ANNUAL DECARBONIZATION PERSPECTIVE 2023

EVOLVED ENERGY RESEARCH

CARBON-NEUTRAL PATHWAYS FOR THE UNITED STATES

ABOUT THIS REPORT

This report investigates options for long-term deep decarbonization pathways for the United States. It is the second in a series of annual updates that aim to move pathways analysis beyond isolated proofs-of-concept towards becoming a practical implementation tool for addressing next-stage challenges in energy and climate change mitigation.

Breakthrough Energy Foundation provided financial support for this work.

Version 2023-10-12

A special thanks to David Paolella (Breakthrough Energy) for his feedback and support.

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Please cite this report as: Haley, B., Jones, R.A., Williams, J.H., Kwok, G, Farbes, J., Bentz, D., Schivley, G. Jenkins, J., Annual Decarbonization Perspective: Carbon Neutral Pathways for the United States 2023. Evolved Energy Research, 2023.

EVOLVED ENERGY RESEARCH

ABOUT EVOLVED ENERGY RESEARCH

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Its consulting work and insight, supported by sophisticated technical analyses of energy systems, is designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies.

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List of Abbreviations and Acronyms

AEO	*Annual Energy Outlook*
ADP	*Annual Decarbonization Perspective*
ATB	*Annual Technology Baseline*
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COBRA	Co-Benefits Risk Assessment
DAC	Direct air capture
DDPP	Deep Decarbonization Pathways Project
DOE	Department of Energy
EER	Evolved Energy Research
EIA	Energy Information
EJ	Exajoule
EV	Electric vehicle
FAME	Fatty acid methyl ester
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonne
GW	Gigawatt
H_2	Hydrogen
HEFA	Hydroprocessed esters and fatty acids
HTGR	High-temperature gas reactor
HVAC	Heating, ventilation, and cooling
IRA	Inflation Reduction Act
ISO	Independent system operator
kWh	Kilowatt-hour
LCOE	Levelized cost of energy
MHa	Megahectare
MJ	Megajoule
Mt	Megatonne
MW	Megawatt
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Council
NO_x	Nitrogen oxides
NPV	Net present value
NREL	National Renewable Energy Laboratory
OSW	Offshore wind
$PM_{2.5}$	Particulate matter with diameter less than 2.5 microns
PV	Photovoltaic
R&D	Research and development
ReEDS	Regional Energy Deployment System
RIO	Regional Investment and Operations
RTO	Regional transmission operator
SMR	Small modular reactor
SO_x	Sulfur oxides
TES	Thermal energy storage
TWh	Terawatt-hour

I INTRODUCTION

Purpose of this Report

This report investigates long-term deep decarbonization pathways for the United States. These are detailed technical blueprints for the transition of the US economy to net-zero greenhouse gas emissions by 2050, including the production and use of energy, the land carbon sink, and non-energy greenhouse gas emissions. We used sophisticated, fine-scaled software, the EnergyPATHWAYS and RIO modeling platforms, to map the infrastructure changes, technologies, and costs required to reach net-zero emissions by mid-century along various alternative pathways while maintaining U.S. economic productivity and a reliable energy system.

This report is the second in a series of annual updates that aim to move pathways analysis beyond isolated proofs-of-concept towards becoming a practical implementation tool for addressing next-stage challenges in energy and climate change mitigation. Since the publication of the 2022 Annual Decarbonization Perspective (ADP) for the U.S., a sister ADP for Europe has also been undertaken.

As with ADP 2022, this report is accompanied by a publicly available database of results and input assumptions. For the first time, many of these outputs are being reported at a state level. This provides a standard, public benchmark for use in technical analysis and policy-making and allows year-on-year comparisons highlighting how new developments in technologies, costs, policies, and global markets affect the outcomes of different decarbonization decisions, and what additional policies or investments might be needed to get on track to net-zero.

Policy Relevance

This report does not prescribe policy, but it does highlight what policy outcomes and technological advances are needed to meet climate goals. It informs investment planning for capital intensive businesses, points to critical gaps in R&D, quantifies potential land use and socio-economic transition challenges, clarifies the risks of overreliance on specific technologies, and helps focus the energy policy debate on useful questions.

Passage of the Inflation Reduction Act (IRA) of 2022 and Infrastructure Investment and Jobs Act (IIJA) of 2021 constitute major changes in federal climate policy, the details of which were finalized after last year's ADP modeling. This year's ADP incorporates IRA and IIJA as the reference case and all but one of the net-zero scenarios assume IRA policies. Our approach to modeling IRA provisions come from the Rapid Energy Policy Evaluation and Analysis Toolkit (REPEAT) project, an effort lead by Princeton's ZERO Lab in partnership with Evolved Energy, which makes use of the same modeling tools (EnergyPATHWAYS & RIO) used here.

REPEAT and ADP have different objectives and focus, so we clarify here the differences between the two studies. The REPEAT project has a near- to medium-term focus (e.g. from now to 2035) with scenarios that incorporate expert judgment about likely outcomes of policy measures, with a special focus on the intricacies of policy implementation, and a publication schedule designed to be relevant to immediate policy decisions. Because of its focus on policy impact, REPEAT includes several scenarios spanning uncertainty with respect to policy implementation, but considers only a single 'net-zero pathway' scenario for benchmarking purposes and does not consider sensitivities related to technology availability, cost and performance, or macro-economic conditions. By contrast, the ADP has a longer-term focus (to mid-century), explores a broader set of scenarios and potential pathways to net-zero, and considers only one 'current policies' scenario. Efforts have been made to align inputs between REPEAT and ADP. However, in many cases, the results in this ADP report are ahead of those in the recent REPEAT report published spring of 2023, which primarily made use of inputs from ADP 2022. A forthcoming update from the REPEAT Project will make use of inputs from ADP 2023.

It is our hope that the ADP plays a critical complementary role to REPEAT and similar projects by identifying policy gaps and by helping decision-makers and society at large to anticipate future choices and prepare for changes along the way.

II ANALYSIS FRAMEWORK

This analysis addresses the questions "what are the infrastructure, spending, and natural resources requirements for decarbonizing the U.S. economy by mid-century?" and "how do these change if factor X is changed?" Factor X represents many variables of potential importance, from rates of consumer adoption to societal restrictions on what technologies or land uses are allowed. The questions are answered by the modeling of scenarios and comparison of the model results. In contrast to ADP 2022, this report focuses primarily on a core set of scenarios and has a limited number of sensitivities. Instead, separate sensitivities will be run specifically for the exploration of various in-depth topic areas and released as individual reports in this series in the months ahead. The feedback our team received last year indicated that fewer sensitivities, combined with a broader release of data, including a focus on state-level results, would be more helpful to stakeholders and decision makers.

Scenarios

Scenarios represent different avenues to decarbonization based on societal preferences or policy restrictions regarding what technologies and resources may or may not be used, although different scenarios share many commonalities. For each scenario, the pathway to net-zero greenhouse gas emissions in 2050 is modeled in every year starting from the present, for all the infrastructure stocks and activities within all major economic sectors and subsectors, with a temporal granularity of every hour of the year for electricity, and a geographic granularity of 27 separate regions into which the U.S. is divided.

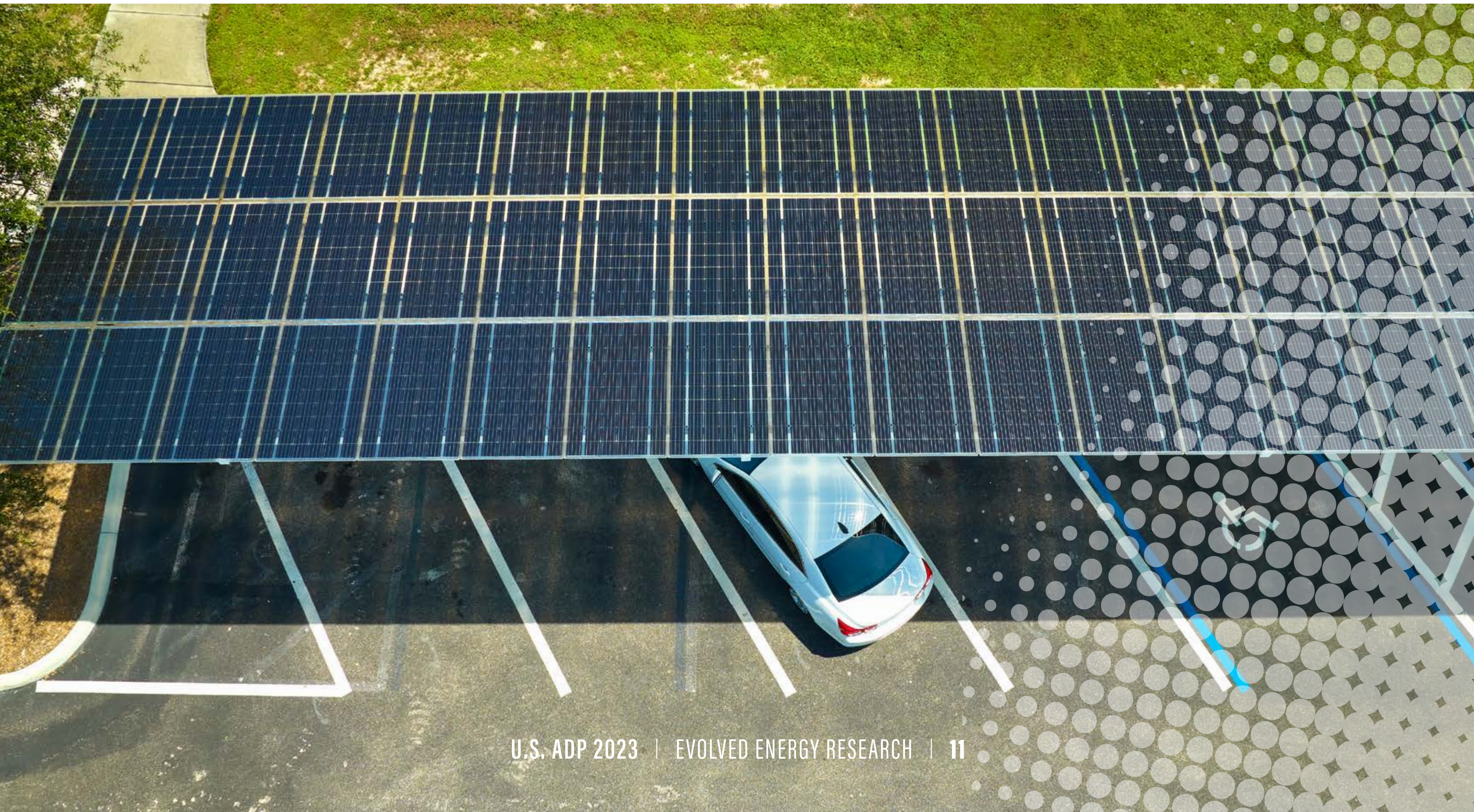
There are eight distinct scenarios, which are briefly described in Table 1 below.

TABLE 1. Scenarios

Scenario	Description
Baseline	This reference scenario is based on the DOE's Annual Energy Outlook 2023 and assumes little electrification of demand-technologies and no IRA tax credits for energy supply technologies.
Current Policy	This reference scenario is based on Princeton's REPEAT mid scenario and incorporates IRA and IIJA. It has the same demand for energy services as the net-zero cases but does not achieve deep decarbonization. It is used as a basis of comparison for the cost, emissions, infrastructure, land use and other attributes of the net-zero cases.
Central	This is the least-cost pathway for achieving net-zero greenhouse gas emissions by 2050 in the U.S. It is economy-wide and includes energy and industrial CO_2, non-CO_2 GHGs, and the land CO_2 sink. It is built using a high electrification demand-side case, and on the supply-side has the fewest constraints on technologies and resources available for decarbonization.
Drop-In	This net-zero scenario is designed to minimize capital, labor, and institutional disruption. It delays the uptake of electrification technologies by twenty years, caps renewable build at historical rates, and disallows new long-distance transmission or pipelines.
Low Demand	This net-zero scenario reduces the demand for energy services from that used in the other net-zero scenarios. It is designed to explore how high levels of conservation and energy efficiency, achieved through behavior change, planning, policy, and other means, could reduce requirements for low-carbon infrastructure and land.
Low Land	This net-zero scenario limits the use of land-intensive mitigation solutions, including bioenergy crops, wind and solar power generating plants, and transmission lines. It is designed to explore the effect of societal barriers to the siting of low-carbon energy infrastructure for environmental and other reasons.
Slow Consumer Uptake	This net-zero scenario delays by twenty years the uptake of fuel-switching technologies including electric vehicles, heat pumps, fuel-cell vehicles, etc. It is designed to explore the effects of slow consumer adoption on energy system decarbonization, including the impacts on electricity and alternative fuel demand. In many cases, for example the adoption of electric vehicles, the uptake of electric technologies is slower than assumed in the Current Policy scenario.
100% Renewables	This net-zero scenario allows only wind, solar, biomass, and other forms of renewable energy by 2050. It is designed to explore the effects of eliminating fossil fuels and nuclear power altogether on energy infrastructure, electric power, and the production of alternative fuels and feedstocks.

The main differences between ADP 2023 and ADP 2022 scenarios are the following:

1. A 50% reduction in greenhouse gas emissions relative to 2005 by 2030 has not been enforced across all scenarios. Instead, a separate sensitivity has been used to highlight the additional actions necessary to reach this goal (consistent with the current U.S. Nationally Determined Contribution target for 2030). Otherwise, a straight-line emissions reduction from 2021 to 2050 was assumed, which results in emissions 40% below 2005 levels by 2030.
2. The implementation of the Drop-In scenario has been changed. The Drop-In scenario emphasizes a transition that minimizes capital, labor, and institutional disruption in the U.S., which last year's ADP approached by using a cost multiplier of 1.5 on greenfield technologies. While this did capture the spirit of the scenario, implementation was cumbersome and the exact inputs difficult to explain. This year, the Drop-In scenario is implemented differently, based on three main elements: (a) slow consumer uptake of fuel-switching technologies; (b) reducing the build rate of wind and solar capacity to historical levels; and (c) disallowing major transboundary infrastructure projects, including electricity transmission and hydrogen and CO_2 pipelines.
3. The High Hydrogen scenario was dropped. This was not because hydrogen plays a smaller role in ADP 2023, but in fact the opposite: hydrogen plays an earlier role in all scenarios, due to the IRA's 45V hydrogen tax credits. As a result, we felt that a separate High Hydrogen scenario no longer provided additional insights.



Sensitivities

Sensitivities begin with the Central scenario and are used to determine the effects on the energy system of changing a single key variable. Two sensitivities were run this year, described in Table 2 below.

TABLE 2. Sensitivities

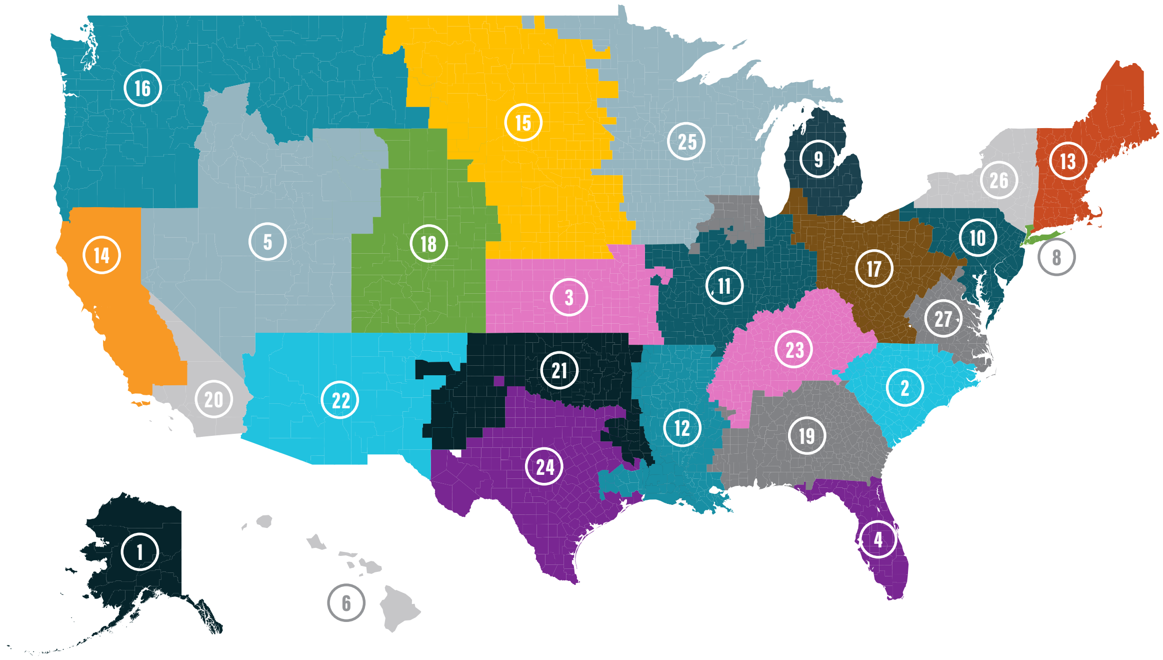
Sensitivity	Description
Central 50x30	This sensitivity is based on the Central scenario and implements achieves a 50% emissions reduction below 2005 levels in 2030. It is used to show the additional actions needed to reach the U.S. Nationally Defined Contribution under the Paris Agreement.
Central No IRA	This sensitivity is based on the Central scenario but excludes IRA tax credits for energy supply technologies. Comparisons with this scenario highlight the impacts of IRA on the development of a net-zero energy system.

Modeling Dimensions

The EnergyPATHWAYS model is a stock accounting tool and calculates annual and sub-annual energy demand and demand-side equipment cost based on user-defined scenarios. Outputs from the EnergyPATHWAYS model are fed into RIO, a linear program that finds the least-cost solution for meeting energy demands through 2050 while obeying constraints such as emission targets and resource potentials. Additional details of the modeling methodology are provided in the ADP Supporting Material.

The spatial and temporal dimensions used in ADP 2023 match those used in ADP 2022. The 27 model zones (Figure 1) follow NERC, ISO, and RTO regional boundaries and use the geographic names from EIA's National Energy Modeling System (NEMS), which are approximations of jurisdictional borders (for example, the "Texas" zone does not fully conform to the borders of that state). As explained in the modeling updates section below, the new downscaling methodologies are used to produce data outputs that map exactly to a state geography. Temporally, infrastructure stocks are updated on an annual basis, with hourly resolution across 40 representative sample days per year in electricity system operations including sector coupling with carbon management (CCUS and DAC), fuel production, and other flexible loads (see e.g. Figure 54 to Figure 57).

FIGURE 1. Zonal representation in the model



1	Alaska	8	Metropolitan New York	15	Northern Great Plains	22	Southwest
2	Carolinas	9	Michigan	16	Northwest	23	Tennessee Valley
3	Central Great Plains	10	Mid-Atlantic	17	Ohio Valley	24	Texas
4	Florida	11	Middle Mississippi Valley	18	Rockies	25	Upper Mississippi Valley
5	Great Basin	12	Mississippi Delta	19	Southeast	26	Upstate New York
6	Hawaii	13	New England	20	Southern California	27	Virginia
7	Metropolitan Chicago	14	Northern California	21	Southern Great Plains		

III MODELING UPDATES

As part of the annual update to our modeling, we conducted a review of key data sources. We updated to the most recent versions that were available for inclusion as of July 1, 2023. This included:

- The U.S. Department of Energy's Annual Energy Outlook 2023 for energy service demand, equipment stocks, and baseline demand technology forecasts; fossil fuel prices; and delivery prices for different energy carries (electricity, pipeline gas, etc.)
- The National Renewable Energy Laboratory's Annual Technology Baseline 2023 for renewable costs and performance.

Additionally, other technology inputs were also adjusted. The most consequential of these are highlighted in other Modeling Updates subsections below, and others are noted in the ADP Supporting Materials.

Technology Build Rate Constraints

Improvement: The Inflation Reduction Act made it necessary to include new build rate constraints for many technologies in the model. Without them, the model frontloads the build of technologies to take advantage of the IRA tax credits in ways that are clearly unrealistic. In ADP 2022 the only build rate constraints were placed on biomass and e-fuel technologies, in order to smooth out unrealistically rapid build in the last model period (2046-2050). Now in ADP 2023, build rate constraints have been applied, by necessity, across many supply-side technologies. Table 3 shows initial build rates and the minimum time required for the build rate to double from the previous period.

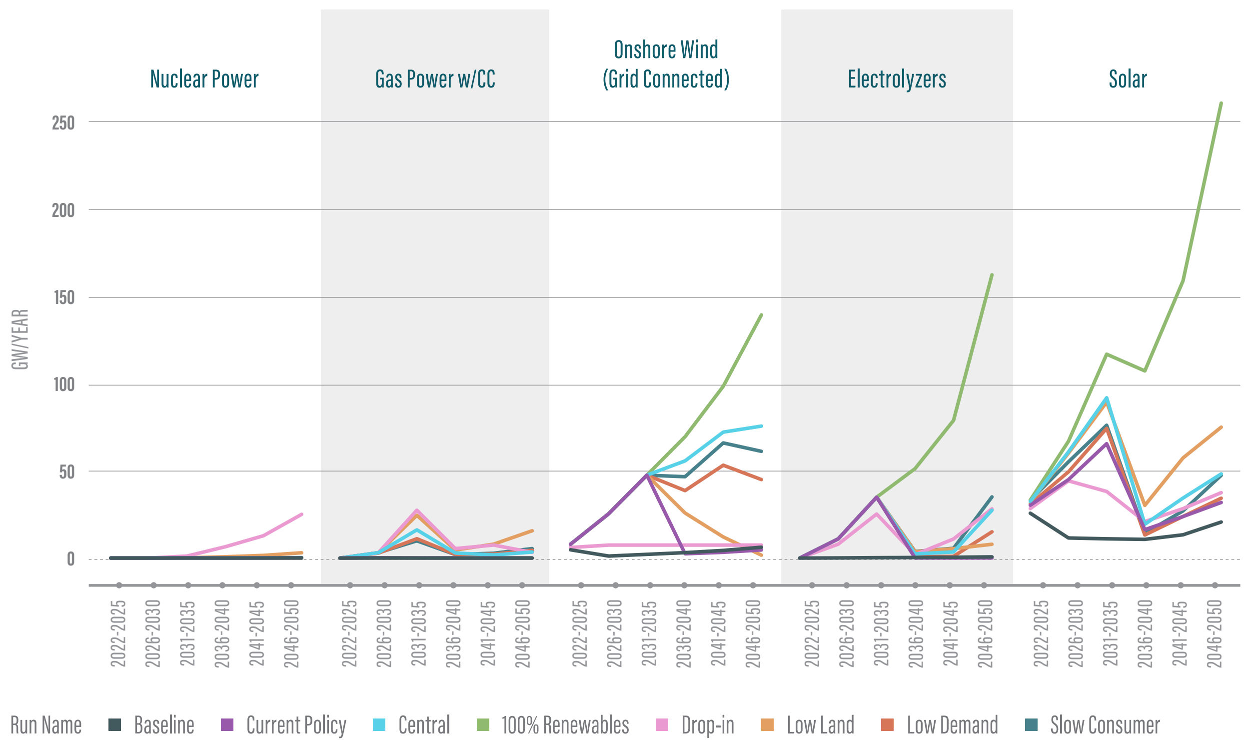
While these build rates are important, realistic trajectories are not well understood. Given the myriad factors involved, plus the fact that the act of modeling or predicting the system can influence the system itself, these are not possible to determine with accuracy in the long-term. Philosophically we have attempted to constrain technologies build rates so that: (1) long-term outcomes are minimally impacted; (2) systemic bias between technologies is minimized; (3) technology maturity is acknowledged (a less mature technology may start at a lower build rate but may also grow faster); and (4) assumptions can be shared across scenarios, except where differences are part of the design of the scenario itself. An example of the last principle is demonstrated in the two renewable energy bookend scenarios, 100% Renewables and Drop-In. Build rates for renewables and other low-carbon technologies allow both scenarios to be feasible and the resulting constraints are also shared by the rest of the scenarios. These philosophical principles are in line with the objectives of the ADP, but note that the build rates in Table 3 have been set differently in other Evolved Energy Research work, depending on the focus of the research questions.

TABLE 3. Technology build rate constraints

Technology	Starting annual build rate (GW per year)	Time to double annual build rate (years)	Justification
Utility-scale Solar PV	29.1 GW in 2023 34.7 GW in 2024 (Frozen at 15 GW in Drop-In Scenario)	2025-2028 – 5 years 2029-2050 - 10 years (Frozen at 15 GW in Drop-In Scenario)	Starting build rate based on EIA's Short- Term energy outlook, accessed July 2023.
Onshore Wind	7.4 GW in 2023 7.5 GW in 2024 16.8 GW in 2025 (Frozen at 7.5 GW in Drop-In Scenario)	2026-2034 – 5 years 2034-2050 - 10 years (Frozen at 7.5 GW in Drop-In Scenario)	Starting build rate based on EIA's Short- Term energy outlook, accessed July 2023, then returning to historical max build in 2025.
Offshore Wind	1 GW in 2024 (Frozen at 7.5 GW in Drop-In Scenario)	2025-2050 – 5 years (Frozen at 7.5 GW in Drop-In Scenario)	Allows for near-term state targets to be met.
Electrolysis	2 GWth output in 2026	2027-2030 – 9 months 2031-2050 – 10 years	Starting build rate based on early growth rate of solar PV. Maturation happens in the early 2030s.
CCS Technologies	5 GW in 2029	2030-2050 – 5 years	Later start year due to construction/permitting times.
Nuclear	3.5 GW in 2031	2032-2050 – 5 years	Later start year due to construction/permitting times.
Advanced biofuels	4 GW in 2024	2030-2050 – 10 years	Starting build rate based on historical ethanol plant build rates.
Advanced e-fuels	4 GW in 2024	2032-2050 – 10 years	Starting build rate based on historical ethanol plant build rates.

Result: The modeled build rates of key technologies is shown in Figure 2. Onshore wind is seen to be most constrained, with no spread between scenarios through 2035 (except Drop-In). The 45V tax credits also drive a tight clustering of electrolysis build in the next decade. Most technologies show a steep decline in annual build after IRA tax credits expire, with the steepest declines coming in solar PV and electrolysis. While this boom-and-bust cycle has been observed historically, it is unlikely to play out quite so starkly in the real world, either because companies curtail investment at the peak or because supplemental state or federal policies moderate the trough. As in ADP 2022, we add modest penalties in the modeling for changes in annual build rates. With penalties set at a sufficiently high level, these can be used to smooth build. However, doing so also introduces other artifacts, and thus, the steep decline after 2035 is simply left for the reader to interpret. Except for onshore wind in the 100% Renewables scenario, none of the modeled build rate constraints are binding in 2050.

