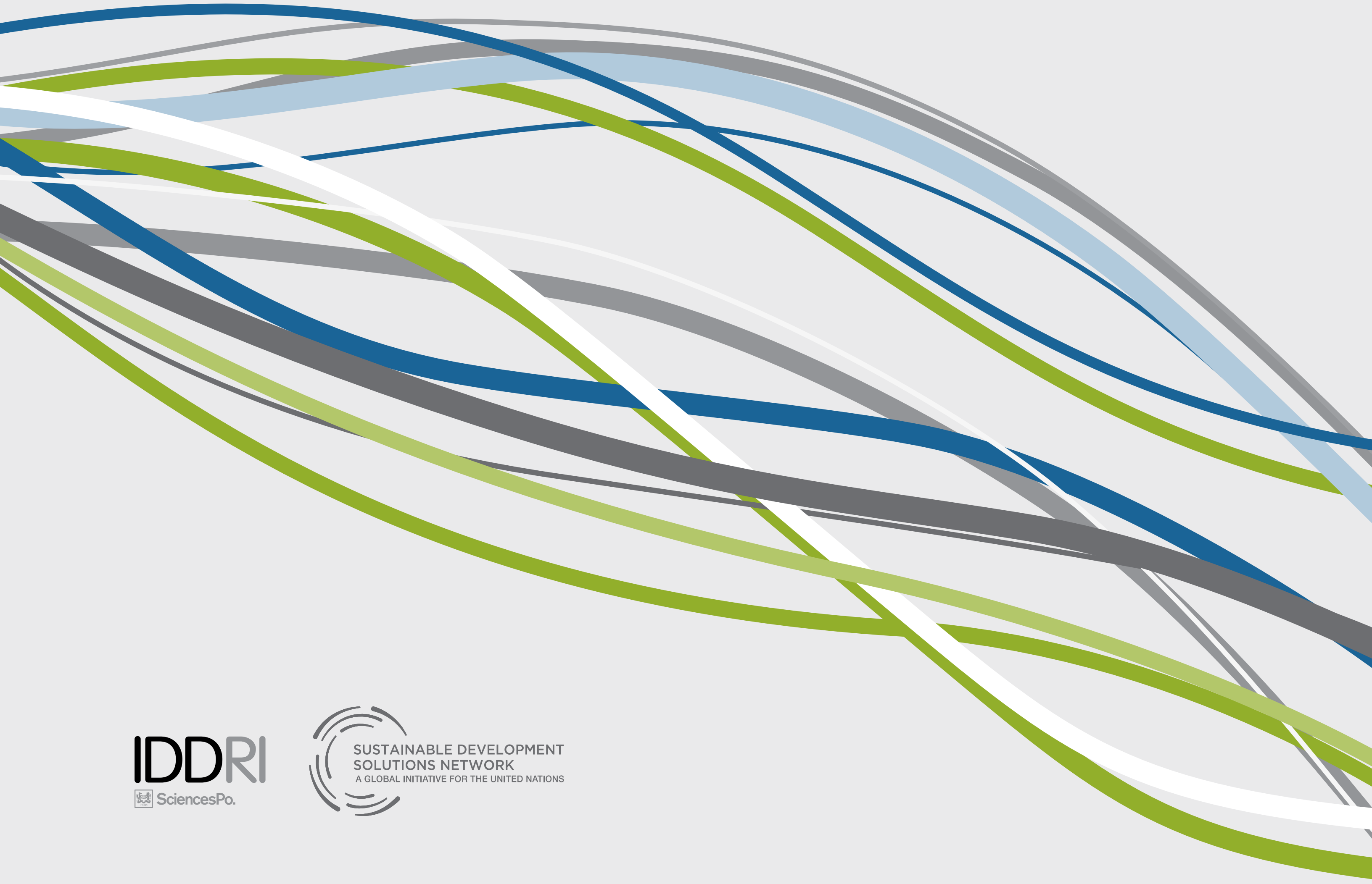
United States Chapter

pathways to
deep decarbonization

2014 report



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SUSTAINABLE DEVELOPMENT
SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

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Preface

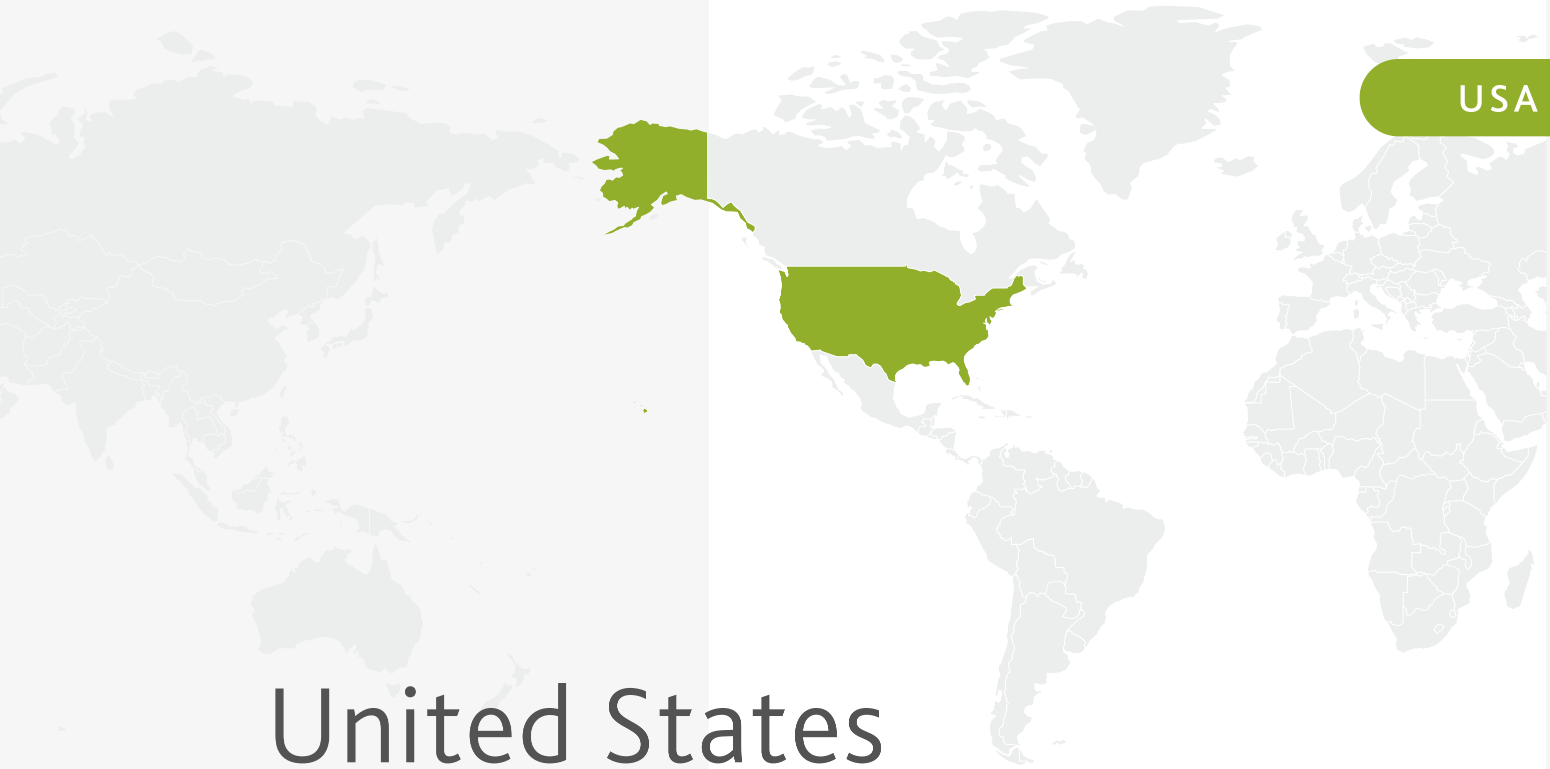
The Deep Decarbonization Pathways Project (DDPP) is a collaborative initiative, convened under the auspices of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), to understand and show how individual countries can transition to a low-carbon economy and how the world can meet the internationally agreed target of limiting the increase in global mean surface temperature to less than 2 degrees Celsius (°C). Achieving the 2°C limit will require that global net emissions of greenhouse gases (GHG) approach zero by the second half of the century. This will require a profound transformation of energy systems by mid-century through steep declines in carbon intensity in all sectors of the economy, a transition we call "deep decarbonization."

