COLUMBIA UNIVERSITY
School of Professional Studies

Master of Science in Sustainability Science

SUSC PS5120, Technology of Renewable Energy
Thursdays, 6:10pm – 8:00pm, Fall 2020 (Sept 10 – Dec 17)
Number of credits: 3

Instructor:	Jonathan Hollander, PhD; Lecturer, School of Professional Studies jh4249@columbia.edu; 347.649.7585
Office Hours:	By appointment. I will also be available after class on Thursdays from 8:00pm.
Response Policy:	I will respond to emails and text messages within 24 hours. I will be available over the weekends to answer questions, if necessary. My preferred method of discussing substantive issues is a phone call.

Course Overview

Renewable energy is generated from natural processes that are continuously replenished. Solar and geothermal are examples of primary energy sources, while wind and wave power are secondary and tertiary energy sources resulting from atmospheric interactions with primary sources such as solar. In order to have a sustainable environment and economy we must reduce (and eventually stop) emitting CO_2 into the atmosphere. This requires that the fossil fuel based technologies underlying our present electricity generation and transportation systems be replaced by renewable energy. In addition, the transition to renewable technologies will move nations closer to energy independence and thereby reduce geopolitical tensions associated with energy trading.

This course begins with a review of the basics of electricity generation and the heat engines that are the foundation of our current energy systems. Here we will emphasize the inherent inefficiency associated with the conversion of thermal energy to electrical and mechanical energy. The course then covers the most important technologies employed to generate renewable energy. These are hydroelectricity, wind, solar thermal, solar photovoltaic, geothermal, biomass/biofuel and tidal power. In each case, we will answer four questions:

- How does the technology work? [We will look at the technical advantages of each technology as well as the limits imposed by geology, geography and the energy density of the source.]
- How much energy does it generate today? [We will look at data gathered by the U.S. Energy Information Administration, the National Renewable Energy Laboratory and the International Energy Agency.]
- What is the potential for growth in the future? [Are important technical/scientific breakthroughs necessary or is the technology limited by cost and/or public policy issues.]
- How does it compare on a cost basis to conventional energy generating methods? [We will estimate the direct levelized cost of the energy generated and also indirect costs associated with land use and possible environmental damage.]

The course ends with a description of energy storage technologies, energy markets and possible pathways to a renewable energy future.

A student who has completed this course will be able to work either for companies that deploy renewable energy systems or for government agencies that license and regulate energy providers. They will be able to contribute at the interface between technology development, energy supply management, and energy policy.

The class requires an undergraduate background that includes a year of physics and chemistry. Concepts presented in the course require strong analytical understanding of our environment and materials science.

This is an elective course and is approved to satisfy “Area 4 – Scientific Tools for Responding to Sustainability Challenges” curriculum area requirement for the M.S. in Sustainability Science program.

Master of Science in Sustainability Science

Learning Objectives

By the end of this course, students will:

L1. Describe the principles of physics and chemistry that control our present and future energy generation and transmission systems.
L2. Be able to evaluate the potential for growth of a proposed renewable energy technology.
L3. Be able to compare the strengths and weaknesses of renewable energy to those of other carbon free sources of energy – e.g., nuclear fission.
L4. Be able to participate in the siting of renewable energy installations – e.g., off-shore wind, solar thermal and solar photovoltaic.
L5. Be able to evaluate claims made regarding the intermittency of renewable energy and the role of emerging energy storage technologies.

Readings

The following books will be placed on reserve at the library. They describe the principles of renewable energy. In addition, papers that describe aspects of the energy technology studied each week will be provided as pdfs.

1. Armstrong, Robert, Forsberg, Charles and Golay, Michael, "The MIT Low-Carbon Energy Economy Workshop, Final Report", http://energy.mit.edu/wp-content/uploads/2016/05/LCW-Final-Report_v4- Affliation-changed.pdf, 2015.
2. Boyle, Godfrey, "Renewable Energy, Power for a Sustainable Future", Second Edition, Oxford University Press, 2004.
3. Demirel, Yasar, "Energy: Production, Conversion, Storage, Conservation and Coupling", Second Edition, Springer, 2016.
4. Dunlap, Richard, "Sustainable Energy", Cengage Learning, 2015.
5. Jaffe, Robert L. and Taylor, Washington, "The Physics of Energy", Cambridge University Press, 2017.
6. Jenkins, Nicholas and Ekanayake, Janaka, "Renewable Energy Engineering", Cambridge University Press, 2017.
7. MacKay, David J. C., "Sustainable Energy – Without the Hot Air", UIT Cambridge Ltd., 2009.
8. O'Sullivan, Meghan, Overland, Indra and Sandalow, David, "The Geopolitics of Renewable Energy", http://energypolicy.columbia.edu/sites/default/files/CGEPTheGeopoliticsOfRenewables.pdf, 2017.
9. Perez-Arriaga, Ignacio and Knittel, Christopher, "The Utility of the Future", http://energy.mit.edu/research/utility-future-study/, 2016.
10. Prentiss, Mara, "Energy Revolution – The Physics and the Promise of Efficient Technology", The Belknap Press of the Harvard University Press, 2015.
11. Wolfson Richard, "Energy, Environment, and Climate", Second Edition, W. W. Norton, 2008.

