Energy+Environmental Economics

Pathways to Deep Decarbonization in the United States

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California Air Resources Board

May 13, 2015

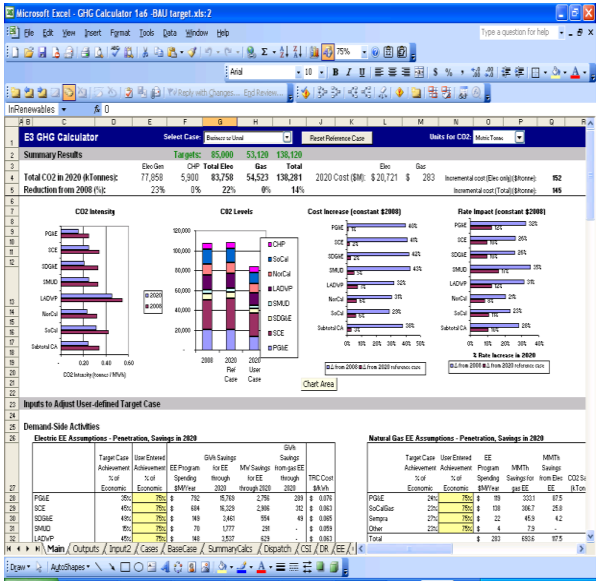
Roadmap

+ **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)

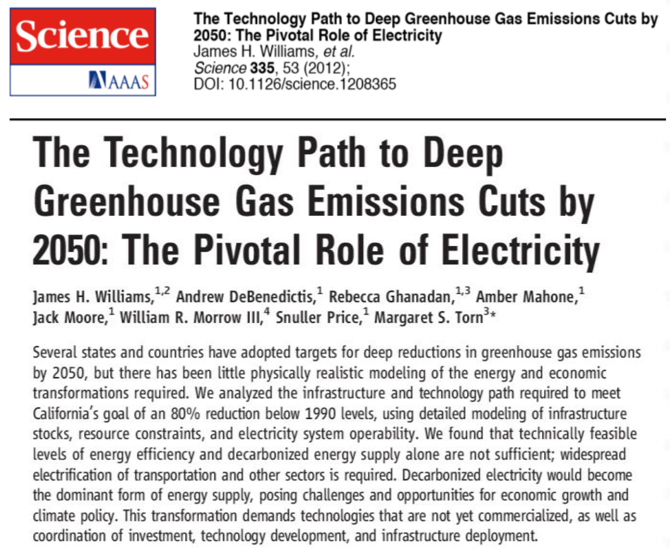
- Electricity sector specialists, founded 1989
- Rigorous analysis on a wide range of energy issues
- Advise utilities, regulators, gov't agencies, power producers, technology companies, and investors
- Offices in San Francisco and Vancouver, international practice includes China and India
- Key advisor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

California Climate Policy Analysis



2008

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



Science
AAAS

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

The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity

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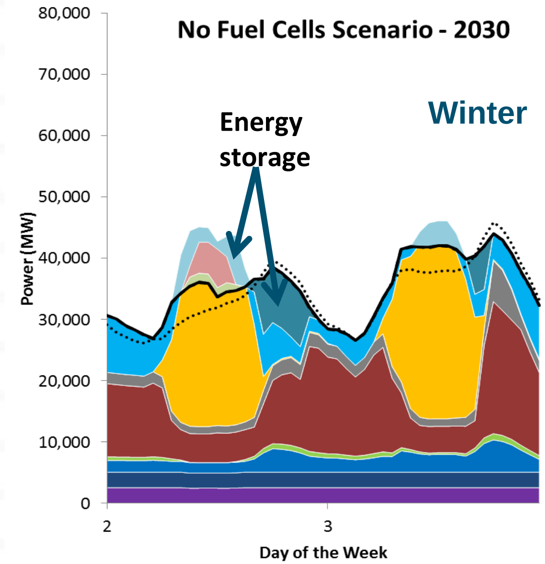
Several states and countries have adopted targets for deep reductions in greenhouse gas emissions by 2050, but there has been little physically realistic modeling of the energy and economic transformations required. We analyzed the infrastructure and technology path required to meet California's goal 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.

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**

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

IDDRI
SciencesPo.

+ **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**

pathways to
deep decarbonization

2014 interim report

ECONOMY

Blueprints for Taming the Climate Crisis

JULY 8, 2014

Eduardo Porter
ECONOMIC SCENE

EMAIL
FACEBOOK
TWITTER
SAVE

Here's what your future will look like if we are to have a shot at preventing devastating climate change.

Within about 15 years every new car sold in the United States will be electric. In fact, by midcentury more than half of the American economy will run on electricity. Up to 60 percent of power might come from nuclear sources. And coal's footprint will shrink drastically, perhaps even disappear from the power supply.

This course, created by a team of energy

UN issued with roadmap on how to avoid climate catastrophe

Report is the first of its kind to prescribe concrete actions that the biggest 15 economies must take to keep warming below 2C

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Energy & Sustainability » Climatewire

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Clean Energy to Stave Off Catastrophic Climate Change Possible by 2050, Barely

The world is not on track to keep global warming below 2 degrees Celsius but can still hold that line with tremendous effort

UN: Avoiding climate disaster is tough but feasible

07/08/14 01:51 PM

What is the Purpose of National Deep Decarbonization Pathways?

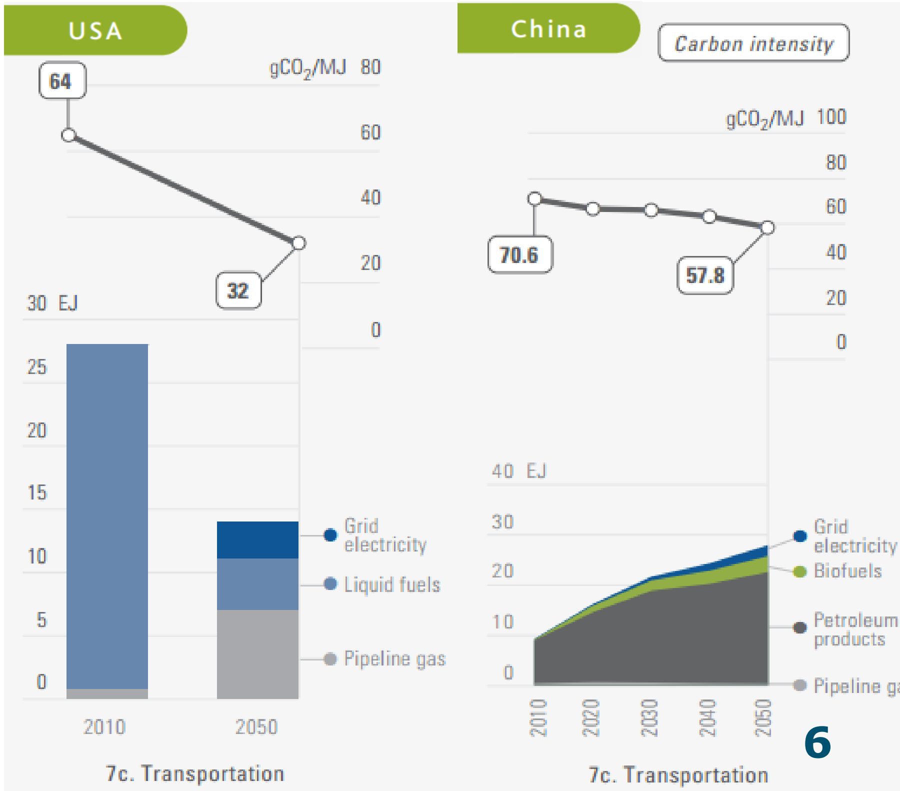
+ Improve the international climate discourse

- 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

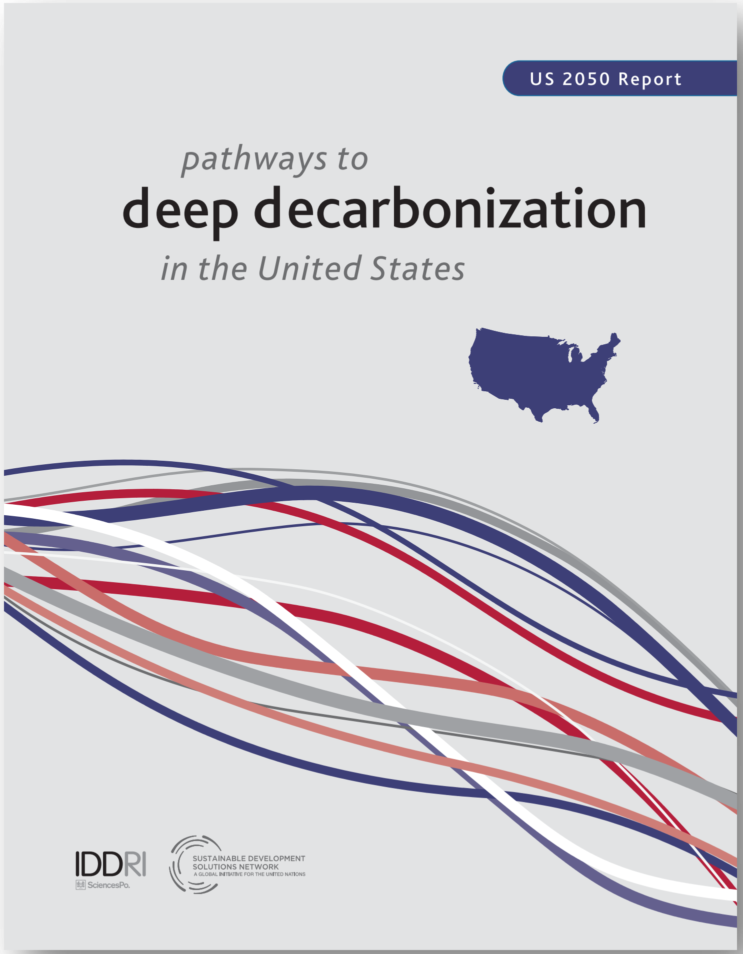
+ Encourage cooperation

- 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 →



U.S. Deep Decarbonization Report



E3, UC, LBNL, PNNL team

Williams *et al*. Nov. 2014

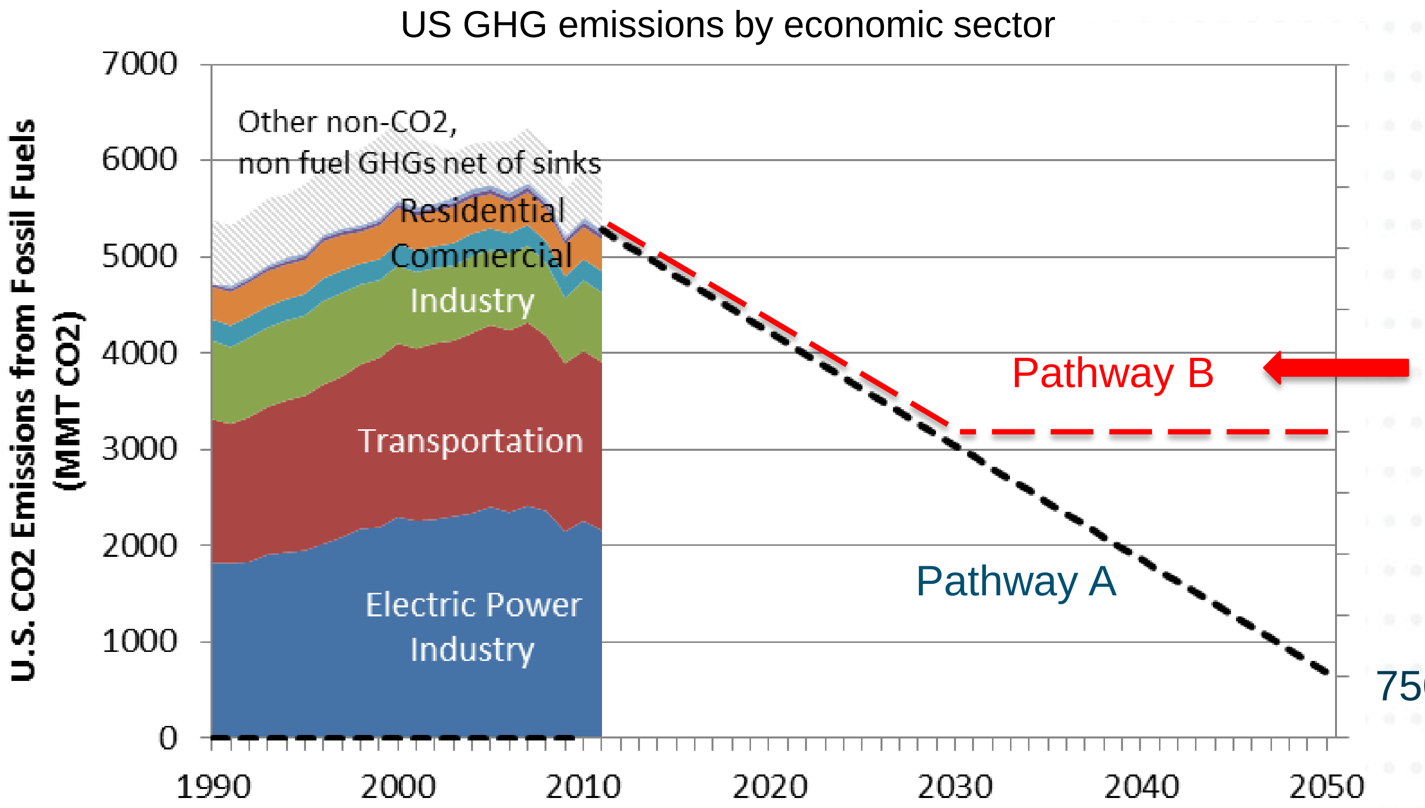
What would it take for US to achieve 80% GHG reduction below 1990 level by 2050?

- ***Is it technically feasible?***
- ***What would it cost?***
- ***What physical changes are required?***
- ***What economic and policy changes are implied?***

Report available at http://unsdsn.org

Current Emissions & 2050 Target

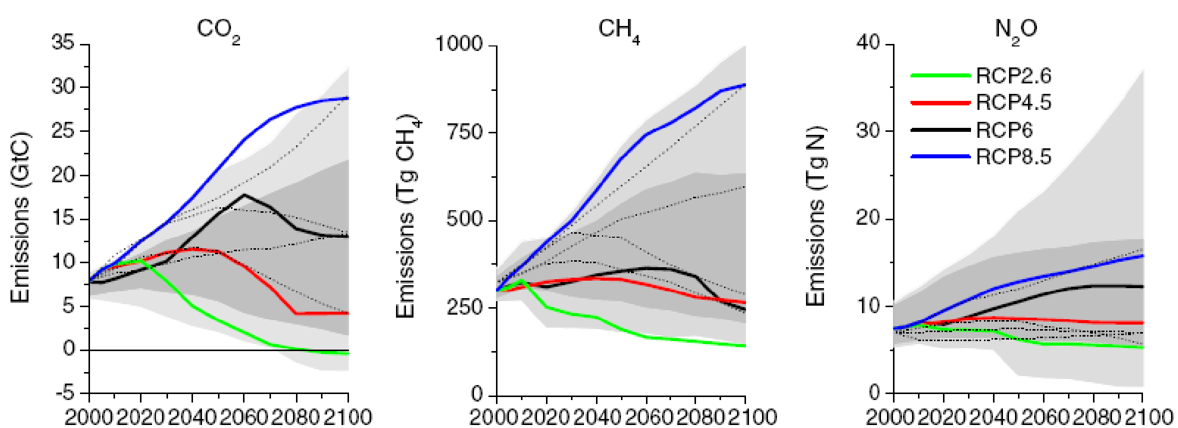
- CO2 from energy in 2010 was 5405 MMT (17 tons/person)
- DDPP US 2050 target is 750 MMT (1.7 tons/person)
- Net 2050 CO2e target 1080 MMT → 330 net from other sources



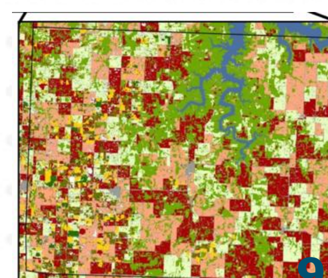
2050 analysis is important for avoiding intermediate solutions that fall short of long term goals

