SUSTAINABLE ENERGY SYSTEMS

(EAS 574/PUBPOL 519/ESENG 599/RCNSCI 419)
Fall Term 2019
SYLLABUS

Time	Tuesday and Thursday, 2:30 – 4:00 pm
Location	1040 Dana Bldg.
Instructor	**Greg Keoleian** Peter M. Wege Professor of Sustainable Systems Professor, Sustainable Systems, School for Environment and Sustainability Professor, Civil and Environmental Engineering Director, Center for Sustainable Systems
Office	3504 Dana Bldg.
Phone	764-3194
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Office Hrs	Tuesday and Thursday, 4:00 – 5:00 pm or by appointment
Graduate Student Instructors	**Ellen Abrams, egabrams@umich.edu** *Optional Recitation*: Wednesday 6:00 – 7:00 pm in 3552 Dana *Office Hours*: Monday 3:00 – 5:00 pm in 3552 Dana and Wednesday 5:00 – 6:00 pm in 3552 Dana **Nate Hua, nhua@umich.edu** *Optional Recitation*: Tuesday 6:00 – 7:00 pm in 3552 Dana *Office Hours*: Tuesday 7:00 – 8:00 pm in 3552 Dana and Wednesday 1:00 – 3:00 pm in 3012 Dana

DESCRIPTION

This course examines the production and consumption of energy from a systems perspective **to accelerate sustainable energy transformations**. Sustainability is examined by studying global and regional environmental impacts, economics, energy efficiency, consumption patterns and energy policy. First, the physics of energy and energy accounting methods are introduced. Next the current energy system that encompasses supply (resource extraction, conversion processes) and demand (end-uses) is covered. Strategies and interventions to address climate change and other sustainability challenges are explored in depth with an emphasis on emerging renewable energy technologies (e.g., biomass, wind, and photovoltaics), building technologies, alternative vehicle technologies, and end-use efficiency and conservation.

This is an interdisciplinary course that integrates the following analytical tools for advancing energy sustainability:
- Technology Assessment
- Economic and Policy Analysis
- Energy Analysis and Environmental Sustainability Assessment

Students from SEAS, Engineering, Public Policy, Business, and other fields provide important perspectives useful for transforming energy systems to enhance sustainability.

LEARNING OBJECTIVES

- **Characterize current and future states** for energy supply and demand (trends, challenges, opportunities, projections) **from technology, policy, business, and sustainability perspectives**
  - Energy supply: fossil, nuclear, renewables (wind, solar, biomass, geothermal, tidal, wave)
  - Energy demand: mobility, commercial and residential buildings, industry
- **Develop energy models** for energy supply and demand technologies and sectors
  - Resource assessment and siting of renewable technologies
  - Energy systems analysis of end use sectors
- **Evaluate the sustainability performance** of the current and future energy systems, technologies and use patterns
  - Apply analytical tools (model life cycle energy, carbon emissions, levelized cost, cost of conserved energy, etc.) to explore technologies and pathways for a sustainable energy future
  - Examine alternative and disruptive technologies (e.g., connected and automated vehicles, smart buildings, energy storage)
- **Analyze strategy and policy** to promote sustainable energy transformations
  - Identify key business strategies and government policies influencing energy supply and demand
  - Recommend key market and policy levers for accelerating energy transformations

FORMAT

Learning in this course is facilitated through lecture, case studies and discussions, readings, in class exercises, assignments, field trips, and term projects. Analytical skills are developed and demonstrated through problem sets, a term project and the mid-term and final exams. Required readings on canvas reinforce topics and concepts covered in lecture; reference materials on Canvas (optional reading) include supplemental articles, reports, data and web sites. Class participation is a key element of the course and critical analysis and discussion of course topics is expected in class and through the blog.

COURSE RESOURCES

1. **Course readings and other reference are available on Canvas**: https://umich.instructure.com/
2. **Key energy websites:**

a. US Department of Energy, Energy Information Administration: http://www.eia.doe.gov/
b. International Energy Agency: http://iea.org/
c. US DOE Office of Energy Efficiency and Renewable Energy (EERE) http://energy.gov/eere/office-energy-efficiency-renewable-energy
d. Renewable Energy World News and Network: http://www.renewableenergyworld.com/
e. OpenEnergyInfo Gateway to world energy information/ data http://en.openei.org/wiki/Main_Page

COURSE OUTLINE

Part A. Introduction and Energy Fundamentals

1. Sustainability challenges and opportunities (Sept 3)
2. Physics of energy (Sept 5)

Part B. Energy and Carbon Accounting

3. Energy accounting I: EIA convention (Sept 10)
4. Energy accounting II. LCA convention (Sept 12)
5. Energy growth analysis and carbon accounting (Sept 17)

