Master of Science in Sustainability Science

SUSC Carbon Capture Utilization and Storage (CCUS)

Once per week, 4-6 PM
3 credits

Instructor: David Goldberg, Lamont Research Professor, Lamont-Doherty Earth Observatory
goldberg@ldeo.columbia.edu, (845) 365-8674

Response Policy: Available after class or via email for discussions.

Facilitator/Teaching Assistant: Yes

Course Overview

This course covers the technical and non-technical aspects of Carbon Carbon Utilization and Storage (CCUS), one of our most important and achievable tools to mitigate climate change. The course begins by presenting our global energy needs and the environmental motivation for CCUS and its natural analogues. We will review the basic concepts and methods involved in CO₂ capture, trapping, and monitoring, as well as established methods for modeling the fate of CO₂ in the subsurface. We will then consider the needs and implications of CO₂ capture from industrial sources (power plants) and directly from ambient air and examine current examples from around the world. We will go on to discuss integrating CCUS with renewable energy sources (negative emission) and ocean storage options. We will think through the challenges associated with CCUS, including the transportation of CO₂ to storage locations, regulations and incentives, and the public view and acceptance of this technology. The course will end with a discussion of where do we go from here to find pathways to a carbon neutral future. Each class will include a 10-minute student-led presentation and 10-minute student-led Q&A discussion about current news and developments in CCUS. Small student groups will also each assess a CCUS project and present to the class. The course grade will be based on these presentations, class participation, and a final exam.

At the conclusion of this course, each student will have gained a practical understanding of the potential for CCUS solutions to mitigate climate change and gain experience in presenting related technical and non-technical information to their peers. This will critically inform decision making and hone communication skills for future careers in fossil and renewable energy generation, power distribution, manufacturing, environmental policy, and scientific outreach. An undergraduate background in any field of science or engineering is required. This course is elective.

Learning Objectives

This course will focus on the scientific methods and tools, as well as the non-technical aspects, of CCUS that determine its application as critical means to mitigate climate change and offer a bridging technology between today’s energy usage and tomorrow’s carbon-neutral environment. Students completing the course will learn:

1. Basic understanding of the carbon cycle and technologies used for carbon mitigation
2. Common and novel approaches in carbon capture, both from point sources and from ambient air
3. Common and novel approaches for carbon storage, and the underlying physics and chemistry
4. Common uses for industrially sourced CO₂
5. Current news on global CCUS; student presentations and Q&A responses
6. How scientific tools used for a ‘geoengineering’ problem connect to socio-economic forces

Assignments and Evaluation

Class Participation (20%) (Learning Objectives 1-6)

Class participation, including oral communications, exercises important job skills. Weekly readings will be assigned and will help develop class discussions. Participation includes class attendance, contribution of questions, and active discussions in class. Classroom participation makes up 20% of the final grade.
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Student Presentations (20%) (Learning Objectives 5-6)

Each student will select a topic regarding global CCUS news from available resources, make a 10-minute presentation and lead a 10-minute Q&A discussion about current news and developments in CCUS. This provides a tool for students to explore new interests and builds their presentation abilities and receptiveness to open discussion about topical material in a rapidly evolving field. One or two topics will be presented per class, depending on the number of enrolled students. Individual student presentations make up 20% of the final grade.

Group Projects (20%) (Learning Objectives 1-6)

Small groups of 3-5 students will construct, develop, and present a research project regarding CCUS using the information and knowledge gained during the semester. Students will select a subject and approach, assess both technical and non-technical issues, consider available data and project constraints, and prepare an oral presentation (15 minutes) to be delivered to the class. Evaluation will be based on time management in the presentation, critical thinking about the subject, clarity of the assessment, and responses to questions. Group projects make up 20% of the final grade.

Final Exam (40%) (Learning Objectives 1-4, 6)

The final exam will be based on the topics covered during the semester, including background and methods, applications, technical assessment tools, and non-technical considerations for the implementation of CCUS in real and hypothetical projects. The final exam will be graded on a scale of 0-100 and make up 40% of the final grade.

Course Description and Lecture Topics (week-by-week course outline)

Week 1 Introduction/Carbon Cycle. The carbon cycle, and its impact on global warming. Carbon reservoirs and feedbacks. Why is the carbon cycle important? What is CCU/S? Sources for current CCU/S projects and recent developments; plan for weekly student presentations.


Week 3 Natural Analogues. Natural sources of CO₂ accumulations, onland uses. Long term carbon cycle and fate of CO₂ in the subsurface and ocean. Implications and potential for engineered systems.


Week 6 Monitoring, Measurement, and Verification. The importance of MMV for subsurface CCU/S. Methods and approaches, and their advantages/disadvantages, for leak detection, plume monitoring, and induced fracturing. Examples from Sleipner (Norway), Cascadia (US).

Week 7 Capture methods. Technical methods for carbon capture from fossil fuel plants, including solvent-based, membranes, and novel approaches. Direct air capture processes and technologies.
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Week 8 **Transportation.** Modes of CO₂ transport in an integrated energy system. Pipeline considerations and the formation of clathrates. Offshore transport options, shipping and the impact of source-sink distances. How can efficiencies in transportation be gained?

