COLUMBIA UNIVERSITY
School of Professional Studies

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
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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 CO_2 capture, trapping, and monitoring, as well as established methods for modeling the fate of CO_2 in the subsurface. We will then consider the needs and implications of CO_2 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 CO_2 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 CO_2
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.

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 2 **Energy and Emissions.** Current sources of CO_2 emissions, energy generation and demand. Trends in fossil fuel use. What means are available to moderate CO_2 emissions? Carbon stabilization wedges and CCU/S opportunities. Sequence/timing of responses.

Week 3 **Natural Analogues.** Natural sources of CO_2 accumulations, onland uses. Long term carbon cycle and fate of CO_2 in the subsurface and ocean. Implications and potential for engineered systems.

Week 4 **Geological storage and Trapping.** Geological trapping. Solubility and Geochemical trapping. Uncertainties, risks and combined mechanisms. Assessing leakage through wells. Global carbon storage projects.

Week 5 **Mineralization and Modeling.** Flow and hydrological modeling. Reactive transport and injection modeling. The potential for long-term storage through mineralization. Upscaling in offshore settings.

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.

Week 8 **Transportation.** Modes of CO_2 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 CO_2? Key opportunities and factors in carbon recycling. CO_2 flooding for EOR/EGR. Technical approaches for syngas reforming, liquid fuel conversion, and electrolysis. Industrial uses for clement 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 11 **Regulations, Policy, and Financial Aspects.** The need for global energy use, climate mitigation, and regulation. CO_2 emission and GDP, costs of CCU/S implementation. Carbon pricing, discount rates, and the levelized cost of energy. Global policy, regulation, and investments.

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

Sundquist, ET; Ackerman, KV; Parker, L; 2009. An Introduction to Global carbon cycle management, in *Carbon Sequestration and its Role in the Global Carbon Cycle,* Geophys. Monograph Series 183, Am. Geophys. Union, 10.1029/2009GM000914

Kump, LR; Kasting, JF; Crane, RG; 2004. *The Earth System,* 2nd ed, Pearson Education, Inc., Upper Saddle River, NJ

Siegenthaler, U; Sarmiento, JL; 1993. Atmospheric carbon dioxide and the ocean, Nature, 365, 119-125.

Week 2 - Sept 10: Energy and Emissions

Pacala, S; Socolow, R, 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies, Science, 305, 968-972.

Hansen, J; Sato, M; 2004. Greenhouse gas growth rates, Proc. Nat. Acad, Sci., 101 (46), 16109-16114; https://doi.org/10.1073/pnas.0406982101

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

LeQuere, C; et al; 2018. Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, 2018 https://doi.org/10.5194/essd-10-2141-2018

Week 3 - Sept 17: Natural Analogues

Baines, SJ; Worden RH; 2004. The long-term fate of CO_2 in the subsurface: natural analogues for CO_2 storage, In *Geological Storage of Carbon Dioxide.* Geological Society of London, Special Publications, 233, 59-86, London UK

Fessenden, JE; Stauffer, PH; Viswanathan, HS; 2009. Natural Analogs of Geologic CO_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

Kelemen, PB; Matter, J; 2008. In situ carbonation of peridotite for CO_2 storage, Proc. Nat. Acad. Sci., 105, 17295-17300, www.pnas.org/cgi/doi/10.1073/pnas.0805794105.

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_2 storage site (Sleipner, North Sea), In *Geological Storage of Carbon Dioxide.* Geological Society of Lon don, Special Publications, 233, 165-180, London UK

Gunter, W; Bachu, S; Benson, S; 2004. The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide, In *Geological Storage of Carbon Dioxide.* Geological Society of London, Special Publications, 233, 129-145, London UK

US Dept of Energy; 2015. Carbon Storage Atlas, 5th edition, NETL, Office of Fossil Energy, https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf

Week 5 - Oct 1: Mineralization and modeling

Oelkers, EH; Gislason, SR; Matter, J; 2008. Mineral Carbonation of CO2 , Elements, 4, 333–337, DOI: 10.2113/gselements.4.5.333

Goldberg, DS; Takahashi, T; Slagle, AL; 2008. Carbon dioxide sequestration in deep-sea basalt. *Proc. Nat. Acad. of Sci* 105, 9920-9925.

