Roadmap

+ **Background**
  - California climate policy analysis
  - Deep Decarbonization Pathways Project

+ **U.S. Deep Decarbonization Analysis**
  - Approach
  - Results
  - Carbon cycle science implications
  - Summary and policy implications
Energy and Environmental Economics (E3)

+ Electricity sector specialists, founded 1989
+ Rigorous analysis on a wide range of energy issues
+ Advise utilities, regulators, gov’t agencies, power producers, technology companies, and investors
+ Offices in San Francisco and Vancouver, international practice includes China and India
+ Key advisor to California state government on climate policy, electricity planning, energy efficiency
California Climate Policy Analysis

The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity
James H. Williams, et al.
Science 335, 53 (2012);
DOI: 10.1126/science.1208365

Several states and countries have adopted targets for deep reductions in greenhouse gas emissions by 2050, but there has been little physically realistic modeling of the energy and economic transformations required. We analyzed the infrastructure and technology path required to meet California’s goal of an 80% reduction below 1990 levels, using detailed modeling of infrastructure stocks, resource constraints, and electricity system operability. We found that technically feasible levels of energy efficiency and decarbonized energy supply alone are not sufficient; widespread electrification of transportation and other sectors is required. Decarbonized electricity would become the dominant form of energy supply, posing challenges and opportunities for economic growth and climate policy. This transformation demands technologies that are not yet commercialized, as well as coordination of investment, technology development, and infrastructure deployment.

2008
+ AB32 analysis for CPUC, CEC, ARB
+ Options and costs for electricity and natural gas sectors
+ CO2 market design for electricity sector

2012
+ Independent analysis by E3-LBNL-UCB team of CA goal of 80% reductions by 2050
+ Publication in Science highlights electricity role

2015
+ Analysis of 2030 GHG target for CA energy principals
+ GHG reductions and costs for different decarbonization pathways
Deep Decarbonization Pathways Project (DDPP)

- National strategies to keep global warming below 2°C
- 15 countries, >70% of current global GHG emissions
  - OECD + China, India, Brazil, South Africa, Mexico, Indonesia
- 2014 report to UN Secretary General Ban Ki-moon
What is the Purpose of National Deep Decarbonization Pathways?

+ Improve the international climate discourse
  - Cards on the table: transparent assumptions about technologies and cost, clarity about national ambitions, benchmark for progress
  - Shift of focus: from policy abstractions to energy sector transformation, concrete problem solving, mutual benefits

+ Encourage cooperation
  - Share best practices
  - Concretely understand different national perspectives
  - Identify areas for collaboration on RD&D, policy, finance
  - Identify market opportunities for low carbon technologies

Clear difference in approach to transportation between China and US in DDPP interim report
What would it take for US to achieve 80% GHG reduction below 1990 level by 2050?

- Is it technically feasible?
- What would it cost?
- What physical changes are required?
- What economic and policy changes are implied?
Current Emissions & 2050 Target

- CO2 from energy in 2010 was 5405 MMT (17 tons/person)
- DDPP US 2050 target is 750 MMT (1.7 tons/person)
- Net 2050 CO2e target 1080 MMT → 330 net from other sources

US GHG emissions by economic sector

2050 analysis is important for avoiding intermediate solutions that fall short of long term goals
GCAM Used to Model Non-Energy and Non-CO$_2$ Emissions

+ IAM used in IPCC Fifth Assessment Report
+ Biomass production and indirect LUC emissions
+ Non-energy and non-CO$_2$ GHG mitigation
+ Assess sensitivity to terrestrial carbon sink assumptions
+ Analysis by Andy Jones, LBNL + Haewon McJeon, PNNL

IPCC 2014; van Vuuren et.al. 2011
PATHWAYS used to model energy emissions

- Represents physical infrastructure of energy system
- 80 demand sectors, 20 supply sectors
- Annual time steps with equipment lifetimes
- Incorporates infrastructure inertia
- Makes decarbonization pathways “real”

**New Vehicles by Vintage**

**Total Stock by Year**
PATHWAYS Model Methodology: Bottom-Up Energy Demand

+ Infrastructure stock rollover model (keeps track of “stuff” e.g. number of light bulbs by type and vintage)
PATHWAYS Model: Sectoral and Geographic Granularity

+ 9 US Census regions separately modeled
+ Allows for an understanding of sectoral impacts and equity differences in future energy systems
+ Illustrates the challenges of certain sectors
+ Focuses policymakers on difficult choices
+ A light bulb is not a water heater. California is not Texas.
PATHWAYS Design Principles

- Conservative assumptions about economy, lifestyles
- Technology is commercial or near-commercial
- Environmental sustainability (limits on biomass, hydro)
- Infrastructure inertia
- Electricity system reliability

