Magnitude of the Challenge

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Introduction to Conversation 6

Energy Technology and Policy in the Symposium
“Destiny Studies for a Small Planet”

Celebrating the Career of Rob Socolow

Princeton University • 15 April 2019
<table>
<thead>
<tr>
<th></th>
<th>Population (millions)</th>
<th>ppp-GDP (trillion $)</th>
<th>Energy (ej)</th>
<th>Fossil E (percent)</th>
<th>Fossil CO$_2$ (MtC)</th>
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</thead>
<tbody>
<tr>
<td>World</td>
<td>7530</td>
<td>120.6</td>
<td>625</td>
<td>82%</td>
<td>9404</td>
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<td>China</td>
<td>1386</td>
<td>22.2</td>
<td>136</td>
<td>87%</td>
<td>2596</td>
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<tr>
<td>USA</td>
<td>326</td>
<td>19.6</td>
<td>98</td>
<td>85%</td>
<td>1422</td>
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<tr>
<td>India</td>
<td>1339</td>
<td>9.4</td>
<td>41</td>
<td>74%</td>
<td>648</td>
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Of primary energy for electricity, 67% was from fossil fuel.
World energy-related CO₂ emissions hit record high

In 2018 emissions grew at the fastest rate since 2013. Emissions from coal-fired power plants contributed the largest share of this growth.

35 billion metric tons

Source: International Energy Agency

JOHN MUYSKENS/THE WASHINGTON POST
Deep reductions needed to reach goal of $\Delta T < 2^\circ$C

Emissions pathways 1990-2100

50% chance of $\Delta T < 2^\circ$C requires emissions ~80% below “low policy” by 2050.
The challenge of reducing CO$_2$ emissions

- The path to a 50% chance of $\Delta T < 2$°C requires 2050 emissions about 44 GtCO$_2$/yr below the “Low Policy” path.
- That’s about 12 GtC. Avoiding 1 GtC/yr in 2050 requires... 
  - energy use in buildings cut 20-25% below BAU in 2050, or
  - fuel economy of 2 billion cars ~60 mpg instead of 30, or
  - carbon capture & storage for 800 1-GWe coal-burning power plants, or
  - 700 1-GWe nuclear plants replacing 700 1-Gwe coal plants, or
  - 1 million 2-MWe(peak) wind turbines replacing 700 1-Gwe coal plants or
  - 2,000 1-GWe(peak) photovoltaic power plants replacing 700 1-Gwe coal plants

The 1 GtC/yr figures are from the famous Pacala & Socolow “Stabilization Wedges” paper in Science, 13 August 2004.
Novel CCS Strategy in Context of a Diverse Energy Technology Portfolio on Path to Zero US Emissions by 2050

Robert H. Williams
Andlinger Center for Energy and the Environment, Princeton University

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**IEA Below 2 Degrees (B2DS)**

- **B2DS of IEA (2017):** diverse portfolio of technologies & strategies for getting US to zero emissions by 2050
- **Foci:** electricity generation + novel CCS strategy in variant of B2DS of IEA (2017):
  - By 2050 all fossil fuel (FF) “rebuild” capacity sited near sites for sequestration via enhanced oil recovery (EOR)
  - Decarbonized FF power brought to market by wires, including long wires
  - CO$_2$ capture technologies “designed from scratch” for CCS are commercialized (Allam Cycle)

Moniz: "Getting a move on CCS is very important...Right now that's not happening. If you don't do that, the job is much, much tougher." 2019 EFI report on CA emissions goals
CO₂ Enhanced Oil Recovery: Squeezing more oil out of mature fields

A Way Forward Based on What We Already Do Well:

- **Conventional EOR** represents current practice.
- **Conventional EOR+** requires oil provider to undertake monitoring and verification of permanency of CO₂ sequestration.
- **Advanced EOR+** includes co-optimizing EOR for oil recovery & CO₂ sequestration.
**US CO₂ Sequestration Potential via EOR**

Major US CO₂ EOR Opportunity Regions (red #s are % of national potential)