Power, I; Wilson, S; Dipple, G; 2013. Serpentinite Carbonation for CO_2 sequestration, Elements, 9, 115-121.

Gislason, SR; Oelkers,EH; 2014. Carbon storage in basalt. *Science*, *344*(6182), 373-374.

Week 6 - Oct 8: Monitoring, Measurement, and Verification

Arts, R; Eiken, O; Chadwick, A; Zweigel, P; van der Meer, B; Kirby, G; 2004. Seismic monitoring at the Sleipner underground CO_2 storage site, In *Geological Storage of Carbon Dioxide.* Geological Society of London, Special Publications, 233, 181-191, London UK

Monea, M; Knudsen, R; Worth, K; et al; 2009. Considerations for Monitoring, Verification, and Accounting for Geologic storage of CO_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

Zoback, MD; Gorelick, SM; 2012. Earthquake triggering and large-scale geoloica storage of carbon dioxide, Proc. Nat. Acad. Sci, 109-26, www.pnas.org/cgi/doi/10.1073/pnas.1202473109

Week 7 - Oct 15: Capture methods

Lackner, K; 2010. Washing carbon out of the air, Scientific American, **302** (6), 48–53 doi:10.1038/scientificamerican0610-66.

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.

Svalestuen, J; et al., 2017. Mission Innovation - CO_2 capture, Ch. 2. US DOE, Houston TX https://www.energy.gov/fe/downloads/accelerating-breakthrough-innovation-carbon-capture-utilization-and-storage

Week 8 - Oct 22: Transportation

Haszeldine, RS; Zhou, D; Zhang, Y; 2014. Engineering Requirements for Offshore CO_2 Transportation and Storage: A Summary Based on International Experiences, Edinburgh Research Expl., UK-China (Guangdong) CCUS Centre, 1-58.

Zammerilli, A; Wallace, B; 2015. A review of the CO2 pipeline infrastructure in the US, DOE/NETL-2014/1681 , www.netl.doe.gov.

Goldberg, DS; Aston, L; Bonneville, A; et al; 2018. Geological storage of CO_2 in sub-seafloor basalt: the CarbonSAFE pre-feasibility study offshore Washington State and British Columbia, *International Carbon Conf. 2018*, Reykjavik, IS

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 - CO_2 utilization, Ch. 3. US DOE, Houston TX https://www.energy.gov/fe/downloads/accelerating-breakthrough-innovation-carbon-capture-utilization-and-storage

National Academies of Sciences, 2019. *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*. Washington, DC: https://doi.org/10.17226/25232.

Week 10 - Nov 12: Negative emissions

Minx, JC; Lamb, WF; Callaghan, MW, et al; Negative emissions- research landscape and sysnthesis, Environ. Res. Lett. **13** (2018) 063001 https://doi.org/10.1088/1748-9326/aabf9b

Fuss, S; Lamb, WF; Callaghan, MW, et al; Negative emissions- costs, potentials, and side effects, Environ. Res. Lett. **13** (2018) 063002 https://doi.org/10.1088/1748-9326/aabf9f

National Academies of Sciences, 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: https://doi.org/10.17226/25259.

Week 11 - Nov 19: Regulations and Financial Aspects

Socolow, R; Pacala, S; 2006. A plan to keep carbon in check, Scientific American, www.sciam.com, 50-57.

IPCC, 2018: Summary for Policymakers. *In:* Global Warming of 1.5°C – IPCC Special Report. World Meteorological Organization, Geneva, Switzerland, 32 pp., https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/

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

Krupp, F; Keohane, N; Pooley, E; 2019. Less than zero, Foreign Affairs, 98-2, 142-153.

Szizybalski, A; Kollersberger, T; Möller, F; Martens, S; Liebscher, A; Kühn, M; 2014. Communication supporting the research on CO2 storage at the Ketzin pilot site, Germany – a status report after ten years of public outreach, Energy Procedia 51, 274 – 280, www.sciencedirect.com, doi: 10.1016/j.egypro.2014.07.032

New Carbon Economy Consortium, 2018. Build a new carbon economy, Carbon180, https://carbon180.org/newcarboneconomy