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



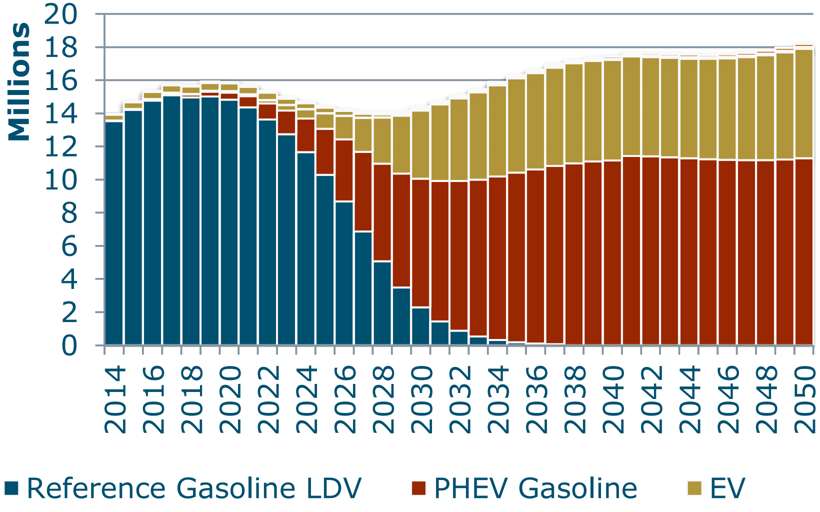
IPCC 2014; van Vuuren et.al. 2011



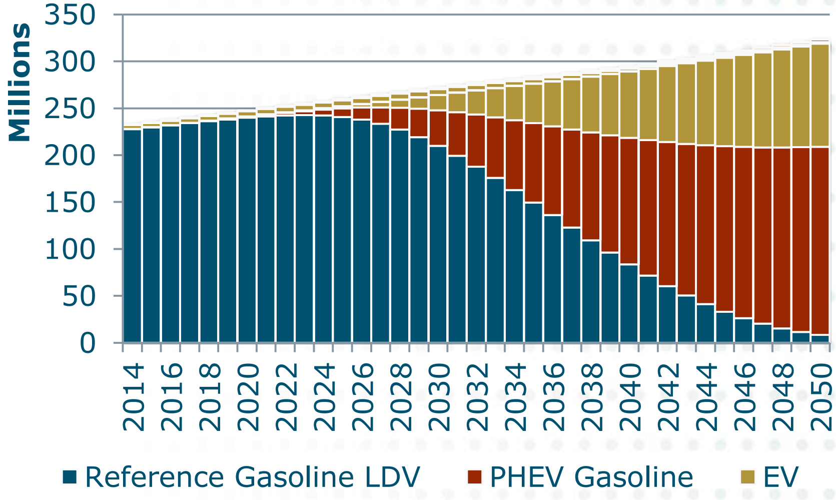
PATHWAYS used to model energy emissions

- 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

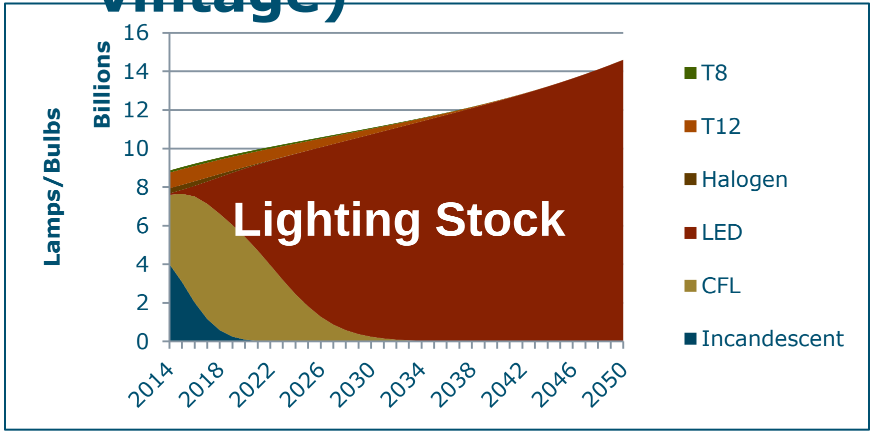


Total Stock by Year



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)



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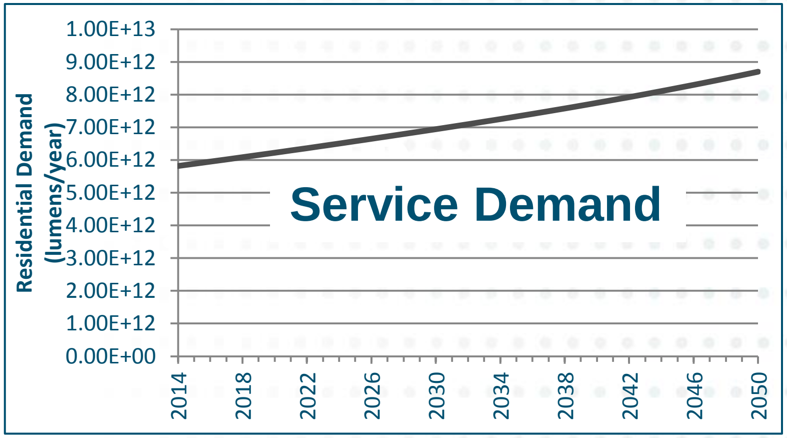

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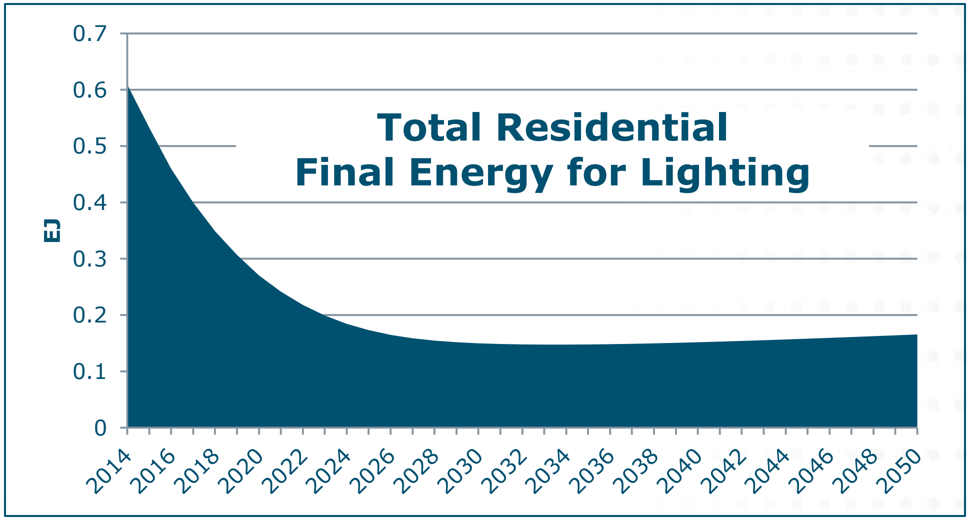
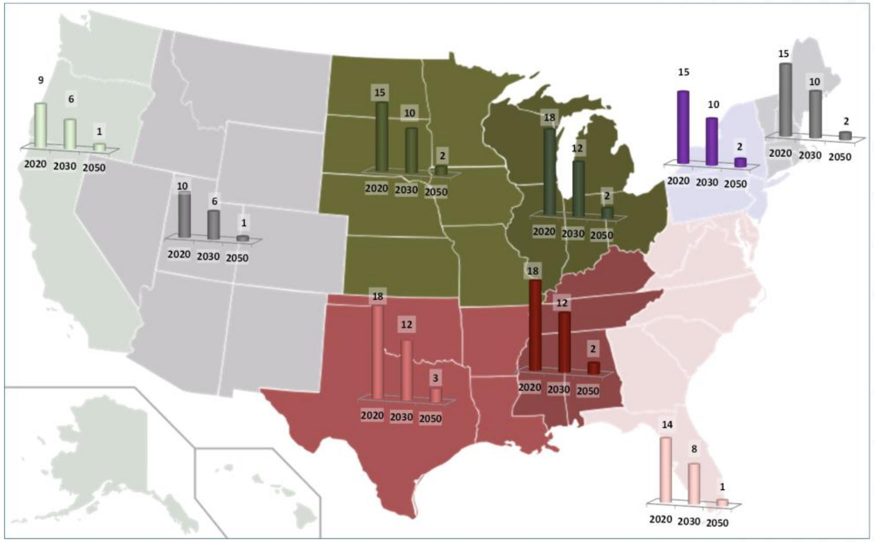


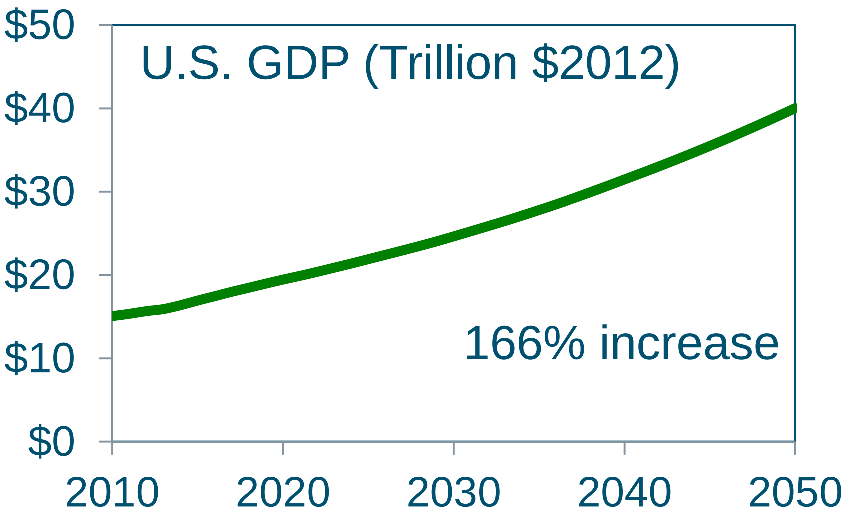
PATHWAYS Model: Sectoral and Geographic Granularity

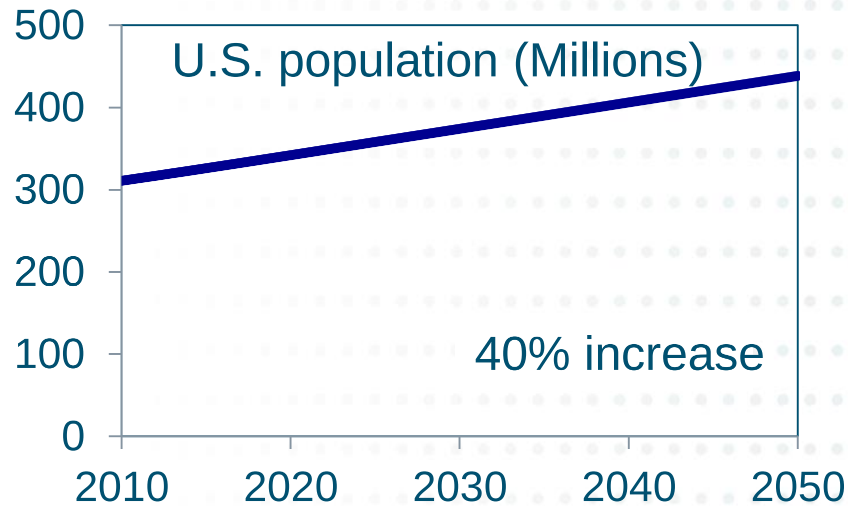
- 9 US Census regions separately modeled
- Allows for an understanding of sectoral impacts and equity differences in future energy systems
- Illustrates the challenges of certain sectors
- Focuses policymakers on difficult choices
- A light bulb is not a water heater. California is not Texas.



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**

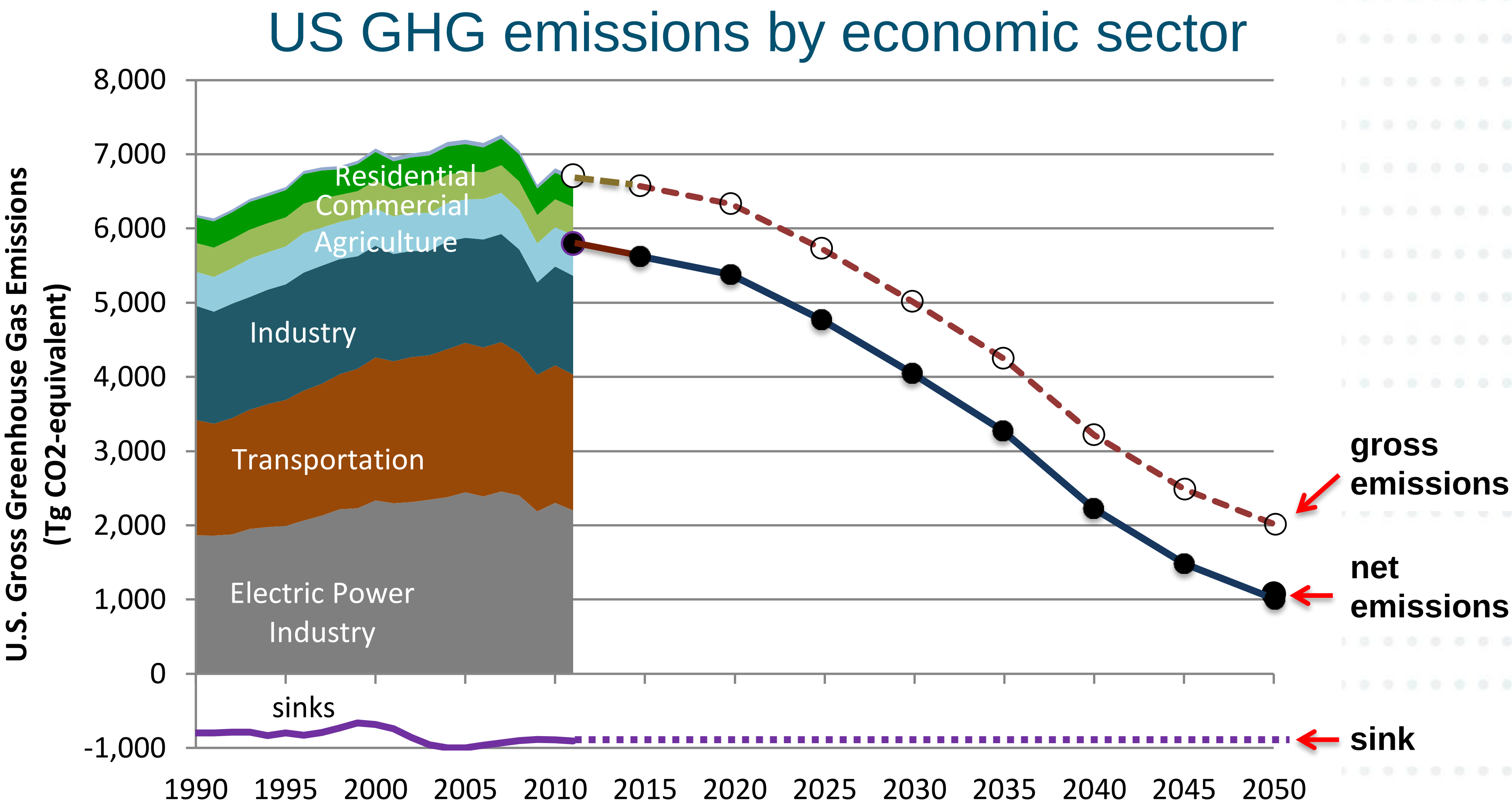




U.S. National Energy Modeling System and 2013 Annual Energy Outlook reference case

RESULTS

80% Reduction in CO_2e by 2050 is Achievable

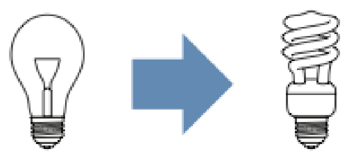


Based on US EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2011, Table 2-2

