2023 U.S. Annual Decarbonization Perspective

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Agenda

- Project purpose
- Methods overview
- Results summary
  - Overview of updates
  - Results comparisons with 2022

Decarbonization pathways studies of the U.S. have proliferated since 2016

- Long-term pathways are necessary for business, government, and NGOs for the following reasons:
  - Helps government policy making and informs goal setting
  - Informs technology investments and R&D priorities
  - Helps capital-heavy business plan expenditures and operations
  - Frames trade-offs between low carbon pathways for the public
- Evolved Energy Research modeling tools have been recognized as best-in-class for study of long-term pathways and have been across many recent studies
- The large number of such studies and lack of transparency with respect to the differences between them threatens to confuse as much as to inform.

The annual refresh aims to fill a current gap in U.S. Decarbonization Analysis

- **Standardization** – Standard for benchmarking that is universally recognized as credible and rigorous
- **Continuity** – Effective long-term planning requires a process of regular updating. To date deep decarbonization studies remain a series of snapshots of possible futures, sometimes disjointed, without continuity between research efforts.
- **Access** – The relevant energy-system outputs from existing deep decarbonization studies are unavailable to many who could make good use of the information.
- **Technology Agnosticism** – A wide ranging set of pathways should be produced with a clear articulation of trade-offs between them while minimizing bias

ADP publication components

1. Annual report explaining updates and presenting results
   - 6-8 scenarios with continuity between years + additional sensitivities
2. Publication of model inputs/outputs
   - Technology assumptions
   - Key outputs on a state geography
3. Periodic white papers on topics of interest in the community

Funding is provided by Breakthrough Energy Foundation

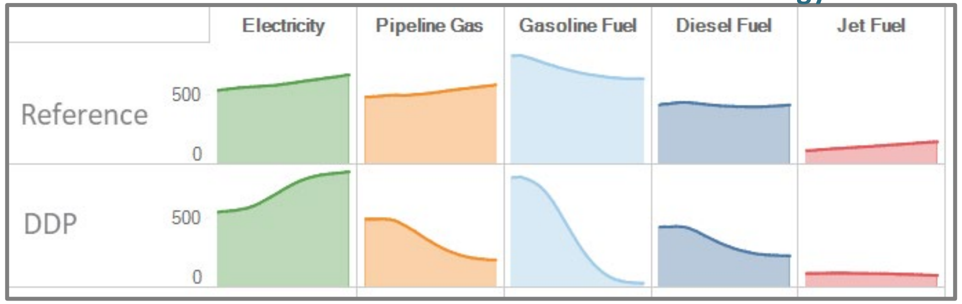
Methods overview

Analytical tools

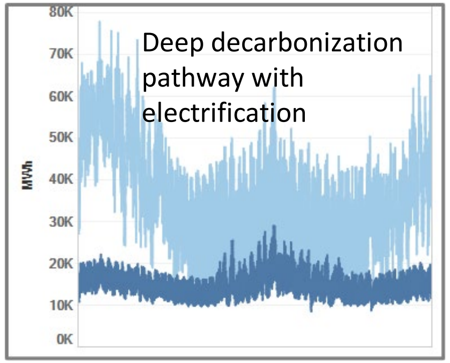
EnergyPATHWAYS (EP) is our demand-side stock-rollover accounting model that produces scenarios based on exogenous service-demand and sale shares

RIO is a supply-side macro-energy model that finds the lowest cost investment and operations plan with best-in-class temporal and spatial granularity

Annual End-Use Energy Demand

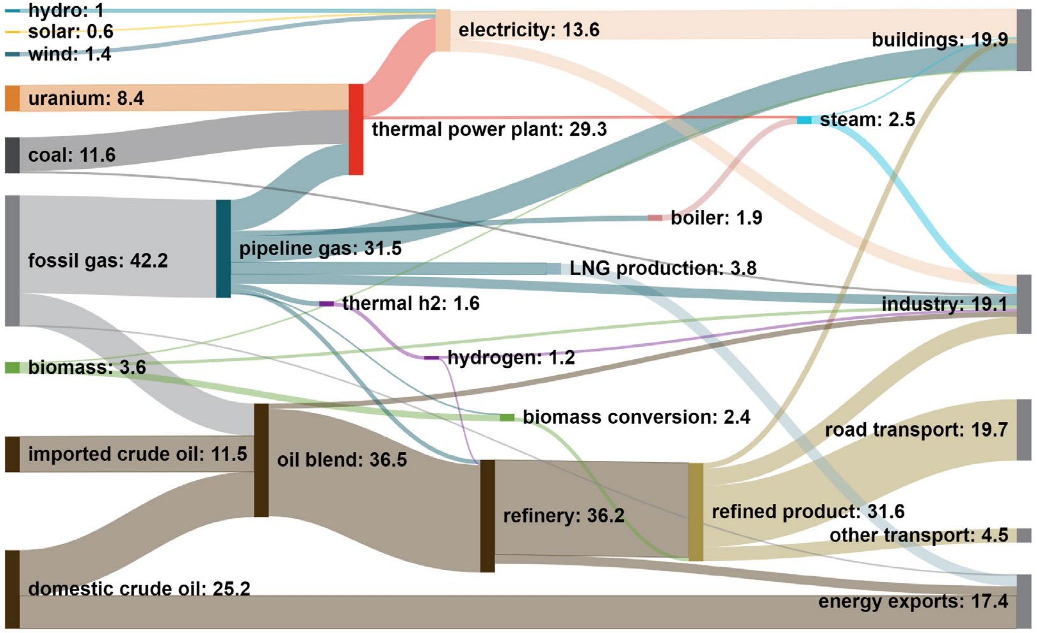


Hourly Load Shape



Deep decarbonization pathway with electrification

2021 Energy System



EnergyPATHWAYS Subsectors

Buildings

	Subsector		# Technologies
Commercial	commercial air conditioning	12 building types	22
	commercial cooking		4
	commercial lighting		26
	commercial other		N/A
	commercial refrigeration		18
	commercial space heating		18
	commercial unspecified		N/A
	commercial ventilation		4
	commercial water heating		7
	district services		N/A
	office equipment (non-p.c.)		N/A
	office equipment (p.c.)		N/A
Residential	residential air conditioning	3 building types	13
	residential clothes drying		3
	residential clothes washing		4
	residential computers and related		6
	residential cooking		3
	residential dishwashing		2
	residential freezing		4
	residential furnace fans		N/A
	residential lighting		39
	residential other uses		14
	residential refrigeration		6
	residential secondary heating		N/A
	residential space heating		18
	residential televisions and related		5
	residential water heating		6

Transportation

	Subsector	Sub-category	# Technologies
Transportation	aviation		N/A
	buses	3 duty cycles	5
	domestic shipping		N/A
	freight rail		N/A
	heavy duty trucks	2 duty cycles	6
	international shipping		N/A
	light duty autos		10
	light duty trucks	2 types	11
	lubricants		N/A
	medium duty trucks		6
	military use		N/A
	motorcycles		N/A
	passenger rail	3 types	N/A
	recreational boats		N/A

Industry

	Subsector	Sub-category
Industry	agriculture-crops	4 process types
	agriculture-other	4 process types
	aluminum industry	6 process types
	balance of manufacturing other	9 process types
	bulk chemicals	50 process types
	cement	8 process types
	coal mining	2 process types
	computer and electronic products	10 process types
	construction	3 process types
	electrical equip., appliances, and components	9 process types
	fabricated metal products	9 process types
	food and kindred products	9 process types
	glass and glass products	7 process types
	iron and steel	8 process types
	machinery	9 process types
	metal and other non-metallic mining	2 process types
	oil & gas mining	2 process types
	paper and allied products	7 process types
	petroleum refining	1 process type
	plastic and rubber products	9 process types
	transportation equipment	9 process types
	wood products	9 process types

*Electrolysis load is modeled as an energy supply technology

RIO Supply Technologies

New Build Decisions

Electricity

Type	Name
fixed profile	offshore wind|1
	offshore wind|2
	offshore wind|3
	offshore wind|4
	offshore wind|5
	offshore wind|6
	offshore wind|7
	onshore wind|1
	onshore wind|2
	onshore wind|3
	onshore wind|4
	onshore wind|5
	rooftop solar - com
	rooftop solar - pro
	rooftop solar - res
	utility-scale solar pv|1
hydro	upgrades to existing hydro
	non-powered dams
thermal	biomass power allam w/cc
	coal power w/cc
	coal w/cc - retrofit
	gas combined cycle
	gas combined cycle w/cc
	gas combustion turbine
	gas w/cc - retrofit
	mothballed generator
	nuclear smr - steam turbine generator
	nuclear smr - retrofit

Fuels & CO2

Type	Name
energy conversion	alcohol-to-x
	bio-gasification ch4 w/cc
	bio-gasification fischer-tropsch w/cc
	bio-gasification h2 w/cc
	biomass fast pyrolysis w/cc
	cellulosic ethanol
	corn ethanol w/cc
	corn to switchgrass conversion
	electrolysis h2
	ethanol gasoline blending
	fischer-tropsch liquids
	haber-bosch
	hydrogen liquefaction
	methanation
	steam reforming
	steam reforming w/cc
	lng production
	lng production electric
	lng production electric retrofit
	direct air capture - solid sorbent
	onshore wind|energy_park

Blends & Commodities

Type	Name
blend	21 final energy types
	7 biomass blend types
commodity	62 biomass feedstock types
	20 geologic sequestration bins
	16 land sink enhancement measures
	21 non-CO2 mitigation measures

Energy Storage

Type	Name
blend	h2 storage salt cavern
	h2 storage underground pipes
	nuclear thermal energy storage
electric	li-ion
	long duration storage

Transmission & Pipelines

Type	Name
inter-zonal	Electricity
	Hydrogen
	CO2

RIO Endogenized Industry

New Build Decisions

Steam

	Type	Name
Steam Production	conversion	electric boiler
	conversion	h2 boiler
	conversion	industrial heat pump
	conversion	thermal storage - resistor
	blend storage	thermal energy storage
	conversion	pipeline gas boiler
	conversion	electric boiler

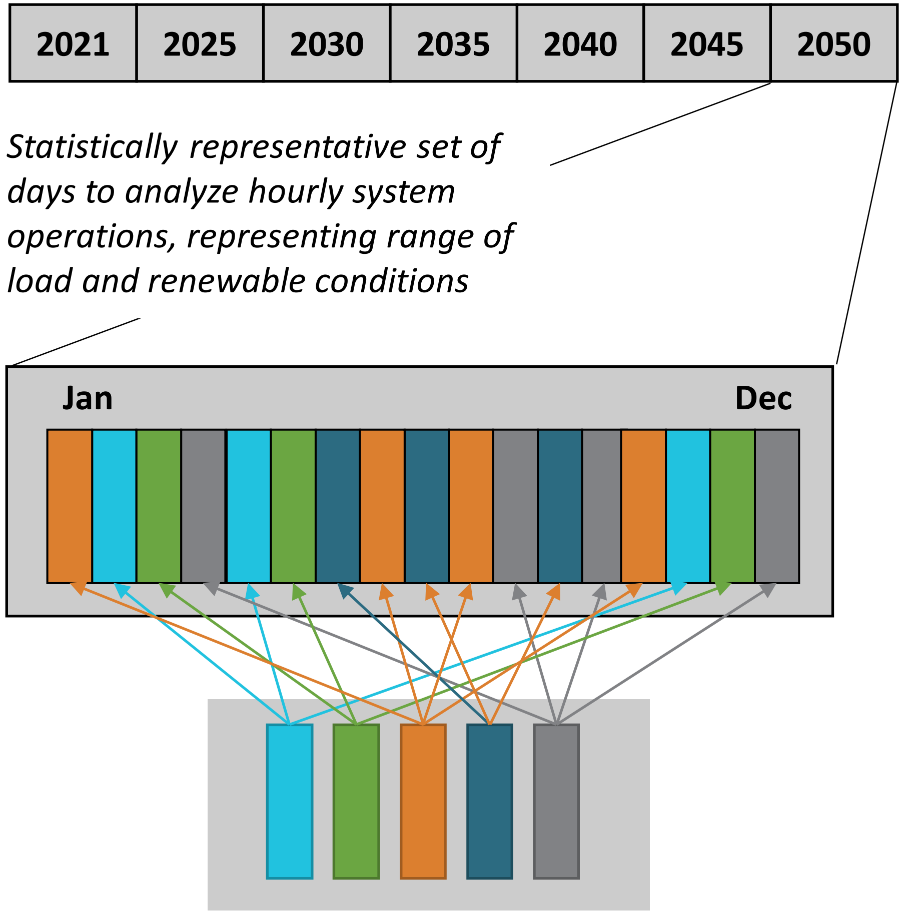
Iron & Steel

	Type	Name
Iron & Steel	conversion	coke plant w/cc
	conversion	BF/BOF
	conversion	BF/BOF w/cc
	conversion	DRI
	conversion	EAF
	conversion	H2 DRI
	conversion	steel - cold rolling
	conversion	steel - continuous casting
	conversion	steel - h2 cold rolling
	conversion	steel - h2 continuous casting
	conversion	steel - h2 hot rolling
	conversion	steel - hot rolling

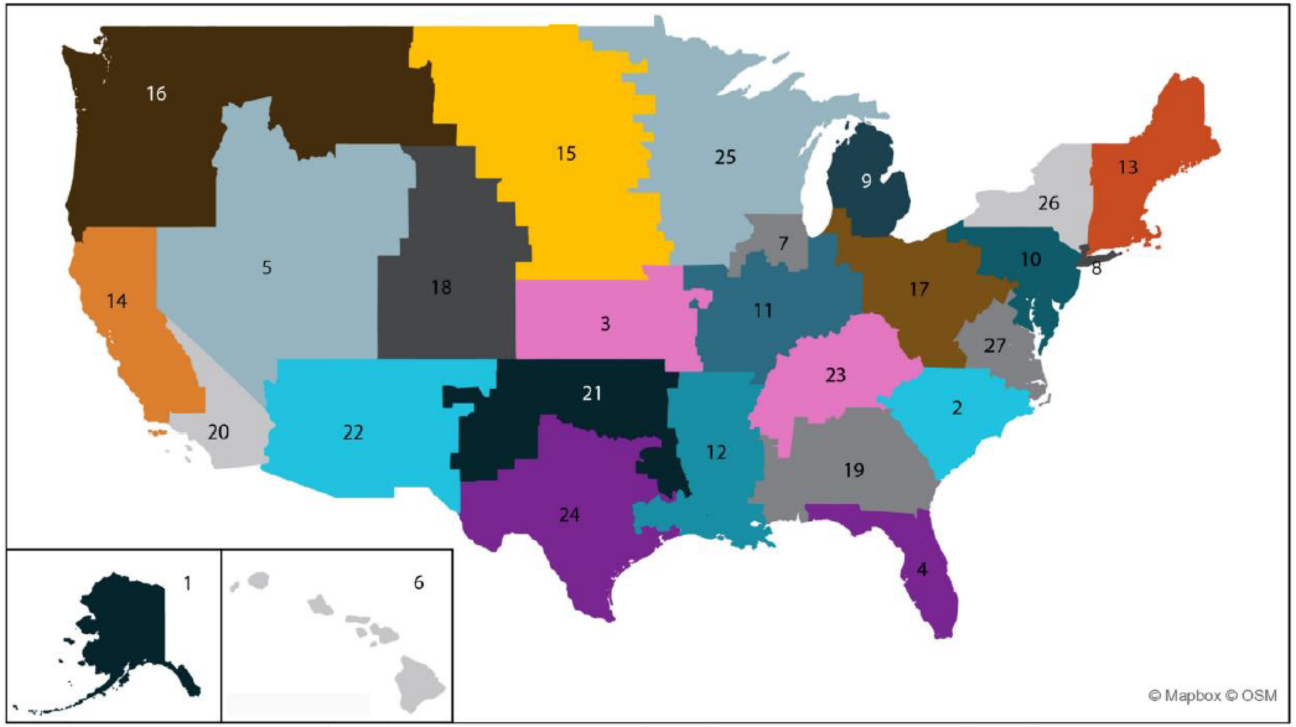
Cement & Lime

	Type	Name
Cement & Lime	conversion	clinker production - conventional
	conversion	clinker production - direct separation ccs
	conversion	clinker production - direct separation ccs retrofit
	conversion	clinker production - oxyfuel biomass ccs
	conversion	clinker production - oxyfuel gas ccs
	conversion	lime production - conventional
	conversion	lime production - direct separation ccs
	conversion	lime production - direct separation ccs retrofit
	conversion	lime production - oxyfuel biomass ccs
	conversion	lime production - oxyfuel gas ccs
	conversion	kiln_burner_biomass
	conversion	kiln_burner_h2
	conversion	kiln_burner_msw
	conversion	kiln_burner_pipeline gas

Temporal and spatial granularity



Statistically representative set of days to analyze hourly system operations, representing range of load and renewable conditions



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 Valey
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		

hourly operations, 40 sample days per year, state of charge tracking between sample days

Scenarios

Net-Zero in 2050

Scenario	Description
Baseline	Based on the DOE's Annual Energy Outlook 2023.
IRA	This scenario is based on Princeton's REPEAT mid scenario.
Central	High electrification demand-side case, and on the supply-side has no additional constraints on technologies and resource availability.
Low Demand	Starts from Central and reduces the demand for energy services.
Low Land	Starts from Central and limits the use of land-intensive mitigation solutions, including bioenergy crops, wind and solar power generating plants, and transmission lines.
100% Renewables	Starts from Central and disallows any primary energy from fossil fuels in 2050.
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.
Drop-In	Starts from Slow Consumer Uptake and caps renewable build at historical rates and disallows new long-distance transmission or pipelines.

Collaborations with NREL

- Joint projects:
  - Electrification Futures Study (EFS)
  - North American Renewable Integration Study (NARIS)
  - High electrification load shapes (ongoing)
- NREL Data/Tools Employed
  - Annual Technology Baseline
  - ReEDS transmission costs and supply curves for select technologies
  - Wind and solar geospatial datasets
  - Wind Toolkit & National Solar Radiation Database
  - System Advisor Model (SAM)

Results Summary

Sankey diagram comparison

2021 vs. 2050 IRA

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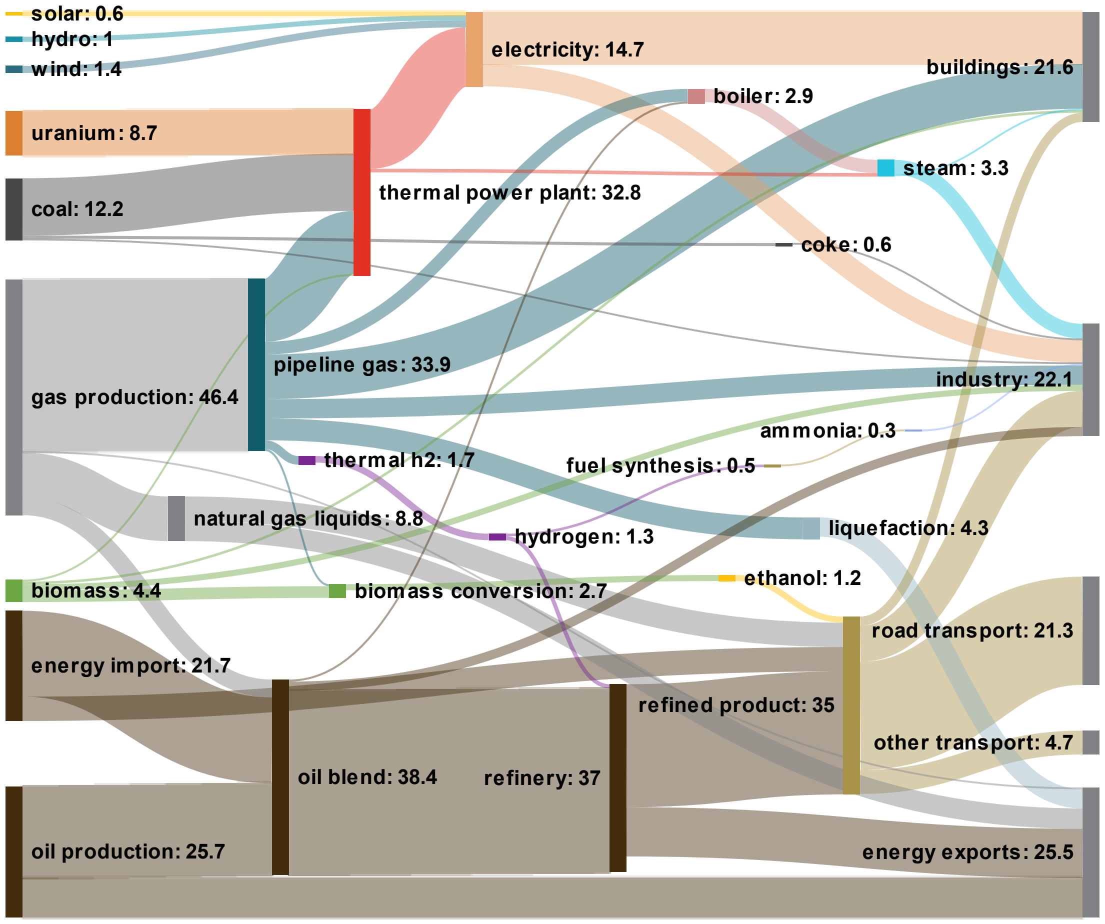
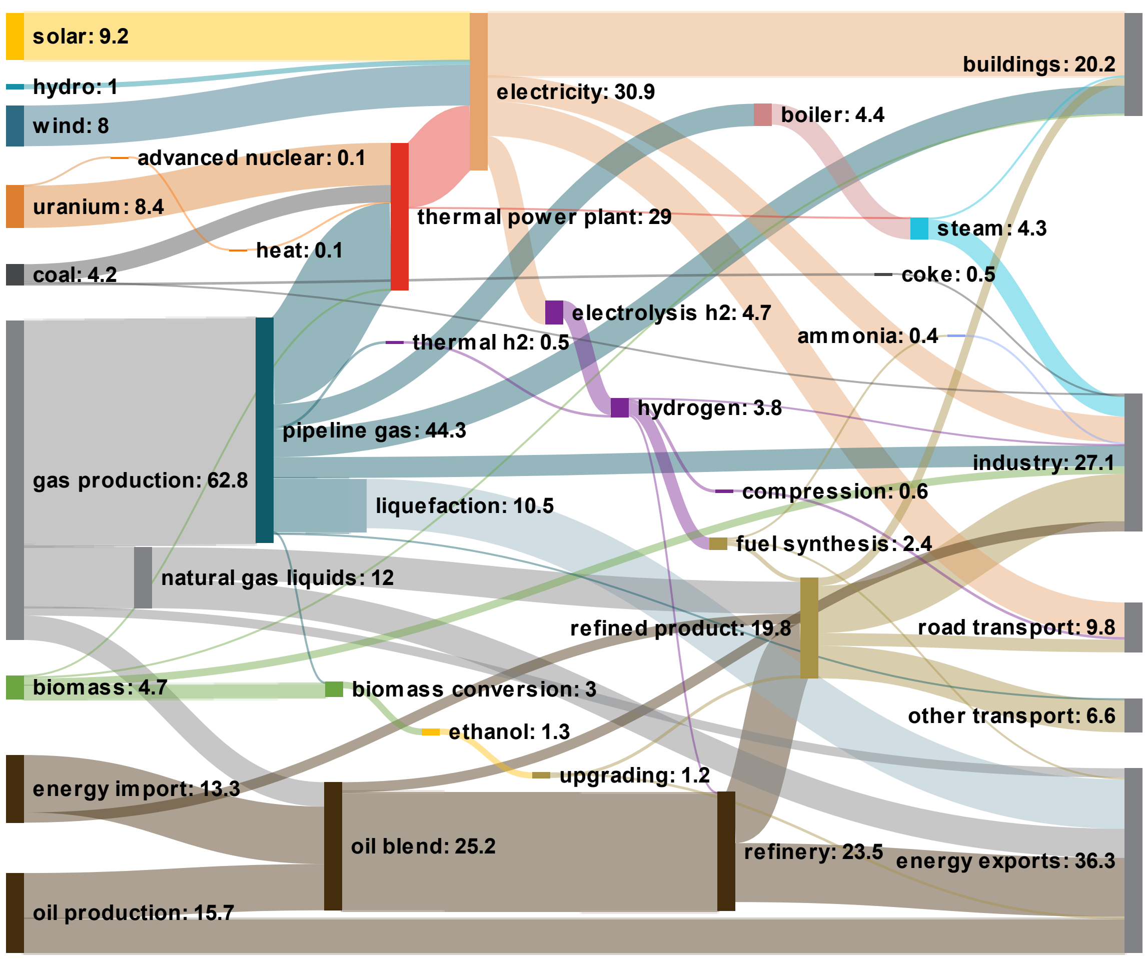
2021



