General Course Information:

ELEN E6906, Topics Course, FUTURE ENERGY: ECONOMICS, SYSTEMS, POLICIES

Instructor Information

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Course Description Climate change is bringing, and will continue to bring for the foreseeable future, profound changes to our approach to energy, including production, consumption, public policies and engineering systems to enable the changes. The goal of this course is to provide a holistic view of these changes from the combined perspectives of economics, science and engineering, and public policy.

We will begin by reviewing the first four chapters of D.S. Kirschen and G. Strabac's "Fundamentals of Power System Economics", 2nd edition ("Introduction", "Basic Concepts from Economics", "Markets for Electrical Energy", "Participation in Markets for Electrical Energy"). We will largely bypass electricity markets and related optimizations, which are covered well in texts and other courses.

We will study the science, economics and policy implications of climate change, including related models. Since much is work in progress, we will attempt to present both sides of arguments, e.g., the "Dismal Theorem" and the counterargument. We will proceed to understand the basics of all the major renewable energy sources, and understand the consequences of their variabilities on applications and prices. We will get an understanding of the challenges faced by regulators from the coexistence of grid and renewables' power, and their various approaches from around the globe. We will examine the challenges to systems from significant wind and solar penetrations, the necessary role for storage systems, various approaches for sharing stored energy, the role of transmission networks, energy system expansion design.

Reading, discussing and researching the contents of the papers listed below will be central to the course. Students will take turns at presenting the papers, and leading class discussions.

Course Prerequisite Students must have either taken ELEN 6767, "Internet Economics, Engineering and the Implications for Society", or have good understanding of the following economic concepts: social welfare maximization; elasticity; competitive, oligopoly, monopoly markets; subadditivity in cost functions with large fixed cost; first and second best pricing; average cost pricing; Cournot & Bertrand pricing; Ramsey pricing; Price of Anarchy; Pigovian taxes; Coasian bargaining; externalities.

Course requirements: Active participation; homework; two papers; project with oral presentation.

Grading policy:
35% active participation
15% homework
15% mid-term paper
15% project and oral presentation
20% final exam paper

Themes & Reading:

1. **Fundamentals of Energy Production and Use, True Cost of Energy**

   (i) Fundamentals of Renewable Energy
   Basic characteristics of biomass, hydropower, wind, solar, geothermal energy sources; intermittency and environmental externalities; policies for renewable energy transition.

   D. Timmons, J.M. Harris, B. Roach, "The Economics of Renewable Energy", Global Development and Environment Institute, Tufts University

   M. Roser, "Why did renewables become so cheap so fast?"
   https://ourworldindata.org/cheap-renewables-growth

   (ii) Social Costs of Various Energy Sources

   C. Olson, F. Lenzmann, "Bringing the Social Costs and Benefits of Electric Energy from Photovoltaics Versus Fossil Fuels to Light", MRS Energy and Sustainability: A Review Journal", Materials Research Society, pp 1-29, 2016

   (iii) Status, Prospects of Renewable Energy

   National Research Council, "Electricity for Renewable Resources: Status, Prospect and Impediments", chapter 4 – "Economics of Renewable Electricity", National Academic Press, Washington, DC, 2010

2. **Climate Change: Science, Economics, Policies**

   (i) Models for Estimating the Social Cost of Carbon

   National Academy of Sciences, "Framework for Estimating the Social Cost of Carbon", chapter 2, "Valuing Climate Change: Updating Estimation of the Social Cost of Carbon Dioxide", 2017, 39-60

W.D. Nordhaus, J. Boyer, “The Structure and Derivation of RICE-99”, chapter 2 in “Warming the World, Economic Models of Global Warming”, MIT Press, 2000

W.D. Nordhaus, “Revisiting the social cost of carbon”, PNAS, vol. 114, no. 7, Feb. 14, 2017, 1518-1523

(ii) “Dismal Theorem” and Counterargument

M. L. Weitzman, “Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change”, Review of Environmental Economics and Policy, volume 5, issue 2, summer 2011, pp. 275–292 doi:10.1093/reep/rer006

R. S. Pyndyck, “Fat Tails, Thin Tails, and Climate Change Policy”, National Bureau of Economic Research, Working Paper 16353, Sept. 2010
http://www.nber.org/papers/w16353

(iii) Policy Implications

N . Siami, R. A. Winter, “Jevon’s Paradox Revisited: Implications for Climate Change”, Economics Letters, 206, 2021
https://doi.org/10.1016/j.econlet.2021.109955

P. Aghion, C. Hepburn, A. Teytelboym, D. Zenghelis, “ Path Dependence, Innovation and the Economics of Climate Change”, chapter 4, “Handbook on Green Growth”, 2014

3. **Economics and Pricing of Power under High Penetration of Renewable Energy**

Y. Matsuo et al., “Investigating the Economics of the Power Sector under High Penetration of Variable Renewable Energy”, Applied Energy, vol. 267, 113956, 2020

L. Hirth, “The Market Value of Variable Renewables: The Effect of Solar and Wind Power Variability on their Relative Price”, Energy Economics, vol. 38, 2013, pp 218-236

4. **Regulators’ Dilemma**
Regulators, notably in California, have the problem of setting prices and subsidies for centralized, stable grid power, which is subject to high sunk and fixed costs, and decentralized, variable power from PV/solar panels, with contrasting societal impacts.

