Outline

• CO$_2$ stabilization and the pace of transformation
• Transformation pathways
• Enabling environments for technology deployment
• Technology R&D portfolios
CO$_2$ Stabilization and the Pace of Transformation
Emissions Peak and Then Decline For Stabilization

Source: Kheshgi et al., Global Biogeochemical Cycles, 2003
Long-Term Stabilization Requires Transformation

<table>
<thead>
<tr>
<th>Efficiency / Reduce Demand</th>
<th>Decarbonize Global Economy</th>
<th>Negative GHG Emissions</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Energy Intensity in 2050 (MJ per $ GDP)</th>
<th>Carbon per unit of Energy in 2050 (kg C per GJ)</th>
<th>Negative GHG Emissions (Year)</th>
<th>Mean °C Rise in 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>12</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>RCP 8.5</td>
<td>9</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>RCP 4.5</td>
<td>7</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>RCP 2.6</td>
<td>5</td>
<td>5</td>
<td>2070</td>
</tr>
</tbody>
</table>

Sources: van Vuuren et al., Climatic Change (2011); IPCC AR5 (2013)
Pace of Investment Inadequate

Reducing GHGs 50% below 2005 by 2050 requires all steps below:

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Nuclear plants, 1,000 MW</td>
<td>30</td>
<td>&lt; 1</td>
<td>~40</td>
</tr>
<tr>
<td>Coal and gas plants with CCS, 500 MW</td>
<td>55</td>
<td>&lt; 1</td>
<td>~70</td>
</tr>
<tr>
<td>Wind turbines, 4 MW</td>
<td>15,600</td>
<td>8,100</td>
<td>~18,000</td>
</tr>
<tr>
<td>Solar PV, m² panels</td>
<td>325 million</td>
<td>370 million</td>
<td>~315 million</td>
</tr>
</tbody>
</table>

Source: IEA Energy Technology Perspectives 2010: Scenarios and Strategies to 2050
Transformation Spans the Economy

Source: IPCC AR5 WG3, Ch 10 (2014)
Transformation Pathways
Future Emissions Scenarios Sketch Out Transformation Pathways

Source: IPCC AR5 Synthesis Report, Figure SPM.5 (2014)
Transformation Pathways to Inform Climate Change Risk Management

“Given the inherent complexities of the climate system, and the many social, economic, technological, and other factors that affect the climate system, we can expect always to be learning more and to be facing uncertainties regarding future risks.”

“…a valuable framework for making decisions about America’s Climate Choices is iterative risk management. This refers to an ongoing process of identifying risks and response options, advancing a portfolio of actions that emphasize risk reduction and are robust across a range of possible futures, and revising responses over time to take advantage of new knowledge.”

Americas Climate Choices (NRC 2011)
Mitigation Cost Increases in Scenarios with Limited Availability of Technologies

**Table SPM.2** | Increase in global mitigation costs due to either limited availability of specific technologies or delays in additional mitigation relative to cost-effective scenarios. The increase in costs is given for the median estimate and the 16th to 84th percentile range of the scenarios (in parentheses). In addition, the sample size of each scenario set is provided in the coloured symbols. The colours of the symbols indicate the fraction of models from systematic model comparison exercises that could successfully reach the targeted concentration level. (Table 3.2)

<table>
<thead>
<tr>
<th>2100 concentrations (ppm CO₂-eq)</th>
<th>no CCS</th>
<th>nuclear phase out</th>
<th>limited solar/wind</th>
<th>limited bioenergy</th>
<th>medium term costs (2030–2050)</th>
<th>long term costs (2050–2100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 (430 to 480)</td>
<td>138% (29 to 297%)</td>
<td>4</td>
<td>7% (4 to 18%)</td>
<td>6% (2 to 29%)</td>
<td>64% (44 to 78%)</td>
<td>29</td>
</tr>
<tr>
<td>500 (480 to 530)</td>
<td>not available (n.a.)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>44% (2 to 78%)</td>
<td>37% (16 to 82%)</td>
</tr>
<tr>
<td>550 (530 to 580)</td>
<td>39% (18 to 78%)</td>
<td>11</td>
<td>13% (2 to 23%)</td>
<td>8% (5 to 15%)</td>
<td>18% (4 to 66%)</td>
<td>15% (3 to 32%)</td>
</tr>
<tr>
<td>580 to 650</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>16% (5 to 24%)</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

**Symbol legend**—fraction of models successful in producing scenarios (numbers indicate the number of successful models)

- : all models successful
- : between 50 and 80% of models successful
- : between 80 and 100% of models successful
- : less than 50% of models successful

Source: IPCC AR5 Synthesis Report, Table SPM.2 (2014)
Important Roles for CCS Across Sectors/Fuels