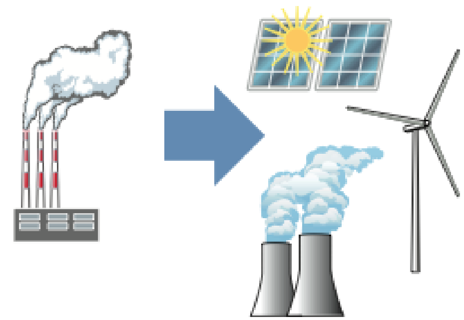
3 Pillars of Deep Decarbonization

Strategy

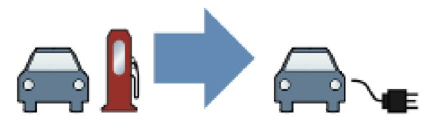
Energy Efficiency



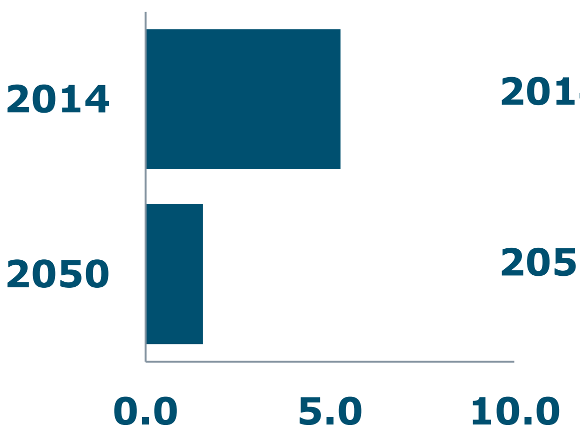
Decarbonization of Electricity



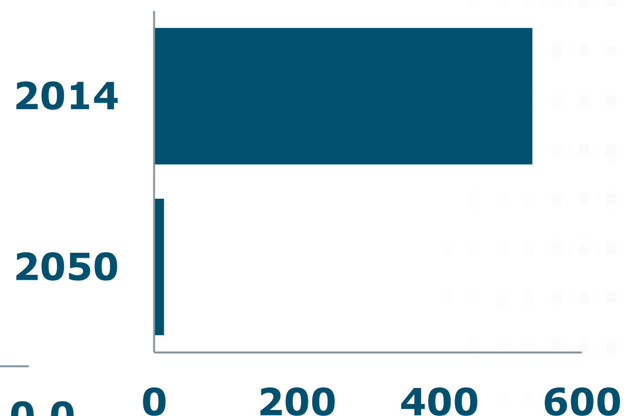
End Use Fuel Switching to Electric Sources



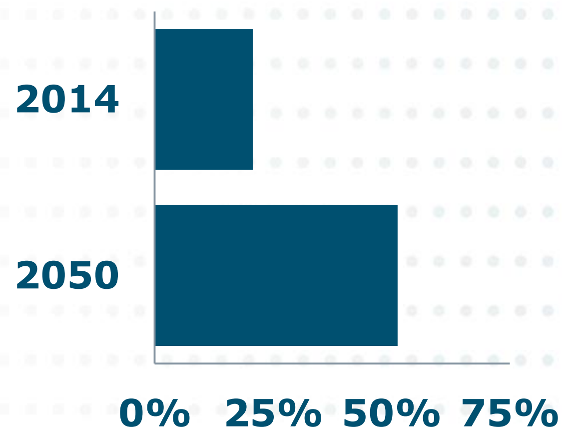
Key Metric of Transformation



Energy Intensity of GDP (GJ/$2005)



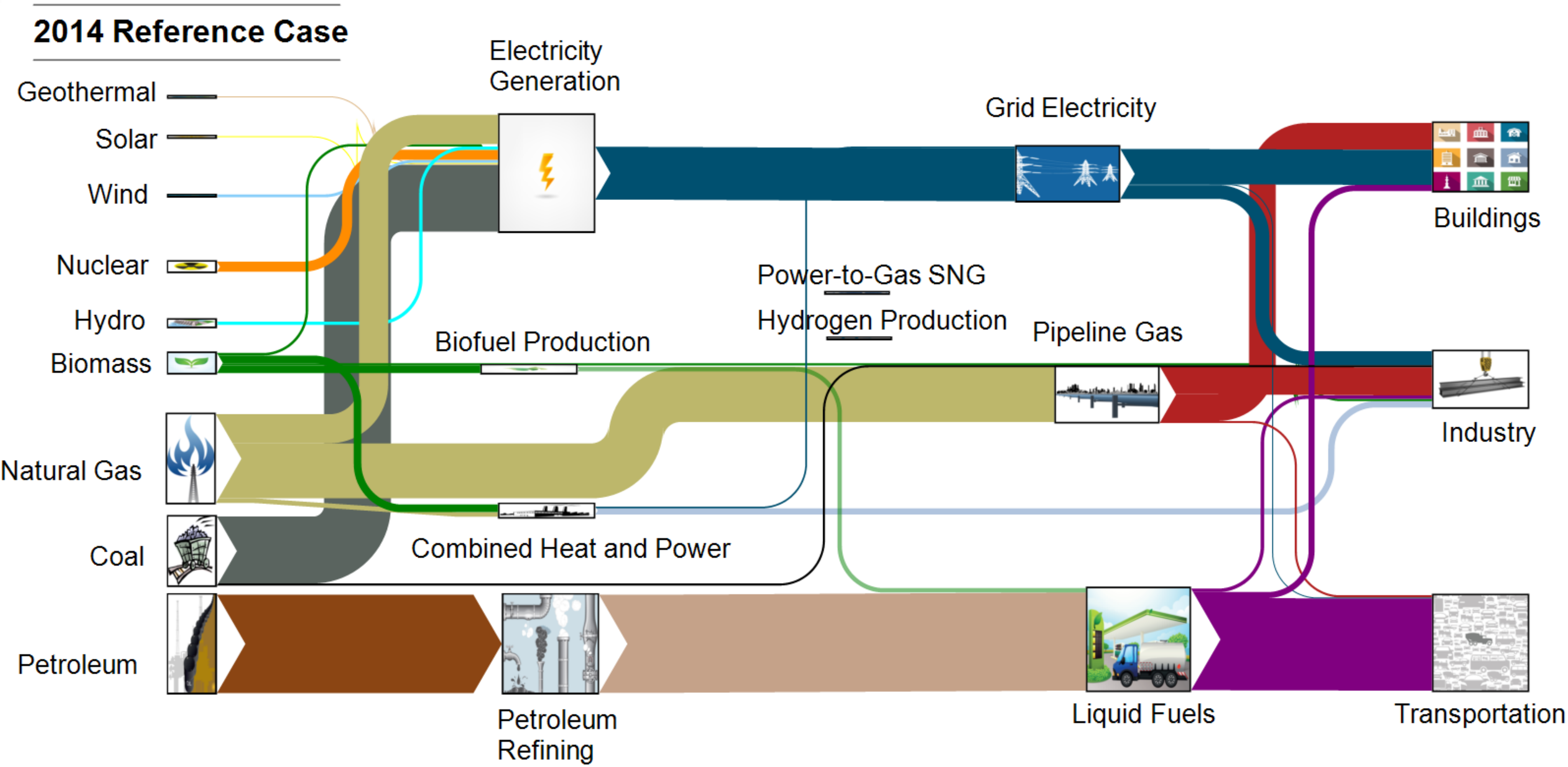
Electricity Emissions Intensity (gCO2/kWh)



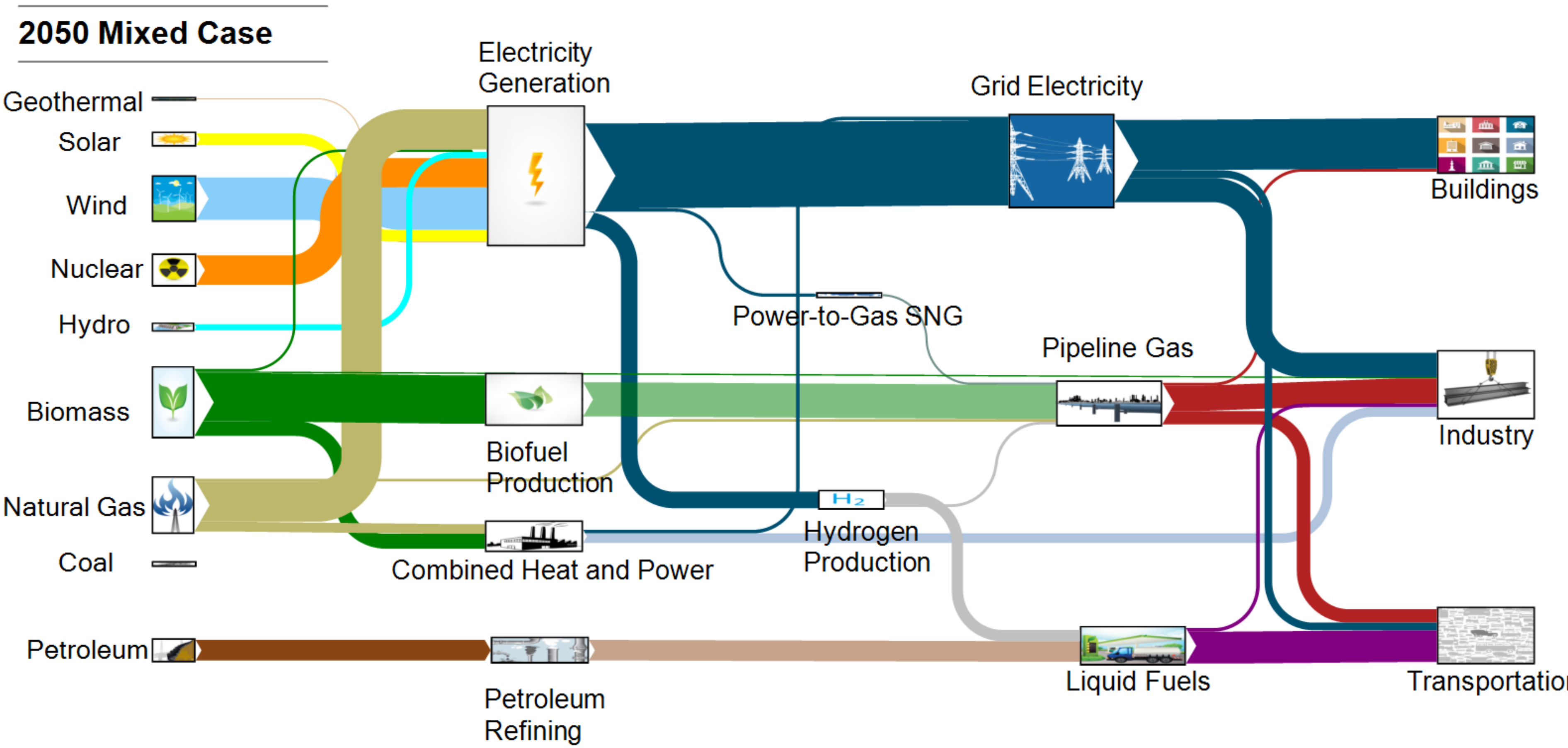
Share of Electricity and Electric Fuels in Total Final Energy (%)

