Annual Decarbonization Perspective 2023
Wind, Solar & Transmission Siting

May 2024

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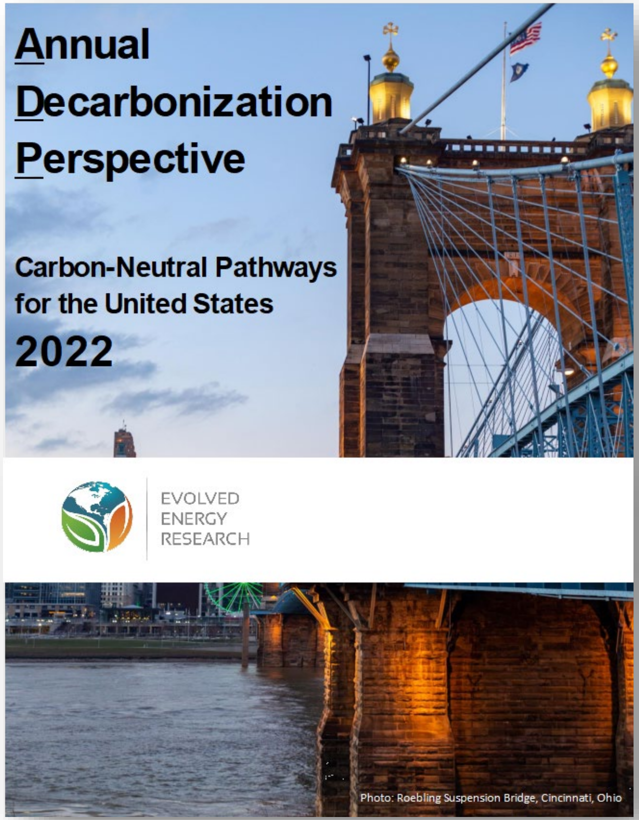
This report's purpose

- This report follows from the 2023 Annual Decarbonization Perspective
  It contains two sections that address the topic of renewable siting:
  - **Renewables Downscaling from ADP 2023:** Detailed visualizations of the renewable portfolios in ADP 2023
  - **Renewable Siting Sensitivities:** A sensitivity analysis that explores the implications of slower siting of wind, solar, and transmission

Purpose of *Annual Decarbonization Perspective*

- Fill a gap in long-term decarbonization analysis for the U.S. by delivering a standardized, annually updated, technology agnostic, and publicly accessible data and report
  - 6-8 scenarios with continuity between years, plus additional sensitivities
  - Publication of model inputs/outputs with detailed technology assumptions
  - Key outputs on a state geography level
- Work funded by Breakthrough Energy



Analytical tools

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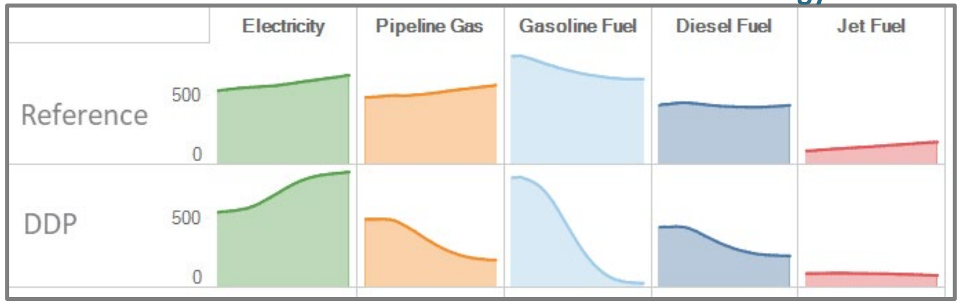
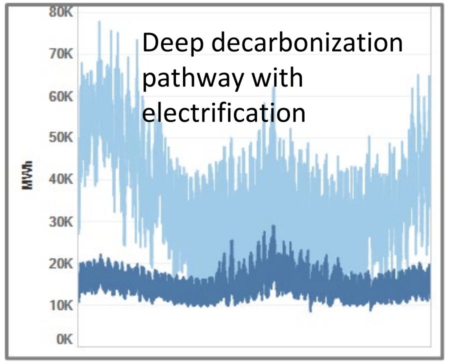
EnergyPATHWAYS (EP) is EER's demand-side stock-rollover accounting model. It produces scenarios based on exogenous service-demand and sale shares

