The Past, Present, and Future Role of Technological Forecasting for Carbon Capture and Sequestration and Direct Air Capture

Course: IDS.412

Assignment: Integrated Paper

Name: Aaron Schwartz

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1) Introduction – A Tale of Two Technologies

On April 13, 2017, U.S. Secretary of Energy Rick Perry arrived at the W.A. Parish Generating Station, in Thompsons, Texas, about 25 miles southwest of downtown Houston. The facility held the record as the second largest fossil fuel power plant in the United States. But Mr. Perry had arrived to bestow a new record on the plant, as he oversaw the opening of the world's largest post-combustion carbon capture and storage (CCS) project. The new Petra Nova CCS facility was set to capture more than 5,000 tons of CO2 each day from one of the power plant's coal-burning units. Captured, but then put to use. Sequestered CO2 would be pumped through a pipeline 81 miles to the West Ranch Oil Field, where it would be used for Enhanced Oil Recovery (EOR) and increase oil production from 500 to 15,000 barrels a day, a 3,000% increase in oil output (Department of Energy 2017). Revenues from the extracted oil would help cover the projects $1 billion price tag (U.S. Energy Information Administration 2017).

Three years later, a very different type of public figure visited a very different type of record-breaking CO2 capture facility. On March 10, 2020, climate activist Gretta Thunberg visited the world's first commercial-scale direct air capture (DAC) facility in Hinwil, Switzerland built by Swedish company Climeworks (Climeworks 2020). Unlike the Petra Nova CCS project, neither power production nor oil extraction play a role in the Hinwil facility's CO2 capture operation. Rather, the plant removes CO2 directly from the air and provides it to nearby greenhouses. The 18 modular air capture units there cost between $3 and $4 million, capturing CO2 at a cost between $500 and $600 per metric ton (Gertner 2019).

These two visits, by a staunch conservative and fossil fuel ally in Texas and by perhaps the world's most vocal young climate activist in Switzerland, offer a telling symbolism of the often head-scratching world of CO2 capture. It's a world that brings together big oil and climate activists, lean startups and multi-billion-dollar energy companies. It's a world which some say is the key to averting climate catastrophe, and others claim poses a catastrophic distraction away from real climate progress. All of these reasons make CO2 capture technologies an important, complex and exciting candidate for analysis.

Recent publications by the IPCC and IEA make the case for CCS playing a "pivotal role" in the transition to a low or zero-carbon energy future (Budinis, et al. 2018). However, there still exists a tremendous amount of uncertainty surrounding both CCS and DAC. Nonetheless, models used to forecast climate change scenarios, or Integrated Assessment Models (IAMs) are increasingly incorporating these technologies. It is important to understand not only the state of these technologies as they stand today, but how they compare with expert forecasts and assessments over the past decades. Looking at the past can give us a better understanding of how we should trust and incorporate forecasts of these important technologies into current-day modeling efforts.

This paper will focus on the role of forecasting in the rise of CO2 capture technologies as tools for climate change mitigation. First, we will introduce CCS and DAC technology in greater detail. Next, we will examine how the state of knowledge of these technologies has developed and evolved over the past three decades by looking at their treatment in subsequent assessments performed by the Intergovernmental

Panel on Climate Change. Then, we will take a closer examination at historic cost estimates for both technologies, considering how these estimates have evolved over time. Then we will look ahead to the future, comparing how various studies choose to incorporate CCS and DAC into Integrated Assessment Models, and investigating some of their key modeling assumptions. By considering the role of forecasting for CCS and DAC in the past, present, and into the future, we critically evaluate how technological forecasting may best be used as a tool in our fight against climate change.

2) The Technologies

Carbon capture and storage is not a single technology. Rather, it refers to a suite of technologies, which used together, allow for the capture and storage of CO2 emissions from a point source, such as a coal fired power plants, natural gas combined cycle turbines, ethanol production plants, or other CO2 producing facilities. According to the Global CCS Institute (GCCSI), there are three major steps to CCS: capture, transport, and storage. First, CO2 is separated from other gasses emitted from the point source via a chemical process. Then, it is compressed and transported to the point of storage, commonly by pipeline. Finally, the CO2 is pumped into geological formations deep underground, such as saline aquifers. These storage sites are usually over a kilometer beneath the earth’s surface.

CCS has been deployed commercially since the early 1970s, although it was developed not for the purposes of greenhouse gas (GHG) reduction, but rather oil extraction. Enhanced Oil Recovery (EOR) is a process by which captured CO2 is pumped into oil wells, rather than permanent geologic storage facilities, to aid in the oil extraction process. Only in recent decades has CCS been promoted for applications focusing exclusively on GHG reduction, beginning with the Greenhouse Gas Control Technologies Conference Series in 1997 (Pollak, Johnson Phillips and Vajjhala 2011).