Pathways to Deep Decarbonization in the United States, Mixed case results

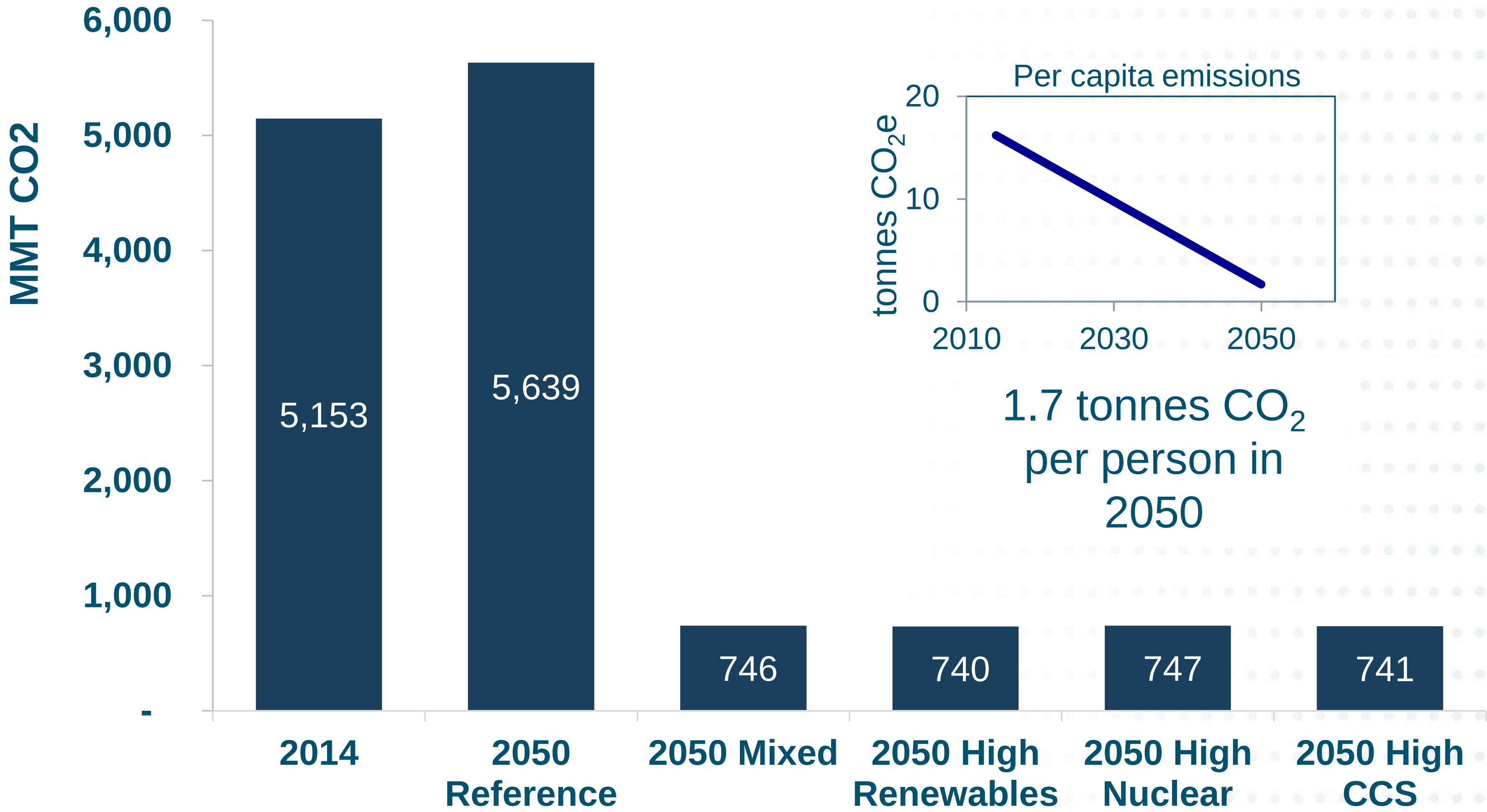
Current U.S. energy system in 2014



Decarbonized energy system in 2050

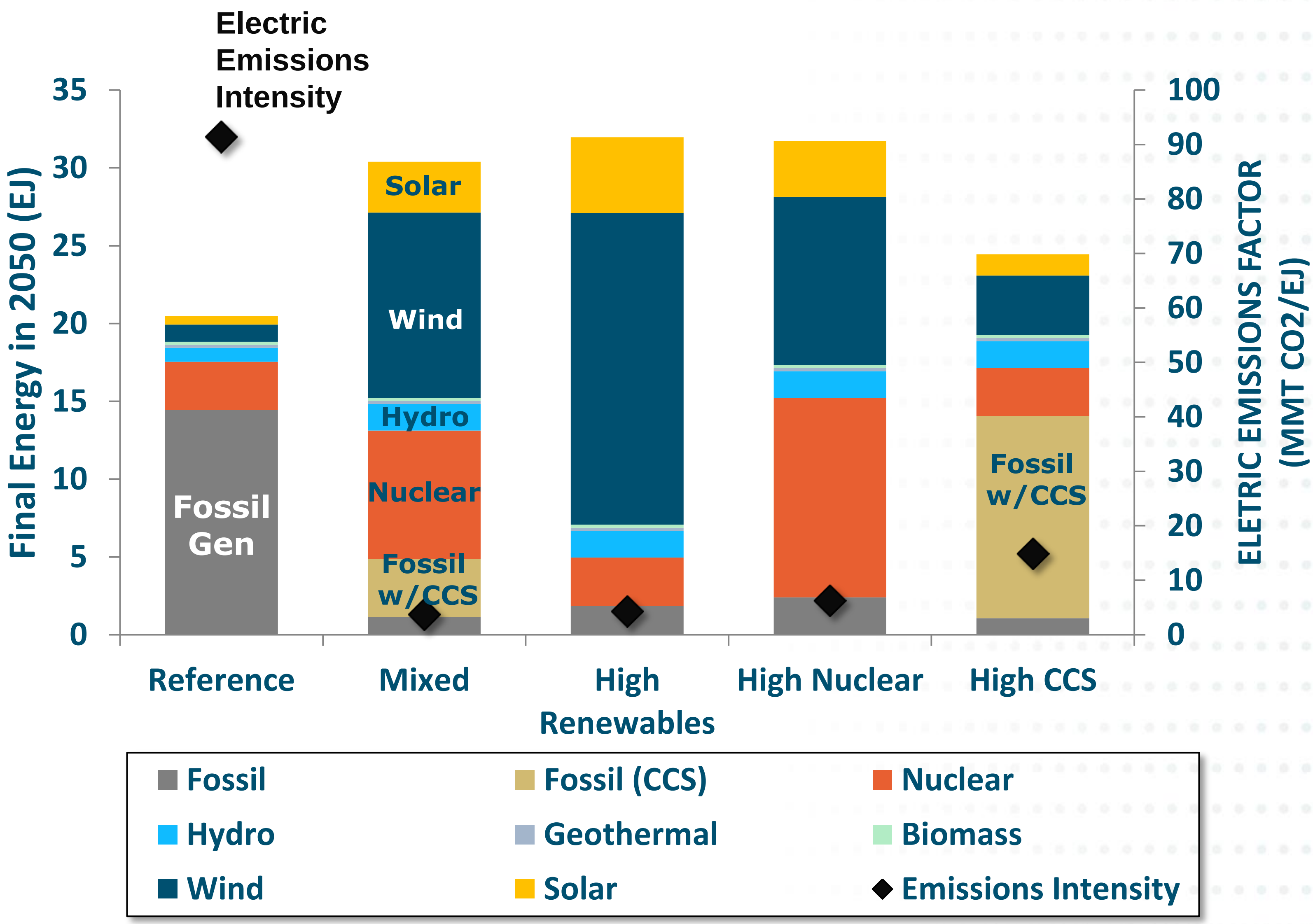


Multiple Pathways Are Technically Feasible

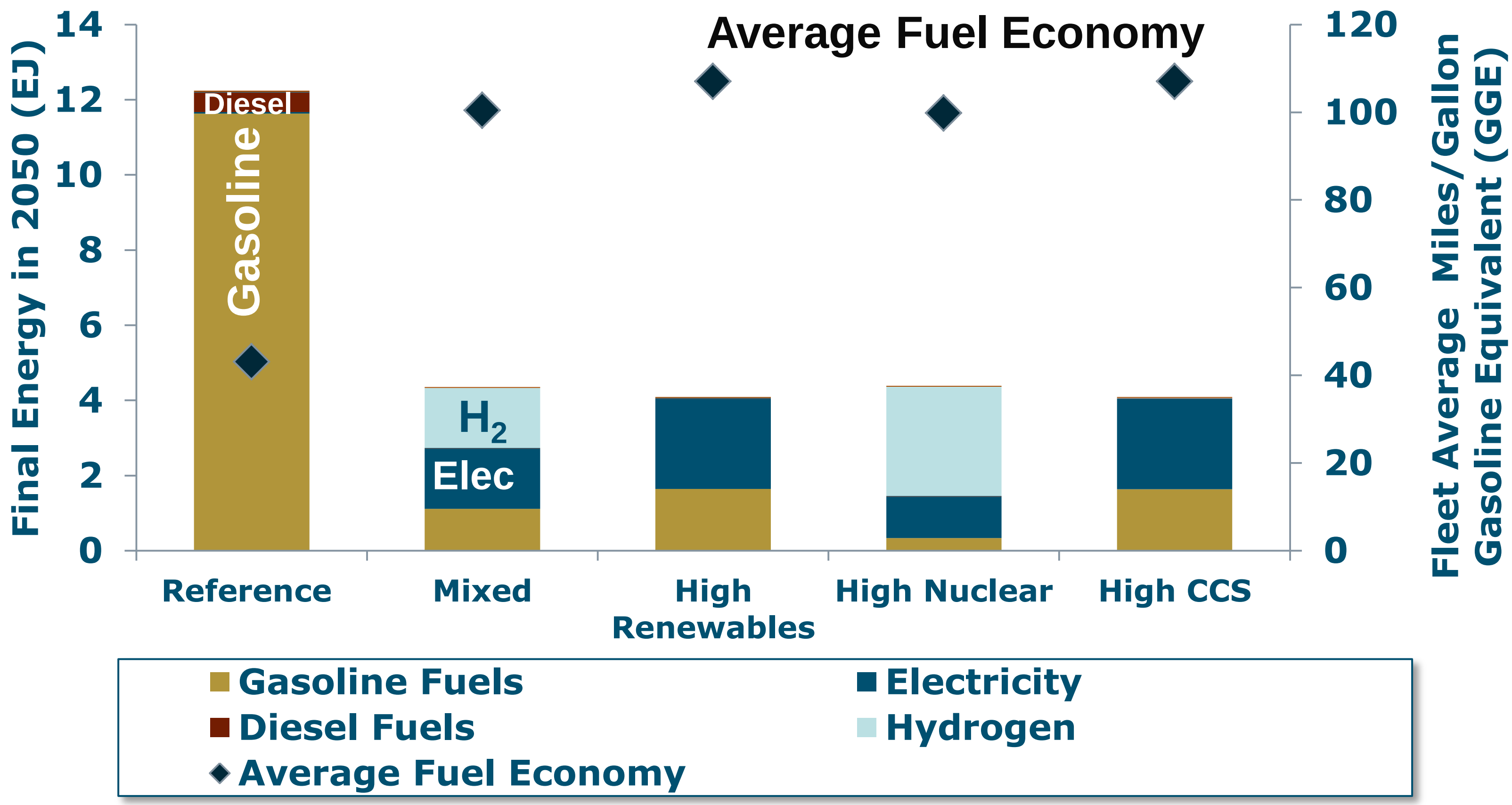


1.7 tonnes CO_2 per person in 2050

2050 Generation Mix Final Energy by Scenario



2050 LDV Final Energy Demand by Fuel Type and Average Fleet Fuel Economy



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 H_2) and fuel types (e.g., liquid fuels to electricity) is needed, given constraints?

Deep Decarbonization Problem-Solving: Some Novel Solutions

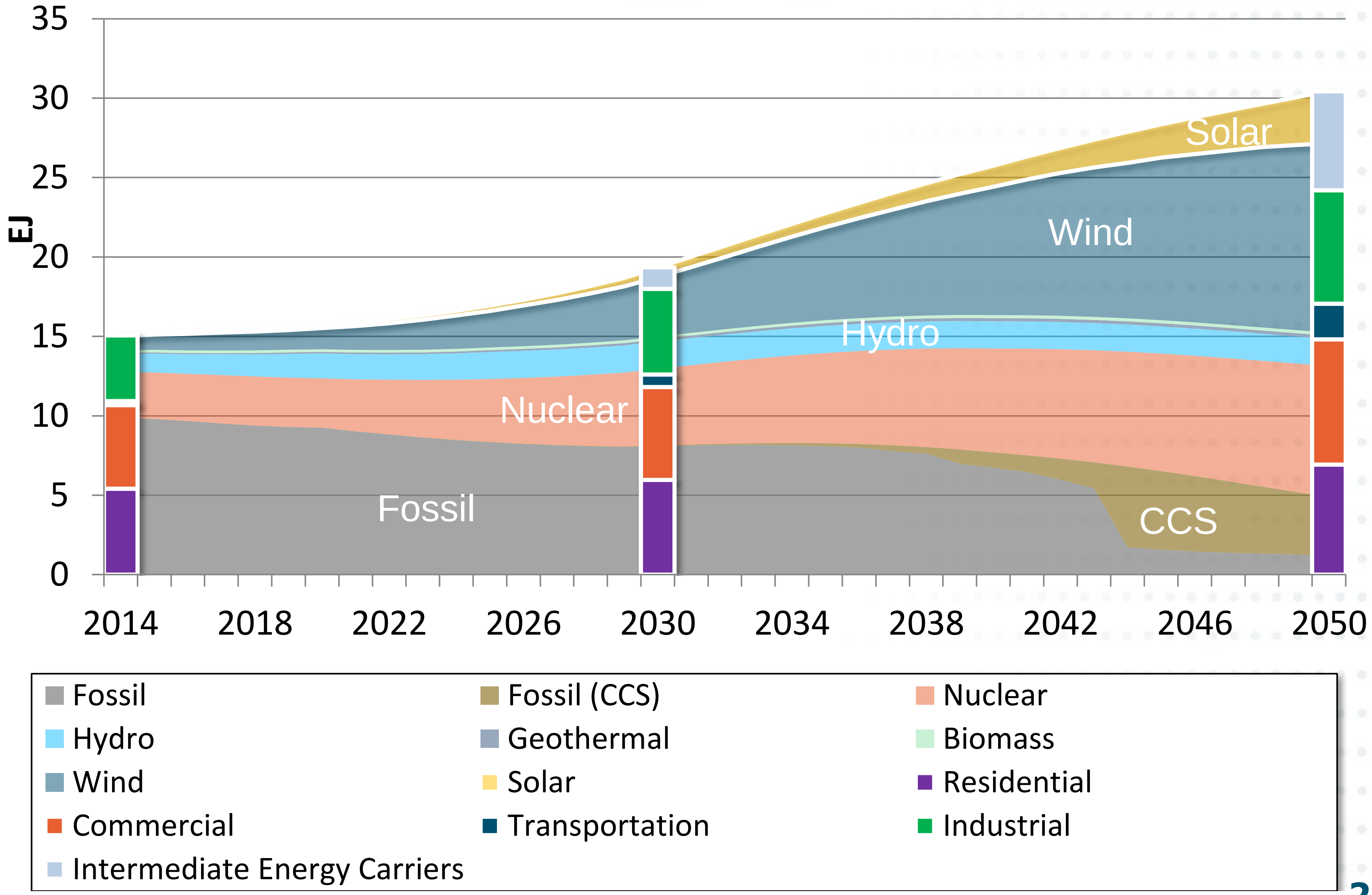
1. **Variable generation (wind, solar): → Use production of hydrogen and synthetic methane to balance power system & provide low carbon fuel**

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**

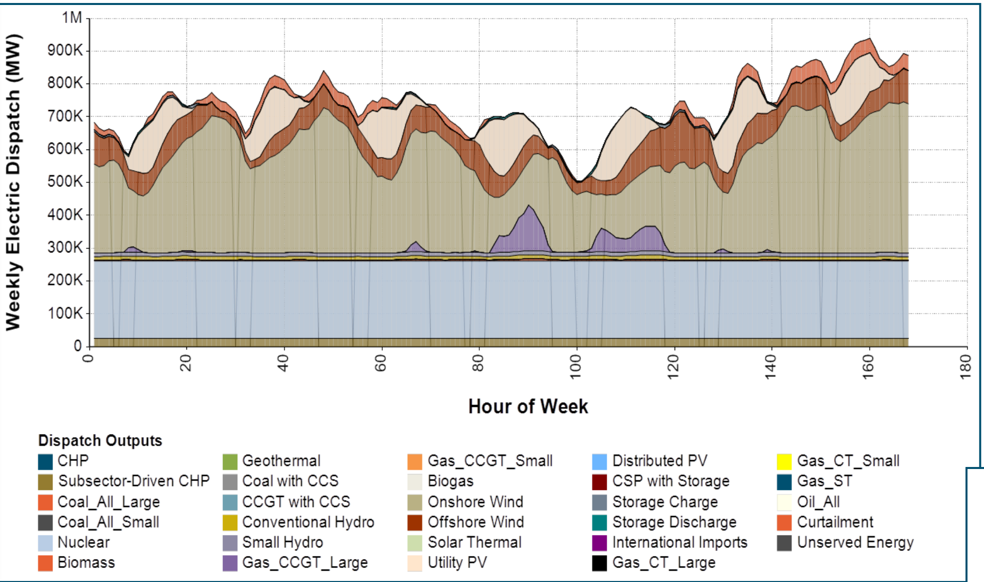
4. **Biomass → not used for ethanol because it is scarce and has better uses, such as biogas and biodiesel, while alternatives exist for LDV fuels**

Electricity Increasingly Dominated by Non-Dispatchable Generation



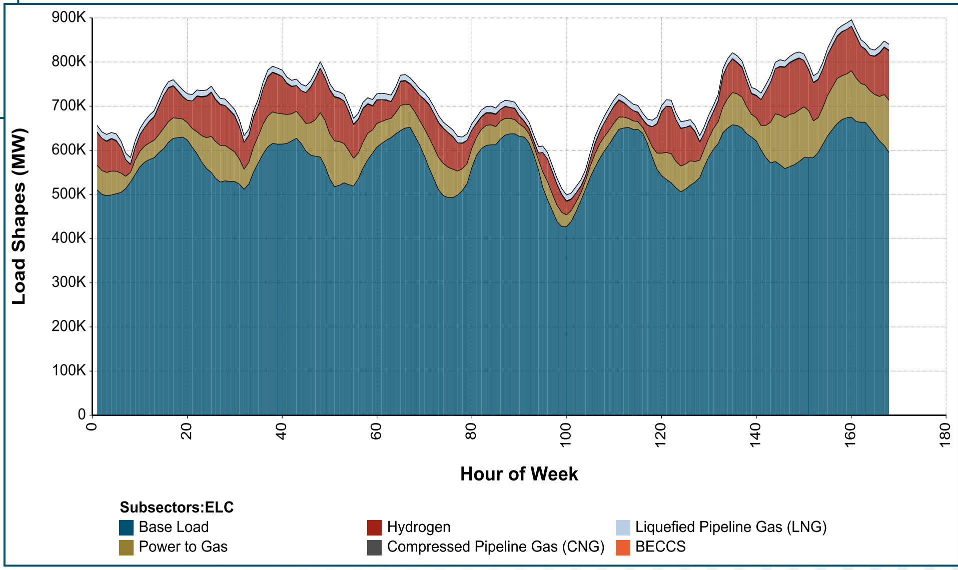
Pathways to Deep Decarbonization in the United States, Mixed case results