2050 IRA



Sankey diagram comparison

2050 IRA vs. 2050 Central

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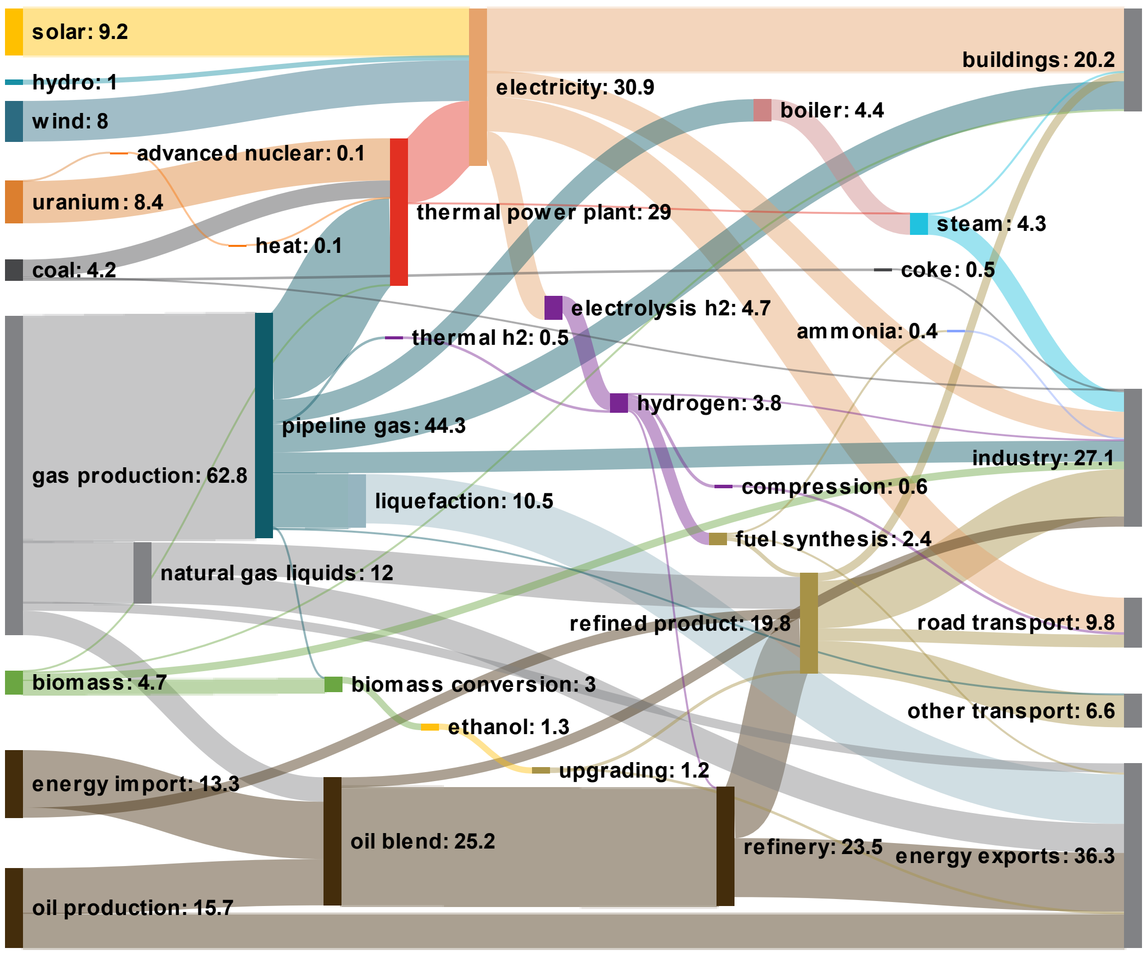
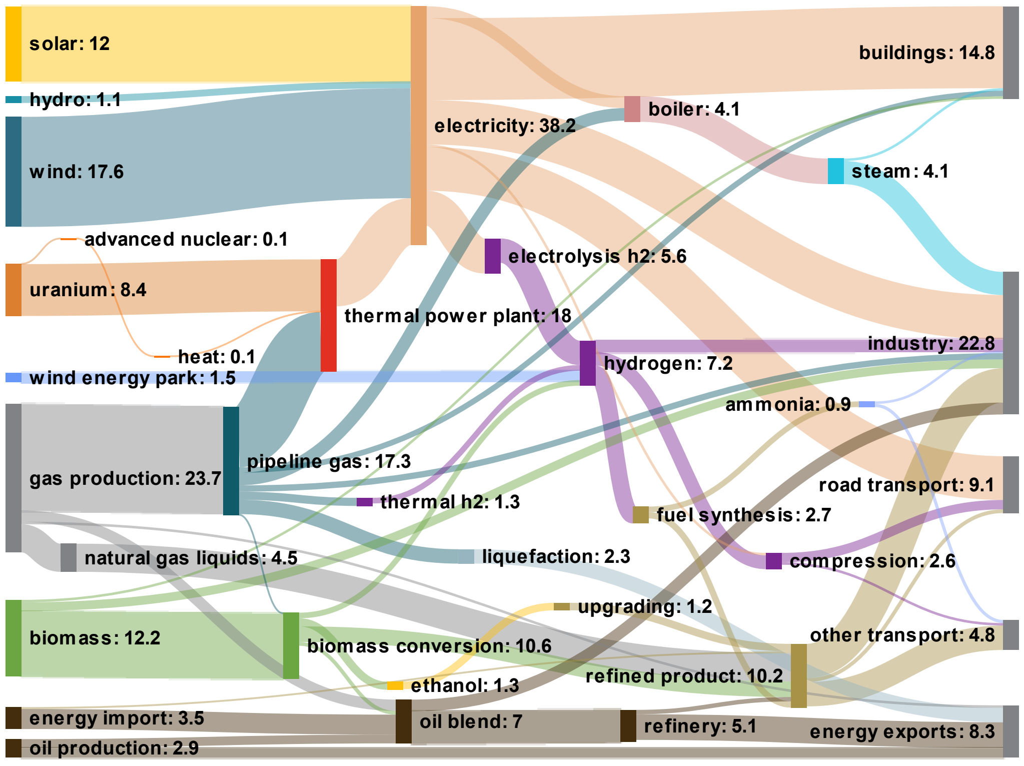
2050 IRA



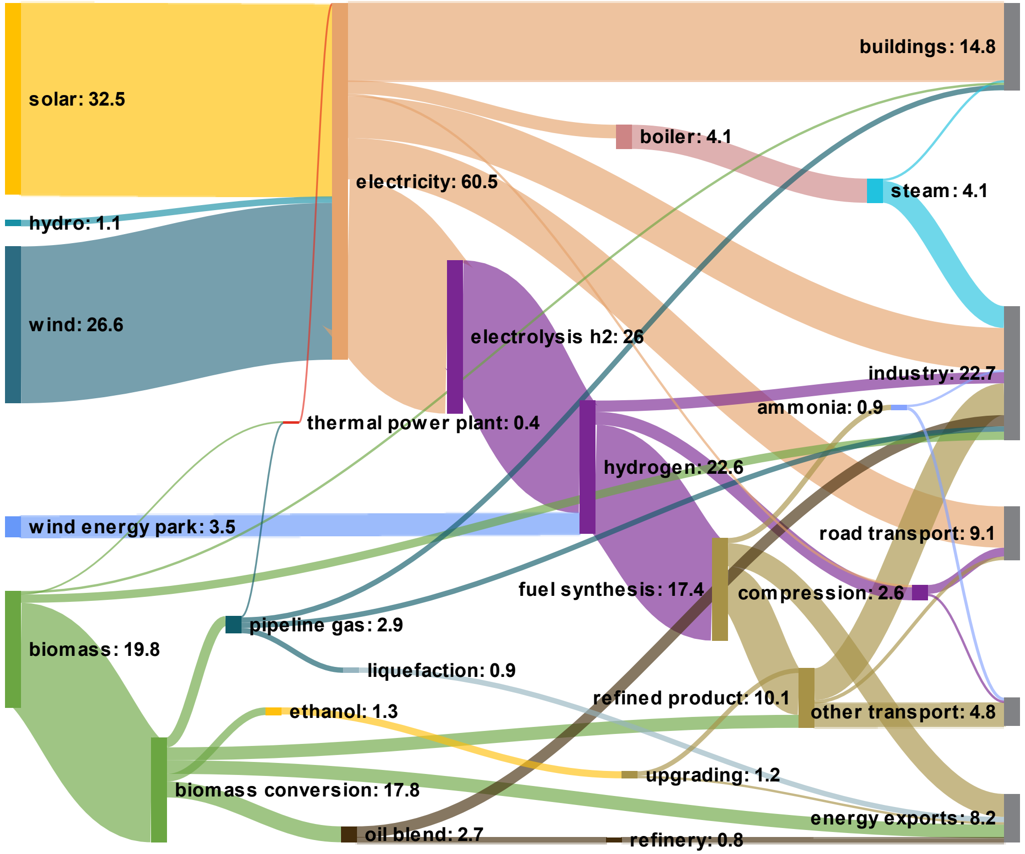
2050 Central



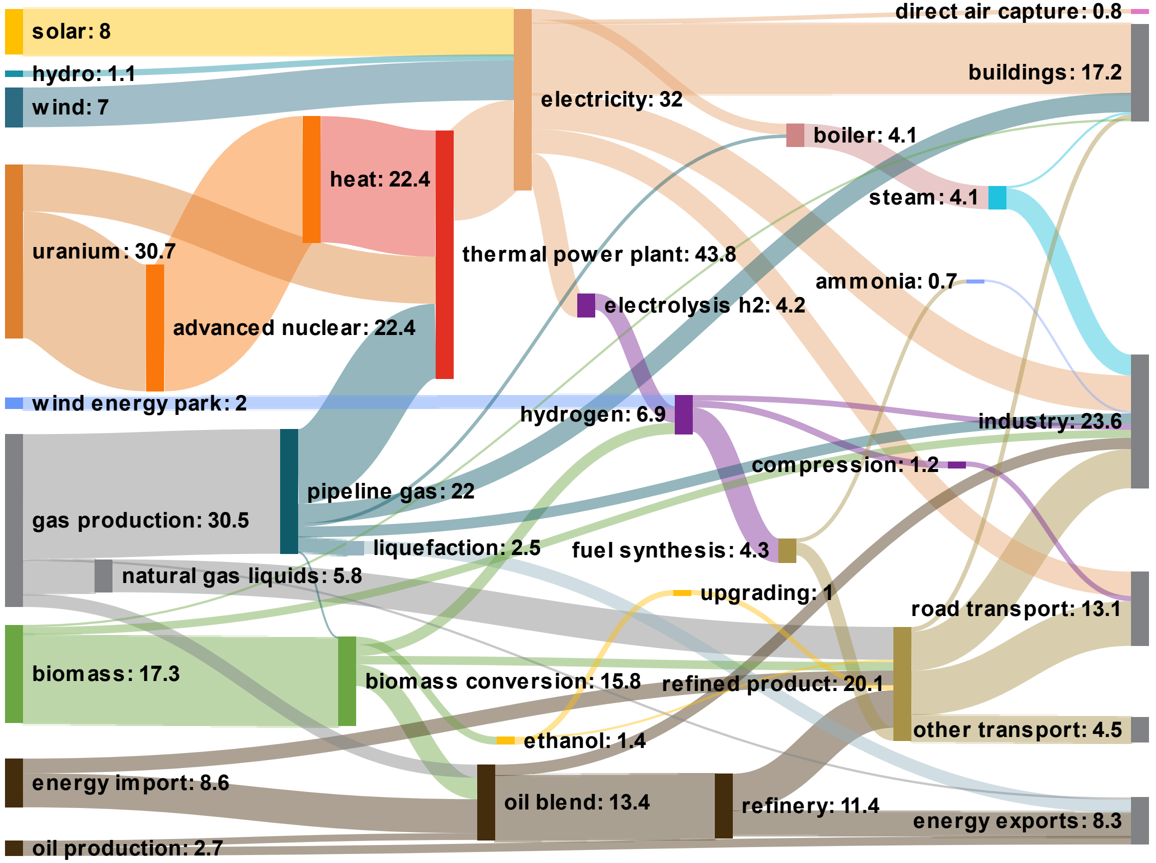
Sankey diagram comparison

2050 100% Renewables vs. 2050 Drop-In

2050 100% Renewables



2050 Drop-In



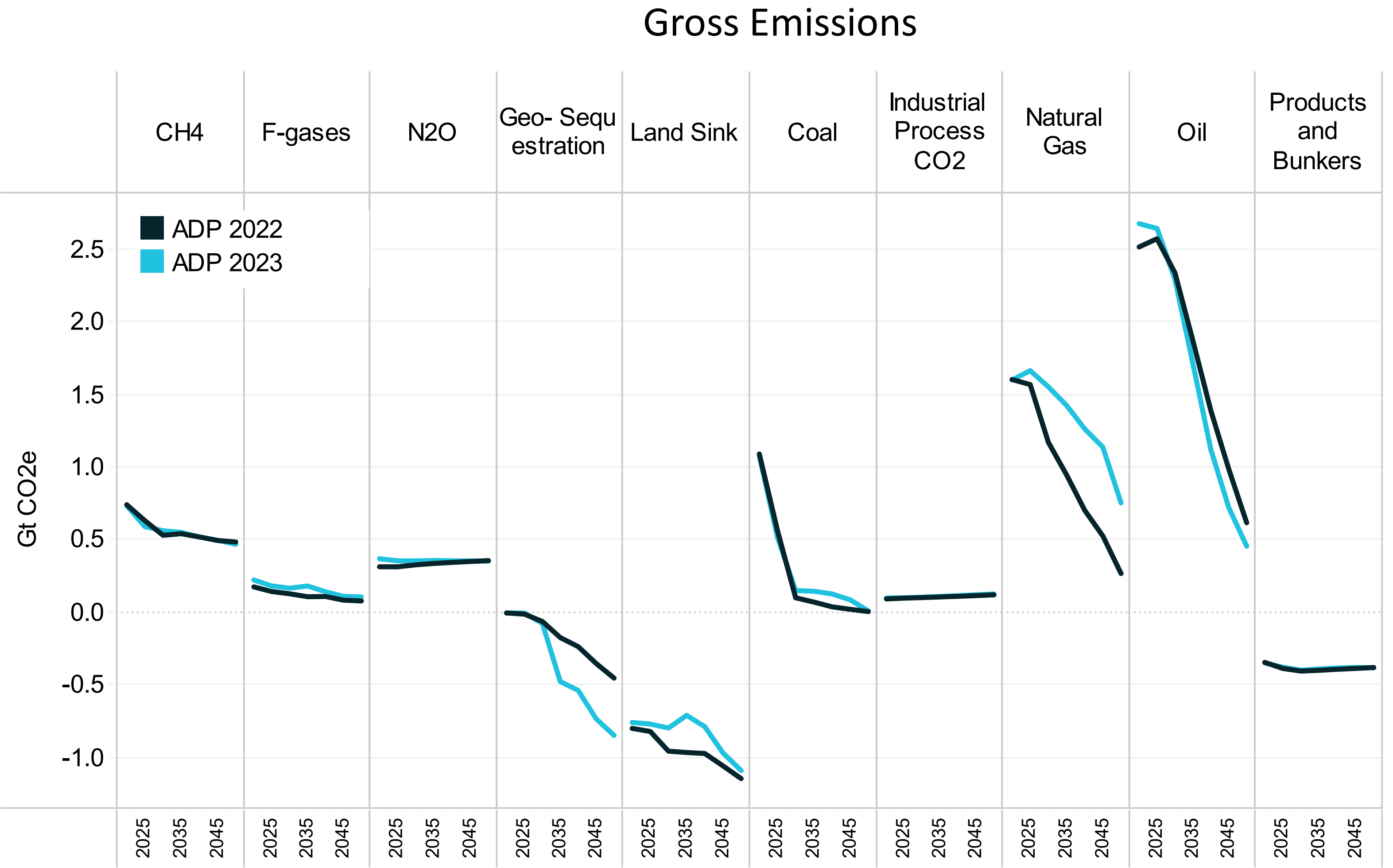
Key modeling updates since ADP 2022

- IRA tax credits, AEO 2023, ATB 2023
- Technology build rate constraints
- Cement, Iron & Steel
- Ethanol to Jet Fuel
- Direct Air Capture technology
- Heat Pump Cost
- Energy Park Technologies
- U.S. Baseline Land-Sink

Emissions ADP 2022 vs. 2023

Focus: IRA tax credits, ATB 2023

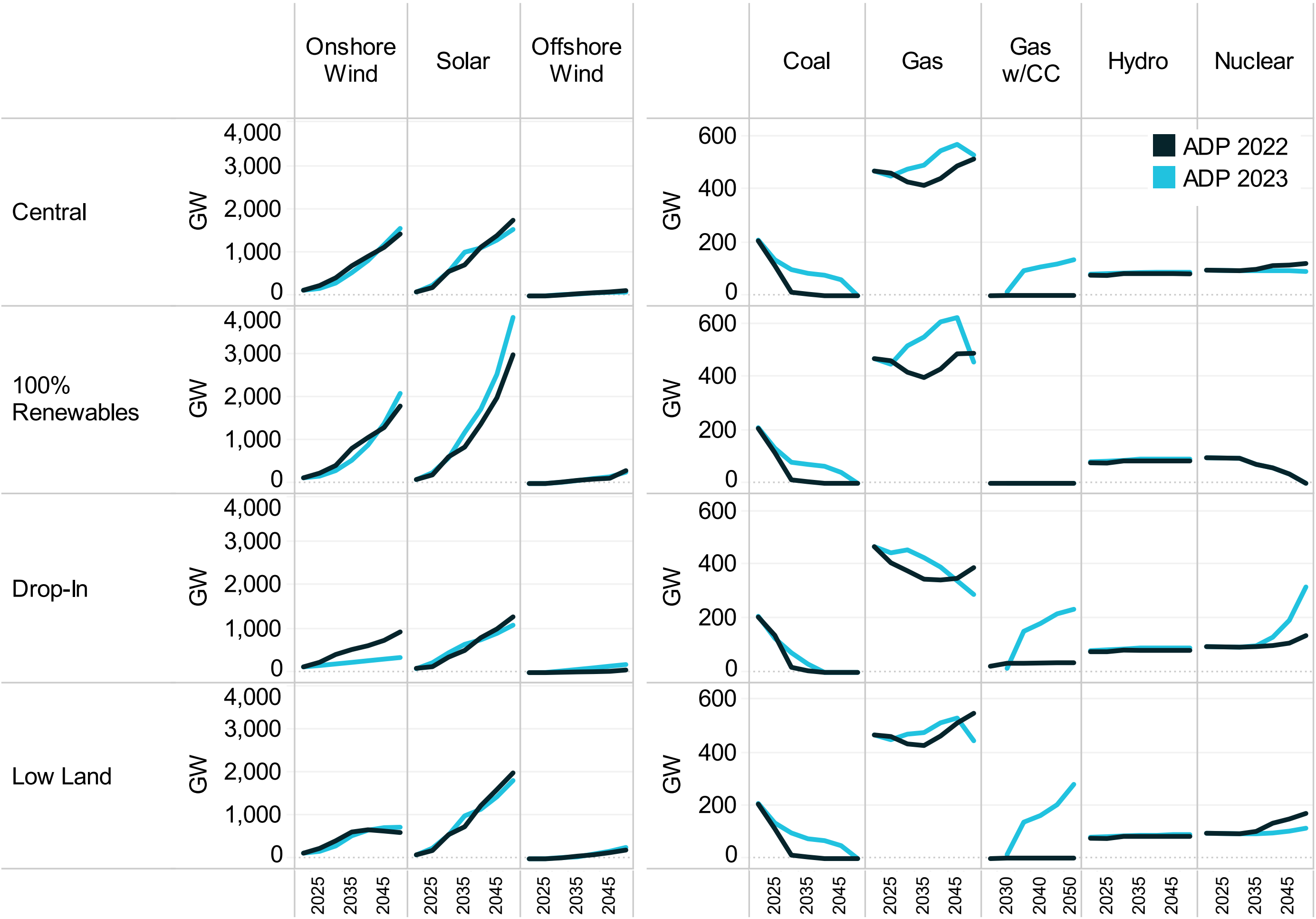
- Differences in geologic sequestration and natural gas are significant.
- The 2023 ADP has 843 Mt carbon sequestration in 2050 compared with 449 Mt last year.
- That difference comes from captured CO2 in the power sector from gas generation.



Electricity Capacity ADP 2022 vs. 2023

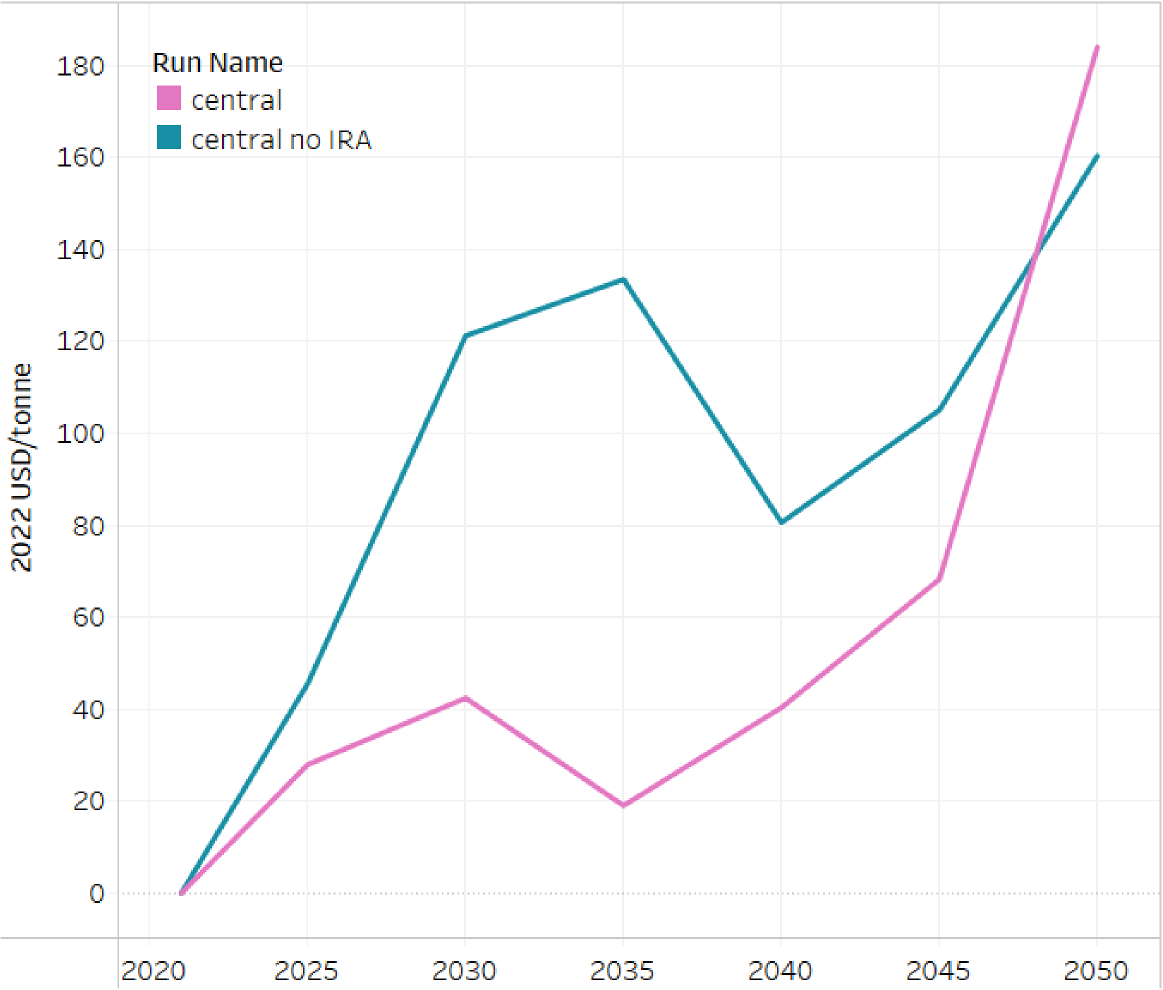
Focus: IRA tax credits, ATB 2023

- Gas with carbon capture and slower retirement of coal are among the more significant changes
- Without IRA tax credits, but applying net-zero constraints, gas with carbon capture falls from 135 GW to 44 GW
- 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

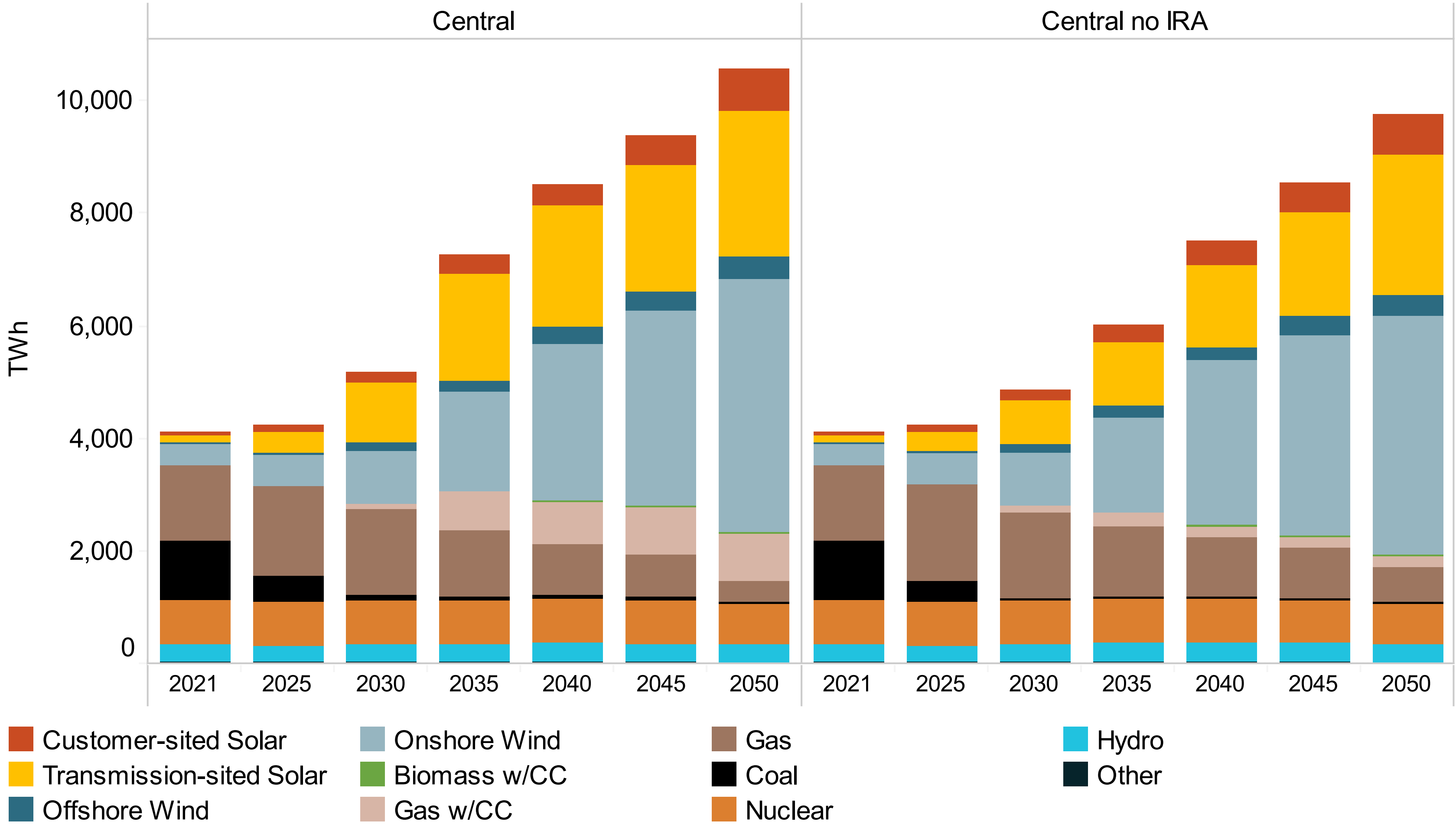


Emissions constraint shadow prices

- IRA tax credits reduce the marginal cost of emissions reductions in a net-zero scenario by $80-100/tonne in the 2030s
- Emissions reductions for things not explicitly targeted by IRA fall in competitiveness against those measures that do receive tax credits.
  - Retirement of coal
  - Broad enhancement of the land-sink
  - Broad non-CO2 reductions