Part C. Energy Supply

6. Fossil energy resources (Sept 19)
7. Electricity from fossil resources (Sept 24)
8. Electricity from nuclear fuels and other generating systems (Sept 26)
9. Electricity: Power Plant Economics and Regulation (Oct 1)

Part D. Energy Demand

10. Industrial and Commercial Sectors (Oct 3)
11. Residential Sector (Oct 8)
12. Transportation Sector (Oct 10)

MIDTERM (Oct 17)

Part E. Renewable Energy Technologies and Policy

13. Introduction renewable energy technologies and policy (Oct 22)
14. Wind energy (Oct 24)
15. Hydropower, Marine and Geothermal (Oct 29)
16. Solar energy (Oct 31)
17. Biomass: electricity (Nov 5)
18. Biomass: transport fuels (Nov 7)

Part F. Other Emerging Sustainable Energy Technologies and Policy

19. Which option? Electric Vehicles (EV), Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) or Fuel Cell Vehicles (FCV) (Nov 12)
20. Building technologies and policy (Nov 14)
21. Storage technologies: electricity storage and carbon storage (sequestration) (Nov 19)

PART G. Course Synthesis

22. Climate science: global energy balance (Nov 21)
23. Climate mitigation and policy (Nov 26)
24. Term project posters (Dec 3 and 5)
25. Course review (Dec 10)
26. Optional review session: Q/A format (Dec 11; first study day)

FINAL EXAM (Dec 13)

PART A. INTRODUCTION AND ENERGY FUNDAMENTALS

Sept. 3 **1. Sustainable Energy Systems: Issues for the 21st century**

What are the critical challenges for a sustainable energy future?
Sustainable energy systems: definitions, indicators
Key energy stakeholders
Levers: conservation, efficiency, investments, divestments
Course objectives

Reading(*)

UN Sustainable Development Goals (SDG 7 – Energy)
https://sustainabledevelopment.un.org/sdg7
https://www.iea.org/weo/weomodel/sds/

Global Energy Assessment Toward a Sustainable Future Key Findings Summary for Policymakers Cambridge University Press xii – xviii.
http://www.iiasa.ac.at/Research/ENE/GEA/doc/GEA-Summary-web.pdf

Energy Technology Perspectives: Catalyzing Energy Transformations, Executive Summary. IEA 2017. (browse)
https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2017ExecutiveSummaryEnglishversion.pdf

References (**) Chu, S. and A. Majundar "Opportunities and Challenges for a Sustainable Energy Future" *Nature* (2012) 488.7411: 294-303. (browse)

Building a Sustainable Energy Future National Science Foundation (2009)
http://www.nsf.gov/nsb/publications/2009/comments_se_report.pdf

Energy for the Poor: Underpinning the Millennium Development Goals Department for International Development, United Kingdom, August 2002.
https://www.iatp.org/documents/energy-for-the-poor-underpinning-the-millennium-development-goals

Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. National Academy of Sciences 2010. overall conclusions and recommendations; full book

Sustainable Energy for All
Overview
http://www.se4all.org/sites/default/files/l/2014/12/fp_se4all_overview.pdf
Tracking Progress:
https://www.seforall.org/sites/default/files/2019-05/TrackingSDG7_execsum-2019.pdf

NOTES:
(*) Readings are available on CANVAS both through PAGES and FILES/A. RESOURCES
(**) REFERENCES are not required readings; they are additional resources that may be useful.

Sept. 5 **2. Physics of Energy: Laws of Thermodynamics**

Energy Forms and Conversion
First and Second Laws and Efficiencies
Devices: Heat Engines, Refrigerators and Heat Pumps
Instantaneous and Average Power

Reading

Chapter 2: The Physics of Energy, Ross, M.

References

Principles of Heat Engines (p. 197- 200) and Refrigeration (p. 362-363) in *Energy systems and sustainability* G. Boyle, B. Everett and J. Ramage Eds. Oxford University Press, 2003
Thermodynamics resource (some useful material but much is more advanced than this course): http://hyperphysics.phy-astr.gsu.edu/hbase/heacon.html#heacon

PART B. ENERGY ANALYSIS AND CARBON ACCOUNTING

Sept. 10 **3. Energy Accounting I: EIA Conventions**

Energy Carriers: Liquid, Gaseous and Solid Fuels, Electricity
Primary Energy
Heat Rates and Power Plant Efficiency
Site Energy
Measurement issues

Reading

Chapter 4: Energy Carriers and Energy Accounting, Ross, M.

References EIA main glossary: http://www.eia.gov/tools/glossary/index.cfm

Sept. 12 **4. Energy Accounting II: LCA Conventions**

Resource Energy (Total Fuel Cycle Accounting)
Total Fuel Cycle (Upstream and Combustion) Energy
Feedstock (Embodied in Materials) and Process Energy
Life Cycle Energy Analysis

Reading

Chapter 4: Energy Carriers and Energy Accounting, Ross, M.

