Finding an “Optimal” Path to 2050 Decarbonization Goals

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Substantial Effort Beyond NDCs Will Be Required

Global Emissions

- Peaking global emissions requires more than NDCs, and more than developed countries
- Precipitous drop for pursuing a high likelihood of < 2°C post-2030

Global Temperature

From EPRI analysis by Richels, Rose, Blanford, and Rutherford, “The Paris Agreement and Next Steps in Limiting Global Warming”
How Deep Will Decarbonization Targets Be?

- Natural gas reversed U.S. emissions trend, but additional actions required to meet goals moving forward
- Clean Power Plan is the climate policy du jour, but what’s next?
  - Post-2030 power sector targets?
  - Targets in other sectors?
  - Ambitions outside of the U.S.?
- Reliance on market-based instruments vs. regulatory approaches?
US-REGEN 48-State Version: EPRI’s In-House Electric Sector and Economy Model

Capacity Expansion Economic Model, Long Horizon to 2050

State-Level Resolution for Policy and Regulation Analysis

Innovative Algorithm to Capture Wind, Solar, and Load Correlations in a Long-Horizon Model

For more information, see our website at http://eea.epri.com
2050 U.S. Generation Mix

Observations

- Natural gas prices materially impact power sector investments
- CPP reinforces market trends
- Using a piecemeal regulatory approach will impact technological pathways (and achievable emissions reductions)
  - Overlapping policies?
  - Post-2030?
Power Sector CO₂ Emissions
Assuming AEO 2016 Load and Fuel Prices, PTC/ITC Extensions

Historical

80% Below 2005
U.S. Low-Carbon Electricity by 2050 (95% Below 2005)

Generation

Capacity

Annual TWh

Capacity

Installed GW

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How Cheap Will Low-Carbon Technologies Be?

Observations

- Targets and technologies determine generation mix
- Cost reductions moving forward will be critical
- Supply.curve-like dynamics, sunk costs, and functional attributes (energy/capacity/flexibility) drive portfolio diversity
  - Unmodeled drivers of diversification: Uncertainty, public acceptance
  - Interactions with other sectors and load shapes
Technical and Economic Challenges of Very High Renewables

Key Takeaways

• Diminishing marginal returns for increasing renewable energy deployment
  o Varies by region (e.g., higher in regions without transmission)
  o Varies by technology (e.g., higher with solar)
• Energy storage is valuable at high renewable penetration levels, but potential revenues diminish with increased storage deployment
• Already observing value deflation for solar in recent market experience in California

US-REGEN Results for California in 2030

“Technical and Economic Challenges of Flexible Operations: Case Studies of California and Texas” EPRI annotated PowerPoint (#3002008242) is free and publicly available
GHG Emissions with Economy-Wide 80% Cap

US-REGEN Results: All Sectors, All Gases

Observations

- 80% target by 2050 entails ambitious transformations
- Decarbonization in power sector early enables reductions in other sectors through electrification
- Higher-abatement-cost sectors reduce emissions once targets tighten
### Beyond 2050: How to Think about Zero Emissions (and Below)?

<table>
<thead>
<tr>
<th>Goal</th>
<th>Emphasis</th>
<th>Focus Areas for RD&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Path 1: Zero Gross Emissions</strong></td>
<td>Emphasis on developing substitutes for fuels in end uses</td>
<td>Electrification, biofuels, hydrogen, and demand reduction</td>
</tr>
<tr>
<td>(i.e., without negative emissions strategies)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Path 2: Zero Net Emissions</strong></td>
<td>Emphasis on carbon dioxide removal (CDR) options alongside substitutes for end-use fuels</td>
<td>Electrification and CDR (e.g., bioenergy with carbon capture and storage, direct air capture, afforestation)</td>
</tr>
<tr>
<td>(i.e., including negative emissions strategies)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Path 3: Negative Emissions</strong></td>
<td>Emphasis on negative emissions technologies, geoengineering, and substitutes for end-use fuels</td>
<td>All of the above, but full tilt on negative emissions technologies and geoengineering</td>
</tr>
</tbody>
</table>

**Under deep decarbonization, the availability and cost of carbon dioxide removal (CDR) technologies impact the abatement challenge for other sectors**
Key Takeaways

Desirability of “optimal” pathways will vary by stakeholder
- Subject to range of constraints, uncertainties, and tradeoffs among objectives
- Roles of modeling to identify and avoid suboptimal pathways and to iteratively refine goals, policies, and implementation

Stringency of long-term targets matters
- Basics: 50% vs. 80%? 2050 vs. 2100? Power sector vs. economy wide?
- Even if “deep decarbonization” by 2050 is the objective, the details matter: Covered sectors and gases? 80/90/100%? Net vs. gross emissions?

Pathways depend on technological cost/performance/availability as well as the policy approaches taken to achieve stated goals
Strategic Insights: How Deep? How Cheap?