Electricity Dispatch and Flexible Loads Eastern Interconnect – July 2050



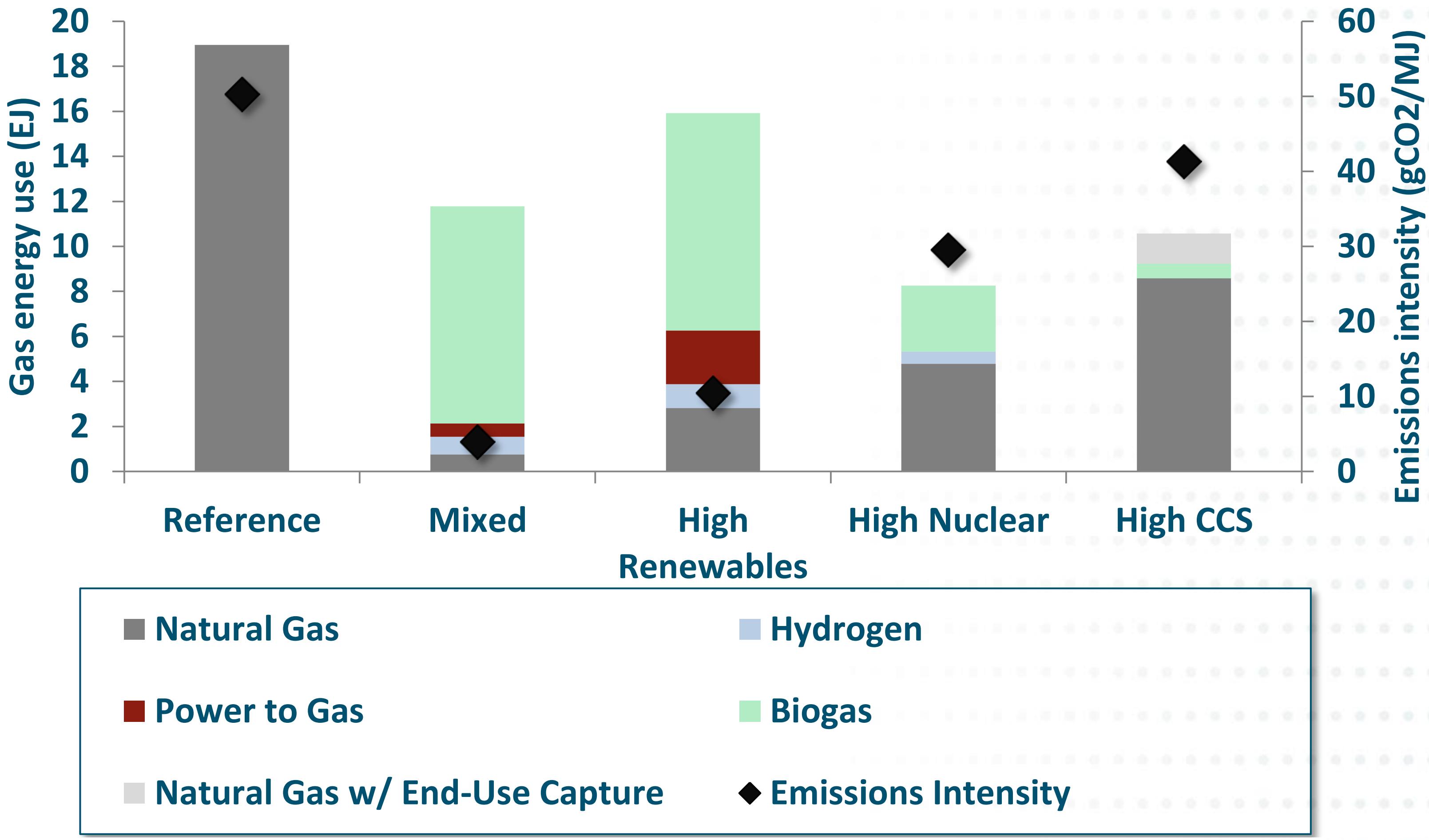
Hourly dispatch by generation type

Hourly dispatch by load type

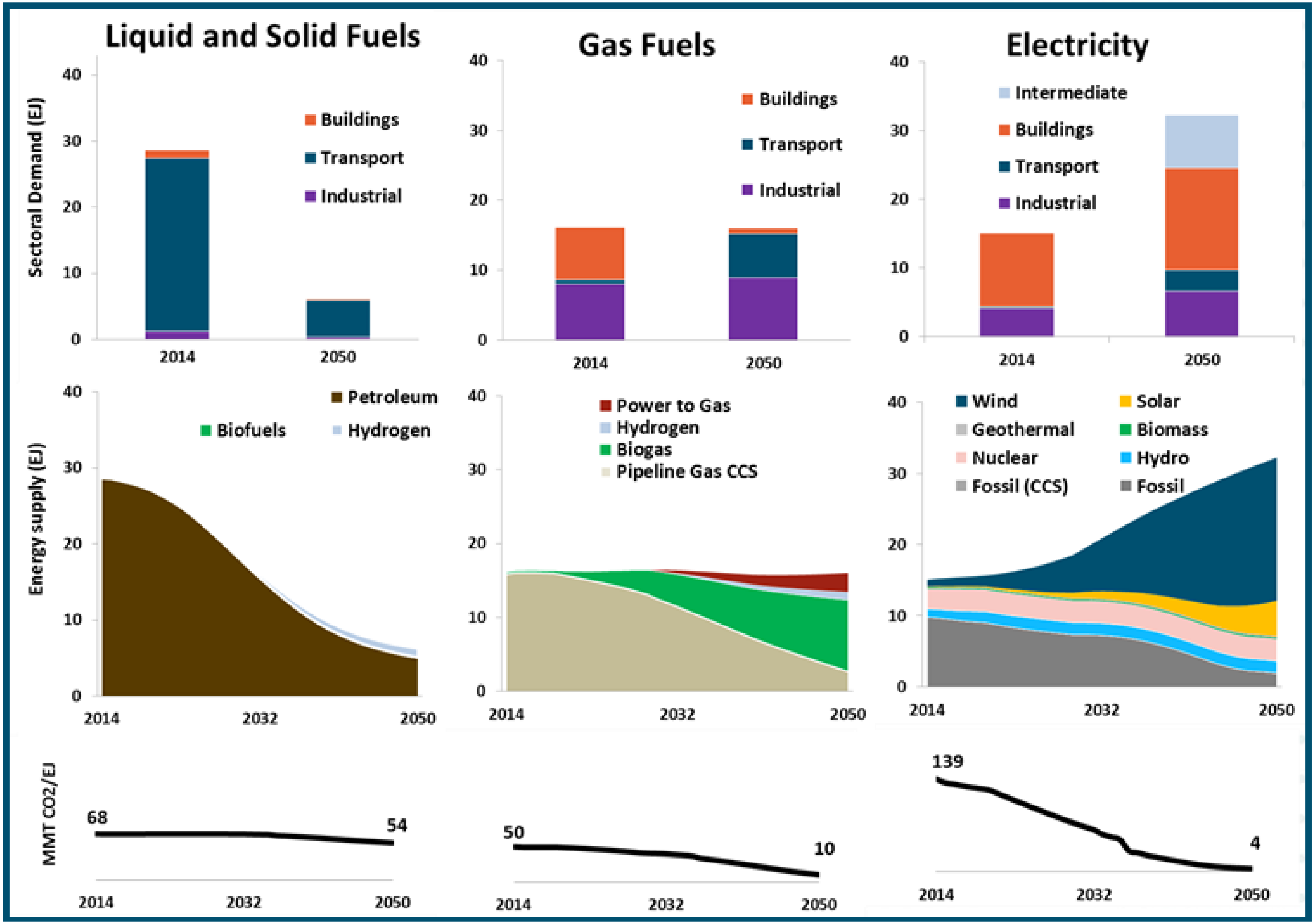


Organizing energy system to efficiently utilize non-dispatchable generation is one of the key challenges and opportunities of deep decarbonization in the U.S.

Pipeline Gas Composition in 2050



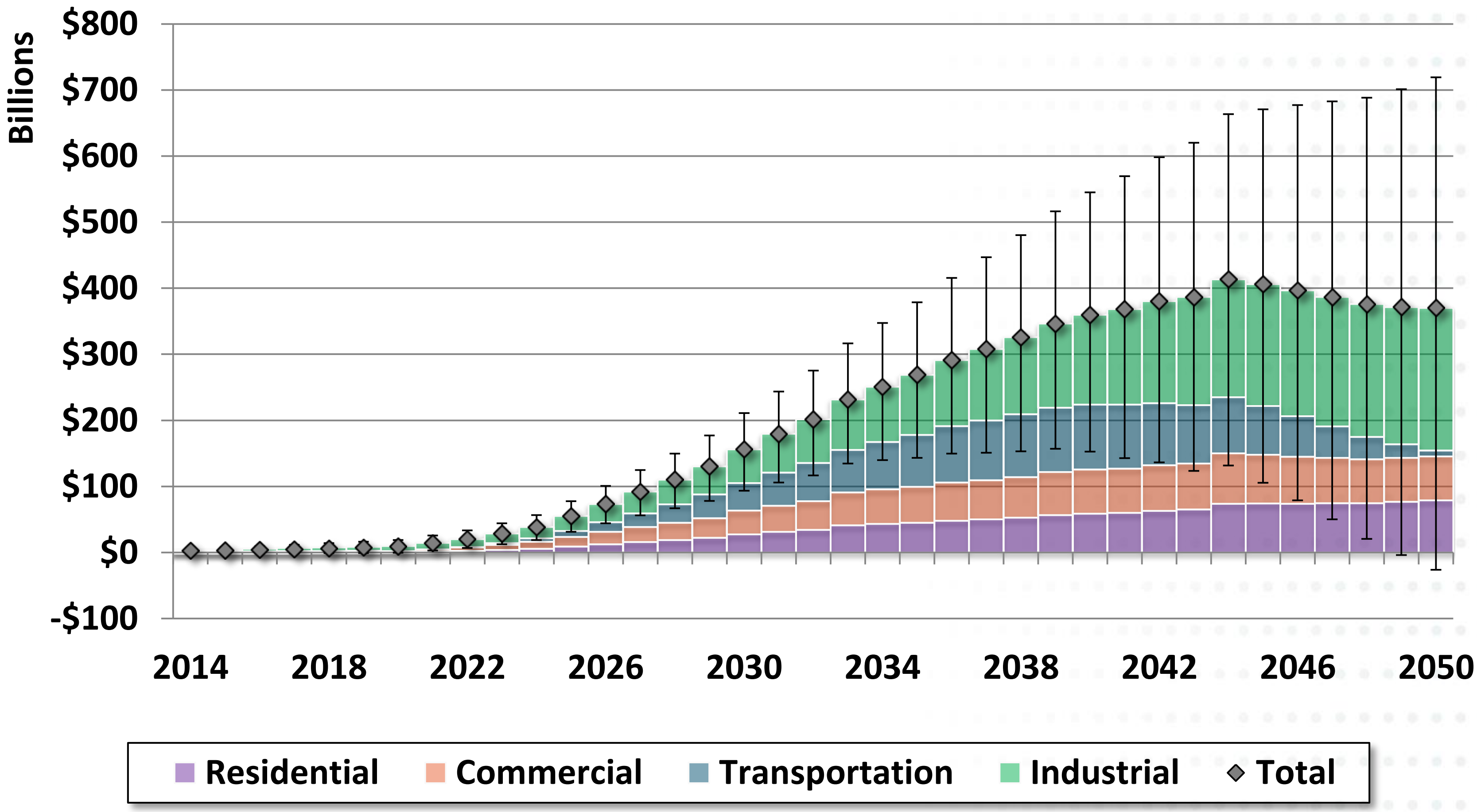
Low Carbon Transition in High Renewables Case



Pathways to Deep Decarbonization in the United States, Mixed case results

Net Energy System Cost

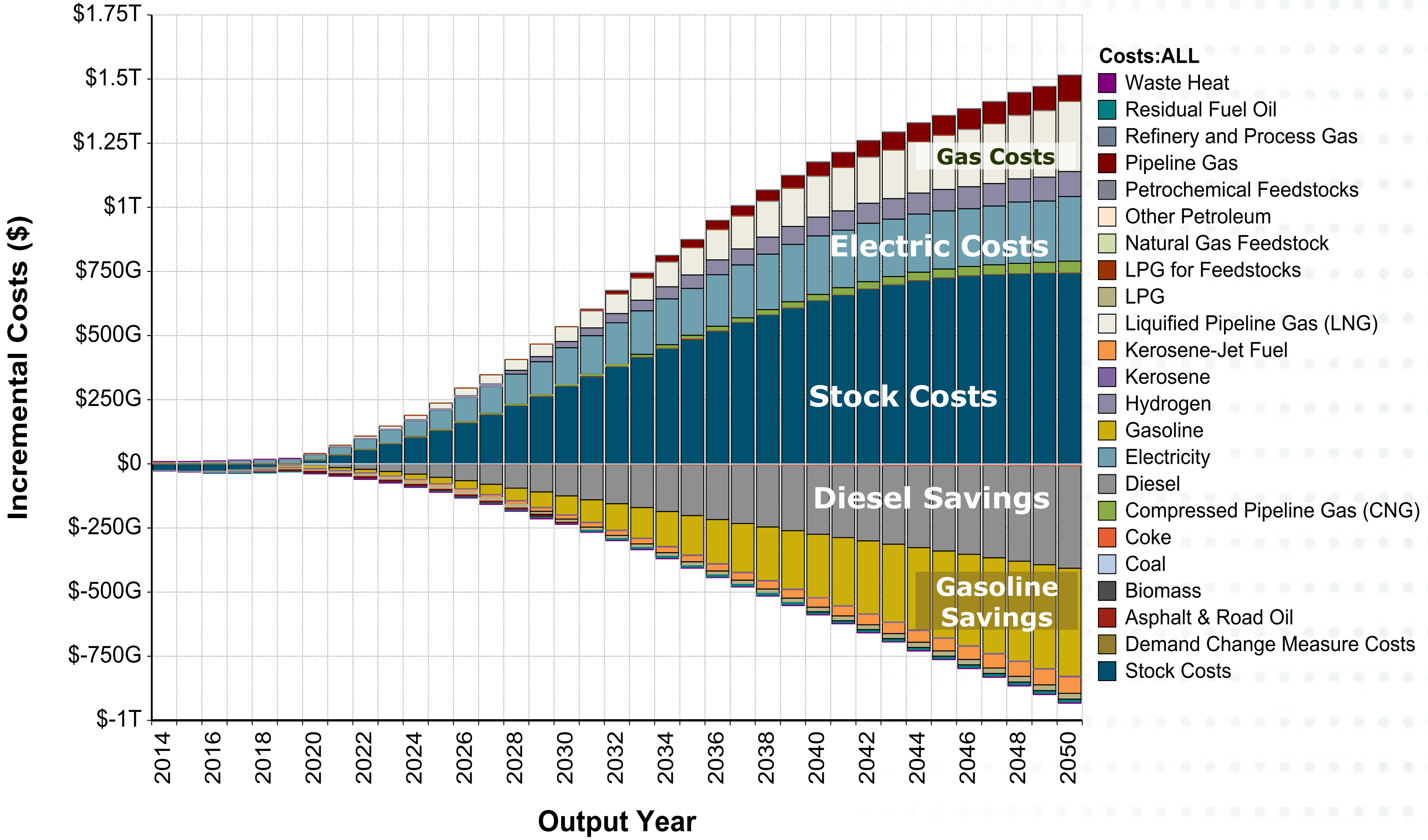
- Median 2050 net energy system cost ~1% of GDP ($40T)
- Uncertainty range -0.2% to + 1.8%



Pathways to Deep Decarbonization in the United States, Mixed case results

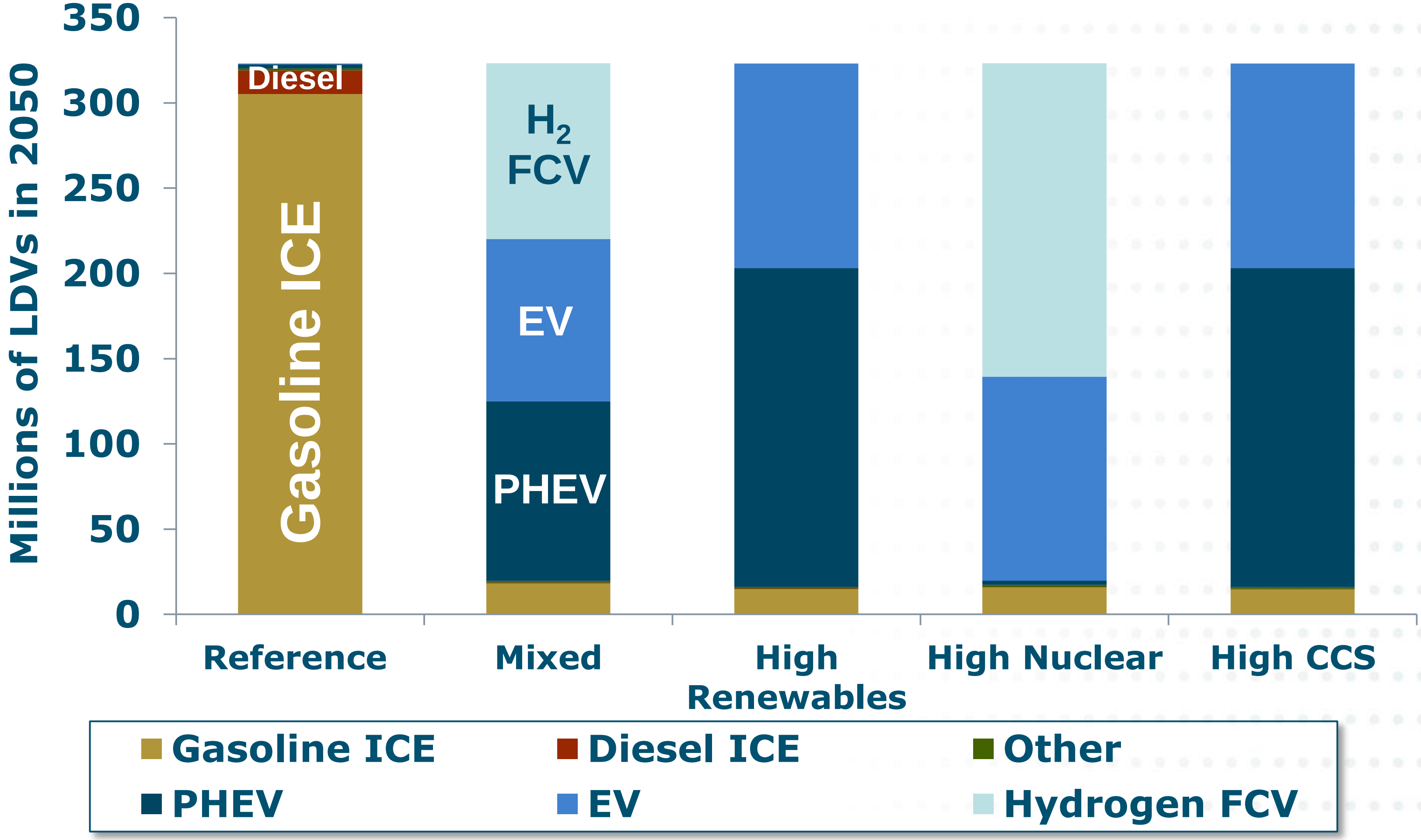
Net Cost Components

- Costs = mostly fixed costs, savings = mostly fuel savings
- Lower net cost if technology costs lower, fossil fuels higher