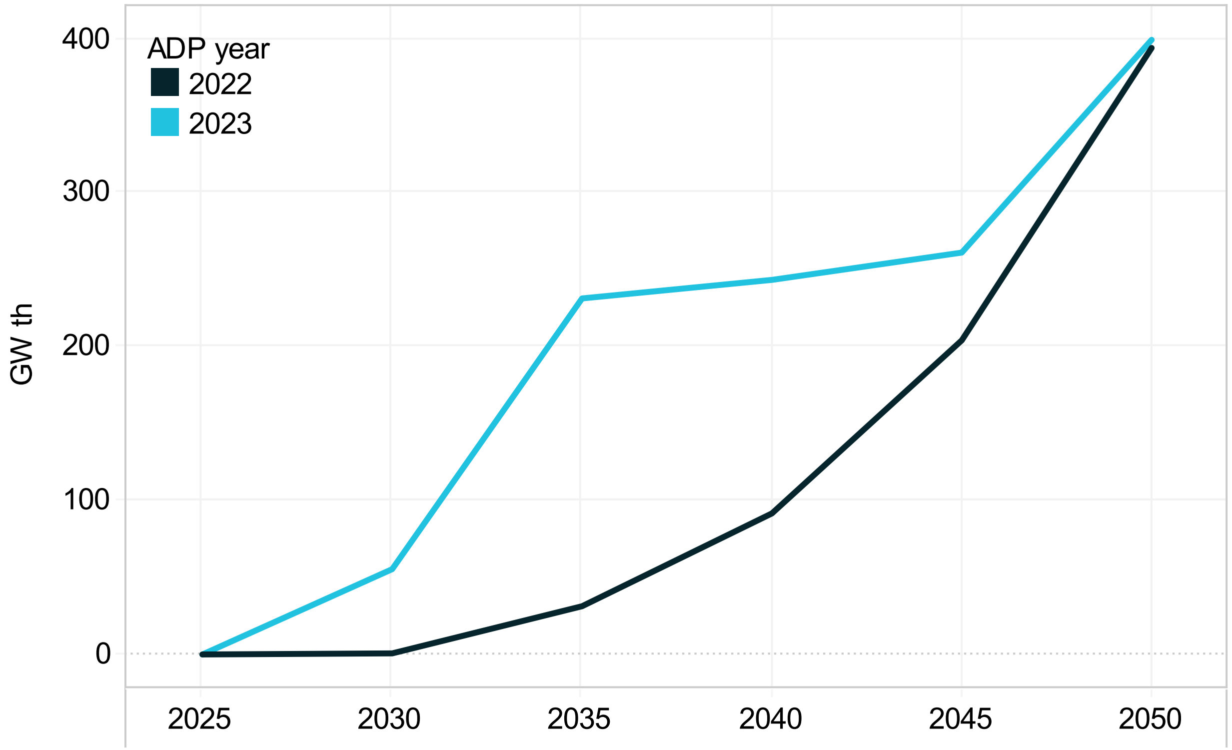
Electricity generation comparison between Central and Central no IRA



Electrolysis Capacity ADP 2022 vs. 2023

Focus: IRA tax credits, ATB 2023

- ADP 2022 and 2023 central scenario reach similar electrolysis build in 2050, but the 2023 ADP builds these electrolyzers roughly a decade sooner.
- As has been demonstrated in research by Evolved Energy Research and others excess electrolytic load when renewable penetrations are too low can increase emissions by diverting electricity that would 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.



Technology build rate constraints

The Inflation Reduction Act made necessary the inclusion of new build rate constraints for many technologies in the model. Without them, the model frontloads the build of technologies to take advantage of the tax credits in ways that are clearly unrealistic.

Technology	Starting Build Rate (per year)	Years between build rate doubling	Explanation
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 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 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.

Output build rates of key technologies

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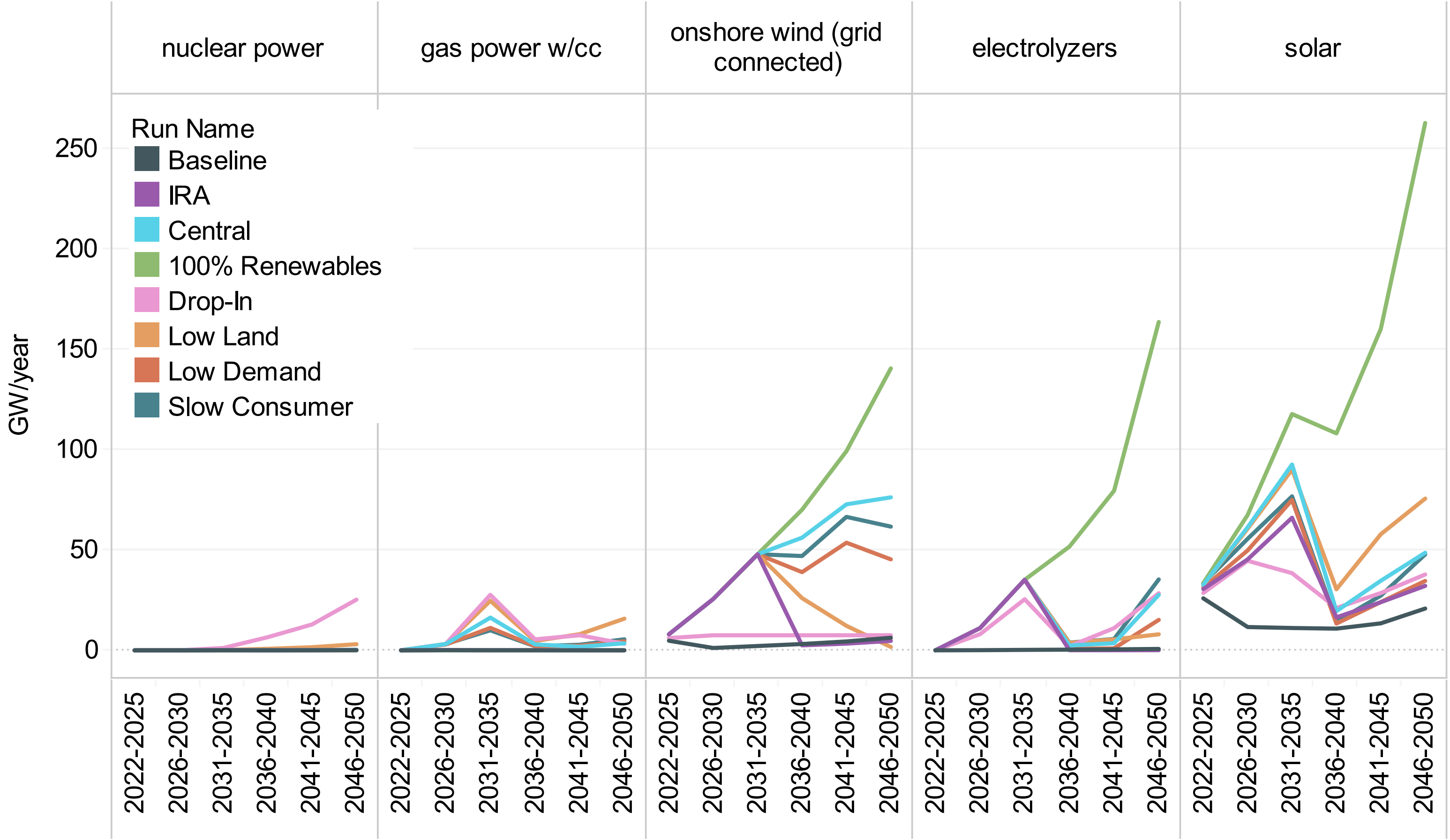
Philosophically we have attempted to constrain technologies so that:

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)
4. Assumptions can be shared across scenarios, except where differences are part of the scenario itself.

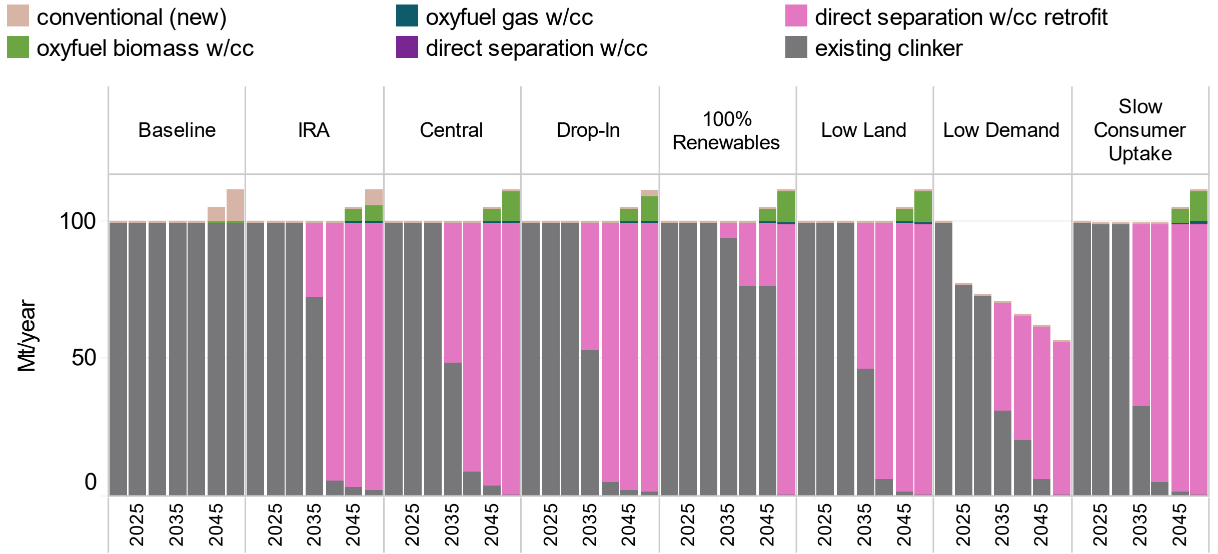


Cement and lime

- The higher resolution in ADP 2023 leads to more concrete insight into a low carbon transition in cement and lime, and indicates what specific measures appear most competitive given current assumptions about future technology and fuel costs.
- In all scenarios, the main trend seen in the modeling is the retrofitting of existing kilns with direct separation technology with CCS. 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.

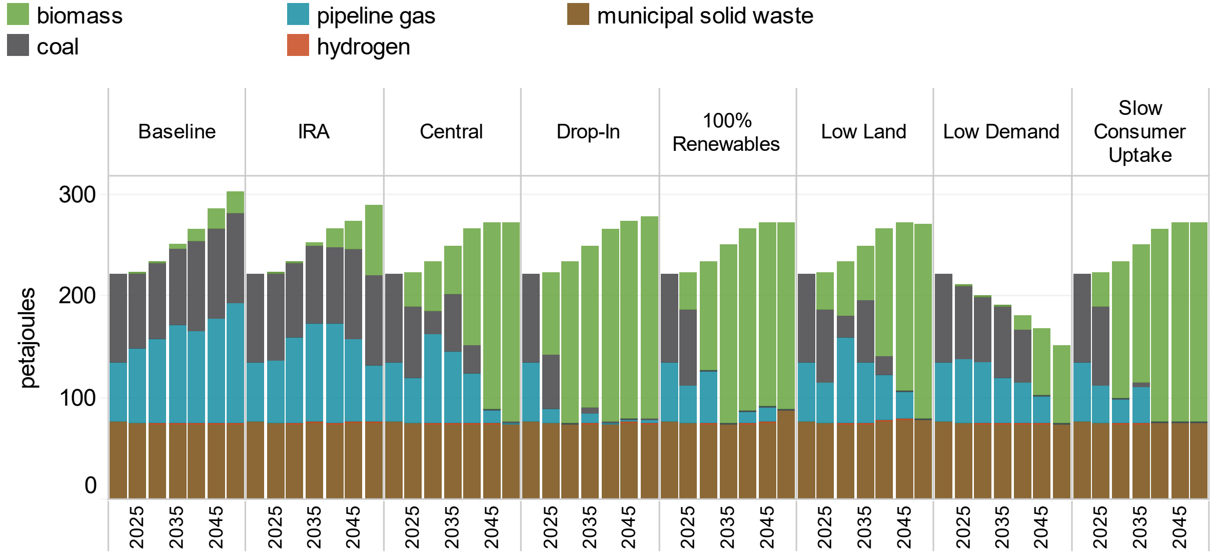
Cement Capacity

(a) Clinker Technology



Kiln Heat Source

(b) Kiln Heat Source



Steel production

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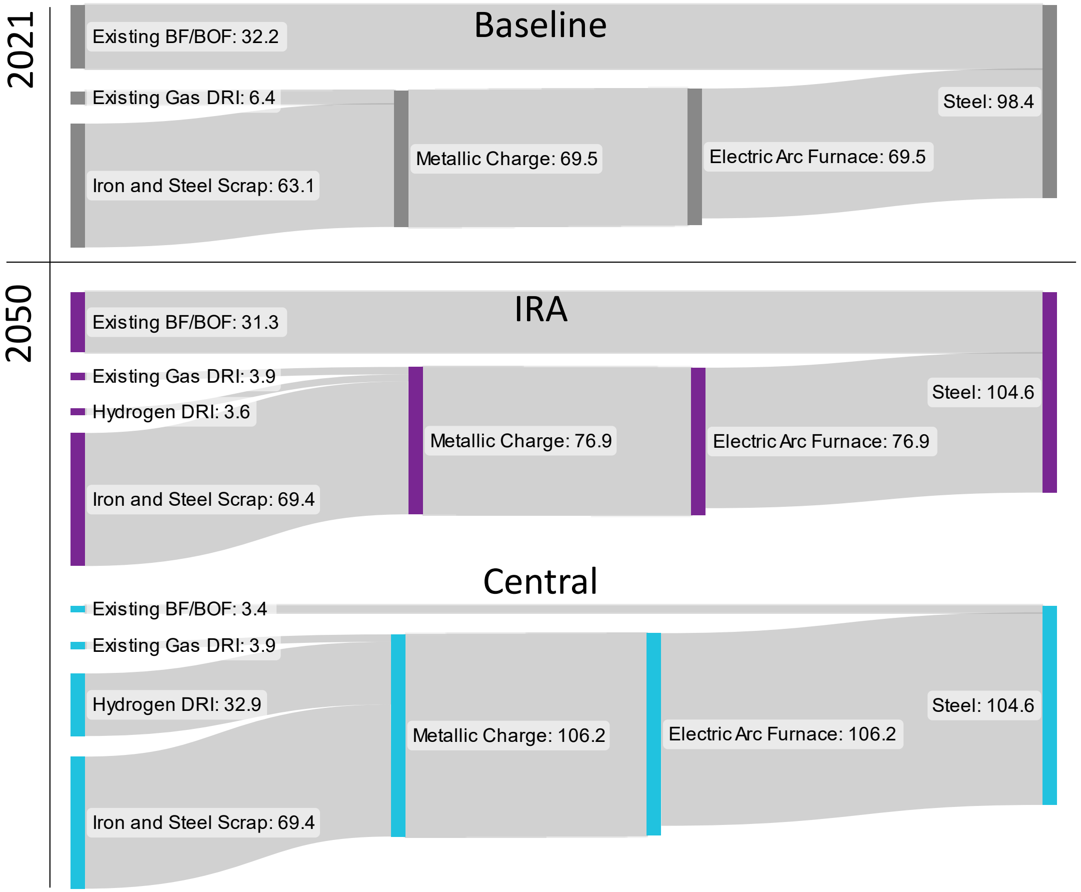
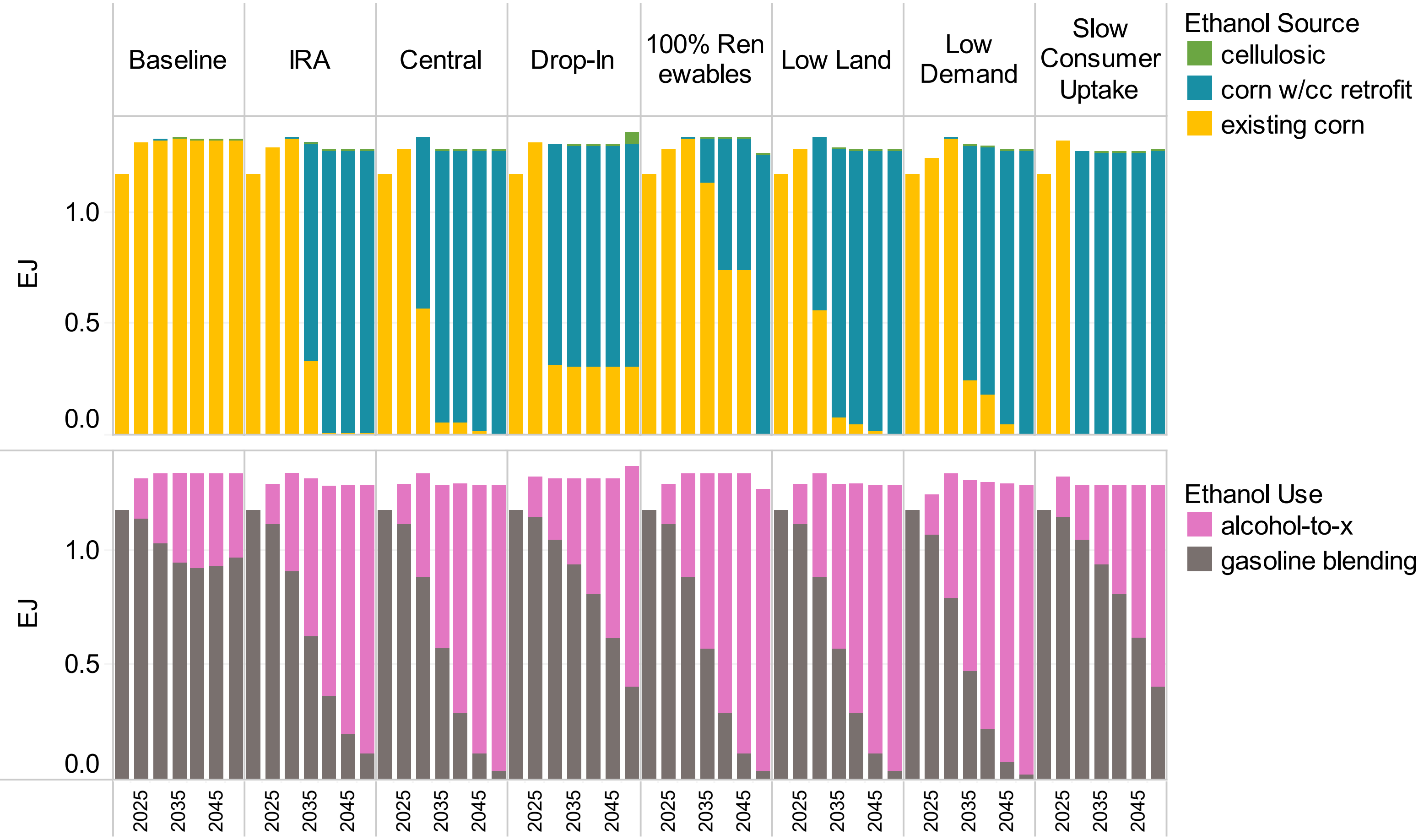
- In the Central case, more than 95% of steel is manufactured using EAF
- Scrap inputs at roughly current levels comprise 70% of the EAF input charge, and H2-DRI comprises most of the remaining 30%.
- BF/BOF production is reduced 90% below today's level.
- The main change in the energy mix is hydrogen's growth to 30-40% by 2050 in the net zero cases, and a comparable reduction in coke and coal.



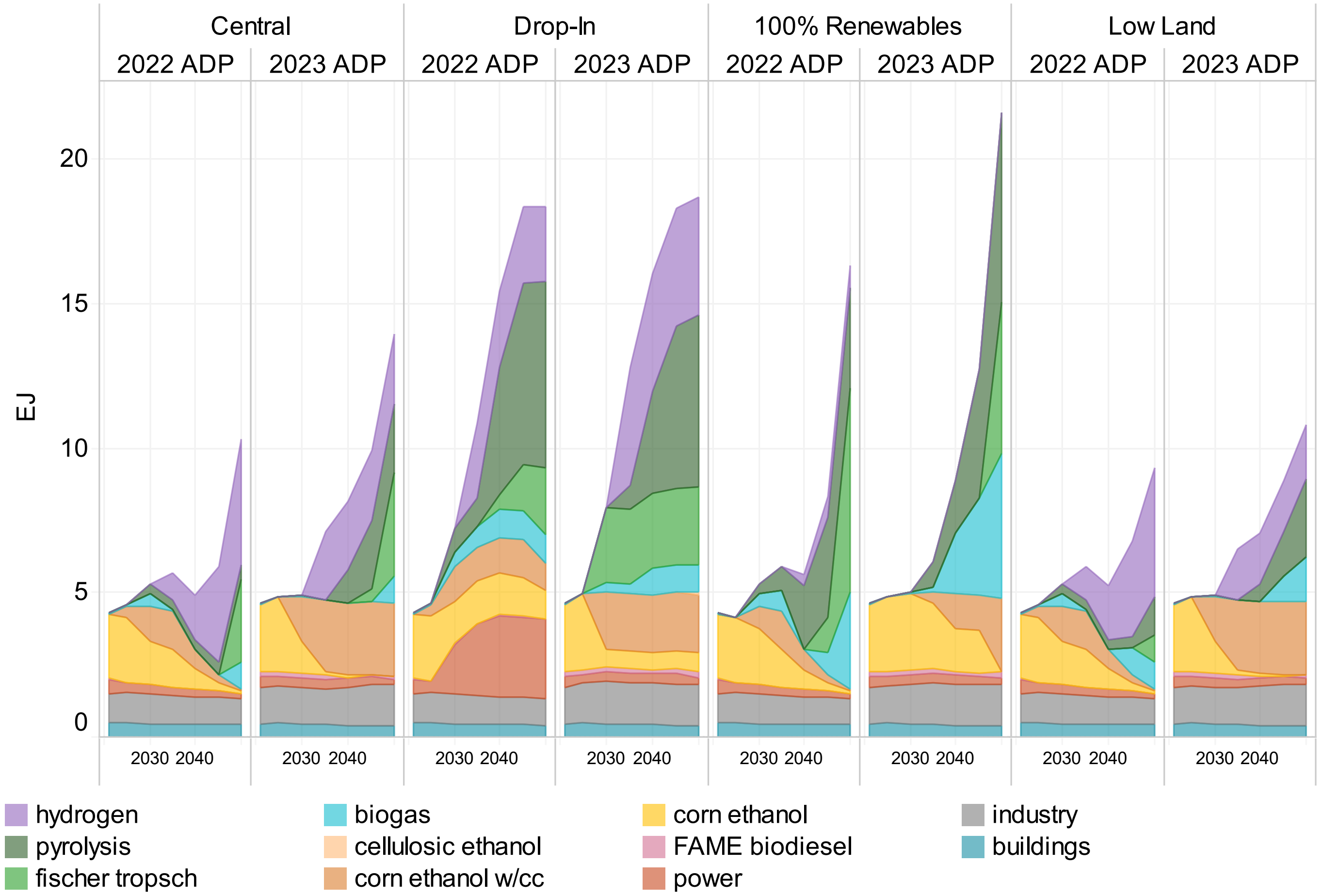
Ethanol production and its use

- Recent advancements in catalysts have opened a new pathway for existing ethanol to be upgraded to jet fuel. This technology wasn't included in the 2022 ADP and hadn't yet been studied in any national decarbonization studies we are aware of at that point.
- Ethanol to jet is technology consistently selected across all scenarios. It is especially competitive when paired with carbon capture on existing ethanol.



Biomass ADP 2022 vs. 2023

- Between 2022 and 2023 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 producing e-fuels) have seen expected costs revised downward.
- Most biomass applications outside of corn ethanol have not seen dramatic changes.

