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Carbon capture and storage across fuels and sectors in energy system transformation pathways

Matteo Muratori[a,*], Haroon Kheshgi[b], Bryan Mignone[b], Leon Clarke[a], Haewon McJeon[a], Jae Edmonds[a]

[a] Pacific Northwest National Laboratory – Joint Global Change Research Institute, 5825 University Research Court, College Park, MD, 20740, United States
[b] ExxonMobil Research and Engineering Company, 1545 Route 22 East, Annandale, NJ 08801, United States

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ABSTRACT

Carbon capture and storage (CCS) is broadly understood to be a key mitigation technology, yet modeling analyses provide different results regarding the applications in which it might be used most effectively. Here we use the Global Change Assessment Model (GCAM) to explore the sensitivity of CCS deployment across sectors and fuels to future technology cost assumptions. We find that CCS is deployed preferentially in electricity generation or in liquid fuels production, depending on CCS and biofuels production cost assumptions. We consistently find significant deployment across both sectors in all of the scenarios considered here, with bioenergy with CCS (BECCS) often the dominant application. As such, this study challenges the view that CCS will primarily be coupled with power plants and used mainly in conjunction with fossil fuels, and suggests greater focus on practical implications of significant CCS and BECCS deployment to inform energy system transformation scenarios over the 21st century.

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1. Introduction

Stabilizing atmospheric greenhouse gas (GHG) concentrations implies a transformation of the global energy system, including widespread deployment of low- or zero-carbon technologies. For over a decade, modeling studies using integrated assessment models (IAMs) have made the case that deployment of carbon capture and storage (CCS) technologies increases the feasibility and decreases the mitigation costs associated with deep GHG reduction goals (Krey et al., 2014; Clarke et al., 2014). For example, among the 11 models that attempted to run scenarios without CCS in the EMF-27 study, only four were able to produce scenarios achieving radiative forcing goals of 2.6 W/m^2 by 2100 (Krey et al., 2014). Scenarios generated by IAMs that reach these goals without CCS entail substantially higher climate change mitigation costs than scenarios from the same models that include CCS (Akashi et al., 2014). Recent studies have emphasized the role of bioenergy coupled with CCS (BECCS), as opposed to fossil fuels coupled with CCS (Rose et al., 2014). BECCS could yield net negative emissions by effectively removing CO_2 from the atmosphere and sequestering it, and it is often widely deployed in scenarios of deep GHG reduction (Rose et al., 2014; Koelbl et al., 2014; van Vliet et al., 2014; Muratori et al., 2016a).

While the potential value of CCS is well established, the ultimate application for the technology – the sectors in which it deploys and the fuels with which it is associated – is not. The most recent IPCC assessment report stated that, "*in the long term, the largest market for CCS systems is most likely found in the electric power sector*" (Bruckner et al., 2014). Yet, other studies have shown that CCS, particularly in conjunction with bioenergy, could be a valuable contributor in the liquid fuels sector. For example, Luckow et al. (2010) show that in deep GHG reduction scenarios, BECCS is deployed in liquid fuels production as well as in electricity generation, two sectors that have significant GHG emissions, and thus sectors that can potentially provide significant climate change mitigation.

This uncertainty regarding the most appropriate future applications for CCS stems in part from the fact that, while multiple studies have highlighted the importance of CCS – and BECCS in particular – in achieving deep GHG reductions, the factors controlling the deployment of CCS across sectors and fuels has not been systemically explored. Studies such as EMF-27 have largely ignored variations in the cost and performance of CCS and have focused instead on the implications of having or not having CCS available in any form and on differences in model behavior.

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[*] Corresponding author. Present address: National Renewable Energy Laboratory, Golden, CO, United States.
E-mail address: matteo.muratori@nrel.gov (M. Muratori).

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In this paper, we examine the application of CCS across sectors and fuels in a single IAM. We focus on two important drivers of this outcome: uncertainty in future CCS technology costs and uncertainty in biofuels production costs. We find that the sector in which CCS is preferentially deployed (electricity generation or liquid fuels production) varies directly with these assumed technology costs. Nevertheless, across the range of technology cost assumptions and CO_2 mitigation pathways considered here, we consistently find that CCS deploys significantly across both sectors, with the dominant share often in conjunction with bioenergy, rather than with fossil fuels. We provide an explanation for this result in terms of the costs of competing technologies, showing that BECCS always becomes cost-competitive when the carbon price is sufficiently high, due to its assumed net negative emissions, and discuss the implications for future research on energy transformation pathways.

2. Methods

2.1. Potential applications for CCS technologies

Carbon capture and storage technologies could potentially be used in a variety of existing and future industries and applications, including: natural gas processing; hydrogen and chemicals production; production of materials such as iron and cement; production of liquid fuels; and electricity generation. However, CCS technologies have not yet been broadly deployed commercially. Historically, CCS has been used in the gas processing industry, especially coupled to enhanced oil recovery (EOR) applications (Alvarado and Manrique, 2010). In the United States, where EOR is most widely employed, around 60 Mt of CO_2 per year are currently used for EOR applications (Wallace et al., 2014). Other industrial applications, such as production of iron, steel, chemicals, or cement, have also been proposed for CCS, given the nature of the processes used, which could provide for economically competitive use of CCS.

