## The role of energy systems analysis in understanding how rapidly the world's energy system can be decarbonized?

Eric D. Larson, PhD Senior Research Engineer and Head Energy Systems Analysis Group Andlinger Center for Energy and the Environment Princeton University Princeton, New Jersey, USA

Department of Chemical and Environmental Engineeering University of Seville Seville, Spain 13 November 2018





### What do I mean by "energy systems analysis"

- Applying knowledge from science, engineering, and economics to gain insights on technical, environmental, economic, and societal consequences of engineered systems designed to help solve major energy-related problems like climate change.
  - Engineered systems include new energy supply technologies (e.g., carbon capture and storage systems, renewable energy systems, energy storage systems, advanced modular nuclear reactors), energy demand technologies (e.g., smart buildings, electric vehicle fleets), energy networks (e.g., electricity grids, natural gas pipeline networks, autonomous vehicle systems), and others.
- Energy systems analysis includes
  - assessing how different public policies (e.g., carbon mitigation policies) might impact the commercial deployment of engineered systems.
  - communicating results to inform technology developers and practitioners, as well as public and private decision-making stakeholders.
- + Energy systems analysis emphasizes understanding systems. Individual pieces are represented as accurately as needed to understand the system.



The Energy Systems Analysis Group at Princeton University

A unit of The Andlinger Center for Energy and the Environment focusing research and teaching on major energy challenges:

- + 1 billion people lack electricity
  ~3 billion cook/heat w/dirty fuels
- More than 80% of the world's energy use today is fossil fuel
- The world's "carbon budget" is being rapidly spent
- Electricity from wind and sun is expanding, but storage is expensive



Source: IPCC, Fifth Assessment Report, Working Group III Contribution, 2014.





The Energy Systems Analysis Group at Princeton University

- Engineering and economic systems modeling and analysis to inform policy.
- + Assessing prospective energy, environmental, and economic performance of advanced technology systems.
- Advanced thermochemical fossil fuel and biomass conversion systems, with integrated CO<sub>2</sub> capture.
- + Modeling future electric grids.
- + "Rapid Switch".



Biofuel

with CCS

Petroleum

fuels





Biofuel

with CCS

Petroleum

fuels

1.00

0.75

0.50

0.25

0.00

-0.25

#### Humanity's carbon mitigation challenge







Integrated assessment models & scenarios provide a level of optimism and public assurance of a viable low-carbon future

Is the optimism justified?

Are we paying sufficient attention to transition risks?



IEA, Energy Technology Perspectives (2017)





In reality - a massive, disruptive and capital intensive infrastructure transformation?

*Bottlenecks* and constraints are inevitable with such rapid, large-scale change.







# Rapid Switch – a global, multi-disciplinary collaboration seeking insights to maximize the pace of decarbonization

- In-depth regional, sectoral, and technological assessments of bottlenecks on, constraints to, and implications of rapid decarbonization:
  - Industrial bottlenecks -- critical material supplies, manufacturing capacities and supply chains
  - Human and organizational capacities for systems and infrastructure transformations
  - + Socio-political, regulatory, behavioral norms, and other influences
  - + Broader socio-economic consequences of transitions

andlinger center

 Goal: Inform technology innovation and investment decisions, human resource development efforts, policies aimed at accelerating mitigation and/or adaptation measures.



ERGY SYSTEMS

#### High level questions at the heart of Rapid Switch



ENERGY SYSTEMS ANALYSIS GROUP

capacity etc.

andlinger center

#### Energy productivity challenge



(megajoules primary energy used per GDP\$)

By 2060, India and China are projected to have

- (a) The highest energy productivity in the world.
- (b) Achieved bigger energy productivity gains than any other countries

Courtesy of Joe Lane and Chris Greig, The University of Queensland





11

#### Low-carbon electricity supply challenge



Courtesy of Joe Lane and Chris Greig, The University of Queensland





#### Solar-dominated VRE challenge for India



IEA, 2°C Scenario in 2060





### Lost generation from early coal-plant retirements (2° scenario)



Courtesy of Joe Lane and Chris Greig, The University of Queensland

2°C scenario from IEA, Energy Technology Perspectives 2017





🕏 PRINCETON UNIVERSITY

Potential for CCS to reduce the coal phase-out?

andlinger center

vironment



🕏 PRINCETON UNIVERSITY

#### Some Initial Rapid Switch Research Questions

Case study approach focussing on India and/or U.S.