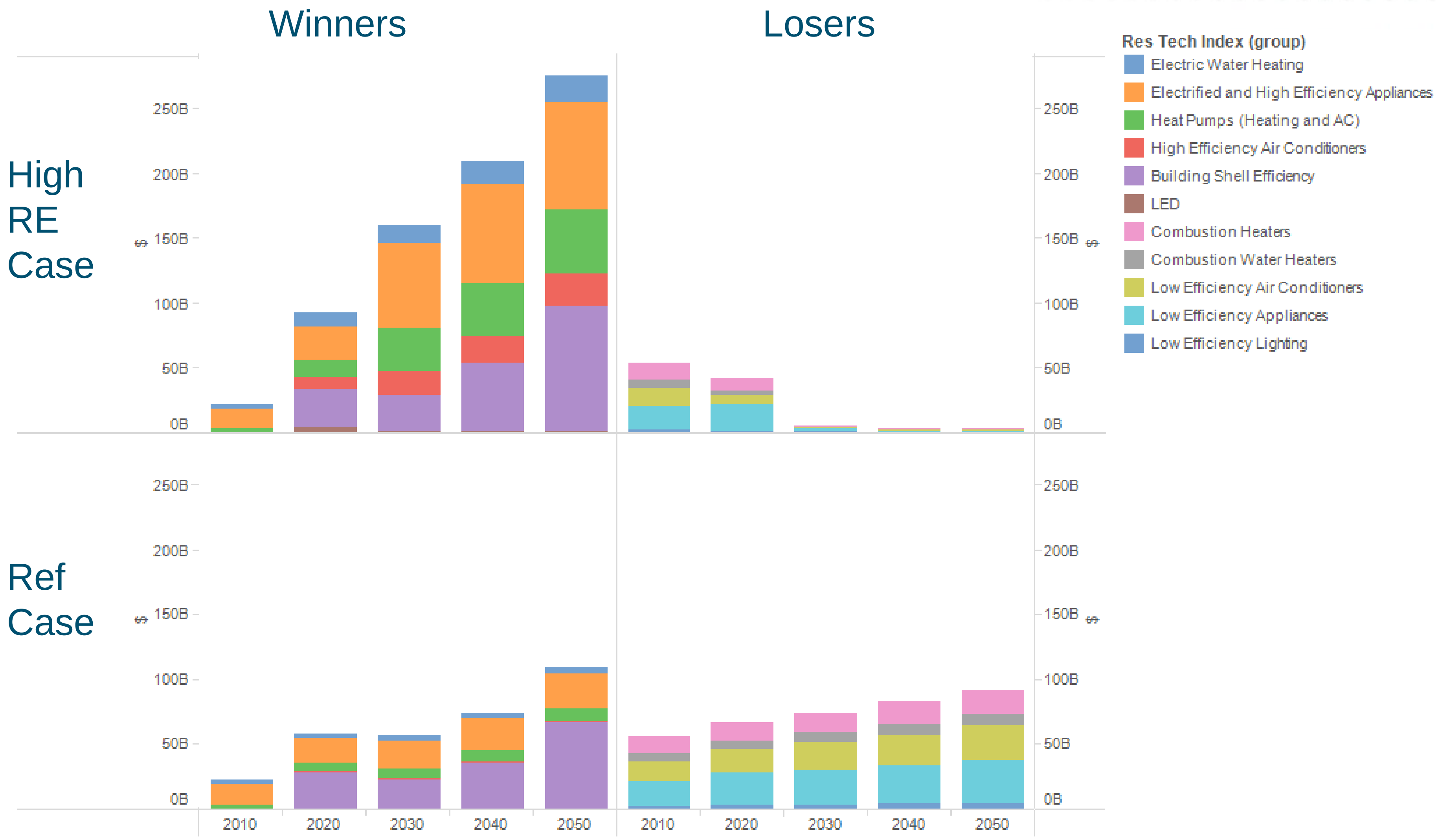


Pathways to Deep Decarbonization in the United States, High renewables case

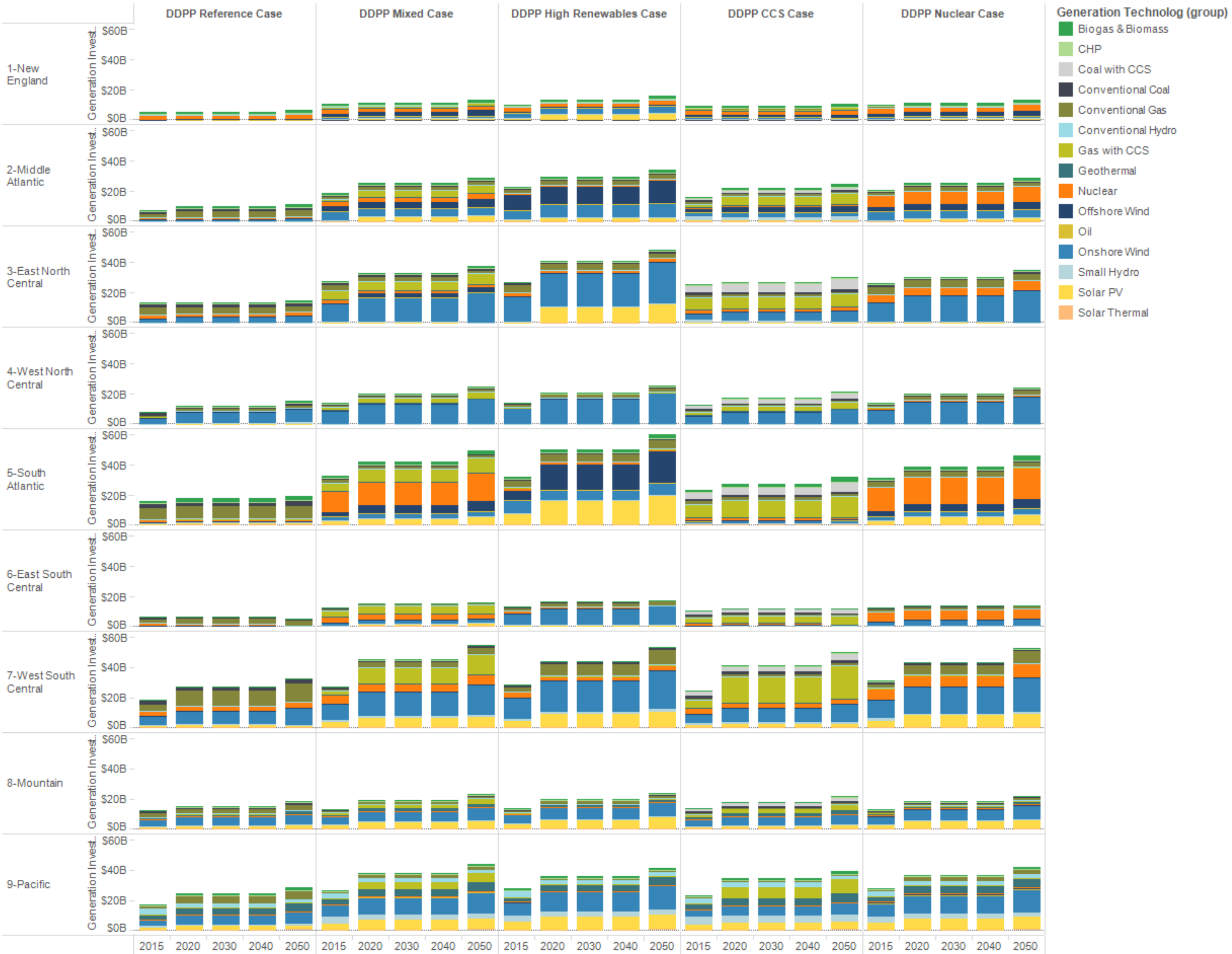
2050 LDV Stock by Scenario



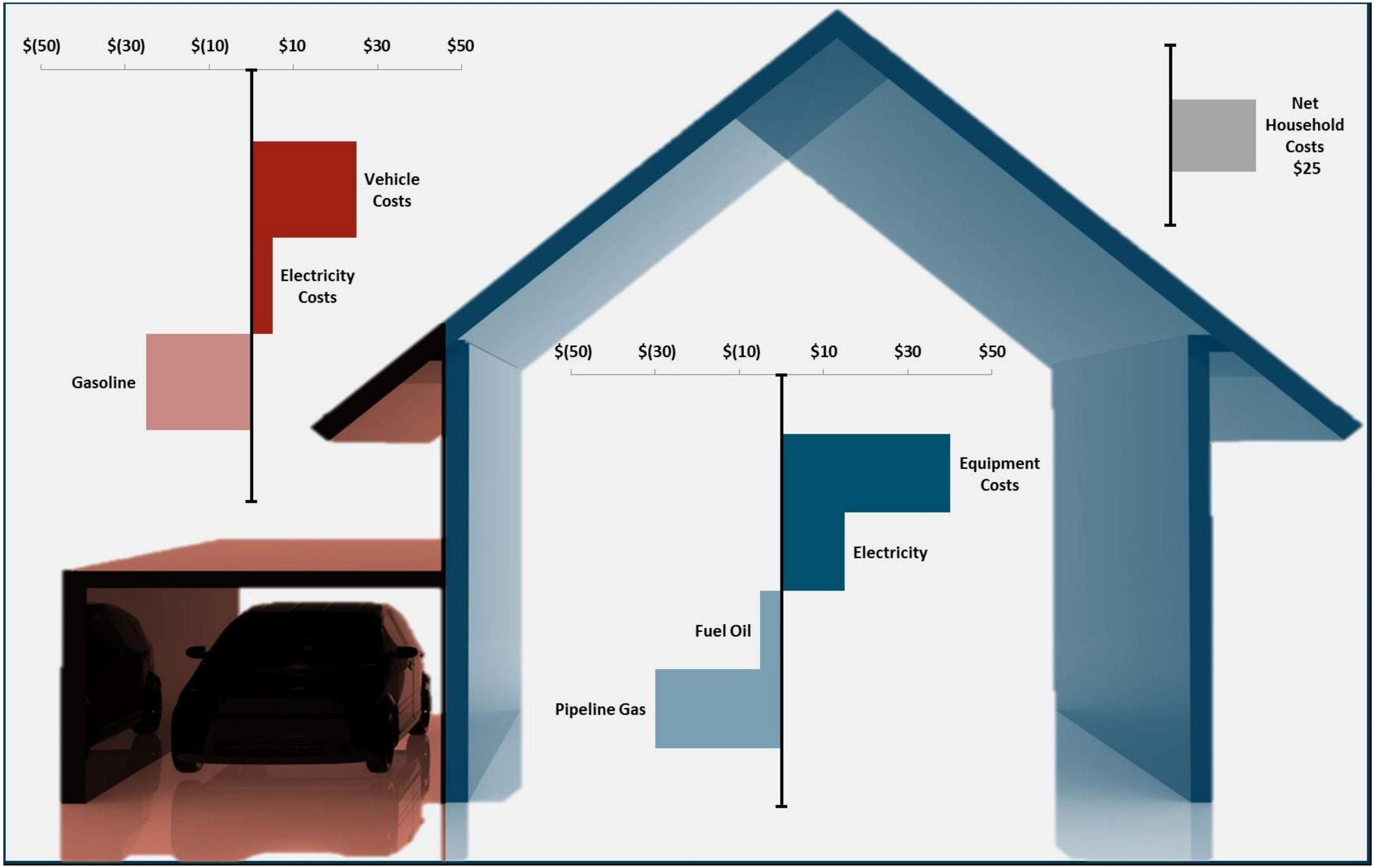
Residential Energy Efficiency & Fuel Switching Investment by Decade



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

CARBON CYCLE SCIENCE IMPLICATIONS

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

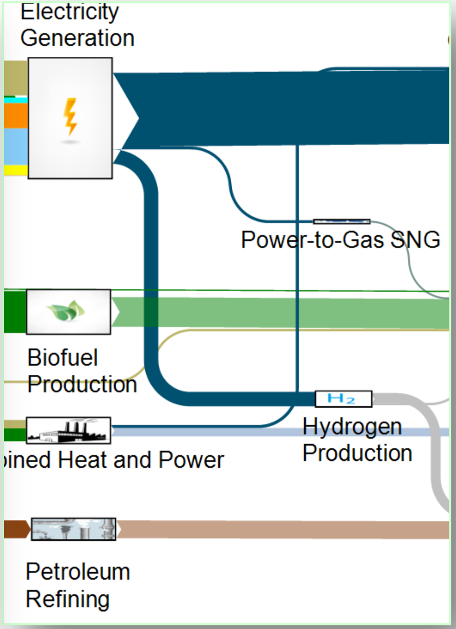
Bio-Energy

LBL-USDA switchgrass expt.
M. Torn

LULUCF

UMBS AmeriFlux site
C. Gough

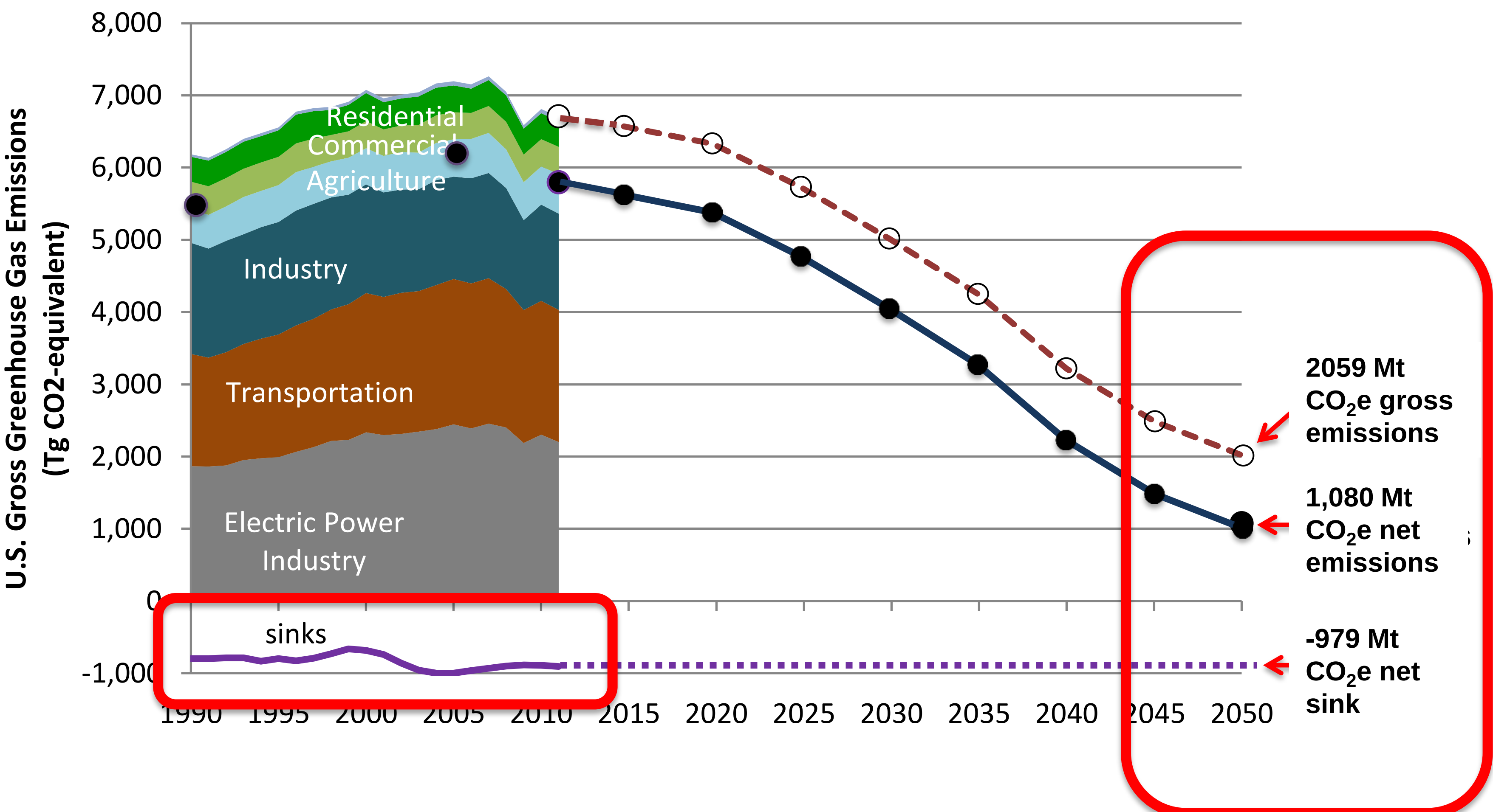
Non-CO_2 GHGs



Infrastructure

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

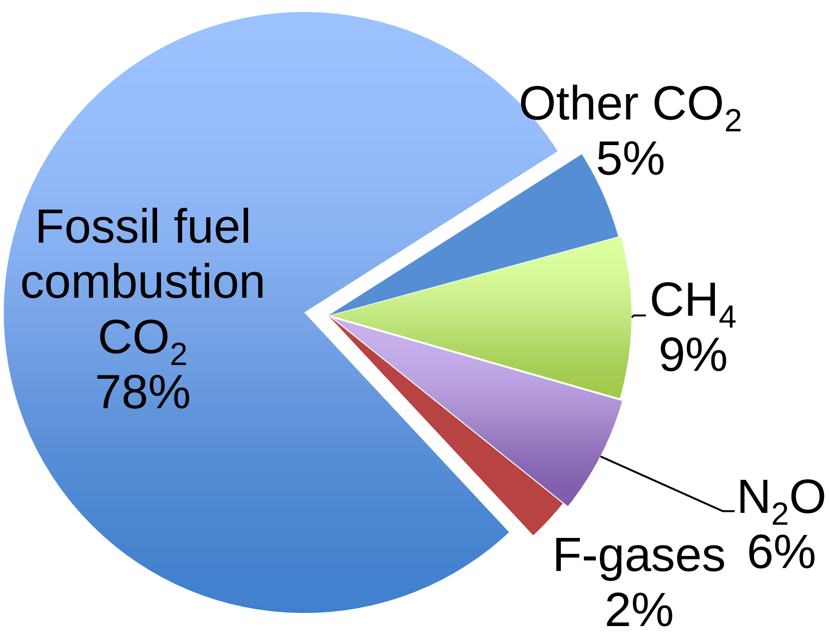


Based on US EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2011, Table 2-2