As of November 2019, there were 19 large scale CCS facilities in operation worldwide. All but 5 of these projects use captured carbon for EOR, and projects cover a range of industries, including natural gas processing, fertilizer production, iron and steel production, hydrogen production, ethanol production, and electric power generation. Including those under construction, in advanced development and early-stage development, that number increases to 51. Including operating CSS facilities and the four currently under construction, these facilities will capture 40 million tons of CO2 each year (Global CCS Institute 2019).

Like CCS, direct air capture also requires the capture, transport, and storage of CO2. However, rather than capture emissions from a point source, DAC removes CO2 from ambient air. Since CO2 is in much lower concentration in ambient air, DAC technologies require a much greater volume of air to pass through them in order to capture the same quantity of CO2. However, unlike CCS technology, DAC facilities can be located anywhere on Earth. Because of this, storage costs can often be substantially reduced compared to CCS, since DAC facilities can be located close to the geologic storage site.

There are two primary chemical methods used to perform the removal of CO2 from ambient air. The first and more developed "is based on using water solutions containing hydroxide sorbents with a strong affinity for CO2, such as sodium hydroxide, calcium hydroxide and potassium hydroxide." Designs of these systems are large scale, and capture CO_2 on the order of 1 million tCO_2/year. The second type of technology is newer and involves “amine materials bonded to a porous solid support.” DAC systems utilizing this capture technology are based on smaller, modular designs. In this paper, we will refer to the former technology type as “water-based” DAC, and the later as “amine-based” DAC (Budinis, et al. 2018).

Since DAC is a much newer technology than CCS, the first commercial DAC facilities have come online only in the past few years. Only one company, Climeworks, has commercial-scale DAC deployed, with 14 modular DAC plants utilizing the amine-based DAC technology to be built by 2019 or to be completed during 2020 (Beuttler, Louise and Wurzbac 2019). The first large-scale DAC facility in the United States, utilizing water-based DAC technology, is in early development by Carbon Engineering, and is scheduled for completion in 2025 (Global CCS Institute 2019).

3) Carbon Capture Technologies and the IPCC

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 as a joint effort by the World Meteorological Organization and the United Nations Environment Program, with a mandate “to assess available scientific and socio-economic information on climate change and its impacts and on the options for mitigating climate change and adapting to it.” Its Assessment Reports, released regularly under a multi-year assessment cycle, Special Reports, and Technical Papers, have become “standard works of reference, widely used by policymakers, scientists, and other experts.” (IPCC 2005) Indeed, the IPCC has been called “the world’s leading authority on climate change,” and in 2007 shared the Nobel Peace Prize with climate activist Al Gore for "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change" (Sample 2007) (Nobel Media AB 2020). The IPCC does not perform its own research nor make recommendations to policy makers or scientists; rather, it compiles, summarizes, and assesses the current state of knowledge of both peer-reviewed and non-peer reviewed literature. Nonetheless, the IPCC can have a tremendous influence on climate-related research, as well as creating public awareness of various technological options associated with climate change mitigation.

The IPCC’s most recent major publication, the “Special Report on Global Warming of 1.5 °C,” released in 2018, discusses “the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways.” In this report, adoption of CCS technology is highly integrated into its evaluation of societal and technical pathways which limit global temperature rise to 1.5 °C. For example, the report presents four “illustrative model pathways” of how society may achieve this goal, which consider different forecasts of energy demand and energy generation mixes through 2100. Three of the four scenarios outlined include the use of CCS with fossil fuels. The report also acknowledges the role of DAC as a carbon dioxide removal (CDR) technology, and “all pathways” which limit temperature rise to 1.5 °C include the substantial incorporation of CDR technologies. Thus, by the time of the report’s release, CCS and DAC had established themselves as important technologies for climate change mitigation.

But have they always been? The IPCC has released five Assessment Reports since its establishment, each one integrating the current state of knowledge surrounding climate change. Examining how CCS and DAC technologies have been incorporated into past IPCC assessments offers valuable insights into how the state of knowledge of these technologies has evolved over the years.

3.1) IPCC Assessment Reports One – Three

Carbon capture and storage is not mentioned as a mitigation option in the First Assessment Report (AR1). Similarly, CCS "was not listed among the recommended mitigation options in the IPCC second assessment report published in 1995" (Meadowcroft and Langhelle 2009). Indeed, the Summary for Policymakers of IPCC Working Group II, which examines GHG mitigation strategies, states that "CO2 capture and disposal may be ultimately limited for technical and environmental reasons, because not all forms of disposal ensure prevention of carbon re-entering the atmosphere." However, by the Third Assessment Report (AR3), the IPCC began taking notice of CCS technologies. This report, published in 2001, states that CCS technologies "have become much better understood during the past few years, so they can now be seriously considered as mitigation options alongside the more well established options," and that "physical removal and storage of CO2 is potentially a more viable option than at the time of SAR [Second Assessment Report]." (Meadowcroft and Langhelle 2009). DAC is not mentioned in AR3.