However, industrial processes currently account for less than 20% of global CO_2 direct emissions (*i.e.*, emissions from direct combustion or use of fossil fuels, not including, for example, emissions from electricity used by industry) (IEA STATISITCS, 2015), and CCS might only be amenable to a fraction of this. While these sectors may serve as early applications of CCS and could promote technology development, deployment of CCS technologies at a scale that contributes significantly to climate change mitigation over the 21st century requires deployment in sectors with greater CO_2 emissions. These include the electric power sector as well as the liquid fuels production sector (if there is a large expansion of biofuel production). In the electricity sector, CCS technologies can be coupled to a variety of technologies, using fossil or bio-energy, and relative costs will be an important factor in their deployment. Similarly, CCS technologies can be coupled to the production of liquid fuels in a variety of different processes, as summarized in Fig. 1.

The most appropriate applications for CCS in liquid fuels production is an important consideration for future energy system transformation pathways. For petroleum-based fuels, currently the dominant type of transportation fuel, about 7% of the crude oil energy content is used for fuel processing (refining of crude oil), and thus could potentially be captured. The remaining energy, and related emissions, are associated with the fuel combusted on-board vehicles and are not suitable for capture. This greatly limits the climate change mitigation potential of CCS coupled to petroleum-based fuels production. By contrast, production of liquid fuel from other sources requires much more energy than petroleum-based fuels, with coal-to-liquid conversion leading to significantly higher CO_2 emissions. CCS technologies could reduce this gap, making coal-based liquids comparable to petroleum-based fuels in terms of total emissions (process and combustion emissions), but such substitution would not reduce overall CO_2 emissions from current levels.

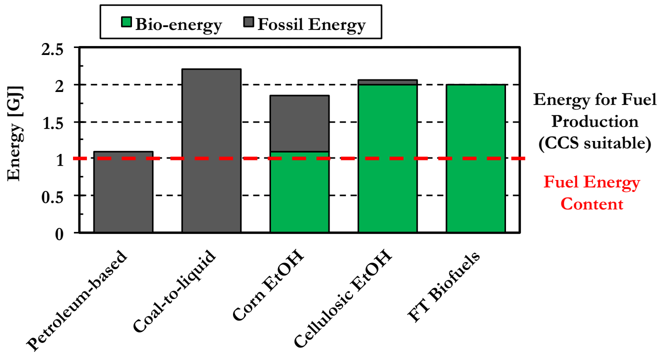

Fig. 1. Energy content and energy consumed in the production of liquid fuels. The red line (=1) indicates the energy that ends up in the fuel itself. Everything above the red line is the energy required for the production of the fuel. Only the emissions associated with large stationary sources of CO_2 are potentially suitable to be captured with CCS technologies, and these are approximately the emissions above the red line, with those below the red line coming from small and mobile sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Production of ethanol (EtOH) from corn also requires a significant amount of energy. Today this energy primarily comes from fossil fuels, and CCS technologies could be used to capture some of the associated emissions. In addition, CO_2 produced during fermentation, which accounts for a portion of the life cycle emissions and is easier to capture than combustion flue streams (Kheshgi and Prince, 2005), could also be captured, further reducing total emissions. Cellulosic ethanol and Fischer-Tropsch (FT) biofuels, while not widely available today, could potentially be produced with almost no use of fossil energy. These biofuels are estimated to have low net emissions without CCS, assuming biomass is grown with no land-use-related emissions, and could potentially lead to net-negative emissions if coupled to CCS. Because of the greater mitigation potential of cellulosic ethanol and Fischer-Tropsch biofuels, these biofuel options are a key focus of the remainder of this paper.

For industrial applications, and production of liquid fuels, the production schedule is not dictated by the demand system, while electricity production must match demand in every instant, following seasonal patterns and daily fluctuations (Muratori et al., 2014). This reduces the constraints on the operation of CCS systems in these sectors, since the main industrial output (*e.g.* liquid fuel) can be more easily stored.

2.2. The global change assessment model

The Global Change Assessment Model (GCAM) is a community integrated assessment model (IAM) developed and maintained by Pacific Northwest National Laboratory at the Joint Global Change Research Institute (GCAM, 2016). GCAM is a dynamic-recursive economic model driven by assumptions about population and labour productivity that determine potential gross domestic product at 5 year time steps. It includes technology-rich representations of the economy, energy sector, and land use. GCAM is global in scope and the energy and economic systems are disaggregated into 32 geopolitical regions, explicitly linked through international trade in energy commodities, agricultural and forest products, and other goods and emissions permits. 283 land regions are included in the model. GCAM is linked to a climate model of intermediate complexity that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations, and accelerated deployment of energy technology.

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