Resources

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: https://library.columbia.edu/.

SPS Academic Resources
The Office of Student Affairs provides students with academic counseling and support services such as online tutoring and career coaching: http://sps.columbia.edu/student-life-and-alumni-relations/academic-resources.

Course Requirements (Assignments)

You will be evaluated on four elements integral to the course: (1) problem sets that demonstrate understanding of particular classroom concepts, (2) discussion board contributions, (3) final paper and presentation, and (4) class participation.

Problem sets: Most weeks, students will have an assignment comprised of quantitative problems and 'short answer' essay questions. The assignment must be completed within one week and submitted via Canvas prior to the start of the following week's class. The quantitative problems will support Learning Objectives L1, L2, and L4, while the essay questions will support L1, L3, and L5.

Discussion boards: The field of renewables is ever evolving and projects are going up all over the world at an incredible pace. Newspapers, magazines, and internet media organizations cover noteworthy developments in the industry. Each student is required to post two articles to the Canvas discussion board along with a 1-2 paragraph written take-away. Examples of an article topic: a new technology in R&D, a renewables project proposed / being built / operating, community impacts, etc. Your post should not merely summarize the article, but expand upon it; for example: what are the implications, what is the likelihood of success, what technical features are represented and are they a departure from the norm, what are the economics of a project? Additionally, you will be responsible for responding to two of your classmates' posts. Read the original article and any posted discussion, and then contribute 1-2 paragraphs of your own analysis as a reply. In short, your deliverables are:

1. Keep current on industry news by reading from your preferred sources.
2. Twice during the semester, post a link to an article that interests you on the Canvas discussion board.
3. Write 1-2 paragraphs along with your links that go beyond the information presented in the article.
4. Summarize the article in ~1 minute at the top of the next class session (see "Class participation" below).
5. Read your fellow classmates' posts and select two discussions to contribute an additional 1-2 paragraph analysis.

Final paper and presentation: Each student should select a topic/problem related to renewable energy whose resolution requires both technical and economic analysis. Project topic proposals should be submitted by November 12 for faculty review and approval. Example topics include: successful integration of wind power and high-voltage DC transmission, an upper estimate of solar thermal power generation for California, and flow batteries for grid scale energy storage.

Your consideration of this topic will culminate in a written report due on December 3 and an in-class presentation split between class on December 10 & 17. The paper will be no more than 10 pages in length. Your analysis should include the following elements: (1) the scope of the problem, (2) how the renewable technology compares to conventional energy generation in terms of cost and climate impact, and (3) proper citation of the scientific/technical literature. The last two scheduled class sessions will feature a brief presentation from each student based on their project, limited to 8 minutes plus 4 additional minutes Q&A.

Class participation: You are expected to listen attentively and engage during class. The quality of your participation is judged by whether it breaks new ground or elevates the discussion. You should pull from your personal experience or outside readings. You will be expected to summarize your two discussion board posts at the beginning of the following class.

Because of the importance of class participation, your attendance is required. If the instructor is not informed about the circumstances of an absence, it will be considered unexcused and penalized by 1% of your final grade for each absence.

Evaluation/Grading

In each of the above, you will be graded along four dimensions: (1) the analytical diligence with which you have formulated your ideas, (2) the creativity of your ideas, (3) a demonstration of your learning and progress that has occurred throughout the semester, and (4) the quality with which you present your idea both written and oral.

The final grade will be calculated as described below:

FINAL GRADING SCALE

Grade	Percentage
A+	98–100 %
A	93–97.9 %
A-	90–92.9 %
B+	87–89.9 %
B	83–86.9 %
B-	80–82.9 %
C+	77–79.9 %
C	73–76.9 %
C-	70–72.9 %
D	60–69.9 %
F	59.9% and below

ASSIGNMENT	% Weight
Problem sets	40%
Discussion boards	20%
Final paper and presentation	35%
Class participation	5%

Course Policies

Participation and Attendance
You are expected to complete all assigned readings, attend all class sessions, and engage with others in online discussions. Your participation will require that you answer questions, defend your point of view, and challenge the point of view of others. If you need to miss a class for any reason, please discuss the absence with me in advance.

Late work
Work that is not submitted on the due date noted in the course syllabus without advance notice and permission from the instructor will be graded down 1/3 of a grade for every day it is late (e.g., from a B+ to a B).

Citation & Submission
All written assignments must cite sources and be submitted to the course website (not via email).

School Policies

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 http://sps.columbia.edu/student-life-and-alumni-relations/academic-integrity-and-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.

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/services/ods/support.

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 considered confidential and it is not acceptable to share the recording outside the purview of the faculty member and registered class.

Master of Science in Sustainability Science

Course Schedule/Course Calendar

Guest lecturers will join our class periodically throughout the semester. These may include technologists, entrepreneurs, and energy regulators.