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

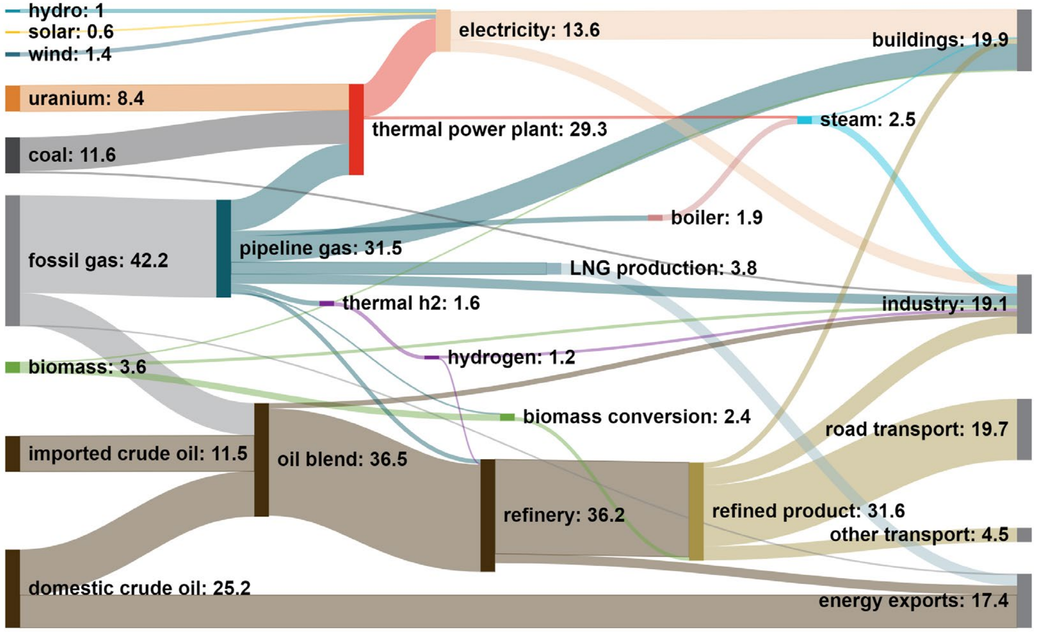
Annual End-Use Energy Demand



Hourly Load Shape



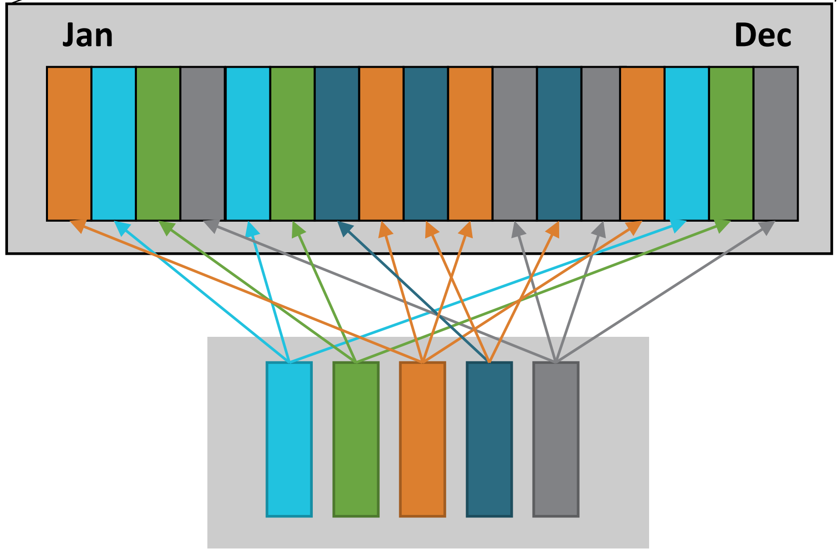
2021 Energy System

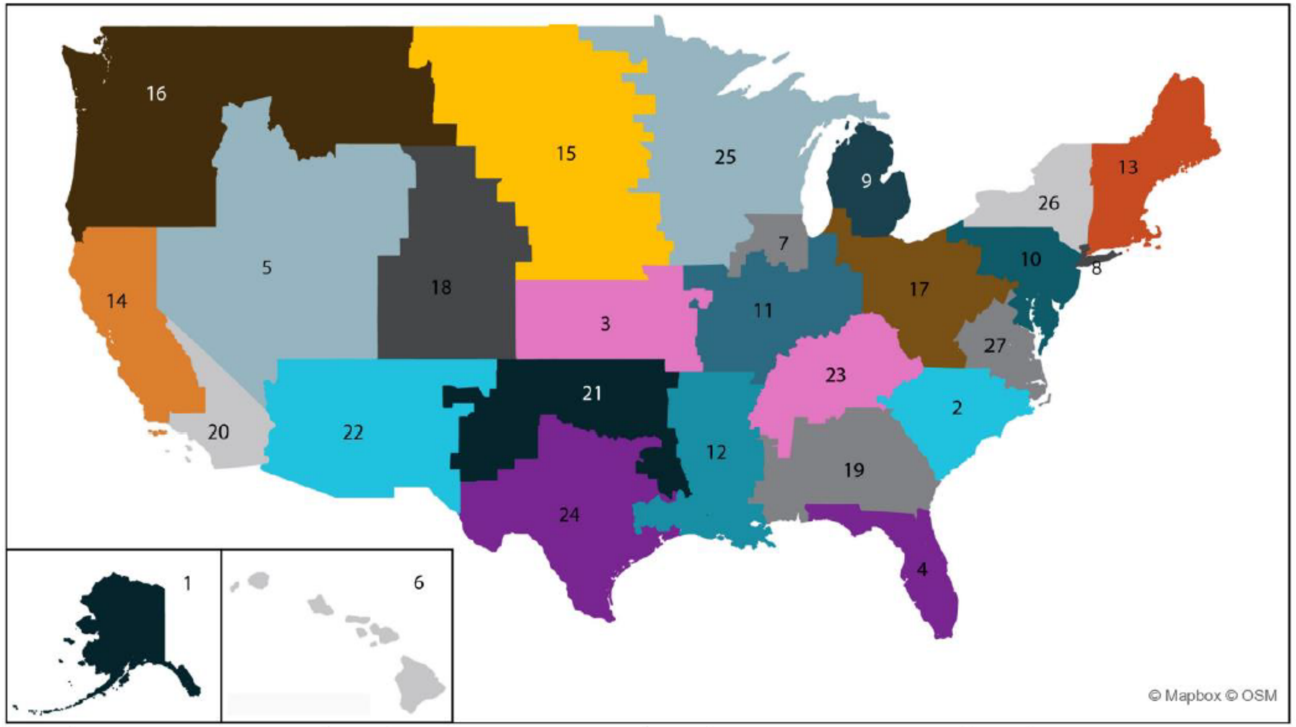


Temporal and spatial granularity

2021	2025	2030	2035	2040	2045	2050

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

Long-term energy modeling

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"Plans are useless, but planning is indispensable" – Eisenhower

- Long-term low emissions pathways illustrate not what will happen, but what could happen. They help us to understand and foresee:
  - Critical decision points and societal choices.
  - Strategies that are robust across a wide range of scenarios.
  - The competitive landscape of technologies, including the role of markets and policies, barriers to adoption, and research focal points.
  - The need for workable compromises, which compels engagement by society, policymakers, and the public with the realities of a low-carbon energy transition.
- Decarbonization pathways are a coherent framework for constructing narratives for a transition to a low-carbon energy system

Renewables Downscaling from ADP 2023

Downscaling purpose

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- Low carbon energy sources have enormous potential, but the resources are geographically diffuse.
- Wide-spread deployment of infrastructure is necessary to capture these diffuse resources in the quantities demanded by reaching net zero in the U.S. economy.
- Detailed infrastructure maps have proven to be a potent means of communicating this aspect of long-term energy pathways.
- Downscaled maps are meant to convey an impression of the lived experience of interacting with the emerging energy system. They are illustrative, **not** prescriptive.
- Examining and comparing maps across years and across scenarios provide a way to contrast the choices facing the energy system in the transition to net-zero.