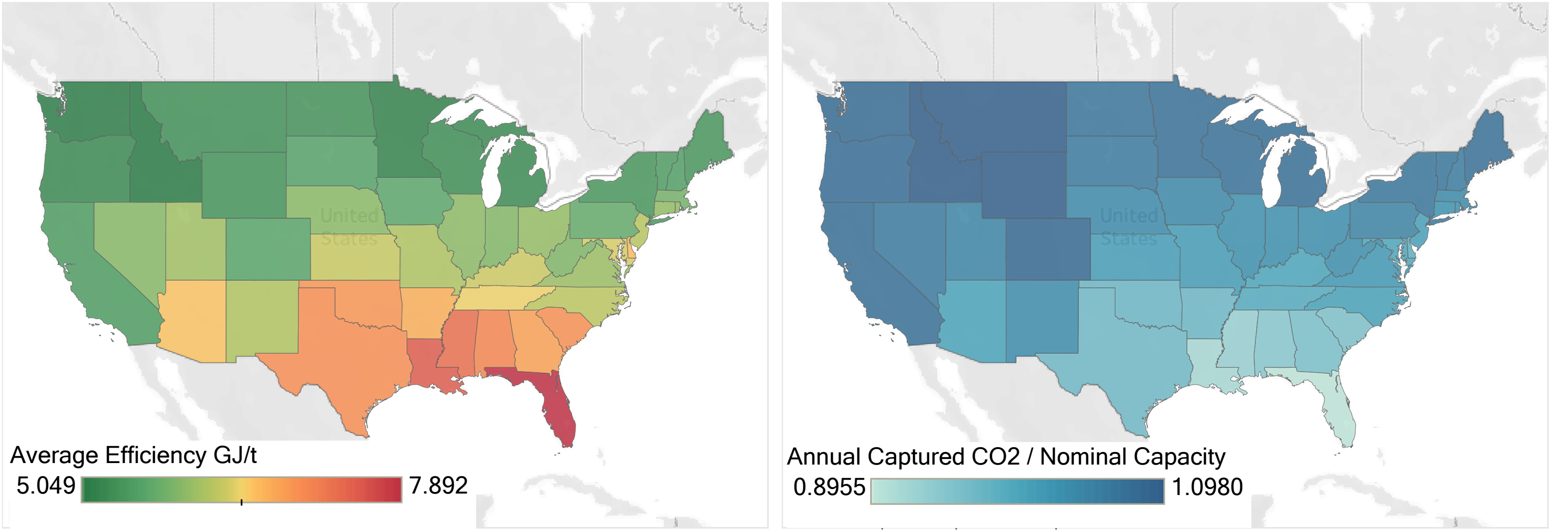


Direct Air Capture technology updates

Improvement:

DAC model for liquid solvent and solid sorbent techs 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 across each state were averaged to create efficiency and capture rate values, shown for the solid sorbent technology

Solid Sorbent Technology



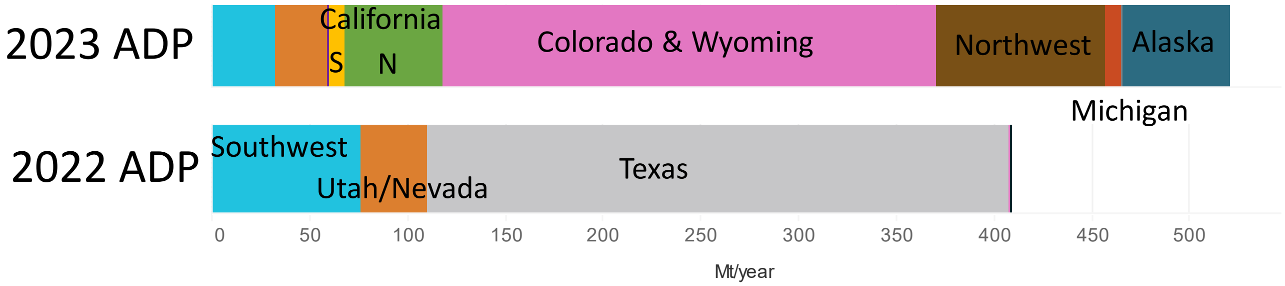
Average Capture Efficiency*

Annual Capture Rate

Result:

Last year the Drop-In scenario built over 400 Mt/year DAC capacity with 75% built in Texas. This year, Drop-In scenario built 520 Mt/year the majority was built in mountain west and in the northwest.

Drop-In Scenario DAC Capacity



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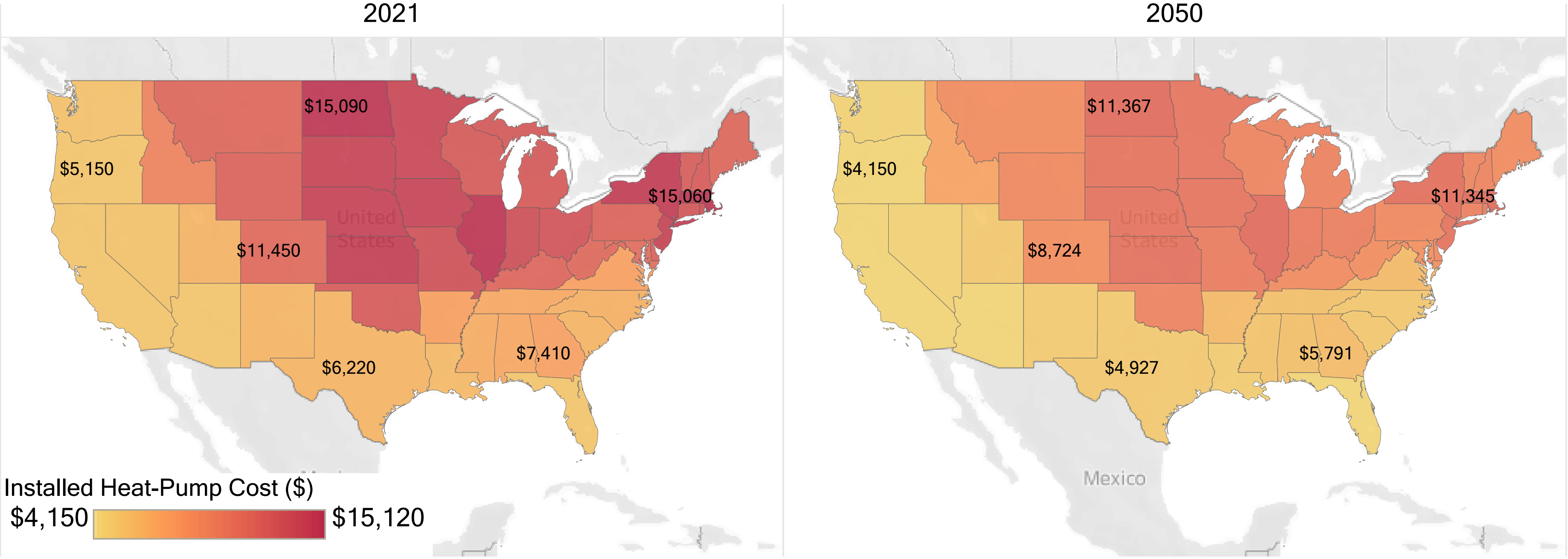
* Efficiency numbers do not include the potential savings from the use of heat pumps

Heat pump technology cost

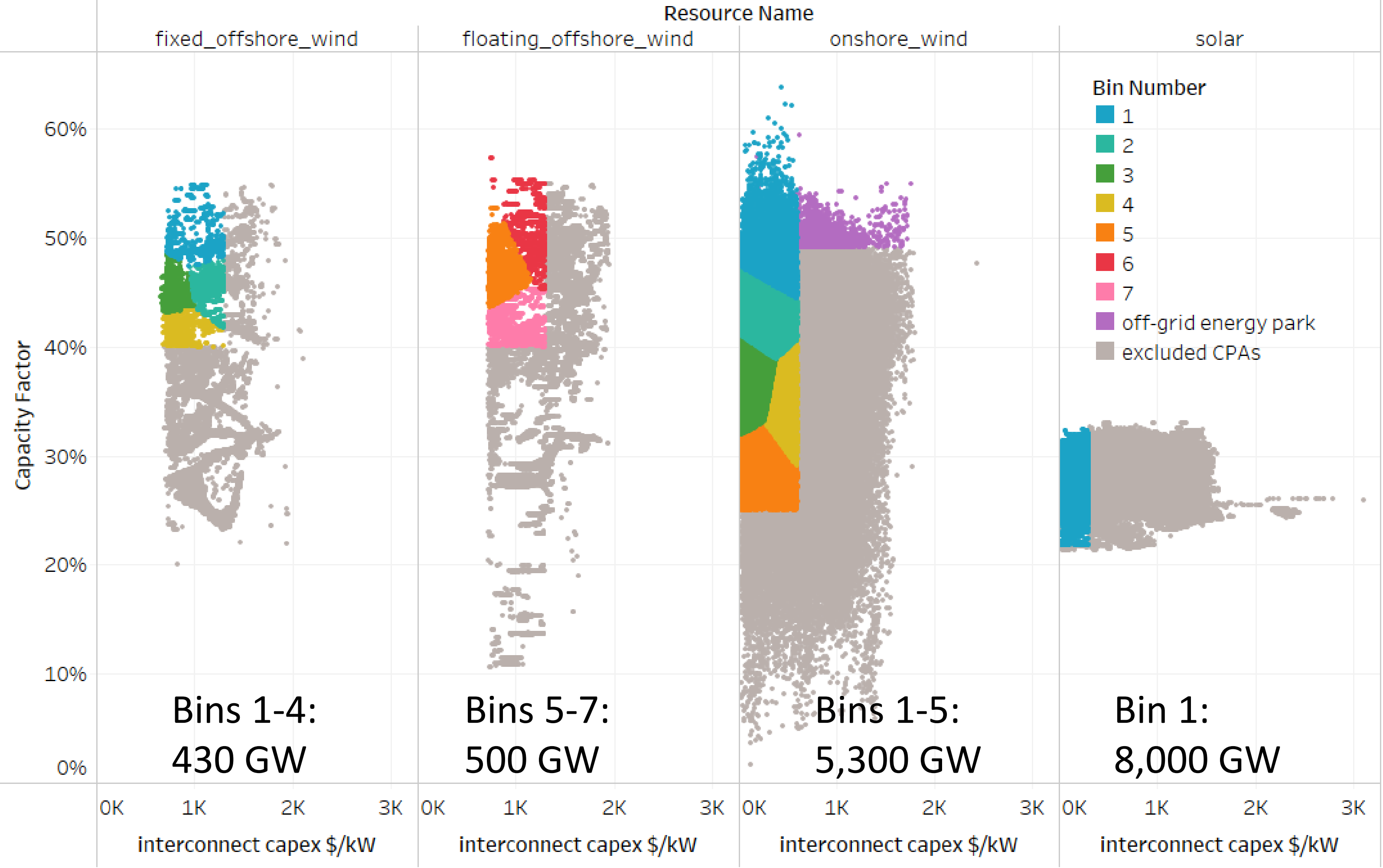
Single family home installed heat pump cost



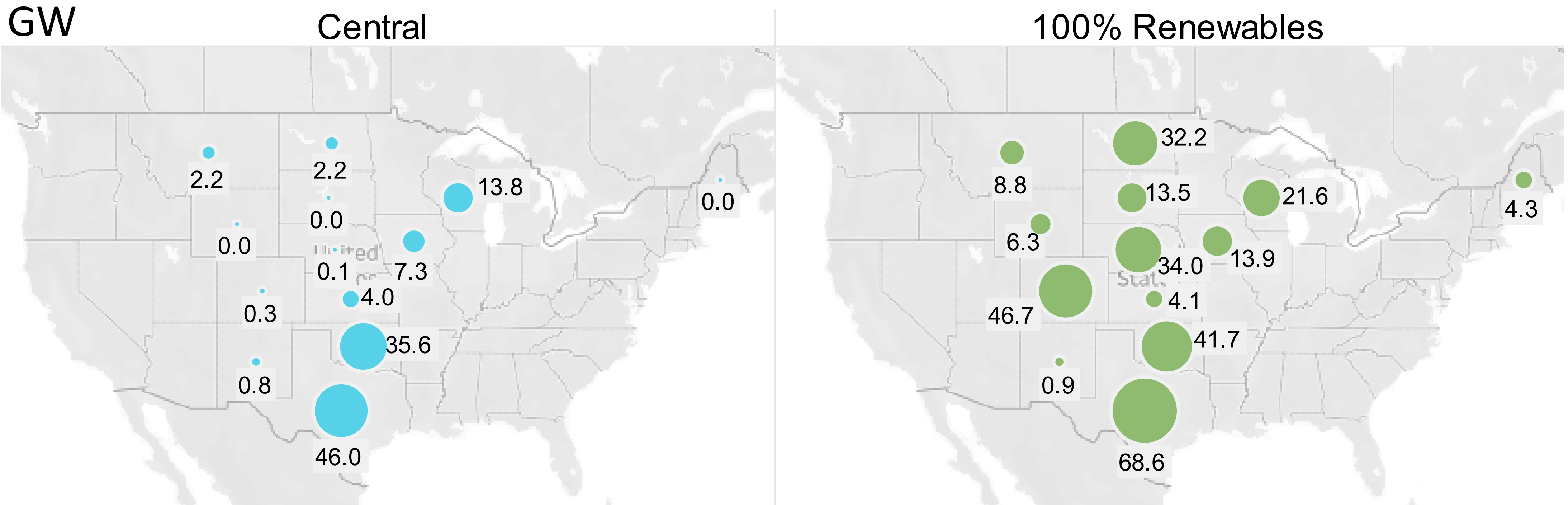
- Residential heating system cost in our past work (like EFS) have assumed uniform size across the U.S.
- These assumptions have been updated using NREL ResStock data and an analysis of peak heating demand across U.S. counties.

Energy park potential

- We have developed an Energy Park technology representation as part of the 2023 ADP by isolating those candidate project areas with the highest capacity factors and highest transmission costs
- It is understood that moving hydrogen in bulk can be an order of magnitude cheaper than moving electricity. This creates an opportunity to develop wind resources further from population centers for the purpose of creating fuels and then piping those fuels to different demand applications.



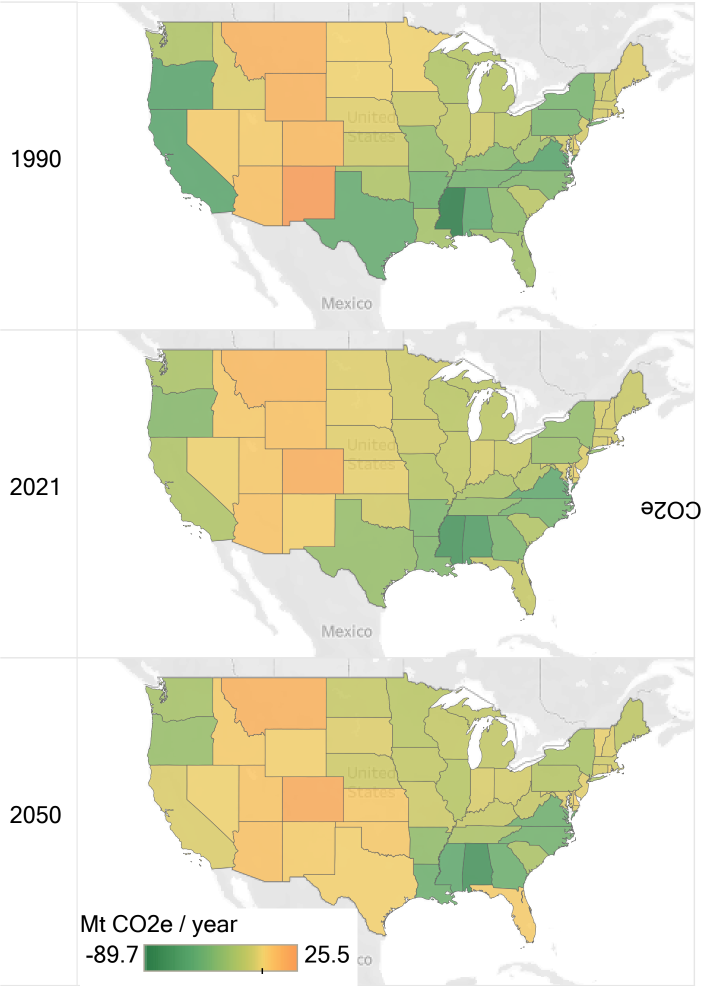
Energy park deployment

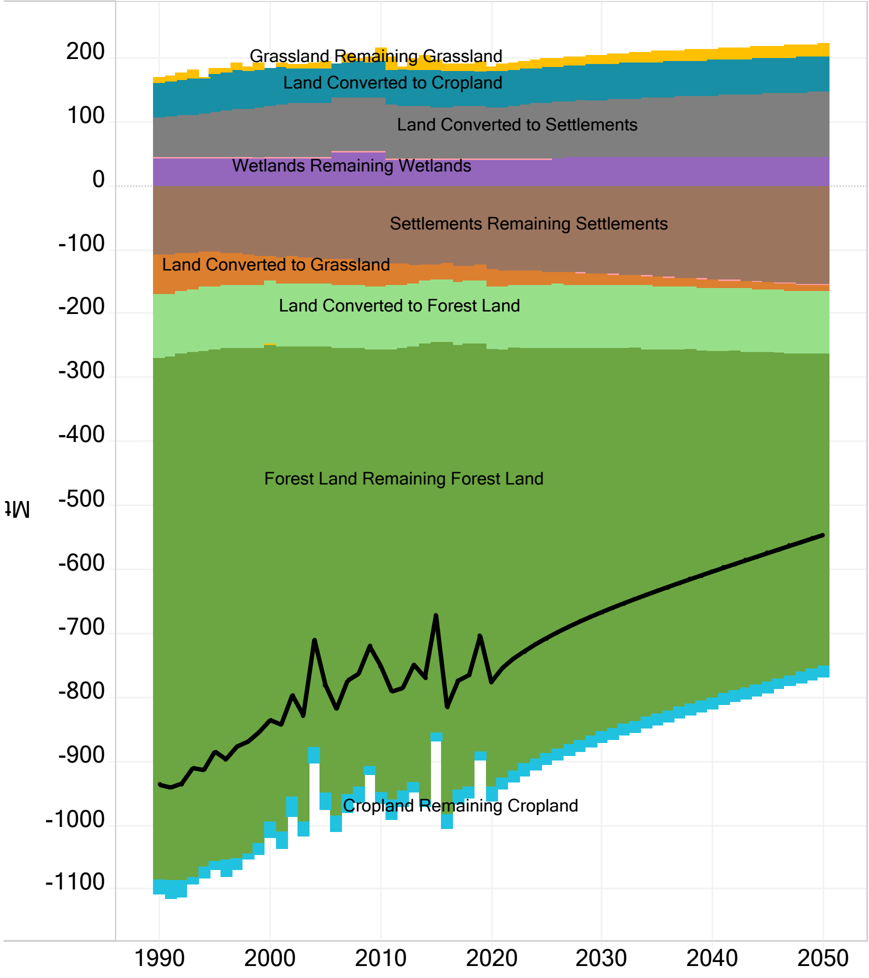


- Energy parks for hydrogen production were used by the model across all net-zero scenarios
- This is an important exception to a dynamic that is often discussed in our past work, which is the value of grid connected electrolysis for balancing a high renewable power system (electrolysis can still be 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 transmission and minimizing siting conflicts becomes more important.

U.S. baseline land sink

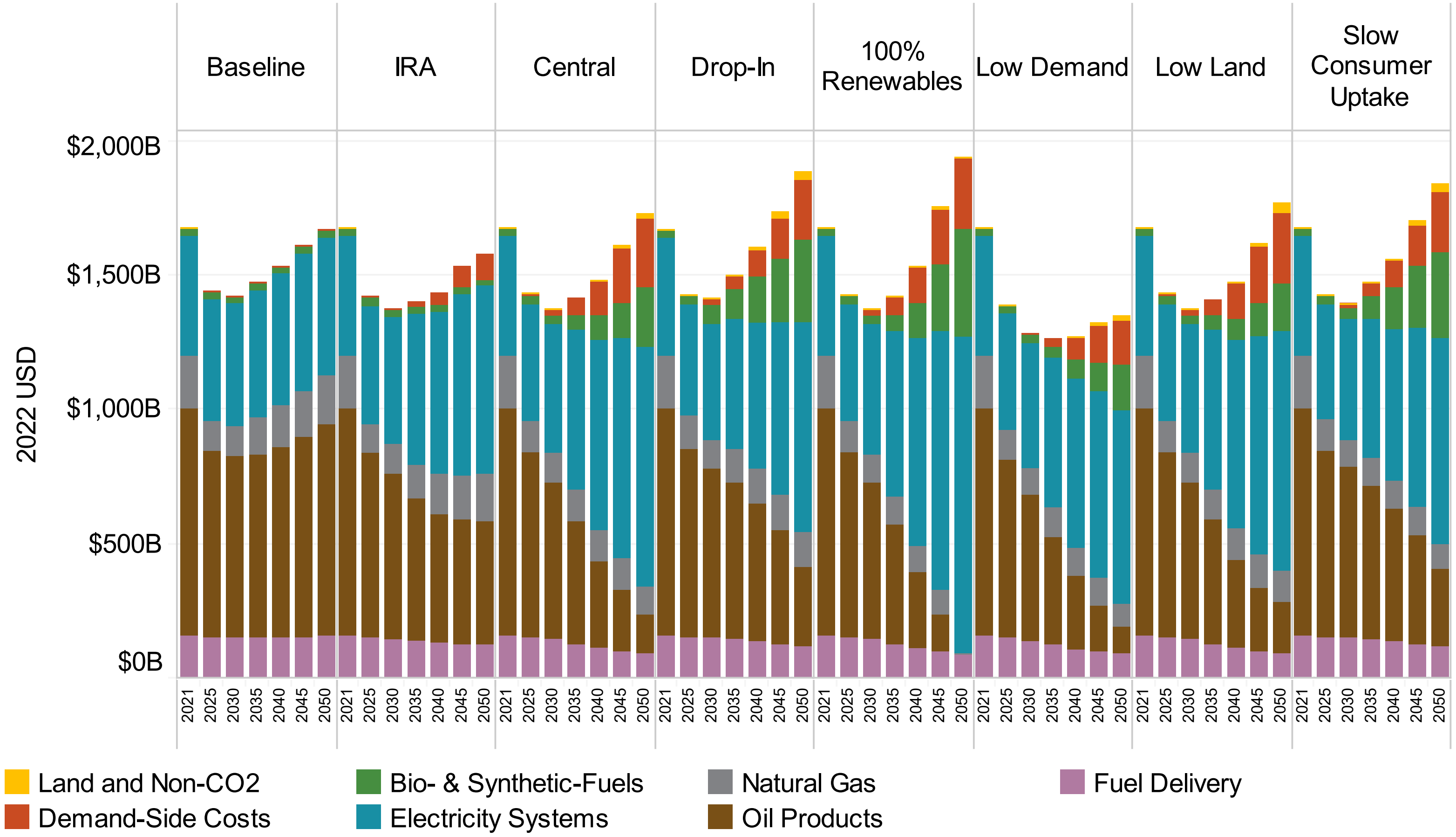
- New outputs provide a better look at total greenhouse gas emissions for a sub-national geography and the existing land-sink baseline is better understood compared to ADP 2022.
- This data can be very important for states trying to understand what a low carbon energy transition looks like within their boundaries.





Gross energy system cost

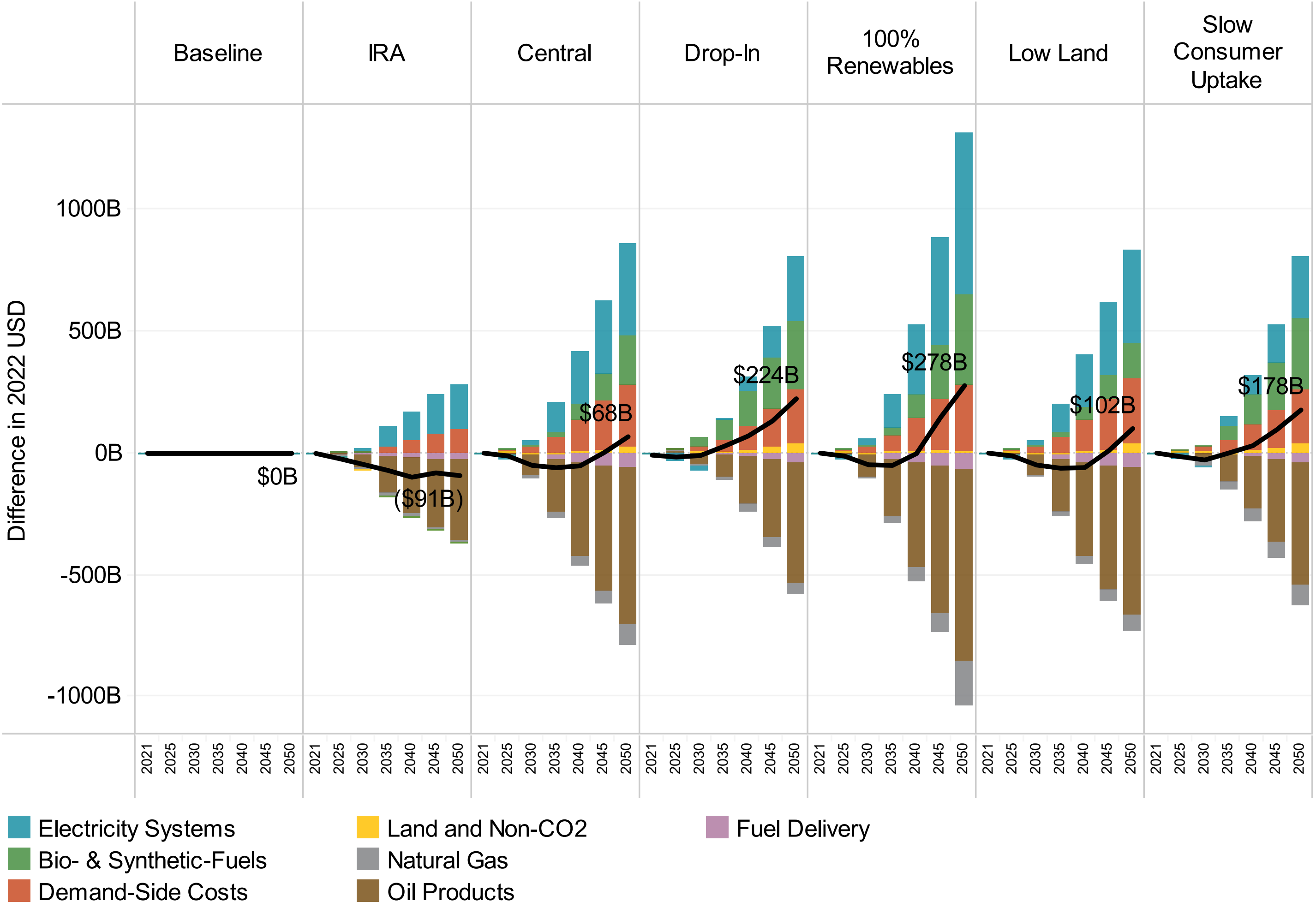
- The gross annual system cost of the net-zero energy system as well as land sector and non-energy, non-CO2 mitigation measures is shown across all scenarios.
- For energy system costs, this is the annualized cost capital and operating cost for both energy supply (electricity and fuels) and energy end-use 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 for 2021.