Date	***Key Theme*** **Addressed Topics and Activities**	**Readings and Evaluations (due at class date listed)**
Sept 10	*Energy and power: concept overview* Current energy generation and demand; measuring energy and power. Primary energy sources, their energy density and CO_2 emissions.	Dunlap – Ch. 1.1, 1.2 Boyle – Ch. 1.1, 1.2, 1.3 Wolfson – Ch. 1 & 2 Jenkins & Ekanayake – Ch. 1
Sept 17	*Electricity generation and transmission* Energy production and transport over the grid. Transformers and their role in high voltage transmission. Trade-offs between AC and DC transmission.	Dunlap – Ch. 1.3, 1.6 Wolfson – Ch. 3 Jenkins & Ekanayake – Ch. 10 Problem Set 1
Sept 24	*Thermodynamics and heat engines* The first and second laws of thermodynamics; internal energy, heat, and work. Energy transfer by conduction, convection, and radiation. The importance of phase transitions in heat engines. Efficiency of heat engines and heat pumps. Co-generation and combined cycle power generation.	Dunlap – Ch. 1.4, 1.5 Boyle – Ch. 1.1, 2.9 Wolfson – Ch. 4 & 5 Problem Set 2
Oct 1	*Hydropower* The historical growth and global distribution. Orographic precipitation in different climate zones. The advantages of different turbine designs (e.g., impulse vs. reaction). Flow-of-river and reservoir based systems.	Dunlap – Ch. 11 Boyle – Ch. 5 Wolfson – Ch. 10.1 Jenkins & Ekanayake – Ch. 3 Problem Set 3
Oct 8	*Wind power* Growth and global distribution of wind power. The physics, distribution and seasonality of wind in the atmosphere. The design of airfoils – drag and lift. The design of wind turbines. The efficiency and siting of wind turbines. Wind variability and forecasting. Integrating wind power into the grid. On-shore vs off-shore wind farms. Civil resistance to wind power.	Dunlap – Ch.10 Boyle – Ch. 7.1 – 7.9 Wolfson – Ch. 10.2 Jenkins & Ekanayake – Chapter 2 Problem Set 4

Oct 15	*Solar thermal and concentrating heat* Solar radiation and the available solar resource. Stefan-Boltzmann and Planck laws. Measuring insolation. Heat trapping and radiative balance. Low and medium temperature solar collectors. Concentrating solar energy with solar troughs and towers. Estimating the capacity factor for solar thermal power plants.	Dunlap – Ch. 9.1, 9.2 Boyle – Ch. 2 Wolfson – Ch. 9.1 – 9.4 Jenkins & Ekanayake – Ch. 4 & 6 Problem Set 5
Oct 22	*Solar photovoltaics* Electron energy bands in semiconductors, doping, and p-n junctions. Principles of generating an electric current in a Si cell. I-V characteristics for a single solar cell and for multi-cell combinations.	Dunlap – Ch. 9.3 – 9.5 Boyle – Ch. 3 Wolfson – Ch. 9.5 – 9.8 Jenkins & Ekanayake – Ch. 5 Problem Set 6
Oct 29	*Biomass power and biofuels* C3 and C4 photosynthesis and the natural conversion of sunlight to biomass. Monosaccharides, disaccharides, and complex carbohydrates. Global food production and land use. The importance of nitrogen fixing and fertilizers. The Net Energy Balance (NEB) of biomass and biofuels.	Dunlap – Ch. 16 Boyle – Ch. 4 Wolfson – Ch. 10.3 Jenkins & Ekanayake – Ch. 8 Problem Set 7
Nov 5	*Ocean kinetics and geothermal power* Devices for generating power from the hydrokinetics of oceans, including currents, waves, and tides. Heat transfer in the earth. Ground source heat pumps. Hydrothermal, geo-pressured and enhanced geothermal energy systems: current status and future prospects.	Dunlap – Ch. 13 & 15 Boyle – Ch. 6 & 9 Wolfson – Ch. 8 Jenkins & Ekanayake – Ch. 7 Problem Set 8
Nov 12	*Energy storage and power recovery* Pumped hydro and compressed gas storage. Mechanical (flywheels) and electrochemical (batteries and fuel cells) storage. Storage as an enabling component of the renewable energy landscape.	Dunlap – Ch.18 Wolfson – Ch. 11 Jenkins & Ekanayake – Ch. 10.8 Problem Set 9 **Final paper proposal**
Nov 19	*Energy economics* The 'Overnight' cost of power plant construction vs. the levelized cost of power. Wholesale electricity markets – the uniform clearing price. Investing in energy projects – the discount rate, payback time, and the project's Net Present Value.	Jenkins & Ekanayake – Ch. 1 & 9 Boyle – Ch. 10.7 & Appendix A1

Dec 3	*Charting a path to zero-carbon* Reducing carbon emissions in electricity generation and transportation. Does the concept of "baseload power" still make sense? The role of nuclear energy in a low carbon environment. Pricing carbon.	Dunlap – Ch. 21 Boyle – Ch. 10 Wolfson – Ch. 15 & 16 **Final paper due (10 pg. max)**
Dec 10	*Innovating the future* Technological research, development, and deployment. The role of universities, startups, and multinationals. Policy enablers. Leapfrogging conventional energy production.	Catch-up on missing assignments / readings.
Dec 17	**Final Presentations**	