Currently, the DDPP comprises 15 Country Research Partners composed of leading researchers and research institutions from countries representing 70% of global GHG emissions and different stages of development. Each Country Research Partner has developed pathway analysis for deep decarbonization, taking into account national socio-economic conditions, development aspirations, infrastructure stocks, resource endowments, and other relevant factors. The pathways developed by Country Research Partners formed the basis of the DDPP 2014 report: Pathways to Deep Decarbonization, which was developed for the UN Secretary-General Ban Ki-moon in support of the Climate Leaders' Summit at the United Nations on September 23, 2014. The report can be viewed at deepdecarbonization.org along with all of the country-specific chapters.

This chapter provides a detailed look at a single Country Research Partner's pathway analysis. The focus of this analysis has been to identify technically feasible pathways that are consistent with the objective of limiting the rise in global temperatures below 2°C. In a second—later—stage the Country Research Partner will refine the analysis of the technical potential, and also take a broader perspective by quantifying costs and benefits, estimating national and international finance requirements, mapping out domestic and global policy frameworks, and considering in more detail how the twin objectives of development and deep decarbonization can be met. This comprehensive analysis will form the basis of a report that will be completed in the first half of 2015 and submitted to the French Government, host of the 21st Conference of the Parties (COP-21) of the United Nations Framework Convention on Climate Change (UNFCCC).

We hope that the analysis outlined in this report chapter, and the ongoing analytical work conducted by the Country Research Team, will support national discussions on how to achieve deep decarbonization. Above all, we hope that the findings will be helpful to the Parties of the UNFCCC as they craft a strong agreement on climate change mitigation at the COP-21 in Paris in December 2015.

Contents



United States

Energy and Environmental Economics, Inc.

1 Country profile

1.1 The national context for deep decarbonization and sustainable development

The United States is the world's second largest emitter of greenhouse gases (GHGs), and one of the highest per capita consumers and producers of energy and fossil fuels. Deep decarbonization will require a profound transformation of the way energy is produced, delivered, and used, in a transition that is sustained over multiple generations. This analysis provides insight into what very low-carbon energy systems in the U.S. could look like and describes key steps and alternative routes to reaching a level of energy-related CO_2 emissions that is consistent with an increase in global mean temperature below 2°C. In 2010, U.S. energy-related emissions were approximately 18 metric tons of CO_2 per person. For the U.S. to do its share in reaching the 2°C target, by 2050 this per capita emissions level will need to decrease by an order of magnitude. Developing a long-term strategic vision of how the U.S. can reach this goal is essential for informing near-term policy and investment decisions and for conveying to domestic and international audiences how the U.S. can provide climate leadership while maintaining economic growth and improving standards of living.

The U.S. currently does not have comprehensive federal climate legislation or a binding national GHG emissions target. Nonetheless, the U.S. has taken important steps in low-carbon policy and technology deployment at the federal, state, and local government levels. Significant recent federal government executive branch actions include setting vehicle fuel economy standards, which will nearly double for passenger cars and light trucks by the 2025 model year relative to 2010, and establishing appliance energy efficiency standards for more than 50 product categories, leading to dramatic reductions in unit energy consumption for technologies such as refrigeration and lighting. In June 2014, the Obama Administration announced plans to apply the federal Clean Air Act to CO_2 emitted by power plants, setting a target of a 30% reduction below 2005 levels by 2030, which, if implemented successfully, will hasten the transition from uncontrolled coal generation to natural gas or coal with CCS.

In the U.S., states have primary jurisdiction over many key elements of the energy system, including electric and natural gas utilities, building codes, and transportation planning. This has enabled many states to develop climate and clean energy policies in the absence of federal legislation. Twenty states have adopted GHG emission targets, 29 states have renewable portfolio standards (RPS) for electricity generation, and 39 states have building energy codes. Nine Northeastern states have joined the Regional Greenhouse Gas Initiative, the first market-based program in the U.S. for reducing power sector emissions. California, with a legally binding statewide GHG target for 2020, a deep decarbonization goal for 2050, ambitious sectoral policies, and a carbon market, is a national test case for demonstrating the cost and feasibility of a low-carbon transition.

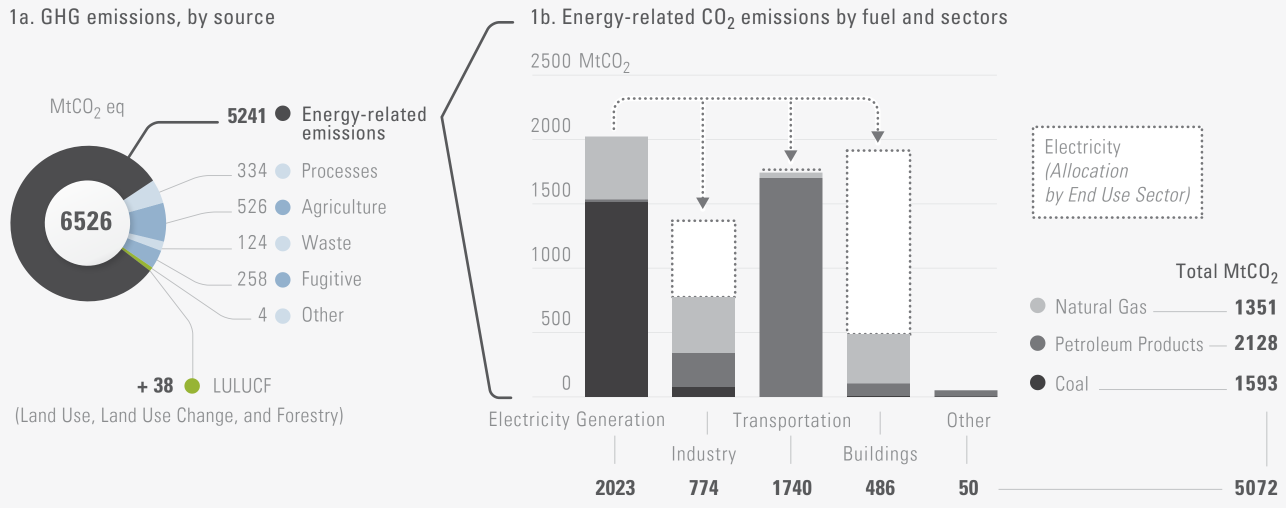
1.2 GHG emissions: current levels, drivers, and past trends

U.S. GHG emissions are dominated by CO_2 from fossil fuel combustion. In 2012, energy-related emissions of all kinds (including fugitive emissions from fuels) accounted for 5,499 $MtCO_2e$, nearly 85% of total gross GHG emissions of 6,526 $MtCO_2e$ (Figure 1a). Of these, 5,072 Mt (78%) were fossil fuel combustion CO_2, which is shown disaggregated by fuel source and end-use sector in Figure 1a.