Week 9 **Utilization.** What can we make with captured CO₂? Key opportunities and factors in carbon recycling. CO₂ flooding for EOR/EGR. Technical approaches for syngas reforming, liquid fuel conversion, and electrolysis. Industrial uses for element and materials. Balancing production and storage.

Week 10 **NETs (negative emissions).** Integrating CCU/S with renewable energy to achieve global emission targets. Current NET options, and opportunities using CCU/S. Wind and geothermal power sources and storage options. Examples: CarbFix and Kerguelen.


Week 12 **Public acceptance.** Perceived barriers to CCU/S as an enabling solution. Addressing cost and technical issues. Addressing public opinion and communicating CCU/S. Examples: Ketzin (Germany), Quest (Canada)

Week 13 **Student group presentations.**

Week 14 **Final Exam**

**Selected Readings (specific chapters/papers per week)**

Course materials and assigned readings will draw on published papers and reports on CCUS and geoengineering from the IPCC WG5 and the NRC; recent and historical journal articles, conference proceedings, and current news and newsletters on the topic. The current list of course reading materials each week listed below.

**READINGS SUSC PS5350**

**Week 1 - Sept 3: The carbon cycle/Course introduction**


**Week 2 - Sept 10: Energy and Emissions**


Hansen, J; et al; 2013. Assessing "Dangerous Climate Change": Required reduction of carbon emissions to protect young people, future generations, and nature, PLOsone (online), [https://doi.org/10.1371/journal.pone.0081648](https://doi.org/10.1371/journal.pone.0081648)

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Week 3 - Sept 17: Natural Analogues
Fessenden, JE; Stauffer, PH; Viswanathan, HS; 2009. Natural Analogos of Geologic CO\textsubscript{2} sequestration: some general implications for engineered sequestration, In *Carbon Sequestration and its Role in the Global Carbon Cycle*. Geophysical Monograph, 183, 135-146, Am. Geophysical Union, McPherson, B; Sundquist, E. (eds), Washington DC

Week 4 - Sept 24: Geological Storage & Trapping
Zwiegel, P; Arts, R; Lothe, AE; Lundberg, EB; et al; 2004. Reservoir geology of the Utsira formation at the first industrial-scale underground CO\textsubscript{2} storage site (Sleipner, North Sea), In *Geological Storage of Carbon Dioxide*. Geological Society of London, Special Publications, 233, 165-180, London UK

Week 5 - Oct 1: Mineralization and modeling
Oelkers, EH; Gislason, SR; Matter, J; 2008. Mineral Carbonation of CO\textsubscript{2} , Elements, 4, 333–337, DOI: 10.2113/gselements.4.5.333
Power, I; Wilson, S; Dipple, G; 2013. Serpentinite Carbonation for CO\textsubscript{2} sequestration, Elements, 9, 115-121.

Week 6 - Oct 8: Monitoring, Measurement, and Verification
Monea, M; Knudsen, R; Worth, K; et al; 2009. Considerations for Monitoring, Verification, and Accounting for Geologic storage of CO\textsubscript{2} In *Carbon Sequestration and its Role in the Global Carbon Cycle*. Geophysical Monograph, 183, 303-316, Am. Geophysical Union, McPherson, B; Sundquist, E. (eds), Washington DC

Week 7 - Oct 15: Capture methods
Smit, B; Reimer, J; Oldenburg, C; Bourg, I; 2014. Introduction to Carbon Capture and Sequestration, Vol. 1, Ch. 4-7, Berkeley Lectures on Energy, Imperial College Press.
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Week 8 - Oct 22: Transportation
Haszeldine, RS; Zhou, D; Zhang, Y; 2014. Engineering Requirements for Offshore CO₂ Transportation and Storage: A Summary Based on International Experiences, Edinburgh Research Expl., UK-China (Guangdong) CCUS Centre, 1-58.

Week 9 - Oct 29: Carbon Utilization
Davis, SJ; Lewis, NS; Shaner, M; Aggarwal, S; et al; 2018. Net zero emissions energy systems, Science, 360, DOI: 10.1126/science.aas9793
De luna, P; Hahn, C; Higgins, D; Jaffer, SA; Jaramilla; Sargent, EH; 2019. What would it take for renewably powered electrosynthesis to displace petrochemical processes? Science, 364, DOI: 10.1126/science.aas3506
Park, A; et al., 2017. Mission Innovation - CO₂ utilization, Ch. 3. US DOE, Houston TX

Week 10 - Nov 12: Negative emissions

Week 11 - Nov 19: Regulations and Financial Aspects
Zapantis, A; Townsend, A; Rassool, D; 2019. Policy priorities to incentivize large scale deployment of CCS, Global CCS Institute (online), https://www.globalccsinstitute.com
Webb, RM; Gerrard, MB; 2019. Overcoming Impediments to offshore CO₂ storage: Legal issues in the United States and Canada. Environmental Law Institute, 49, 10634

Week 12 - Nov 26: Public acceptance