Electric Energy Systems Transformation

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NSF ENG

Investing in engineering research and education and fostering innovations to benefit society
ENG and SBIR/STTR R&RA Budgets ($M)

- ENG
- SBIR/STTR
- ENG ARRA
- SBIR/STTR ARRA

FY Appropriated Funds

Bar chart showing ENG and SBIR/STTR R&RA budgets from FY 2008 to FY 2017 Request.
Global CO2 Emissions

Source: UNFCCC, UNEP, Climate Action Tracker, Bloomberg New Energy Finance
Major Energy Transitions are Slow!
Carbon Budget for 2 Degree

Data: IPCC/CDIAC/GCP/Peters et al. 2015

Cumulative emissions (Gt CO₂)

- Total Quota: 3670
- Non-CO₂: 770
- Past Fossil Fuels and Industry: 1465
- F14
- SYR
- Past LUC: 533
- Future LUC: 138
- Future Fossil Fuels and Industry: 765
- Total remaining CO₂ quota: 903 Gt CO₂
Figure 3. Estimated Renewable Energy Share of Global Electricity Production, End-2014

Based on renewable generating capacity in operation at year-end 2014.
Figure 4. Renewable Power Capacities* in World, EU-28, BRICS, and Top Seven Countries, 2014
Total Hydro 1055 GW
Figure 16. Solar PV Global Capacity, 2004–2014

World Total: 177 Gigawatts
Figure 17. Solar PV Capacity and Additions, Top 10 Countries, 2014

Gigawatts

- Germany: +1.9 (38.4)
- China: +10.6 (41.2)
- Japan: +9.7 (17.7)
- Italy: +0.4 (18.0)
- United States: +6.2 (20.3)
- France: +0.9 (16.9)
- Spain: ~0 (16.9)
- United Kingdom: +2.4 (14.5)
- Australia: +0.9 (12.1)
- India: +0.7 (12.1)

Legend:
- Added in 2014
- 2013 total
Figure 22. Wind Power Global Capacity, 2004–2014

World Total: 370 Gigawatts
Figure 23. Wind Power Capacity and Additions, Top 10 Countries, 2014

<table>
<thead>
<tr>
<th>Country</th>
<th>Added in 2014</th>
<th>2013 Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>+23.2</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>+4.9</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>+5.3</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>~0</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>+2.3</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>+1.7</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>+1.9</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>+1.0</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>+0.1</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>+2.5</td>
<td></td>
</tr>
</tbody>
</table>
Wind and solar energy have grown faster than expected

Report: Trancik Lab, MIT, 2015

Source: Trancik, MIT, 2015
Renewables growth under countries’ climate pledges (INDCs)

Power capacity, wind and solar

- China
- U.S.
- EU-28
- India
- Japan

Source: Trancik, MIT, 2015

Report: Trancik Lab, MIT, 2015
All methodologies show a downward trend in PV system pricing.

Reported pricing and modeled benchmarks historically had similar results; however, they have recently diverged in estimated pricing.
PV: Utility Scale vs Residential

- **PV Generation costs:**
  - residential-scale systems: 16.7¢/kWh
  - utility-scale PV systems: 8.3¢/kWh

- **Reasons for this gap:**
  - lower total plant costs per installed kilowatt for larger facilities
  - greater solar electricity due to optimized panel orientation and tracking;
  - other economies of scale and efficiencies

- **Avoided transmission and distribution costs by residential-scale systems are not large enough to significantly impact this gap in generation costs.**
Competing Requirements for the Electric Grid

• Reliability
  – Capacity adequacy, fuel security, system operations and control, cybersecurity, resilience to extreme events, variability of renewable generation, leveraging demand demand flexibility

• Sustainability
  – Renewable generation, energy efficiency

• Cost
  – Economic growth, quality of life, low income consumers, developing nations,
Electric Grid Characteristics

- High voltage transmission network - a *mesh* network
- Distribution networks - largely *radial* networks
- *Dynamic system* with multiple time scales
- Milliseconds, seconds, minutes, hours, days, months, and years
- Electric energy storage - very expensive
- Energy produced must equal energy consumed on a second-by-second basis – *power balance*
  
  - *A complex hierarchical control system to ensure stability and performance of the large scale networked power system*
Power Balance

- *Power balance* – balance power generation and consumption on a second-by-second basis
- Traditional Approach: *adjust supply to meet demand with reliability*
- Natural uncertainty in consumption [load]
- Use of reserve capacity to manage uncertainty and contingencies
- Day-ahead – hourly schedules, one day ahead
- Real-time – 5 minute schedules, 15 minutes ahead
- Automatic generation control using system frequency
- Deregulation of the electricity sector – *unique mix of engineering and economics*
Variability of Wind and Solar

- Power output varies in all time frames:
  - Annual
  - Seasonal
  - Daily
  - Hours
  - Minutes
  - Seconds