3.2) IPCC Special Report on Carbon Dioxide Capture and Storage

In 2005, Working Group III of the IPCC published the "Special Report on Carbon Dioxide Capture and Storage" (hereon referred to as the *Special Report).* This report, published in between the Third and Fourth Assessment Reports, specifically focuses on CCS as a climate change mitigation option, and includes nine chapters which describe the sources, capture, and transport of CO2, storage options, costs and economic potential, and implications for GHG accounting. Although, like the Assessment Reports, the *Special Report* did not include new research or offer specific recommendations, it was highly influential in introducing CCS as a climate change mitigation option to policy makers, the scientific community, and the general public. In their book "Catching the Carbon" Meadowcroft and Langhelle emphasize that "it is difficult to overstate the significance of the *IPCC Special Report*…for 15 years the IPCC assessment reports have provided the scientific anchor for climate change policy debates, and so the relatively favorable evaluation of emissions reduction potential of CCS contained in the *Special Report* could hardly be ignored." Although the *Special Report* does not include climate change scenario forecasting through IAM's as do the Assessment Reports, it does identify "gaps in knowledge that would need to be addressed in order to facilitate large-scale deployment" of CCS technology for climate change mitigation (IPCC 2005).

The *Special Report* is the first of the IPCC publications to mention DAC. However, it is only mentioned in passing, and is not described as a practical solution for CO2 capture, since the concentration of CO2 in ambient air is so low. The only reference cited on the topic describes how DAC "appears feasible but needs to be demonstrated" (Lackner 2003).

3.3) IPCC Assessment Reports Four – Five

The Fourth Assessment Report (AR4) was released in 2007 and lists early applications of CCS among "key mitigation technologies and practices currently commercially available.” It also includes “CCS for gas, biomass and coal-fired electricity generating facilities” among “key mitigation technologies and practices projected to be commercialized before 2030.” Indeed, the Summary for Policymakers states that CCS in underground formations has “the potential to make an important contribution to mitigation by 2030” (IPCC 2007).

AR4 is the first of the Assessment Reports to mention DAC technology, although as in the *Special Report*, discussion is limited to a few sentences. It cites cost estimates as low as 75 $/tCO2 using a calcium hydroxide as a sorbent (water-based DAC), although notes that “no experimental data on the complete process are yet available to demonstrate the concept, its energy use and engineering costs.” (IPCC 2007)

By the time Working Group II released its section of the Fifth Assessment Report (AR5) in 2014, CCS had established itself as a recognized component in climate change mitigation pathways. For example, the Summary for Policymakers describes how “at the global level, scenarios reaching about 450 ppm CO2 are also characterized by more rapid improvements in energy efficiency and a tripling to nearly a quadrupling of the share of zero- and low-carbon energy supply from renewables, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS), or bioenergy with CCS (BECCS) by the year 2050.” (IPCC 2014) It also notes that all of the technology needed to create a commercial scale CCS facility at a fossil fuel generation plant already exist, and that such facilities could be built in the near term under the proper financial or regulatory conditions. Additionally, it identifies policy and economic barriers to the widespread adoption of CCS, namely “well-defined regulations concerning short- and long-term responsibilities for storage are needed as well as economic incentives.”

AR5 continued the trend within the Assessment Reports of dedicating increased attention to DAC technology. Compared to the previous report, which only identifies one method for DAC, AR5 notes that there are "a number of proposed capture methods." It also incorporates more recent literature on DAC cost projections, citing a 2012 study projecting DAC costs at 40 – 300 $/tCO2 for water-based DAC or 165 – 600 $/tCO2 for amine-based DAC. Nonetheless, it cites a 2011 U.S. Government Accountability Office technological assessment which "concluded that all DAC methods were currently immature" (IPCC 2014).

