# STIA 402: Clean Energy Innovation

Georgetown University School of Foreign Service

Instructor: Dr. Varun Sivaram, Douglas Dillon Fellow and Acting Director of the Program on Energy Security and Climate Change at the Council on Foreign Relations

## Course Overview

Mitigating climate change will require adopting breakthrough clean energy technologies at scale. This course will focus on the power sector, and students will understand the science behind major clean energy technologies that will be crucial to decarbonizing the sector, including: solar, wind, geothermal, hydroelectric, marine, and nuclear power, as well as energy storage. (This unit will require some familiarity with basic physics, but otherwise will endeavor to build technical fluency from the ground up.) Students will also study the economics behind technological change to understand what is needed to take a laboratory breakthrough to scale production and commercial diffusion. Finally, students will investigate which policies can accelerate innovation as well as which can stunt it, and we will conclude with recommendations for U.S. policy on the domestic and international stages.

We will follow Georgetown's policies on plagiarism and academic integrity.

## Learning Goals

- Have a basic technical understanding of various clean energy solutions, achieve literacy in assessing their performance metrics, and gain exposure to research frontiers
- Understand the economic factors that drive clean energy adoption and recognize energy market limitations that impede technology uptake
- Appreciate the double-edged sword of policy in advancing or obstructing innovation and understand the policy options available to support domestic and international innovation

## Grading

- **50%: Final Paper**: Students can choose to write about any of the weekly sessions for their final paper. The paper should have a focused thesis and respond critically to one or more of the assigned readings. Students are also expected to go beyond the readings to enrich the research behind their paper in constructing an original argument.
- **15%: In-Class Reading Presentation:** Each class session, 1–2 students will make a presentation answering discussion questions about the assigned readings for that session. Students will be assessed on the thoughtfulness and rigor of their presentations
- **15%: Problem Sets**: There will be three problem sets over the semester, each of which will be worth 5% of the grade. Some class time will be set aside to work through problem sets.
- **20%: Participation**: To earn participation credit, students should read the background material ahead of class and contribute to the discussion.

**Textbook:** W.B. Bonvillian and C. Weiss, "Technological Innovation in Legacy Sectors," Oxford University Press, 2015.

**Course Schedule (14 weeks total*)**

***Unit I: Context and Overview (3 Weeks)***

1. Why the World Needs Clean Energy Innovation

2/3. Theory of Technological Change

***Unit II: Clean Energy Technologies to Decarbonize the Power Sector (5 Weeks)***

4. Introduction to Energy and the Power Sector
5. Wind and Solar Power
6. Hydroelectric and Geothermal Power
7. Nuclear Power and Carbon-Capture-and-Storage
8. Energy Storage and the Grid

***Unit IV: How Markets and Policy Can Accelerate Innovation (5 Weeks)***

9. Funding Energy Innovation
10. Balancing Innovation and Deployment

12/13. Creating a National Innovation Ecosystem

14. Promoting Innovation Orchards and Advanced Manufacturing

BONUS: Fostering International Collaboration

***Final Papers Due (End of Term)***

*** One class session, date TBD, will include a roundtable session at the Council on Foreign Relations with a guest lecturer**

## Class Session Descriptions and Reading Lists

### *Unit I: Context and Overview*

#### Why the World Needs Clean Energy Innovation:

What will it take to confront global climate change, and are existing clean energy technologies and approaches up to the task? This session will present the case for why innovation is desperately needed, at a scale and speed unprecedented in the energy sector but consistent with success stories like the biomedical, electronics, and information technology sectors.

*Reading:* Varun Sivaram and Teryn Norris, "The Clean Energy Revolution: Fighting Climate Change with Innovation," *Foreign Affairs,* May/June 2016.

#### Theory of Technological Change:

What is technological change, how does it unfold, what drives it, and why is energy a particularly difficult sector to disrupt? This class session will cover: taxonomy of technological change; overview of general purpose technologies and combinatorial evolution of technology; theory of dominant designs and new industry evolution; spillover benefits of research and development and firm incentives to invest across the technology cycle; technology diffusion, pull vs. push drivers of technological change; and the barriers posed to innovation by legacy sectors like energy.