• Research part of an ongoing collaboration with PNNL’s integrated assessment group

• Greater mitigation in electricity generation than in liquid fuels

• Modeled least-cost pathways to GHG stabilization deployed CCS in both electricity and liquid fuels (biofuels)

• Bioenergy with CCS (BECCS) competitive due to combination of carbon price and assumed net negative emissions, while bioenergy without CCS is not

Source: Muratori et al., submitted
Pace of Least-Cost Decarbonization Projected to Differ Between End-Use Sectors

Source: Muratori et al., submitted
Enabling Environments for Technology Deployment
CCS: Recommendations Advanced Initiated by Gleneagles G8 (2005)

- Demonstrating CO$_2$ capture and storage
- Taking concerted international action
- Bridging the financial gap for demonstration
- Creating value for CO$_2$ for commercialisation of CCS
- Establishing legal and regulatory frameworks
- Communicating with the public
- Infrastructure
- Retrofit with CCS capture

Source: IEA/CSLF Report to the Muskoka 2010 G8 Summit
Climate Impacts in the Context of Other Drivers

Table 10-10 | Summary of findings.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Climate change drivers</th>
<th>Sensitivity to climate change</th>
<th>Sign</th>
<th>Other drivers</th>
<th>Relative impact of climate change to other drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter tourism</td>
<td>Temperature, Snow</td>
<td>Positive for suppliers</td>
<td>Negative</td>
<td>Population, Lifestyle, Income, Aging</td>
<td>Much less</td>
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<tr>
<td>Summer tourism</td>
<td>Temperature, Rainfall, Cloudiness</td>
<td>Positive for suppliers in high altitudes and latitudes, Neutral for tourists</td>
<td>Negative for suppliers in low altitudes and latitudes</td>
<td>Population, Income, Lifestyle, Aging</td>
<td>Much less</td>
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<tr>
<td>Heating demand</td>
<td>Temperature, Humidity, Cold spells</td>
<td>Positive for suppliers, Negative for consumers</td>
<td>Negative for suppliers, Positive for consumers</td>
<td>Population, Income, Energy prices, Technology change</td>
<td>Less</td>
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<tr>
<td>Health services</td>
<td>Temperature, Precipitation</td>
<td>Positive for suppliers, Negative for consumers</td>
<td>Positive for suppliers, Negative for consumers</td>
<td>Aging, Income, Diet/Lifestyle</td>
<td>Less</td>
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<tr>
<td>Water infrastructure and services</td>
<td>Temperature, Precipitation, Storm Intensity, Seasonal Variability</td>
<td>Negative for water users, Positive for suppliers, Spatially heterogeneous</td>
<td>Negative for water users, Positive for suppliers, Spatially heterogeneous</td>
<td>Population, Income, Urbanization, Regulation</td>
<td>Less in developing countries, Equal in developed countries</td>
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<tr>
<td>Transportation</td>
<td>Temperature, Precipitation, Storm intensity, Seasonal variability, Freeze/thaw cycles</td>
<td>Positive for all users, Positive for transport construction industry</td>
<td>Negative for all users, Positive for transport construction industry</td>
<td>Population, Income, Urbanization, Regulation, Mode shifting, Consumer and commuter behavior</td>
<td>Much less in developing countries, Less in developed countries</td>
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<tr>
<td>Insurance</td>
<td>Temperature, Precipitation, Storm intensity, Seasonal variability, Freeze/thaw cycles</td>
<td>Neutral for suppliers, Neutral for suppliers</td>
<td>Negative for consumers, Neutral for suppliers</td>
<td>Population, Income, Regulation, Product innovation</td>
<td>Less or equal in developing countries, Equal or more in developed countries</td>
</tr>
</tbody>
</table>

Source: AR5 WG2 Ch10, Arent et al. 2014
## Barriers to GHG Reduction Options: Industry