FIGURE 2. Modeled build rates of key technologies



Wind and Solar Transmission Cost

Improvement: In partnership with Princeton ZERO Lab, we are using supply curves of available renewable energy projects developed for the REPEAT Project. New methods are used to map transmission from a renewable candidate project area (CPA) to large load centers, not just the nearest substation. This increases the total transmission distance and the cost of projects that are far from load centers. A visualization of these transmission costs for onshore resources are shown in Figure 3.

FIGURE 3. Renewable project interconnection cost heat map ($/MW)

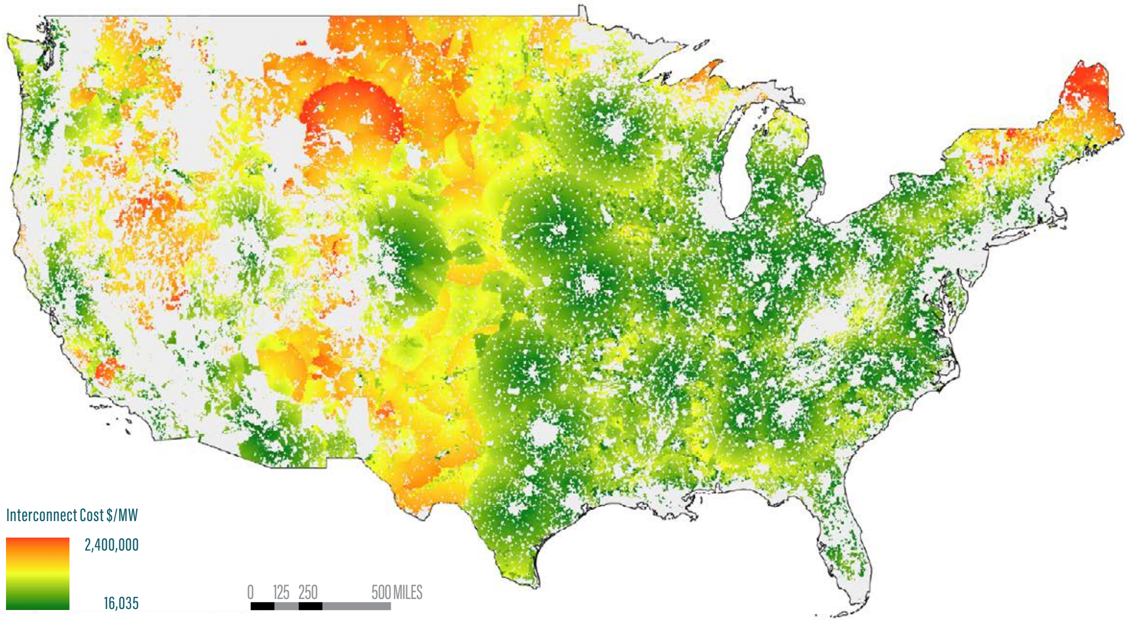


Image credit: Benjamin Preneta

Result: Some renewable energy projects are higher cost in ADP 2023 than last year. This is particularly true for remote projects, and contributes to the greater competitiveness of other electric technologies.

Cement and Lime

Improvement: This year's ADP has added substantial new detail to the modeling of cement, in two ways: dividing cement manufacturing into distinct process steps, and distinguishing between process emissions and energy-related emissions. These changes allow more explicit targeting of emission reduction measures to specific steps in cement production than was possible in our previous modeling.

The key process steps in cement manufacturing are calcining, in which limestone (calcium carbonate) is heated at high temperature to produce lime (calcium oxide); clinkering, in which lime is sintered with specialized clays in a rotary kiln at even higher temperatures to produce clinker; and grinding, in which clinker is blended with gypsum and ground up to produce Portland cement.

The result of these steps is that on average, for every ton of cement produced, about 1 ton of CO_2 is emitted. These emissions are of two different types: (1) process emissions, in which the chemical reaction in the calcination of limestone releases CO_2 directly, independent of emissions from the energy inputs required. About 60% of current emissions from cement production are process emissions; and (2) energy emissions, mainly from the combustion of fuels used to provide process heat. These constitute about 40% of current emissions from cement production. On a plant-to-plant basis, energy emissions can differ substantially depending on the type of fuel used (e.g. coal, natural gas, etc).

RIO's optimization now allows economic competition among different decarbonization measures targeted to these process steps and emission types. The available measures include:

- Efficiency Improvements: Modernizing equipment and optimizing processes can reduce energy consumption and emissions. RIO represents this with new state-of-the-art efficient cement kilns.
- Alternative Fuels: The use of alternative fuels such as biomass and hydrogen for process heat reduces energy-related CO_2 emissions compared to fossil fuel combustion. Direct electrification was not considered as a kiln heat source in this year's analysis, but will be included in future years.
- Direct separation CCS: Direct separation technology entails the physical separation of the calcination reaction from the heat input to that reaction, resulting in a highly concentrated stream of process CO_2 for capture and storage. This emerging technology, which is currently at the early commercialization stage, is available in RIO both for retrofits of existing kilns and for new kilns.
- Integrated CCS: The modeling of integrated CCS plants that capture both process and energy emissions has two options: natural-gas fueled oxy-combustion CCS, and biomass-fueled CCS, which provides the potential for negative emissions.
- Alternative Materials: Using supplementary cementitious materials (SCMs, as for example in LC3 cement blends), limestone, fly ash, and slag can reduce the amount of clinker needed in cement, reducing the per-ton emissions from cement production. We model this in the ADP Low Demand scenario, but it is not included in the optimization in other cases due to present uncertainty about costs.

Lime production is an intermediate step in the production of cement. Both quicklime (calcium oxide) and hydrated lime (calcium hydroxide) are also used extensively in other applications such as manufacturing of iron and steel, water treatment, and construction. Process emissions from the calcining of limestone is responsible for about 80% of the CO_2 emissions from lime production, with the remainder from energy. In RIO, lime production has a similar menu of decarbonization options to that of cement, including energy efficiency, alternative fuels for process heat, and carbon capture and storage.

Result: The higher resolution in ADP 2023 leads to more concrete insight into which measures appear most competitive in a low carbon transition in the cement and lime sector, given current assumptions about future technology and fuel costs. In all scenarios the main trend is the retrofitting of existing kilns with direct separation technology with CCS (Figure 4). This transition can be conducted in stages as economics and emissions limits dictate, with CCS initially applied to process emissions only, and subsequently to energy emissions from the whole plant. In the Central case, about 90% of cement production uses this technology by 2040. Oxyfuel CCS with biomass emerges in the 2040s as the main technology used in new kiln construction, providing a negative emission technology. In the Low Demand case, using alternative materials to limit the clinker content of cement reduces overall clinker production by half compared to the baseline. Biomass becomes dominant as a kiln heat source in all scenarios, replacing coal and natural gas, with municipal solid waste maintaining its current share. Hydrogen was not selected by the model.

FIGURE 4. (a) Clinker capacity (Mt/y) (b) Heat sources in cement kilns (PJ)

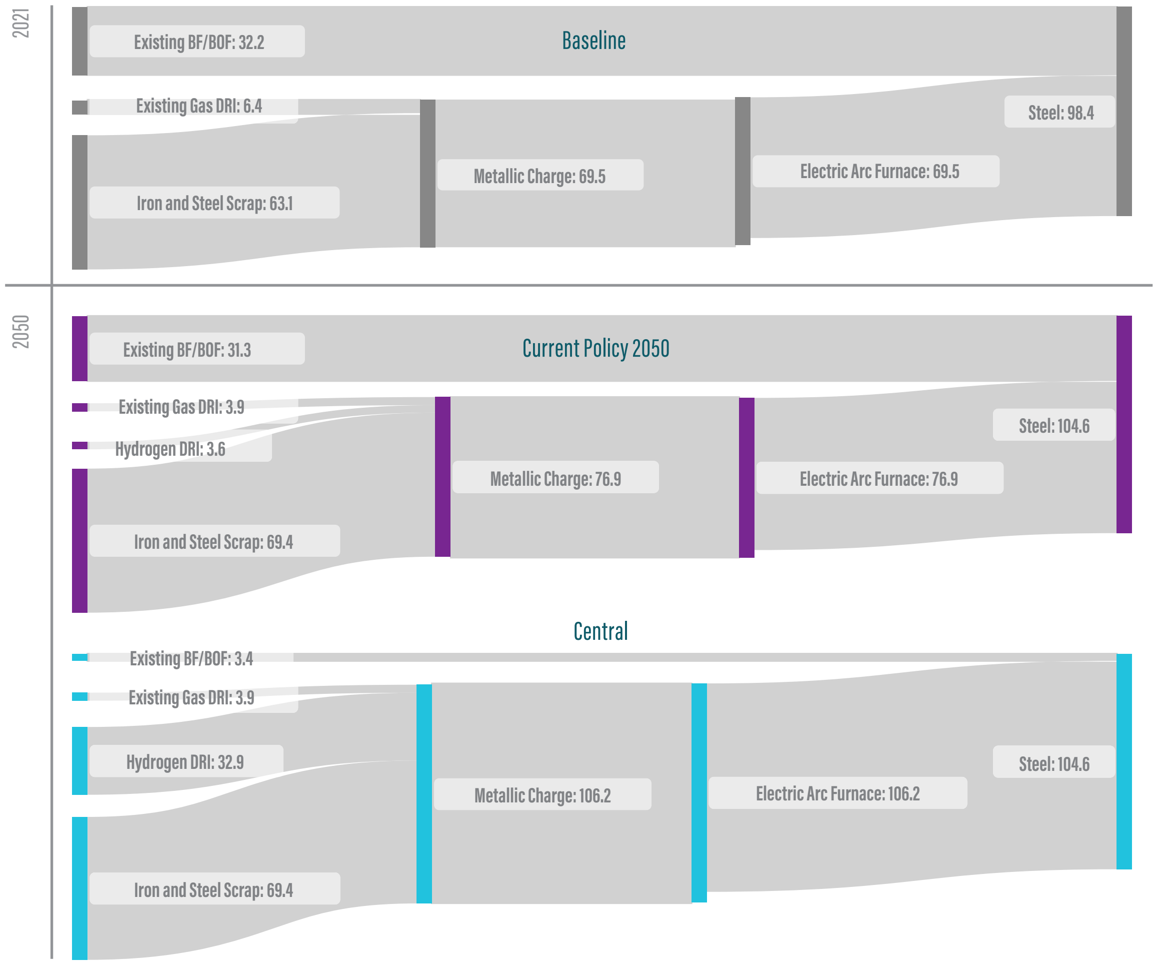
Iron and Steel

Improvement: The modeling of iron and steel production in ADP 2023 adds significant new detail to the treatment of different manufacturing processes, emissions sources, and decarbonization options. Currently, the U.S. produces most of its steel via two distinct routes. The first is traditional "primary steel" manufacturing, starting with iron ore that is converted in blast furnaces (BFs) to pig iron, which is converted in turn to steel in basic oxygen furnaces (BOFs). The other is "secondary steel" manufacturing (a.k.a. steel recycling), in which scrap metal is converted directly into steel in electric arc furnaces (EAFs). Primary steel manufacturing is carried out in a small number of large integrated BF/BOF steel mills that are concentrated geographically and produce about 30% of U.S. steel. Since this pathway starts with the conversion of coal into metallurgical coke, which is then used to chemically reduce iron ore, with additional heat inputs from the further combustion of coal or natural gas, it also produces the vast majority of steel-related CO_2 emissions. Secondary steel manufacturing is carried out in hundreds of smaller, more geographically dispersed EAF plants and produces about 70% of U.S. steel. The principal energy input to EAF is electricity, so direct CO_2 emissions are primarily process emissions and constitute a small share of steel-related CO_2 emissions. A relatively small fraction of the input to EAFs comes from plants that produce direct-reduced iron (DRI), a process that operates at lower temperatures, has lower energy demand, and can use gaseous fuels such as natural gas or hydrogen to substitute for coke or coal. In combination, DRI-EAF is another primary steel pathway, though a minor one in the U.S. at present. The raw steel produced by all the methods described above then goes through continuous casting or hot/cold rolling to produce final products. The energy use and emissions associated with these final steps are relatively small across all the pathways.

The three main decarbonization options modeled in the RIO optimization build on the existing pathways: (1) retrofitting existing integrated steel plants with CCS, including coke ovens, blast furnaces, and basic oxygen furnaces; (2) building new scrap/EAF capacity to replace BF/BOF capacity; and (3) building new DRI/EAF capacity to replace BF/BOF capacity, where the DRI is hydrogen-fueled (H_2-DRI). The results of this three-way competition are driven by the availability of scrap for recycling, which is modeled with a supply curve; hydrogen tax credits in the Inflation Reduction Act; and the relative costs of different fuels and technologies. Another factor to be added to the modeling in future years is the availability of high-grade iron ore. Aggressive material efficiency measures in which less steel is used in the economy are modeled in the Low Demand case.

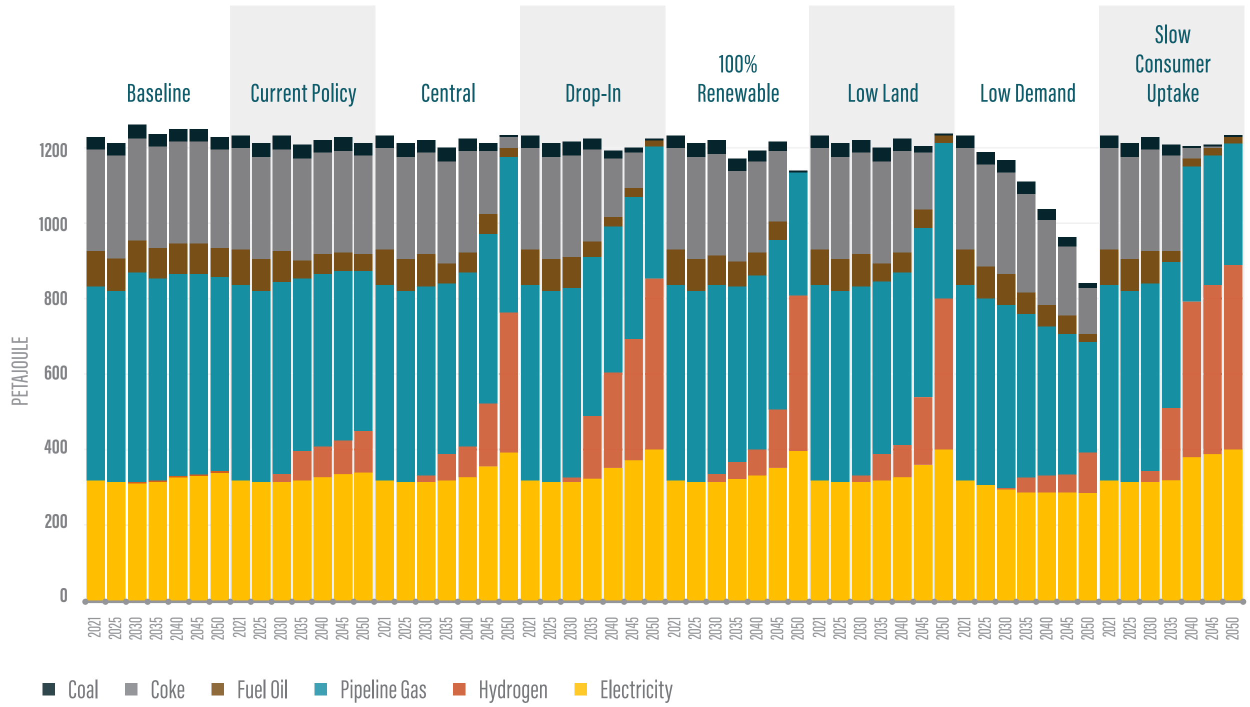
Results: In the Central case, more than 95% of steel is manufactured using EAF (Figure 5). Scrap inputs at roughly current levels comprise 70% of the EAF input charge, and H_2-DRI comprises most of the remaining 30%. BF/BOF production is reduced 90% below today's level. In the Current Policy case, which has no carbon constraint, existing BF/BOF production continues at nearly today's level, while the use of scrap increases slightly and a small amount of H_2-DRI is added. The main change in the energy mix (Figure 6) is hydrogen's growth to 30-40% by 2050 in the net zero cases, and a comparable reduction in coke and coal.

FIGURE 5. Steel manufacturing pathways in Baseline 2021, Current policy 2050, and Central 2050 scenarios



Note: Numbers refer to metric tons of iron or steel produced. BF = blast furnace, BOF = basic oxygen furnace, DRI = direct reduced iron.

FIGURE 6. Energy inputs (PJ) to iron and steel production by fuel type, 2021-2050

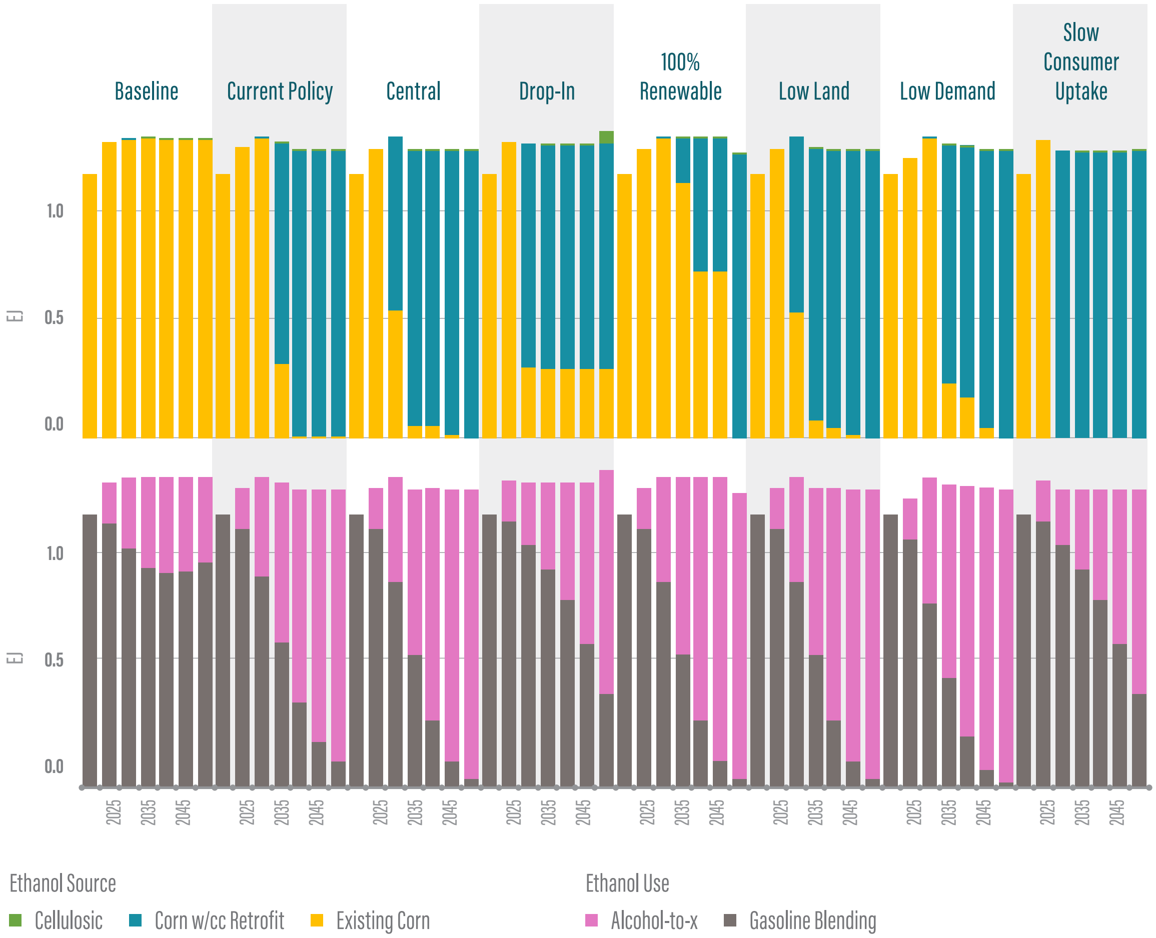


Ethanol to Jet Fuel

Improvement: Recent advancements in catalysts have opened a new pathway for existing ethanol to be upgraded to jet fuel. This technology wasn't included in ADP 2022 and hadn't yet been studied in any national decarbonization studies that we are aware of at that point. Assumptions in ADP 2022 matched those that we first made in the Princeton Net Zero America study, which is that ethanol for corn is gradually phased out as light duty vehicles are electrified, and miscanthus is instead grown on that land for use in other bioenergy applications. Using inputs developed with Third Way for a detailed study of sustainable aviation fuel, we have now introduced the new ethanol upgrading pathway and endogenized the decision of whether that land should be repurposed or should continue to grow corn for ethanol.

Result: Ethanol to jet fuel technology is consistently selected by the model across all scenarios. It is especially competitive when paired with adding carbon capture to existing ethanol plants. In ADP 2022 carbon capture on ethanol was limited because the total volume of ethanol was declining as a result of vehicle electrification. In ADP 2023, with new applications for its use, the total volume of ethanol does not decline significantly, and carbon capture is used extensively. These dynamics are seen in Figure 7. The competition between corn and miscanthus could be affected by factors not included in this year's modeling, such as water availability, or breakthroughs in cellulosic ethanol technology.

FIGURE 7. Ethanol production by technology (top) and ethanol uses (bottom)



Improved Technology Retrofits

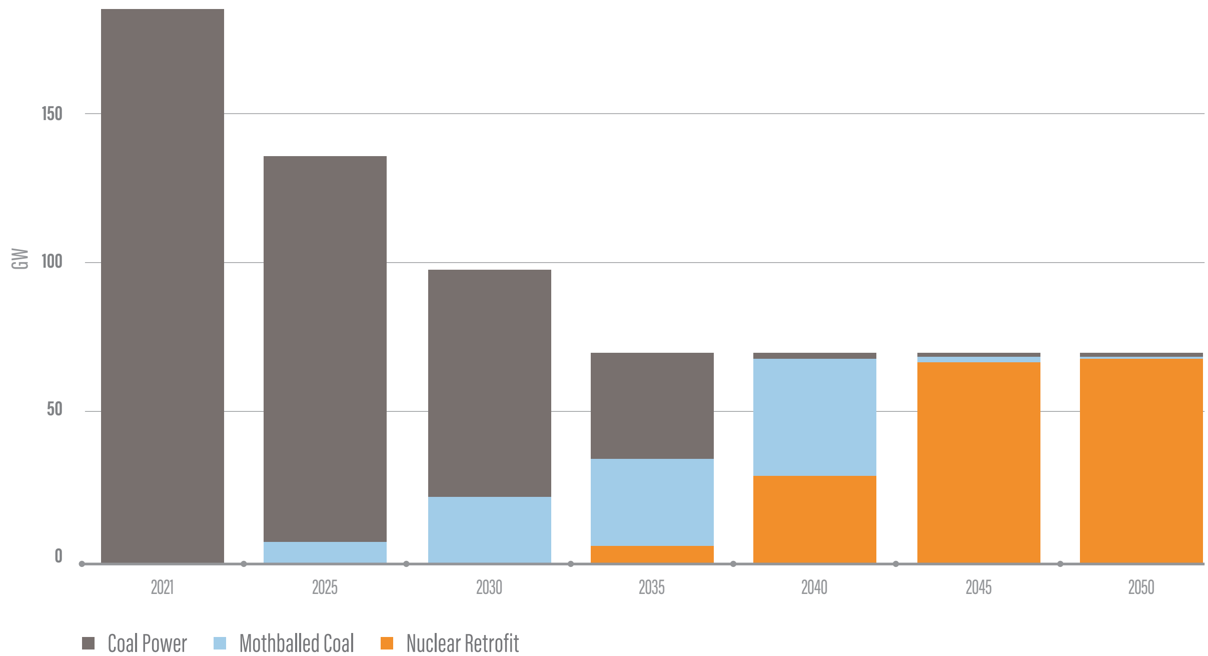
Improvement: The RIO model has new features that allow for more robust treatment of technology retrofits. This is important not only for the Drop-In scenario, where it is a special focus, but in all scenarios in ADP 2023. We expect the number of identifiable retrofit opportunities to only increase in future ADP reports.

Result: Retrofits play a large role in many of the technology transitions. These include:

- Coal and gas power plants adding carbon capture or being repurposed to host new nuclear reactors
- Ethanol production being retrofit with carbon capture
- Cement and lime kilns being retrofit with carbon capture
- Switching of heat sources for cement
- Electrifying the liquifaction process in existing LNG export terminals

Figure 8 shows the retrofit outcomes for coal power plants in the Drop-In scenario. By 2050, roughly a third of current coal capacity is repowered as nuclear. For many coal power plants this transition entails mothballing the generators. Mothballed plants are modeled in RIO as a separate technology with annual fixed O&M reduced by 90%, and without the ability to generate power. Without mothballing, fewer nuclear retrofits would be achieved, because coal plants would need to be retired faster than new nuclear is likely to be built. Mothballing enables existing coal power plant sites to be maintained and readied for later repowering, even as the coal power plant ceases operation. The typical duration that a site is maintained in mothballed status before a nuclear plant commences operation is approximately 10 years, with several of these years spent in the construction of the new reactor.

FIGURE 8. Retrofits of coal power plants in Drop-in scenario (GW)



Direct Air Capture

Improvement: The two leading direct air capture (DAC) technologies at present are:

1. Liquid solvent capture: This method uses large fans to push ambient air over a liquid solution, typically containing amines or hydroxides, that binds with CO_2. Once the CO_2 is captured, the solvent undergoes a process of regeneration by heating, which releases pure CO_2 gas that can then be stored or utilized and readies the solvent for further capture. This technology is similar to the solvent-based carbon capture used in some industrial processes.