References

Keoleian, G. et al. "Application of LCI to Fuel Tank System Design" *Intl JLCA* 1998.
GREET (Argonne National Lab): http://greet.es.anl.gov/

Sept. 17 **5. Energy Growth Analysis and Carbon Accounting**

International and US Statistics
Energy and Carbon Intensity
Carbon Emission Factor
Role for Conservation and Energy Efficiency
Growth Rates
Growth Rate Formalism
Forecasts and Future Scenarios

Readings

Chapter 5: The US Energy Use & Related Greenhouse Gas Emissions, Ross, M.
Excel growth chart tutorial
Annual Energy Outlook With Projections to 2050 - Executive Summary
https://www.eia.gov/outlooks/aeo/
International Energy Outlook - Highlights

References

EIA *Annual Energy Review (superseded -- see MER for key annual tables),*
http://www.eia.doe.gov/emeu/aer/contents.html
EIA *Monthly Energy Review (MER)* http://www.eia.gov/totalenergy/data/monthly/
EIA *State Energy Profiles,* http://tonto.eia.doe.gov/state/
Key World Energy Statistics - International Energy Agency
https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf
U.S. Energy System Center for Sustainable Systems Factsheet
http://www.css.umich.edu/factsheets/us-energy-system-factsheet
GHG Emission Factors:
https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf
The Outlook for Energy A View to 2040 – Exxon Mobil
https://corporate.exxonmobil.com/en/energy/energy-outlook

PART C. ENERGY SUPPLY

Sept. 19 **6. Fossil Energy Resources**

Distribution and Classification of Fossil Resources: Oil, Natural Gas, Coal
Unconventional: Oil Sands/Oil Shale/Shale Gas/Coal Bed Methane
Oil Sands and GHG emissions
Shale Gas and Hydraulic Fracturing (fracking)
Projections of Future Supply, What is Peak Oil
Drilling Offshore in the US?

Readings

Chapter 7: Energy Resources in *Energy Resources in Mineral Resources, Economics and the Environment,* Kesler, S.

Oil sands basics
https://www.canadasoilsands.ca/en/what-are-the-oil-sands(browse)
Shale gas basics: http://energy.gov/fe/shale-gas-101
"The End of Cheap Oil" C. Campbell/J.H. Laherrère, *Scientific American*, March 1998
USGS World Petroleum Assessment 2000 Executive Summary
Two perspectives on Fracking:
http://www2.epa.gov/hydraulicfracturing (browse)
http://www.marcellusprotest.org/ (browse)

References

BP Statistical Review of World Energy
http://www.bp.com/statisticalreview
Shale in the US:
http://www.eia.gov/energy_in_brief/article/shale_in_the_united_states.cfm
Chapter 5: Fossil Fuel Resources in *Energy Systems Engineering* Vanek and Albright (mirlyn on-line)
Chapter 3: Fossil Energy Resources, Ross, M.
Potential Oil Production from the Coastal Plain of the Arctic National Wildlife Refuge: Updated Assessment (EIA) May 2000, p vii – viii.
Masnadi, M.S., et. al. "Global Carbon Intensity of Oil Production" *Science* (2018) 361(6405): 851-853.
Potential Impacts of Proposed Oil and Gas Development on the Arctic Refuge's Coastal Plain: Historical Overview and Issues of Concern
http://training.fws.gov/Pubs7/arctic_oilandgas_impact.pdf
Offshore Oil
http://www.boem.gov/Oil-and-Gas-Energy-Program/

Sept. 24 **7. Electricity from Fossil Sources**

U.S. and World Fuel Mix
Power Generation Technologies
Transmission and Distribution
Can Supply Meet Demand? Capacity Factor, Load Curves, Peak Demand
Plant Efficiency and Life Cycle Efficiency
Your electricity bill

Readings *Top 9 Things You Didn't Know About Americas Power Grid* DOE
http://energy.gov/articles/top-9-things-you-didnt-know-about-americas-power-grid
G. Aubrecht "Production and Distribution of Electricity" Chapter 6 in *Energy* Prentice Hall, 1995.