Electricity generation constituted 2,023 Mt (40%) of CO_2 emissions from fossil fuel combustion in 2012. With electricity emissions allocated to end-use sectors, the building sector (both residential and commercial) is the largest emissions source (38%), followed by transportation (34%) and industry (27%). Transportation-sector CO_2 emissions are almost entirely from direct fossil fuel combustion, while industrial-sector CO_2 emissions are divided between direct fuel combustion and electricity consumption, and building-sector emissions are primarily from electricity consumption (Figure 1a).

U.S. fossil fuel combustion CO_2 emissions rose from 1990 through 2005, mainly due to population and GDP growth. This growth was partly offset by improvements in energy efficiency, measured as a reduction in the energy intensity of GDP (Figure 2a). Emissions declined from 2005 to 2010, largely due to the economic slowdown after 2008. The electricity and transportation sectors accounted for the bulk of growth in CO_2 emissions from fossil fuel combustion between 1990 and 2010 (Figure 2a). The continued decline in emissions since 2010 is due to a combination of factors, including coal displacement in power generation by inexpensive natural gas.

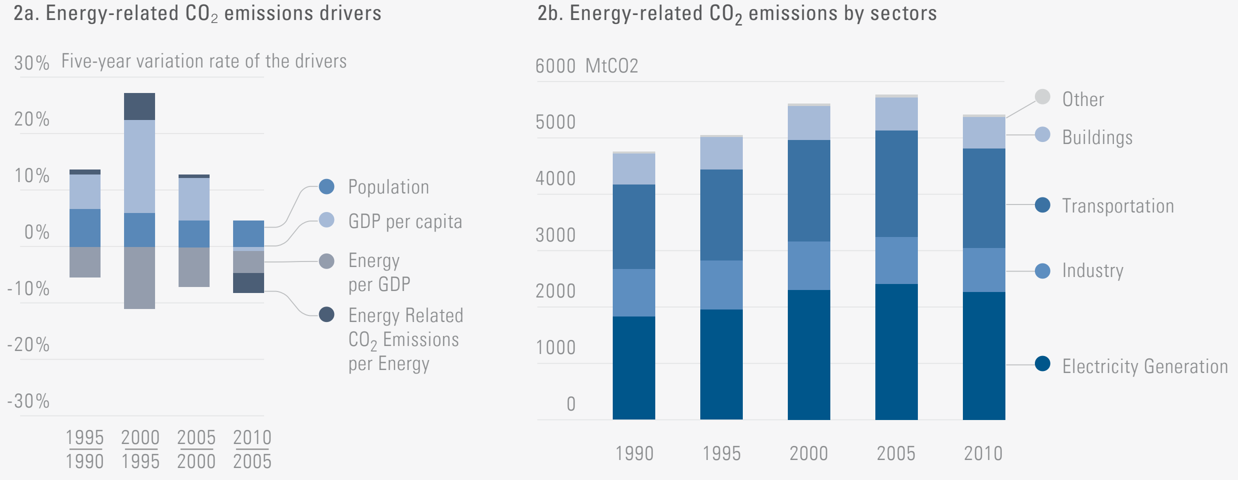
Figure 1. Decomposition of GHG and Energy CO_2 Emissions in 2012


1a. GHG emissions, by source

1b. Energy-related CO_2 emissions by fuel and sectors

Source: U.S. Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012, April 15, 2014.
Excludes impact of LULUCF net sink, which would reduce net emissions by 979 MT CO2e in 2012.
http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf

Figure 2. Decomposition of historical energy-related CO_2 Emissions, 1990 to 2010


2a. Energy-related CO_2 emissions drivers

2b. Energy-related CO_2 emissions by sectors

Source: Based on EPA, 2014 and data from the U.S. Energy Information Administration (EIA), http://www.eia.doe.gov.
Note: Buildings, transportation, and industry emission are direct /emissions only, and electricity use, which is categorized separate.
National deep decarbonization pathways

2 Illustrative deep decarbonization pathway

2.1 Illustrative deep decarbonization pathway

2.1.1 High-level characterization

This study's most important finding is that it is technically feasible for the U.S. to reduce CO_2 emissions from fossil fuel combustion to less than 750 $MtCO_2$ in 2050, which is 85% below 1990 levels and an order of magnitude decrease in per capita emissions compared to 2010. This finding is demonstrated by preliminary modeling results for four different scenarios: a main case, plus three alternative scenarios that more heavily emphasize renewable, CCS, or nuclear power generation. All four scenarios assume continued growth in key macroeconomic indicators and energy service demand drivers, consistent with the U.S. Energy Information Administration (EIA) Annual Energy Outlook 2013 reference case (Table 1).

Table 1. Selected Economic Indicators and Energy Service Demand Drivers

Indicator	Unit	2010	2050*	AAGR 2010-2050
Population	Million person	310	441	0.9%
GDP	$Billion ($2005)	13,063	34,695	2.5%
GDP per capita	$/person	42,130	78,723	1.6%
Industry value added	$Billion ($2005)	2,337	4,925	1.9%
Residential floor area	Million square meter	17,691	28,102	1.2%
Commercial floor area	Million square meter	7,539	11,167	1.0%
Passenger transport	Billion kilometers traveled	7,834	11,121	0.9%
Freight transport	Billion ton-kilometers	7,004	10,361	1.0%

* 2050 values based on AEO 2013 Reference Case (2010-2040) extrapolated to 2050 using linear 2020-2040 growth rates

Scenario design objectives

The scenarios in this study were developed to explore how deep decarbonization in the U.S. can be achieved through a technological transformation of its infrastructure over time, subject to a variety of economic, technical, and resource constraints. Key constraints (design objectives) considered in this analysis are described in Table 2.

Modeling approach

The scenarios were developed using Pathways, a granular bottom-up energy balance model, with 80 energy demand subsectors and 20 energy supply pathways, modeled separately in each of the nine U.S. census regions. Pathways incorporates a stock rollover model, which makes stock additions and retirements in annual time steps, and an hourly electricity dispatch model. The analysis also used the global integrated assessment model GCAM to develop resource assumptions for domestic biomass use in the U.S. The scenario results shown here are preliminary.

