Syllabus as of 1/13/2015. Please see Sakai for updates.

**Electricity Markets**

Nicholas School of the Environment  
Duke University

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**Time**  
T-Th 8:30am – 9:45am

**Location**  
Gross Hall 103

**Instructor**  
Dalia Patino Echeverri  
dalia.patino@duke.edu  
Phone: 919-613-7461  
Office hours:  
Tuesdays and Thursdays 9:45-10:15am @ Gross Hall,  
Fridays 10:30-11:30am @LSRC A150A.

**Teaching Assistants**  
Rubenka Bandyopadhyay  
rb171@duke.edu  
Office hours: Mondays: 10:30-11:30 am, Wednesdays: 12-1 pm.

Eric Williams  
eric.lee.williams@gmail.com  
Office hours:

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**Course Description**

This course examines basic concepts in economics and engineering necessary to understand the operation of power markets. It pays particular attention to a challenging question that the electricity industry poses to regulators: how to provide the right incentives for adequate investment in generation and transmission so that electricity is reliable, affordable, and clean?

The objectives of the course are to provide you with knowledge and tools for analyzing the behavior of power markets, the effect of different policies, and the possible solutions to the most pressing unresolved issues.

**Prerequisites**

Admission by permission of instructor.
Syllabus as of 1/13/2015. Please see Sakai for updates.

The class will build on a background of undergraduate economics, and computer based quantitative analysis (e.g. MS Excel). The material will also include basic concepts of physics, finance, optimization, probability, and statistics. I do not expect every student to have a strong background in all these areas. However, if you do not have previous knowledge in at least two of these areas, you may struggle in the class. If you are concerned about the background material but have a strong interest in the class and a positive attitude towards learning at a fast pace I encourage you to enroll and interact often with me on how to keep up with the concepts and tools unfamiliar to you.

Please do not ask me if you can audit this class. I do not allow auditors because in my experience students that audit do not read or do homework and therefore waste their time coming to class. If you are a Fuqua student, you are welcome to enroll as long as you NEVER use the differences in schedule and school requirements (e.g. spring break, field trips, internship) as an excuse for being late with homework or for rescheduling quizzes.

Some of the concepts I recommend you to review before classes start, are:-Electricity Industry Fundamentals: Fundamentals of electricity generation (coal, natural Gas, wind, solar photovoltaic cell, solar thermal, nuclear, geothermal), NamePlate Capacity, Heat rate, Capacity Factor, air emissions. Familiarity with EIA's AEO (http://www.eia.doe.gov/oiaf/aeo/), eGrid Database (http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html), IECM software (http://www.cmu.edu/epp/iecm/) (this will be covered by Tim Johnson in his Energy Technologies class during the month of January – see if you can audit those lessons or learn on ). EPA's Acid Rain Program (http://www.epa.gov/airmarkets/progsregs/arp/index.html). Energy units and units conversion.
- Calculus: Derivatives and partial derivatives. Maxima and minima of a function. Lagrange multipliers
-Probability: Experiments, sample spaces, probability of events, discrete and continuous random variables, pdf, cdf, expected value, variance, probability distributions (normal, uniform, exponential, binomial, weibull), stochastic processes (Brownian motion, Geometric Brownian motion, Mean Reverting Processes) Montecarlo simulation.
-Excel: Functions, Array Functions, Tables and Pivot Tables, Active Controls, Macros (Procedures and functions), Solver, data Analysis.

Textbooks and Readings

Syllabus as of 1/13/2015. Please see Sakai for updates.

Other recommended readings

- Available on Sakai-->Resources-->Complementary readings

Supplemental readings as indicated in class schedule below, many available on the internet, and others available via Sakai.

Sakai and PC compatibility

Readings, class announcements, schedule changes, grades, power point slides and working files (excel) will all be posted to the course Sakai site. Students are also encouraged to use Sakai’s discussion boards to continue the discussion of course issues beyond the classroom. Anyone having trouble working with the Sakai site should seek help from their fellow students, or contact Information Technology.

Occasionally I will post excel files that illustrate some quantitative analysis. I use a windows PC with MS Office 2013 and it is your responsibility to solve all the compatibility issues to keep up with the materials posted.