![Graphs showing U.S. GDP and population growth](image)

U.S. GDP (Trillion $2012): 166% increase

U.S. population (Millions): 40% increase

RESULTS
80% Reduction in CO$_2$e by 2050 is Achievable

US GHG emissions by economic sector

Based on US EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2011, Table 2-2

Energy+Environmental Economics
3 Pillars of Deep Decarbonization

Key Metric of Transformation

Energy Efficiency

Decarbonization of Electricity

End Use Fuel Switching to Electric Sources

Pathways to Deep Decarbonization in the United States, Mixed case results
Current U.S. energy system in 2014

2014 Reference Case

- Geothermal
- Solar
- Wind
- Nuclear
- Hydro
- Biomass
- Natural Gas
- Coal
- Petroleum

Energy flows:
- Electricity Generation
- Grid Electricity
- Power-to-Gas SNG
- Hydrogen Production
- Pipeline Gas
- Combined Heat and Power
- Biofuel Production

End uses:
- Buildings
- Industry
- Liquid Fuels
- Transportation

Energy + Environmental Economics
Decarbonized energy system in 2050

2050 Mixed Case

- Geothermal
- Solar
- Wind
- Nuclear
- Hydro
- Biomass
- Natural Gas
- Coal
- Petroleum

Electricity Generation

Grid Electricity

Power-to-Gas SNG

Pipeline Gas

Hydrogen Production

Combined Heat and Power

Biofuel Production

Petroleum Refining

Liquid Fuels

Transportation

Buildings

Industry
Multiple Pathways Are Technically Feasible

Pathways to Deep Decarbonization in the United States
2050 Generation Mix Final Energy by Scenario

![Graph showing energy distribution by scenario and final energy in 2050 (EJ) for different energy sources: Fossil, Fossil (CCS), Nuclear, Wind, Solar, Hydro, Geothermal, Biomass. The graph also includes electric emissions factor (MMT CO2/EJ) and emissions intensity.]

- **Reference**
- **Mixed**
- **High Renewables**
- **High Nuclear**
- **High CCS**

Legend:
- Fossil
- Fossil (CCS)
- Nuclear
- Wind
- Solar
- Hydro
- Geothermal
- Biomass
- Emissions Intensity
2050 LDV Final Energy Demand by Fuel Type and Average Fleet Fuel Economy

Final Energy in 2050 (EJ)

- Gasoline Fuels
- Diesel Fuels
- Hydrogen
- Average Fuel Economy

Average Fuel Economy

- Fleet Average Miles/Gallon Gasoline Equivalent (GGE)

Reference
Mixed
High Renewables
High Nuclear
High CCS
Key Determinants of Low Carbon Energy Systems

**Electricity Mix**
What is the mix of renewables, nuclear, and fossil fuels with CCS in electricity generation?

**Biomass Supply and Use**
What is the maximum limit on sustainable biomass energy resources; where is bioenergy used?

**CCS**
Is CCS feasible in power generation, industry, and biomass refining; if so, how much?

**Electricity Balancing**
How much storage is needed to balance electricity supply and demand; what is the technology mix?

**Fuel Switching**
How much switching of fuels (e.g., gasoline to H₂) and fuel types (e.g., liquid fuels to electricity) is needed, given constraints?
1. Variable generation (wind, solar): Use production of hydrogen and synthetic methane to balance power system & provide low carbon fuel

2. Natural gas pipeline → decarbonize using gasified biomass and electricity-produced fuels

3. Industry, heavy duty transport → replace liquid fossil fuels with partly decarbonized pipeline gas

4. Biomass → not used for ethanol because it is scarce and has better uses, such as biogas and biodiesel, while alternatives exist for LDV fuels
Electricity Increasingly Dominated by Non-Dispatchable Generation

Pathways to Deep Decarbonization in the United States, Mixed case results
Organizing energy system to efficiently utilize non-dispatchable generation is one of the key challenges and opportunities of deep decarbonization in the U.S.
Pipeline Gas Composition in 2050

- **Reference**
- **Mixed**
- **High Renewables**
- **High Nuclear**
- **High CCS**

**Gas energy use (EJ)**

- **Natural Gas**
- **Hydrogen**
- **Power to Gas**
- **Biogas**
- **Natural Gas w/ End-Use Capture**

**Emissions intensity (gCO2/MJ)**

- **Reference**
- **Mixed**
- **High Renewables**
- **High Nuclear**
- **High CCS**

- **Emissions Intensity**
Low Carbon Transition in High Renewables Case

Pathways to Deep Decarbonization in the United States, Mixed case results
Median 2050 net energy system cost ~1% of GDP ($40T)