<table>
<thead>
<tr>
<th>Energy efficiency for reducing energy requirements</th>
<th>Emissions efficiency, fuel switching and CCS</th>
<th>Material efficiency</th>
<th>Product demand reduction</th>
<th>Non-CO₂ GHGs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological Aspects: Technology</strong></td>
<td></td>
<td></td>
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<tr>
<td>+ many options available</td>
<td>+ fuels and technologies readily available</td>
<td>+ options available</td>
<td>− slower technology turnover can slow technology improvement and operational emission reduction</td>
<td>+/− approaches and technologies available for some sources</td>
</tr>
<tr>
<td>− technical risk</td>
<td>− retrofit challenges</td>
<td></td>
<td></td>
<td>− lack of lower cost technology for PFC emission reduction</td>
</tr>
<tr>
<td>+ cogeneration mature in heavy industry</td>
<td>+ large potential scope for CCS in cement production, iron and steel, and petrochemicals</td>
<td></td>
<td></td>
<td>− lack of control of HFC leakage in refrigeration systems</td>
</tr>
<tr>
<td>− non-transparent and technically demanding</td>
<td>− limited CCS technology development, demonstration and maturity for industry applications</td>
<td></td>
<td></td>
<td>− lack of certification of refrigeration systems</td>
</tr>
<tr>
<td>interconnection procedures for cogeneration</td>
<td></td>
<td></td>
<td></td>
<td>− regulatory barriers to HFC alternatives in aerosols</td>
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<tr>
<td><strong>Technological Aspects: Physical</strong></td>
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<tr>
<td>+ less energy and fuel use, lower cooling needs, smaller size</td>
<td>− lack of sufficient feedstock to meet demand</td>
<td></td>
<td>− reduction in raw and waste materials</td>
<td>− lack of certification of refrigeration systems</td>
</tr>
<tr>
<td>− concentrating suitable heat loads for cogeneration</td>
<td>− CCS retrofit constraints</td>
<td></td>
<td>− transport infrastructure and industry proximity for material/waste reuse</td>
<td>− regulatory barriers to HFC alternatives in aerosols</td>
</tr>
<tr>
<td>− retrofit constraints on cogeneration</td>
<td>− lack of CO₂ pipeline infrastructure</td>
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<tr>
<td>− limited scope and lifetime for industrial CO₂ utilization</td>
<td>− carbon dioxide infrastructure</td>
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<tr>
<td><strong>Institutional and Legal</strong></td>
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<tr>
<td>− impact of non-energy policies</td>
<td>− fragmented and weak institutions</td>
<td></td>
<td>− regulatory and legal instruments generally do not take account of externalities</td>
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</tr>
<tr>
<td>+ energy efficiency policies (10.11)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>− market barriers</td>
<td></td>
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<tr>
<td>− regulatory, tax/tariff and permitting of cogeneration</td>
<td>− lack of acceptance of unconventional manufacturing processes</td>
<td></td>
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<tr>
<td>−/+/− grid access for cogeneration</td>
<td>− lack of acceptance of unconventional manufacturing processes</td>
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<tr>
<td><strong>Cultural</strong></td>
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<tr>
<td>− lack of trained personnel</td>
<td>− social acceptance of CCS</td>
<td></td>
<td>− public participation, human capacity for management decisions</td>
<td>− lack of information/education about solvent replacements</td>
</tr>
<tr>
<td>−/+/− attention to energy efficiency</td>
<td></td>
<td></td>
<td></td>
<td>− lack of awareness of alternative refrigerants</td>
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<tr>
<td>− lack of acceptance of unconventional manufacturing processes</td>
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<tr>
<td>− cogeneration outside core business</td>
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<tr>
<td>− lack of consumer and policymaker knowledge of cogeneration</td>
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<tr>
<td><strong>Financial</strong></td>
<td></td>
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<tr>
<td>− access to capital and short investment payback requirements</td>
<td>− lack of sufficient financial incentive for widespread CCS deployment</td>
<td></td>
<td>− businesses, governments, and labour favour increased production</td>
<td>− recycled HFCs not cost competitive with new HFCs</td>
</tr>
<tr>
<td>− high overhead costs for small or less energy intensive industries</td>
<td>− liability risk for CCS</td>
<td></td>
<td>− cost of HFC incineration</td>
<td></td>
</tr>
<tr>
<td>+/− factoring in efficiency into investment decisions (e.g., energy management)</td>
<td>− high CCS capital cost and long project development times</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>− cogeneration economic in many cases</td>
<td>− upfront cost and potentially longer payback period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−/− market value of grid power for cogeneration</td>
<td>− reduced production costs</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>−/− high capital cost for cogeneration</td>
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</tbody>
</table>

Source: AR5 WG3 Ch10, Fischedick et al. 2014
Transformation is Subject to Practical Barriers

Source: Muratori et al. 2016
Technology R&D Portfolios
Emerging Energy Technology

Investing to meet growing energy demand and manage climate change risks

- Increase Supply
  - Advanced biofuels and algae
  - Natural gas to products

- Expand Energy Access
  - Hydrocarbon and renewable energy systems
  - Power generation technologies

- Improve Efficiency
  - Internal combustion engine efficiency
  - Light-weighting and packaging reduction

- Mitigate Emissions
  - Carbon capture and sequestration
  - Methane emissions reduction

- Good Science for Sound Policy
  - Climate science, economics, and policy
  - Resilience and preparedness

Source: Exxon Mobil Annual Shareholders Meeting, May 2016
Thank You