Course Assignments

Written assignments should be presented using Times Roman 12 pt font, single-spaced text, 1” margins. All assignments should be posted on Sakai. If we ask for a hard-copy, please save paper by printing double sided and not using a cover sheet. Problem sets can be hand-written if the text and math are written clearly and then scanned and uploaded to Sakai.

The assignments will ask you to solve some of the problems of the Kirschen & Strbac book (or variations), and to develop quantitative models to conduct other analysis related to the U.S. electricity industry. I encourage you to work in study groups of up to three people on these problem sets and help each other learn. However, each student must submit his or her own copy of the assignment and you are not allowed to directly copy another student’s work. An example of appropriate problem set collaboration would be for Student A to explain the math used in the problem to Student B. Then Student B goes off by himself and completes the problem again and writes up his own explanation. It would be inappropriate for Student B to directly copy the math or the explanation/interpretation directly from Student A. Study groups are most effective when everyone attempts to do the problem sets BEFORE meeting as a group. Only if you really try to solve the problem on your own will you realize whether you understand the problem and its solution. It is very easy to hear someone’s explanation and think you understand the problem, but you may not. This will also help insure that you are using study groups in ways that are consistent with the Nicholas School Honor Code.

There are two long assignments that ask for a comprehensive analysis of a pressing policy problem in Nickls. The first of these assignments needs to be completed independently without asking or consulting your class-mates, teaching assistants or professors; the second is to be conducted in teams (team size TBD, perhaps 3-4 members). In previous years these assignments have required quantitative analysis of the alternatives for new generation in a region, which in turn requires the forecast of future load and electricity prices given a set of scenarios that have
Syllabus as of 1/13/2015. Please see Sakai for updates.

different fuel prices, emissions allowances prices, and transmission congestion levels. Students have been asked to submit their computer models and a written report. Details on the requirements will be provided when assignments are posted.

**Assignments summary**

<table>
<thead>
<tr>
<th>#</th>
<th>Posted</th>
<th>Due</th>
<th>Points</th>
<th>Covers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thursday after lecture 1</td>
<td>Friday after lecture 3</td>
<td>4</td>
<td>History of the US Electric System</td>
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<tr>
<td>2</td>
<td>Thursday after lecture 3</td>
<td>Friday after lecture 5</td>
<td>4</td>
<td>Chapter 2 of Kirschen &amp;Strbac</td>
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<tr>
<td>3</td>
<td>Thursday after lecture 5</td>
<td>Friday after lecture 7</td>
<td>7</td>
<td>Chapter 3 of Kirschen &amp;Strbac and excel model to clear the market</td>
</tr>
<tr>
<td>4</td>
<td>Thursday after lecture 7</td>
<td>Friday after lecture 9</td>
<td>7</td>
<td>Chapter 4 of Kirschen &amp;Strbac and optimization model for unit commitment</td>
</tr>
<tr>
<td>5</td>
<td>Thursday after lecture 9</td>
<td>Friday after lecture 11</td>
<td>7</td>
<td>Market Clearing - UC and ED models</td>
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<tr>
<td>6</td>
<td>Thursday after lecture 11</td>
<td>Friday after lecture 13</td>
<td>7</td>
<td>Physics I</td>
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<tr>
<td>7</td>
<td>Thursday after lecture 13</td>
<td>Friday after lecture 14</td>
<td>7</td>
<td>Physics II</td>
</tr>
<tr>
<td>8</td>
<td>Thursday after lecture 15</td>
<td>Friday after lecture 17</td>
<td>7</td>
<td>Chapter 5 and research on ancillary services markets in the US</td>
</tr>
<tr>
<td>9</td>
<td>Thursday after lecture 17</td>
<td>Friday after lecture 19</td>
<td>7</td>
<td>Power flows from multiple bilateral transactions and LMPs</td>
</tr>
<tr>
<td>10</td>
<td>Thursday after lecture 19</td>
<td>Friday after lecture 21</td>
<td>14</td>
<td>Chapter 7 and an intro to NickIso (individual)</td>
</tr>
<tr>
<td>11</td>
<td>Thursday after lecture 21</td>
<td>Friday after lecture 23</td>
<td>7</td>
<td>Capacity markets and Transmission rights – Chapter 7 and end of Chapter 6</td>
</tr>
<tr>
<td>12</td>
<td>Friday after lecture 22 (April 1)</td>
<td>April 27th @ midnight</td>
<td>14</td>
<td>Transmission investment – Transmission planning – Decarbonization of the U.S. electricity system NickIso (teams) 7 points for the document and 7 points for the oral presentation</td>
</tr>
</tbody>
</table>
Grading
Each assignment will be evaluated using a numbered grade (0-100) and your overall numbered grade will be determined using the following weights:

Assignments (12): 90 (points as specified in table above)
*Attendance, participation, quizzes: 10
Total: 100

Letter grades of A, A-, B+, B, B-, C+, C, C-, or F will be assigned according to numbered grades in the following way:

- Above 100: A+
- (95-100]: A
- (90-95] A-
- (85-90] B+
- (80-85] B
- (75-80] B-
- (70-75] C+
- (65-70] C
- (60-65] C-
- 60 or below F

Participation. You are expected to prepare for class by reading the assigned reading prior to the class. Frequently there will be a quiz on the assigned readings and/or the concepts and tools discussed in previous classes. Sometimes I will ask you to prepare the quiz in advance (e.g. write a short summary -less than a page- of the assigned readings). Your grade from class participation will depend on your class attendance, the quality and quantity of your interventions in class, participation in Sakai discussions, and your written summaries and quizzes. Please post these summaries to Sakai. You will NOT receive graded feedback on summaries or quizzes.

Policy on late assignments. Most assignments will be posted by Thursday at 2:30PM and are due 7 days later on Friday by midnight. Late assignments will not be accepted. If you are ill or have a family emergency that prevents you from being able to complete the assignment on time, please submit the web-based short-term illness form prior to the class in which the assignment is due. The short-term illness form can be found at: http://www.duke.edu/flu/getting_sick/index.html#students, or www.aas.duke.edu/trinity/t-reqs/illness/. You are governed by the Nicholas School Honor Code in completing this form (see below). If you do not complete this form before class, the standard late policy will apply. With the exception of assignments 10 and 11, an assignment that is not submitted because of illness or family emergency will be excluded from your grade calculation (i.e. the remaining assignments will have more weight). Any other missed assignments will receive a grade of zero.

Policy on late submissions of NickIso assignment. The nickiso assignments (i.e. A10 and A11) will receive a penalty of 30% per day late. If you are ill or have a family emergency that prevents you from being able to complete the computer based analysis on time, please submit the web-based short-term illness form prior to the class in which the assignment is due (see above).
Syllabus as of 1/13/2015. Please see Sakai for updates.

will not be a penalty if the analysis report is submitted as soon as your illness or emergency is over. I will have a final exam for those unable to complete the NickIso assignment.

Policy on quizzes and class participation. Most or all quizzes will be unannounced. There will not be opportunities to make up a missed quiz under any circumstance; however the quiz with the lower grade will be not be considered for calculating the overall grade of quizzes. Everyone is expected to participate in class. Occasionally bonus points will be given for answering challenging questions during class or solving a problem on the board. In those cases, the grade from participation and attendance may rise above 100%.

Email. When you email us please include ENV717 as the first word in your subject.

Nicholas School Honor Code and the Duke Community Standard

All activities of Nicholas School students, including those in this course, are governed by the Duke Community Standard, which states:

“Duke University is a community dedicated to scholarship, leadership, and service and to the principles of honesty, fairness, respect, and accountability. Citizens of this community commit to reflect upon and uphold these principles in all academic and nonacademic endeavors, and to protect and promote a culture of integrity. To uphold the Duke Community Standard:

• I will not lie, cheat, or steal in my academic endeavors;
• I will conduct myself honorably in all my endeavors; and
• I will act if the Standard is compromised.”

Please add the following affirmation to the end of all assignments and sign your name beside it:

“I have adhered to the Duke Community Standard in completing this assignment.”

Class etiquette

1. Please make sure you do everything you can to make our classroom culture a comfortable learning environment for everyone. We will likely have people from many different backgrounds in this class and you should all feel comfortable and make each other comfortable while participating.
2. Please take responsibility for making the class successful. As the instructor I assure you I will try to do my best, but what you learn in the class will be largely dependent on your attitude and work. Ask yourself what you can do during each class to move the course forward in a positive way.
3. I really hope you are NEVER late. I know 8:30 is early, but I assure you that coming early to class will save you more sleep :-). If for an exceptional reason you must enter the class late, please do so quietly. If for any reason the door is locked please knock. I prefer this short disruption than you missing an entire class.
Syllabus as of 1/13/2015. Please see Sakai for updates.