Net Cost of Achieving Net-Zero Greenhouse Gases

EVOLVED ENERGY RESEARCH

- Costs are net of the Baseline scenario and represent the sum of levelized capital costs and variable costs in each modeled year.
- The Central scenario has a net cost of $68B/y above that level and $159B/y above the IRA scenario.
- Total investment in electricity generation is $4.5T in the Central scenario



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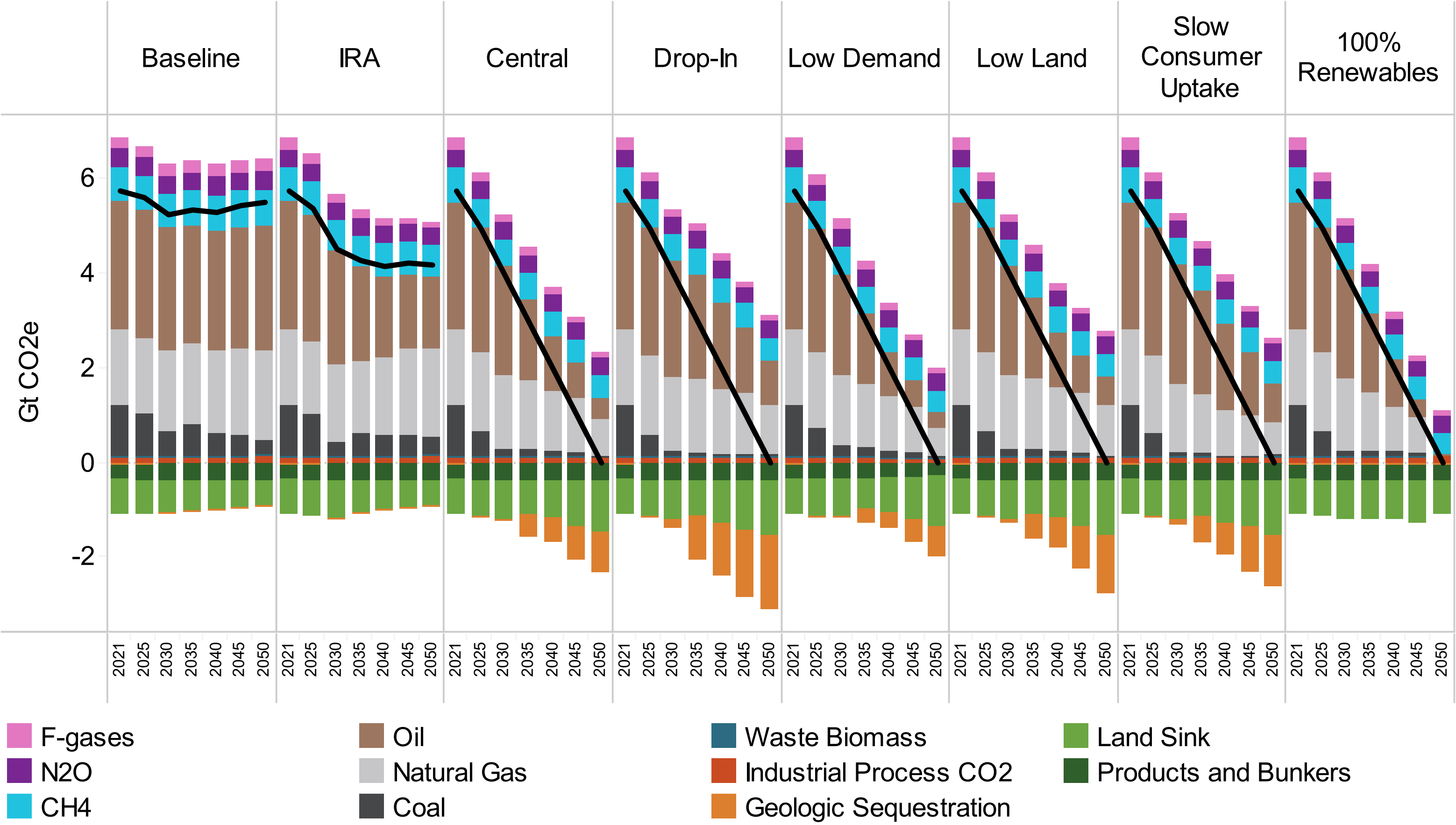
Supplemental Results

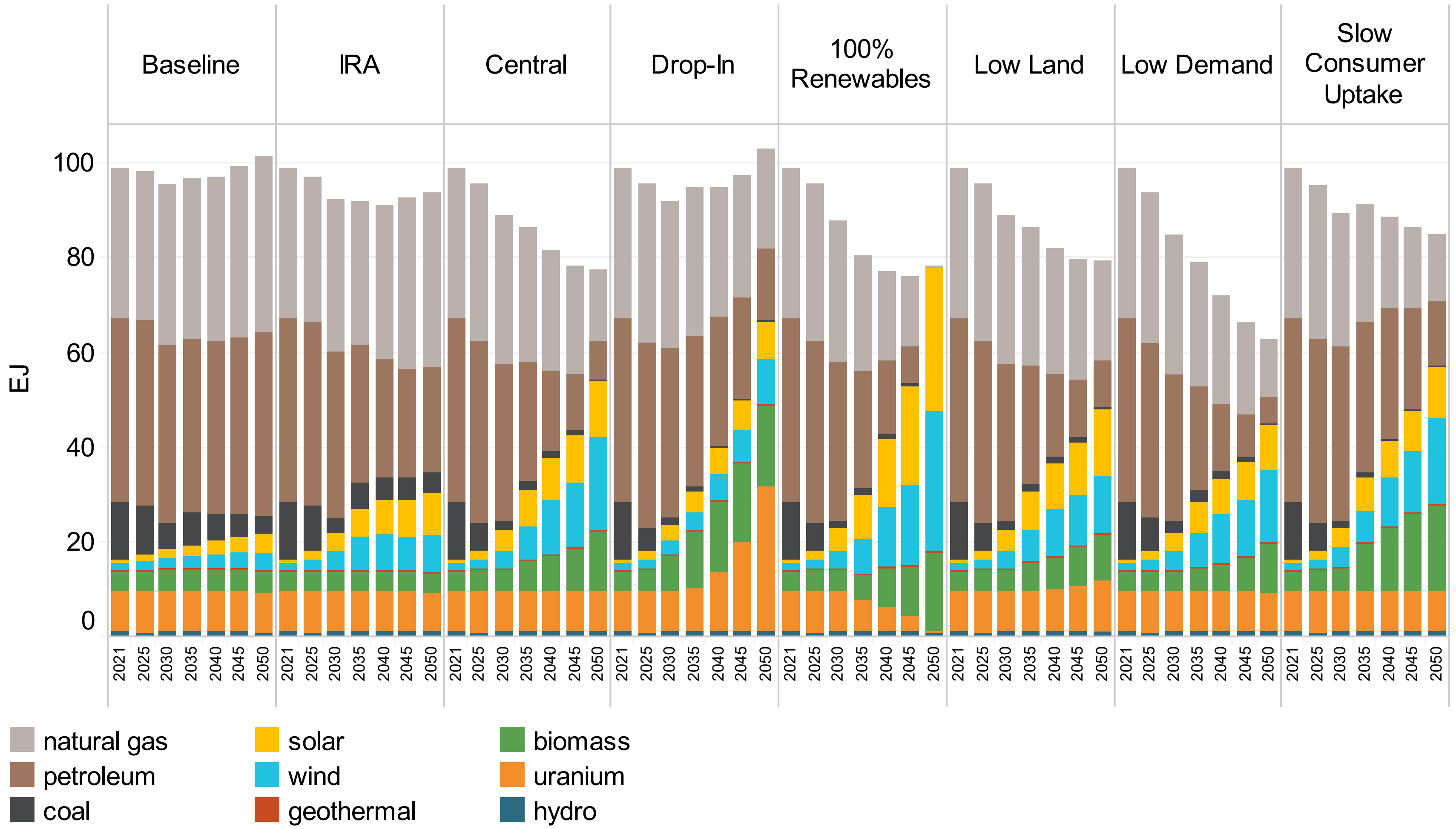
Greenhouse gas emissions by scenario (Gigatonnes)

EVOLVED ENERGY RESEARCH

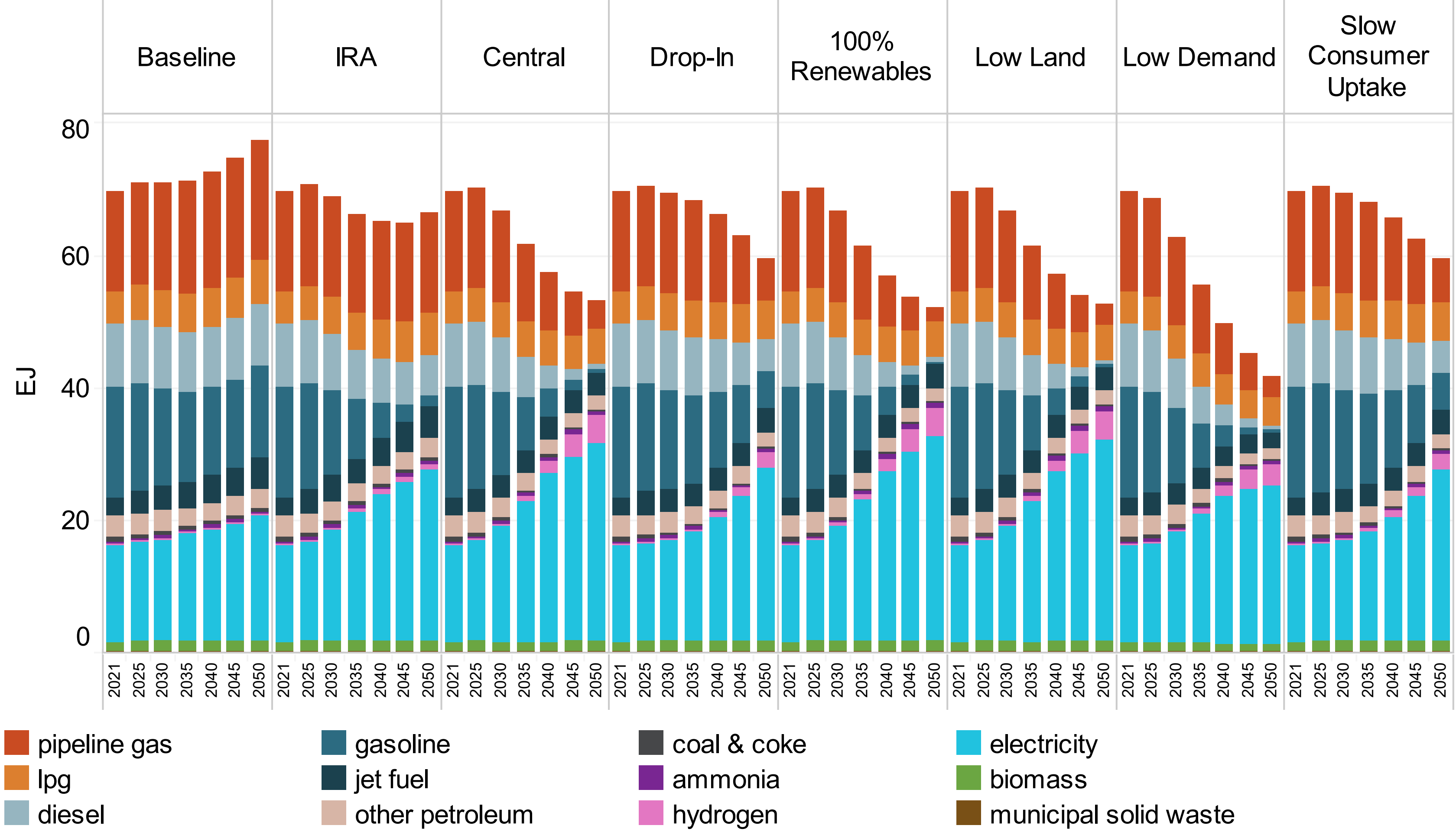
All net-zero scenarios are constrained to take a straight line path to net-zero emissions in 2050. The IRA scenario is shown to reduce annual emissions by one gigatonne per year in the year 2035 from 5.34 gigatonnes in the baseline to 4.27 gigatonnes in the IRA scenario. IRA policies induce 100 million tonnes per year of CO2 capture by 2040, primarily from cement and ethanol, but most of this captured CO2 is used to synthesize fuels rather than being sequestered. This provides a pairing with hydrogen produced from electrolysis.



Primary energy consumed domestically

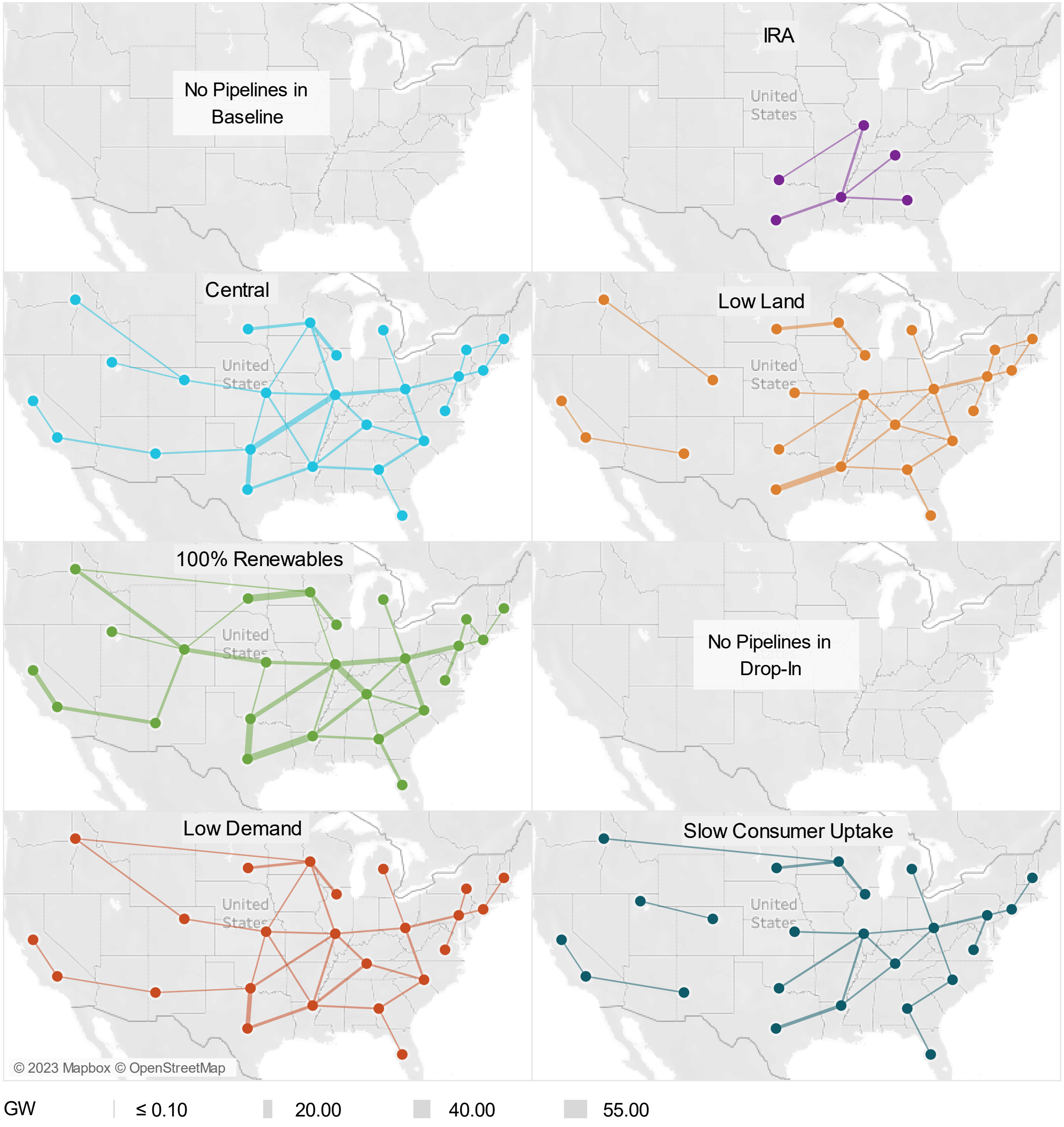


Final energy



Electric Transmission

Hydrogen Pipelines



Electricity capacity

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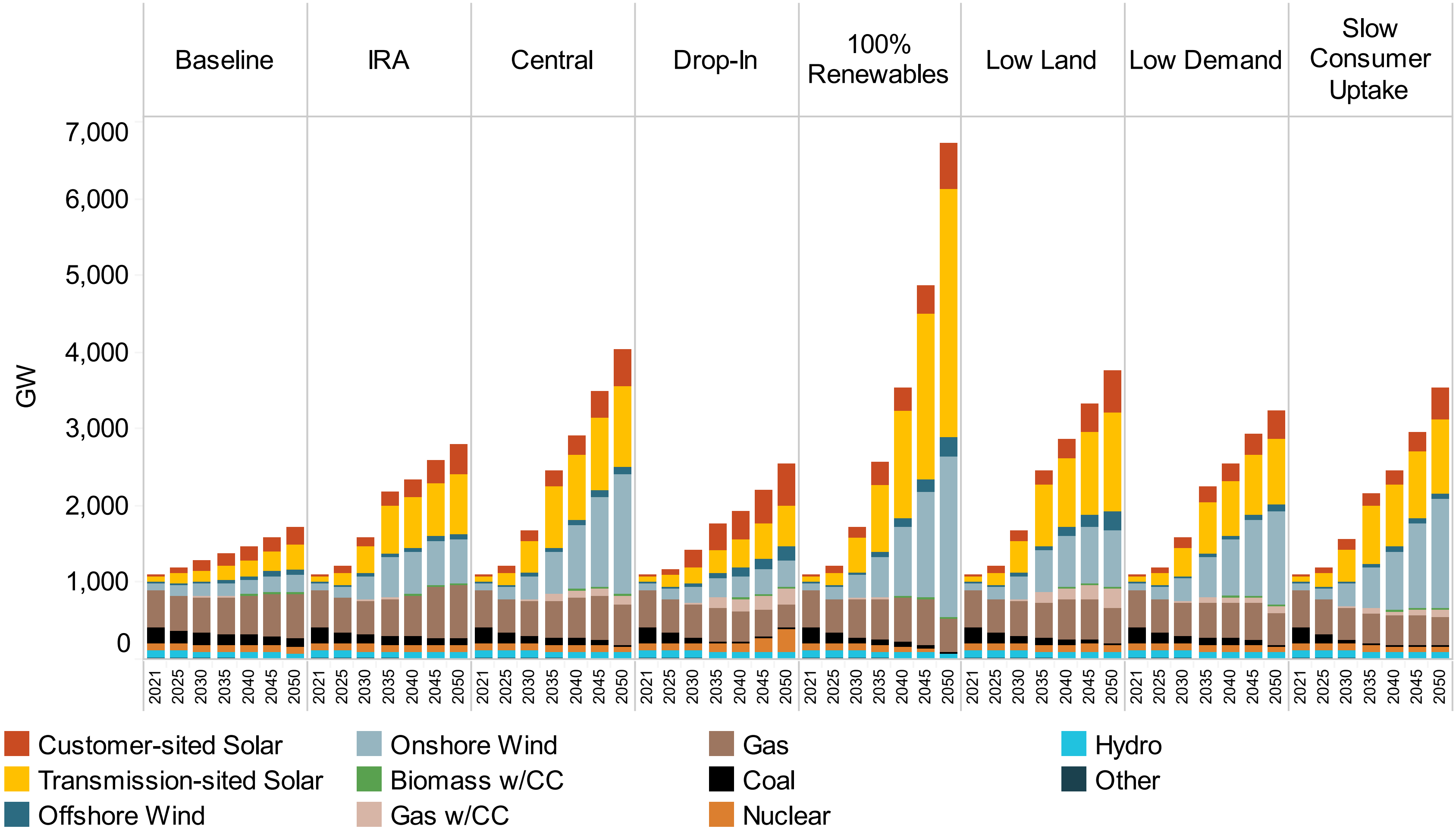

Electricity generation

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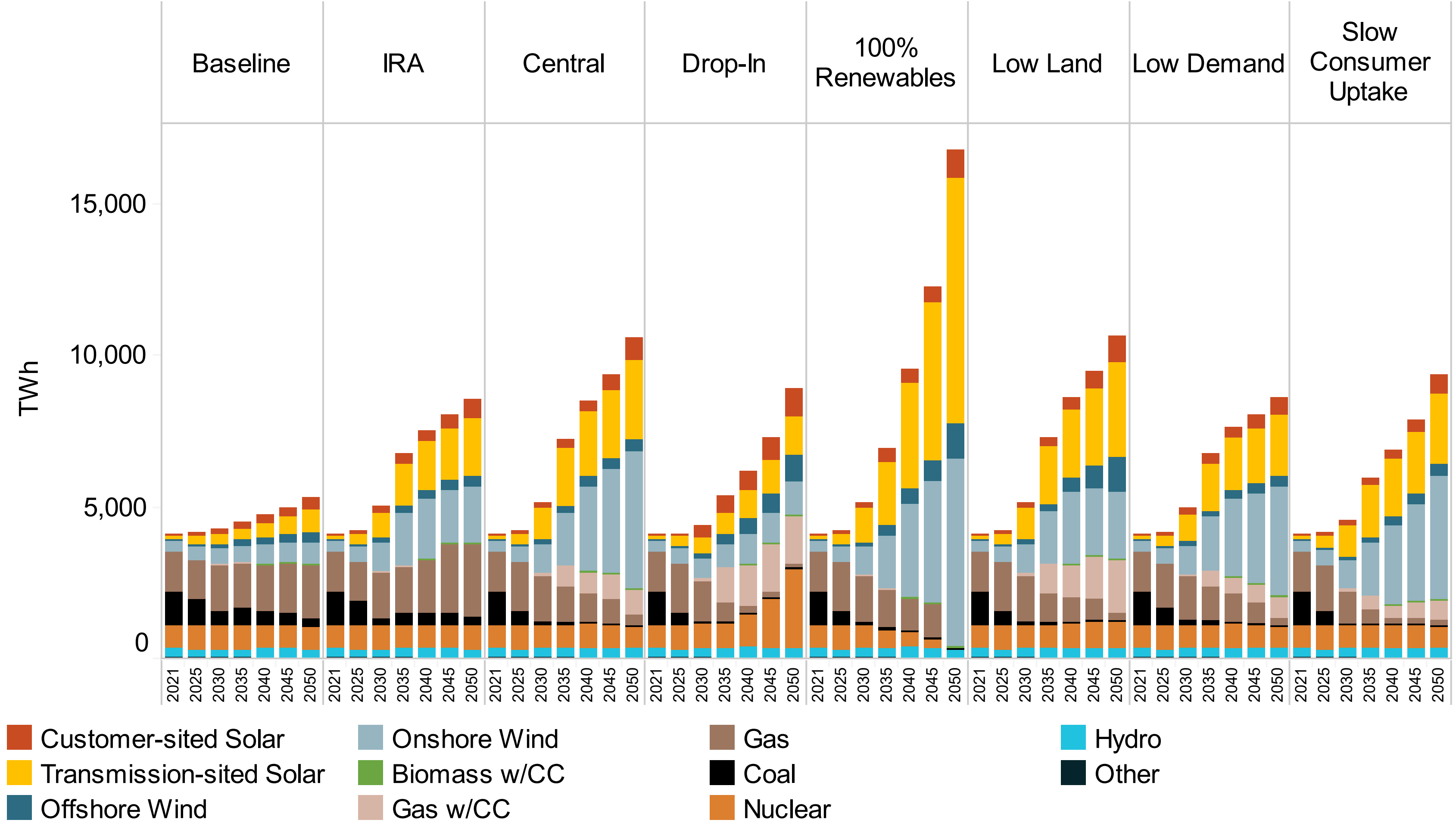
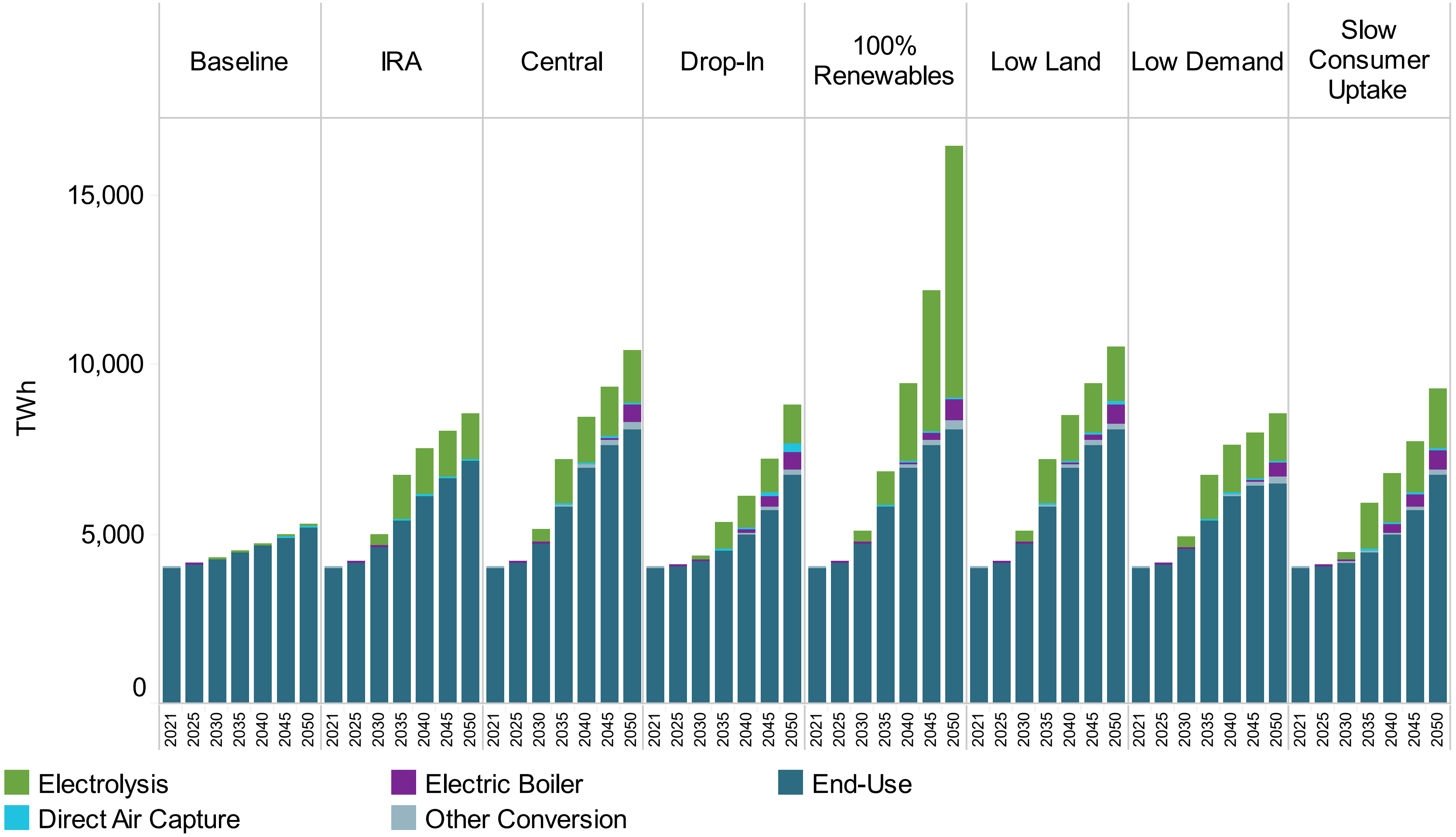
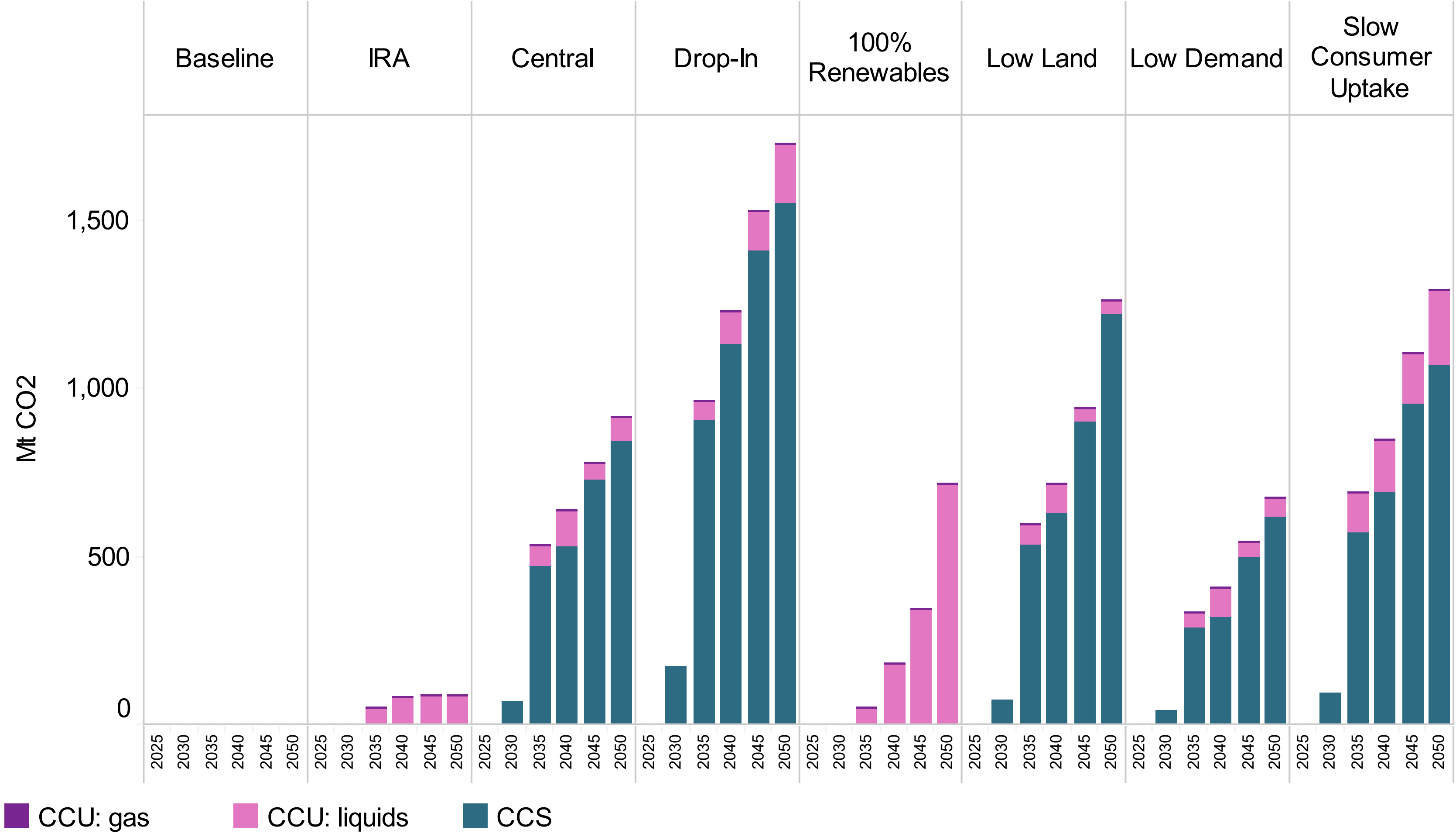