3.4) Discussion

The IPCC reports offer a convenient way of evaluating the state of knowledge of carbon capture and storage and direct air capture technologies over the past three decades. For the first two assessment cycles, CCS was not acknowledged as a technological option for climate change mitigation. However, CCS already had a long history of use by U.S. oil and gas companies for EOR since the 1970s. For example, plants which went online in 1972, 1982, 1986 performing industrial separation of CO2 for EOR are still operational in the U.S. today (Global CCS Institute 2019). So why wasn't CCS being considered as a viable climate change option from the earliest IPCC assessment report? AR2 notes that CO2 storage was a key bottleneck and acknowledged that adoption of CCS was constrained by uncertainty regarding CO2 re-entering the atmosphere after being pumped underground. Indeed, for companies utilizing CO2 for EOR at this time, there was little thought regarding the fate of the CO2 after it had been pumped into the oil well. Uncertainty surrounding CO2 storage seems to be an issue which remains a challenge for adopting CCS at scale. AR5 cites "short- and long-term responsibilities" surrounding storage as one of the key barriers to adoption. Indeed, a 2011 paper by Pollak, et al. cites permitting, property-rights, and long-term stewardship as the three issues that "must be resolved for [Geologic Sequestration] projects to be viable." This helps explain why, although technology to capture, transport, and store CO2 from industrial processes existed well before AR1, it was not considered a viable option for climate change mitigation until decades later. The tricky economics of CO2 capture aside, of the three primary technologies which constitute CCS, storage seemed to be the key bottleneck in its adoption into climate mitigation strategies.

The IPCC Assessment reports also offer the opportunity to track the incorporation of an entirely new technology, direct air capture, into discourse surrounding climate change mitigation. Rather than representing any one technology, DAC today is an umbrella term referring to a suite of technologies capable of removing CO2 from ambient air. But at the time of the first serious mention of DAC in the AR4, the scientists only had one such technology for CO2 capture from ambient air, calcium hydroxide sorbents, in their toolbox. AR5, however, reflects the tremendous increase in research activity surrounding DAC since the previous report, and the introduction of new technologies for CO2 capture. It cites five studies examining CO2 capture methodologies and notes that "there are a number of proposed capture methods." In technological forecasting for the role of DAC in climate change mitigation, it is important to consider how the costs and commercial availability of each of these technology types may evolve over time. Additionally, just as new technologies were introduced for DAC between the Fourth and Fifth Assessment report, expert forecasts must also anticipate the emergence of new CO_2 capture methods which are currently in the experimental phase.

AR5 notes that "storage technologies [for DAC are] assumed to be the same as CCS." Thus, the same issues surrounding CO_2 storage from CCS – site permitting, well assessment and monitoring, short- and long-term well liability issues – also apply for DAC. Fortunately, DAC can "piggyback" off of progress made in these areas over the past decades for CCS and avoid some of the storage bottlenecks which prevented CCS from being a viable technology for climate change mitigation for many years.

4) Technological Forecasting

The IPCC reports offer a useful overview of the state of knowledge of carbon capture and storage and direct air capture technologies for climate change mitigation, and how this knowledge has developed over the past three decades. Nonetheless, these reports, excluding the "Special Report on Carbon Dioxide Capture and Storage", offer fairly high-level summaries of these technologies. A more detailed look at how cost estimates have evolved for CCS and DAC can help us understand the factors which will influence the actual costs of these technologies in the future. Furthermore, over the past five years, the first commercial CCS and DAC facilities have come online. This offers us the opportunity, for the first time, to compare cost estimates to operational CCS and DAC facility costs.

4.1.1) Costs of Carbon Capture and Storage

The 2005 "IPCC Special Report on Carbon Dioxide Capture and Storage", which contains a chapter titled "Cost and Economic Potential," is a logical place to begin a more thorough analysis of the costs of CO2 capture. In the executive summary of this chapter, the authors note that "the literature reflects a widely held belief that the cost of building and operating CO2 capture systems will fall over time as a result of technological advances." They also note that of the three major components of CCS -– capture, storage, and transport – the costs of capture "dominate" CCS integration into fossil-fuel power plants. Furthermore, they note that all three of these components are commercially available, and that major costs of large-scale CCS development involve combining these technologies at scale.

The *Special Report* offers cost estimates for various types of new (greenfield) power plants, including supercritical pulverized coal (SCPC), natural gas combined cycle, integrated gasification, and hydrogen power plants. Since the only operational CCS power plant facilities are SCPC plants, we will limit our analysis to this facility type. Furthermore, while the authors present a range of power plant costs with and without capture, such as capital costs, costs of energy, emissions rates, and more, we will limit ourselves to discussion of mitigation costs of CO2 avoided and the cost of CO2 captured, both in $/tCO2. The cost of CO2 captured is the increased cost of a power-plant incorporating CCS compared to an identical plant without CCS, per ton of CO2 captured. This is a widely used measure by both industry and in the literature. The mitigation cost of CO2 avoided reflects the total cost of CCS, including capture, transport, and storage, compared to an identical plant without CCS. Additionally, since the CCS capture process itself requires energy, and thereby fossil fuel consumption, this cost also factors in the increased energy costs, fuel consumption and CO_2 produced in powerplants outfitted with CCS (and hence cost of CO_2 "avoided" rather than CO_2 "captured"). The mitigation cost is a particularly useful measure, as these costs "are directly comparable to a market price or tax on CO_2 emissions" (Rubin, Davison and Herzog 2015) The authors estimate the cost of mitigation for SCPC plants with CCS and geologic storage between a low-range estimate of 45 \$/tCO_2 and upper-range estimate of 114 \$/tCO_2 avoided, and the cost of capture from 33 – 58 \$/tCO_2 (in \$2013).

