COLUMBIA UNIVERSITY
School of Professional Studies

Master of Science in Sustainability Science

SUSC Carbon Capture Utilization and Storage (CCUS)

Once per week, Thurdays 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 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 5-10 minute student-led presentations and 5-10 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 mid-term and final exams.

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 (15%) (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 15% of the final grade.

Student Presentations (15%) (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 15% of the final grade.

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

Small groups of 2 students each 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 (5-10 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.

Mid-term and Final Exams (20/30%) (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 exams will be graded on a scale of 0-100 and make up 50% of the final grade.

Course Description and Lecture Topics (approximate 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, on-land 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, Reporting, 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 **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 DAC Hubs.

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 **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 11 **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 12 **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?

Weeks 12-13 **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, NRC; recent and historical journal articles, conference proceedings, and current news and newsletters on the topic. Current course reading materials are listed below. Note that readings will be posted on *Courseworks* and may be updated during the semester.

READINGS SUSC PS5350

Class 1: The carbon cycle/Course introduction

***Kump**, LR; Kasting, JF; Crane, RG; 2004. *The Earth System,* 2nd ed, Pearson Education, Inc., Upper Saddle River, NJ
Harvey, C, K House, Every Dollar Spent on This Climate Technology Is a Waste, *NYT Opinion*, 16 Aug 2022
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. AGU Monograph Series 183, 10.1029/2009GM000914
Siegenthaler, U; Sarmiento, JL; 1993. Atmospheric carbon dioxide and the ocean, *Nature,* 365, 119-125.
Zickfeld, Z; Azevedo, D; Mathesius, S; Matthews, DH, 2021. Asymmetry in the climate–carbon cycle response to positive and negative CO_2 emissions, *Nature Climate Change,* https://doi.org/10.1038/s41558-021-01061-2.
Eglinton, T; Galyb, V; Hemingway, JD; et al., 2021. Climate control on terrestrial biospheric carbon turnover, *Proc. Nat. Acad, Sci.,* https://doi.org/10.1073/pnas.2011585118

Class 2: 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.
Davis, SJ *et al;* 2013. Rethinking Wedges, *Environ. Res. Lett.* 8, 011001, https://iopscience.iop.org/article/10.1088/1748-9326/8/1/011001/pdf
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

Class 3: 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.

Class 4: Geological Storage & Trapping

***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

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

Socolow, R, 2005. Can we bury global warming? *Scientific American,* 49-55.

Ajayi, T., Gomes, J. S., Bera, A.,2019. A review of CO_2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches, *Petroleum Science* 16:1028–1063 https://doi.org/10.1007/s12182-019-0340-8

Class 5: Mineralization and modeling

***Snæbjörnsdóttir**, et al; 2020. Carbon dioxide storage through mineral carbonation, *Nature Review*

Oelkers, EH; Gislason, SR; Matter, J; 2008. Mineral Carbonation of CO_2, Elements, 4, 333–337, DOI: 10.2113/gselements.4.5.333

Raza, A., et al., 2022. Carbon mineralization and geological storage of CO_2 in basalt: Mechanisms and technical challenges, *Earth Sci Reviews*

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.

DePaulo, D, et al; 2021. Opportunities for large-scale CO_2 disposal in coastal marine volcanic basins based on the geology of northeast Hawaii, *Int’l J Greenhouse Gas control, 110,* https://doi.org/10.1016/j.ijggc.2021.103396

Class 6: Monitoring, Reporting, and Verification

***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

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

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

Arcusa, S.H., 2022. Why should I trust you (sequestration)? Robust certification schemes crucial to carbon sequestration. I-WEST, blog. https://iwest.org/certification-of-carbon-sequestration/

Class 7: 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*.

Diederichsen, K., R. Sharifian, J. F. Kang, Y. Liu, S. Kim. B. Gallant, D. Vermaas, T. A. Hatton, 2022. Electrochemical methods for carbon dioxide separations, Nature Reviews 2:68, www.nature.com/nrmp

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

McQueen, et al. 2021. A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, *Prog. Energy,* **3** 032001, https://doi.org/10.1088/2516-1083/abf1ce.

Class 8: Negative emissions

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

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

Anderson & Peters, 2019. *The trouble with negative emissions, Science,* 354:6309*,* http://science.sciencemag.org/,

and **Lackner et al.,** 2019. The promise of negative emissions, *Science,* 354:6313, http://science.sciencemag.org/

Uden, S, P. Dargusch, C Greig, 2021. Cutting through the noise on negative emissions, *Joule* 5, 1956–1970.