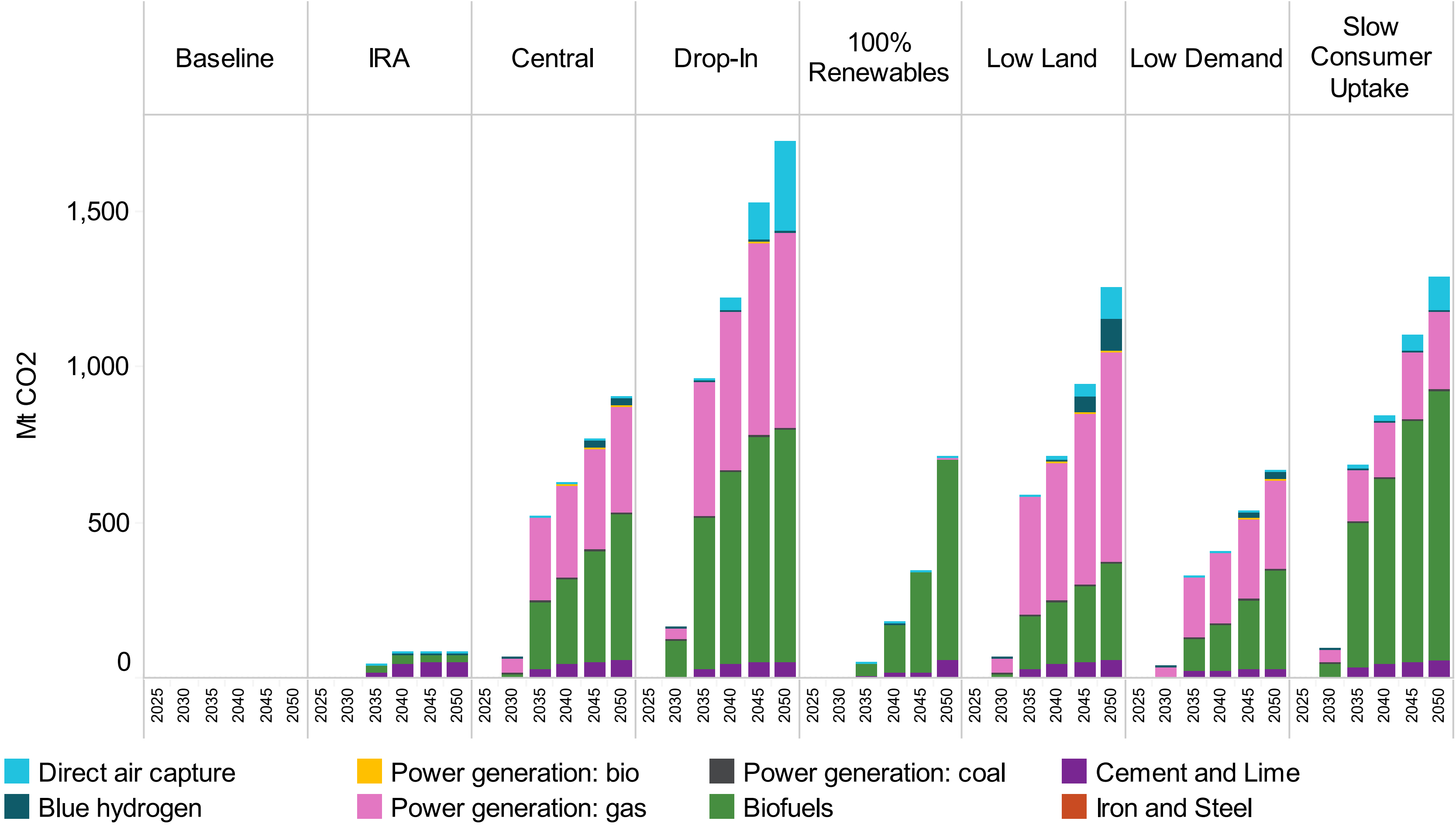
Electricity load



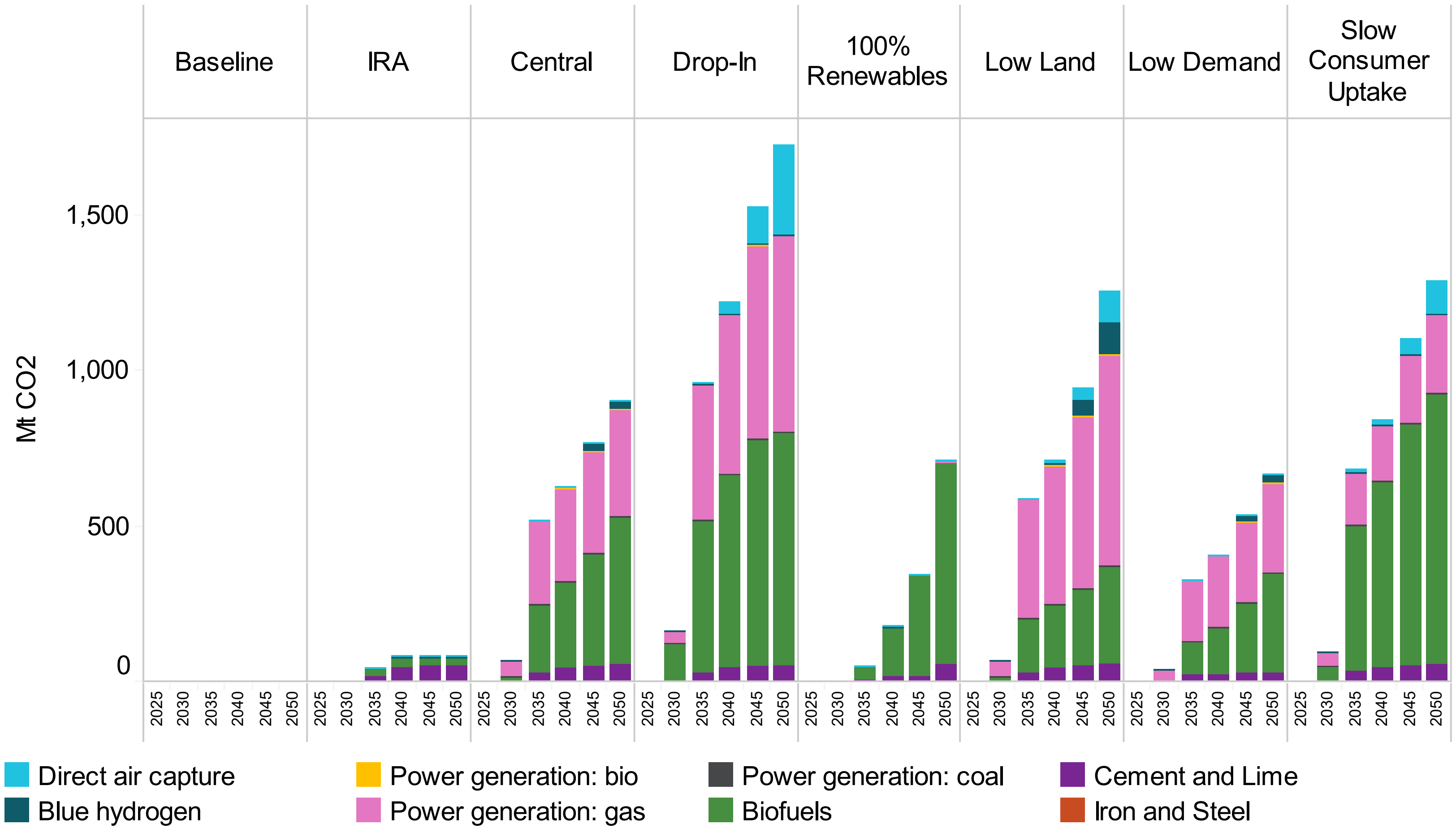
Use of captured carbon



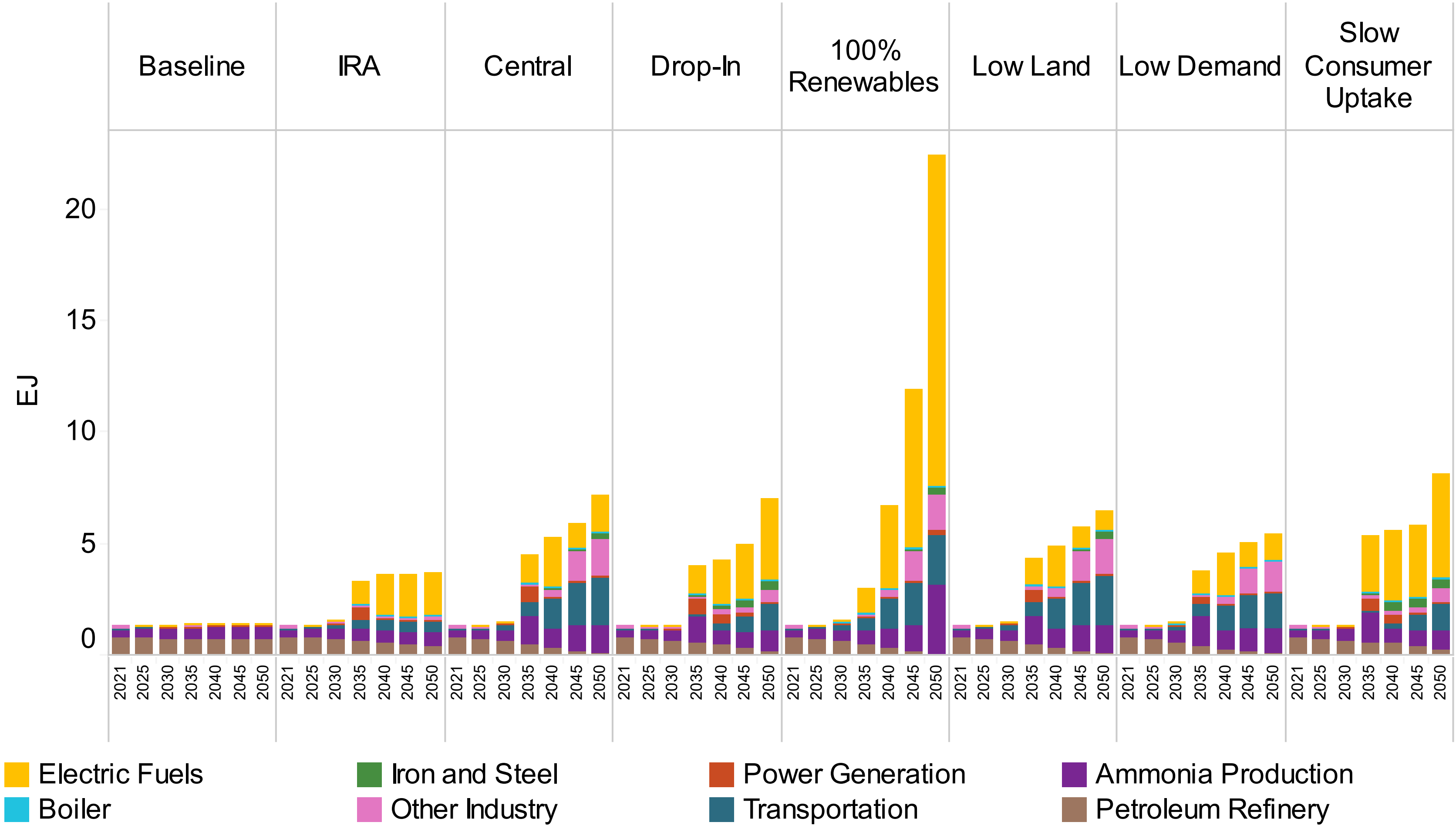
Source of captured carbon



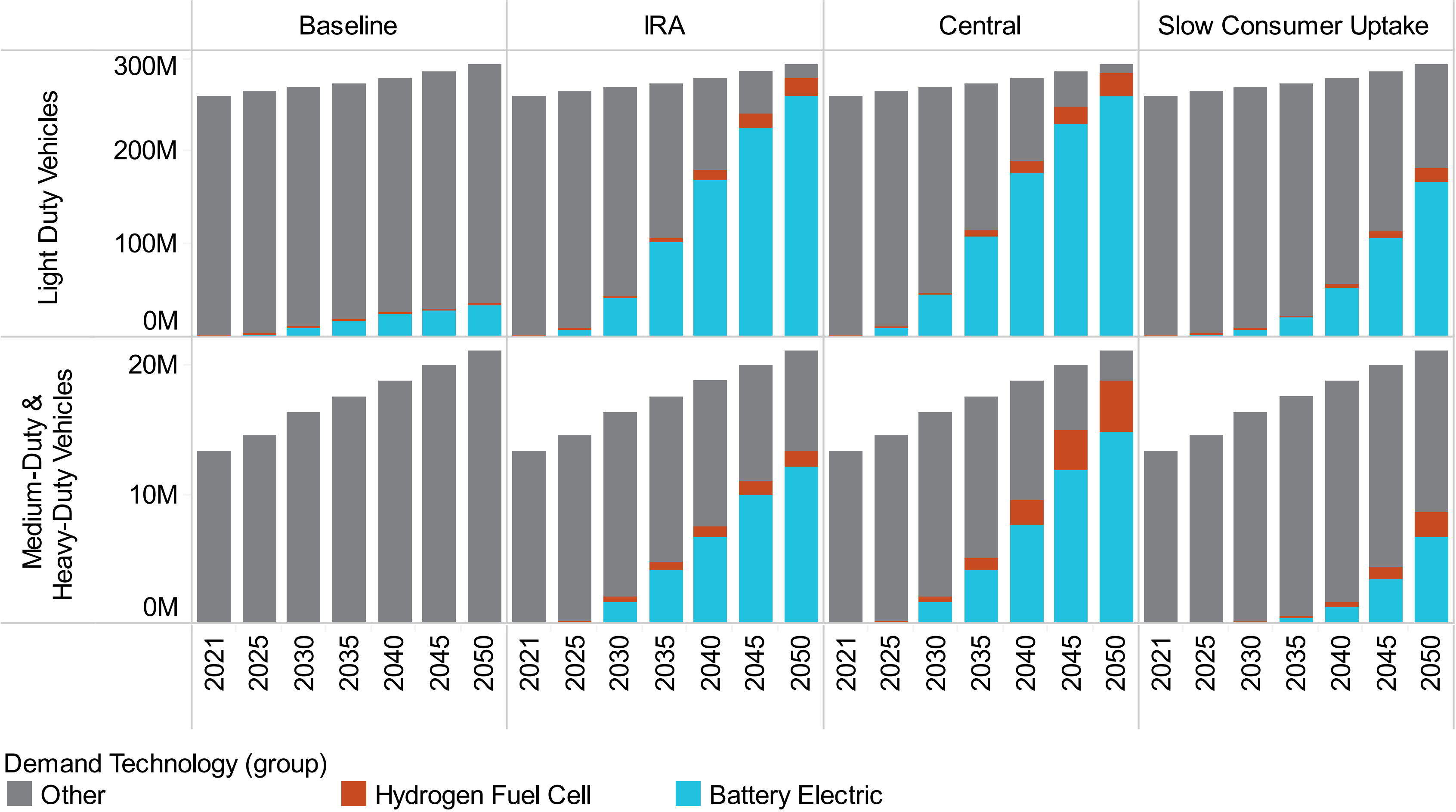
Hydrogen production



Hydrogen consumption



On road transportation stock



Residential building heating technologies

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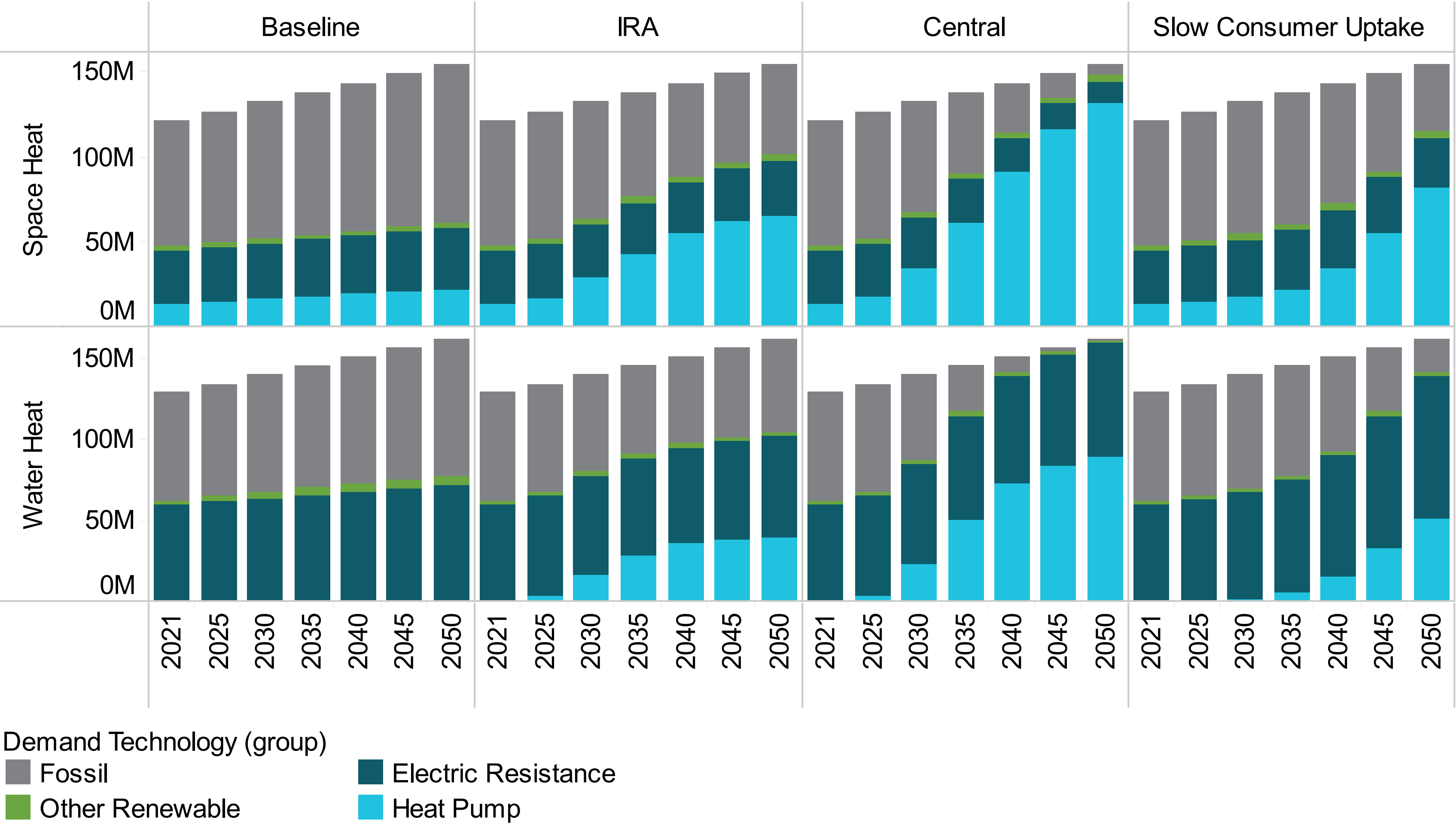
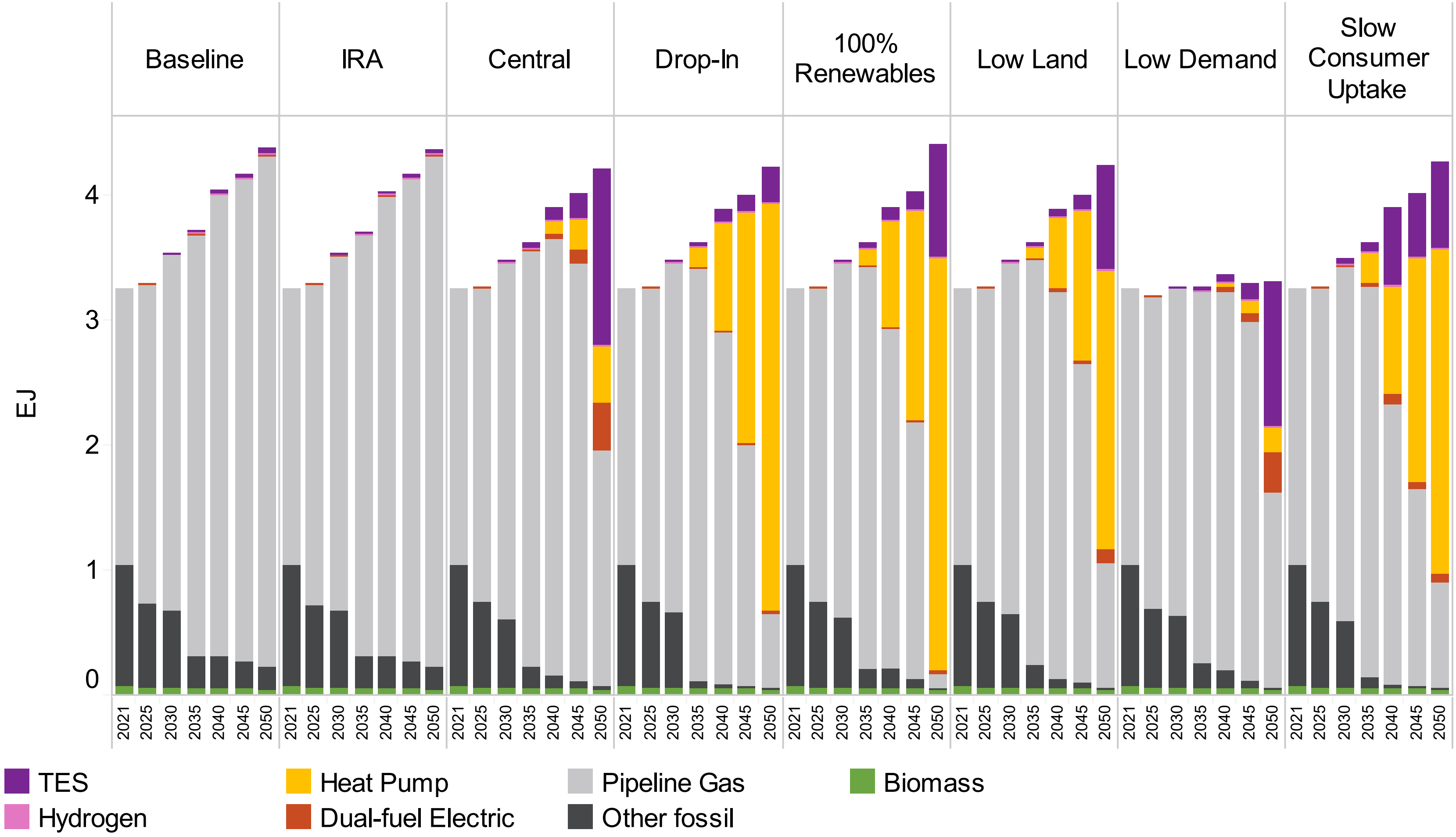
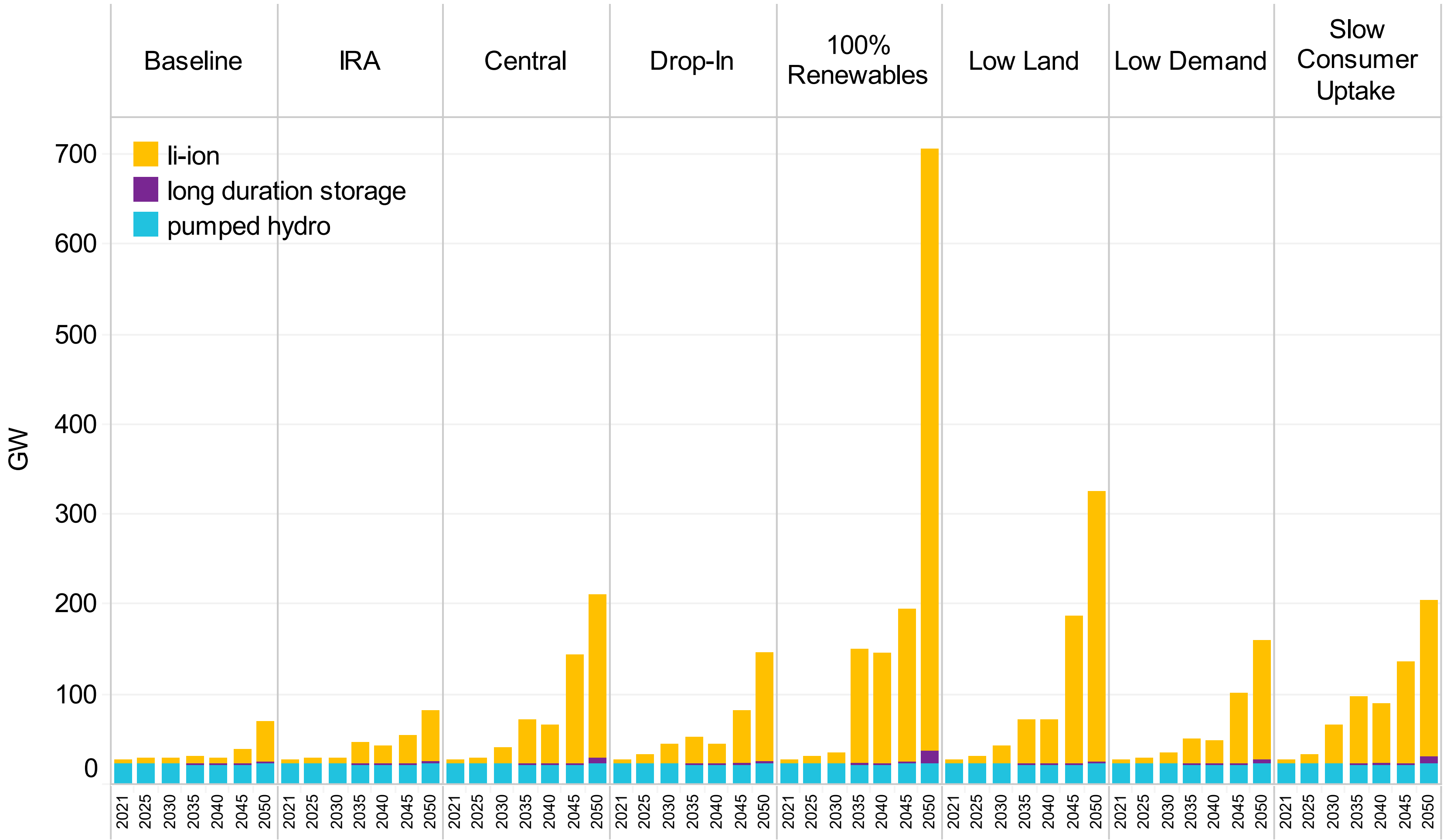


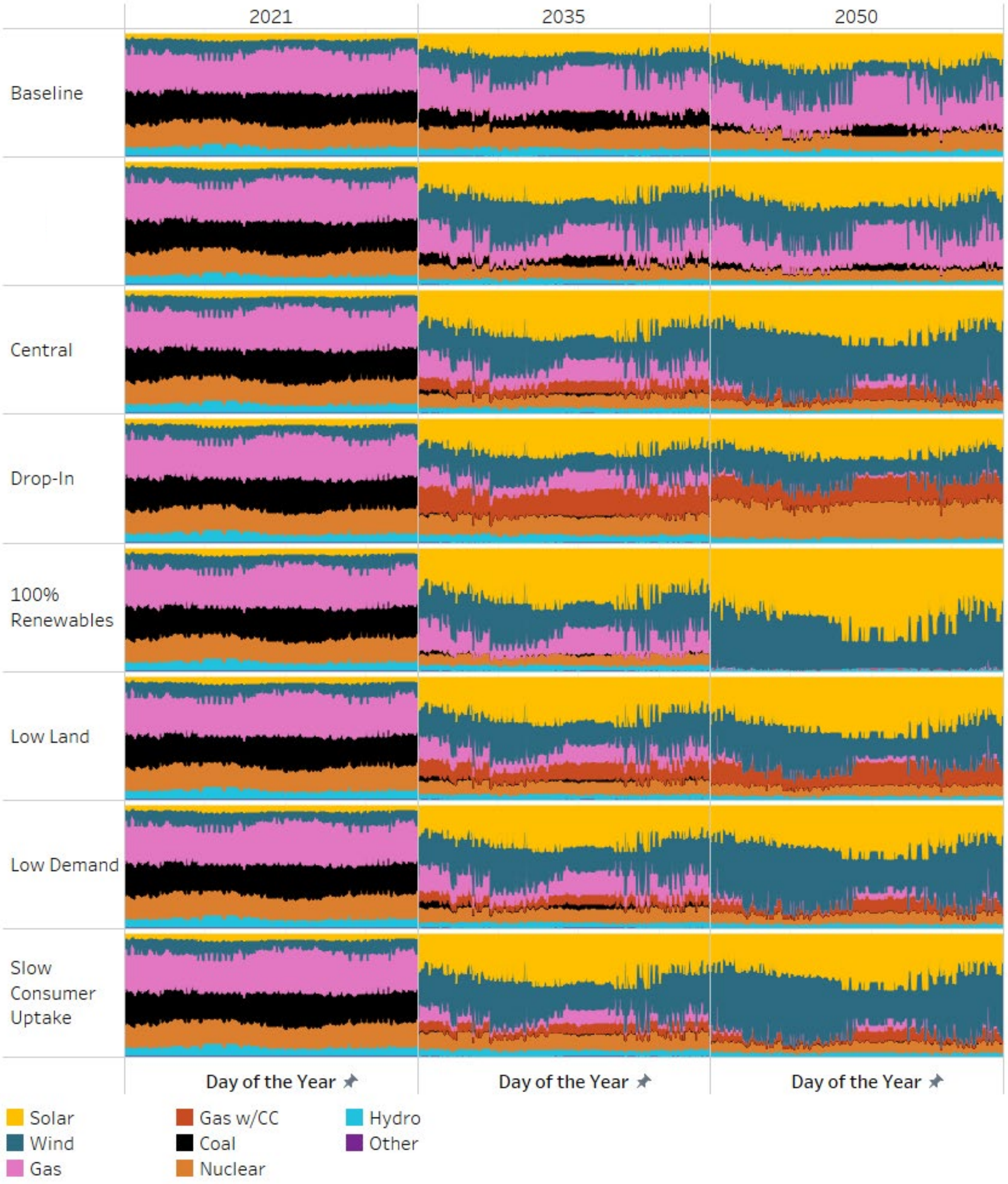
Steam production

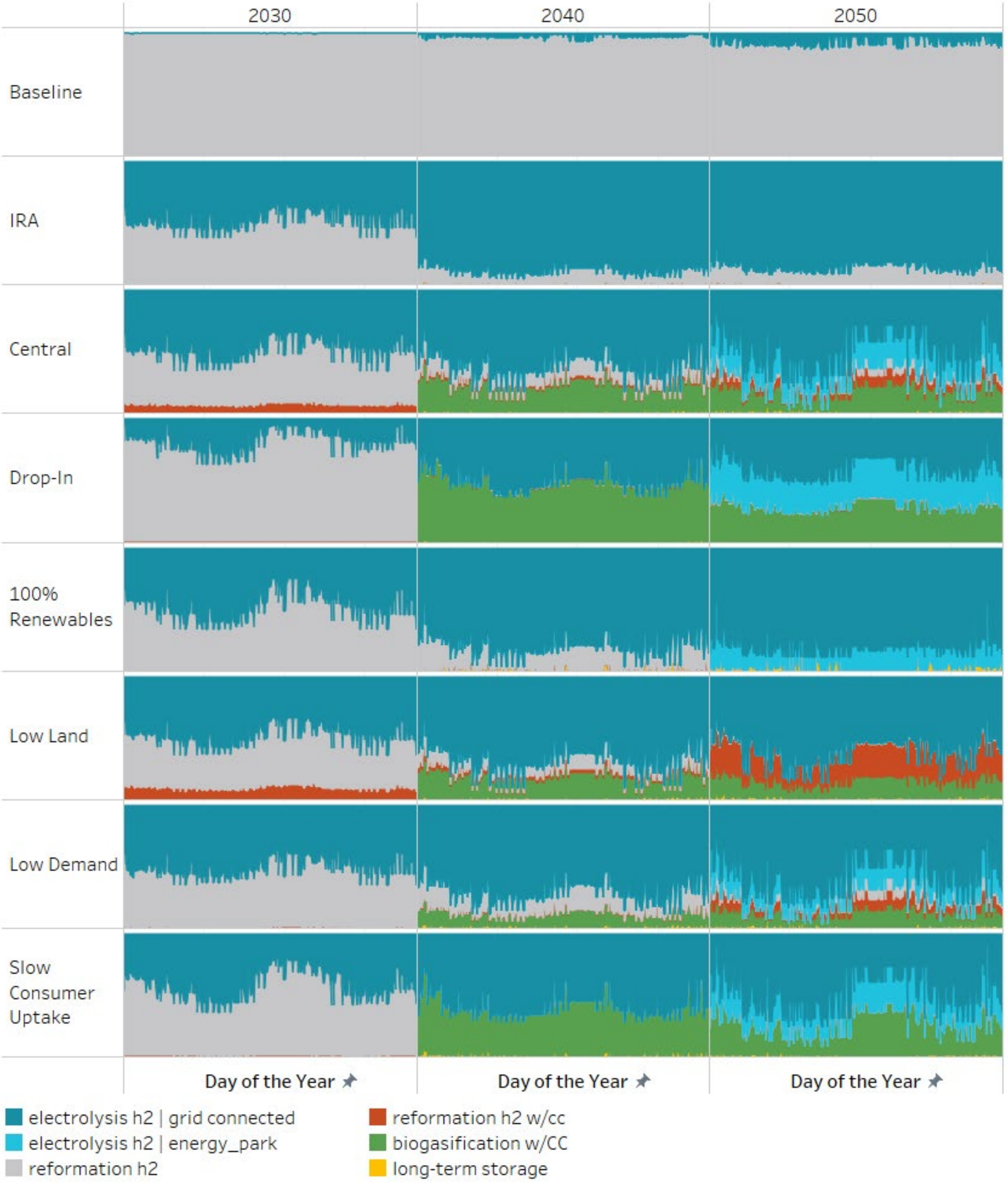


Electricity storage capacity (GW)

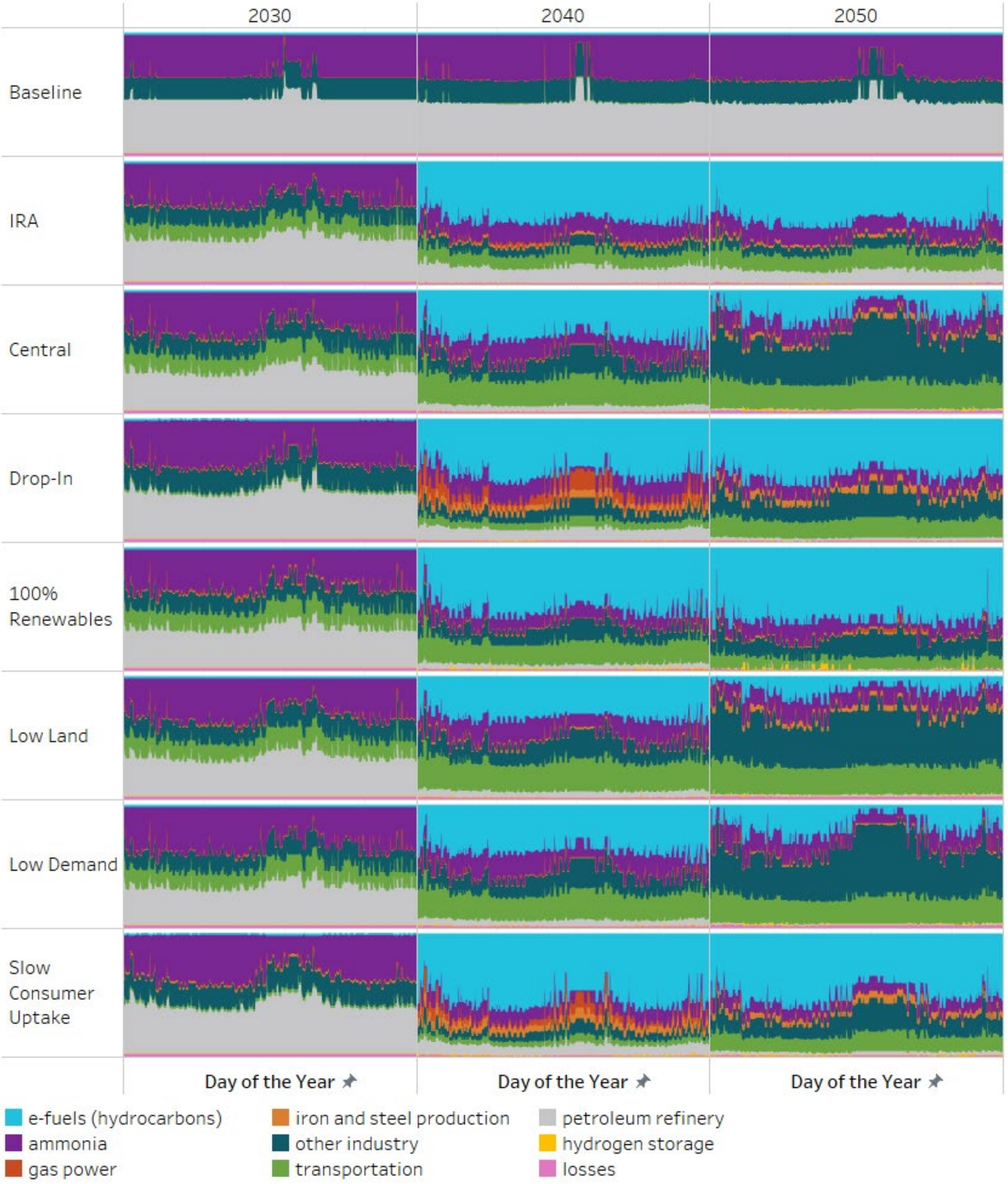


Generation share of U.S. electricity by day of the year and scenario





Hydrogen Production



Hydrogen Consumption

THANK YOU