In Deeply Decarbonized System, ***Non-CO_2 GHGs*** *Become Dominant Form of Emissions*

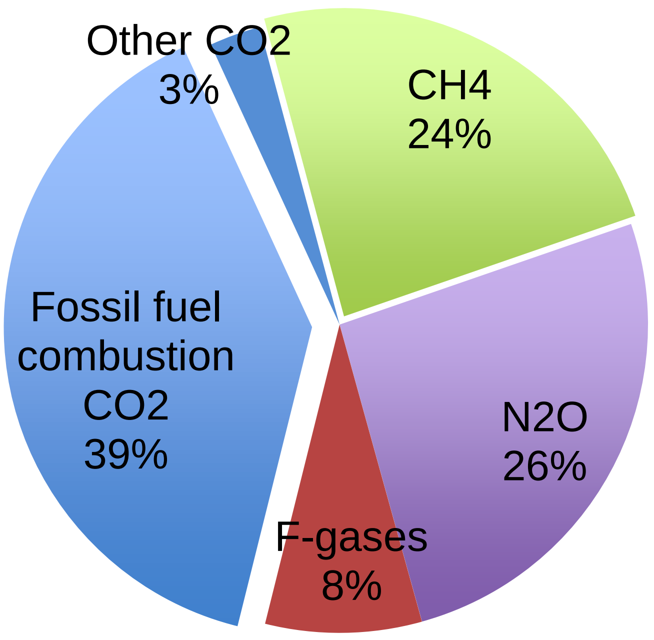
- Decline in absolute terms from present
- Increase in share of total CO2e from **17%** *in 2012* to **58%** in 2050

2012 EPA inventory



Energy CO_2: 5,066 Mt CO_2e
Non-energy: 1,435 Mt CO_2e

2050 Pathways



Energy CO_2: 750 Mt CO_2e
Non-energy: 1,161 Mt CO_2e

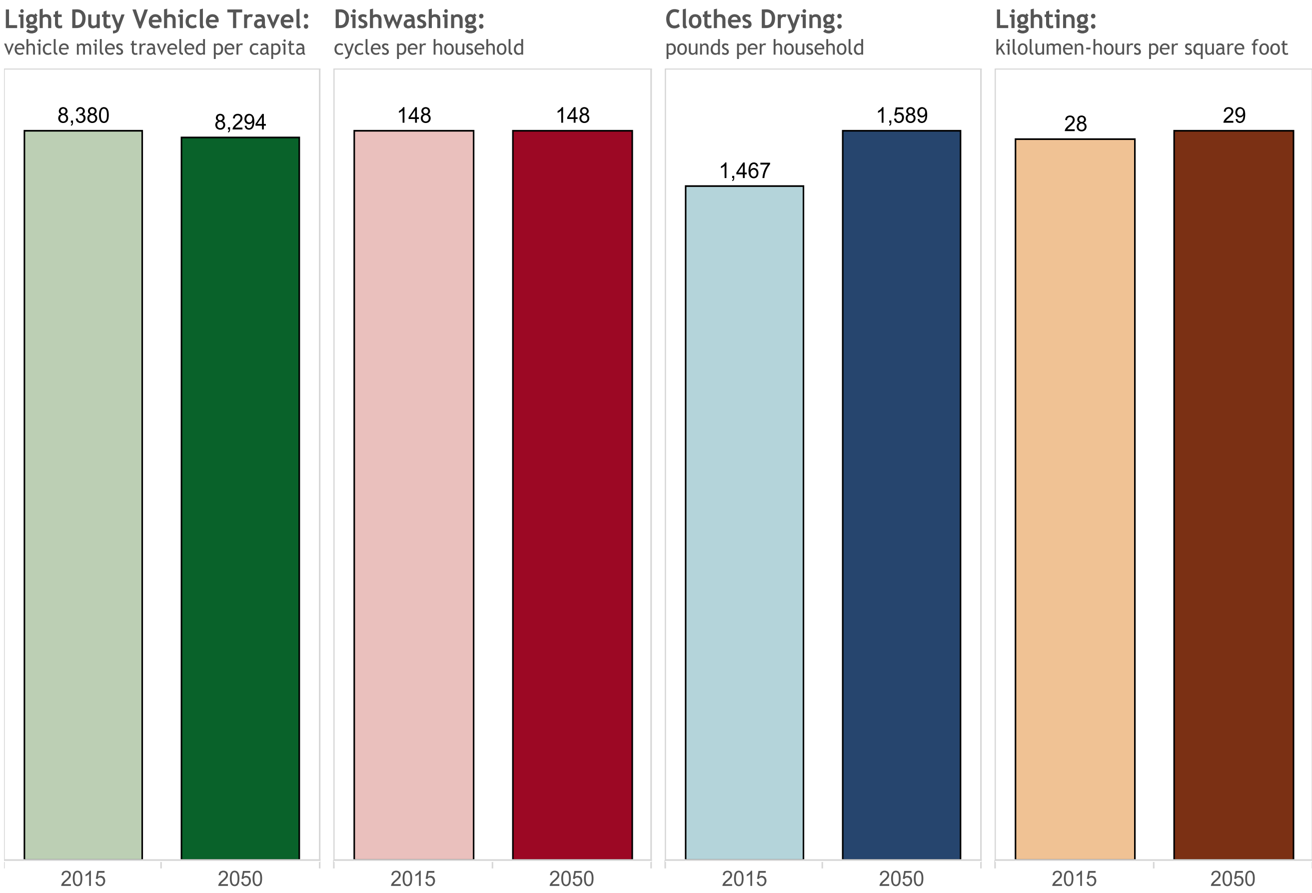
Energy+Environmental Economics

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.**

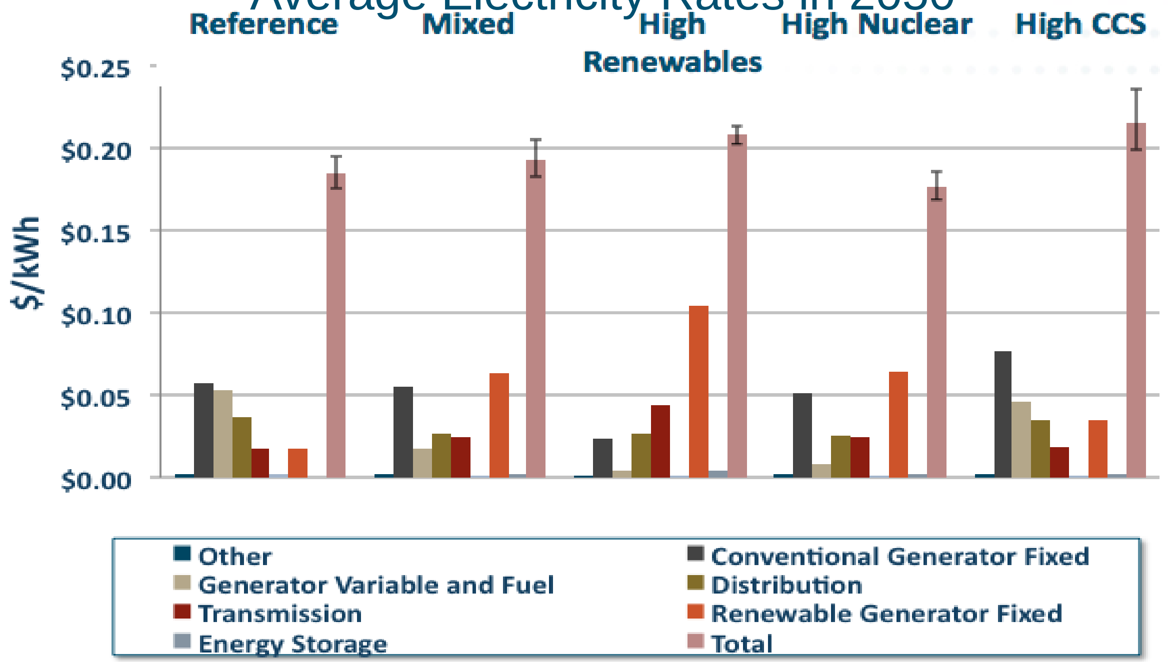


Four Seeming Paradoxes:
2. Energy Economy

- **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

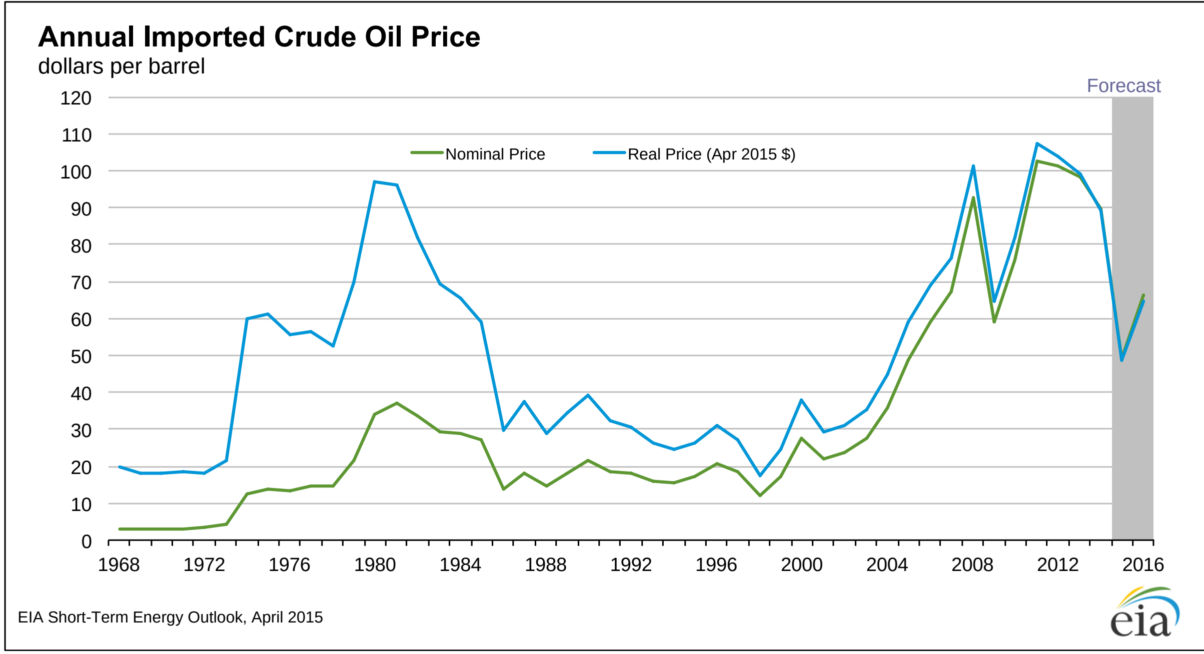
- **However, the change in consumer costs for energy goods and services is likely to be small**