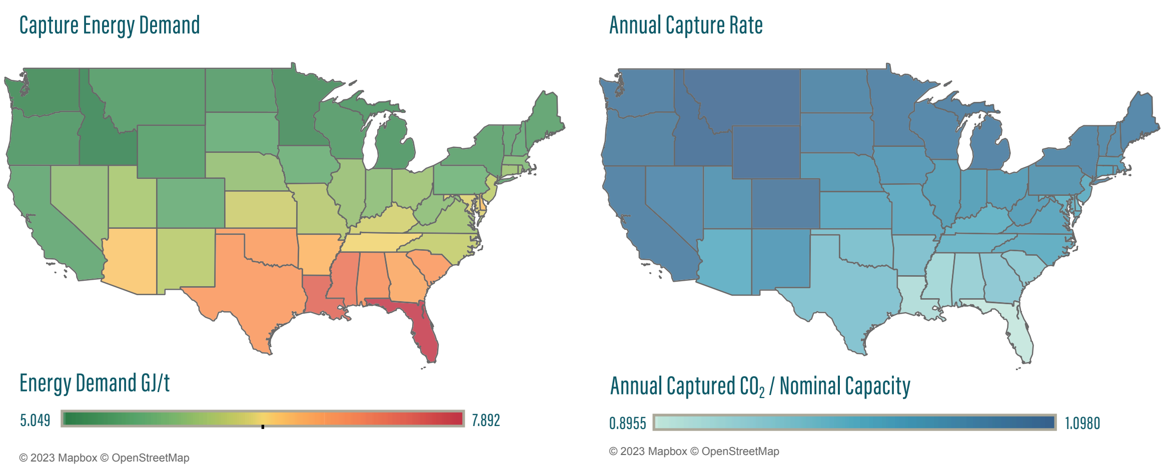
2. Solid sorbent capture: In this approach, ambient air is passed over a solid sorbent,that selectively binds with CO_2. After these materials are saturated with CO_2, they undergo a

process of regeneration by heating to release the captured CO_2. An advantage of solid sorbents is that they can be used in a more compact form factor than liquid solvents, and lower temperature heat is required in the regeneration process.

ADP 2022 used technology-neutral inputs that didn't specifically represent either technology. The variable performance of DAC with respect to ambient climate was also not captured. In general, solid sorbent technologies perform better in cool dry conditions, while liquid solvent does best in warm humid environments. These distinctions can make large differences in where DAC is likely to be competitive within the U.S., and between the U.S. and other countries.

To pursue the question of geographic suitability, EER built an hourly DAC model for both liquid solvent and solid sorbent technologies with characteristics based on recent literature and simulated these technologies across 1,035 locations across the U.S. using 22 years of historical weather data. The best locations within each state were averaged to create statewide values for capture energy demand (energy input per tonne captured) and capture rate (annual tonnes captured per tonne of nominal DAC capacity), shown for the solid sorbent technology in Figure 9.

FIGURE 9. Solid sorbent direct air capture technology capture efficiency and capture rate by state. Efficiency is shown before savings associated with use of heat pumps.

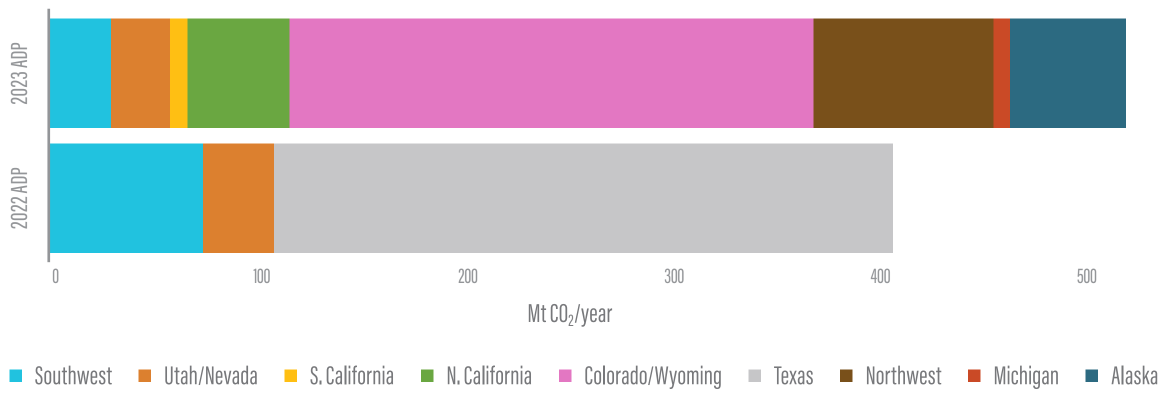


Result: The analysis showed solid sorbent technology outcompeting liquid solvent technology in most locations based on our specific inputs and assumptions. Part of this competitiveness was because solid sorbent DAC can make use of heat pumps to supply the lower quality heat needed to recharge to sorbent.

Direct air capture in the most advantageous locations in the U.S. showed lower cost compared to ADP 2022; however, it was still not economically deployed in the Central scenario in ADP 2023. But as in last year's work, the scenarios that constrained the deployment of one or more technologies (for example, electrification, biomass, nuclear, wind and solar) had direct air capture playing a critical role. This highlights the important "backstop" role that DAC may play in more constrained futures.

Last year the Drop-In scenario built just over 400 Mt/year DAC capacity, with 75% of it built in Texas and most of the remaining capacity built in the Southwest. These are places where solid sorbent technologies are expected to perform worse than in cooler climates further north. This year, after incorporating such factors, the Drop-In scenario built 520 Mt/year with none of it built in Texas. Instead, the majority was built in the mountain west and northwest regions. Other places with good sequestration potential such as California and Michigan also saw DAC built, despite not having particular advantages in wind and solar generation. With the use of more efficient heat pumps for solid sorbent DAC systems, the importance of sites with the absolute lowest levelized cost for wind and solar (such as Texas) has been reduced.

FIGURE 10. DAC capacity by state, ADP 2023 vs. ADP 2022

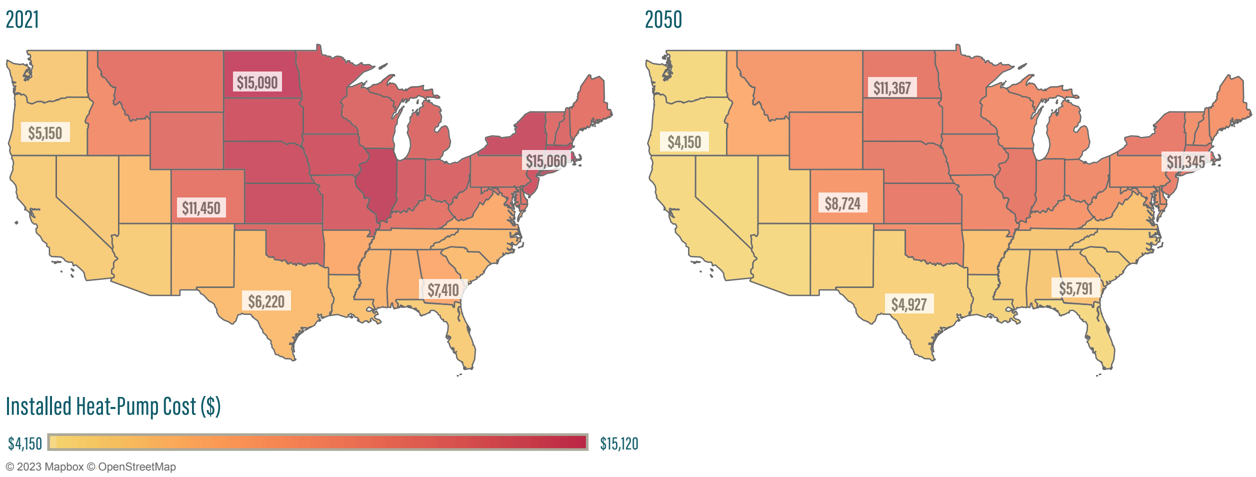


Heat Pump Technology Cost

Improvement: Residential heating system cost in our previous work has been based on inputs to EIA's NEMS model and an assumed uniform unit size across the U.S. These assumptions have been updated in ADP 2023 using NREL ResStock data and an analysis of peak heating demand in each U.S. county.

Result: Sizing heat pumps based on local climate results in a large cost spread across states as seen in Figure 11. With this update the average cost of a heat pumps increased, and our datasets are better benchmarked to state databases in New York and Massachusetts with installed heat pump costs.

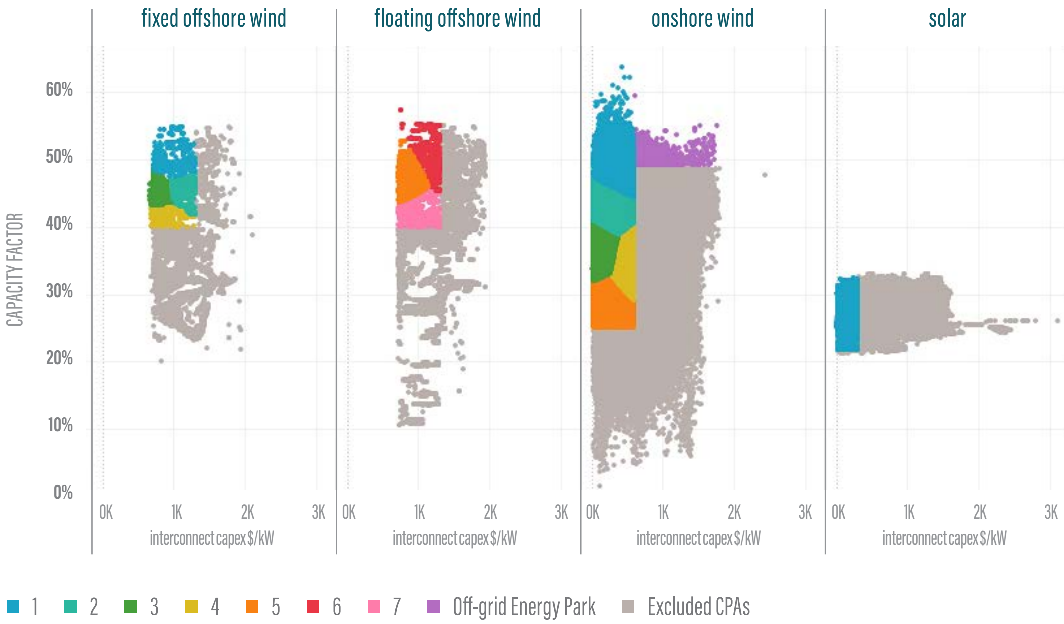
FIGURE 11. Single family home installed heat pump cost for 2021 and 2050



Energy Parks

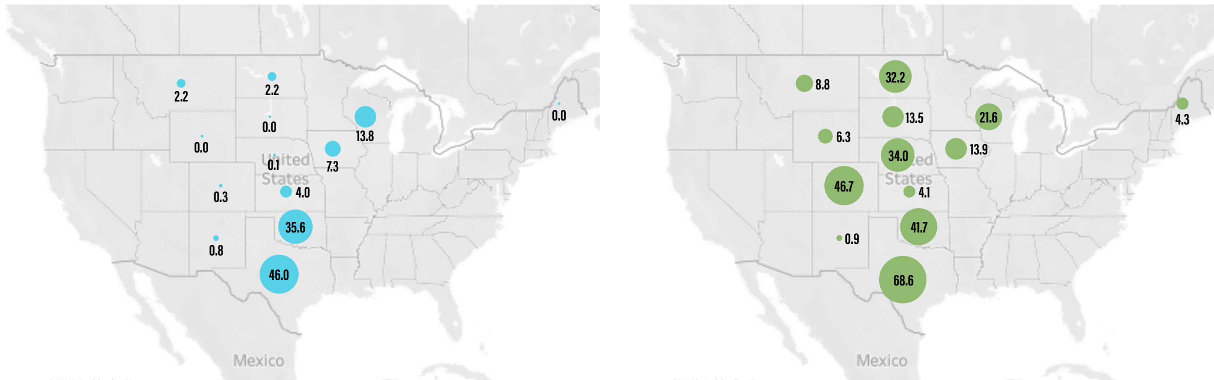
Improvement: As described in the discussion of wind and solar transmission cost, the ability to connect generation to loads is one of the principal barriers to achieving higher levels of renewable generation in the U.S. This is particularly true across much of the Wind Belt, a particularly windy stretch of the country that extends from Texas north to the Dakotas with outstanding wind resources and low population density, but also with lower electricity load. Many of these wind resources are not developed in energy models because the cost of transmission interconnections makes them uneconomic. Instead, wind development is often placed closer to population centers, increasing the likelihood of siting conflicts, even though some of this wind may be producing e-fuels and not actually serving local electric loads. However, there is a potential way out of this conundrum, based on the understanding that transporting fuels in bulk via pipeline, barge, or rail can be an order of magnitude cheaper than transporting electricity (except when the final energy use is electricity itself, and would involve an inefficient conversion from fuel back to electricity). This situation creates an opportunity to develop wind and solar resources further from population centers in "energy parks," where off-grid generation is used specifically to produce fuels, which are transmitted via pipeline to different demand applications. We have developed a representation of potential energy parks as part of ADP 2023 by identifying those candidate project areas with the highest capacity factors and highest transmission costs, shown in Figure 12.

FIGURE 12. Wind and solar resource binning of candidate project areas (CPAs)



Result: Energy parks for hydrogen production were used by the model in all net-zero scenarios except Low Land. This is an important exception to a dynamic that is often discussed in our previous work, which is the value of grid connected electrolysis for balancing a high renewable power system (electrolysis can still be co-located with renewables while being grid connected). This value provided by electrolysis has diminishing returns as the penetration of e-fuel production on a system climbs, and at that point, the cost savings that come from avoiding new transmission build and minimizing siting conflicts becomes more important. Energy park build by state is shown in Figure 13. Most of the energy park resource is built in the Wind Belt in places where transmission interconnection cost is high, as shown in Figure 3, but interestingly northern Maine also presents opportunities for energy parks that are built in the 100% Renewables scenario. We plan on further investigating this possibility in our future research.

FIGURE 13. Wind energy parks built for electrolysis production in Central and 100% Renewables scenarios (Gigawatts)

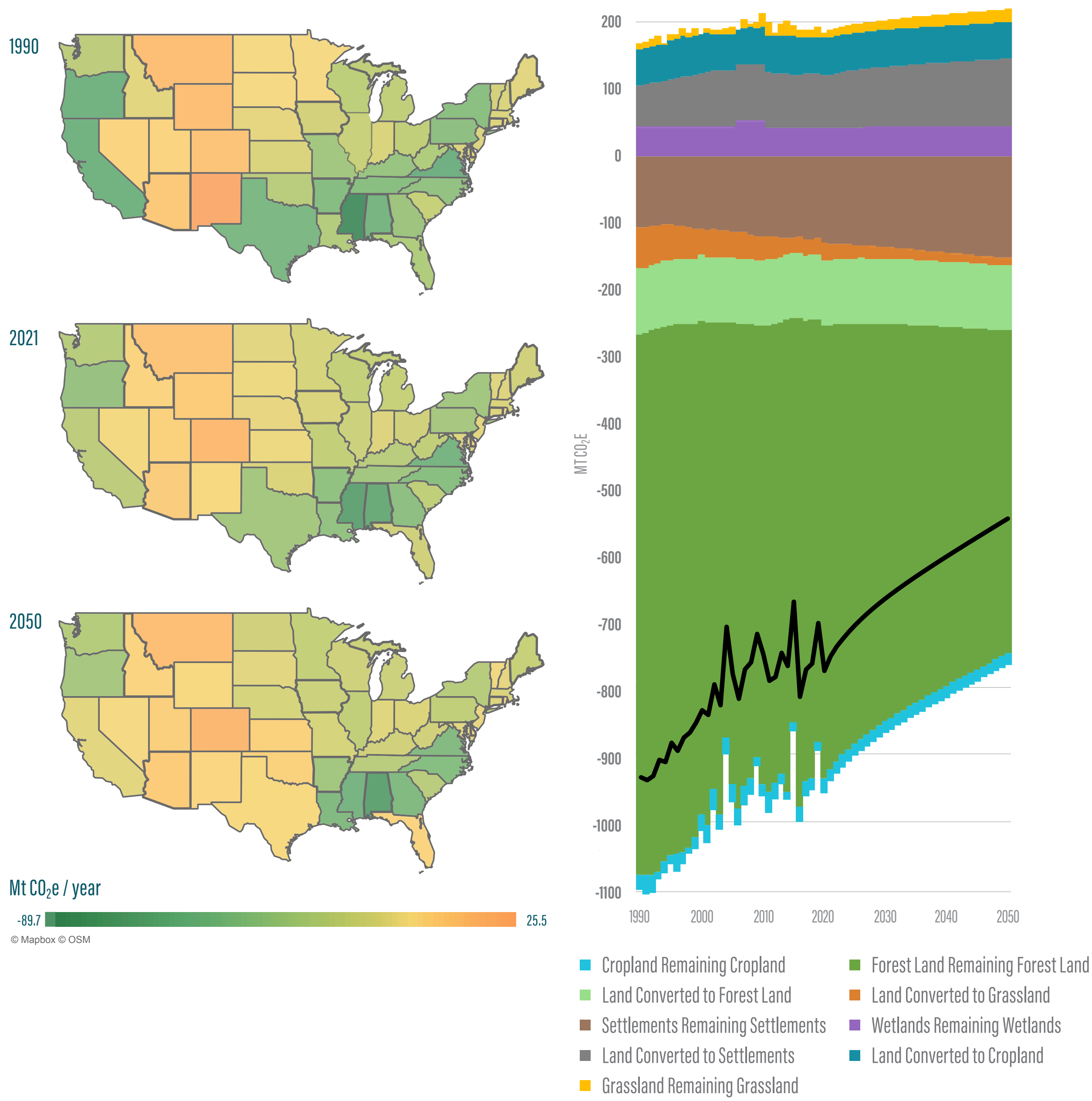


State-Level Non-CO_2 and Land-Sink Modeling

Improvement: Our previous modeling of non-CO_2 greenhouse gas emissions and the U.S. land carbon sink did not include a disaggregation of these emissions sources and sinks across the U.S. In ADP 2023 we have used new data from the EPA to specify this data at the state level. Doing so has also allowed us to better analyze the trends associated with the existing U.S. land sink.

Result: New outputs provide a better look at total greenhouse gas emissions for a sub-national geography and the existing land-sink baseline is better understood compared to ADP 2022. Figure 14 provides a snapshot of the total U.S. land-sink starting in 1990 and projected through 2050, along with how this land sink is distributed geospatially across the U.S. This information can be very valuable for states trying to understand what a low carbon energy transition within their boundaries looks like. The declining land sink shown in Figure 14 is the baseline projection. However, new land mitigation measures in all net-zero scenarios result in a growing land sink (not pictured here).

FIGURE 14. Baseline land-sink for the U.S. projected through 2050



State Level Outputs

Improvement: The EnergyPATHWAYS and RIO models perform calculations using the geographic zones shown in Figure 1. While these geographies do line up with certain planning jurisdictions in the electric power system, the do not map easily to states, which are a more important political geography for understanding climate change mitigation efforts. To make the ADP results more usable to the broader energy community we have undertaken a downscaling of key results to states.

Result: State level outputs are provided for many outputs in the supplemental data released with ADP 2023.

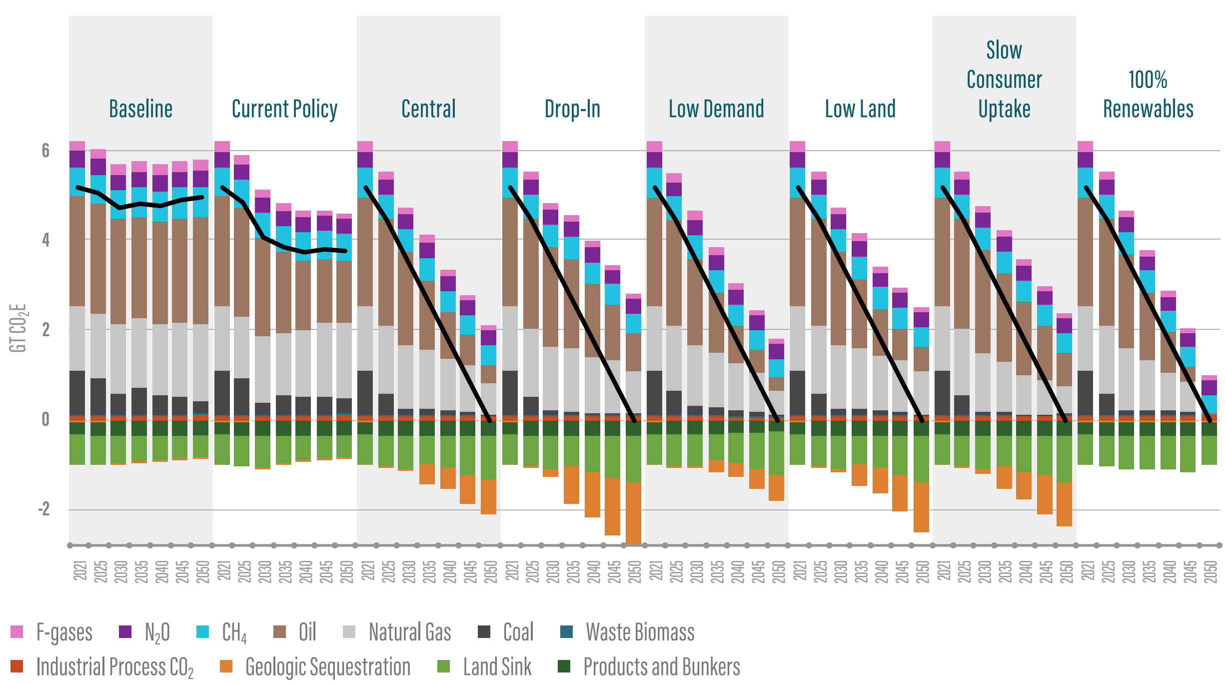
IV SUMMARY OF RESULTS

The high-level results of this analysis are described below, organized into three sections: emissions, energy system, and costs. Additional results are provided in the Supplemental Results section at the end of this report. We have attempted here to provide a brief description of the overall results and also to highlight the changes relative to ADP 2022.

Emissions

Emissions for each scenario are shown in Figure 15. All net-zero scenarios are constrained to take a straight line path to net-zero emissions in 2050. The Current Policy scenario is shown to reduce annual emissions relative to the baseline by one gigatonne per year in 2035, and from 5.34 gigatonnes in the baseline to 4.27 gigatonnes in the Current Policy scenario in 2050. IRA policies induce 100 million tonnes per year of CO_2 capture by 2040, primarily from cement and ethanol, but most of this captured CO_2 is paired with hydrogen produced from electrolysis to synthesize fuels rather than being geologically sequestered.

FIGURE 15. Greenhouse gas emissions by scenario (Gigatonnes)



Energy System

Energy system decarbonization is based on four strategies or "pillars": (1) using energy more efficiently; (2) decarbonizing electricity (3) electrifying end uses; and (4) capturing carbon, which is either sequestered geologically or used to make carbon-neutral fuels. All of these strategies are on display in the 2050 Sankey diagrams shown in Figure 16 - Figure 23.

Sankey diagrams track the flow of energy starting with primary energy on the left and ending with final energy on the right. Primary energy, final energy, and many of the conversion steps in between, are separately detailed in figures in the Supplemental Results at the end of this report.

Comparing the current energy system in Figure 16 with the Current Policy scenario in 2050 in Figure 17, the impact of the tax credits are clear in the expanding share of renewables, use of electrolysis, and shrinking of petroleum fuels. Also apparent is the increase in energy exports, particularly LNG, that is projected in EIA's 2023 Annual Energy Outlook. As in ADP 2022, the net zero scenarios assume U.S exports that decrease proportionally to the global fuel demands in the International Energy Agency's World Energy Outlook 2022 (in the IEA net zero scenario).