References

"Electricity" in EIA *Monthly Energy Review*:
http://www.eia.gov/totalenergy/data/monthly/#electricity
"Centralized Electric Power Systems" Chapter 9 in *Energy for Sustainability Technology, Planning and Policy* John Randolph and Gilbert M. Master Island Press 2008.
Life Cycle Assessment of Coal-fired Power Production June 1999 • NREL/TP-570-25119

https://www.nrel.gov/docs/fy99osti/25119.pdf
AC vs DC http://energy.gov/articles/war-currents-ac-vs-dc-power

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Sept. 26 **8. Electricity from Nuclear Fuels and Other Generating Systems**

What about Nuclear Power?
Nuclear Fuel Cycle
Nuclear Waste Storage in the US: Yucca Mountain
Japan Nuclear Disaster and Impact on the Nuclear Industry
Cogeneration/Combined Heat and Power
Distributed Power, Microgrids; the "Smart Grid"

Readings

"Advanced Nuclear Energy Technologies" in *World Energy Assessment: Energy and the Challenge of Sustainability* UNDP September 2000, p. 306-318 + notes
Nuclear Fuel Cycle – World Nuclear Association
http://www.world-nuclear.org/education/nfc.htm
Discussion questions - https://www.theguardian.com/environment/damian-carrington-blog/2011/apr/21/chernobyl-nuclear-power-fukushima
Deutch, JM and Moniz, EJ "The Nuclear Option" *Sci. Amer*. (2006) 295(3): 76- 83.
International Atomic Energy Agency: http://iaea.org/ (browse)
US Nuclear Industry: http://www.eia.gov/nuclear/ (browse)
Combined Heat and Power DOE Infographic
http://energy.gov/articles/top-10-things-you-didn-t-know-about-combined-heat-and-power
What is the Smart Grid?
https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid

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References

Fukushima Daiichi Accident:
IAEA https://www.iaea.org/sites/default/files/fr-brochure.pdf
World Nuclear Organization http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx
Underground Ice Wall: http://www.nytimes.com/2016/08/30/science/fukushima-daiichi-nuclear-plant-cleanup-ice-wall.html?_r=0
What is Distributed Power?
http://www.dg.history.vt.edu/ch1/introduction.html

Oct. 1 **9. Electricity: Power Plant Economics and Regulation**

Fixed and Variable Costs (Capital, Fuel, O&M)
Wholesale and Retail Prices; Energy Markets
Tradeable SO_2 Permits with Caps
Demand Side Management and Conservation

Readings

Chapter 19: Simple Economic Analysis of a New Power Plant, Ross, M.

References

NREL Energy Technology Cost and Performance Data for Distributed Generation: https://www.nrel.gov/analysis/tech-cost-dg.html

Levelized Cost of Electricity Calculator: https://www.nrel.gov/analysis/tech-lcoe.html

"*Generation Technologies for a Carbon-Constrained World" EPRI* Journal (2006) Summer Issue.

Regional Greenhouse Gas Initiative (RGGI) – cap and trade http://rggi.org/

PART D. ENERGY DEMAND

Oct. 3 **10. Industrial Sector**

Energy Consumption by Manufacturers: Fuel and Non-fuel
Energy and Carbon Intensity
Efficiency Gains, Theoretical Limits
Cost of Conserved Energy

Readings

A. Lovins "Energy Strategy: The Road Not Taken" *Foreign Affairs* (1976) 55(1): 65-66.

Manufacturing Energy and Carbon Footprints DOE (browse) http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs (browse)

Worrell et al., "Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector" *Energy* (2001) 26: 513-536.

References

Chapter B4: Industrial Energy Consumption & Efficiency, Ross, M.

Advanced Manufacturing Office (DOE) http://energy.gov/eere/amo/advanced-manufacturing-office

Manufacturing Energy Consumption Survey (MECS) http://www.eia.doe.gov/emeu/mecs/contents.html

Theoretical Minimum Energies to Produce Steel, Executive Summary, U.S. Department of Energy Office of Industrial Technologies, March 2000.

Oct. 3 **10. Commercial Sector**

Commercial Buildings Energy Consumption
Heat and Cooling Loads
LEDs
E-Commerce and the Internet: Saving Energy?
LEED

Reading

Commercial Buildings Center for Sustainable Systems Factsheet http://css.umich.edu/factsheets/commercial-buildings-factsheet

LEED US Green Building Council: http://www.usgbc.org/leed (browse)

References

Commercial Buildings Energy Consumption Survey
http://www.eia.doe.gov/emeu/cbecs/
LEDs (EERE): https://energy.gov/eere/ssl/solid-state-lighting
Solid State Lighting: LEDs and OLEDs 2015 IEEE
http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7134817

Oct. 8

11. Residential Sector

Residential Buildings Energy Consumption
Heating and Cooling Loads and Degree Days
Building Envelope (e.g., walls, windows)
Modeling heat loss through windows
Building Codes and Appliance Standards

Readings

"Energy Conservation" Chapter 7 in *Energy and the Environment,* Kraushaar and Ristinen, 1999.
EERE Energy Savers: https://www.energy.gov/energysaver/energy-saver (browse website)
Jochem, EK "An Efficient Solution" *Sci. Amer*. (2006) 295(3): 64- 67.
US DOE Building Codes Program
http://www.energycodes.gov/ (browse site)
US DOE Appliance Standards
http://energy.gov/eere/buildings/appliance-and-equipment-standards-program (browse site)