Illustrative scenario

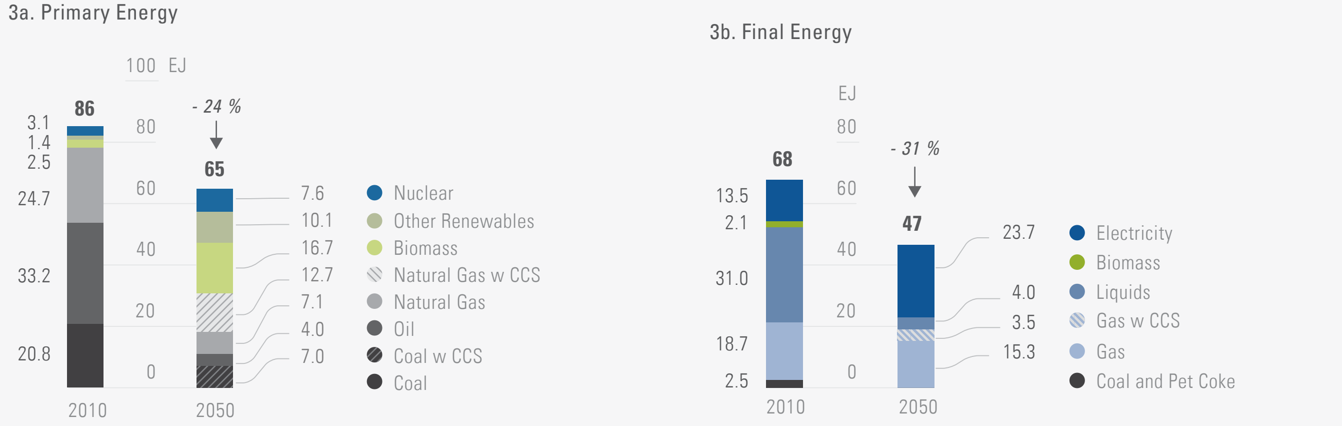
The transition to a low-carbon energy system involves three principal strategies: (1) highly efficient end use of energy in buildings, transportation, and industry; (2) decarbonization of electricity and other fuels; and (3) fuel switching of end uses from high-carbon to low-carbon supplies. All three of these strategies must be applied to achieve deep decarbonization, as demonstrated in an illustrative deep decarbonization scenario ("main case"). Table 3 describes the measures by which these strategies were implemented, and Table 4 shows the quantitative results. Despite a near doubling of GDP between 2010 and 2050, U.S. total final energy consumption declines from 68 to 47 EJ. The result is a 74% reduction in economic energy intensity (MJ/$). Average annual rates of technical energy efficiency improvement are 1.7% in residential buildings, 1.3% in commercial buildings, 2.2% in passenger transportation (in part from switching to electric drivetrains), and 0.7% in freight transportation.

For the main case, primary energy supply[1] decreases by 24% from 2010 to 2050 (Figure 3a). Petroleum falls from the largest share of primary energy in 2010 (39%) to 6% in 2050, while biomass increases to 26%. Collectively, fossil fuels (oil, coal, and natural gas, with and without CCS) decrease from 92% of primary energy supply in 2010 to 47% of primary energy in 2050. Final energy decreases by 31% over the same time period (Figure 3b). The liquid fuels share of final energy falls from 46% to 9%, while electricity's share of final energy rises from 20% to 51%, and gaseous fuels grow from 28% to 41%.

Table 2. Scenario Objectives and Analysis Approach

Scenario Objectives	Analysis Approach
Avoid or limit early retirement of existing infrastructure	Use granular annual stock rollover model with infrastructure inertia, allow equipment to cover full investment cost
Avoid or limit need for new infrastructure	Minimize the use of measures that require the creation of major new types of infrastructure (e.g. CO_2 pipeline)
Emphasize technologies that are already commercialized	Minimize use of non-commercialized technologies and use conservative technology performance assumptions.
Maintain electric reliability	Use hourly dispatch model to ensure adequate capacity and flexibility for all generation mixes
Make decarbonization measures realistic and specific	Require granular subsector decarbonization strategies to isolate difficult cases (e.g. freight, industry) when evaluating feasibility
Avoid environmentally unsustainable measures	Adhere to non-GHG sustainability limits for biomass use, hydroelectricity
Maintain industrial competitiveness	Adopt measures that keep compliance costs as low as possible while achieving the necessary reductions
Achieve emission reductions domestically	Don't assume international offsets will be available
Exclude forest carbon sink	Focus on reducing energy system CO_2, as this is the pivotal transition task and carbon sink behavior is poorly understood
Adapt to regional conditions and preferences	Make decarbonization strategies consistent with regional infrastructure, economics, resources, and policy preferences

Figure 3. Energy Pathways, by source


3a. Primary Energy

3b. Final Energy

Note: Oil primary energy excludes petrochemical feedstocks. Liquids final energy excludes petrochemical feedstock.

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[1] Primary energy is calculated based on the "captured energy" method, in which electricity generation from nuclear and renewable sources (excluding biomass) is converted to primary energy at its equivalent energy value with no assumed conversion losses, i.e. 1 kWh generated = 3.6 MJ.

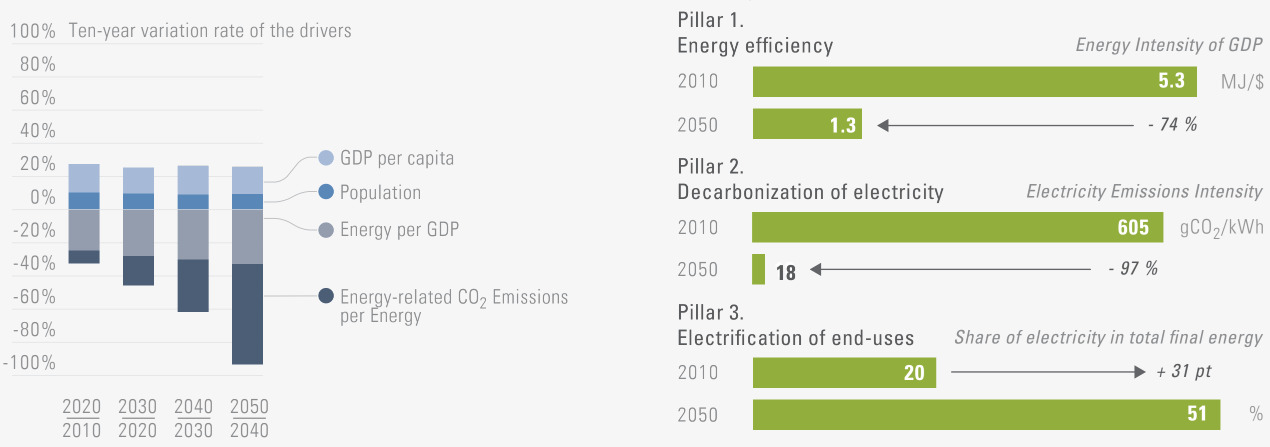
Key drivers of changes in CO_2 emissions between 2010 and 2050 are shown in Figure 4a. A growing U.S. population (+42% cumulative change between 2010 and 2050) and rising GDP per capita (+87%) are more than offset by reductions in the final energy intensity of GDP (-74%) and the CO_2 intensity of final energy (-80%), resulting in an 86% reduction in CO_2 emissions relative to 2010 levels. The three largest contributing factors to CO_2 reductions (Figure 4b) are: (1) improvements in end-use energy efficiency; (2) a near-total decarbonization of electricity generation; and (3) extensive electrification of end-uses. Two additional measures contribute to reductions but are not shown in Figure 4b: (1) fuel switching to partially decarbonized pipeline gas and (2) the use of CCS for some large-scale industrial gas users.

By sector, electricity generation's share of CO_2 emissions falls from 40% in 2010 to 16% in 2050 (Figure 5). The remaining electricity emissions are primarily from residual emissions not captured by CCS for natural gas- and coal-fired generation. Transportation's one-third share of emissions rises to 60% of total final emissions by 2050 (excluding electrified transport), as the remaining fossil fuels in the economy are applied to largely to long-distance transport end-uses (including aviation and military use) that are difficult to electrify or convert to pipeline gas. Industrial direct emissions rise from 15% to 19% of total emissions by 2050, while the residential and commercial sectors are nearly completely electrified, leaving negligible amounts of remaining direct emissions.