FIGURE 16. Sankey diagram for 2021 (Exajoules)

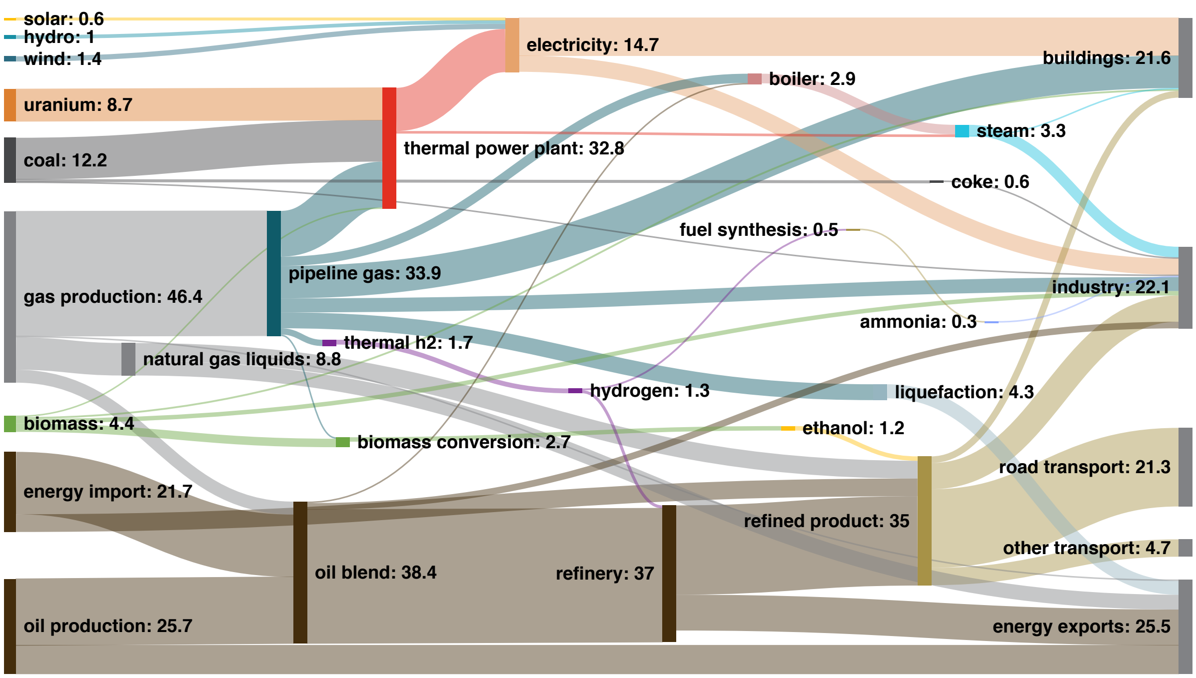


FIGURE 17. Sankey diagram for 2050 Current Policy scenario (Exajoules)

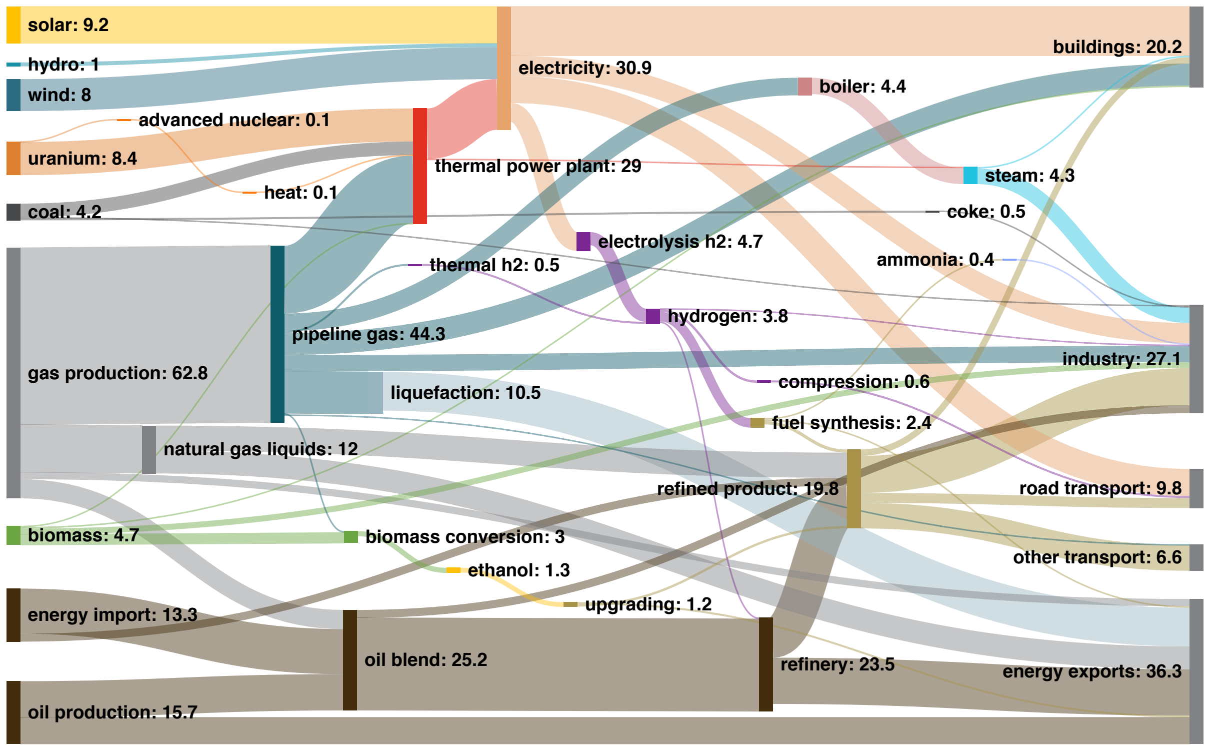


FIGURE 18. Sankey diagram for 2050 Central scenario (Exajoules)

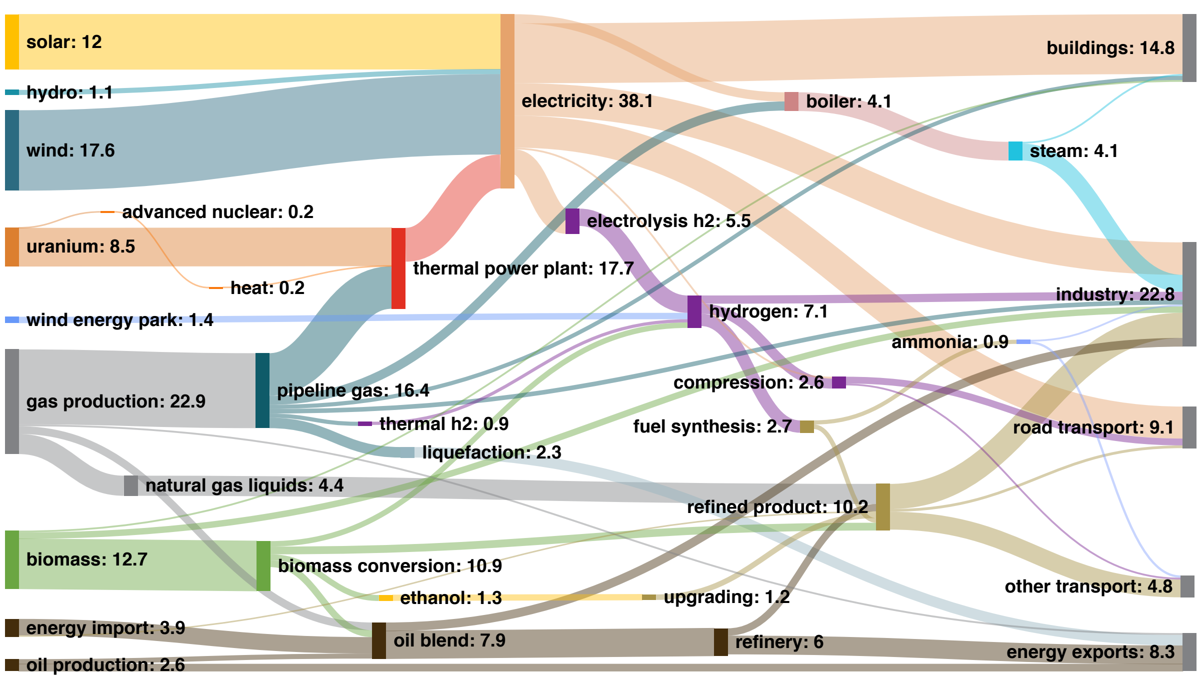


FIGURE 19. Sankey diagram for 2050 100% Renewables scenario (Exajoules)

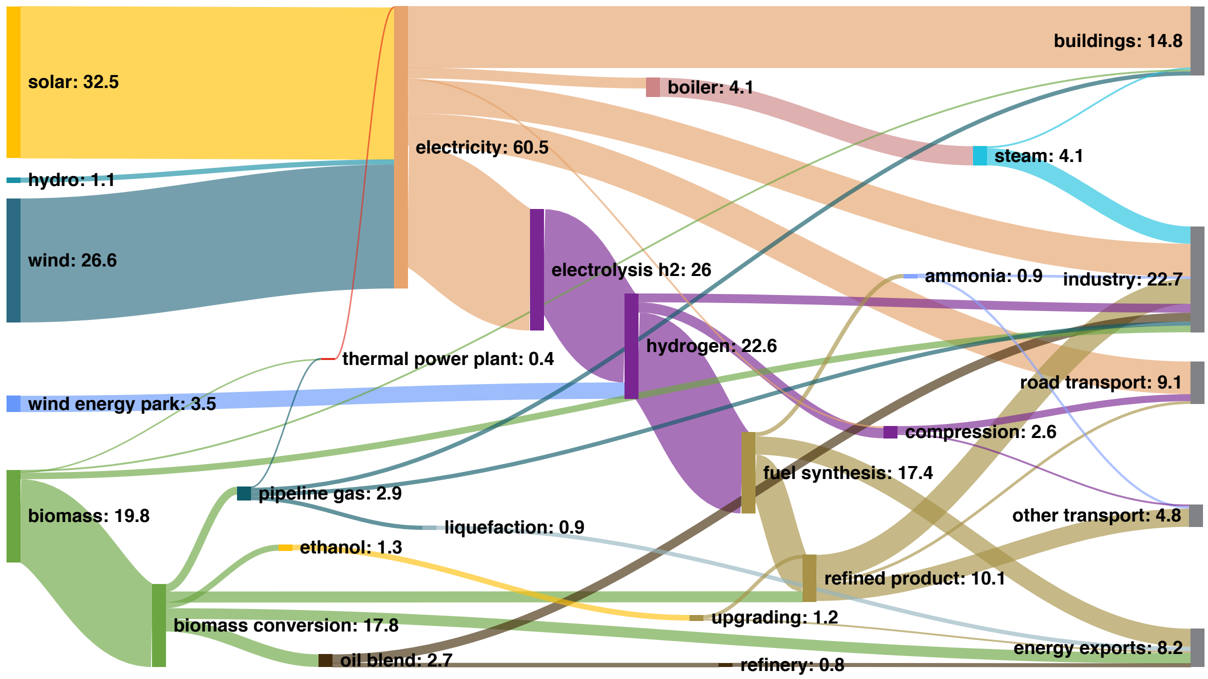


FIGURE 20. Sankey diagram for 2050 Drop-in scenario (Exajoules)

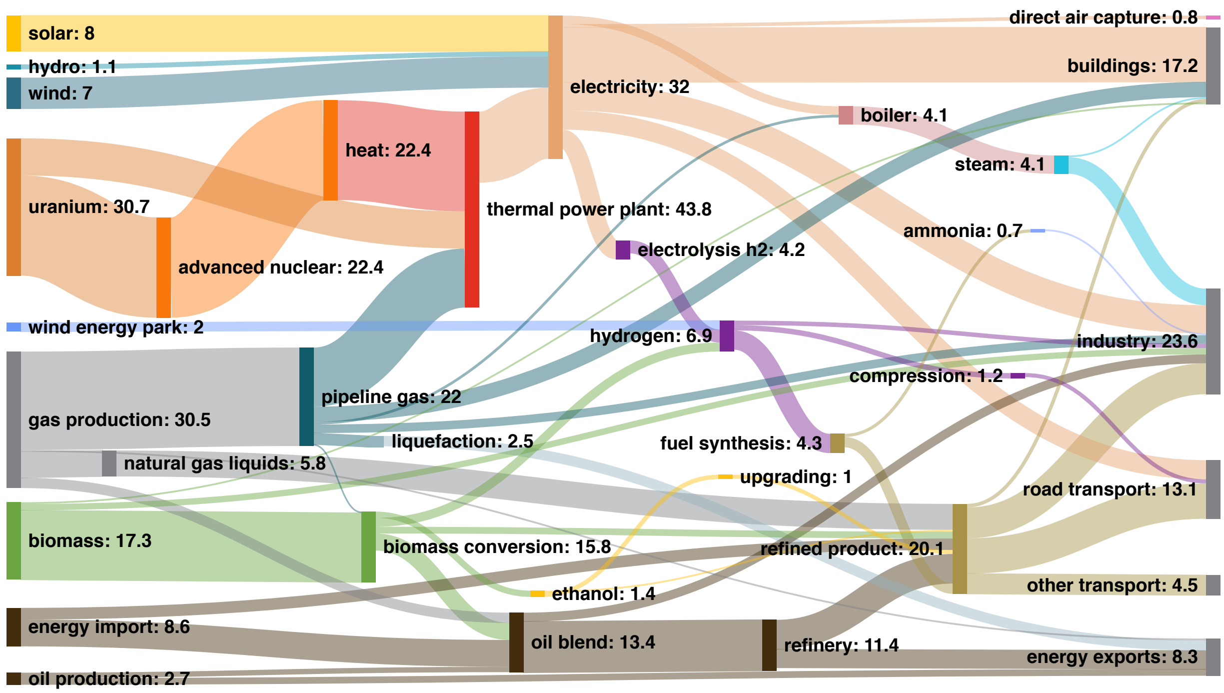


FIGURE 21. Sankey diagram for 2050 Low Land scenario (Exajoules)

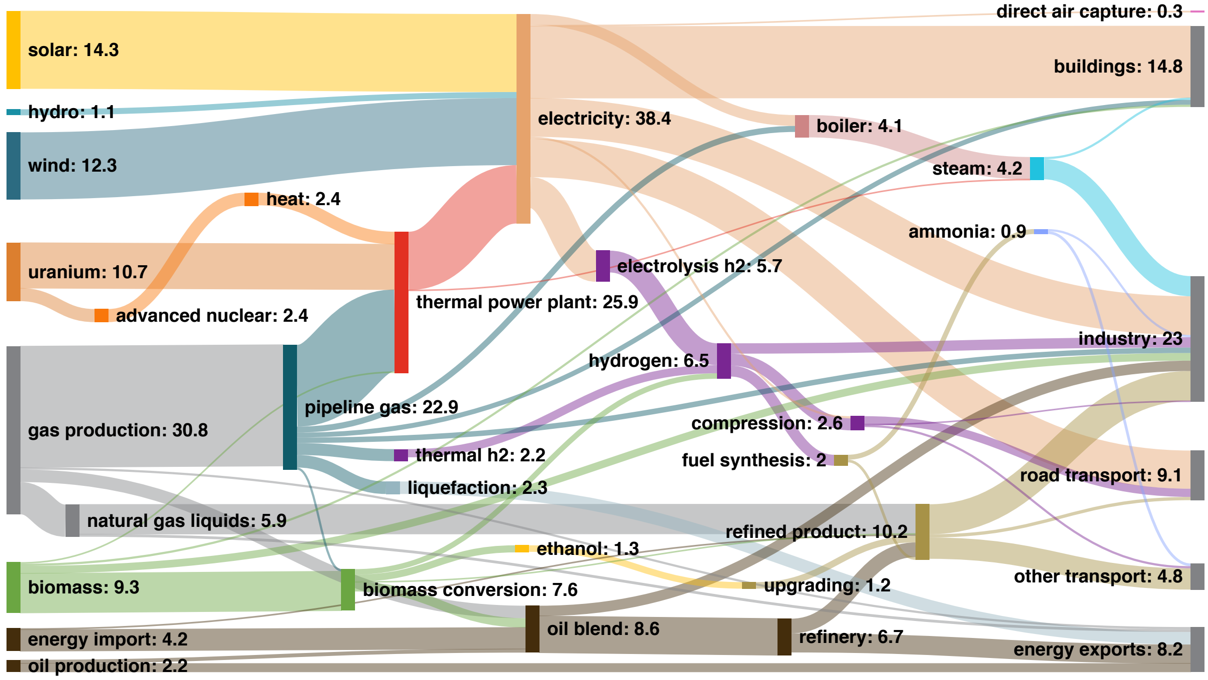


FIGURE 22. Sankey diagram for 2050 Slow Consumer Uptake scenario (Exajoules)

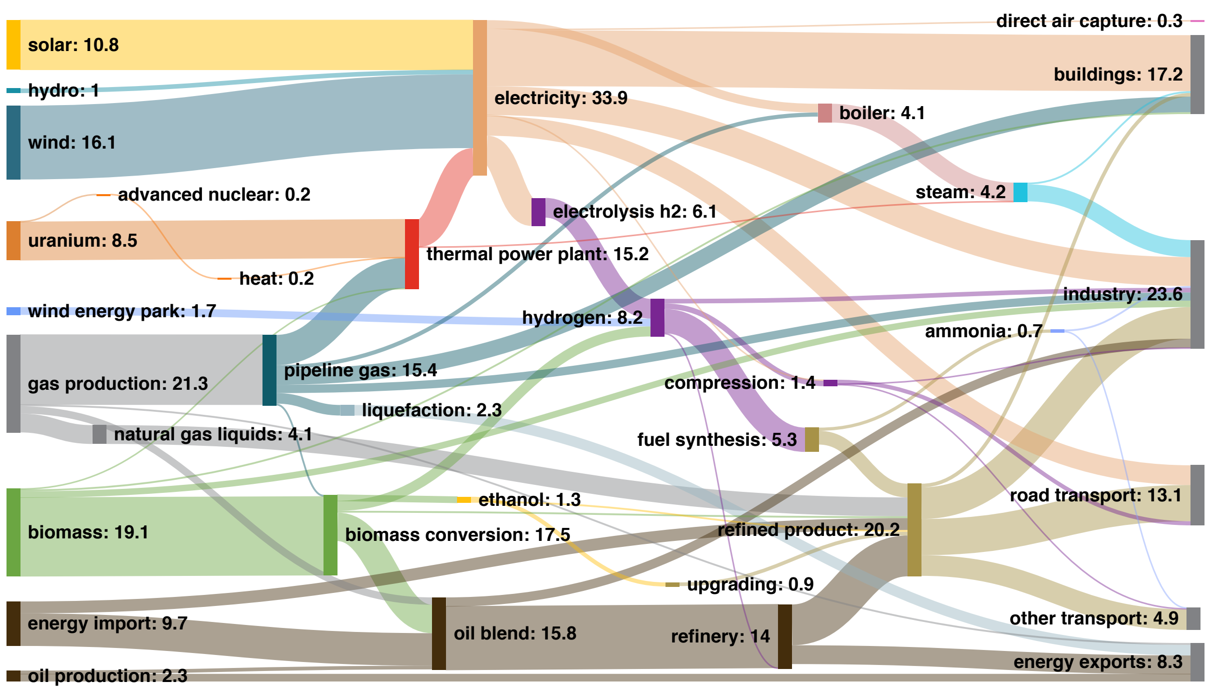
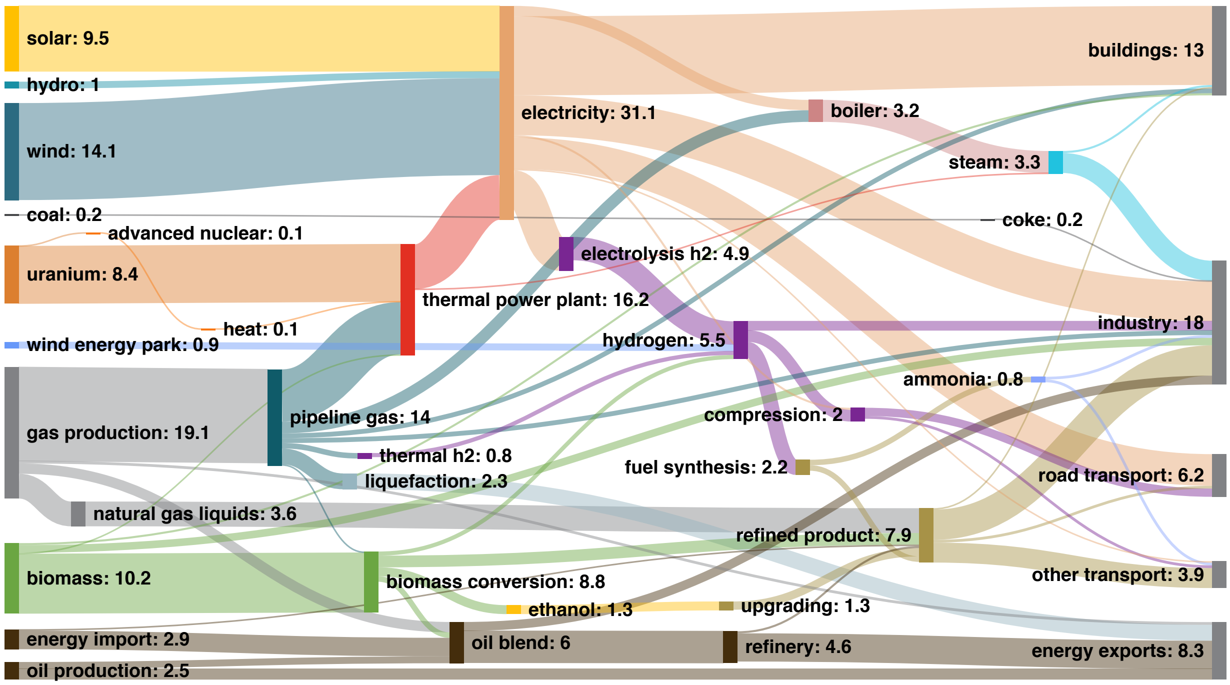


FIGURE 23. Sankey diagram for 2050 Low Demand scenario (Exajoules)



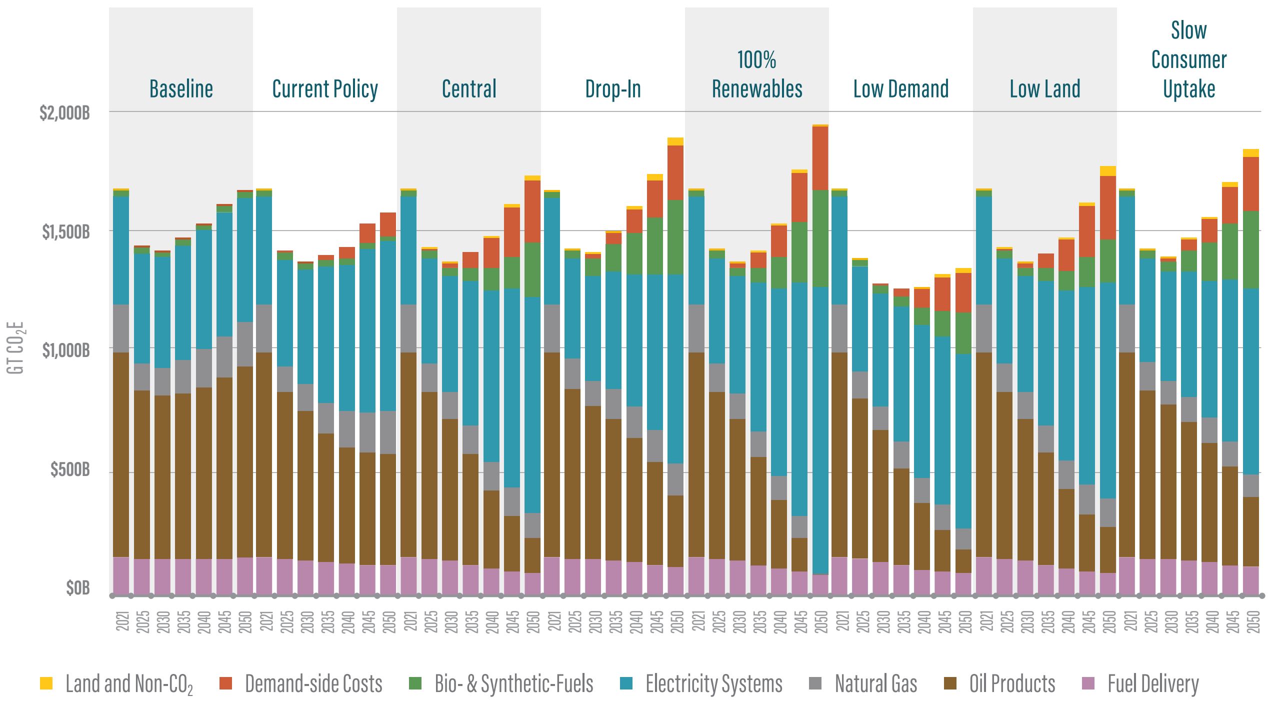
Cost

GROSS COST

The gross annual system cost of the net-zero energy system, plus land sector and non-energy, non-CO_2 mitigation measures, is shown for all scenarios in Figure 24. For energy system costs, this is the annualized cost of capital investments and operating cost for both energy supply (electricity and fuels) and energy end-use technologies (in vehicles, buildings, factories, etc.). Compared to the equivalent figure in ADP 2022, gross energy system cost has increased by roughly 25% due to the difference between 2018 and 2022 dollars. Elevated fuel prices after the invasion of Ukraine are responsible for high energy system costs in 2021.

The lowest cost net-zero scenario in 2050, with one exception, is the **Central** scenario, at $1.73 T/y. The exception is the **Low Demand** scenario at $1.35 T/y, which by definition supplies a lower level of energy services and is therefore not strictly comparable to the other cases (and is not shown in subsequent cost figures for this reason).

FIGURE 24. Annual gross cost of energy and other measures in the transition to net-zero

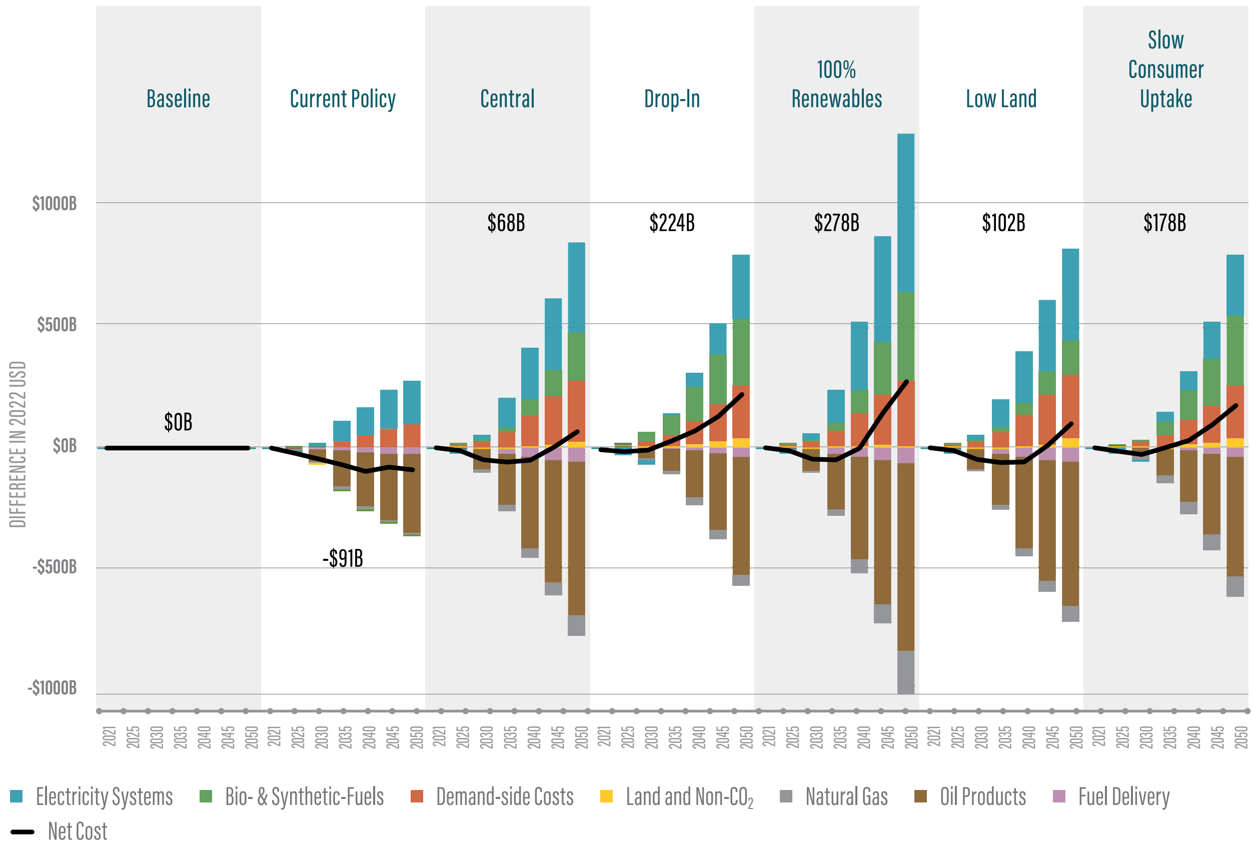


Net cost

In comparison to the **Baseline** scenario's gross cost of $1.67 T/y in 2050, the Current Policy scenario reduces energy system cost by $91B/y in 2050. Strictly speaking this is not entirely a societal cost savings due to spending on the tax credits themselves, but it does translate to a reduction in annual spending on energy by U.S. households and businesses, and subsequently, a reduction in the cost of reaching net-zero in other scenarios. More broadly this reflects a transition in the U.S. energy economy under decarbonization from variable costs toward capital costs. With the exception of biomass feedstock, most costs on the positive side of the net cost curve are fixed costs, and those on the negative side are variable costs.