References

Residential Energy Consumption Survey http://www.eia.doe.gov/emeu/recs/
"Energy Efficiency for Buildings" Chapter 6 in *Energy for Sustainability Technology, Planning and Policy* John Randolph and Gilbert M. Master Island Press 2008.
"Home Energy Saver", Developed by the Environmental Energy Technologies Division at Lawrence Berkeley National Laboratory http://hes.lbl.gov/
Chapter 8 Residential Energy, Ross, M.
Energy Star http://energystar.gov/
Residential Buildings Center for Sustainable Systems Factsheet
http://css.umich.edu/factsheets/residential-buildings-factsheet
L. Lutzenhiser "Social and Behavioral Aspects of Energy Use" *Annu. Rev. Energy Environ*. (1993) 18: 247-89

Oct. 10

12. Transportation Sector

Freight vs Personal
Historical Statistics
VMT Growth
Fuel Economy Trends
Other Key Drivers Impacting Sustainability: Criteria emissions, Price, Safety, Sprawl
Technology Options (Autonomous Vehicles – disruptive technology)

Policy Options

Readings

Heywood, JB "Fueling Our Transportation Future" *Sci. Amer.* (2006) 295(3): 60- 63.
Chapter 22: Transportation: Activity & Energy Use, Ross, M.
Personal Transportation Center for Sustainable Systems Factsheet (browse)
http://css.umich.edu/factsheets/personal-transportation-factsheet
Autonomous Vehicles Center for Sustainable Systems Factsheet (browse)
http://css.umich.edu/factsheets/autonomous-vehicles-factsheet

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References

Transportation Energy Data Book – Oak Ridge National Laboratory
http://www-cta.ornl.gov/data/
DOE/EPA Fuel Economy Guide http://www.fueleconomy.gov/
Annual Urban Mobility Study, Texas Transportation Institute
http://mobility.tamu.edu/ums/
The Future of Transportation Electrification: Utility, Industry and Consumer Perspectives, Lawrence Berkeley National Laboratory August 2018
https://emp.lbl.gov/publications/future-transportation-electrification
Smog Formation - Ground Level Ozone US EPA Site
https://www.epa.gov/ozone-pollution
"Are e-scooters polluters? The environmental impacts of shared dockless electric scooters" https://iopscience.iop.org/article/10.1088/1748-9326/ab2da8

Oct. 14-15 **Fall Study Break**

Oct. 17 **Midterm Exam (in class) Parts A, B, C, D.**

PART E. RENEWABLE ENERGY TECHNOLOGIES AND POLICY

Oct. 22 **13. Introduction to Renewable Energy**

Overview of technologies
Economics
Learning Curves for Renewables
Land Use and Siting
Key policy mechanisms
Renewable Portfolio Standards (RPS)
Production Tax Credits (RTC)
Renewable Energy Certificates (REC)

Reading

US Renewable Energy Center for Sustainable Systems Factsheet
http://css.umich.edu/factsheets/us-renewable-energy-factsheet
NREL Renewable Electricity Futures Study website (browse)
https://www.nrel.gov/analysis/re-futures.html
National Renewable Energy Laboratory website (browse)

https://www.nrel.gov/

"Riding on the Experience Curve" Chapter 1 in *Experience Curves for Energy Technology Policy* OECD/IEA, 2000

Production Tax Credit and Extension (browse)
http://www.ucsusa.org/clean_energy/smart-energy-solutions/increase-renewables/production-tax-credit-for.html

Renewable Energy Certificates (RECs): (browse)
https://www.epa.gov/greenpower/renewable-energy-certificates-recs

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References

Interactive mapping tools from NREL: https://maps.nrel.gov/

Green Power Partnership: http://www.epa.gov/grnpower/

World Renewable Energy Network (WREN) website (browse)
http://www.wrenuk.co.uk/

Levelized Costs of Renewable Electricity
https://www.nrel.gov/analysis/tech-lcoe.html

Renewable Portfolio Standards map (See dsireusa.org site)
http://www.dsireusa.org/resources/detailed-summary-maps/

RPS in the States: Balancing Goals and Implementation Strategies Technical Report NREL/TP-670-41409 December 2007.
https://www.nrel.gov/docs/fy08osti/41409.pdf

Delucchi, MA and MZ Jacobson "Providing all global energy with wind, water and solar power, Part I *Energy Policy* (2011) 39: 1154-69 and Part II 1170-119.
https://web.stanford.edu/group/efmh/jacobson/Articles/I/JDEnPolicyPt1.pdf

Optimization Model for Distributed Power: HOMER
http://homerenergy.com/

Meta analyses of renewable energy technologies: NREL LCA harmonization project
https://www.nrel.gov/analysis/life-cycle-assessment.html

A Framework for Project Development in the Renewable Energy Sector NREL 2013 (NREL/TP -7A40-57963) https://www.nrel.gov/docs/fy13osti/57963.pdf

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Oct. 24 **14. Wind Energy**

Wind Turbine Technologies
Wind Resources and Modeling
Energy Performance and Environmental Impacts
Economics and Economic Development Impacts

Readings

Chapter 21: Renewables: Electricity from the Wind, Ross, M.