4. Cell phones, beepers, eating, and other distracting activities are not appreciated.
5. Please refrain from browsing the internet, checking email or text messaging in class.

Green Classroom Certification
"This course has achieved Duke's Green Classroom Certification. The certification indicates that the faculty member teaching this course has taken significant steps to green the delivery of this course. Your faculty member has completed a checklist indicating their common practices in areas of this course that have an environmental impact, such as paper and energy consumption. Some common practices implemented by faculty to reduce the environmental impact of their course include allowing electronic submission of assignments, providing online readings and turning off lights and electronics in the classroom when they are not in use. The eco-friendly aspects of course delivery may vary by faculty, by course and throughout the semester. For more information on the Green Classroom Certification, visit: sustainability.duke.edu/action/classroom."

Class Topic and Readings Schedule

*Required readings are indicated with an asterisk* and should be completed before the class on which they are listed. Other readings offer supplementary material and/or an alternative presentation of similar information.

1.01/8/2015: Class Overview.

2. 01/13/2015: Structure of the US Electricity Industry
Industry participants (IOU, PPS, Coops, PMAs, non-utilities, Customers). Wholesale and retail competition in the U.S. Provision of Transmission Services to enable wholesale competition (OATT, RTOs). History and status of retail competition. PJM example
*Kirschen & Strbac Chapter 1: pp 1-8.
*Kirschen & Strbac Chapter 2: pp 11-44. (We do not cover this chapter in class because I assume you are all familiar with the material from your previous economics courses. Please read it to refresh your understanding of basic concepts from economics and to do assignment # 2. There may be a quiz on this).

3. 01/15/2015: Markets for electrical energy
The need of managed markets. Trading in wholesale electricity markets (Bilateral and Centralized).

4-5. 01/20/2015-01/22/2015: The producers perspective I
Theory of the firm: Short run behavior. Generation costs and optimal bids.
*Please review: formulation of optimization problems and solution using Lagrangian multipliers.*
Also please install the IECM model and become familiar with it. Please make sure you remember how to represent systems of linear equations in matrix-vector form.
Methods review: how to solve systems of linear equations in excel (i.e. using array functions)
*Kirsch & Strbac Chapter 4: pp 73-90.
*Readings on matrix algebra and how to write and solve a system of linear equations using matrices (posted on Sakai).

Please install matlab for next class: [http://oit.duke.edu/comp-print/software/support/matlab.php#faq-1](http://oit.duke.edu/comp-print/software/support/matlab.php#faq-1)

6. 01/27/2015: The producers’ perspective II: Economic Dispatch (ED) with Elastic Demand

7. 01/29/2015 The producers’ perspective III: Introduction to the Unit Commitment (UC) problem
- Carrion, M., Arroyo, J.M. A Computationally Efficient Mixed-Integer Linear Formulation for the Thermal Unit Commitment Problem. IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 21, NO. 3, AUGUST 2006 1371

8. 02/03/2015: Market Clearing Models: The UC and ED problems from the ISO perspective.

9-10. 02/06/2014 - 02/10/2015: Market Clearing Models II and the challenge of integrating VERs.
Uncertainty and variability in wind and solar energy forecasts.
Ramp capability products in MISO: UC and ED models with ramp capability vs conventional.


--Optional material: MCMC models for wind power analysis
Tools: Generation of synthetic wind power times-series with Markov Chain Monte Carlo techniques.

11. 02/12/2015: Electricity I: A bit of physics to understand system security and ancillary services
Current, Voltage, Resistance, DC systems, Edison's power system
*02/13/2015: Duke Yale Career Fair

12. 02/17/2015: Electricity II: A bit more on physics to understand system security and ancillary services - Basics of AC systems
Edison DC generator. AC generator.
Methods review: Trigonometry; sine, cosine, identities.