Average Electricity Rates in 2050



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

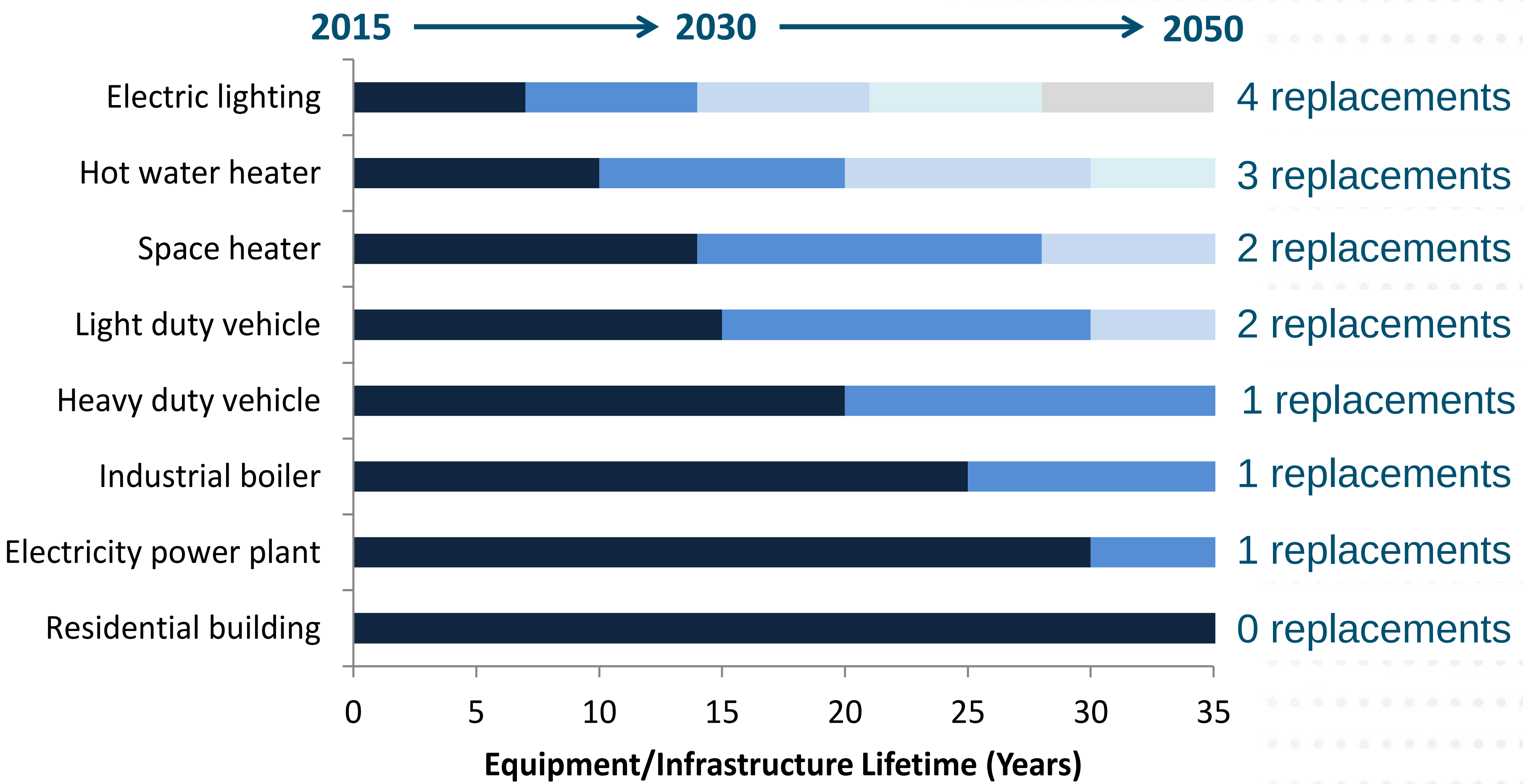


Four Seeming Paradoxes: 4. Policy Challenges

- **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

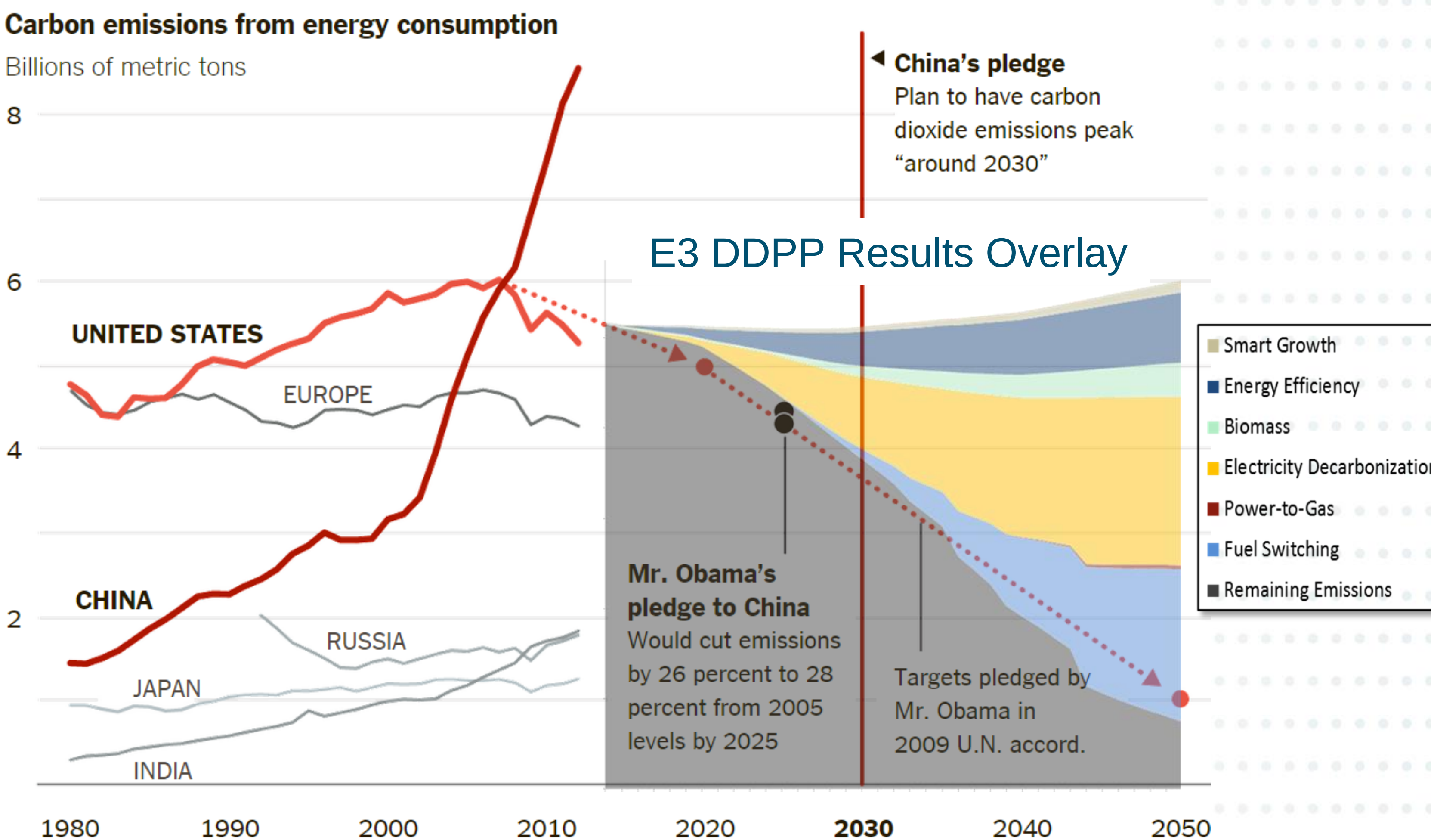
Timing for Action is Limited

- 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



Source: NY Times November 12th, 2014 + Deep Decarbonization Pathways in the United States, 2014

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

Energy+Environmental Economics

Thank You!

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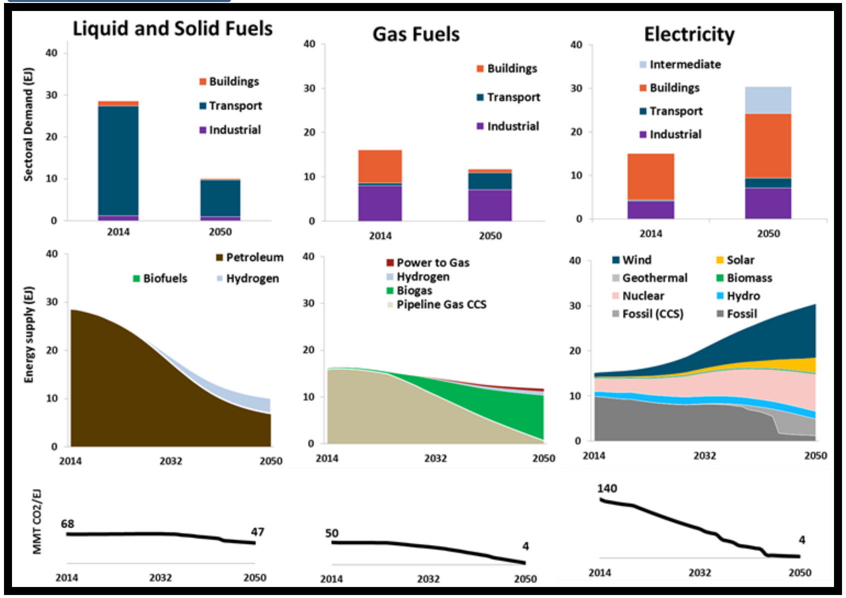
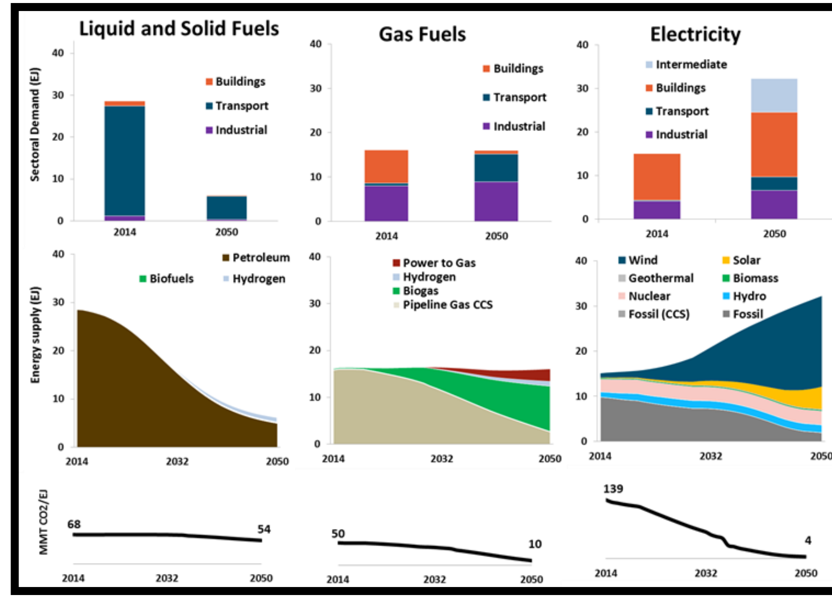
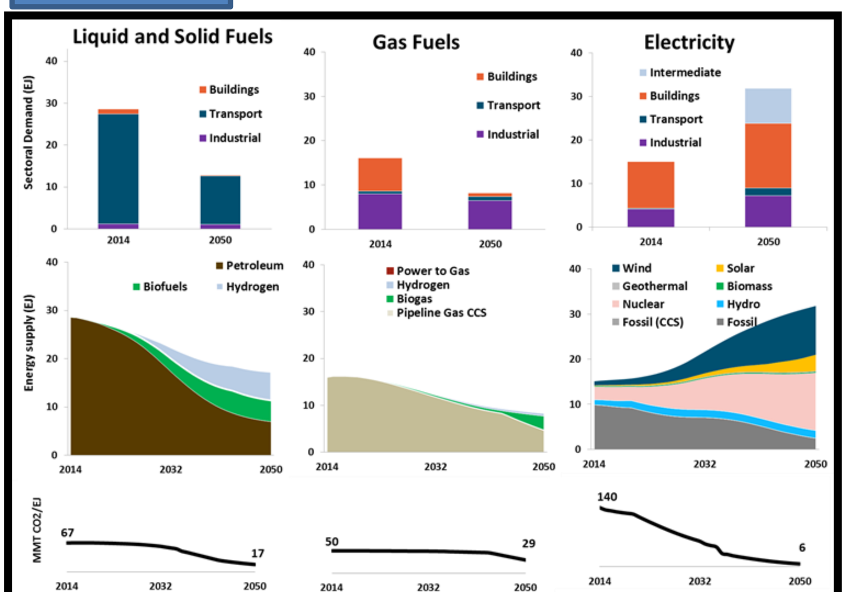
Mixed



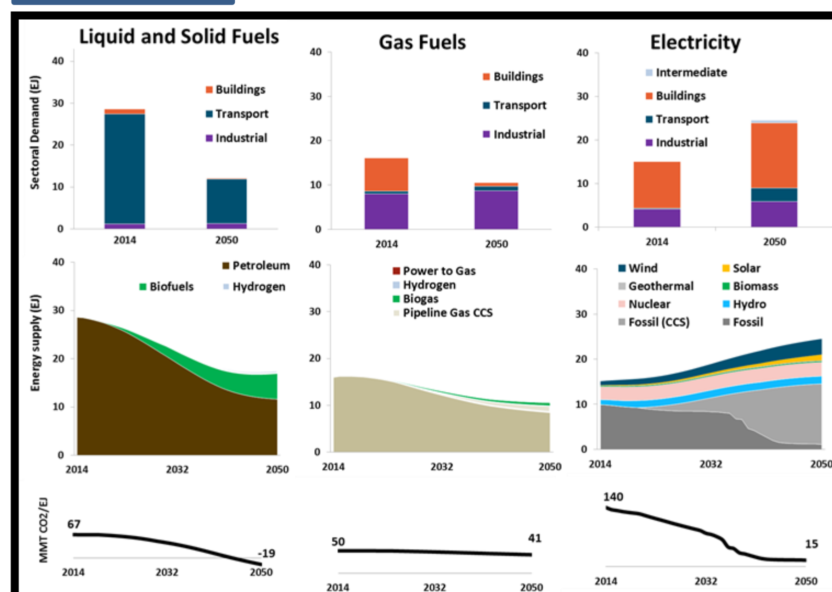
High Renewables



High Nuclear

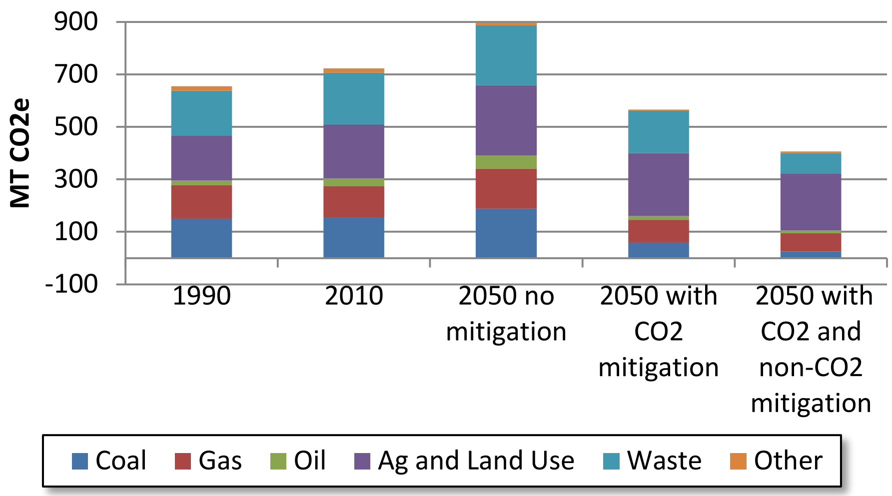


High CCS



Non-Energy and Non-CO_2 GHG Mitigation

GCAM analysis shows non-CO_2 and non-energy mitigation strategies consistent with 80% reduction target

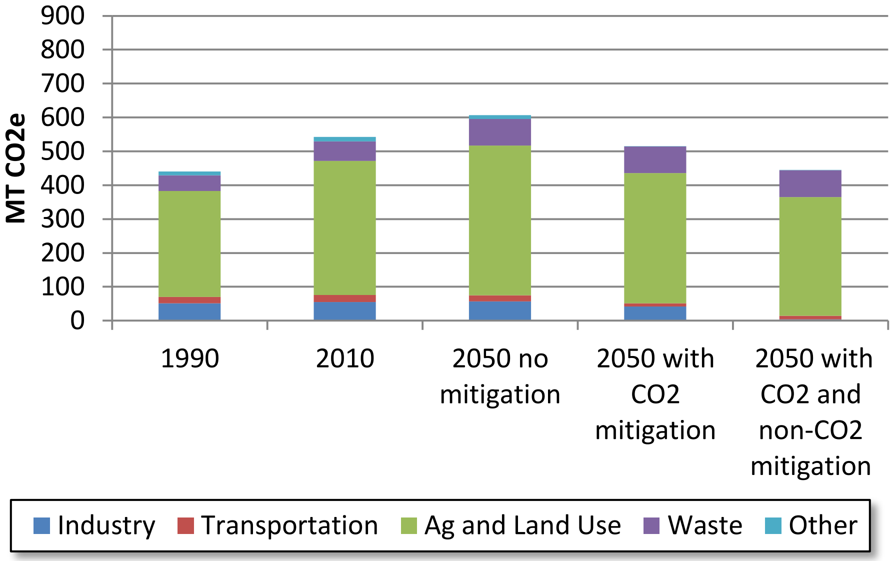


CH_4 Mitigation

Terrestrial sink sensitivity analysis

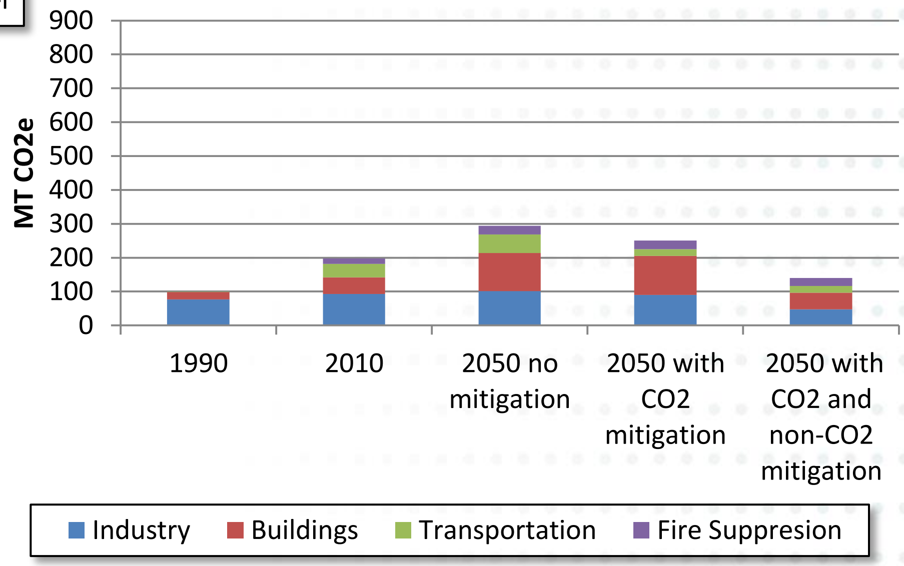
Sink sensitivity	1990 sink +50%	1990 sink +25%	Central Case	1990 sink -25%	1990 sink -50%
2050 terrestrial CO_2 sink	1,247	1,039	831	623	416
Allowable 2050 gross CO_2e	2,327	2,119	1,911	1,704	1,496
Fossil fuel + industrial CO_2	1,312	1,109	796	711	513
Non-CO_2 emissions (all)	1,017	1,009	992	991	983
% Reduction in fossil fuel + industrial CO_2	74%	78%	84%	86%	90%
% Reduction in non-CO_2	10%	10%	12%	12%	13%
% Reduction in net CO_2e	80%	80%	82%	80%	80%

N_2O and F-gas Mitigation



N_2O Mitigation

F-gas Mitigation



Principal Non-CO_2 Mitigation Strategies by Subsector

Subsector	Absolute Reduction ($MtCO_2e$)	Percent Reduction
CH_4		
Landfills	**82**	**73%**
Coal	35	58%
Enteric Fermentation	16	9%
Natural Gas	16	19%
N_2O		
Agricultural Soils	**33**	**9%**
Adipic Acid Production	27	96%
Nitric Acid Production	10	89%
Fluorinated Gases		
Air Conditioning	**64**	**63%**
Solvents	32	82%