Wind Energy Basics (EERE): (browse)
https://www.energy.gov/eere/wind/wind-energy-basics
https://www.energy.gov/eere/wind/wind-energy-technologies-office

Wind Technologies Market Report 2017 (DOE): (browse key findings)
https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report

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References

Wind Energy Center for Sustainable Systems Factsheet
http://css.umich.edu/factsheets/wind-energy-factsheet
Executive Summary and Overview, *20% Wind Energy by 2030 Increasing Wind Energy's Contribution to U.S. Electricity Supply* DOE/GO-102008-2567, July 2008.
https://www.nrel.gov/docs/fy08osti/41869.pdf
Chapter 12 Wind Energy Systems, in *Energy Systems Engineering* Vanek and Albright
NREL Wind maps: http://www.nrel.gov/gis/wind.html
NREL Wind:
https://www.nrel.gov/wind/ (browse)
https://www.nrel.gov/news/program/2019/tall-towers-tap-greater-wind-resource-potential.html
WINDExchange (EERE): https://windexchange.energy.gov/
American Wind Energy Association: http://www.awea.org/

Oct. 29 **15. Hydropower and Other Renewable Electricity Sources**

Hydropower Potential and Impacts
Geothermal Potential and Technology
Other: Tidal and Wave Energy

Readings

Hydroelectric Power USBR 2005
Hydropower Overview, USBR and IEA
DOE Geothermal Basics (EERE) browse
https://energy.gov/eere/geothermal/geothermal-basics
EERE Marine and Hydrokinetic Technology: http://energy.gov/eere/water/marine-and-hydrokinetic-energy-research-development

References

Renewables for Heating and Cooling Untapped Potential, IEA 2007.
World Commission on Dams http://www.internationalrivers.org/node/348
DOE Hydropower Technologies Program (including technology overview)
https://www.energy.gov/eere/water/water-power-technologies-office
Geothermal Energy Center for Sustainable Systems Factsheet
http://css.umich.edu/factsheets/geothermal-energy-factsheet
Marine and Hydrokinetic Resource Assessment
http://energy.gov/eere/water/marine-and-hydrokinetic-resource-assessment-and-characterization

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Oct. 31 **16. Photovoltaics**

PV and BIPV Technologies
Solar Resources and Modeling
Energy Performance and Environmental Impacts
Economics and Net Metering

Readings

Keoleian, G.A., and G. McD. Lewis, "Application of Life Cycle Energy Analysis to

Photovoltaic Module Design" *Progress in Photovoltaics* (1997) 5(4): 287-300.
PV technology web site (EERE): browse
http://energy.gov/eere/energybasics/articles/solar-energy-technology-basics
Chapter 20 Renewables: Photovoltaic Electricity, Ross, M.

References

Photovoltaic Energy Factsheet
http://css.umich.edu/factsheets/photovoltaic-energy-factsheet
NREL PVWatts Calculator http://pvwatts.nrel.gov/
Chapter 10 Solar Photovoltaic Technologies, in *Energy Systems Engineering* Vanek and Albright (mirlyn online)
Solar Radiation Resource Maps of US
http://www.nrel.gov/gis/solar.html
Solar Radiation Resource Data of US
http://rredc.nrel.gov/solar/old_data/nsrdb/
https://maps.nrel.gov/nsrdb-viewer/
Solar Energy Industry Association (US): http://www.seia.org/

Nov. 5 **17. Biomass: Electricity**

Biomass Technologies Introduction
Biomass Productivity and Modeling
Biopower: MSW, willows/switch grass/ poplar, wood waste

Readings

U.S. Billion-Ton Update: US DOE, July 2016 Executive Summary (PDF pages 21-33)
https://energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf
Keoleian, G.A. and T.A. Volk. "Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance." *Critical Reviews in Plant Sciences*, (2005) 24:385–406.
Wood-biomass-for-energy Forest Products Lab USFS 2004

References

Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System NREL 1997
Biomass Maps (NREL): http://www.nrel.gov/gis/biomass.html
Biomass Energy — Focus on Wood Waste Federal Energy Management Program ORNL 2004-02581/abh, July 2004.
U.S. Billion-Ton 2016 Report Summary and Comparison to 2011
http://energy.gov/sites/prod/files/2016/07/f33/summary_and_comparison_factsheet_bt16.pdf