*Intermittency, uncontrollability, and uncertainty - principal causes of difficulty at the operational level in integration of wind and solar into the grid.*
California Duck Curve

Figure 1. The CAISO duck chart

Source: CAISO 2013
Enablers of Renewables Integration

- New transmission infrastructure including DC
- Larger balancing areas and geographic aggregation
- Improved forecasting
- Stochastic optimization for smart operations
- Demand side control
- Distributed deployment and control
- More frequent intra-day markets
- Storage
- Electric transportation
- Conversion to transportation fuels
Imagine if we had Cost Effective Storage and PV

10.7 kW PV, 6 kWh Li-ion battery, electronics/controls
ECCS: Renewables DCL


• Purpose: support creative ideas addressing the continuing rise of renewable electric power generation.
ECCS: Renewables DCL

• Does large penetration of renewables affect power quality & grid stability? If so, what needs to be done? New policy? New automation?

• Are current market mechanisms appropriate going forward?
  – What policies should be in place to avoid undesired economic consequences of the evolution to the next generation grid?

• Do protection systems need redesign as the penetration of renewables increases?
Funded Proposal Topics (14 Grants)

- Grid stability analysis techniques with stochastic renewables (Mathieu; Chow).
- Policy issues for long term planning of the transition from thermal-dominated electric energy systems to a renewable-dominated design (Conejo; Tong).
- Stochastic optimization/mixed-integer programming for topology control of future grid (Oren/Sen)
- Design of new market mechanisms (Gupta/Turitsyn; Li; Poolla; Parvania/Scaglione; Zhu)
- Prosumer-centric energy management incorporating behavior modeling (Xie; Saad/Poor/Mandayam) – including use of Nobel prize winning “prospect theory” methodology by the latter team.
- Applying allometry (development of biological shapes) to understanding of power distribution network structure (Dobson).
- New framework for power system protection (Santoso).
CRISP: Critical Resilient Interdependent Infrastructure Systems & Processes

- FY15 funding for CRISP: $20 million
  - *Type 1 Awards*: 3-year projects, $500k max
  - *Type 2 Awards*: 3-4 year projects, $1M-$2.5M
CRISP Program Goals

1. Create new approaches/solutions for design/operation of infrastructures as processes/services
2. Enhance understanding/design of ICIs and processes under disruptions from any cause
   – natural, technological, organizational or malicious
   – various timescales and intensities
3. Create knowledge for innovation in ICIs to safely, securely, and effectively expand range of goods and services they enable
4. Improve ICI’s effectiveness, efficiency, dependability
Engineering Research Centers

- Future Renewable Electric Energy Delivery and Management Systems Center (FREEDM)
- Center for Ultra-Wide Resilient Electric Energy Transmission Networks (CURENT) – joint with DoE
- Quantum Energy and Sustainable Solar Technologies (QUEST)- joint with DoE
- Smart Lighting
- New ERC Competition *underway*
Industry-University Cooperative Research Centers

- Power Systems Engineering Research Center (PSERC)
- Energy-Smart Electronic Systems (ES2)
- Energy Harvesting Materials and Systems (CEHMS)
- Grid-Connected Advanced Power Electronic Systems (GRAPES)
- Advanced Vehicle and Extreme Environment Electronics (CAVE3)
- Novel High-V/T Materials and Structures (HVT)
- Next Generation Photovoltaic
- Silicon Solar Consortium
- Wind Energy Science, Technology and Research (WindSTAR)
The most important way to speed up the gradual transition to renewables is to lower overall energy use through efficiency gains. The faster global demand rises, the more difficult it is to supply a large fraction of it.

Vaclav Smil, Scientific American, January 2014
IEA on Energy Efficiency

Energy efficiency potential used by sector in the WEO 2012 New Policies Scenario

Source: IEA, WEO 2012

August 4, 2015
Negative Emissions Technologies

… the CO2 trend “is perfectly in line with a temperature increase of 6 degrees Celsius, which would have devastating consequences for the planet.”

Fatih Birol
IEA chief economist
QUESTIONS?

IDEAS, SUGGESTIONS!

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Electric Energy Projections

- Global electricity demand rising by 65 percent 2014-2040
- Residential and commercial electricity demand rises by 70 percent 2014-2040; industry up 55 percent
- Industrial growth eases post-2030 as China’s economy shifts from manufacturing
- Transportation electricity demand doubles 2014-2040, but only 2 percent of total use

Source: Exxon Annual Energy Outlook
Wind and Solar Capacity Projections

**WIND**

- WEO 2002
- WEO 2004
- WEO 2006
- WEO 2008
- WEO 2009
- WEO 2010
- WEO 2011
- WEO 2012
- WEO 2013
- WEO 2014
- WEO 2015

- Actual
- BNEF forecast

**SOLAR**

- Revised up 5-fold since 2000
- Revised up 14-fold since 2000

Electricity System R&D Needs

• Develop and refine interoperable grid architectures and new system designs
• Develop software and visualization tools that use new data from transmission and distribution system devices for enhanced, real-time operations and control
• Research material innovations and develop transmission and distribution component designs for higher performance, reliability, and resilience
• Embed intelligence, communication, and control capabilities into distributed energy resources and systems such as microgrids to support grid operations
Electricity System R&D Needs