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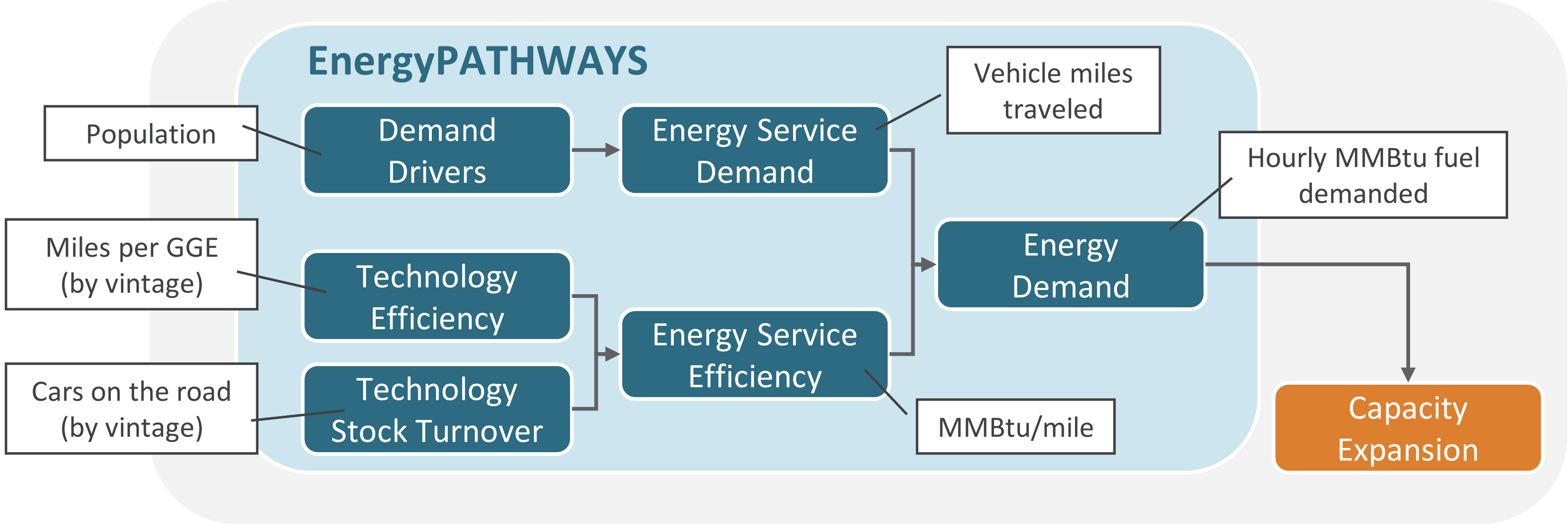
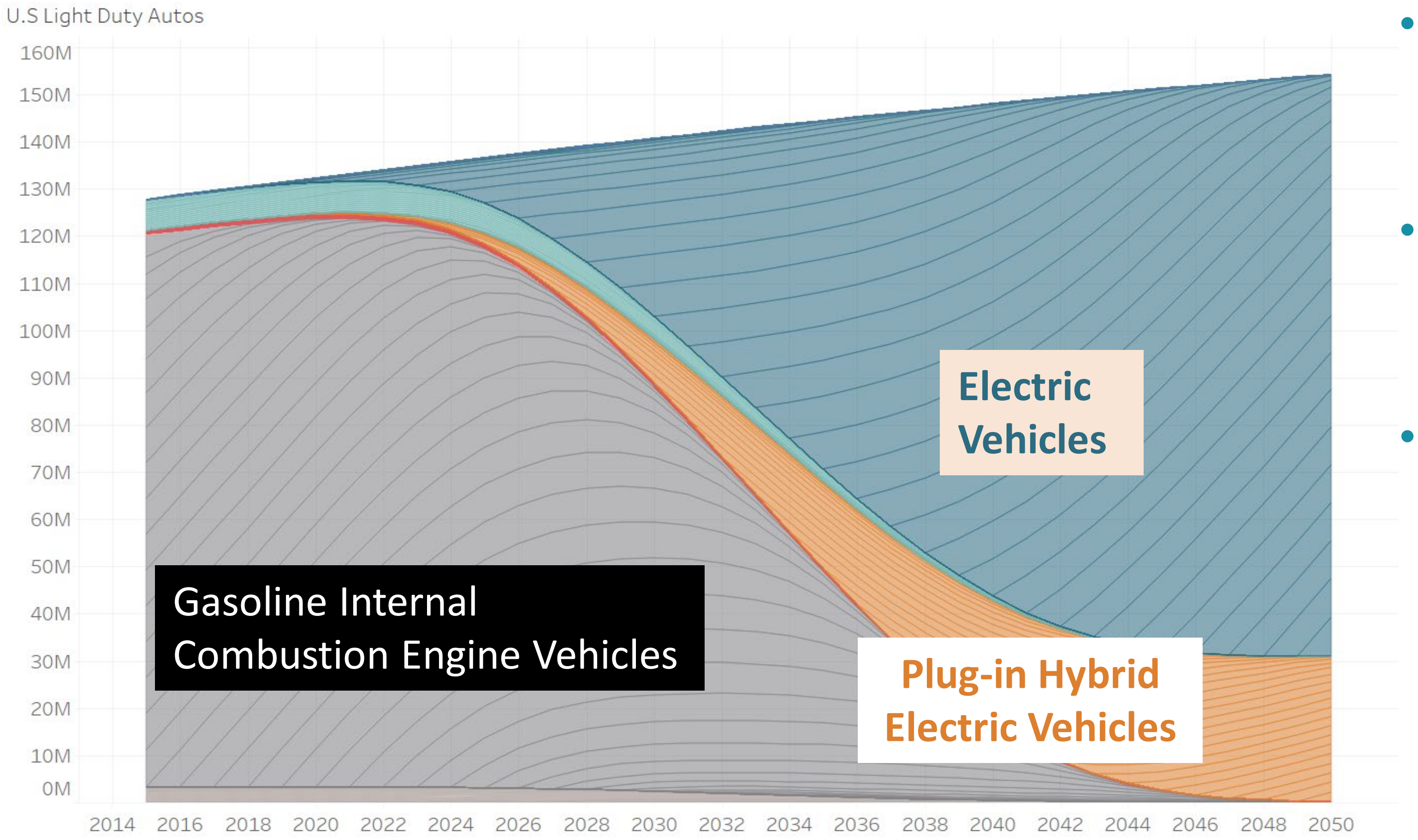
Bottom-up stock turnover models

- EER uses a model called EnergyPATHWAYS, a bottom-up stock accounting model
- The model tracks explicit user decisions about technology adoption and produces final-energy demand and hourly profiles for future years



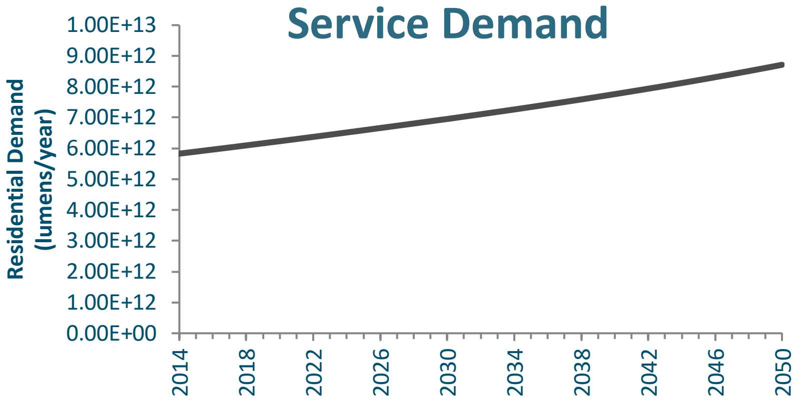
*GGE – Gallon of gas equivalent

Example stock-rollover for Light Duty Automobiles



- Lines denote the vintage of the vehicle stock (i.e., when it's placed in service)
- Vintage impacts technology attributes (efficiency and cost) that can change over time
- Many technologies also have service demand that differs by age (new vehicles are driven more than old vehicles)

Projecting energy demand from the “bottom-up”