R. Braeutigam, “Optimal Policies for Natural Monopolies”, Chapter 23 of “Handbook of Industrial Organizations”, Vol. 2, Ed. R. Schmalensee and R. Willig, North Holland, 2007

S. Borenstein, “ The Economics of Fixed Cost Recovery by Utilities”, The Electricity Journal, 29 (7), Sept. 2016, pp 5-12

S. Borenstein, “The Private Net Benefits of Residential Solar PV: The Rise of Electricity Tariffs, Tax Incentives, and Rebates”, National Bureau of Economic Research Working Paper 21342, July 2015

F.A. Wolak, “The Evidence from California on the Economic Impact of Inefficient Distribution Network Pricing”, National Bureau of Economic Research Working Paper 25087, Sept. 2018

5. **Future Energy Systems & Networks**

(i) Implications of Significant Wind Generation Penetration

GE Energy, “Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements”, Executive Summary, March 2008

M. Black, G. Strbac, “Value of Bulk Energy Storage for Managing Wind Power Fluctuations”, IEEE Trans. Energy Conversion, vol. 22 (1), March 2007, 197-205

M. A. Ortega-Vazquez, D.S. Kirschen, “Estimating the Spinning Reserve Requirements in Systems with Significant Wind Power Generation Penetration”, IEEE Trans. Power Systems, vol. 24 (1), February 2009, 114-124

(ii) Role of Storage and Transmission for Renewable Energy Sources

K.Z. Rinaldi, J.A. Dowling, T.Y. Ruggles, K. Caldeira, N.S. Lewis, “Wind and Solar Resource Droughts in California Highlight the Benefits of Long-Term Storage and Integration with the Western Interconnect”, Environ. Sci. Technol, 2021, 55, 6214-6226

M. Arbabzadeh, R. Sioshanshi, J.X. Johnson, G.A. Keoleian, “The Role of Energy Storage in Deep Decarbonization of Electricity Production”, Nature Communications, https://doi.org/10.1038/s41467-019-11161-5

(iii) Tackling Storage Needs for Renewable Energy Sources

D. Kalathil, C. Wu, K. Poola, P. Varaiya, “The Sharing Economy for the Electricity Storage”, IEEE Trans. Smart Grid, 10 (1), Jan. 2019, 556-567

V.Duelkar, J. Nair, A.A. Kulkarni, “Statistical Economies of Scale in Battery Sharing”, arXiv:1912.00462v1, Dec. 1, 2019, also in J. Energy Storage, 2021

(iv) Transmission Systems

T.B. Tsuchida, R. Gramlich, “Improving Transmission Operation with Advanced Technologies: A Review of Deployment Experience and Analysis of Incentives”, Grid

Strategies & Brattle Group

P.A. Ruiz, J. Caspary, L. Butler, “Transmission Topology Optimization Case Studies in SPP and ERCOT”, 2020

(v) Carbon Aware Datacenters

B. Acun, B. Lee, F. Kazhamiaka, K. Maeng, U. Gupta, M. Chakkaravarthy, D. Brooks, C.-J. Wu, “Carbon Explorer: A Holistic Framework for Designing Carbon Aware Datacenters”, ASPLOS ’23, March 2023, Vancouver BC, Canada, pp 118-132

(vi) Energy System Expansion Design Optimization

C. Skar, R. Egging, A. Tomasgard, “The Role of Transmission and Energy Storage for Integrating Large Shares of Renewables in Europe”, International Association for Energy Economics, Q1, 2016

C. Skar, G. Doorman, A. Tomasgard, “The future European power system under a climate policy regime”, ENERGYECON 2014, May 2014, 318-325

6. Case Studies

University of Texas, Energy Institute, “The Timeline and Events of the February 2021 Texas Electric Grid Blackouts”, 2021

M. Nurunnabi, N.K. Roy, E. Hossain. H.R. Pota, “Si**ze** Optimization and Sensitivity Analysis of Hybrid Wind/PV Micro-Grids – A Case Study for Bangladesh”, IEEE Access,vol.7, Oct. 2019