

## **General Course Information:**

ELEN E6570, 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", 2<sup>nd</sup> 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 growth of storage systems, various approaches for sharing stored energy, carbon-aware datacenter design, techniques for transmission network control, and 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

**Papers read in course, arranged by themes:**

**Theme 1: Basic Economics of Renewable Energy**

1. D. Timmons, J.M. Harris, B. Roach, “The Economics of Renewable Energy”, Global Development and Environment Institute, Tufts University
2. M. Roser, “Why did renewables become so cheap so fast?”  
<https://ourworldindata.org/cheap-renewables-growth>
3. 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
4. National Research Council, “Electricity for Renewable Resources: Status, Prospect and Impediments”, chapter 4 - “Economics of Renewable Electricity”, National Academic Press, Washington, DC, 2010

**Theme 2: Estimation of the Social Cost of Carbon**

5. National Academy of Sciences, “Framework for Estimating the Social Cost of Carbon”, chapter 2 in “Valuing Climate Damages: Updating Estimates of the Social Cost of Carbon Dioxide”, 2017, 39-60
6. 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

**Theme 3: Science & Economics of Climate Change**

7. G.R. Roe, M.B. Baker, “Why Is Climate Sensitivity So Unpredictable?”, Science, 318 (629-632), Oct. 2007
8. 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

9. 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>

#### **Theme 4: Climate Change Policy**

10. 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>
11. P. Aghion, C. Hepburn, A. Teytelboym, D. Zenghelis, “ Path Dependence, Innovation and the Economics of Climate Change”, chapter 4, “Handbook on Green Growth”, 2014

#### **Theme 5: Planning for High Penetration of Renewable Energy**

12. L. Hirth, “The Market Value of Variable Renewables: The Effect of Solar Wind Power Variability on their Relative Price”, *Energy Economics*, vol. 38, 2013, pp 218-236
13. Y. Matsuo et al., “Investigating the Economics of the Power Sector under High Penetration of Variable Renewable Energy”, *Applied Energy*, vol. 267, 113956, 2020

#### **Theme 6: Regulators’ Dilemma**

14. R. Braeutigam, “Optimal Policies for Natural Monopolies”, Chapter 23 of “Handbook of Industrial Organizations”, Vol. 2, Ed. R. Schmalensee and R. Willig, North Holland, 2000  
- Sections 1-4
15. R. Braeutigam, “Optimal Policies for Natural Monopolies”, Chapter 23 of “Handbook of Industrial Organizations”, Vol. 2, Ed. R. Schmalensee and R. Willig, North Holland, 2000  
- Sections 5-8
16. S. Borenstein, “ The Economics of Fixed Cost Recovery by Utilities”, *The Electricity Journal*, 29 (7), Sept. 2016, pp 5-12
17. 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
18. 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

### **Theme 7: Wind Power**

19. GE Energy, “Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements”, Executive Summary, March 2008
20. 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
21. 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

### **Theme 8: Stability & Resilience of Power Grid**

22. P. Denholm, T. Mai, R.W. Kenyon, B. Kroposki, M. O’Malley, “Inertia and the Power Grid: A Guide Without the Spin”, Technical Report NREL/TP-6A20-73856, National Renewable Energy Laboratory, May 2020
23. K. Anderson, X. Li, S. Dalvi, S. Ericson, C. Barrows, C. Murphy, E. Hotchkiss, “Integrating the Value of Electricity Resilience in Energy Planning and Operations Decisions”, IEEE Systems J., vol. 15 (1), March 2021, 204-214

### **Theme 9: Storage for Decarbonization**

24. 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
25. 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>
26. G. Glenk, S. Reichelstein, “Economics of Converting Renewable Power to Hydrogen”, Nature Energy, vol.4, March 2019, 216-222

### **Theme 10: Transmission Systems**

27. B.C. Lesieutre, J.H. Eto, “Electricity Transmission Congestion Costs: A Review of Recent Reports”, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Oct. 2003

28. T.B. Tsuchida, R. Gramlich, “Improving Transmission Operation with Advanced Technologies: A Review of Deployment Experience and Analysis of Incentives”, Grid Strategies & Brattle Group, June 24, 2019
29. P.A. Ruiz, J. Caspary, L. Butler, “Transmission Topology Optimization Case Studies in SPP and ERCOT”, FERC Tech. Conf. on Increasing Day-Ahead and Real-Time Market Efficiency and Enhancing Resilience through Improved Software, Washington DC, June 24, 2020

### **Theme 11: Carbon-Aware Operations & Planning of Datacenters**

30. N. Bashir, T. Guo, M. Hajiesmaili, D. Irwin, P. Shenoy, R. Sitaraman, A. Souza, A. Wierman, “Enabling Sustainable Clouds: The Case for Virtualizing the Energy System”, Proc. ACM Symp. Cloud Computing, November 2021, pp 350-358
31. P. Wiesner, I. Behnke, D. Scheinhert, K. Gontarska, L. Thamsen, “Let’s Wait Awhile: How Temporal Workload Shifting Can Reduce Carbon Emissions in the Cloud”, Proc. Middleware ’21, Virtual Event , Canada, Dec. 6-10, 2021, 260-272
32. A. Radovanovic, R. Koningstein , I. Schneider, B. Chen , A. Duarte , B. Roy, D. Xiao, M. Haridasan, P. Hung, N. Care, S. Talukdar, E. Mullen, K. Smith, M. Cottman , W. Cirne, “Carbon-Aware Computing for Datacenters, IEEE Trans. Power Systems, 2023, 1270-1280
33. 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

### **Theme 12: Storage Economy**

34. 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

### **Theme 13: Case Study of Grid Blackout**

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

### **Student Projects on Energy and Implications for Society - a sample**

- (i) Should a Carbon Tax be an essential mechanism for combating climate change?
- (ii) How best to resolve the Regulator’s Dilemma?
- (iii) Should the wholesale electricity market’s price-setting process be reformed?
- (iv) Is the continuation of subsidies of renewables the right policy?