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Nov. 7 **18. Biomass: Transport Fuels**

Biofuels: Bioethanol, Biodiesel, Algal, Jatropha
Biofuels and Water

Land Use Impacts
Food vs Fuel
Renewable Fuels Standards

Readings

Biofuels Center for Sustainable Systems Factsheet
http://css.umich.edu/factsheets/biofuels-factsheet
Alternative Fuels Data Center (EERE): http://www.afdc.energy.gov/ (browse)
Tilman, D, et al. Beneficial Biofuels--The Food, Energy, and Environment Trilemma. (2009) *Science* **325**, 270-271.
Renewable Fuel Standards (RFS):
http://www.epa.gov/otaq/fuels/renewablefuels/index.htm
(browse)

References

EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels EPA-420-F-09-024 May 2009.
Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus USDA/DOE May 1998 (browse)
US DOE Bioenergy Technologies Office:
https://www.energy.gov/eere/bioenergy
Biomass for Renewable Energy, Fuels, and Chemicals (Chapter 2) Klass, D.L. p. 29-50
R. Dominguez-Faus, et al. "The Water Footprint of Biofuels: A Drink or Drive Issue?" *Environ. Sci. Technol.* 2009, *43,* 3005–3010
Searchinger, Timothy et al. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change. *Science* 319: 1238-1240.
UK Renewable Fuels Agency Review of the Indirect Effects of Biofuels
http://webarchive.nationalarchives.gov.uk/20110407094507/renewablefuelsagency.gov.uk/reportsandpublications/reviewoftheindirecteffectsofbiofuels

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PART F. OTHER EMERGING SUSTAINABLE ENERGY TECHNOLOGIES AND POLICY

Nov. 12 **19. Which Option? Electric Vehicles (EV), Hybrid Electric Vehicles (HEV), Plug in Hybrid Electric Vehicles (PHEV) or Fuel Cell Vehicles (FCV)**

EV, Regenerative Braking
HEV, Matching Load with Efficient Powerplants
PHEV, Extend Range of Electric Drive
FCV, The Fuel Cell Powered Hybrid Vehicle
Incentives and Tax Credits (Feebates, Gas Guzzler Tax, Rebates)

Reading

Hybrid and Plug-In Electric Vehicles Basics: (browse)
https://www.energy.gov/eere/electricvehicles/electric-vehicle-basics
Hydrogen Fuel Cell Vehicles Basics: (browse)
http://www.afdc.energy.gov/vehicles/fuel_cell.html

Demirdöven, N. and J. Deutsch "Hybrid Cars Now Fuel Cell Cars Later" *Science* (2004) 305: 974-976.

References

Turner, J.A. "Sustainable Hydrogen Production Turner" *Science* (2004) 305: 972-974.
PHEV on the Horizon, Building the Business Case *EPRI Journal* Spring 2008.
MacPherson, N.D., G.A. Keoleian, and J.C. Kelly, "Fuel economy and greenhouse gas emissions labeling for plug-in hybrid vehicles from a life cycle perspective" Journal of Industrial Ecology (2012) 16(5): 761-773.
Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - North American Analysis: https://greet.es.anl.gov/files/4mz3q5dw
The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model: https://greet.es.anl.gov/
Ogden, J "High Hopes for Hydrogen" *Sci. Amer.* (2006) 295(3): 84-93.
Fuel Efficient Vehicle Tax Incentive Information Center: http://www.fueleconomy.gov/feg/taxcenter.shtml

Nov 14 **20. Building Energy Technologies and Policy**

Smart buildings
Lighting and LEDs
Heating/cooling technologies
Energy Star Program
Effective Policies

Readings

De Kleine, R., G.A. Keoleian, J.C. Kelly "Optimal replacement of residential air conditioning equipment to minimize energy, greenhouse gas emissions, and consumer cost in the US" *Energy Policy* (2011) 39(6): 3144-3153.

EERE Building Energy Technologies Program (browse site) https://www.energy.gov/eere/buildings/building-technologies-office

Smart Buildings http://energy.gov/sites/prod/files/2014/03/f14/B2G_Tech_Opps--Intro_and_Vision.pdf

US DOE Appliance Standards (browse site) http://energy.gov/eere/buildings/appliance-and-equipment-standards-program

US DOE Building Codes Program (browse site) http://www.energycodes.gov/

References

Energy Efficiency Requirements in Building Codes IEA 2008. P7-32.
Consumer Energy Tax Credits: https://www.dsireusa.org
LEDs (EERE): https://energy.gov/eere/ssl/solid-state-lighting
Solid State Lighting: LEDs and OLEDs 2015 IEEE http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7134817

Nov. 19 **21. Electricity Storage Technologies**
Batteries, Capacitors, Flywheels, Pumped Hydro

Readings

Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide, Sandia National Laboratories, Albuquerque, NM and Livermore, CA: 2010. SAND2010-0815 pages 1-13.

