "Possible" 2020 Scenario

		Scenario						
2020 Scenario	**Target**	**A1 FI**	**A1 B**	**A1 T**	**A2**	**B2**	**B1**	**Avg.**
Possible	450 ppmv	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	550 ppmv	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	650 ppmv	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	750 ppmv	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Speculative	450 ppmv	0.8%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
	550 ppmv	0.8%	0.9%	0.9%	0.9%	0.9%	1.0%	0.9%
	650 ppmv	0.9%	0.9%	1.1%	0.9%	1.0%	n/a	0.9%
	750 ppmv	0.9%	n/a	n/a	0.9%	n/a	n/a	0.9%
Hypothetical	450 ppmv	1.9%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
	550 ppmv	1.9%	2.0%	2.2%	2.1%	2.1%	2.5%	2.0%
	650 ppmv	2.0%	2.1%	2.7%	2.2%	2.4%	n/a	2.0%
	750 ppmv	2.0%	n/a	n/a	2.2%	n/a	n/a	2.1%
Aggressive	450 ppmv	3.6%	3.7%	3.8%	3.8%	3.7%	3.8%	3.7%
	550 ppmv	3.6%	3.9%	4.7%	4.0%	4.3%	6.0%	3.8%
	650 ppmv	3.6%	4.1%	8.3%	4.4%	5.6%	n/a	4.0%
	750 ppmv	3.7%	n/a	n/a	4.5%	n/a	n/a	4.2%

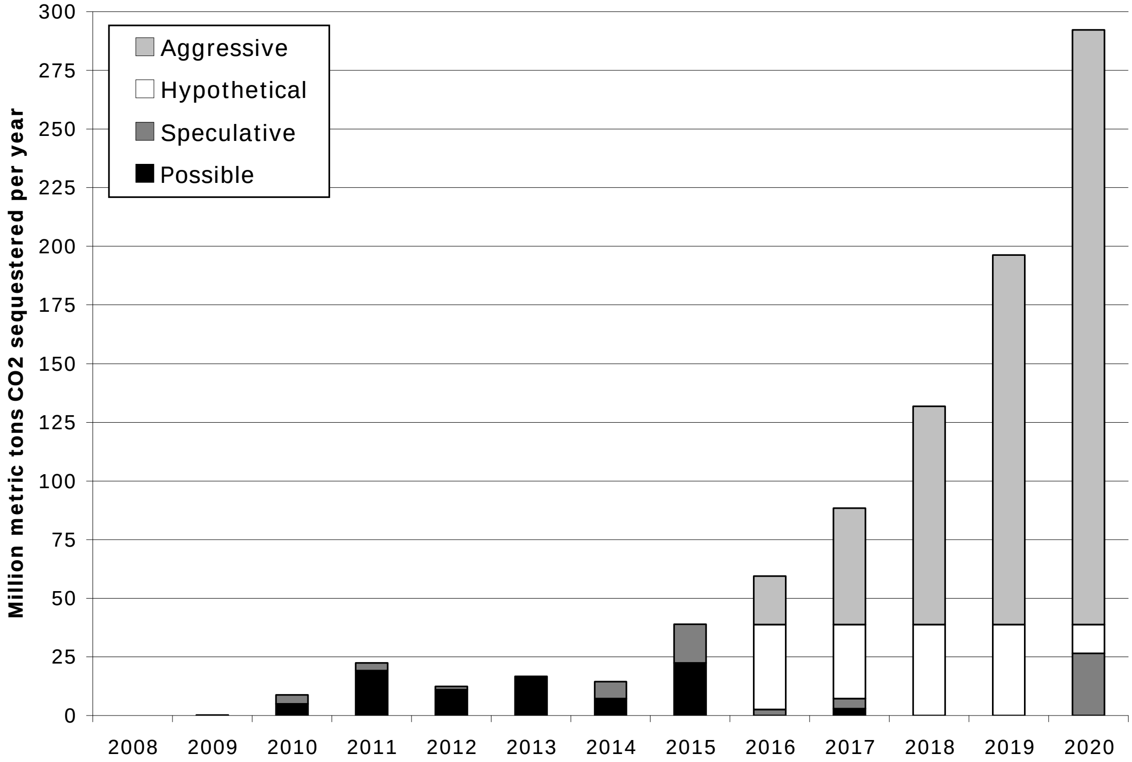
Table 8: Effect of near-term CCS development on the required long-term growth rate

Figure 1: Annual CO_2 sequestration capacity expansions from publicly announced sequestration projects



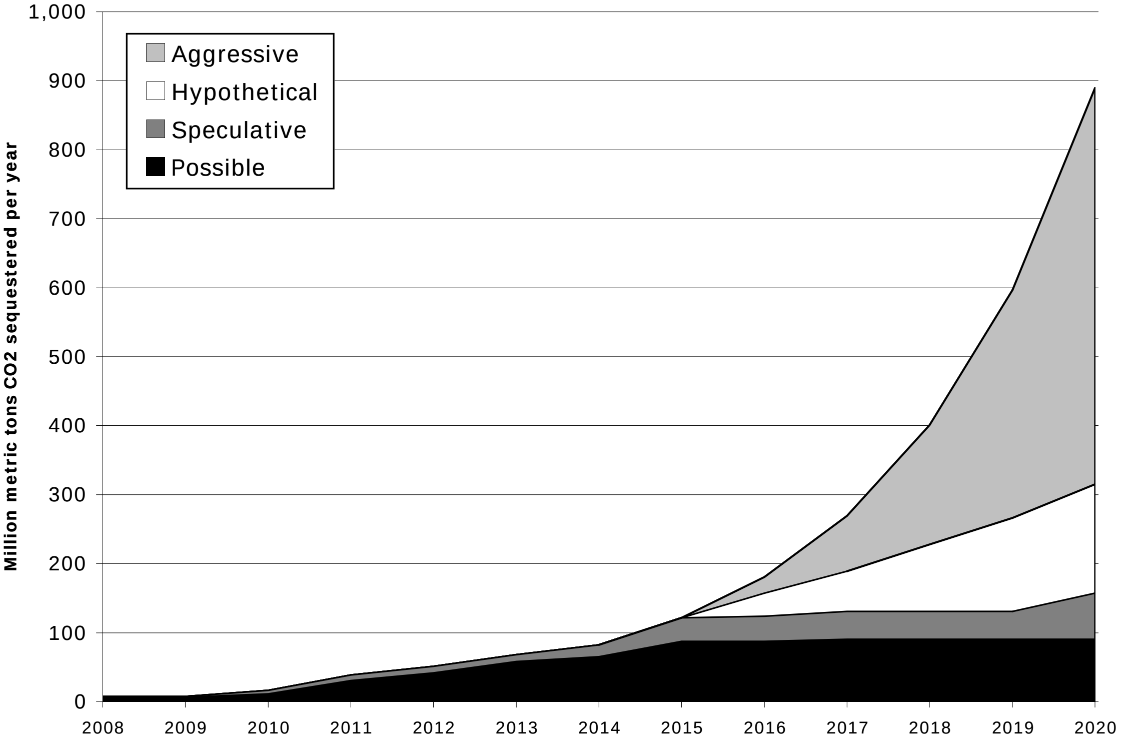
Source: Rai et al. (2008)

Figure 2: Annual CO_2 sequestration capacity expansions in four scenarios to 2020



Source: Rai et al. (2008); author's calculations.

Figure 3: Total CO_2 sequestration capacity in four scenarios to 2020



Source: Rai et al. (2008); author's calculations.

Figure 4: Schematic of analytical approach