Deeper Decarbonization
Carbon Capture to achieve Net-Zero Emissions in the U.S.

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Ben Haley
*Evolved Energy Research*
About Evolved Energy Research

- Energy consulting firm focused on addressing key energy sector challenges posed by energy system transformation
- Lead developers of EnergyPATHWAYS and RIO, two models used to investigate pathways to deep decarbonization
- We advise clients on issues of policy implementation and target-setting, infrastructure investments, R&D strategy, technology competitiveness, and asset valuation
Constraints:
- BAU population, GDP growth
- BAU energy services
- Commercial and near-commercial technology
- infrastructure inertia
- reliable electricity
- no early retirement
- no NETs
- Net FF CO₂ <120 Gt CO₂ to 2100
Three pillars of deep decarbonization (for 80% by 2050)

United States

2050 U.S. Benchmarks

• 2x increase in the share of energy from electricity or electrically derived fuels
• ~99% decrease in the emissions intensity of electricity generation
• 3x drop in energy use per unit GDP
• It is technically possible to transition the U.S. off of fossil fuels at a pace consistent with 350 ppm trajectories.

• Placing the U.S. energy system on a pathway to 350 ppm is affordable and would increase the total cost of the energy system in the U.S. by only 2-3% of GDP.

• Delay is exceedingly costly as a strategy when examining cumulative emissions targets. At current pace, we will exceed our mid-century emissions budget by 2030.

• There are multiple scenarios that achieve this scale and pace of reductions.
350 ppm global trajectories


Earth System Dynamics
Mitigation targets and net CO$_2$ emissions

- 2$^\circ$C
- 1.5$^\circ$C
- 350 ppm

CO$_2$ emissions

CO$_2$ removal
Four Pillars

- 350 PPM analysis reinforces necessity of three pillars defined in previous 80x50 analyses
- 350 PPM also requires the employment of CO2 capture strategies in heavy industry, biorefining as well as the deployment of direct air capture facilities
Carbon Capture and Removal Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Negative Emissions When CO2 Sequestered</th>
<th>Zero Emissions When CO2 Sequestered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Sequestration</td>
<td>Sequestration of additional CO2 in enhanced land sinks (i.e. soil, forests, etc.)</td>
<td>☑</td>
<td></td>
</tr>
<tr>
<td>Direct Air Capture</td>
<td>Technical removal of CO2 from the ambient air</td>
<td>☑</td>
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<tr>
<td>Bioenergy Carbon Capture</td>
<td>Point source capture of CO2 from facilities using bioenergy</td>
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</tr>
<tr>
<td>Fossil Carbon Capture</td>
<td>Point source capture of CO2 from facilities using fossil energy</td>
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</tbody>
</table>
CO2 Source and Sinks in Low-Carbon Economy

**Heavy Industry**
- Iron & Steel
- Cement
- Petrochemicals
- Refineries

**Biorefining**
- Ethanol
- FT Liquids

**Hydrogen Production**
- Steam reforming
- Autothermal reforming
- BECCS

**Direct Air Capture**

**Electricity Generation**
- Post-combustion capture
- Allam cycle

**Utilization**

**Geologic Sequestration**
Scale of Carbon Capture

Range of Capture Volumes from forthcoming U.S. analyses
## Carbon Capture Competitive Landscape

<table>
<thead>
<tr>
<th>Application</th>
<th>Competitors</th>
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</thead>
<tbody>
<tr>
<td>Hydrogen Production</td>
<td>Electrolysis</td>
</tr>
<tr>
<td>Biorefining</td>
<td>On-road electrification; electricity derived fuels</td>
</tr>
<tr>
<td>Heavy Industry</td>
<td>Process electrification; hydrogen</td>
</tr>
<tr>
<td>Electricity Generation</td>
<td>Renewables; batteries; fuel substitution in conventional gas power plants</td>
</tr>
<tr>
<td>Direct Air Capture</td>
<td>All decarbonization strategies including land-based sequestration</td>
</tr>
</tbody>
</table>
Utilization and/or Storage

- Competition between use and sequestration dictated by emissions targets, cost of fossil alternatives, and projected sequestration availability and cost.
Deep Decarbonization vs. Deeper Decarbonization

• Principal activities to go from deep (80% reductions) to net-zero targets is in the area of carbon capture for both sequestration and utilization purposes

• Need near-term technology development, deployment, and policy support to insure that these are available at scale when we need them

• Initial perceptions of carbon capture focused on their cost-effectiveness compared to renewables in power generation. Their importance to achievement of these net-zero targets, deployed in applications across the economy, is not well understood or appreciated
Open Questions

• Available sequestration injection potential
• Public acceptance of CO2 pipelines
• Technology demonstration timelines
• Emissions accounting
• Utilization vs. sequestration breakdown