In 2015 paper "The Cost of CO_2 Capture and Storage," the authors of the *Special Report* perform a reassessment of their costs and economic estimates of CCS 10 years after the report's release. Their analysis revisits the assumptions used based on recent cost analyses of the various technologies associated with CCS in power production applications. The updated mitigation cost of avoided carbon for SCPC power plants range from 46 – 99 \$/tCO_2 (\$2013). Although there is little change in the low-range estimate, the upper-range estimate decreased by over 15%. The authors contribute this change largely to assumptions of increased capacity factors, or the fraction of power a plant is producing compared to its maximum potential power output, of SCPC plants compared to the earlier study, which would lead to a decrease in CO_2 mitigation cost. The updated cost of CO_2 capture ranges from 36 – 53 \$/tCO_2, remaining close to the 2005 range.

At the time of publication of the updated cost analysis, there was only one commercial-scale CCS coal power plant demonstration project in operation. This project, the Boundary Dam Power Station in Saskatchewan, Canada, and operated by SaskPower, came online in 2014. Since then, only one other commercial scale CCS coal power plant has come online, the Petra Nova facility, which opened in Texas in late 2016 and is operated by NRG Energy. A 2017 report commissioned by the GCCSI, “Global Costs of Carbon Capture and Storage,” incorporates data from both of these projects in its own analysis of CCS costs. Unlike the figures presented in the *Special Report*, these figures represent the mitigation cost of CO2 avoided for retrofitting existing SCPC plants with CCS, rather than for building new plants with CCS. The *Special Report* authors point out that retrofitting power plants for CCS is expected to be more expensive than building greenfield capacity with CCS, due to difficulties of integrating CCS inside the existing power plant footprint, lower economies of scale due to the smaller sizes of existing coal plants, and additional equipment costs. Additionally, the 2017 report offers estimates for both first-of-a-kind (FOAK) and Nth-of-a-kind costs (NOAK). FOAK costs represent the costs of the first commercial-scale facility incorporating CCS technology by a project developer. NOAK projections represent costs for subsequent commercial scale projects and are lower than FOAK costs due to “project learning.” The report projects FOAK mitigation costs for a SCPC plant ranging from 72 – 82 \$/tCO2, and costs for later NOAK plants at 54 \$/tCO2. This NOAK mitigation cost lies towards the lower range of the 45 – 114 \$/tCO2 NOAK mitigation costs presented in the *Special Report* update, although since this value represents a higher-cost CCS retrofits, this represents an especially low mitigation cost estimate.

How do these projections compare to the actual costs of the Petra Nova and Boundary Dam facilities? Analysis by the GCCSI estimates cost of CO2 capture at approximately 110 \$/tCO2 at the Boundary Dam project, and 65 \$/tCO2 for the Petra Nova project (Global CCS Institute 2019). A 2015 analysis by SaskPower estimates that they could reduce costs by up to 30% on their planned Shand project, and a 2018 analysis by NRG estimates that "*N*th-of-a-kind" (NOAK) project costs, that is, costs for future CCS retrofits, would be 20% cheaper than the Petra Nova retrofit (Global CCS Institute 2019). Scaling the FOAK values based on these projected cost reductions, we obtain NOAK cost of CO2 capture of 77 \$/tCO2 and 52 \$/tCO2 for NOAK plants by SaskPower and NRG respectively. We can compare these values to the 2015 *Special Report* update range of 36 - 53 \$/tCO2 cost of CO2 captured for NOAK plants, and 33 - 58 \$/tCO2 range from the original 2005 report.