The **Central** scenario has a net cost of $68B/y above the Baseline level, an increase of about 4%, and $159B/y above the Current Policy level. The main components of this cost difference are shown in Figure 25. In general, the net-zero case has higher capital costs from spending on infrastructure, offset by lower fuel costs relative to the baseline. The **100% Renewables** scenario has a net cost of $278B/y (17% higher than Baseline) and the Drop-In scenario has a net cost of $224B/y (13% higher).

FIGURE 25. Net cost of achieving net-zero greenhouse gases. Costs are net of the Baseline scenario and represent the sum of levelized capital costs and variable costs in each modeled year.



Investments

Figure 26 shows capital investment in selected clean energy supply technologies during the period 2022-2050. Total investment in electricity generation is $4.5T in the Central scenario, and ranges from $3.5T to 7.8T across scenarios, compared to $1.3T in the Baseline. This investment is dominated by wind and solar except in the Drop-In scenario, in which investment in nuclear power is the single largest cost component. Importantly, many of the key technologies needed to reach net-zero are not fully commercialized or widely deployed today, such as DAC and electrolysis. The modeled investment levels in Figure 26 are predicated on nth-of-a-kind technology cost forecasts, for example from the NREL Annual Technology Baseline. Timely and proactive investment in R&D and early commercialization is required to attain the market size and price points implied by these levels of investment.

FIGURE 26. Capital investment (2022-2050) by scenario and technology

			BASELINE	CURRENT POLICY	CENTRAL	DROP-IN	100% RENEWABLES	LOW LAND	LOW DEMAND	SLOW CONSUMER UPTAKE
ELECTRICITY	BECCS Power	$4,000B $2,000B	$1B	$1B	$3B	$11B	$10B	$12B	$4B	$2B
	Electricity Storage	$4,000B $2,000B	$41B	$62B	$196B	$122B	$692B	$291B	$128B	$218B
	Energy Park	$4,000B $2,000B	$0B	$0B	$159B	$238B	$406B	$0B	$97B	$194B
	Gas Power	$4,000B $2,000B	$285B	$410B	$262B	$108B	$317B	$240B	$156B	$80B
	Gas Power w/CC	$4,000B $2,000B	$1B	$2B	$254B	$437B	$1B	$494B	$190B	$219B
	Nuclear	$4,000B $2,000B	$57B	$57B	$62B	$1,331B	$2B	$183B	$59B	$62B
	Offshore Wind	$4,000B $2,000B	$206B	$212B	$245B	$457B	$630B	$625B	$222B	$234B
	Onshore Wind	$4,000B $2,000B	$119B	$536B	$1,656B	$223B	$2,208B	$734B	$1,272B	$1,485B
	Solar	$4,000B $2,000B	$623B	$1,278B	$1,658B	$1,263B	$3,514B	$1,895B	$1,343B	$1,470B
FUEL & CARBON MANAGEMENT	Biofuels	$4,000B $2,000B	$8B	$38B	$801B	$1,266B	$1,425B	$499B	$576B	$1,510B
	Blue H_2	$4,000B $2,000B	$0B	$0B	$27B	$1B	$0B	$83B	$22B	$0B
	DAC	$4,000B $2,000B	$0B	$5B	$1B	$238B	$3B	$83B	$0B	$92B
	Decarbonized Steam	$4,000B $2,000B	$9B	$8B	$76B	$166B	$182B	$135B	$55B	$151B
	E-Fuels Synthesis	$4,000B $2,000B	$23B	$69B	$95B	$113B	$399B	$84B	$83B	$150B
	Electrolysis	$4,000B $2,000B	$5B	$186B	$212B	$157B	$763B	$227B	$193B	$228B
	H_2 Storage	$4,000B $2,000B	$0B	$1B	$2B	$1B	$35B	$2B	$2B	$2B

V COMPARISONS WITH ADP 2022

Overview

Comparing results between ADP 2022 and ADP 2023, four main qualitative differences stand out:

1. The use of gas with carbon capture in the power system did not play a large role in the 2022 results, but does so in the 2023 results
2. Where corn ethanol use declined in the 2022 results, it continues at similar levels to today in the 2023 results due to the advent of new catalysts to upgrade ethanol into jet fuel
3. There is earlier use of hydrogen in the 2023 results
4. There is a reduction in net-zero scenario cost because of the IRA tax credits.

Emissions and Electricity Systems

Figure 27 compares emissions between ADP 2022 and ADP 2023. The differences in geologic sequestration and natural gas gross emissions are noteworthy. ADP 2023 has 843 Mt of carbon sequestration in 2050 compared with 449 Mt last year. That difference comes from captured CO_2 in the power sector from gas generation. The reason for the new competitiveness of gas with carbon capture in these scenarios is first, the new updates from NREL's *Annual Technology Baseline* which provide a new set of costs and performance estimates for new and retrofit gas with carbon capture technologies with very high capture rates. This has reduced the representative costs of these technologies in our model relative to other electricity technologies. The second factor is the IRA tax credits, which do not incent all technologies equally. The Central scenario in ADP 2023 builds 135 GW of gas with carbon capture but only 44 GW in the Central no IRA sensitivity where all tax credits are removed.

Also seen are small differences in the modeled trajectory of the land sink. This stems both from the establishment of a new baseline, the relaxation of the 50% by 2030 emissions target, and from the fact that IRA tax credits reduce the marginal cost of CO_2 in the 2030s under an emissions cap. The impacts from the depressed CO_2 price in a cost optimized system are not immediately obvious, but it means that CO_2 reduction measures for things not explicitly targeted by IRA decrease in competitiveness against those measures that do receive tax credits. Broad enhancement of the land sink is one item that declines under those criteria.

A second measure that declines under these criteria is the shutting of coal power plants, which while addressed indirectly through various mechanisms is not as strongly incentivized as other emissions reduction strategies. The impact of this can be seen in Figure 27 with slightly higher emissions from coal and in Figure 28 with a longer tail of coal capacity that gets operated for a smaller number of hours each year.

FIGURE 27. Gross greenhouse gas emissions compared between ADP 2022 and 2023, Central scenario

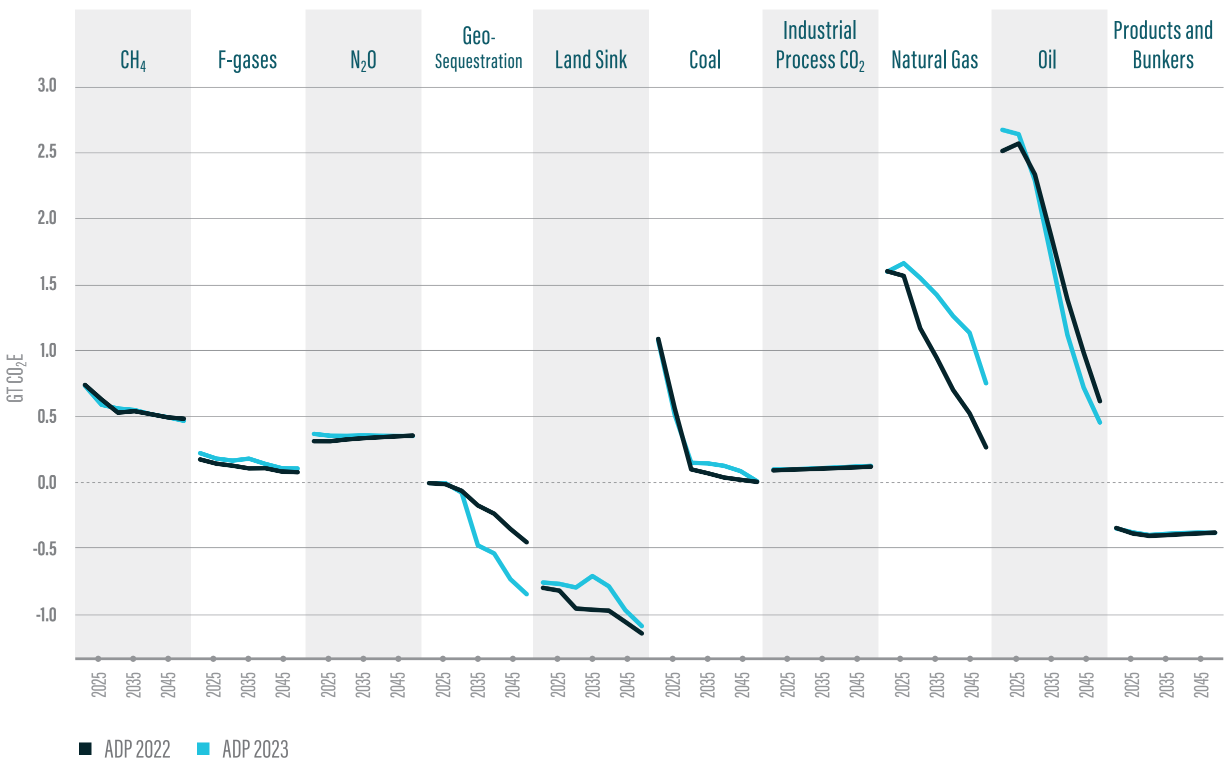


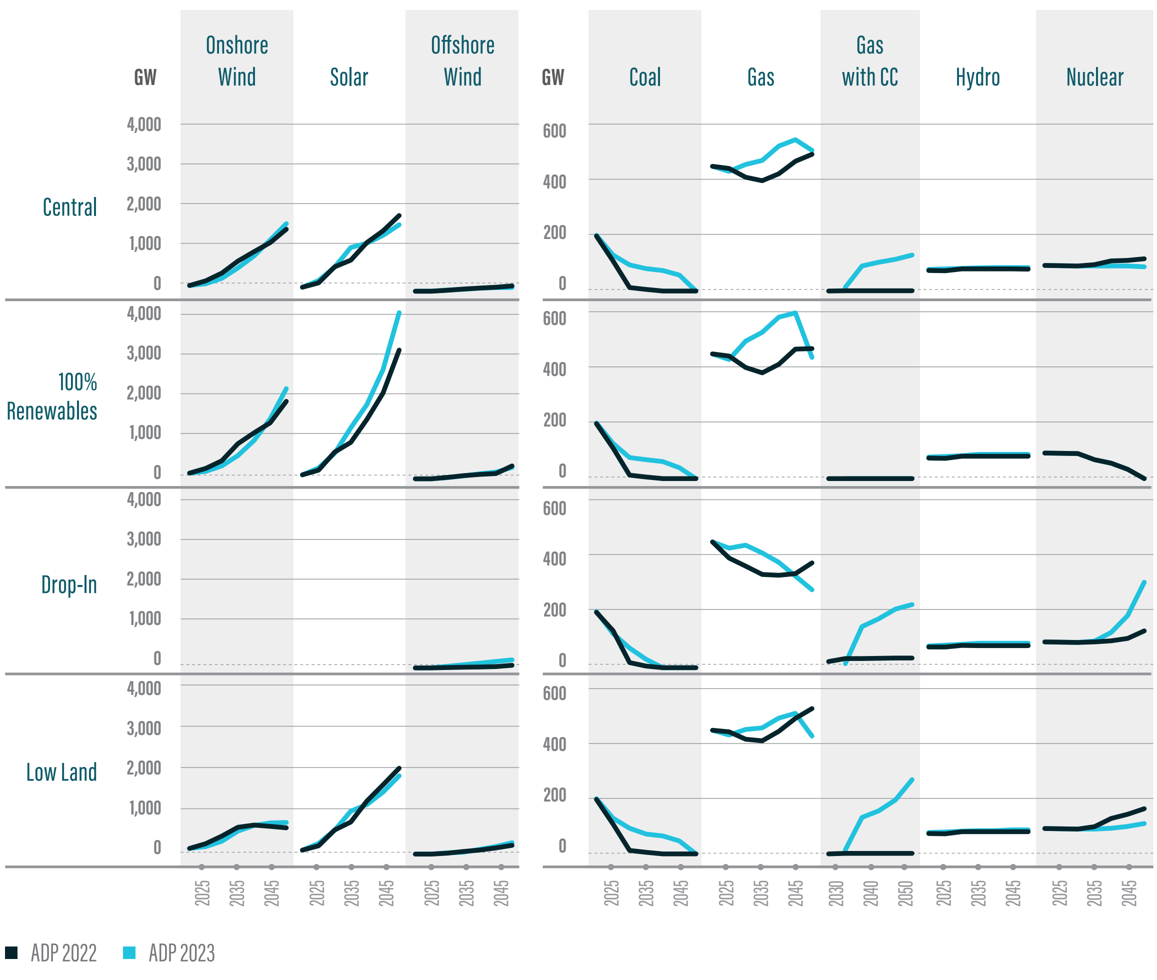
Figure 28 provides a comparison of electricity capacity across multiple technologies, with wind and solar on the left side of the figure and other technologies shown with a different axis on the right side. Trends mentioned above, such as the increase in gas with carbon capture, and slower retirement for coal, are apparent. Other differences include a larger build of nuclear in the Drop-In scenario due to changes in the scenario definition and the constraints put on onshore wind; and, higher wind and solar build in the **100% Renewables** scenario to provide clean fuels for export (ADP 2022 simply assumed exports went to zero in this scenario).

Each of these changes raise new research questions to be investigated. In the case of coal, a slower transition adds realism often missing from pathways that assume that all coal retires this decade. At the same time, this coal cannot run with any frequency if emissions targets are to be met. Whether operating this coal as an intermittent peaking resource can be achieved economically and technically is an open question.

Likewise, the operation of gas with carbon capture in a high renewables system raises questions about the flexibility of these resources and whether achieving the necessary flexibility will result in additional capital costs that ultimately make the resources uncompetitive.

One further implication for the inclusion of more “clean firm” resources in ADP 2023 is that the long-term competitiveness of certain sectoral coupling strategies has fallen. This includes electric steam production and e-fuel production, both of which are reduced in ADP 2023.

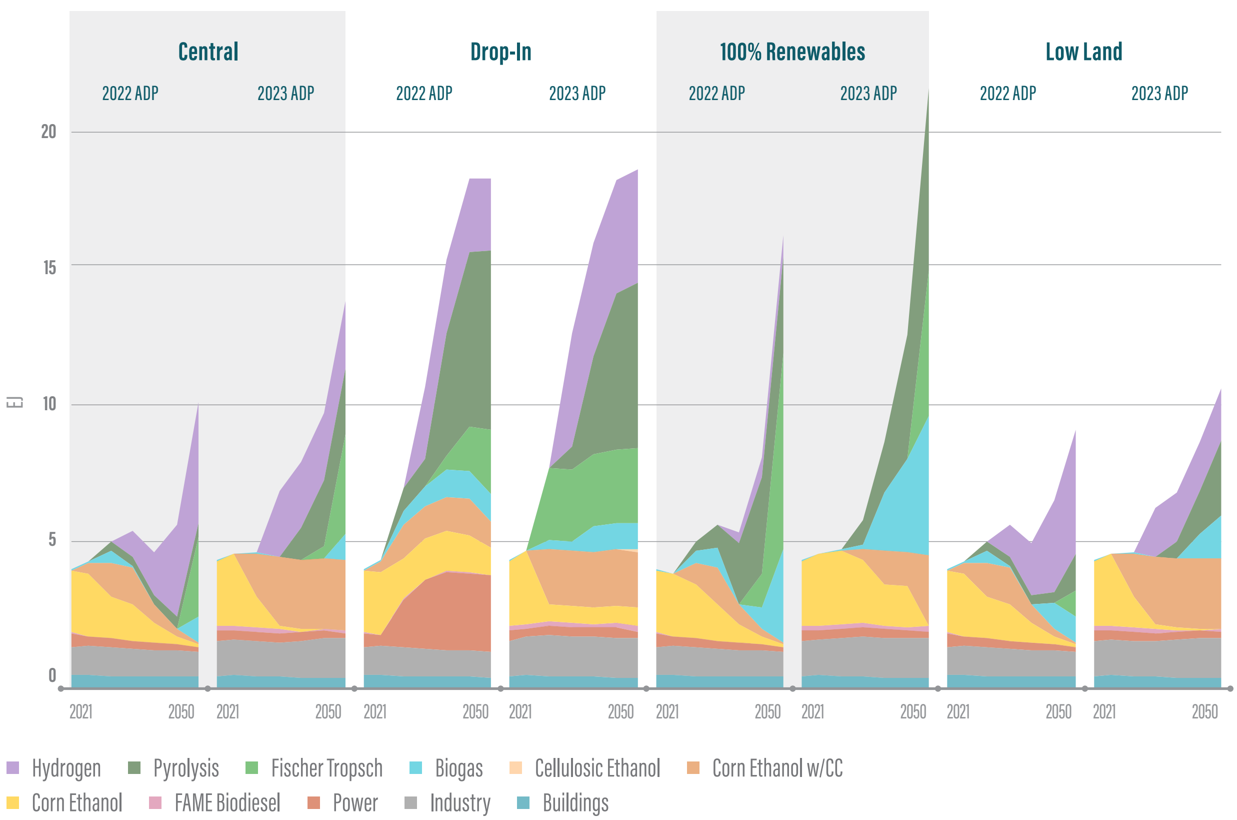
FIGURE 28. Electricity capacity compared between ADP 2022 and 2023



Biomass

The significant differences between ADP 2022 and ADP 2023 with respect to biomass are primarily driven by the ongoing production of ethanol from corn and the use of new technology to cost efficiently produce sustainable aviation fuel from this ethanol. This change is discussed further in the Modeling Updates section of the report. The net result is shown in Figure 29 where overall biomass consumption increased across all scenarios. This runs counter to longer term trends in our modeling work where biomass use in low carbon pathways has generally trended lower as other primary energy sources (namely, renewables for producing e-fuels) have seen expected costs revised downward. Other biomass applications between ADP 2022 and 2023 have not seen dramatic changes. One exception is in the Drop-In scenario where biomass that had been used in the power sector has been diverted to hydrogen and biofuel applications (but with little overall change in biomass demand).

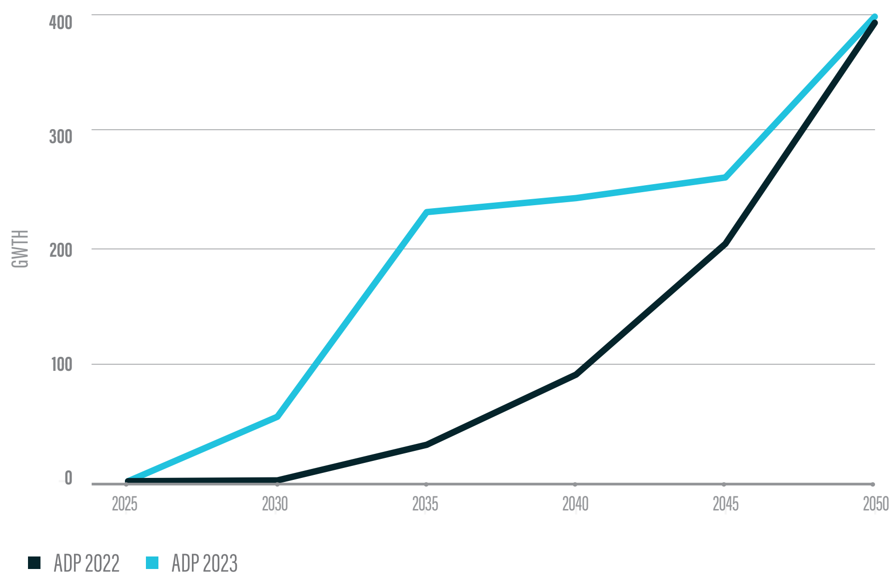
FIGURE 29. Biomass use compared between ADP 2022 and 2023



Hydrogen

A final difference between ADP 2022 and ADP 2023 comes in the acceleration of the hydrogen industry due to the IRA tax credits. Figure 30 shows the capacity of electrolyzers in the Central scenario. Notably, while both reach similar places in 2050, ADP 2023 builds these electrolyzers roughly a decade sooner. Excessive electrolysis load when renewable penetrations are too low can increase emissions by diverting electricity that would otherwise reduce thermal generation towards the production of hydrogen, which is a less efficient application. That said, as clearly demonstrated, the IRA tax credits will help spur an industry that will be critical in the long-term for reaching net-zero targets.

FIGURE 30. Hydrogen electrolysis capacity compared between ADP 2022 and 2023 Central scenarios



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VII SUPPLEMENTAL RESULTS

Scenario Results

PRIMARY ENERGY

FIGURE 31. Primary energy consumed domestically across scenarios

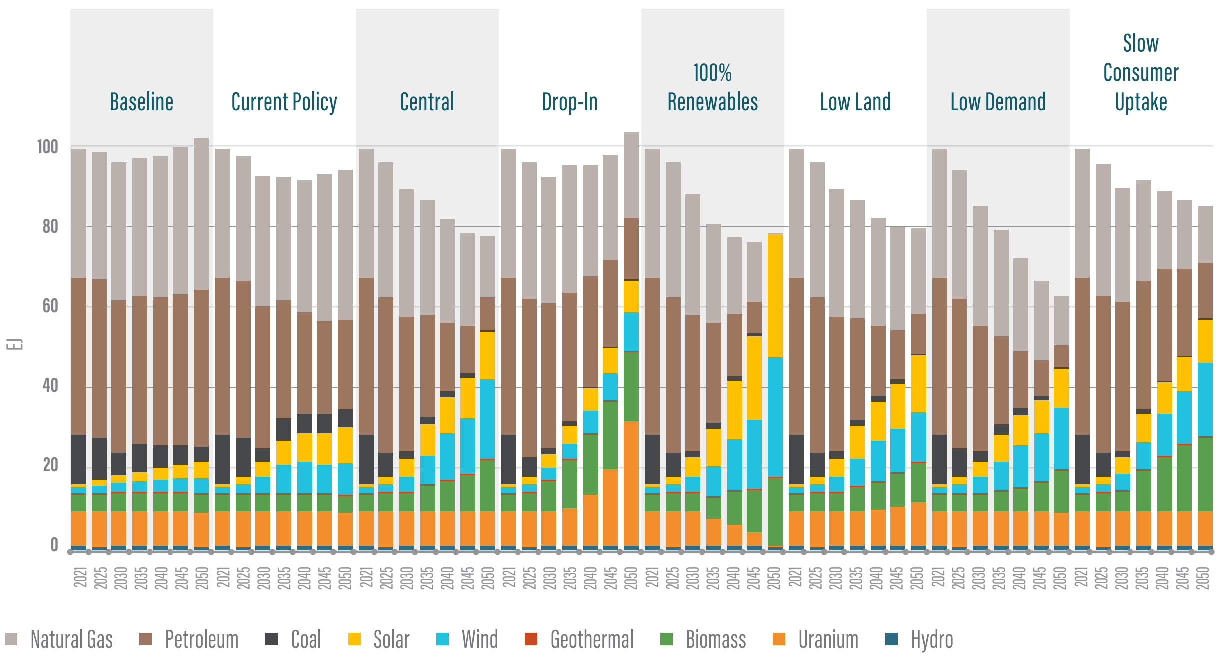
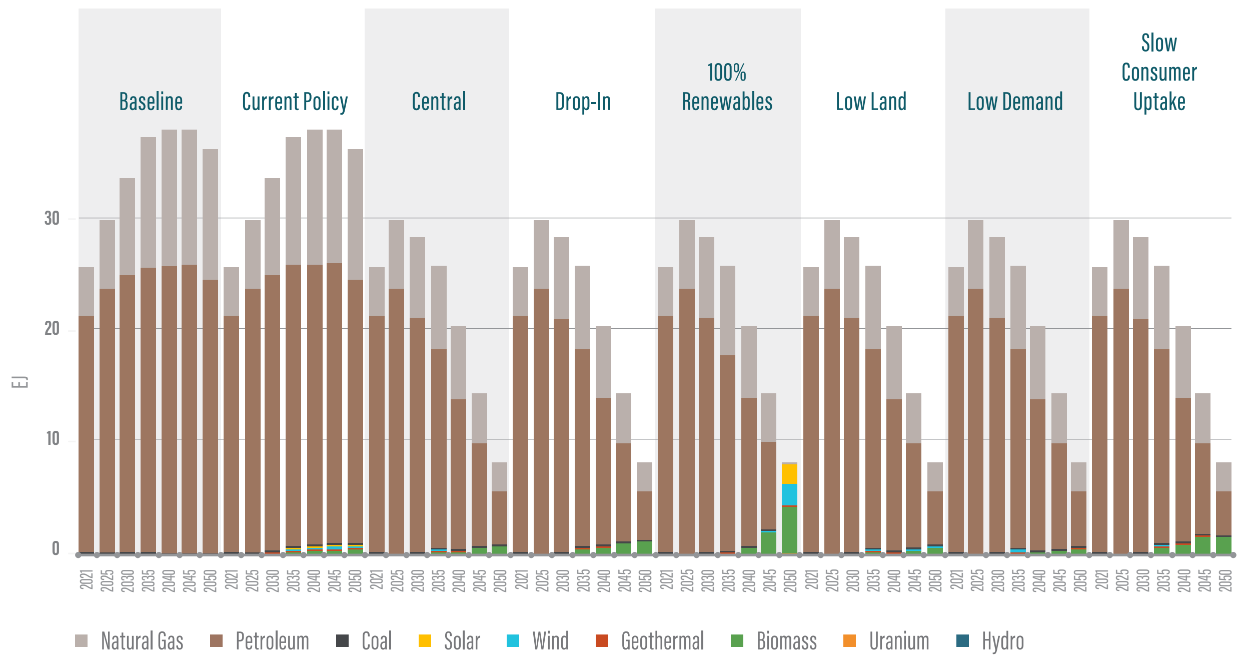
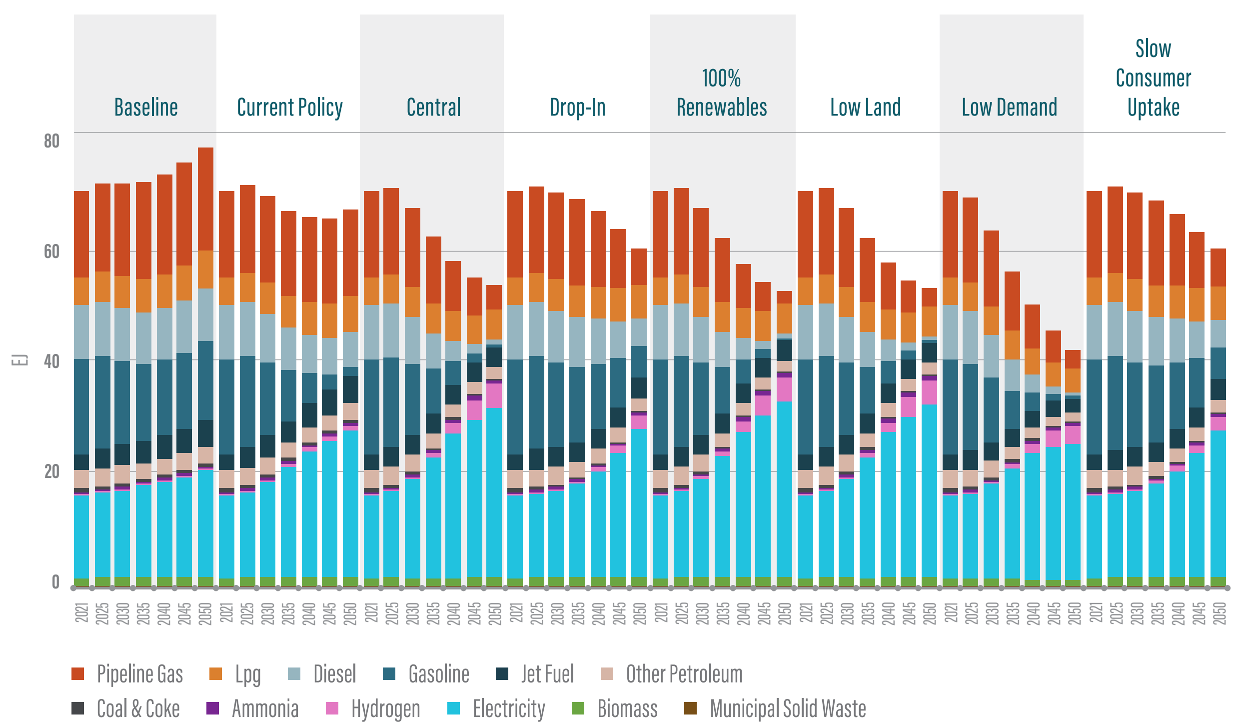