• Improve energy storage capabilities and systems designs that lower costs while increasing capacity and performance, and facilitating integration

• Develop high-fidelity planning models, tools, and simulators and a common framework for modeling, including databases

• Design innovative technologies and resilient and adaptive control systems to improve physical- and cyber-security of the grid
Key Challenges to Deep Renewable Integration

• New transmission infrastructure
• Larger geographic balancing areas
• Greater flexibility in all aspects of power system operations
• Cost-effective energy storage
• Provision of reserves
• Grid management and control
Figure 4: Energy Storage Options: Discharge Time vs. Capacity Ratings
<table>
<thead>
<tr>
<th>NET</th>
<th>2050 Potential (per year)</th>
<th>Key constraints</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afforestation and Other Forestry</td>
<td>1.3 GtCO₂, 0.13-0.38 ppm</td>
<td>Conservative estimates of available land area and carbon yields</td>
<td>Higher estimates for afforestation may conflict with land used for food production or energy crops</td>
</tr>
<tr>
<td>Agricultural Soil Carbon</td>
<td>1.4-3.9 GtCO₂, 0.18-0.50 ppm</td>
<td>Suitable land areas and attainable annual sequestration rates</td>
<td>Fewer trade-offs with other land uses; saturation and risk of impermanence limit cumulative potential</td>
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<tr>
<td>Biochar</td>
<td>~2.2 GtCO₂, ~0.28 ppm</td>
<td>Pyrolysis of 60 EJ per year (3 Gt per year) bioenergy residues and wastes</td>
<td>May conflict with other demands for residues and wastes; assumes 80% stability over century timescales</td>
</tr>
<tr>
<td>BECCS</td>
<td>~1.5 GtCO₂, ~0.19 ppm</td>
<td>Constrained by CCS roll-out and integration with bioenergy, using IEA projections for 2050</td>
<td>Bioenergy supply is a less limiting constraint than CCS development to 2050.</td>
</tr>
<tr>
<td>Direct Air Capture</td>
<td>~0.25 GtCO₂, ~0.03 ppm</td>
<td>This figure assumes use for EOR at a scale equivalent to the current US market</td>
<td>High costs give it very little role pre-2050 in ‘optimal’ mitigation models</td>
</tr>
<tr>
<td>Ocean Liming</td>
<td>~0.25 GtCO₂, ~0.03 ppm</td>
<td>This figure assumes all existing lime wastes from cement production are used for carbon capture</td>
<td>No detailed projections / models available, but similar challenges to DAC</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>6.6-11.1 GtCO₂, 0.85-1.42 ppm</td>
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# Carbon Budgets

Table 1: 2011 and 2014 remaining cumulative carbon budgets for different peak warming and probability thresholds. Data and information are taken from table 2.2 of IPCC Syn, 2014 with cumulative emissions between 2011-2013 calculated from Le Quéré, 2014.

<table>
<thead>
<tr>
<th>Warming*</th>
<th>Likelihood**</th>
<th>Budget (CCE)** in 2011</th>
<th>Emitted (CCE) 2011-2013</th>
<th>Budget (CCE)** in 2014</th>
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<tr>
<td>&lt; 1.5°</td>
<td>66%</td>
<td>400</td>
<td>116</td>
<td>284</td>
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<td></td>
<td>50%</td>
<td>550</td>
<td>116</td>
<td>434</td>
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<tr>
<td></td>
<td>33%</td>
<td>850</td>
<td>116</td>
<td>734</td>
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<tr>
<td>[GtCO₂]</td>
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<td>&lt; 2.0°</td>
<td>66%</td>
<td>1000</td>
<td>116</td>
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<td></td>
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<td>1500</td>
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<td>2684</td>
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<td>3250</td>
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<td>3134</td>
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<td>[GtC]^</td>
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<td>&lt; 1.5°</td>
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<td>109</td>
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<td></td>
<td>50%</td>
<td>150</td>
<td>32</td>
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<td>33%</td>
<td>231</td>
<td>32</td>
<td>200</td>
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<tr>
<td>&lt; 2.0°</td>
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<td>50%</td>
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<td>322</td>
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<tr>
<td></td>
<td>33%</td>
<td>408</td>
<td>32</td>
<td>377</td>
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<td>&lt; 3.0°</td>
<td>66%</td>
<td>653</td>
<td>32</td>
<td>622</td>
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<td>50%</td>
<td>762</td>
<td>32</td>
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<td></td>
<td>33%</td>
<td>885</td>
<td>32</td>
<td>853</td>
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</table>

^Conversion factor: 1 GtC = 3.664 GtCO₂

Source: Pfeiffer et al 2016, Oxford University