4.1.2) Costs of Direct Air Capture

DAC technology is far newer than CCS technology, and there is only one company, Climeworks, which has deployed commercial-scale DAC facilities. As such, efforts at forecasting the cost and adoption of DAC technologies are much more limited, and all such efforts identified in the literature caution the reader as to the high level of uncertainty associated with their estimates. In 2005, Keith, et al. estimate the costs of a water-based DAC system which could be built with existing technology at the time. They estimate the cost for CO2 capture of approximately 140 \$/tCO2, although they "doubt that the system just described is the lowest cost design, even in the near term," and that "no doubt other significant improvements could be made with only moderate development of new technology" (Keith, Minh and Stolaroff 2006). Nonetheless, this cost estimate includes assumptions of decades-long R&D investment prior to the first large-scale deployment “at a total cost of several billion dollars.” Perhaps this explanans the far higher estimates of DAC presented by the American Physical Society (APS) in 2011, which offers a “optimistic” cost of capture estimate of 610 \$/tCO_2 and a “realistic” estimate of 780 \$/tCO_2. By 2007, however, Keith, et al. were claiming lower costs of 100 \$/tCO_2 captured, after deploying the method outlined in his 2005 paper in a working prototype. In 2018, Keith, et al. published estimates of a commercial scale DAC facility with a full “commercial engineering cost breakdown,” presenting a range of 94 – 232 \$/tCO_2 captured (Keith, Holmes, et al. 2018). Nonetheless, a 2019 New York Times article about DAC technology quotes MIT’s Howard Herzog, one of the authors of the *Special Report* chapter on CCS costs, who rejects Keith’s figures and insists that with current technology DAC will cost between 600 and 1000 \$/tCO_2, more in line with the APS estimates (Gertner 2019). The only costs supported by actual operation of a commercial scale DAC facility come from Climeworks, whose 600 \$/tCO_2 observed cost for amine-based CO_2 capture align more with Herzog and APS than Keith. However, they project that they will be able to achieve 100 \$/tCO_2 between 2025 and 2030 (Evans 2017). Development of a commercial scale facility utilizing Keith’s DAC design is currently underway. If his plant can achieve costs as projected, it would represent a tremendous improvement over existing technologies, and prove other leading voices in DAC cost forecasting wrong by, at minimum, a factor of 3.

Other breakthrough technologies show the potential to dramatically reduce the near-term costs of DAC in an even more pronounced fashion. U.S.-based Global Thermostat claims that its secretive amine-based technology will achieve CO_2 capture between 15 – 50 \$/tCO_2 based on data from their prototype system (Kintisch 2014).

4.1.3) Discussion

Although DAC is a far "newer" technology than CCS, credible attempts at developing cost forecasts for both of these technologies emerged around the same time (in 2005). Interestingly, the primary source of uncertainty surrounding cost estimates between the two technologies come from completely different directions. For CCS, the underlying technologies are well understood and developed, but uncertainty arises from combining and deploying them together at scale. For DAC, the primary chemical and industrial processes are still being refined, and breakthrough new methods for CO2 capture from ambient air, especially surrounding amine-based methods, are still being developed. In both cases however, early forecasts performed reasonably accurately in predicting actual costs of early-stage commercial instillations. We can compare Climeworks' first commercial-scale DAC facility operating at a cost of 600 $/tCO2 avoided, with the APS's "optimistic" 2011 estimate of 610 $/tCO2. Furthermore, we can approximately compare the Petro Nova CCS facility's adjusted NOAK 52 $/tCO2 cost of capture estimate with the 33 - 58 $/tCO2 range presented in the *Special Report* over ten years before the facility came online. Of course, these cost estimates do not come from a vacuum, and incorporate data from smaller-scale pilot programs and experiments. Nonetheless, the ability of forecasters in this field to provide insights into costs years into the future with relative accuracy remains impressive. Of course, forecasts do not always reflect reality. For example, the Boundary Dam project was criticized for far exceeding its budget, as reflected in its substantially higher costs of capture when compared to the Petra Nova Project and *Special Report* cost projections (although CCS advocates maintain that these cost overruns were due to “plant refurbishment”) (Global CCS Institute 2017).

Evolving costs, technologies, policies, and practices require reassessment of cost estimates. The 2015 update to the *Special Report* is an excellent example of how experts can offer transparent updates to cost forecasts and should serve as a model for technological forecasters in a range of fields and industries. In addition to a dedicated section identifying key factors broadly affecting CCS costs, the authors present sub-sections identifying “highlights of new/recent technology developments” for various technologies associated with CCS, such as for various combustion technologies, transport, etc. They also update costs from the *Special Report* into a common cost basis ($2013) and offer side-by side comparisons of the original and updated costs. However, unlike a scheduled assessment cycle such as that followed by the IPCC, these updates were published at the whim of the authors. Such detailed re-assessments of costs would be even more valuable if offered under a regular timeline and overseen by a centralized body. This could also allow for critical review and input by academics and industry outside of the peer review process. Indeed, the lack of consensus among academic experts over cost projections for DAC underscores the importance of incorporating a diversity of expert viewpoints into the forecasting process.

5) CCS, DAC and Integrated Assessment Models

Integrated Assessment Models (IAMs) are used to evaluate decarbonization pathways and their impacts on temperature rise over the coming decades. The inputs to these models – cost projects, technical specifications, etc. – as well as various modeling assumptions, have substantial impacts on the models outcomes. There are multiple studies which incorporate a range of CCS and DAC costs into IAM's and other economic assessment models (Pielke Jr. 2009), (Budinis, et al. 2018), (Realmonte, et al. 2019), (Fasihi, Efimova and Breyer 2019). We have examined how costs estimates for CCS and DAC have evolved over time. We now consider how these cost estimates are used in IAMs, and how these models take into account future uncertainty surrounding costs and technological penetration.