FIGURE 32. Primary energy represented in energy exports across scenarios



FINAL ENERGY

FIGURE 33. Final energy demand by fuel type



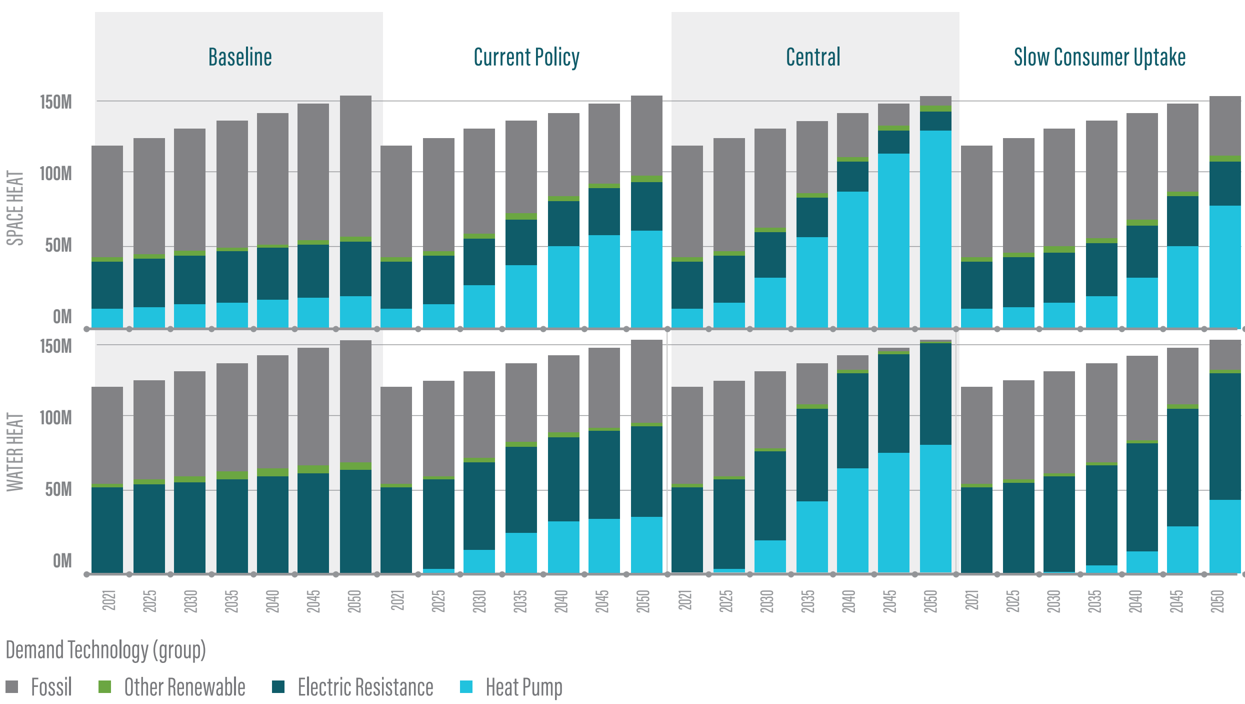
HEALTH BENEFITS

FIGURE 34. Health benefits from reductions in air pollution relative to the Reference scenario

DEMAND TECHNOLOGIES

FIGURE 35. On road transportation vehicle stock

FIGURE 36. Residential building heating technologies



ELECTRICITY

FIGURE 37. Electricity generation

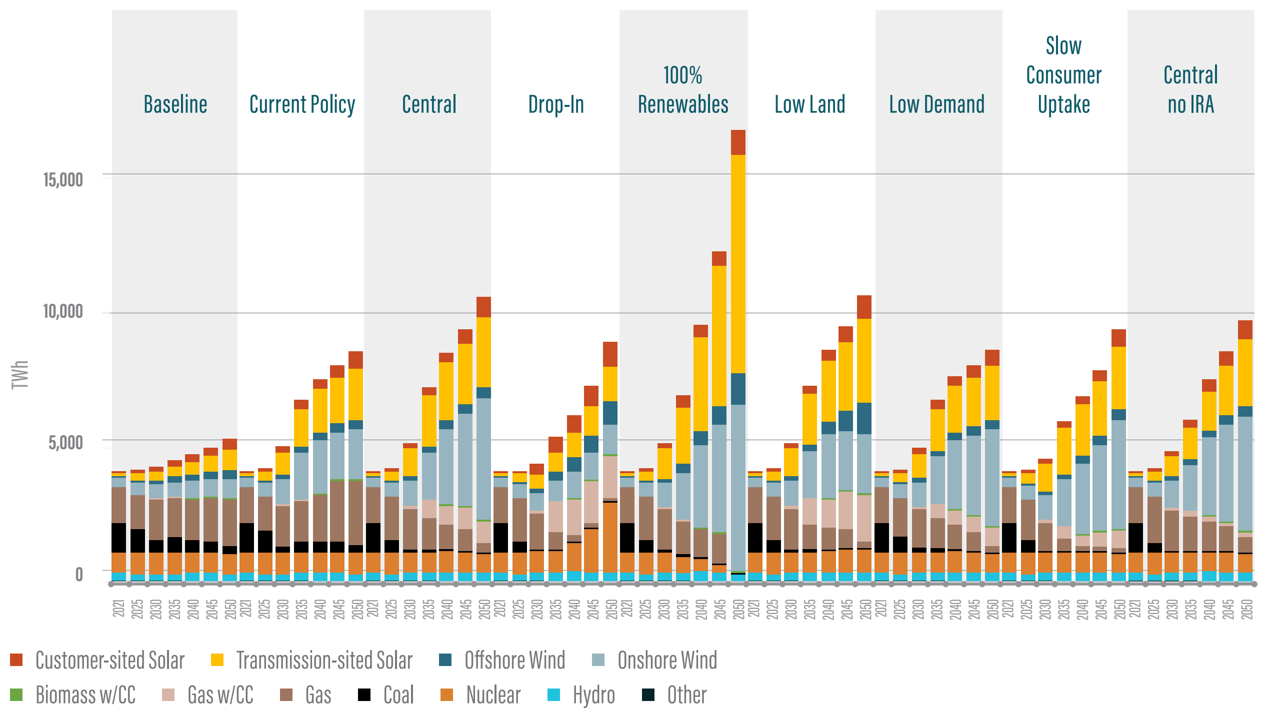


FIGURE 38. Electricity generation capacity

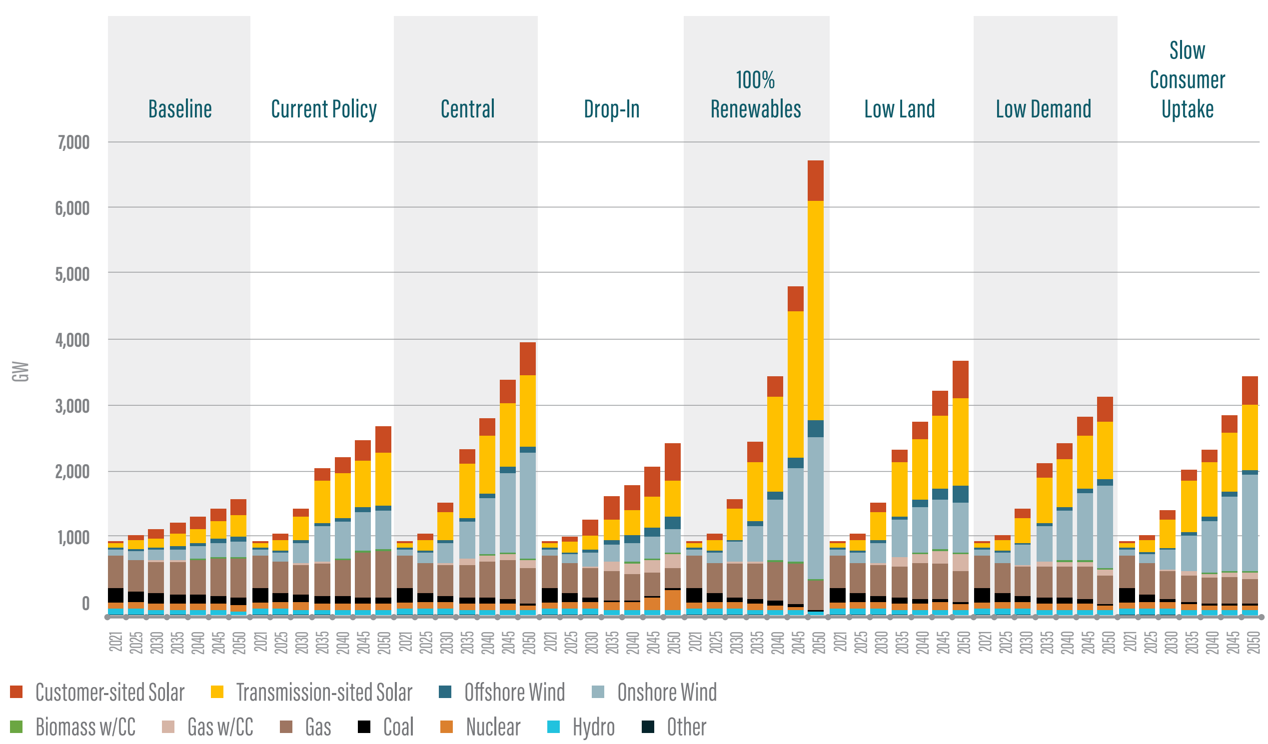
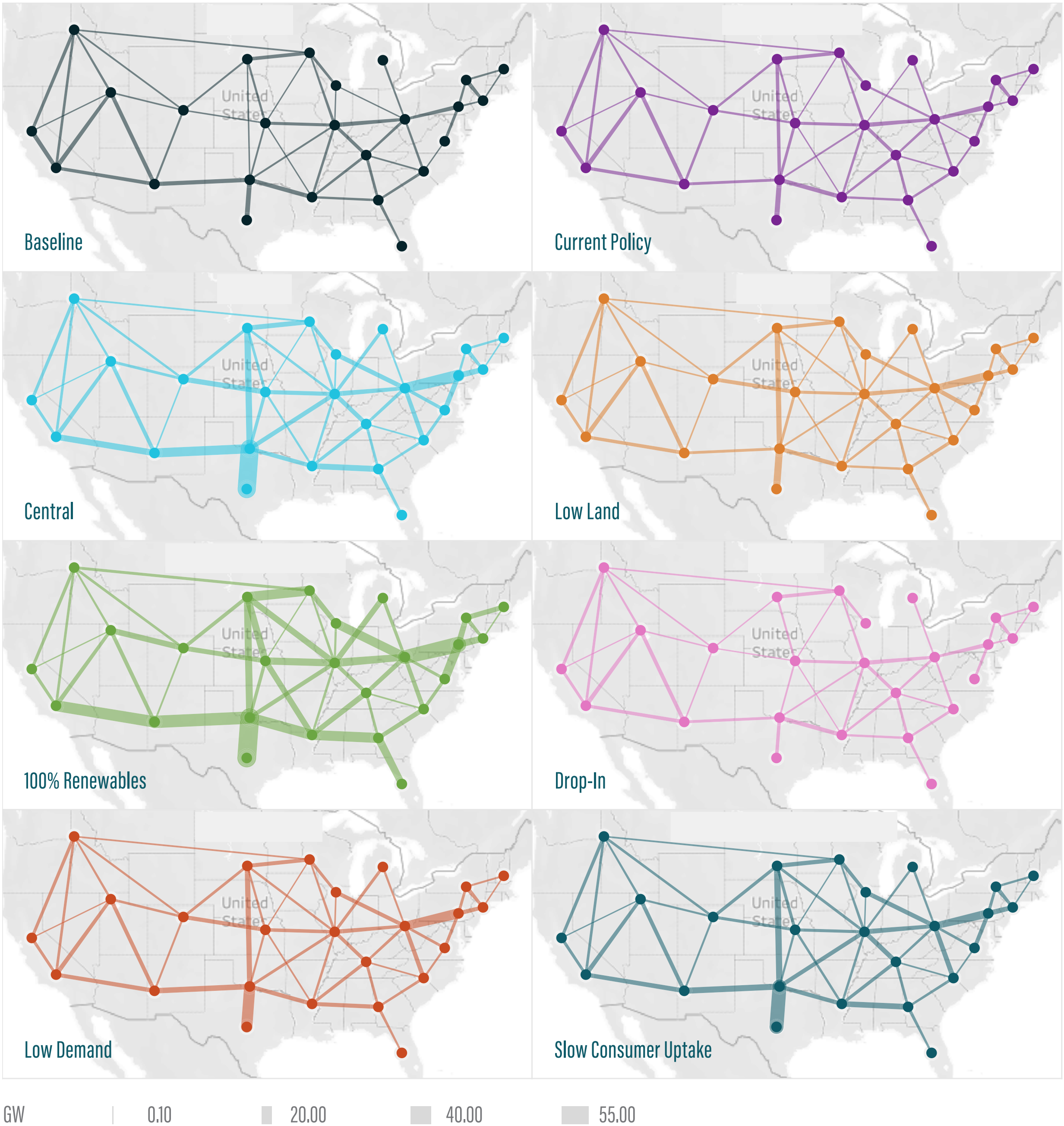
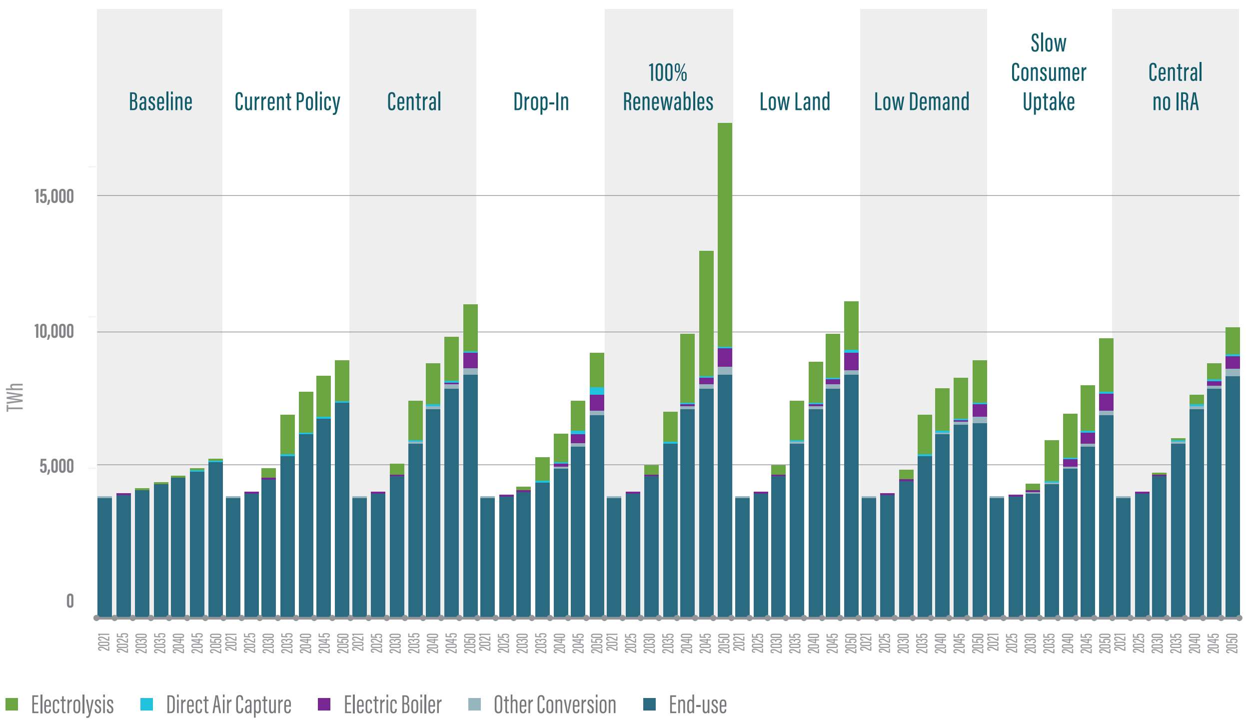