Uncertainty range -0.2% to + 1.8%
- Costs = mostly fixed costs, savings = mostly fuel savings
- Lower net cost if technology costs lower, fossil fuels higher

Pathways to Deep Decarbonization in the United States, High renewables case
2050 LDV Stock by Scenario

- Millions of LDVs in 2050
- Gasoline ICE
- Diesel ICE
- PHEV
- EV
- Hydrogen FCV
- Other

Scenarios:
- Reference
- Mixed
- High Renewables
- High Nuclear
- High CCS
Residential Energy Efficiency & Fuel Switching Investment by Decade

Winners

Losers

High RE Case

Ref Case

Res Tech Index (group)
- Electric Water Heating
- Electrified and High Efficiency Appliances
- Heat Pumps (Heating and AC)
- High Efficiency Air Conditioners
- LED
- Combustion Heaters
- Combustion Water Heaters
- Low Efficiency Air Conditioners
- Low Efficiency Appliances
- Low Efficiency Lighting
Generation Investment by Decade, Region, Technology, and Scenario
Incremental Household Spending in 2050 ($/Month)

Pathways to Deep Decarbonization in the United States, Mixed case results
Dr. Margaret Torn, LBNL, at North American Carbon Program: “U.S. Deep Decarbonization and Carbon Cycle Implications”

Research needed for prediction, management, monitoring, and verification

- Carbon Sink is pivotal but uncertain (LULUCF)
- Biomass fills critical energy needs but sustainability poorly understood
- Non-CO$_2$ GHGs will be larger fraction of emissions
- M&V must address infrastructure change, fuel switching, net-zero fuels
**Carbon Sink** *Due to Land Use, Land Use Change, and Forestry (LULUCF)* *is Pivotal but Uncertain*

- Sink is critical to target setting for both energy & non-energy emissions
- Potentially large impact on cost of mitigation → steep cost curves

Based on US EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2011, Table 2-2
In Deeply Decarbonized System, Non-CO$_2$ GHGs Become Dominant Form of Emissions

- Decline in absolute terms from present
- Increase in share of total CO$_2$e from 17% in 2012 to 58% in 2050

**2012 EPA inventory**

- Fossil fuel combustion CO$_2$: 78%
- Other CO$_2$: 5%
- CH$_4$: 9%
- N$_2$O: 6%
- F-gases: 2%

**2050 Pathways**

- Fossil fuel combustion CO$_2$: 39%
- CH$_4$: 24%
- N$_2$O: 26%
- F-gases: 8%

- Energy CO$_2$: 5,066 Mt CO$_2$e
- Non-energy: 1,435 Mt CO$_2$e
- Energy CO$_2$: 750 Mt CO$_2$e
- Non-energy: 1,161 Mt CO$_2$e
SUMMARY AND POLICY IMPLICATIONS
**Four Seeming Paradoxes:**

1. **Physical Energy System**

- Deep decarbonization will profoundly transform the physical energy system of the U.S.
- However, the consumer experience of using energy goods and services can be relatively unchanged.

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Duty Vehicle Travel: vehicle miles traveled per capita</td>
<td>8,380</td>
<td>8,294</td>
</tr>
<tr>
<td>Dishwashing: cycles per household</td>
<td>148</td>
<td>148</td>
</tr>
<tr>
<td>Clothes Drying: pounds per household</td>
<td>1,467</td>
<td>1,589</td>
</tr>
<tr>
<td>Lighting: kilolumen-hours per square foot</td>
<td>28</td>
<td>29</td>
</tr>
</tbody>
</table>
Deep decarbonization will profoundly transform the U.S. energy economy, in terms of what money is spent on and where investment will flow.

- Energy economy will be dominated by fixed capital costs not fossil fuel costs (e.g. oil price in current system)
- Energy supply will be more geographically distributed than current system

However, the change in consumer costs for energy goods and services is likely to be small
Four Seeming Paradoxes: 3. Macro-Economy

+ Deep decarbonization will have a relatively small direct impact on GDP.

+ However, it can still have significant benefits for the U.S. macro-economy.

- Reduced exposure to volatile oil prices
- Energy costs more predictable, stable investment environment
- Less U.S. engagement with oil-producing regions
- Opportunity for U.S. manufacturing renaissance

![Annual Imported Crude Oil Price](image)
Deep decarbonization does not require federal climate legislation or an end to partisan gridlock. However, it will require that executive branch, state, regional, and sectoral policies are well-designed and well-implemented.