There is a limited literature evaluating the role of DAC in IAMs. For example, the most recent major study which performs such an evaluation cites only four previous efforts (Realmonte, et al. 2019). Common among these analyses is to assume that costs of DAC remain fixed over time and to perform a "sensitivity analysis" examining how model results are affected using different fixed technology cost estimates. Pielke 2009, for example, evaluates DAC integration in IAM's through 2100 using three cost scenarios – an optimistic, mid-range, and pessimistic scenario at 30 $/tCO2, 100 $/tCO2 and $140 t/CO2 respectively. The author acknowledges that "the analysis errs on the side of understating costs" and that energy-related technologies usually see substantial cost reductions over time due to economies of scale. Chen and Massimo use a similar approach, and "take a conservative view and assume investments costs to remain constant in time," which "provides a limiting case for the analysis of DAC." They propose a "realistic" and "optimistic" case of 350 $/tCO2 and 260 $/tCO2 for cost of capture respectively, and like Pielke, model climate scenarios through 2100.

A "sensitivity analysis" approach appears to be the most common approach for modeling CCS technologies as well. For Integrated Assessment Modeling performed for the IPCC Fifth Assessment report, the authors use “Min/Median/Max” estimates for parameters ranging from costs to emissions rates (IPCC 2014). For SCPC plants, these values are 1700/3300/6600 $/kW in capital expenditures, 0/45/290 $/kW for variable O&M costs, and 11/15/28 $/kW for variable O&M costs ($2010).

Another approach identified for arriving at cost estimates is to use average cost values taken from the literature (Viebahn, Vallentin and Höller 2015). The authors use 625 $/kW as their estimate for capital costs of Chinese SCPC plants with CCS and estimate annual O&M costs as a fixed percentage (4%) of this capital cost. These costs are an order of magnitude different from even the minimum cost presented used in the IPCC analysis, offering a telling example of the discrepancies between cost estimates present in the literature. Interestingly, these analyses shy away from compound cost measures such as cost of CO2 avoided which incorporate multiple system costs, even though this measure is useful for comparing CCS costs with a cost of CO2. Indeed, Budinis, et al. note that “among the 64 references listed in the AR5 database webpage, only one reference reports the marginal abatement cost of CCS.”

Additional key factors to consider in modeling using IAM’s are technology learning and adoption rates. Adoption rates, also known as penetration rates, diffusion rates or growth rates, represent how total market share of a technology changes over time. MacFarland and Herzog identify seven areas which influence technology diffusion: “technology characteristics, adopter characteristics, declining technology costs, availability of information, industry characteristics, specialized resources, and general equilibrium effects.” Adoption rates typically follow “s-shape” trajectories characterized by a slow initial growth stage, a rapid growth stage, and a slow saturation phase. It is common to fit a logistic curve to historic technological adoption data to make adoption projections.

Realmonte, et al. note that historical growth rates for energy technologies are typically between 15% and 20% per year, with modular technologies usually achieving higher growth rates than larger, capital intensive facilities. In their analysis of DAC incorporation in IAM's, the authors incorporate a 20% annual growth rate cap for DAC, based on these historical benchmarks, and compare this rate to 15% and 30% growth rate caps. The authors note that these "expansion constraints are the key parameters determining [DAC] deployment, especially for a 1.5 °C [temperature rise] target." Based on these three growth rates, they compare projected DAC diffusion based on IAM model outputs with historical diffusion rates of other power sources. Their comparison is promising for mitigation scenarios which require the rapid scaleup of DAC technologies, and they note that "even if [DAC] deployment may appear incredibly rapid, from 1 to 30 GtCO2/year of removal in only 20 years, other technologies experienced similar patterns in the past."

Penetration rates for CCS are estimated to be far lower than those of DAC. Comparing CCS to similar technologies with "expansive, networked infrastructure (e.g. electric power and natural gas)," MacFarland and Herzog note that one study estimated that CCS "required six to eight decades to diffuse within a region." Nonetheless, other models use more aggressive penetration rates as low as five decades in their projections which show adoption of CCS leading to substantial reductions in carbon prices.