*Reading:*

- Chapters 1–3 in W.B. Bonvillian and C. Weiss, "Technological Innovation in Legacy Sectors (Links to an external site.)," Oxford University Press, 2015.
- W. Brian Arthur. Chapters 1 and 2, "Nature of Technology," Free Press, pp 15-43. 2009.
- Richard Lipsey, Cliff Bekar, and Kenneth Carlaw, "What Requires Explanation?" in "General Purpose Technologies and Economic Growth," MIT University Press, 1998.
- Arnulf Grubler, Nebojsa Nakicenovic, David G. Victor, "Dynamics of Energy Technologies and Global Change," Energy Policy, 27, 1999. [Read until page to 267 (stop at section 4.2).]
- Adam Jaffe, Richard Newell, and Robert Stavins, "Technological Change and the Environment," Handbook of Environmental Economics, Volume I, 2003. [SEMI-SKIM and STOP at page 489]
- Leon Clarke, John Weyant, and Alicia Birky. "On the sources of technological change: Assessing the evidence," Energy Economics, 28, 2006.
- Nagy et al., "Statistical Basis for Predicting Technological Progress," PLOS One, February 28, 2013.

## Unit II: Clean Energy Technologies to Decarbonize the Power Sector

### Introduction to Energy and the Power Sector:

The key to decarbonizing the world's energy systems lies in the power sector. This session will introduce basic energy facts and terms, provide an overview of why the power sector is so important to mitigate climate change, and introduce the 20th century model of the power grid in the industrialized world. The lecture will conclude by laying out a vision for a modern, 21st century power system.

*Reading:*

- Chapter 1, "Energy Primer," from Grubler, Arnold et al. "Global Energy Assessment." International Institute for Applied Systems Analysis. 2012. [Skim pp 102-108; 111-116; 121-125]
- "Energy Primer: A Handbook of Energy Basics," Federal Energy Regulatory Commission, November 2015, pp 35-56.
- "Energy Technology Perspectives," International Energy Agency, 2015. [Read pp. 25-42, 67-72 and 77-97.]
- Chapter 3 from "Quadrennial Technology Review," Department of Energy, 2015. [Read pp. 53-94]
- Chapter 1 from: Masters, Gilbert. "Renewable and Efficient Electric Power Systems." Wiley. 2nd Ed. 2013.

### Wind and Solar Power:

Overview of the wind and solar resources. Basic technical principles of wind energy (including rotors, generators, and power curves) and solar energy (including semiconductors, current-voltage characteristics, system design). Research frontiers in wind and solar technology. Capital and levelized costs of variable renewable energy systems.

*Reading:*

- Excerpts from Chapters 5, 6, and 7 from: Masters, Gilbert. "Renewable and Efficient Electric Power Systems." Wiley. 2nd Ed. 2013.
- Perveen, Rehana et al., "Off-shore wind farm development: Present status and challenges," *Renewable and Sustainable Energy Reviews*, **29** 2015.
- Varun Sivaram, Sam Stranks, and Henry J. Snaith, "Perovskite Solar Cells Could Beat the Efficiency of Silicon," *Scientific American,* July 1, 2015.

### Hydroelectric and Geothermal Power:

Overview of the hydro and geothermal resources; overview of different types of hydropower including run-of-river, pumped storage, conventional dam; water flow through power stations and introduction to turbines; environmental impacts of hydropower; overview of geothermal configurations and thermodynamic cycles; research frontiers including enhanced geothermal systems; economics of baseload and dispatchable renewable energy systems.

*Reading:*

- Chapter 8 from: Masters, Gilbert. "Renewable and Efficient Electric Power Systems." Wiley. 2nd Ed. 2013.
- "Geothermal Technology Roadmap," International Energy Agency, 2013.
- "Hydropower Technology Roadmap," International Energy Agency, 2012.