FIGURE 39. 2050 Electric transmission capacity



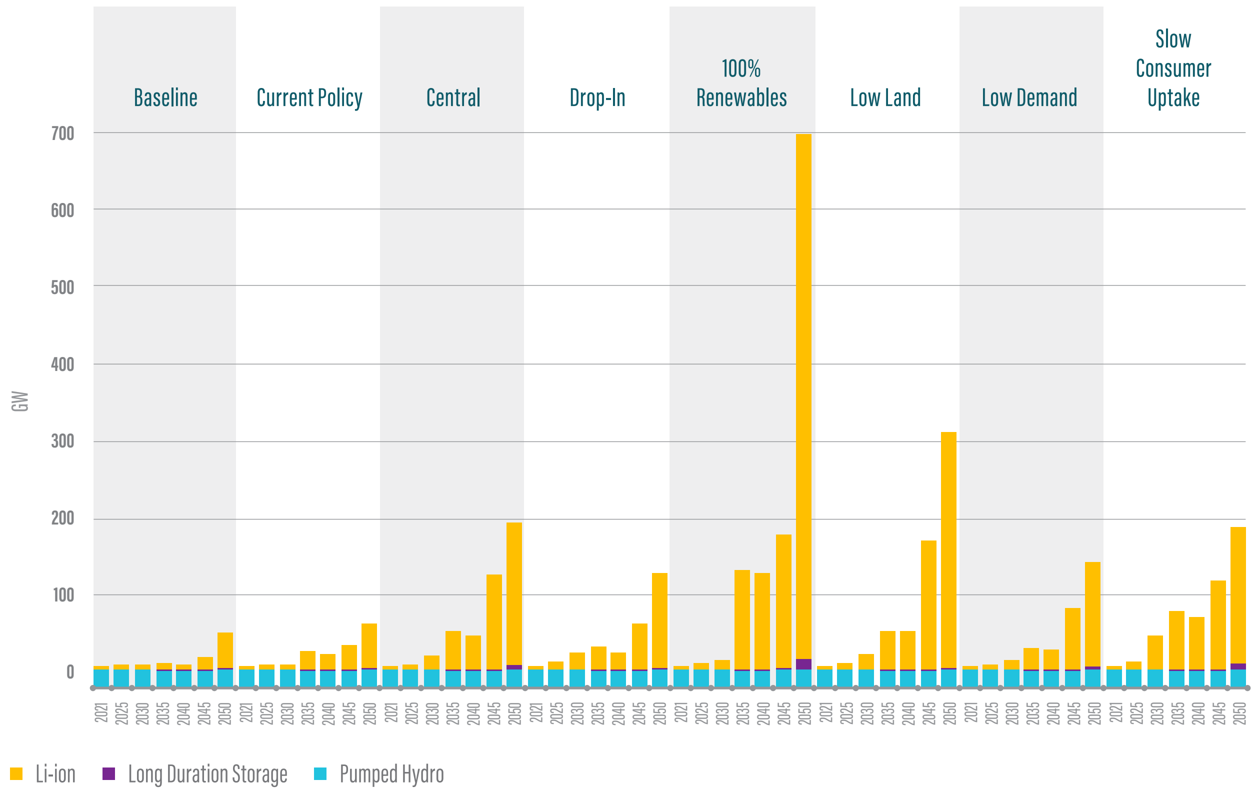
ELECTRIC LOAD

FIGURE 40. Electric Load



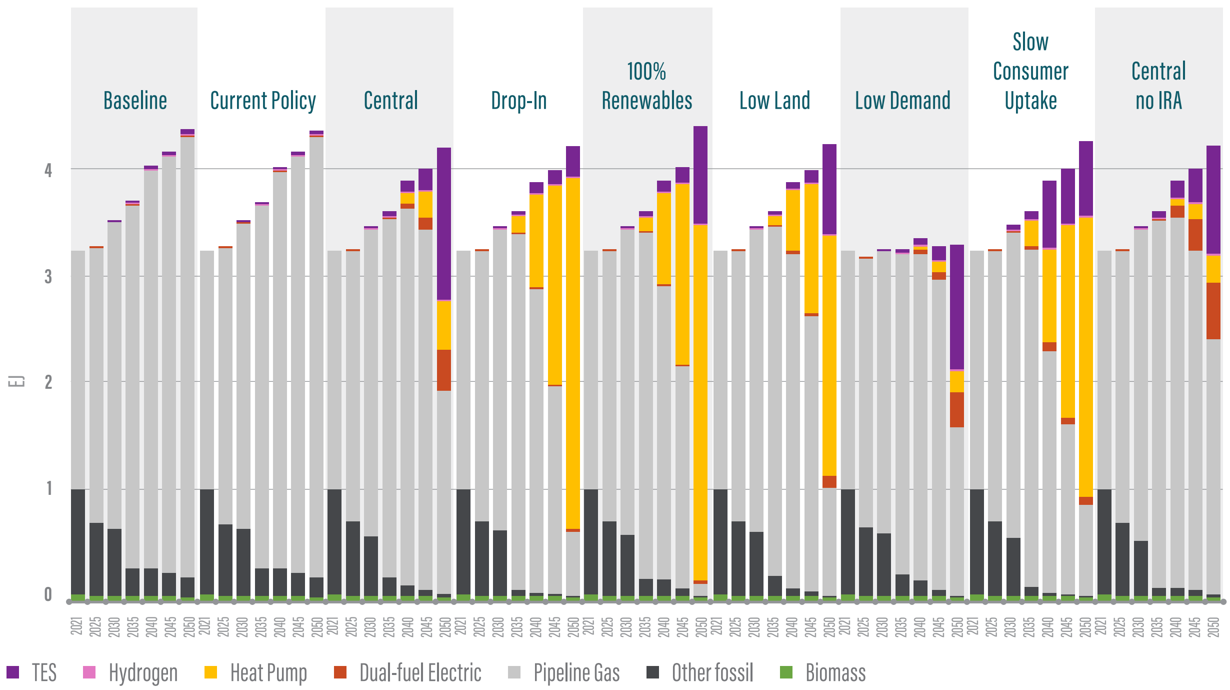
STORAGE

FIGURE 41. Electricity storage capacity between scenarios



STEAM

FIGURE 42. Steam production by technology across scenarios



HYDROGEN

FIGURE 43. Hydrogen production

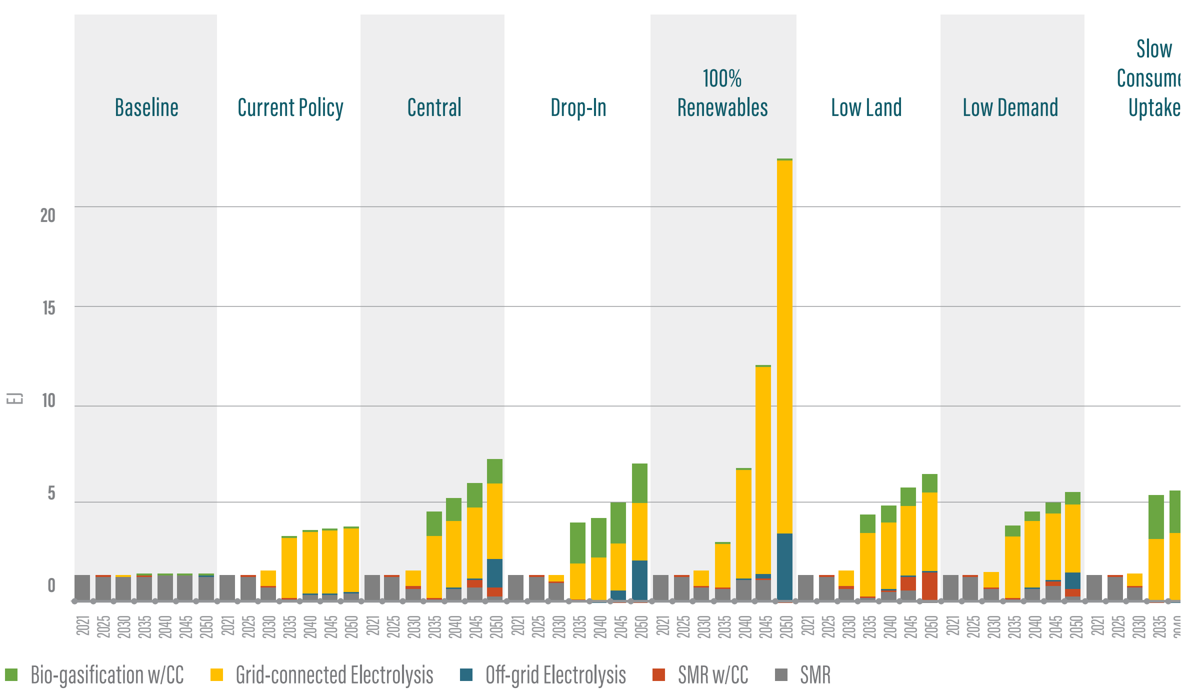


FIGURE 44. Hydrogen consumption

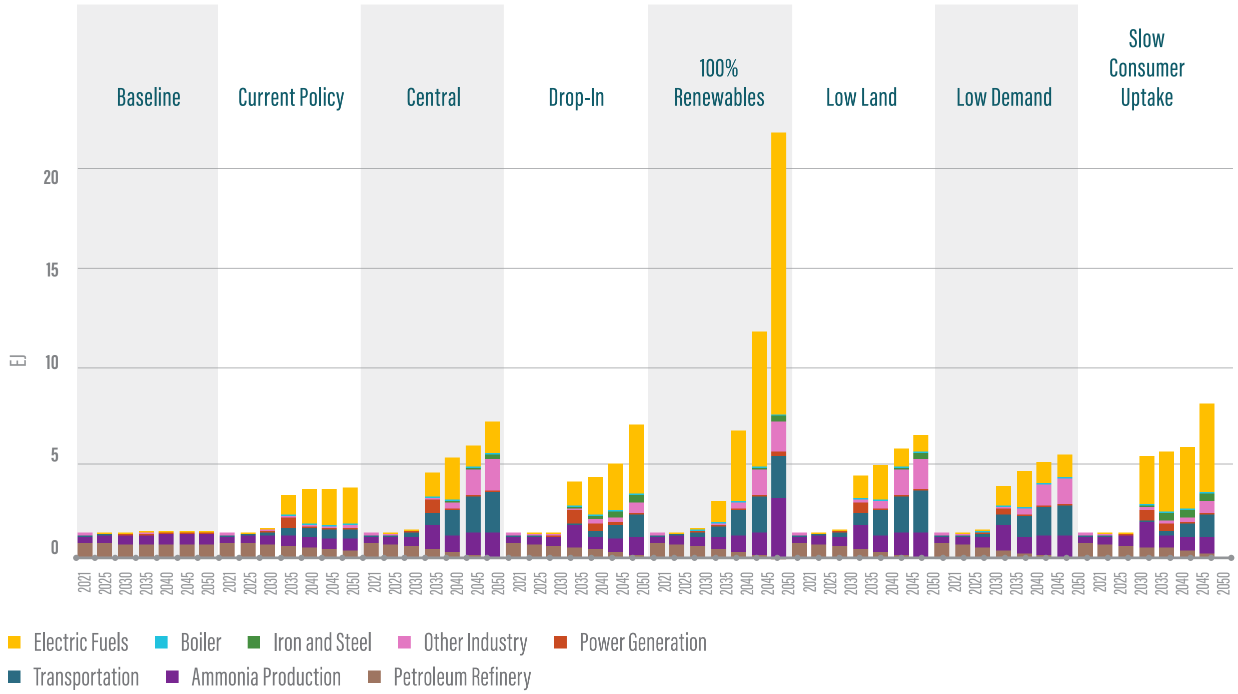
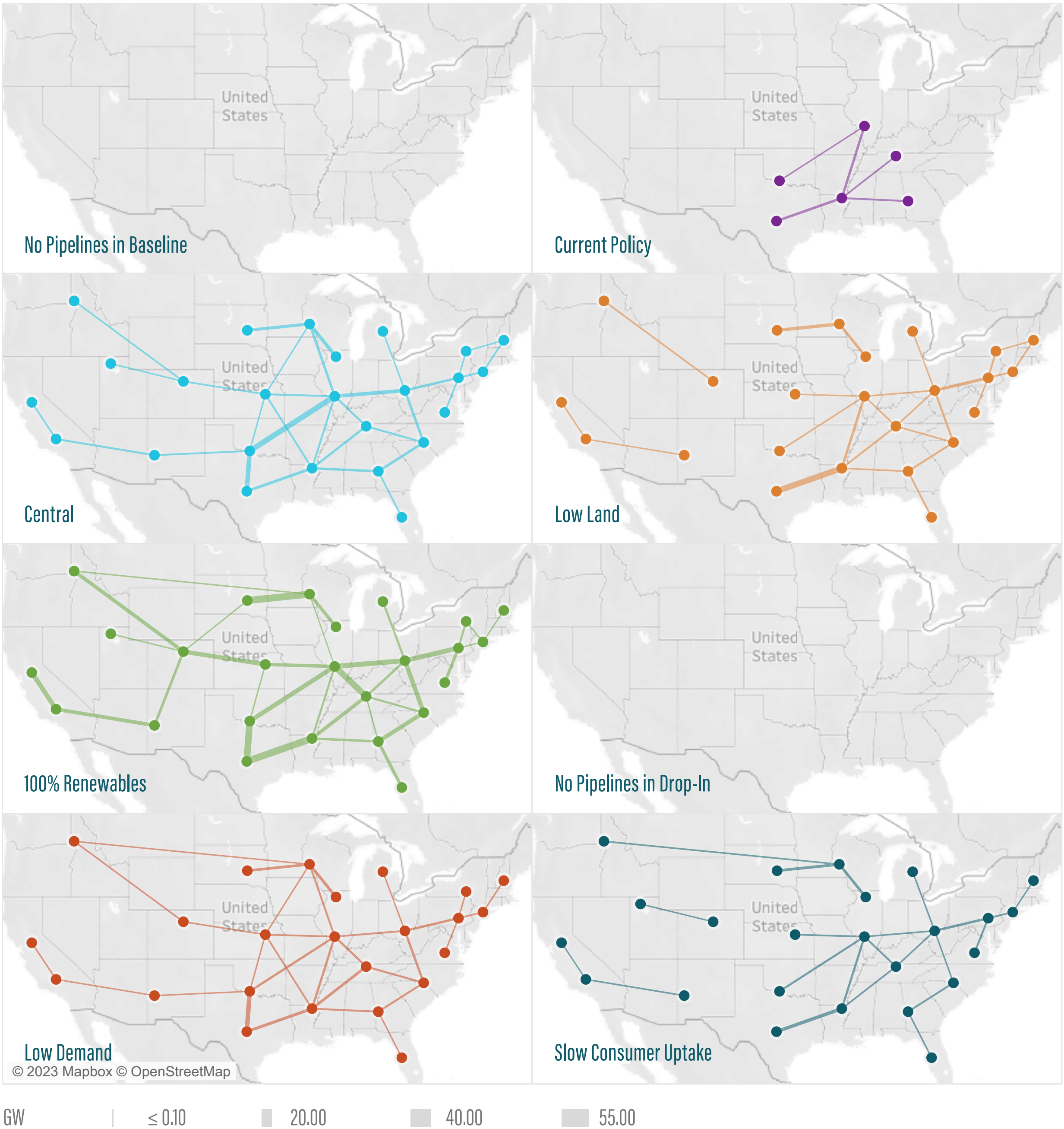
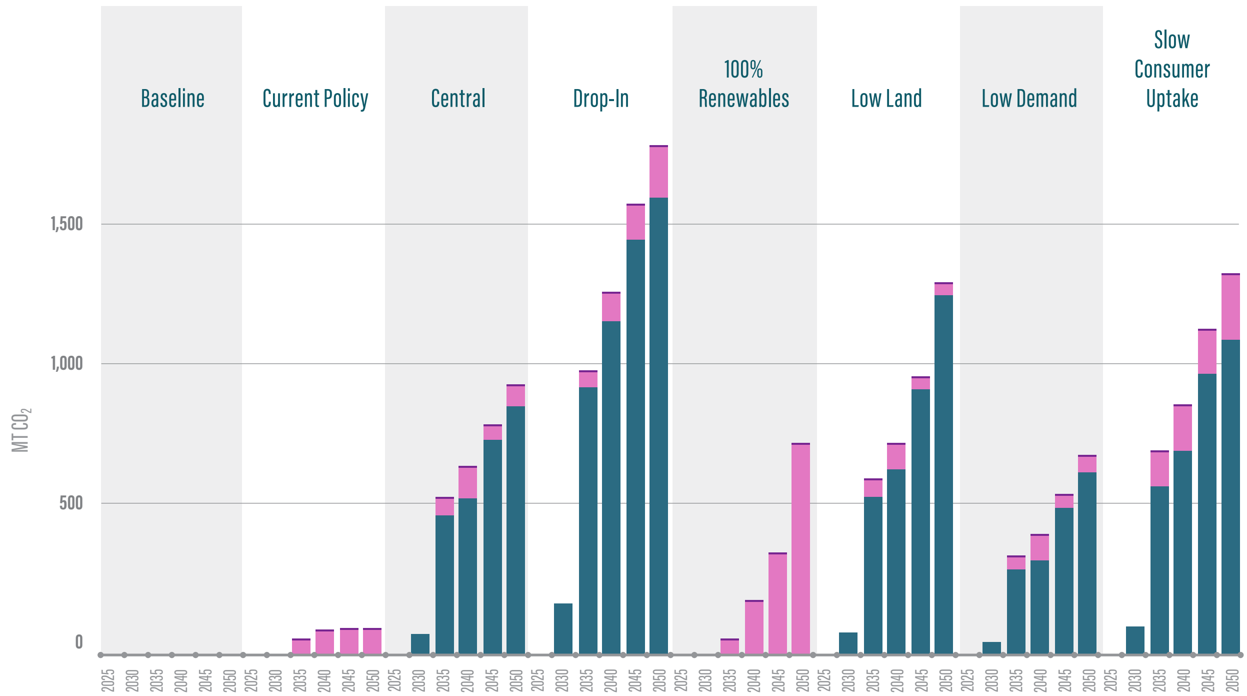


FIGURE 45. 2050 Hydrogen pipelines comparisons between scenarios. Pipelines smaller than 500 MW capacity have been removed from the visual.



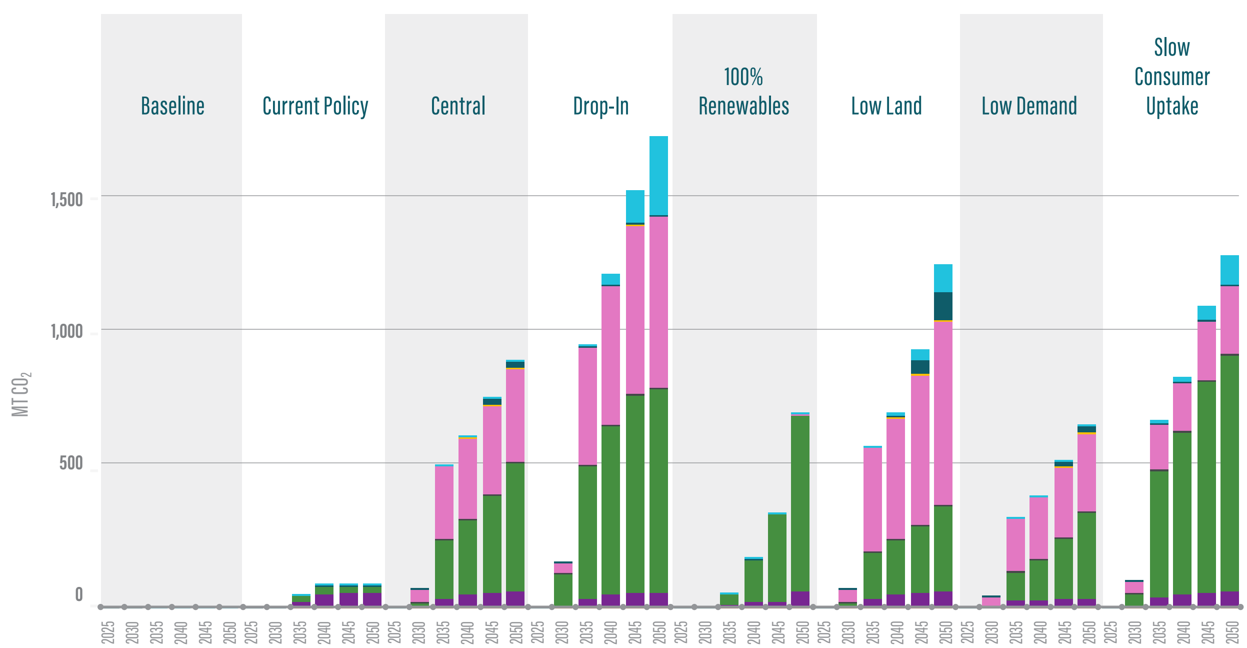
CCUS

FIGURE 46. Carbon capture application



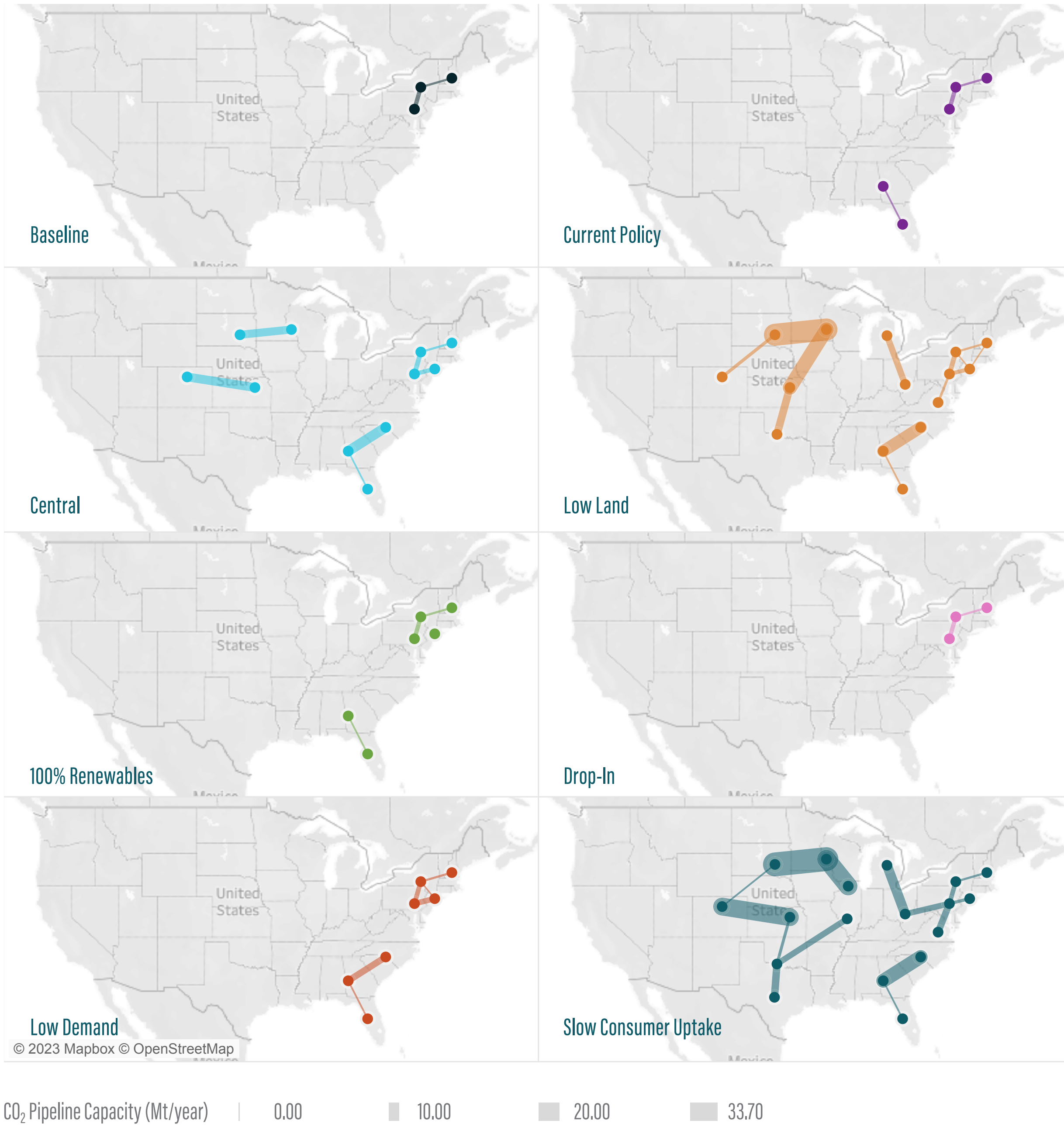
CCU: Gas CCU: Liquids CCS

FIGURE 47. Carbon capture source



Direct Air Capture Blue Hydrogen Power Generation: Bio Power Generation: Gas
Power generation: Coal Biofuels Cement and Lime Iron and Steel