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

Class 9: 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

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

Class 10: Regulations and Financial Aspects

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

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 CO_2 storage: Legal issues in the United States and Canada. *Environmental Law Institute,* 49, 10634

Bordoff, 2017. Trump vs. Obama on the Social Cost of Carbon – and Why It Matters, *Wall Street Journal,* Opinion

McLaren DP, Tyfield DP, Willis R, Szerszynski B and Markusson N, 2019. Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions. *Frontiers Clim.* 1:4. doi: 10.3389/fclim.2019.00004

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/

Class 11: Public acceptance

***Pinkola,** et al, 2017. Integrated sustainability assessment of CCS – Identifying non- technical barriers and drivers for CCS implementation in Finland, *Energy Procedia* 114, 7625 – 7637

Szizybalski, A; Kollersberger, T; Möller, F; Martens, S; Liebscher, A; Kühn, M; 2014. Communication supporting the research on CO_2 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

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

Sparkman, G., N. Geiger, E. Weber, 2022. Americans experience a false social reality by underestimating popular climate policy support by nearly half, *Nature Communications* 13:4779, https://doi.org/10.1038/s41467-022-32412-y

Coan, T., C. Boussalis, J. Cook, M. Nanko, 2021. Computer-assisted classification of contrarian claims about climate change, *Nature Portfolio* 11:22320, https://doi.org/10.1038/s41598-021-01714-4

Class 12: 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 CO_2 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

Schmelz WJ, Hochman G, Miller KG. 2020. Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States. *Interface Focus* 10: 20190065. http://dx.doi.org/10.1098/rsfs.2019.0065

Master of Science in Sustainability Science

Goldberg, D., K. Lackner, P. Han, A. Slagle, and T. Wang, 2013. Co-Location of Air Capture, Subseafloor CO_2 Sequestration, and Energy Production on the Kerguelen Plateau, *Environ. Sci. Technol.* 47, 7521−7529, dx.doi.org/10.1021/es401531y

School and University Policies and Resources

Copyright Policy

Please note—Due to copyright restrictions, online access to this material is limited to instructors and students currently registered for this course. Please be advised that by clicking the link to the electronic materials in this course, you have read and accept the following:

> The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted materials. Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

Academic Integrity

Columbia University expects its students to act with honesty and propriety at all times and to respect the rights of others. It is fundamental University policy that academic dishonesty in any guise or personal conduct of any sort that disrupts the life of the University or denigrates or endangers members of the University community is unacceptable and will be dealt with severely. It is essential to the academic integrity and vitality of this community that individuals do their own work and properly acknowledge the circumstances, ideas, sources, and assistance upon which that work is based. Academic honesty in class assignments and exams is expected of all students at all times.

SPS holds each member of its community responsible for understanding and abiding by the SPS Academic Integrity and Community Standards posted at https://sps.columbia.edu/students/student-support/academic-integrity-community-standards. You are required to read these standards within the first few days of class. Ignorance of the School's policy concerning academic dishonesty shall not be a defense in any disciplinary proceedings.

Diversity Statement

It is our intent that students from all diverse backgrounds and perspectives be well-served by this course, that students' learning needs be addressed both in and out of class, and that the diversity that the students bring to this class be viewed as a resource, strength and benefit. It is our intent to present materials and activities that are respectful of diversity: gender identity, sexuality, disability, age, socioeconomic status, ethnicity, race, nationality, religion, and culture.

Accessibility

Columbia is committed to providing equal access to qualified students with documented disabilities. A student's disability status and reasonable accommodations are individually determined based upon disability documentation and related information gathered through the intake process. For more information regarding this service, please visit the University's Health Services website: https://health.columbia.edu/content/disability-services.

Class Recordings

All or portions of the class may be recorded at the discretion of the Instructor to support your learning. At any point, the Instructor has the right to discontinue the recording if it is deemed to be obstructive to the learning process.

If the recording is posted, it is confidential and it is prohibited to share the recording outside of the class.

SPS Academic Resources

The Division of Student Affairs provides students with academic counseling and support services such as online tutoring and career coaching: https://sps.columbia.edu/students/student-support/student-support-resources.

Master of Science in Sustainability Science

Columbia University Information Technology

Columbia University Information Technology (CUIT) provides Columbia University students, faculty and staff with central computing and communications services. Students, faculty and staff may access University-provided and discounted software downloads.

Columbia University Library

Columbia's extensive library system ranks in the top five academic libraries in the nation, with many of its services and resources available online.