**Nuclear Energy and Carbon Capture and Sequestration:**

**Guest Lecturers: Dr. Colin McCormick, CTO of Valence Strategic, and Dr. Dan Stout, Head of Small Modular Reactors, Tennessee Valley Authority**

Introduction to nuclear fission; overview and history of reactor configurations; waste and proliferation considerations; cost trends from 1950s through today; new research frontiers in Generation IV reactors and small modular reactors; overview of carbon capture and sequestration technologies and research frontiers.

*Reading:*

- Chapter 1 from: Linga Murty, K. and Charit, Indrajit. "An Introduction to Nuclear Materials: Fundamentals and Applications." Wiley (1st Ed.). 2013.
- Nordhaus, Ted et al., "How to Make Nuclear Cheap," The Breakthrough Institute, 2014.
- Banks, John and Boersma, Tim, "Fostering Low-Carbon Energy: Next Generation Policy to Commercialize CCS in the United States," Brookings Institution, 2015.
- Varun Rai, David Victor, and Mark Thurber (2010). "Carbon Capture and Storage at Scale: Lessons from the Growth of Analogous Energy Technologies," Energy Policy, Vol. 38, pp 4089-4098.
- "How to make the most of carbon dioxide," *Nature,* 2016.

**Energy Storage:**

Overview of battery technology, alternative chemistries, and performance metrics; concentrated solar power with thermal storage; flywheels, compressed air, molten salts, and other storage technologies; the hydrogen economy, including synthesis, storage, transportation, and use in fuel cells or clean fuel production; and storage applications in electric vehicles and power grid stabilization

*Reading:*

- Matthew M. Mench, "High Hopes for Hydrogen," *Foreign Affairs,* November/December 2015.
- Sections 9.3 and 9.8 from: Masters, Gilbert. "Renewable and Efficient Electric Power Systems." Wiley. 2nd Ed. 2013.
- "Energy Storage Technology Roadmap," International Energy Agency, 2014.
- Section 3C and Section 8E, "Quadrennial Technology Review," DOE, 2015.
- J. Motavalli, "A Solid Future," *Nature*, 2015.

## ***Unit III: How Markets and Policy Can Accelerate Innovation***

**Funding Energy Innovation:**

How do the various activities that compose innovation get funded? This class session will cover: historical U.S. federal funding for energy R&D; private sector funding including venture capital, institutional, and corporate investment in technologies and companies; the Valley of Death and funding needs beyond R&D.

*Readings:*

- J.J. Dooley, "U.S. Federal Investments in Energy R&D: 1961-2008," U.S. Department of Energy, p. 9, October 2008.
- Benjamin Gaddy, Varun Sivaram, and Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong Model for Innovation," MIT Energy Institute, 2016.
- David G. Victor and Kassia Yanosek, "The Crisis in Clean Energy," *Foreign Affairs*, July/August 2011.
- Juliet Eilperin, "Why the Clean Tech Boom Went Bust," *Wired*, January 20, 2012.

**Balancing Innovation and Deployment:**

**Guest Lecturer: Charles Weiss, Distinguished Professor of STIA, Georgetown Univ.**

Should public policy support new technologies or deploy existing ones, and is there any interaction or tradeoff between the two goals? This class session will cover: push vs. pull drivers of technological change; overview of deployment policies to date including renewable portfolio standards, carbon markets, feed-in tariffs, and public procurement; technological lock-in and barriers to technological succession; policy mechanisms to balance innovation and deployment including performance-based standards.

*Readings:*

- Chapters 8, 10, 11 and 12 in W.B. Bonvillian and C. Weiss, "Technological Innovation in Legacy Sectors," Oxford University Press, 2015.
- Abolhosseini, S. and Heshmati, A., "The Main Support Mechanisms to Finance Renewable Energy Development," Institute for the Study of Labor, 2014.
- Christian Azar and Bjorn Sanden, "The elusive quest for technology-neutral policies," *Environmental Innovation and Societal Transitions* (1)1 June 2011, Pages 135–139.
- W. Brian Arthur, "Competing Technologies, Increasing Returns, and Lock-In by Historical Events," *The Economic Journal*, 99 (394), 1989.
- Robin Cowan (1990). "Nuclear power reactors: A study in technological lock-in," The Journal of Economic History, 50 (3); 541-567.
- David Popp, "Innovation and Climate Policy," *Annu. Rev. Resour. Econ*. 2010. 2:275–98.
- Matt Hourihan and Robert Atkinson, "Inducing Innovation: What a Carbon Price Can and Can't Do," Information Technology and Innovation Foundation, 2011.