13. 02/19/2015: Electricity III: A bit more on physics to understand system security and ancillary services - Generalized Ohm's law for AC systems
Real and reactive power. Resistive and inductive loads. Power factor
Phasor representation. Impedance

*02/23/2015: MP drafts are due

14. 02/24/2015: System security and the need for ancillary services
AC example. Brief history of power system security in the U.S. NERC. How outages and blackouts happen. Different ancillary services
*Kirschen & Strbac Chapter 5: pp105-130.

15. 02/26/2015: Markets for ancillary services
Generators selling ancillary services. Energy Storage Devices participating in ancillary services.
*Kirschen & Strbac Chapter 5: pp130-137.
Sakai Link: https://sakai.duke.edu/access/content/group/0f2bd6e6-f613-4ff0-8f64-8ae5e9e3a409/Documents/Lectures/Lec%2012%20System%20security%20and%20markets%20for%20ancillary%20services/

16. 03/03/2015: Power flow in a transmission network I- Using Kirchhoff current law (KCL) to find current flows
Superposition method to analyze two-bus and three-bus systems.
*Kirschen & Strbac Chapter 6: pp141-165.

17. 03/05/2015: Power flow in a transmission network II- Using Bus Balance Equations to find current flows - Introduction to LMP concept
*Kirschen & Strbac Chapter 6: pp165-192.

03/10/2015 - 02/12/2015: Spring break!

18. 03/17/2015: Power flow in a transmission network III- Calculating flows, and re-dispatch using bus balance equations and KVL - Calculating LMPs
Syllabus as of 1/13/2015. Please see Sakai for updates.

19. 03/19/2015: Capital Investment Decision in Power Generation Capacity Under Uncertainty: The producers perspective
*Kirschen & Strbac Chapter 7
NPV analysis, real options, decision to install and retire power plants.  
*Please make sure you review how to do NPV calculations*
*Kirschen & Strbac Chapter 7: pp205-217.  
-McDonald Chapter 17: Real Options-Investment and the NPV rule, pp. 547-580

20. 03/24/2015: The Consumer’s / ISO perspective: Capacity Markets: Price spikes, reliability and investment
Price and load duration curves.Capacity markets in PJM, CAISO, ISO NE, NYISO.
*Kirschen & Strbac Chapter 7: pp217-226
-Centralized Capacity Market Design Elements, FERC Staff Report, AD13-7-000, August 23, 2013.  
http://www.ferc.gov/CalendarFiles/20130826142258-Staff%20Paper.pdf
file:///C:/Users/dp52/Downloads/m18.pdf

21. 03/26/2015: Transmission rights
Physical and financial transmission rights. Example: PJM FTR market  
*Kirschen & Strbac Chapter 6: pp193-200
http://www.hks.harvard.edu/hepg/Papers/2012/Hogan_Degenrate_Price_033112r.pdf
- FERCs order 1000.  
-Wu F, Varaiya P, Spiller P, Oren S, Folk theorems on transmission access: proofs and counterexamples.-Journal of regulatory economics, 10(1), 1996, 5-23 (available in Sakai)

22. 03/31/2015: Transmission Investment
U.S. transmission system: Eastern and western interconnects and ERCT
Industry organization. Ownership of HV transmission lines. ISO/RTO regions. Cost allocation
*TBA reading on cost allocation for transmission investment in the U.S.
*Kirschen & Strbac Chapter 8: pp227-241.

-Stoft, S, Problems of transmission investment in a deregulated power market. In Competitive Electricity Markets and Sustainability, Edited by Francois Leveque, Professor of Law and Economics, Ecole des mines de Paris, France. Available online from http://stoft.com/ (power system economics, missing chapters)
23. 04/2/2015: MP Symposium

24. 04/07/2015: Transmission Planning
*Kirschen & Strbac Chapter 8: pp241-263.
-Reading on St Clair curves

25. 04/9/2015: De-carbonizing the electricity system in the US - Integrating renewable energy in the US power system. Coping with intermittency, short term variability and transmission constraints Energy storage - The smart grid
- Definition of Effective Load Carrying Capacity, capacity credits for renewable energy.
- Wind energy integration studies.
-Electricity Advisory Committee (EAC), Final Report on Smart Grid. Available on Sakai

26. 04/14/2015: Presentation of the best NickIso Models.

May 1 8:30-1:00PM:
- Oral examination of group analysis of NickIso.