Unlike adoption rates, which describe changes in a technology's deployed capacity, learning rates describe changes in technology costs. Learning rate is defined as the "fractional reduction in cost for each doubling of total production or capacity" (Rubin 2019). Breyer, et al. note that learning rate can have a "substantial impact on DAC cost projections," and suggest that a learning rate of 10-15% is "realistic, when compared to similar technologies." Realmonte, et al.'s analysis of IAM outputs with DAC integration is more sophisticated than those of Pielke and Chan, integrating a learning rate in addition to offering "high" "low" and "floor" assumptions for DAC, although the specific value used for this learning rate is not specified. Rubin, 2019 estimates learning rates for SCPC plants with and without CCS ranging from 1.1% to 9.9% and 5.6% to 12% respectively. Viebhan, et al. offers an explanation for the comparatively low learning rates for CCS technology, noting that "only the additional expenditure for CO2 capture follows the learning curve, whilst the current [SCPC] plant is a widely mature and deployed technology."

5.1) Discussion

IAMs are complicated tools for evaluating climate mitigation pathways. As such, it is necessary abstract away much of the technical details and nuance related to individual technologies. Nonetheless, the level of simplification used in many of these analyses is surprising. Budinis, et al.'s Integrated Assessment Modeling of CCS only uses parameters for investment cost, efficiency, efficiency loss from CCS, and transportation costs as a function of distance. Another major study of CCS integration into IAM's doesn't even take investment cost into account, due to insufficient data

(Koelbl, et al. 2014). Indeed, there is substantial variability among the parameters which modelers choose to incorporate in their highly simplified models of CCS technologies.

Realmonte, et al.'s study, published in Nature Communications, shows a similar level of simplification for DAC. The only parameters used to define DAC systems in the IAM are electricity, heat and cost of CO2 capture. Furthermore, additional assumptions, such a learning and adoption rates, were buried deep in supplemental material or not even identified. In other studies, such rates, although acknowledged as important, were not even used in the modeling effort, as noted above. This makes it especially difficult to compare the complete set of modeling assumptions used between different analyses, let alone confidently compare the results of these studies.

6) Conclusion

Both carbon capture and storage and direct air capture have emerged as important technologies for mitigating the effects of climate change. CCS has risen from a technique used exclusively as a tool used by the oil and gas industry for Enhanced Oil Recovery, and DAC has developed as an entirely new technology. Over the past decades, technological forecasting has played an important role in enabling further exploratory analysis of the impacts of both of these technologies.

By examining the treatment of each of these technologies in the IPCC Assessment Reports, we have seen how expert opinion has evolved over the role and practicality of each of these technologies for climate change mitigation. These reports note the technological differences between CCS and DAC, but more importantly, shed light on the similar barriers that both technologies face, namely, uncertainties surrounding CO2 storage. Furthermore, the *Special Report* demonstrates the power of highly respected institutions such as the IPCC to promote mainstream acceptance of a technology and catalyze future research and development.

A closer examination of cost forecasts for both of these technologies emphasized two very different areas where cost uncertainty arises – in newly technologies being deployed for the first time in the case of DAC, and in deploying well understood technologies in new ways, in the case of CCS. Yet earlier technological learning among the shared components of CCS and DAC, namely CO2 storage and transport, has led to reduced uncertainty among key elements of DAC systems, allowing for more rapid development and acceptance than for CCS. Although data is limited, observed costs from early commercial deployments of both of these technologies support, rather than counter, the expert forecasts made years in the past.

However, this examination has also raised concerns over how these costs are being put to use, namely in the Integrated Assessment Models being used to evaluate various climate change pathways. These analyses often rely on a small subset of cost and technical assumptions for individual technologies, compounding the uncertainties inherent in those assumptions. Furthermore, the specific details of the modeling efforts often remain murky, making reproducibility an issue.

It is important to note that any meaningful evaluation of CCS or DAC in the context of climate change mitigation requires an assessment of many factors beyond those presented here. Public acceptance of the technologies, a cost or tax on carbon, and changes in oil prices are just a few examples of the exogenous factors which may have a tremendous impact on the adoption of these technologies. Public policy will play a crucial role as well. For example, the 45Q tax credit, originally only applicable for CCS projects, was extended in the Bipartisan Budget Act of 2018 to DAC projects as well. Additionally, it increased the value of claimable tax credits for CO2 captured for permanent storage and decreased the value of credits for CO2 captured for EOR. No doubt, such policy actions have a measurable impact on the rate at which industry develops and deploys these technologies, and future analysis may investigate how public policy measures have influenced learning and adoption rates of comparable technologies.

Technological forecasting will continue to play an important role as we evaluate responses to climate change. But as this evaluation of carbon capture and storage and direct air capture show, it is important that technologies are not evaluated in a vacuum. One cannot reasonably engage in efforts at DAC forecasting without considering CCS alongside it. The IPCC recognizes this and attempts to place various climate change mitigation technologies in a broader context in their own Assessment Reports. It would serve academics and industry practitioners alike to strive to do the same.

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