2.1.2 Sectoral characterization

Decarbonization and fuel switching in the main case are described in Tables 3 and 4 and illustrated in Figure 6, which shows the evolution of final energy supply and demand by sector and fuel type over time. Electricity becomes the dominant component (51%) of final energy supply, more than doubling its 2010 share, due to extensive electrification of end uses across all sectors. Final electricity consumption increases from 14 EJ to 24 EJ (from 3,750 TWh to over 6,500 TWh). Most of this increase results from electrification of industry and transportation (light duty vehicles), while buildings show little net change in total electric consumption as

Figure 4. Energy-related CO_2 Emissions Drivers, 2010 to 2050



4a. Energy-related CO_2 emissions drivers

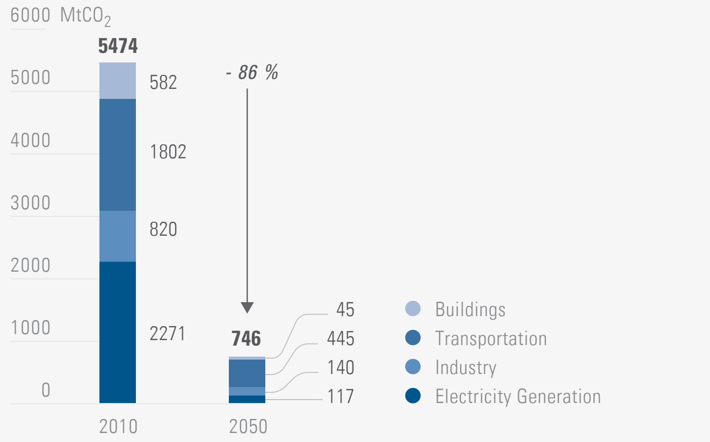
4b. The pillars of decarbonization

Note: Final energy intensity of GDP is shown as a proxy for end-use energy efficiency, though structural factors also drive reductions

reductions in consumption through electric energy efficiency offset growth from the electrification of new loads.

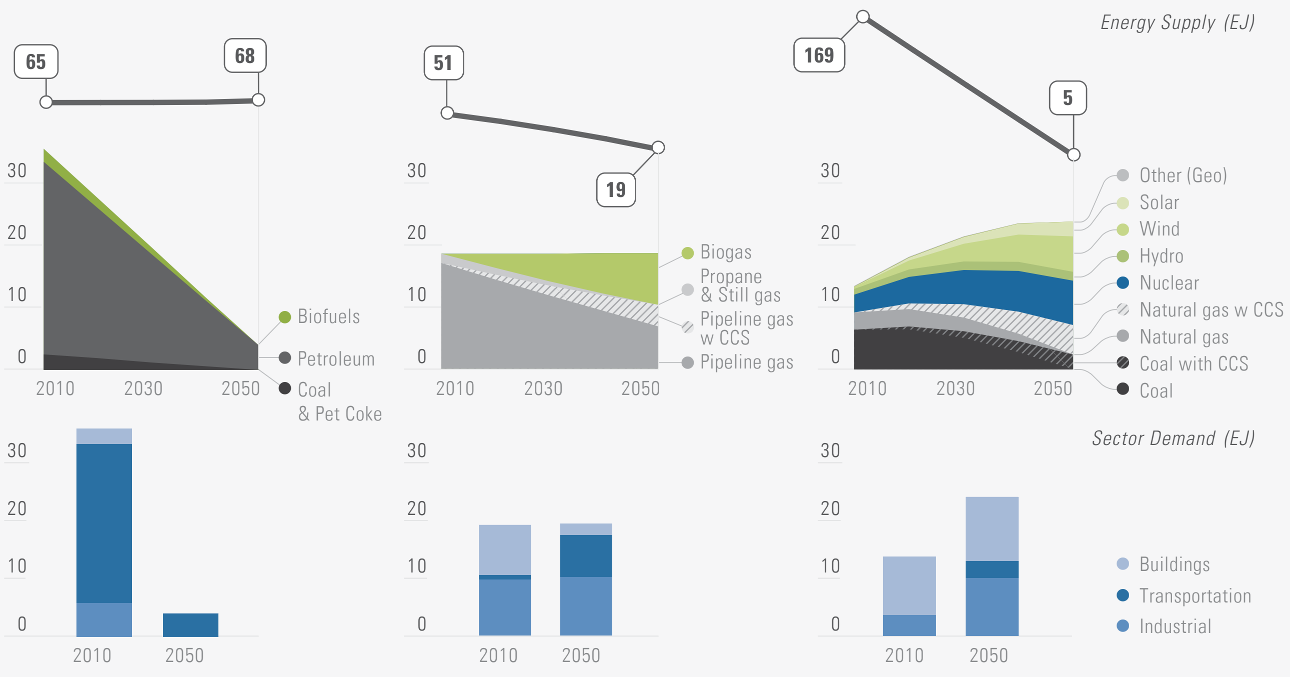
To meet demand, net electricity generation grows by nearly 75% relative to 2010, as shown in the middle right panel of Figure 6. At the same time, a gradual shift in the mix of generation sources results in nearly complete decarbonization of electricity by 2050, with a CO_2 intensity of 18 gCO_2 per kWh (5 gCO_2 per GJ), a 95% reduction from its 2010 value. The 2050 generation mix is a blend of 40% renewables (hydro, solar, wind, biomass, and geothermal), 30% nuclear, and 30% fossil fuel (coal, natural gas) with CCS. No fossil fuel generation without CO_2 removal remains in the system by 2050. With 34% of generation from

Figure 5. Energy-related CO_2 Emissions Pathway, by Sector, 2010 to 2050



Note: 2010 totals based on modeled data. These emissions are 1% larger than EPA inventory totals due to minor change in emissions accounting approach for certain sources.