- Varun Sivaram, "Unlocking Clean Energy Technology," *Issues in Science and Technology*, Winter 2016.

**Creating a National Innovation Ecosystem:**

How can federal and/or state and local governments put together all the pieces that form a national clean energy innovation ecosystem? This class session will cover: national competitiveness; manufacturing and innovation; lessons from other sectors like the military; and policy initiatives to drive private sector innovation.

*Readings:*

- Varun Sivaram, Teryn Norris, Colin McCormick, and David Hart, "Energy Innovation Policy: Priorities for the Trump administration and Congress," ITIF, 2016.
- Jesse Jenkins et al., "Beyond Boom and Bust: Putting Clean Tech on a Path to Subsidy Independence," Breakthrough Institute, April 2012.
- Steven Chu and Arun Majumdar, "Opportunities and Challenges for a Sustainable Energy Future," *Nature* (488), 2012.
- Richard K. Lester and David M. Hart, "Closing the Energy-Demonstration Gap," *Issues in Science and Technology*, Winter 2015.
- American Energy Innovation Council, "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities," February 2015.
- Kelly Sims Gallagher, Arnulf Grubler, Laura Kuhl, Gregory Nemet, and Charlie Wilson (2012)."The Energy Technology Innovation System," Annu. Rev. Environ. Resour., 37:137–62 .
- John P. Weyant (2010). "Accelerating the development and diffusion of new energy technologies: Beyond the "valley of death"," Energy Economics, doi:10.1016/j.eneco.2010.08.008.
- Gary P. Pisano and Willy C. Shih (2009). "Restoring American Competitiveness," Harvard Business Review, Jul-Aug 2009.
- K.G. Mills, E.B. Reynolds, and A. Reamer (2008). "Clusters and Competitiveness: A New Federal Role for Stimulating Regional Economies," Brookings Institute.
- William B. Bonvillian, "The New Model Innovation Agencies: An Overview." *Science and Public Policy*, 2013.
- William B. Bonvillian, "ARPA-E and DARPA: Applying the DARPA Model to Energy Innovation." *Journal of Technology Transfer,* 36, 2011.

**Promoting Innovation Orchards and Advanced Manufacturing**

**Guest Lecturer: William B. Bonvillian, Director, MIT Washington D.C. Office**

*Readings:*

- "Startup Scaleup: Addressing the Manufacturing Challenge for Start Ups," William B. Bonvillian, Annals of Science and Technology, v.1, n.1, First Quarter 2017

- "The new model innovation agencies: An overview," William B. Bonvillian, Science and Public Policy, August 2013.
- "ARPA-E and DARPA: Applying the DARPA model to energy innovation," William B. Bonvillian, Journal of Technology Transfer, October 2011.

**Fostering International Collaboration**

Is there scope for international cooperation on energy innovation, and how might economic competition get in the way? This class session will cover: overview of existing collaborative mechanisms and agreements including the International Energy Agency, Mission Innovation, UN Technology Mechanism, US-China CERC, and US-India PACE; prospects for international public-private innovation partnerships including corporate consortia; the technology transfer debate, intellectual property rights, and prospects for productive partnerships between the United States and emerging economies.

*Readings:*

- Joanna Lewis, "A Better Approach to Intellectual Property?: Lessons from the US-China Clean Energy Research Center," Paulson Institute, 2015.
- David Ockwell, Ambuj Sagar, and Heleen de Coninck, "Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: towards a needs driven approach," *Climatic Change* (131) 3, 2015.
- Varun Rai, Kaye Schultz, and Erik Funkhouser (2014). "International low carbon technology transfer: Do intellectual property regimes matter?" *Global Environmental Change* **24**: 60-74.