References

US Grid Energy Storage Center for Sustainable Systems Factsheet
http://css.umich.edu/factsheets/us-grid-energy-storage-factsheet

Grid Energy Storage DOE December 2013.

Electricity Storage: Technologies and Regulation, National Regulatory Research Institute, June 11, 2011.

Electricity Energy Storage Technology Options EPRI 2010.

Arbabzadeh, M., J.X. Johnson, G.A. Keoleian, P.G. Rasmussen, and L.T. Thompson, "Twelve Principles for Green Energy Storage in Grid Applications" *Environmental Science & Technology*, (2016) 50 (2):1046–1055.

Nov. 19 **21. Carbon Sequestration and Utilization**
Five Sequestration Strategies: Biological (Terrestrial) Sequestration, Carbon Capture, Geologic Sequestration, Ocean Sequestration, Advanced Concepts Clean Coal?

Readings

DOE Sequestration Site
http://www.fossil.energy.gov/programs/sequestration/index.html

Socolow, R. "Can We Bury Global Warming" *Sci Amer* (2005) July 49-55.

"Capturing carbon: Can it save us?" C&ENews February 25, 2019: 38-43

References

Hawkins, DG, DA Lashof and RH Williams "What To Do About Coal" *Sci. Amer.* (2006) 295(3): 68- 75.

Chapter 7 Carbon Sequestration, Vanek and Albright

"Carbon Dioxide Capture and Storage" *IPCC Special Report* (Summary for Policymakers and Technical Summary)

PART G. COURSE SYNTHESIS

Nov 21 **22. Climate Change I: Climate Change Science**
Earth's Energy Balance
Greenhouse Effect
Greenhouse Gases
Feedback Mechanisms
Climate Deniers

Reading

"An introduction to global warming" John R. Barker and Marc H. Ross Am. J. Phys. 67(2): 1216-1226

References

Fifth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) http://www.ipcc.ch/

Inventory of Greenhouse Gas Emissions and Sinks (US EPA) https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

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Nov. 26 **23. Climate Change II: Climate Change Mitigation and Policy**

Carbon Stabilization Targets
Stabilization Wedges
Climate Policy and Carbon Markets
Policies of Developed (EU Climate Policy) and Developing Countries (Clean Development Mechanisms)
Regional, State, City
Business and Industry: stockholders and the insurance sector

Readings

IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Pacala, S. and R. Socolow "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies" *Science* (2004) 305: 968-972.

References

City of Ann Arbor: Climate Action Plan https://www.a2cp.org/sites/default/files/CityofAnnArborClimateActionPlan_low%20res_12_17_12.pdf

Obama's Climate Action Plan: https://obamawhitehouse.archives.gov/sites/default/files/image/president27sclimateactionplan.pdf

Stern Review on the Economics of Climate Change Executive Summary Stern Review Executive_Summary 2006.pdf

Social Cost of Carbon – U.S. EPA https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

US Congress Climate Change History http://www.c2es.org/content/congress-climate-history

EIA Country Analysis Briefs
http://www.eia.gov/beta/international/analysis.cfm
United Nations Framework Convention and Kyoto Protocol
http://unfccc.int/kyoto_protocol/items/2830.php/
State and Local Climate Energy Program (US EPA):
https://www.epa.gov/statelocalclimate
The Stabilization Triangle: Tackling the Carbon and Climate Problem with Today's Technologies. Climate Mitigation Initiative, Princeton University.
Socolow, RJ and Pacca, SW "A Plan to Keep Carbon in Check" *Sci. Amer.* (2006) 295(3) 50 – 59.

Nov. 28	**Happy Thanksgiving! (no class)**

Dec. 3	**24. Term Project Presentations: Group I Posters**
Dec. 5	**24. Term Project Presentations: Group II Posters**
Dec. 5	**Individual Term Project Papers Due (Group I and II)**
Dec. 10	**25. Course Review**
Dec 11	**Optional Review**: Q/A format (Dec 11 is the first study day)

Final Exam:	**Friday, December 13**	**4:00 pm – 6:00 pm**

COURSE REQUIREMENTS AND EVALUATION

Class participation*	10%
Assignments	20%
Term Project	20%
Mid-Term Exam	25%
Final Exam	25%

* Class participation: Attendance in class is required. Participation includes leading class discussion and contributing to the class blog; posing questions and answering questions; sharing articles and news; providing feedback on lectures and course materials; and active participation in the poster session.