Figure 6. Deep Decarbonization Transition Pathways: Main case, 2010-2050



6a. Solid and Liquids

6b. Pipeline Gas

6c. Electricity

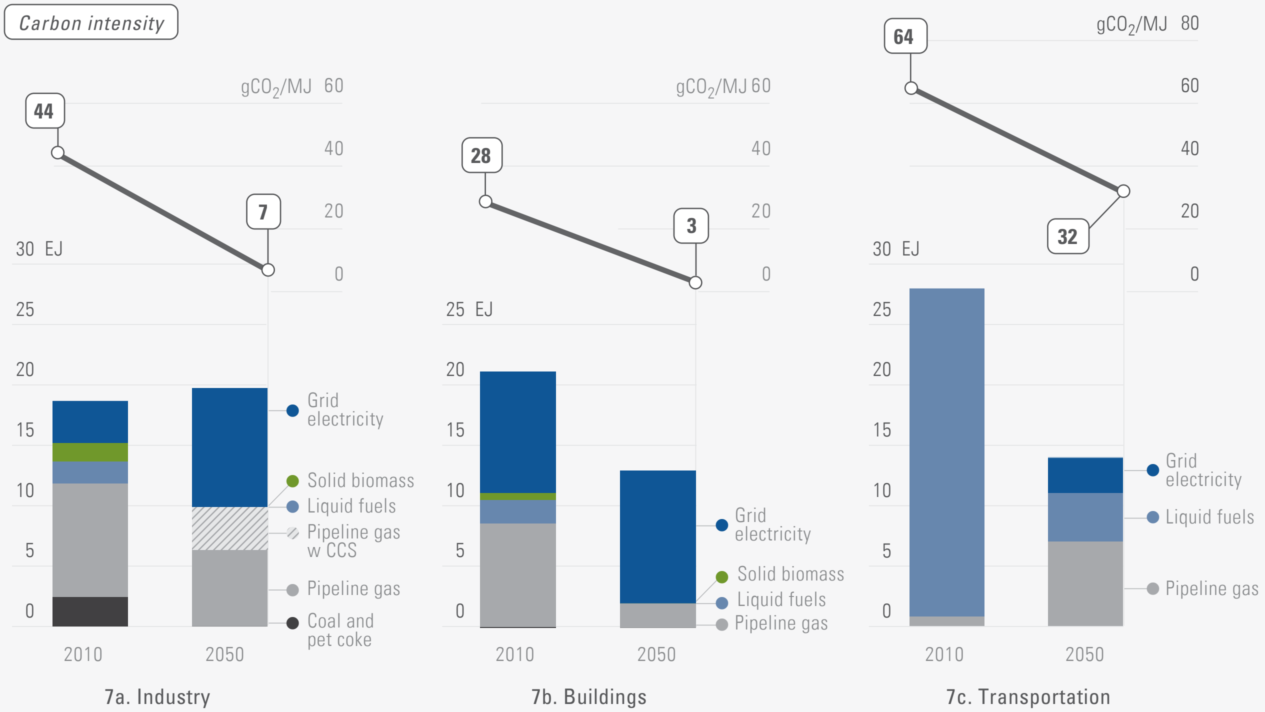
Note: The upper row of this chart shows the change in CO2 emissions intensity of delivered energy by fuel type for 2010 through 2050 (g CO2/MJ is equivalent to Mt CO2/EJ). The middle row shows the composition of delivered energy as it changes over this time period. The bottom row shows energy demand by major end use sector and delivered energy type for 2010 and 2050. "Buildings" combines the residential and commercial sectors. "Liquid" and "gas" here are defined by the primary form in which the fuels are transported. For example, liquefied natural gas used in freight vehicles is transported over gas pipelines, so is included as gas here.

intermittent renewables, the combination of 20% gas-fired CCS generation and 6% hydropower, as well as the use of flexible loads such as "smart" vehicle charging, provide adequate balancing resources for reliability on all time scales.

Despite high levels of electrification across sectors, certain end uses remain technically challenging to electrify, especially in industry and long-distance transportation (commercial and freight trucks, freight rail, shipping), where battery electric energy densities appear insufficient for the foreseeable future. Where technically feasible, these end uses are switched from existing fossil fuel supplies (coal, diesel, gasoline, and fuel oil) to "pipeline gas" as the preferred combustion fuel, including compressed (CNG) and liquefied (LNG) forms. Pipeline gas refers to fuel carried in existing natural gas pipelines, which is partially decarbonized over time using gasified biomass. Biomass constitutes 55% of the pipeline gas supply by 2050, resulting in an emission intensity 60% lower than pure natural gas and more than 66% lower than most petroleum-based fuels. Almost all available biomass in this scenario is converted to gas, rather than liquid or solid fuels, requiring 16.7 EJ of biomass primary energy, slightly less than the 17 EJ maximum limit for sustainable biomass energy use assumed in this study.

This scenario assumes that industry employs CCS on-site for approximately one third (36%) of the sector's use of pipeline gas, the residual combustion fuel. The annual CO_2 storage requirement for generation and industrial CCS combined is approximately 1,200 $MtCO_2$ in 2050. Solid fuels with uncontrolled CO_2 emis-

Figure 7. Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



7a. Industry

7b. Buildings

7c. Transportation

Note: Carbon intensity shown in Figure 7 for each sector includes only direct end-use emissions and excludes indirect emissions related to electricity or hydrogen production.

sions are eliminated in this scenario, and liquid fuels are dramatically reduced, with petroleum product consumption falling by almost 90% from 2010 to 2050. Residual petroleum use is in the transportation sector, where it continues to be used in some light duty and transit vehicles, civilian aviation, and military vehicles and aircraft. See Figures 7a-c for more detail on decarbonization of each end-use sector.

2.2 *Assumptions*

A qualitative description of strategies and assumptions employed across sectors, fuel types, and scenarios is shown in Table 3, organized by the three strategic areas of energy efficiency, energy supply decarbonization, and fuel switching. Energy efficiency options are similar across demand sectors in all scenarios, with variations based on the form of delivered energy and the associated end-use technologies (e.g. electric or internal combustion engine-based drivetrains for vehicles). Energy supply decarbonization strategies vary widely across scenarios based on the type of primary energy used in electricity generation and the amount and allocation of biomass resources (e.g. solid, liquid, and gaseous fuels). Electricity balancing requirements also differ widely depending on generation mix. Fuel switching strategies are closely linked to the supply decarbonization pathways chosen.

2.3 *Alternative pathways and pathway robustness*

Three additional scenarios—high renewable, high CCS, and high nuclear—were developed to demonstrate that multiple strategies and pathways are possible for achieving deep decarbonization in the U.S. They also illustrate some of the differences between low-carbon pathways that policymakers, regulators, businesses, and civic groups must assess on the

Table 3. Technical Options and Assumptions in Deep Decarbonization Scenarios

Area	Technical Options and Assumptions*
Energy Efficiency Strategies	
Residential and commercial energy efficiency	• Highly efficient building shell required for all new buildings • New buildings require electric heat pump HVAC and water heating • Existing buildings retrofitted to electric HVAC and water heating • Universal LED lighting in new and existing buildings
Industrial energy efficiency	• Improved process design and material efficiency • Improved motor efficiency • Improved capture and re-use of waste heat • Industry specific measures, such as direct reduction in iron and steel
Transportation energy efficiency	• Improved internal combustion engine efficiency • Electric drive trains for both battery and fuel cell vehicles (LDVs) • Materials improvement and weight reduction in both LDVs and freight
Energy Supply Decarbonization Strategies	
Electricity supply decarbonization	• Different low-carbon generation mixes with carbon intensity < 20 gCO$_2$ /kWh • Main case mix 40% renewable and hydro, 30% CCS, 30% nuclear • High renewable scenario 75% renewable and hydro, 20% nuclear, 5% natural gas • High CCS scenario 50% fossil CCS, 35% renewable and hydro, 15% nuclear • High nuclear scenario 60% nuclear, 35% renewable and hydro, 5% natural gas
Electricity balancing	• Flexible demand assumed for EV charging, certain industrial and building loads • Hourly/daily storage and regulation from pumped hydro, battery, and compressed air energy storage • High CCS scenario balanced with 30% thermal generation plus 6% hydro • High nuclear scenario balanced with 5% natural gas generation, 6% hydro • High renewable case balanced with 5% natural gas generation, 6% hydro, power-to-gas seasonal storage (hydrogen, SNG), and curtailment
Pipeline gas supply decarbonization	• Synthetic natural gas from gasified biomass provides about one-half of pipeline gas in all scenarios except high CCS, which is 100% natural gas • Hydrogen and SNG produced with wind/solar over-generation provides smaller but important (~10-15%) additional source of pipeline gas in high renewables case
Liquid fuels decarbonization	• Liquid biofuels and hydrogen become large share of transportation fuel in high CCS and high nuclear cases, displacing petroleum • No liquid biofuels or hydrogen in central and high renewables cases; emphasis on fuel switching from petroleum to decarbonized pipeline gas CNG and LNG
Fuel Switching Strategies	
Petroleum	• In central and high renewables cases, petroleum displaced in light duty vehicles by electrification, with 75% of drive cycle in battery electric mode, and in heavy duty vehicles by pipeline gas CNG and LNG • In high CCS and high nuclear case, petroleum displaced by combination of biofuels, battery electric, and hydrogen fuel cell vehicles • Industrial sector petroleum uses electrified where possible, with the remainder switched to pipeline gas
Coal	• No coal without CCS used in power generation or industry by 2050 • Industrial sector coal uses electrified where possible, with the remainder switched to pipeline gas
Natural gas	• Low carbon energy sources replace most natural gas for power generation; about 5% non-CCS gas retained for balancing in some scenarios • Switch from gas to electricity in most residential and commercial energy use, including space and water heating and cooking

*Assumptions are common across all scenarios unless otherwise indicated.