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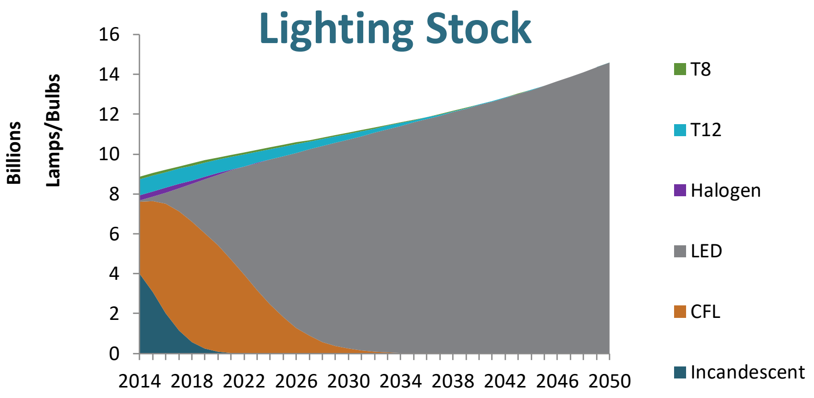

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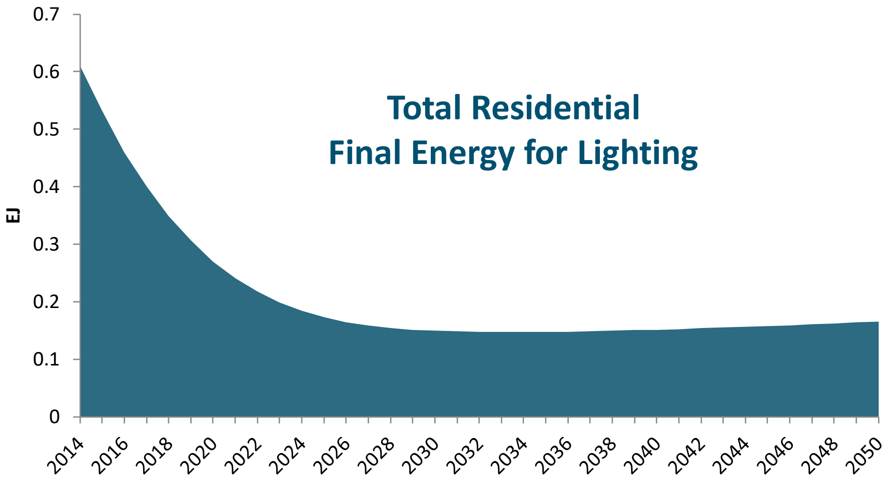
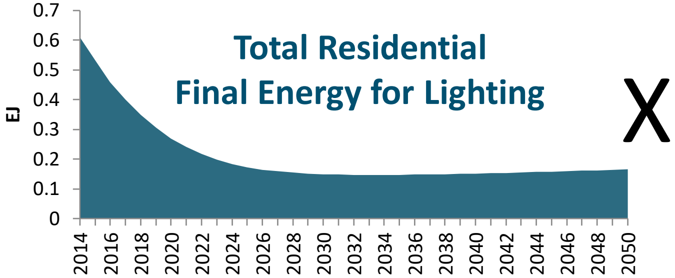


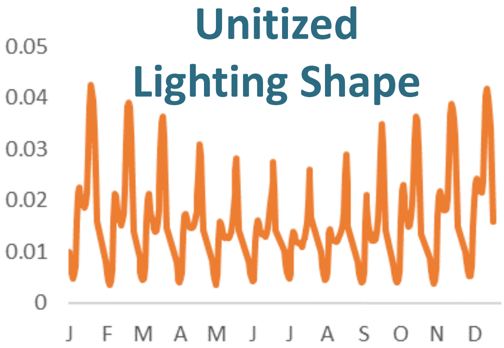
Infrastructure stock rollover model keeps track of “stuff”
(i.e., number of light bulbs by type)

Scenario-based, bottom-up energy model (not optimization-based)

Creating hourly electricity load shapes


Total Residential Final Energy for Lighting

X


Unitized Lighting Shape

=

Projected lighting shape

+

Projected EV shape

+

Projected heating shape

+

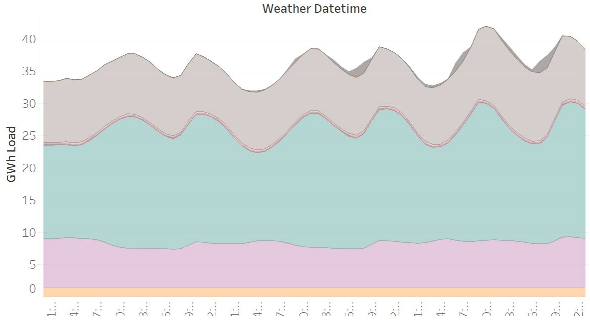
Projected dryer shape

+

Additional demand subsectors

=

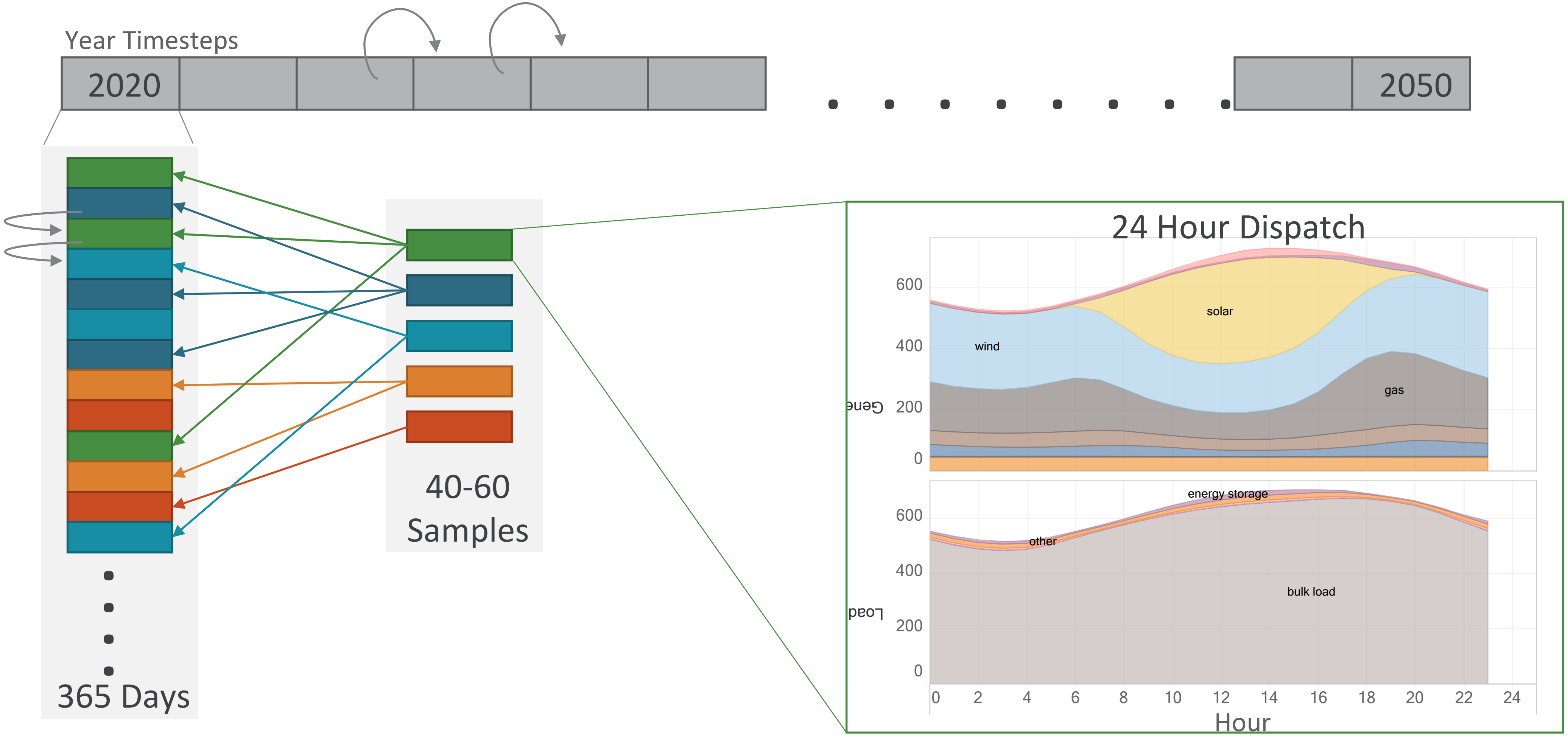
System Load



EnergyPATHWAYS projects future load shapes bottom-up. Annual energy is multiplied by a unitized service demand shape for each subsector and summed across each model region. In the first model year the bottom-up shape is benchmarked against a top-down shape from historical electric utility data. A series of hourly ‘reconciliation factors’ are created from this comparison that represent both bias and random noise not observed in the (often simulated) end-use data. These reconciliation factors are applied to future years.

RIO considers investments and operations to find the least-cost, reliable system

Operations and investment decisions are co-optimized across the study period to find the optimal portfolio



Year Timesteps

2020

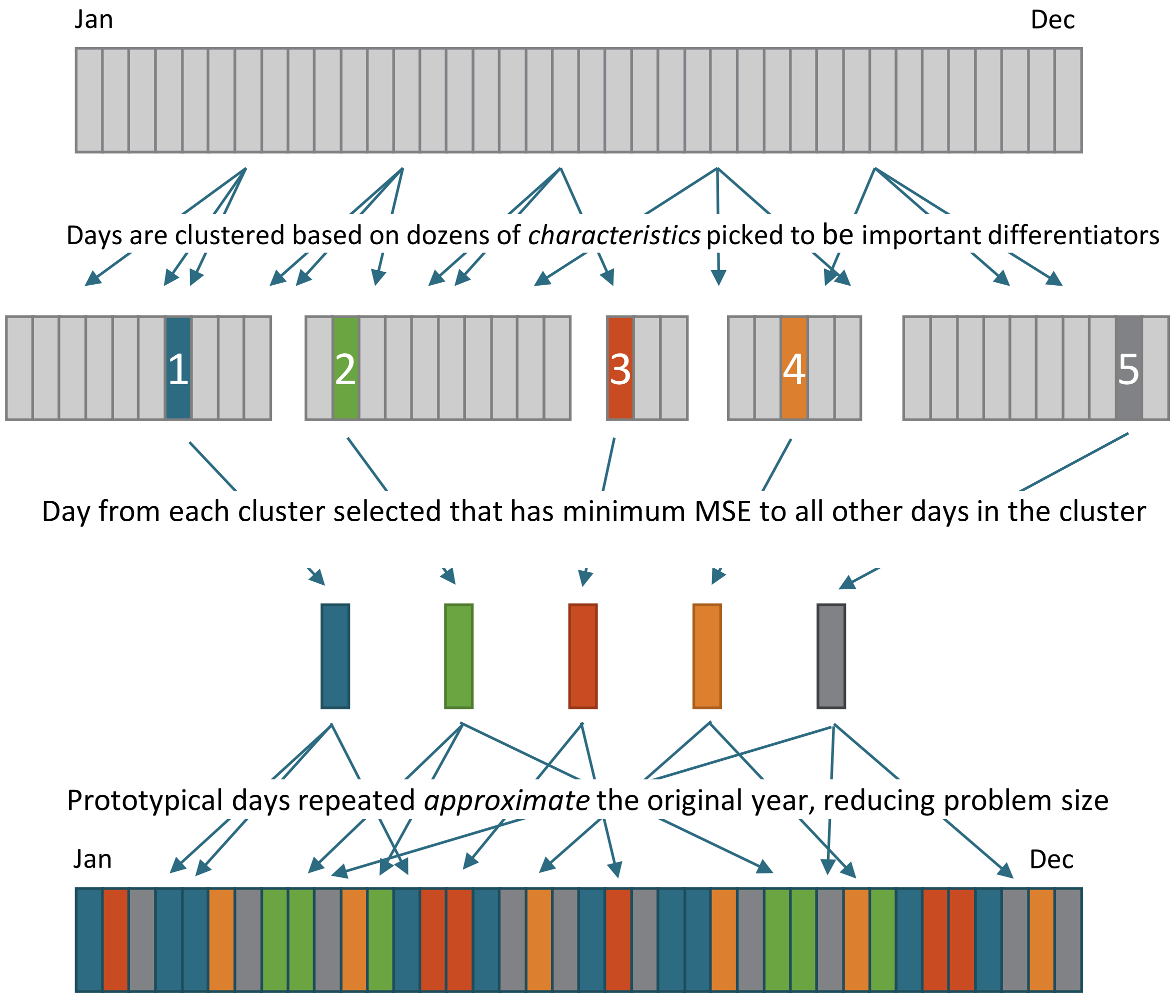
2050

40-60
Samples

365 Days

Day sampling process

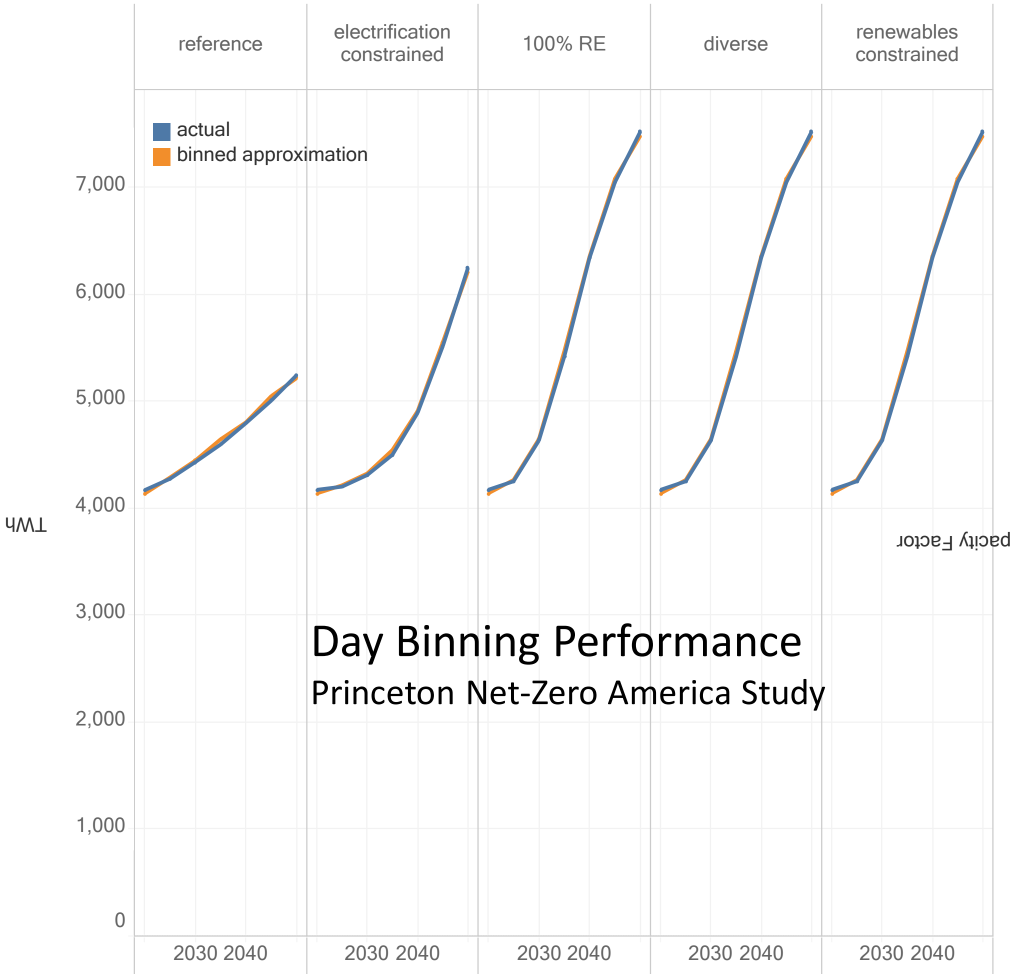
Clustering and validation



Days are clustered based on dozens of *characteristics* picked to be important differentiators

Day from each cluster selected that has minimum MSE to all other days in the cluster

Prototypical days repeated *approximate* the original year, reducing problem size



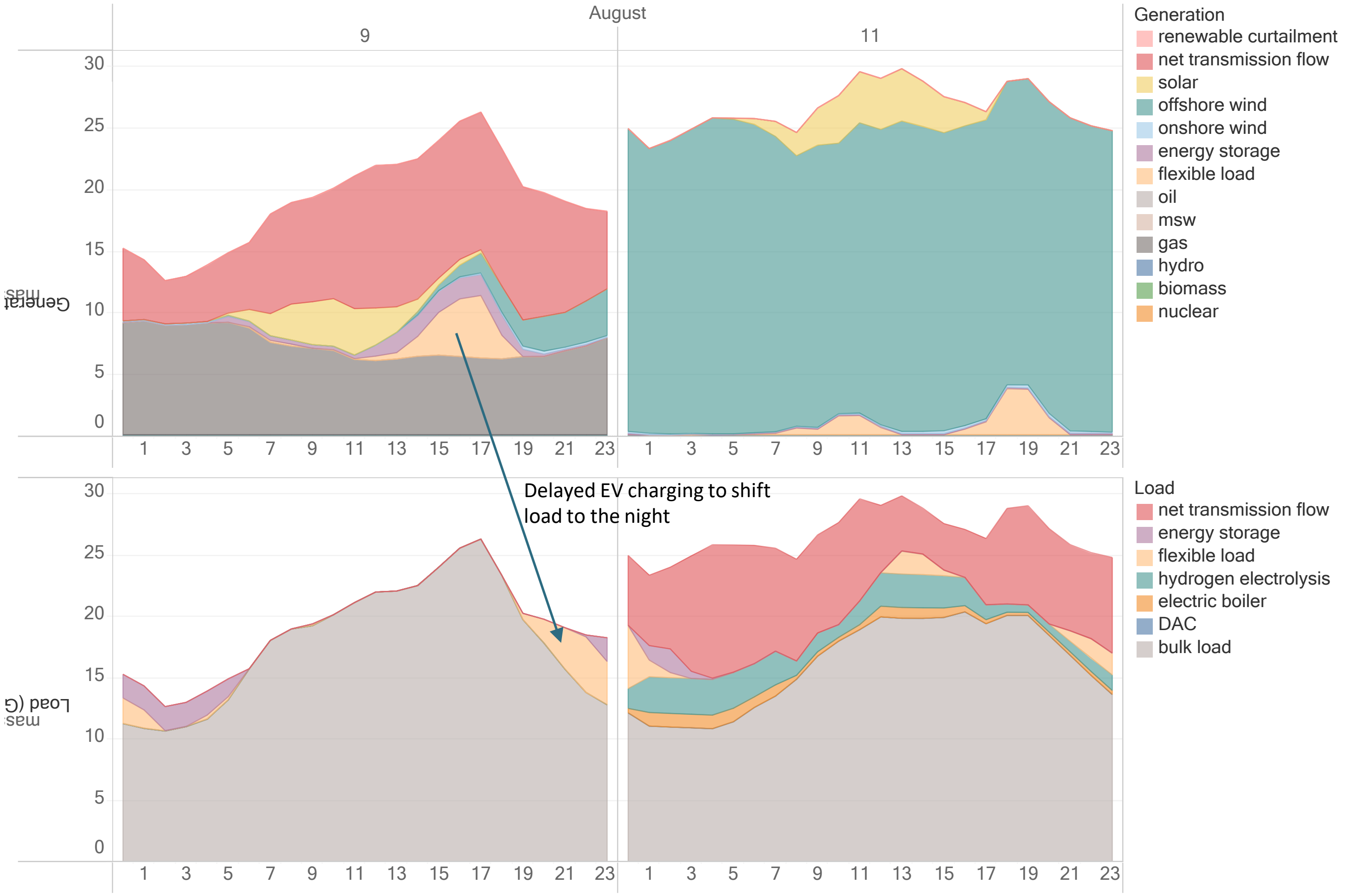
Day Binning Performance

Princeton Net-Zero America Study

Contrasting daily operations in high RE systems

RIO Output example from the Northeast

- Many days look like August 11th: e-fuels are being produced and no thermal capacity is needed at any point during the day.
- But, we need a system prepared for August 9th : Almost no wind is produced, must serve loads only, and thermal generation is needed every hour

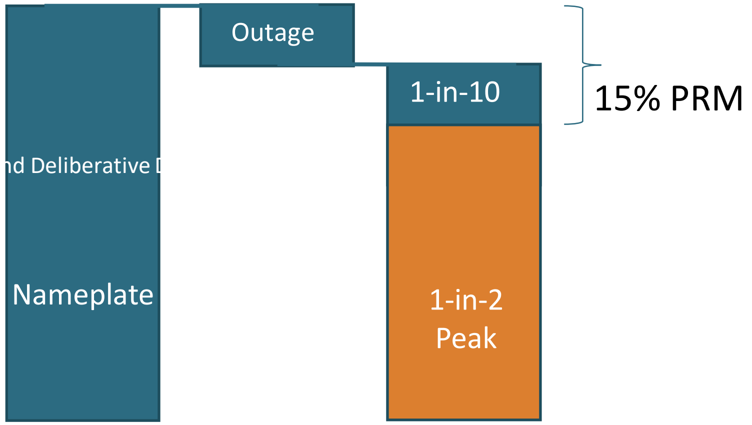


Delayed EV charging to shift load to the night

RIO uses hourly reserve margin constraints by zone to account for changing system make-up

Assessing Reliability Becomes Challenging in Low-Carbon Electricity Systems

Traditional Reserve Margin



nd Deliberative

Nameplate

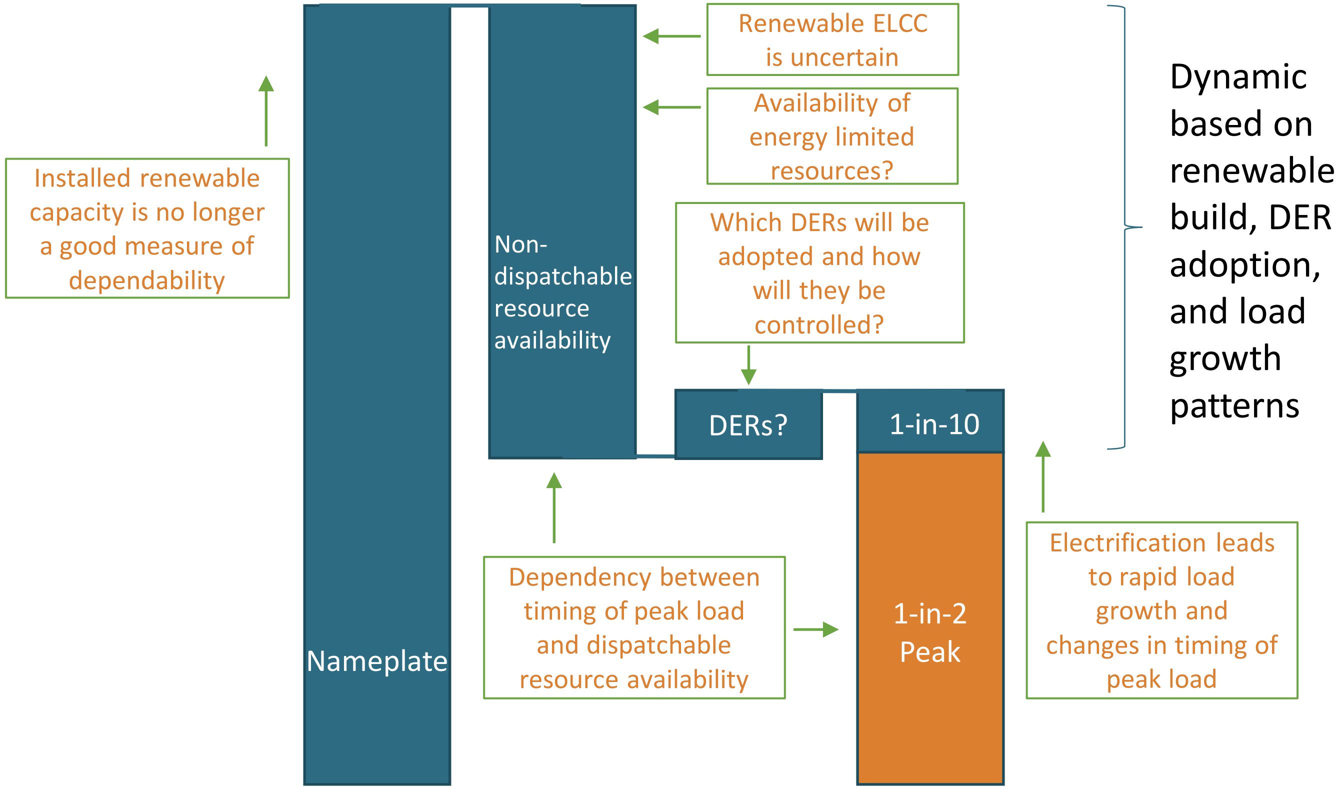
Outage

1-in-10

1-in-2 Peak

15% PRM

Future System Reliability Assessment



Installed renewable capacity is no longer a good measure of dependability

Nameplate

Non-dispatchable resource availability

Renewable ELCC is uncertain

Availability of energy limited resources?

Which DERs will be adopted and how will they be controlled?

DERs?

1-in-10

1-in-2 Peak

Dependency between timing of peak load and dispatchable resource availability

Electrification leads to rapid load growth and changes in timing of peak load

Dynamic based on renewable build, DER adoption, and load growth patterns

Excluded dynamics in RIO

Missing Dynamic	Impact on Model Results	Rational for Exclusion
Price-responsive demand	Higher demand for high-cost energy than may occur in reality	Demand-side inclusion in the optimization increases problem-size, and is imperfect when done; focus on demand-scenarios instead
Integer investment decisions	Technology deployment is less 'lumpy' than in reality	MILP significantly increases solve times; 'rounding' can often reasonably approximate results
Endogenous fuel prices	Reduction in fuel demand may result in a reduction in cost	Projecting long-term supply curve is difficult (shale gas revolution), muted impact when considering global energy markets (oil)
Endogenous technology cost	Delayed-deployment can take advantage of reductions in technology cost	Requires MILP; technology 'learning' occurs globally and RIO reflects U.S. markets only
Imperfect foresight & imperfect coordination	Impact of a Carbon Price induces greater response than in the real world	We add 'friction' multiple places in the optimization, 'right' level of friction is difficult to judge
Higher operational detail in electricity	Disruptive impacts of high variable generation is likely underestimated in the near-term, underestimation of transmission	NREL modeling has shown unit commitment, etc. to not substantially change results for large geographic regions