- Start with what the policies must achieve – physical changes in energy system – before creating policy mechanism.
- Avoid dead-ends that provide short-term GHG reductions but don’t lead to 80% by 2050.
- Reducing capital and financing costs of low carbon technologies is critical → demand-side measures depend on consumer adoption.
- Coordinated planning and investment across sectors and jurisdictional boundaries is critical to reach target and reduce cost.
- Policy actions must take infrastructure inertia into account.
Timing for Action is Limited

A car purchased today, is likely to replaced at most 2 times before 2050. A residential building constructed today, is likely to still be standing in 2050.

Average lifetimes, actual results will vary
Comparison of US Pledge and US DDPP Results

China’s pledge
Plan to have carbon dioxide emissions peak “around 2030”

Carbon emissions from energy consumption
Billions of metric tons

- United States
- China
- Europe
- Russia
- Japan
- India

Mr. Obama’s pledge to China
Would cut emissions by 26 percent to 28 percent from 2005 levels by 2025

Targets pledged by Mr. Obama in 2009 U.N. accord.

Comparing California and US Pathways

- Industry is larger share of emissions in US → bigger challenge for national economy than CA
- Refineries are larger share of California emissions → potential bonus for reducing fossil fuel use
- Generation portfolio choices → California has already chosen renewable path, rejected nuclear
- Renewable resource endowments are different → balancing challenges, diversity opportunities
- Regional integration assumed in US analysis → different boundary conditions than CA 2030 analysis
Thank You!

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Non-Energy and Non-CO$_2$ GHG Mitigation

GCAM analysis shows non-CO$_2$ and non-energy mitigation strategies consistent with 80% reduction target

Terrestrial sink sensitivity analysis

### Sink sensitivity

<table>
<thead>
<tr>
<th>Source</th>
<th>1990 sink</th>
<th>1990 sink +25%</th>
<th>Central Case</th>
<th>1990 sink -25%</th>
<th>1990 sink -50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050 terrestrial CO$_2$ sink</td>
<td>1,247</td>
<td>1,039</td>
<td>831</td>
<td>623</td>
<td>416</td>
</tr>
<tr>
<td>Allowable 2050 gross CO$_2$e</td>
<td>2,327</td>
<td>2,119</td>
<td>1,911</td>
<td>1,704</td>
<td>1,496</td>
</tr>
<tr>
<td>Fossil fuel + industrial CO$_2$</td>
<td>1,312</td>
<td>1,109</td>
<td>796</td>
<td>711</td>
<td>513</td>
</tr>
<tr>
<td>Non-CO$_2$ emissions (all)</td>
<td>1,017</td>
<td>1,009</td>
<td>929</td>
<td>929</td>
<td>983</td>
</tr>
<tr>
<td>% Reduction in fossil fuel + industrial CO$_2$</td>
<td>74%</td>
<td>78%</td>
<td>84%</td>
<td>86%</td>
<td>90%</td>
</tr>
<tr>
<td>% Reduction in non-CO$_2$</td>
<td>10%</td>
<td>10%</td>
<td>12%</td>
<td>12%</td>
<td>13%</td>
</tr>
<tr>
<td>% Reduction in net CO$_2$e</td>
<td>80%</td>
<td>80%</td>
<td>82%</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>
N$_2$O and F-gas Mitigation

**N$_2$O Mitigation**

![Chart showing N$_2$O CO2e mitigation across different years and scenarios with legend indicating industry, transportation, ag and land use, waste, and other categories.]

**F-gas Mitigation**

![Chart showing F-gas CO2e mitigation across different years and scenarios with legend indicating industry, buildings, transportation, and fire suppression categories.]

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Energy + Environmental Economics
## Principal Non-CO₂ Mitigation Strategies by Subsector

<table>
<thead>
<tr>
<th>Subsector</th>
<th>Absolute Reduction (MtCO₂e)</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CH₄</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landfills</td>
<td>82</td>
<td>73%</td>
</tr>
<tr>
<td>Coal</td>
<td>35</td>
<td>58%</td>
</tr>
<tr>
<td>Enteric Fermentation</td>
<td>16</td>
<td>9%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>16</td>
<td>19%</td>
</tr>
<tr>
<td><strong>N₂O</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural Soils</td>
<td>33</td>
<td>9%</td>
</tr>
<tr>
<td>Adipic Acid Production</td>
<td>27</td>
<td>96%</td>
</tr>
<tr>
<td>Nitric Acid Production</td>
<td>10</td>
<td>89%</td>
</tr>
<tr>
<td>Fluorinated Gases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Conditioning</td>
<td>64</td>
<td>63%</td>
</tr>
<tr>
<td>Solvents</td>
<td>32</td>
<td>82%</td>
</tr>
</tbody>
</table>