Table 4. Key Metrics by Scenario

Indicator	Units	2010	2050 Scenario			
			Main	RNE	CCS	Nuclear
Final energy consumption, by sector						
Total all sectors	EJ	67.8	46.6	46.6	46.5	47.3
Residential	EJ	12.0	6.5	6.5	6.5	6.5
Commercial	EJ	9.0	6.4	6.4	6.4	6.2
Transportation	EJ	28.1	14.0	14.0	13.9	14.9
Industry	EJ	18.6	19.7	19.7	19.7	19.7
CO_2 emissions, by sector (incl. electric)						
Total all sectors	$MtCO_2$	5,474	746	710	748	723
Residential	$MtCO_2$	1,228	39	35	54	39
Commercial	$MtCO_2$	1,034	60	48	108	61
Transportation	$MtCO_2$	1,805	459	405	195	310
Industry	$MtCO_2$	1,407	188	222	392	313
Electricity share of final energy, by sector						
Total all sectors	%	20%	51%	47%	51%	46%
Residential	%	43%	94%	94%	94%	94%
Commercial	%	53%	76%	76%	76%	76%
Transportation	%	0%	47%	47%	48%	32%
Industry	%	19%	50%	40%	50%	45%
Electric generation						
Total net generation	TWh	4,036	7,008	8,478	7,016	9,548
Delivered electricity (final energy)	TWh	3,753	6,587	7,969	6,595	8,975
Electricity CO_2 emissions	$MtCO_2$	2,271	117	138	134	155
Renewable energy - non-hydro	%	3%	34%	69%	29%	29%
Renewable energy - hydro	%	7%	6%	6%	6%	6%
Nuclear	%	21%	30%	20%	15%	60%
CCS gas	%	0%	20%	0%	50%	0%
CCS coal	%	0%	10%	0%	0%	0%
Gas	%	21%	0%	5%	0%	5%
Coal	%	48%	0%	0%	0%	0%
Pipeline gas composition						
Final energy	EJ	17	19	21	12	13
Natural gas	%	100%	45%	28%	100%	50%
Electric-SNG	%	0	0%	15%	0%	0%
Electric-H2	%	0	0%	7%	0%	0%
Bio-SNG	%	0	55%	50%	0%	50%
Intensity metrics						
Per capita energy use	GJ/person	219	106	106	105	107
Per capita emissions	tCO_2/person	17.7	1.7	1.7	1.7	1.6
Economic energy intensity	MJ/$	5.19	1.34	1.34	1.34	1.36
Carbon intensity of final energy	gCO_2/MJ	76.8	15. 9	15.7	15.9	15.4
Economic emission intensity	gCO_2/$	419	21	21	21	21
Delivered electric emission intensity	gCO_2/kWh	605	18	17	20	21
Pipeline gas emission intensity	gCO_2/MJ	50	23	14	50	25

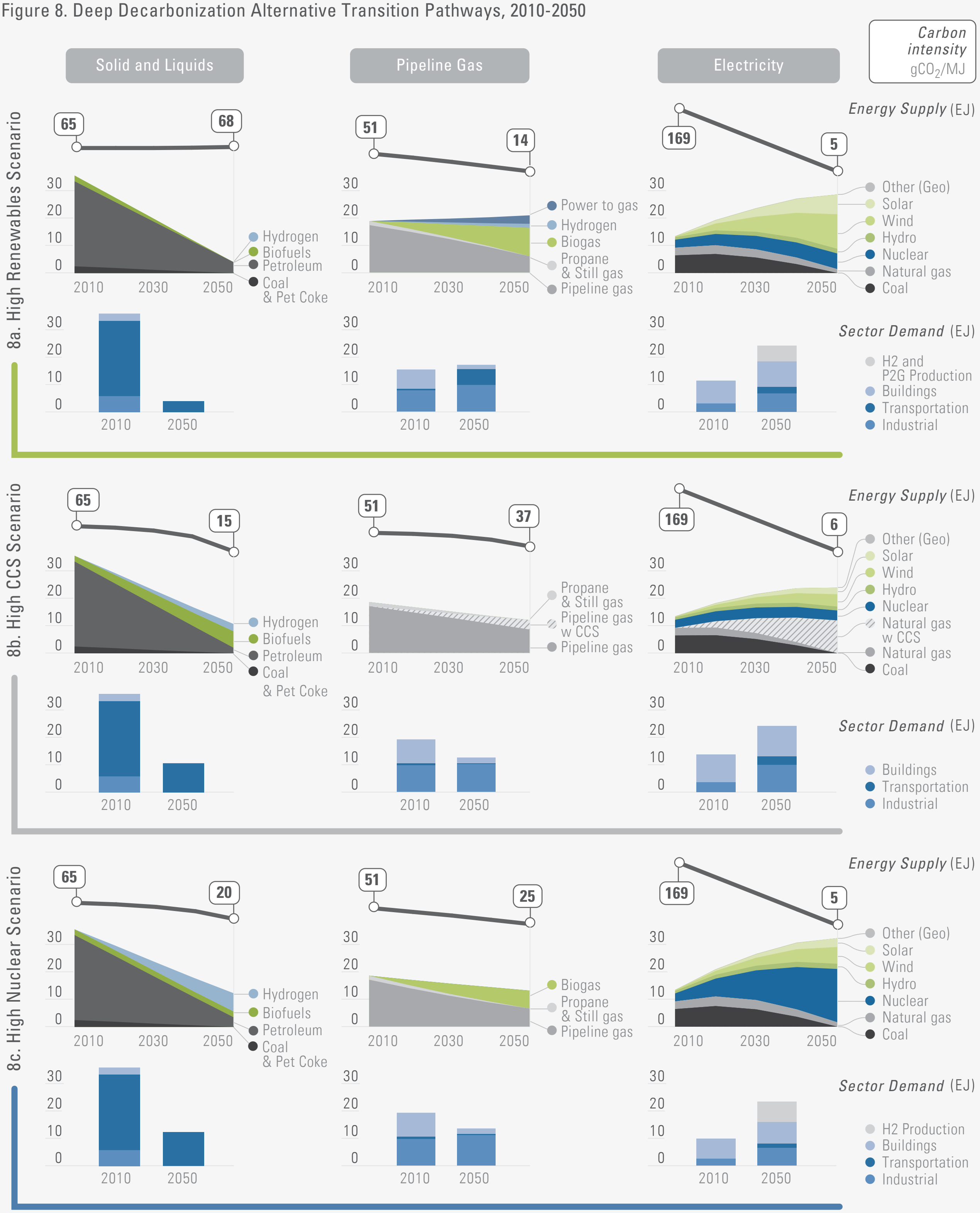
basis of cost, risk, public acceptance, and other criteria. All scenarios result in the elimination of coal without CCS, a nearly 90% reduction in petroleum use, and natural gas use that ranges from current levels to about 70% below current levels. All involve a large expansion of electricity generation and electrification of end uses and expanded use of biomass up to the limits of sustainability (Table 4).