- Decarbonization combines many difficult optimization problems at the same time → Hard to find one “optimal” pathway

<table>
<thead>
<tr>
<th>Feature</th>
<th>Example</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-objective</td>
<td>Creating safe, affordable, reliable, and environmentally responsible energy system</td>
<td>Importance of working across disciplines and accounting for values of different stakeholders</td>
</tr>
<tr>
<td>High-dimensional</td>
<td>With power sector, need a multi-decadal horizon combined with hourly dispatch</td>
<td>Refine our tools, questions, algorithms (and work with operations researchers)</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Many known unknowns and unknown unknowns</td>
<td>Corner solutions are unlikely and adaptive strategies are preferred</td>
</tr>
</tbody>
</table>

- Broad RD&D portfolio across supply- and demand-side options
- Need for both technological and policy-related innovation
Bibliography

- Bistline and Blanford (2016), More Than One Arrow in the Quiver: Why “100% Renewables” Misses the Mark, *PNAS*, 113(28):E3988.

For more information, see our website at [http://eea.epri.com](http://eea.epri.com)
Together...Shaping the Future of Electricity

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U.S. Regional Energy, GHG, and Economy (US-REGEN)

General Equilibrium Economy Model
- Customizable Regions
- Aggregate Economic Representation
- Energy Markets for Oil, Natural Gas, Coal, and Bioenergy
- Iterates with Electric-Sector Model

Energy Demand (Electric & Non-Electric)
- Energy Efficiency across Commercial, Industrial, and Residential Sectors
- Transportation: Detailed Model of Vehicle Technologies

Electric Sector Module
- Endogenously Builds/Retrofits/Retires Capacity
- Simultaneously Capacity Planning and Dispatch
- Co-Optimizes Transmission
Natural Gas Price Uncertainty Represented with EIA’s Annual Energy Outlook Paths

Note: AEO data extends through 2040. Prices held constant through 2050.
US-REGEN Assumed Capital Cost Trajectories

- Solar (CSP)
- Nuclear
- Biomass
- Coal with CCS (IGCC)
- Coal without CCS (SCPC)
- NGCC with CCS
- Wind (Onshore)
- NG Combined Cycle
- Utility-Scale Solar (PV)
- NG Combustion Turbine

Capital Cost ($/kW)

Year:
- 2020
- 2025
- 2030
- 2035
- 2040
- 2045
- 2050

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Technological Cost Sensitivities

Wind

- Use “low scenario” for onshore and offshore wind

Nuclear

- Assume $2,000/kW after 2030
How Cheap Will Low-Carbon Technologies Be?

- Metrics for evaluation: Requires information about marginal costs, value, and system context
- Rapid technological change... but uncertainty moving forward

Sources: energy.gov (left), eia.gov (right)
Many Americans support government action to address climate change, but willingness-to-pay is low (42% unwilling to pay $1/month)

Source: University of Chicago (Energy Policy Institute) and Associated Press (NORC Center) 2016 survey
Global Future of Fossil Fuels in a 2°C World Hinges on CCS

Created using model results from IPCC AR5 WGIII (450 ppm scenarios)
Technical and Economic Challenges of Very High Renewables

Key Takeaways
• System balancing could come from many resources (including trade)
• Negative correlation between solar output and residual load creates profitability challenges
• Very high wind/solar systems require nearly same amount of dispatchable generation as low-renewable systems
• Capacity factors and full-load hours of natural gas units decrease: Reduced utilization of capital drives profile costs and raises market-design questions
## Scenarios for Paris Agreement Analysis

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>India &amp; Other Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>Level 1: Post-2050 leveling off</td>
</tr>
<tr>
<td>BAU</td>
<td>1</td>
</tr>
<tr>
<td>NDC only</td>
<td>2</td>
</tr>
<tr>
<td>NDC +</td>
<td>3</td>
</tr>
<tr>
<td>NDC ++</td>
<td>4</td>
</tr>
</tbody>
</table>

### EU, US, Other G20, China

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>US</th>
<th>EU</th>
<th>OG20</th>
<th>China</th>
<th>Post-2050 reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDC only</td>
<td>NDC</td>
<td>NDC</td>
<td>NDCs</td>
<td>NDC</td>
<td>0%/yr</td>
</tr>
<tr>
<td>NDC +</td>
<td>NDC, 2050 50% (2005)</td>
<td>NDC, 2050 50% (1990)</td>
<td>NDCs, 2050 20% (1990)</td>
<td>NDC, 2050 = 2030</td>
<td>1.5%/yr</td>
</tr>
<tr>
<td>NDC ++</td>
<td>NDC, 2050 80% (2005)</td>
<td>NDC, 2050 80% (1990)</td>
<td>NDCs, 2050 50% (1990)</td>
<td>NDC, 2050 60% &lt; 2050 BAU</td>
<td>4.5%/yr</td>
</tr>
</tbody>
</table>

### India & Other Countries

<table>
<thead>
<tr>
<th>Level</th>
<th>India peak year</th>
<th>OC peak year</th>
<th>Post-peak reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1: Post-2050 leveling off</td>
<td>2060</td>
<td>2060</td>
<td>0%/yr</td>
</tr>
<tr>
<td>Level 2: Mid-century peak and decline</td>
<td>2050</td>
<td>2050</td>
<td>1.5%/yr</td>
</tr>
<tr>
<td>Level 3: Earlier peak and stronger decline</td>
<td>2040</td>
<td>2040</td>
<td>4.5%/yr</td>
</tr>
</tbody>
</table>
What’s Required? Regional Emissions Effort

- All levels of effort non-trivial
- For a chance at < 2°C, significant mid-century abatement needed (at least NDC ++ and Level 3)