- 1. What are plausible scenarios for long-term improvement in energy intensity (energy use per GDP\$)? (India focus)
- 2. What are techno-economic challenges that set the pace for deep penetration of variable renewable electricity (VRE) and how are these best addressed? (India, USA)
- 3. What non-technical constraints will set the pace for deep penetration of VRE, e.g., influence of incumbents, public opposition, consumer behavior? How can they be minimized? (India, USA)
- 4. How long does it take for not-yet-commercial technologies to be deployed commercially at scale? (India, USA)
- What policy and/or regulatory solutions can maximize the pace of transition to decarbonized electricity over the next 50 years? (India, USA)





### How far and how fast can VRE penetrate the (U.S.) grid?



#### Case study USA: VRE penetration into PJM ISO

- + Simulate capacity-expansion scenarios, considering plausible supply-side options:
  - Batteries, e.g., 4-hr vs 8-hr battery, location on grid, capex reductions.
  - Expanded transmission requirements, e.g., scale and locations on grid.
  - Off-shore (and onshore) wind, scale and locations on grid.
  - Nuclear?
  - CO<sub>2</sub> capture and storage?
- Evaluate grid mixes to achieve C-intensity reduction of 33%, 33% to 67%, and 67% to 100%.
  - Estimate deployment rates for storage, generation and transmission systems.
  - Estimate implied early retirements of coal and natural gas resources.
- Evaluate effectiveness of electricity markets (and state/federal policies) to evolve the grid to target mixes (run electricity market simulations for the scenarios produced by capacity expansion simulations).
- Select case study technologies (e.g., off-shore wind or HVDC lines) to assess socioeconomic/socio-behavioural challenges (non-rational processes and motivations) implicit in the capacity-expansion scenarios, e.g., land-use competition, pace of regulatory change, multi-stakeholder conflicts, NIMBY behavior, etc.





#### How rapidly can new technology have an impact?



#### FIGURE 4.3: APPROXIMATE GESTATION TIME RANGES FOR RDD&D (23-67 years)

Note that RDD&D is not a linear process; there can be substantial interaction and iteration across these various activities.

The White House, US Mid-Century Strategy for Deep Decarbonization, November 2016.





#### How rapidly can low-C second generation biofuels grow?

 Second generation biofuels are needed to minimize land-use conflicts / maximize carbon benefits, but technologies are not yet mature.



+ What bottlenecks, constraints, resistances might arise?





#### How fast can an advanced biofuels industry develop?



	Corn ethanol	Scenarios for lignocellulosic biofuel industry					
TARGET total feedstock input, PJ/y	2,150	7,000					
Date when 90% of TARGET is reached	n.a.	2043	2047	2051	2055	2058	2062
Years required from 10% to 90%	17	14	17	20	23	25	27
Average feedstock-energy growth, PJ/y/y	111	417	343	292	254	234	205
Average feedstock-volume growth, Mm <sup>3</sup> /y/y	10	187	154	131	114	105	92





#### Negative emissions envisioned for most 2° scenarios



Source: UNEP 2017 (as cited in Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, U.S. National Academies, 2018).





#### Negative emissions systems

#### BIOLOGICAL

ENGINEERED



Sanchez, et al, "Federal research, development, and demonstration priorities for carbon dioxide removal in the United States," Env. Res. Let., 13, 2018.





🕏 PRINCETON UNIVERSITY

SECTOR

#### How fast can BECCS technology develop in the U.S.?

- What biomass conversion technologies will be most likely to be adopted for BECCS?
- If the Allam cycle proves out in its initial demonstration using natural gas, how long will it take for RDD&D to develop it for biomass / BECCS, and what could speed this up?
- What will bottleneck or constrain biomass feedstock supply scale-up?
- How fast can CO<sub>2</sub> storage be developed?
- What public policy and public acceptance conditions are needed?



#### Cement and CO<sub>2</sub>

- Cement and aggregate mixed together (concrete) is the second most used material on earth behind water.
- + Demand will grow.
- Portland cement dominates.
  - Quarries 2 Cru

Quarrying raw materials

- IEA and WBCSD, *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, 2018.
- LBNL, CO<sub>2</sub> Information Analysis Center, April 2018.
- Image from IEA, *Cement Technology Roadmap*, 2009.







## How fast can alternatives to ordinary Portland cement (OPC) spread?

- Low-C alternatives to ordinary Portland cement (OPC) exist.
- + Pace of OPC replacement will depend, *inter alia*, on changes in:
  - Prescriptive construction codes (that specify OPC)
  - Testing standards/methods based on OPC chemistry that are incompatible with other chemistries.
  - Cost of new concretes, which depend largely on supply-chain logistics controlled by vertically-integrated OPC industry.
  - Availability of materials for alternatives at large enough scale to impact OPC.
  - Conservatism in construction industry (status-quo bias).
  - Sustainability incentives that de-emphasize construction materials.
  - Clarity/transparency of lifecycle assessments of alternatives.
  - Dis-incentives, e.g., large sunk capital in incumbent OPC industry.
- Examine historical precedents; interview industry, standards orgs., and other experts to understand construction industry drivers; develop model.