At the same time, the scenarios are not "drop-in" substitutes. Two key choices—(1) the low-carbon sources of energy used to generate electricity and (2) the amount of biomass allocated to energy supply—tend to constrain options for electricity balancing, forms of delivered energy, and demand-side technologies, resulting in substantially different energy systems with self-consistent packages of technologies. For example, some scenarios depend on decarbonized pipeline gas and some do not; some require CO_2 pipeline and storage infrastructure and some do not; some require continental scale hydrogen production and distribution infrastructure and some do not. The transition pathways for the alternative scenarios are shown in Figures 8a-c.

High renewables scenario

This scenario is similar to the main case in demand-side measures in the residential, commercial, and transportation sectors. It differs significantly in the power sector and industry, because CCS is assumed to not be available. The power sector is decarbonized using primarily solar and wind generation, while maintaining the current share of nuclear power in the U.S. generation mix. Balancing on different time scales is accomplished with a combination of flexible loads, battery and pumped hydro storage, a diverse renewable resource mix, and hydro and natural gas generation. Seasonal balancing is accomplished by overbuilding wind and solar capacity and using periodic over-generation

Figure 8. Deep Decarbonization Alternative Transition Pathways, 2010-2050



to produce hydrogen and synthetic natural gas (SNG). Hydrogen is produced up to technical limits on the amount that can be transported in natural gas pipelines, and SNG is produced from hydrogen thereafter. These produced gases, in addition to providing system balancing, are inserted into the natural gas pipeline system along with SNG from biomass. In the absence of CCS, this partly decarbonized pipeline gas provides a combustion fuel for industry and transportation.

High CCS scenario

This scenario is similar to the main case in demand side measures in the residential, commercial, and industrial sectors, but differs significantly in power and transportation. The details of this scenario are highly sensitive to assumptions about CCS capture rates and biomass conversion rates to liquid biofuels. For 90% CO_2 capture rates, the upper limit on fossil fuel with CCS as a share of generation mix is about 50% before carbon intensities become too high to achieve decarbonization goals through electrification. Since CCS is used on-site in industry, pipeline gas consists entirely of natural gas, and biomass is devoted entirely to liquid biofuels. In transportation, residual fuel requirements beyond electrification are met with a combination of biofuels and hydrogen produced from steam-reformed natural gas with CCS.

High nuclear scenario

This scenario is similar to the main case in demand-side measures in the residential and commercial sectors. It is very different in other ways, being built around production of hydrogen from nuclear generation, which is used in fuel cells that become the main prime mover in both light and heavy duty transportation. Biomass is used both for pipeline gas, which is used primarily in industry, and for liquid transportation fuels.

2.4 *Additional measures and deeper pathways*

Deeper decarbonization could be achieved by the successful development of technologies and measures that were not employed in the scenarios described in this study. These excluded measures are highlighted in Table 5. They include CCS with capture rates in excess of 90%, advanced liquid biofuels, product and industrial redesign for energy and material efficiency, and significant changes in energy service demand.

2.5 *Challenges, opportunities and enabling conditions*

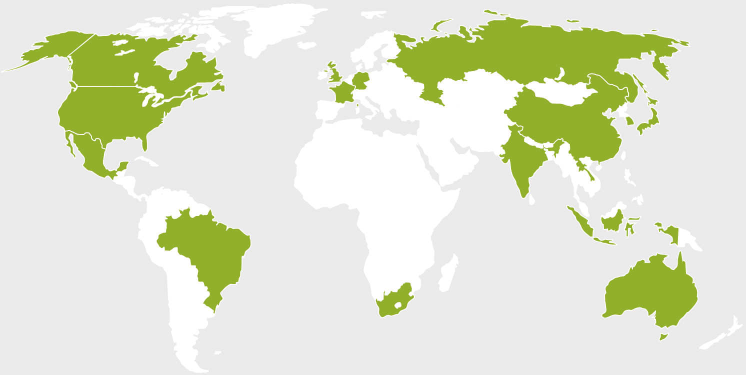
Challenges and enabling conditions for deep decarbonization in the U.S. lie primarily in the realms of cost, policy, public support, and resource limitations. Two key potential resource limitations requiring further study and sensitivity analysis are biomass availability and CO_2 storage capacity. Cost reductions for many low-carbon measures are often a function of market transformation and high volume production, but continued R&D is also important in many areas. Two areas of study seem particularly germane to current challenges in low-carbon technologies: (1) electrochemistry and nanotechnology, to develop the chemistries, catalysts, and physical matrices fundamental to improvements in batteries, fuel cells, chemical processes, and CO_2 capture; (2) biotechnology and genomics, which are fundamental to advances in cellulosic and algal biofuels, biomass SNG production, and biological hydrogen production. Public support must be unwavering to impel policymakers to implement transformational changes in energy systems over the course of decades. Public acceptance is also a key variable, especially with regard to siting of low-carbon infrastructure. A high nuclear scenario, for example, seems very unlikely without aggressive efforts to restore public acceptance of the technology.

Table 5. Technology Assumptions by Scenario

Technology	Included in 2050 Scenario?			
	Central	**RNE**	**CCS**	**Nuclear**
CCS for generation, 90% capture	●		●	
CCS for generation, >90% capture				
Nuclear Gen III	●	●	●	●
Nuclear Gen IV				
Solar PV, solar CSP, onshore wind, shallow offshore wind	●	●	●	●
Deep offshore wind, advanced geothermal				
CCS for industry, 90% capture	●		●	
CCS for industry, >95% capture				
H2 from electricity generation		●		●
H2 from natural gas reforming with CCS			●	
Continental scale H2 production and distribution system				●
Power-to-gas - SNG from electricity generation		●		
Biomass conversion to SNG by AD or gasification and shift	●	●		●
Fischer-Tropsch liquid biofuels, 35% conversion efficiency			●	●
Advanced cellulosic ethanol				
Advanced biodiesel				
Advanced bio-jet fuel				
Biomass generation w CCS				
Fuel cell LDVs				●
Battery electric LDVs	●	●	●	●
CNG passenger and light truck	●	●		
LNG freight	●	●	●	
Fuel cell freight				●
Heat pump HVAC	●	●	●	●
LED lighting	●	●	●	●
Heat pump electric water heat	●	●	●	●
Maximum efficiency shell for new buildings	●	●	●	●
Maximum efficiency shell for retrofits				
Industrial and product redesign				
Structural change in economy				
Reduced demand for energy services				

2.6 Near-term priorities

Although the results here are preliminary, some near-term priorities for investment, policy, and regulatory decision-making in the U.S. are already clear. For instance, significant improvements in end-use energy efficiency—in buildings, appliances, equipment, and vehicles—are critical to deep decarbonization in the U.S. Many types of energy efficiency measures are already cost-effective but face barriers to rapid uptake due to well-known market failures. In these areas, continued improvement of codes and standards at both the federal and state level are a proven remedy. Additionally, it is clear that low-carbon electricity is the linchpin of deep decarbonization, and here too existing state and federal regulatory mechanisms, from renewable portfolio to emission performance standards, can help hasten the transition. Given the long lifetimes of generation assets, meeting a 2°C target by 2050 without stranding assets requires not building new coal generation without CCS. Meanwhile, there is an urgent need for additional R&D to develop low-carbon fuel solutions for industry and freight transport.



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