FIGURE 48. CO_2 pipeline capacity in 2050



HYDROCARBON FUELS

FIGURE 49. Hydrocarbon fuel supply

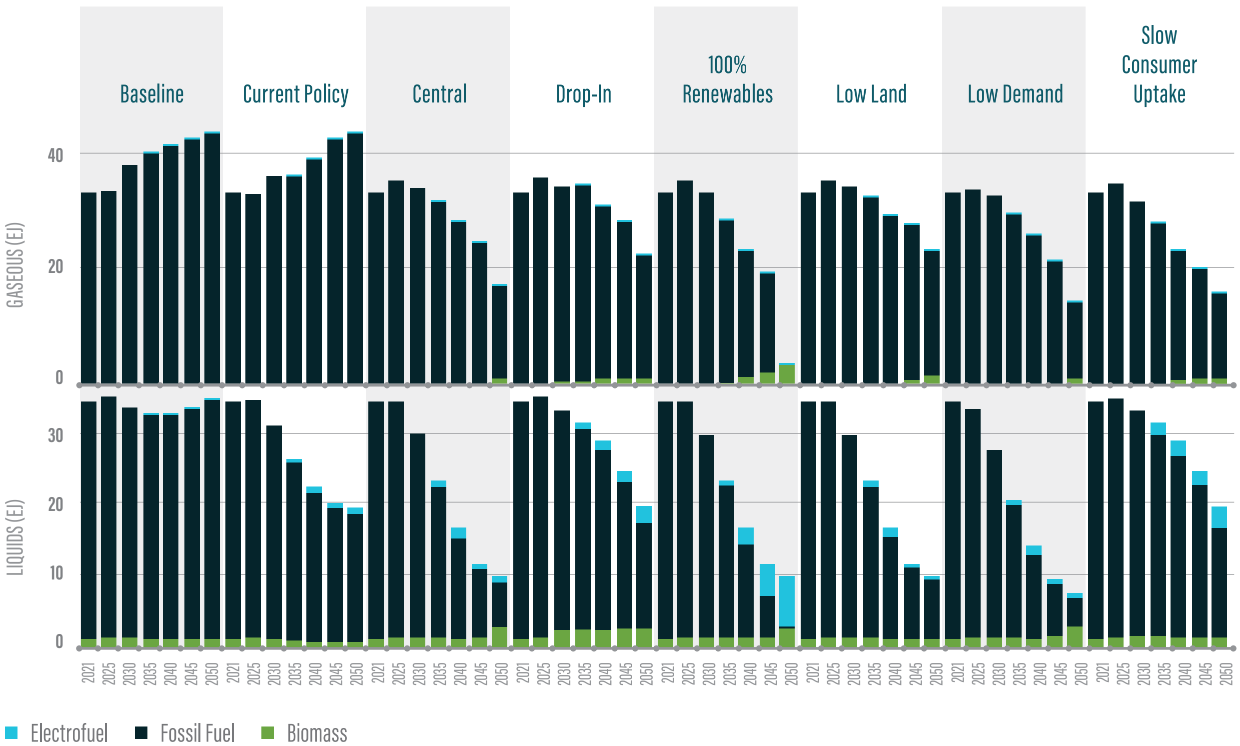


FIGURE 50. Hydrocarbon fuel demand

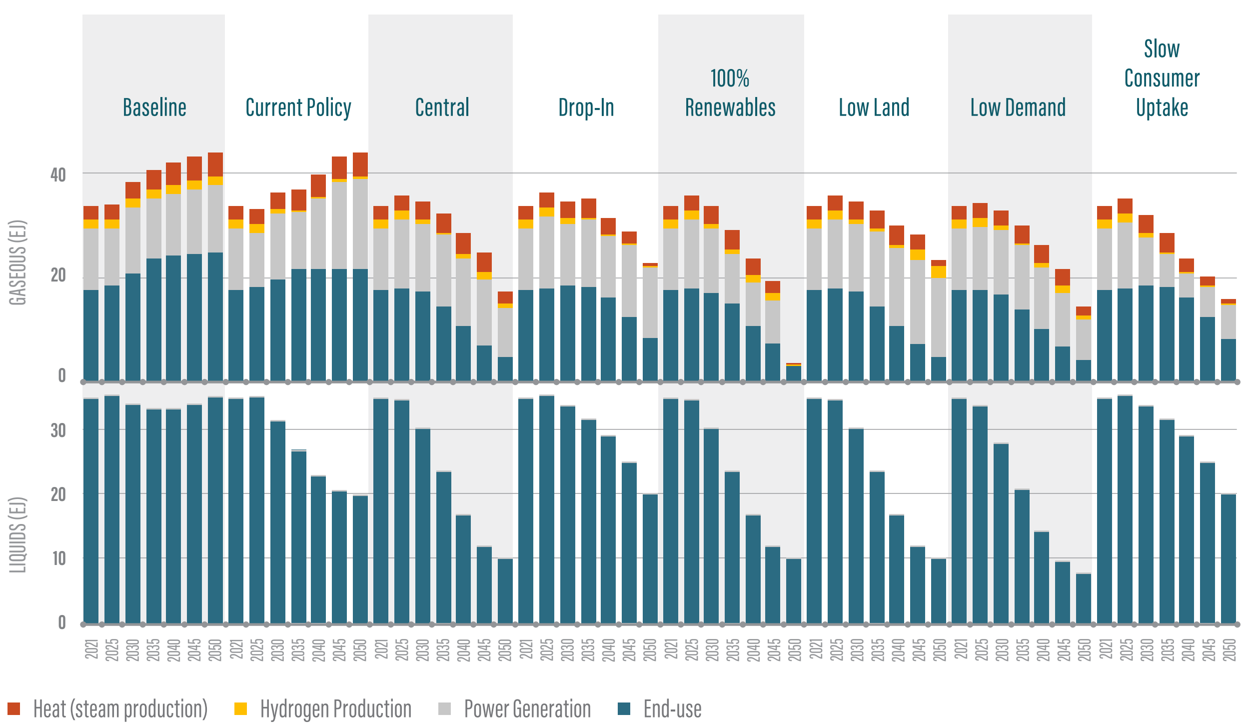


FIGURE 51. Hydrocarbon production capacity

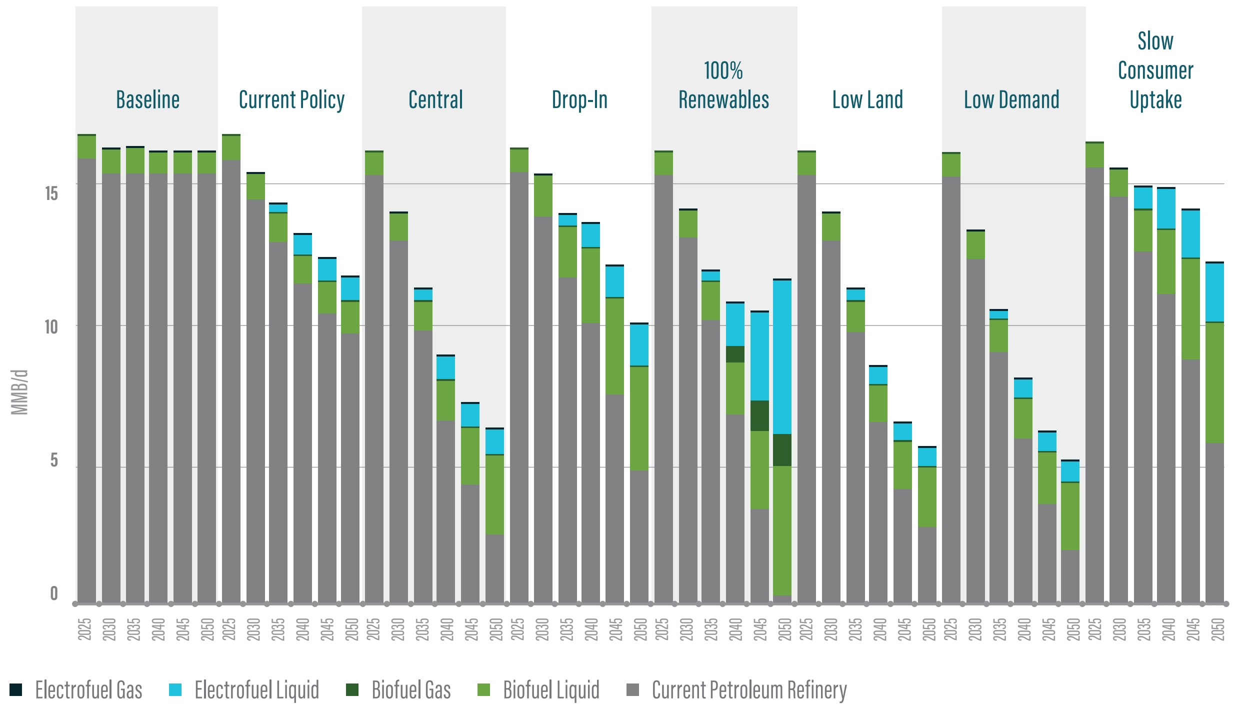
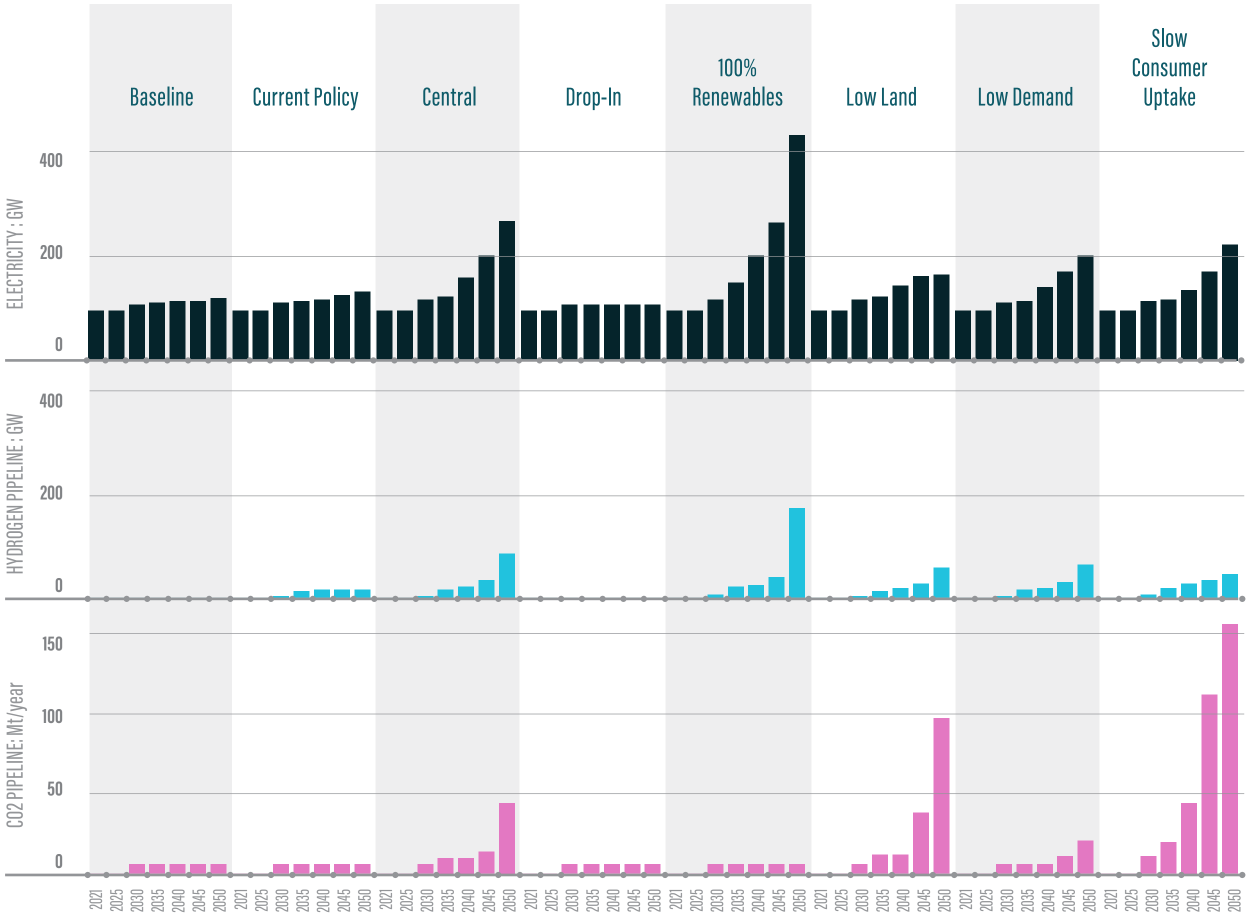
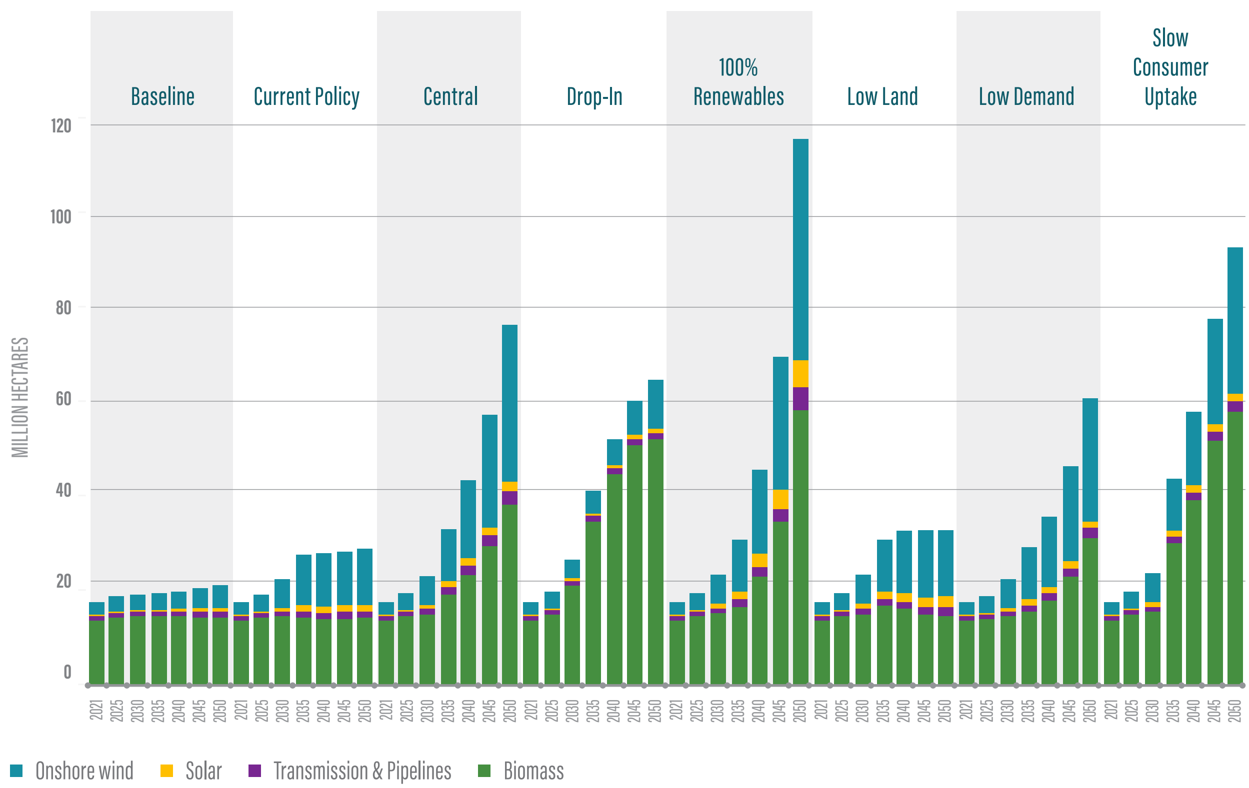


FIGURE 52. Energy transport capacity: electricity transmission, hydrogen pipeline, and CO_2 pipeline



LAND USE

FIGURE 53. Land use for energy infrastructure



Sub-Annual Snapshots

ELECTRICITY OPERATIONS

FIGURE 54. Generation share of U.S. electricity by day of the year and scenario

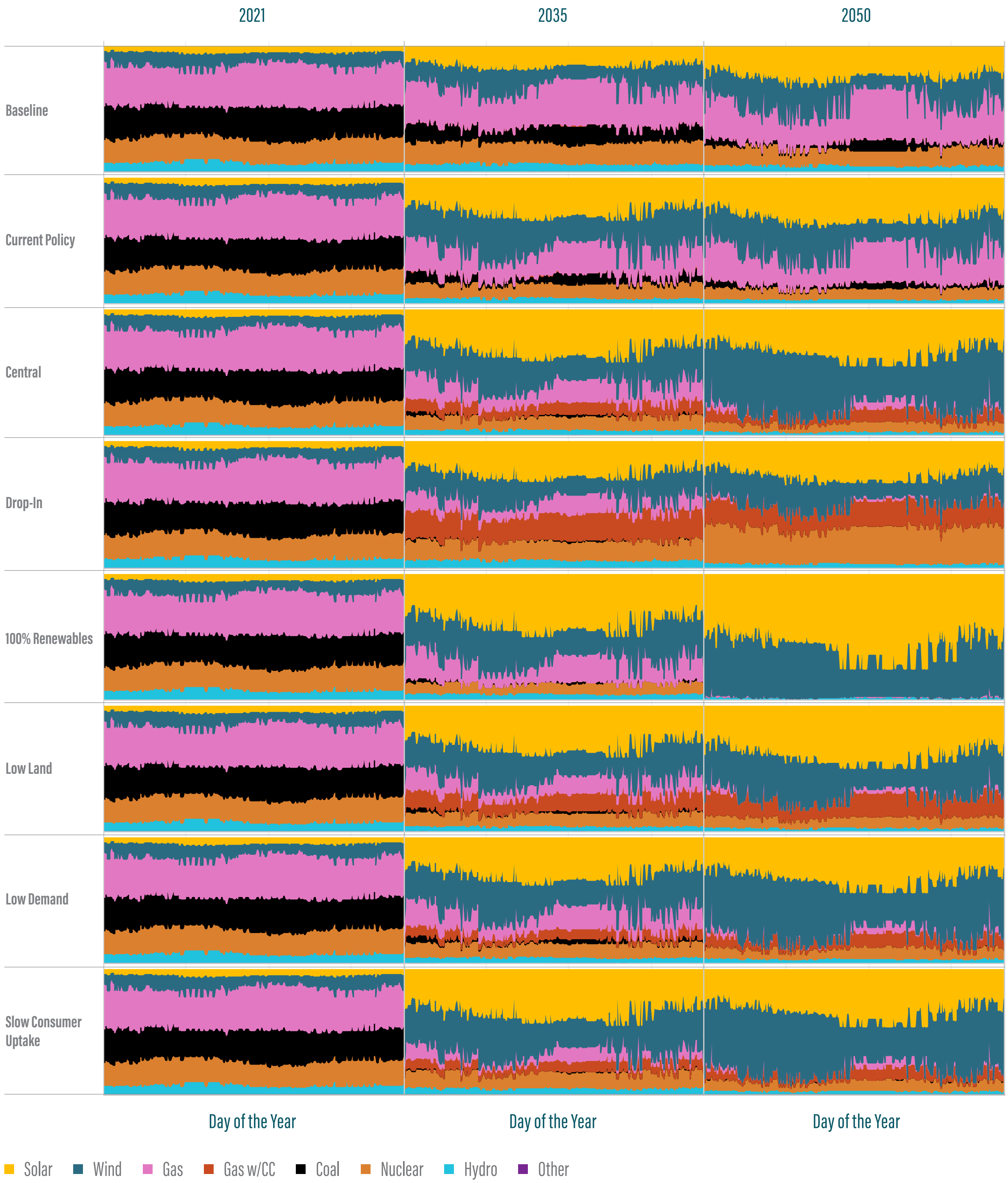
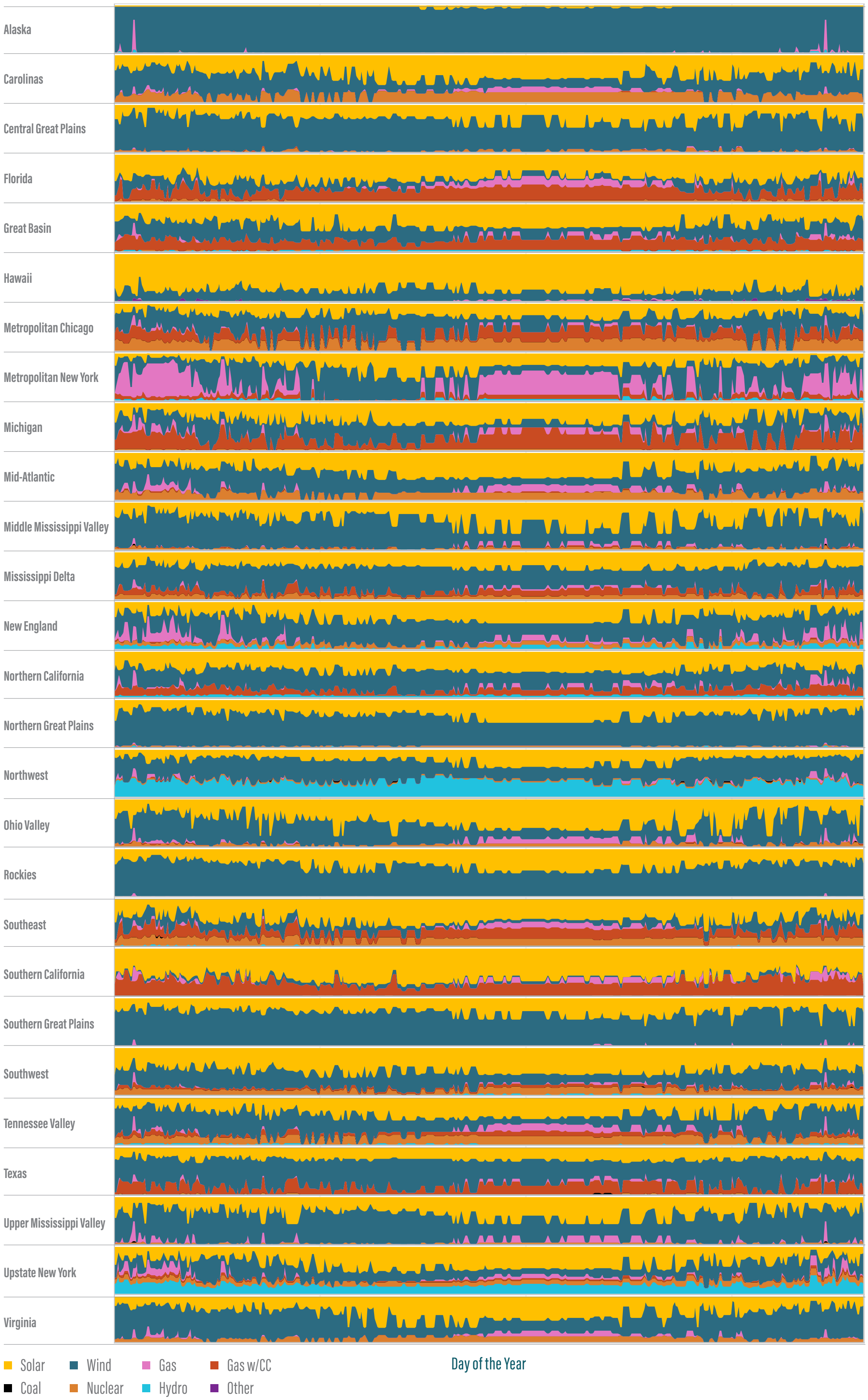


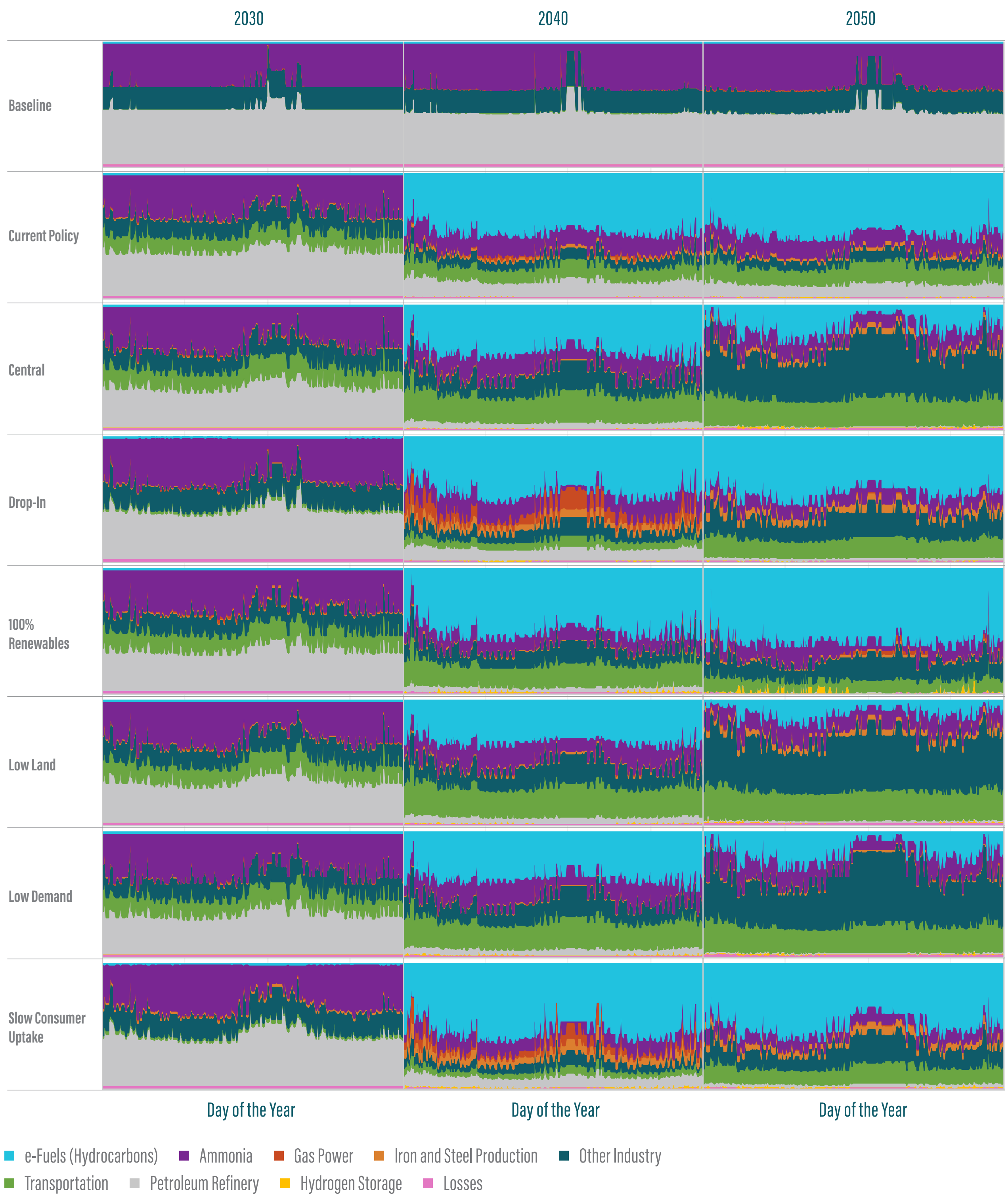
FIGURE 55. Central scenario generation share of U.S. electricity by day of the year and zone.



HYDROGEN PRODUCTION AND USE

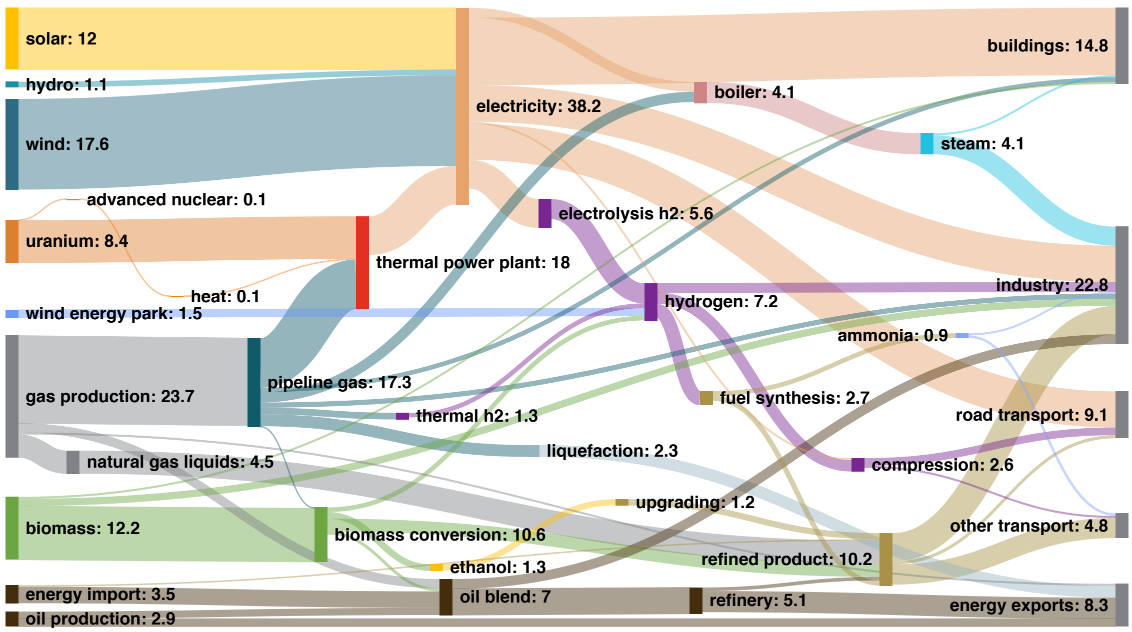
FIGURE 56. U.S. hydrogen production share by day of the year and scenario

FIGURE 57. U.S. hydrogen consumption share by day of the year and scenario



CENTRAL 50X30

FIGURE 58. Sankey diagram for 2050 Central 50x30 scenario (Exajoules)



CENTRAL NO IRA

FIGURE 59. Electricity generation comparison between Central and Central no IRA

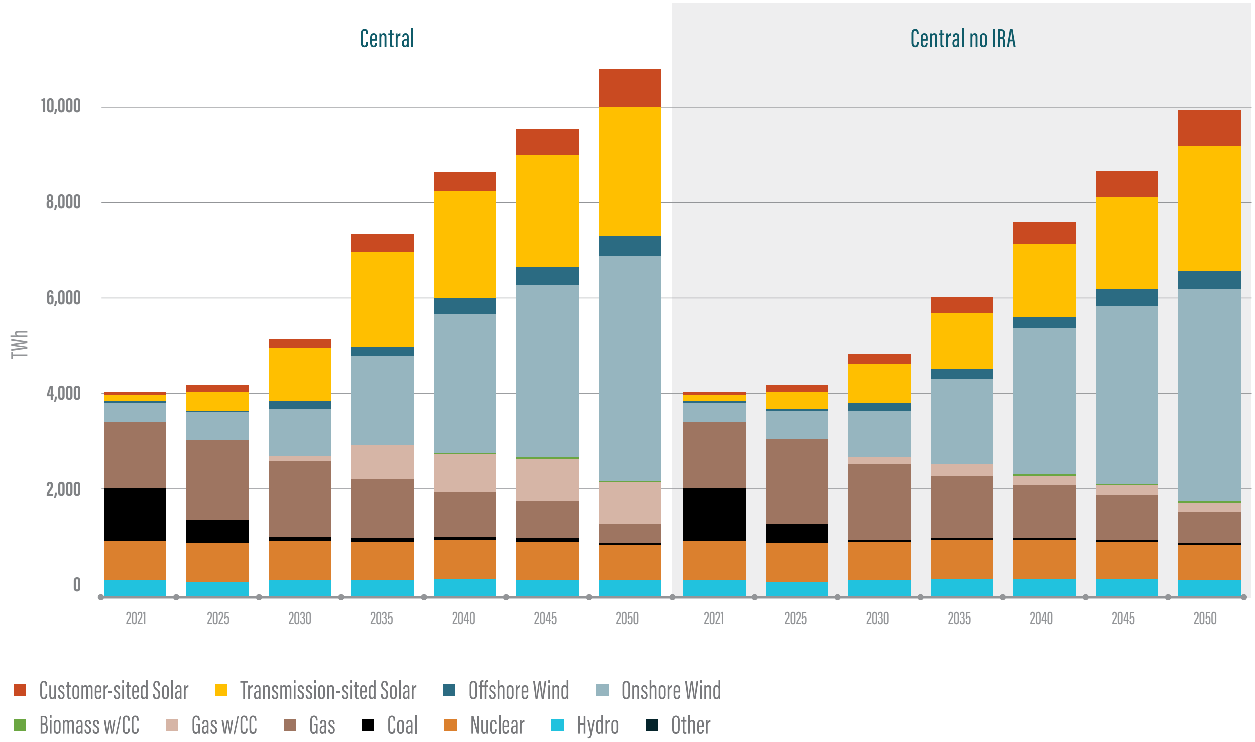
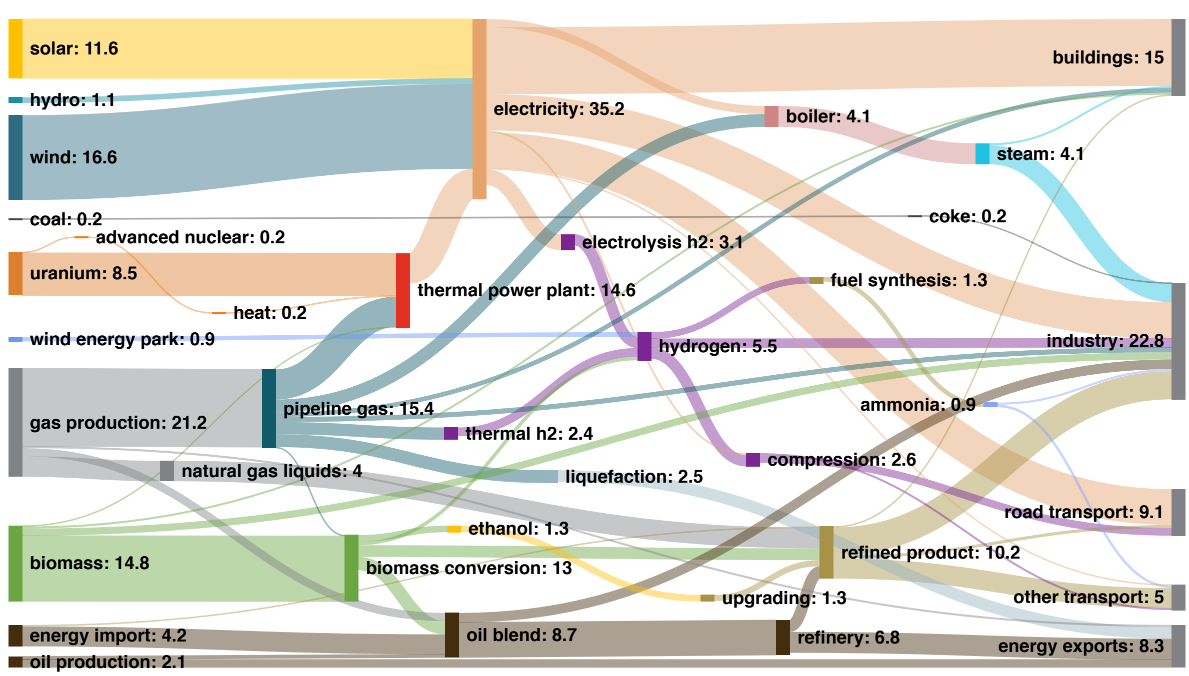


FIGURE 60. Sankey diagram for 2050 Central no IRA scenario (Exajoules)



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