**Advanced EOR+** could meet sequestration needs of IEA B2DS!
Decarbonized FF power by wire by midcentury

• By midcentury all FF power plants will be retired or retired & replaced
• Replacement units equipped with CO₂ capture equipment & located near EOR sites where CO₂ is sequestered (previous slide);
• Generated electricity transported to markets by wire, ultimately via national grid linking regional sub-grids, including HVDC linkages among 3 interconnections
• Result: Less CO₂ infrastructure, more grid infrastructure, but lower electricity prices

US interconnections

Proposed HVDC linkages among regional balancing authorities
High grid penetration by intermittent renewable electricity (IRE) can lead to curtailment; adding more IRE becomes uneconomic.

Least costly strategy for minimizing IRE curtailment: expand market in which IRE is generated & consumed (adding transmission capacity as needed)

1st step (advocated by Gov. Brown): create single electricity market for highly balkanized Western Interconnection (38 balancing authorities!)

Proposal: CCS and IRE communities should consider joining forces to limit constraints to linking regional grids and ultimately creating a national electricity market & grid.
Allam Cycle: “Designed from Scratch” for CCS

Semi-closed “trans-critical” Brayton power cycle

1. CO₂ is the working fluid
2. Fuel is burned in nearly pure O₂,
3. CO₂ recovered (100% capture) by cooling turbine exhaust gases & condensing out H₂O.

• **25 MWₑ** Natural gas (NG)-fired demonstration plant built w/o subsidy (Toshiba/Exelon involved) & is operating.
• Plan is to build 300 MWₑ NG Allam Cycle commercial plant by 2021
• Potential game changer for NG, coal, biomass power:
  • Generation cost for NOAK plant plausibly ~ same as for conventional power plants venting CO₂
  • NG version being designed with fast-ramping capability (zero-carbon “balancing capacity” for grids with much IRE)
Key Generation Features of IEA (2017) 2BDS Revisited

IEA (2017) B2DS Generation mix, 2050:
- 47% IRE
- 31% zero C baseload
- 15% zero C FF balancing capacity
- 7% hydro

- Realize IEA (2017) B2DS 2050 generation mix w/ novel CCS strategy
  - Baseload mix of Allam Cycle gas, coal, & biomass power + geothermal & nuclear
  - w/o Allam cycle, similar mix could be realized at higher cost
- W/o national grid:
  - Similar IRE/baseload mix could be realized at higher cost via extensive bulk, long-duration electricity storage:
    - Pumped hydro and compressed air storage are geographically constrained & probably not adequately w/o something a national grid
    - Advanced (e.g., flow) batteries might one day become available but still at higher cost
  - Decarbonized FF power by wire not possible ➔
    - More extensive CO₂ pipeline system (CCS limited geographically) ➔ higher cost, or
    - More nuclear, less CCS ➔ higher cost
Technology Cost Buydown (TCB): Especially Formidable Challenge for CO₂ Capture

Mountain of Death for New Large-Scale Technologies

- 1ˢᵗ of a kind (FOAK) capture plant (atop “Mountain of Death”—above left) much more costly than NOAK plants (far to right of Mountain)
- Governments comfortable subsidizing TCB for small scale technologies (tiny bit at a time—cumulative subsidies huge) but reluctant to provide large “lumpy” subsidies to support TCB for large-scale novel energy systems
- Way forward possible in California: Low Carbon Fuel Standard (LCFS) has new protocol for qualifying CCS projects, so that, in CO₂ EOR applications 1 tonne of captured CO₂ could plausibly fetch a price [with LCFS (above right) + 45Q credits] ≈ $225/tonne of CO₂
Can we get there from here?
Challenges on the left...

and the right.
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Fawcett et al., SCIENCE, December 4, 2015
If US were to adopt Advanced EOR+ as sole oil source:

- it could export large fraction of oil produced at mid-century—e.g., to non-OECD countries
- Financial risk of ending up with stranded assets would be much reduced relative to seeking new oil fields to develop