Downscaling methods

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- ADP 2023 downscaling was conducted by Greg Schivley and Cecelia Isaac at Princeton University
- The process includes the following steps:
  1. Candidate project areas for wind and solar are created that pre-filter unusable land, determine wind and solar performance, and map transmission to the nearest load center. Available capacity at each site is de-rated based on local population density.
  2. RIO capacity expansion clusters the candidate project areas and then selects from the binned resources to meet scenario constraints at the lowest cost. Clustering is done to reduce computational requirements when multiple projects may have similar economics.
  3. A random selection of candidate project areas with the lowest levelized cost of energy are selected from each bin. This random selection reverses population density de-rating for a better visualization of results
  4. Selected candidate project areas are plotted. Aesthetic decisions are made to highlight projects.
- More information regarding the latest methods from Princeton can be found here

Caveats and future improvements

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- The specific locations for future renewable development are indicative only—they illustrate one specific outcome of many possibilities
- Choosing candidate projects based on lowest levelized cost of energy misses many real-world factors that can be more important when siting projects
- Borders used when plotting solar and wind projects make small projects appear larger than their actual on-the-ground footprint

Central Scenario, 2025

Metric	Installed (GW)
Large PV	169
Customer-sited PV	78
Onshore Wind	173
Offshore Wind	2
Wind energy parks	0
Nuclear	95
Gas w/cc	0

Central Scenario, 2035

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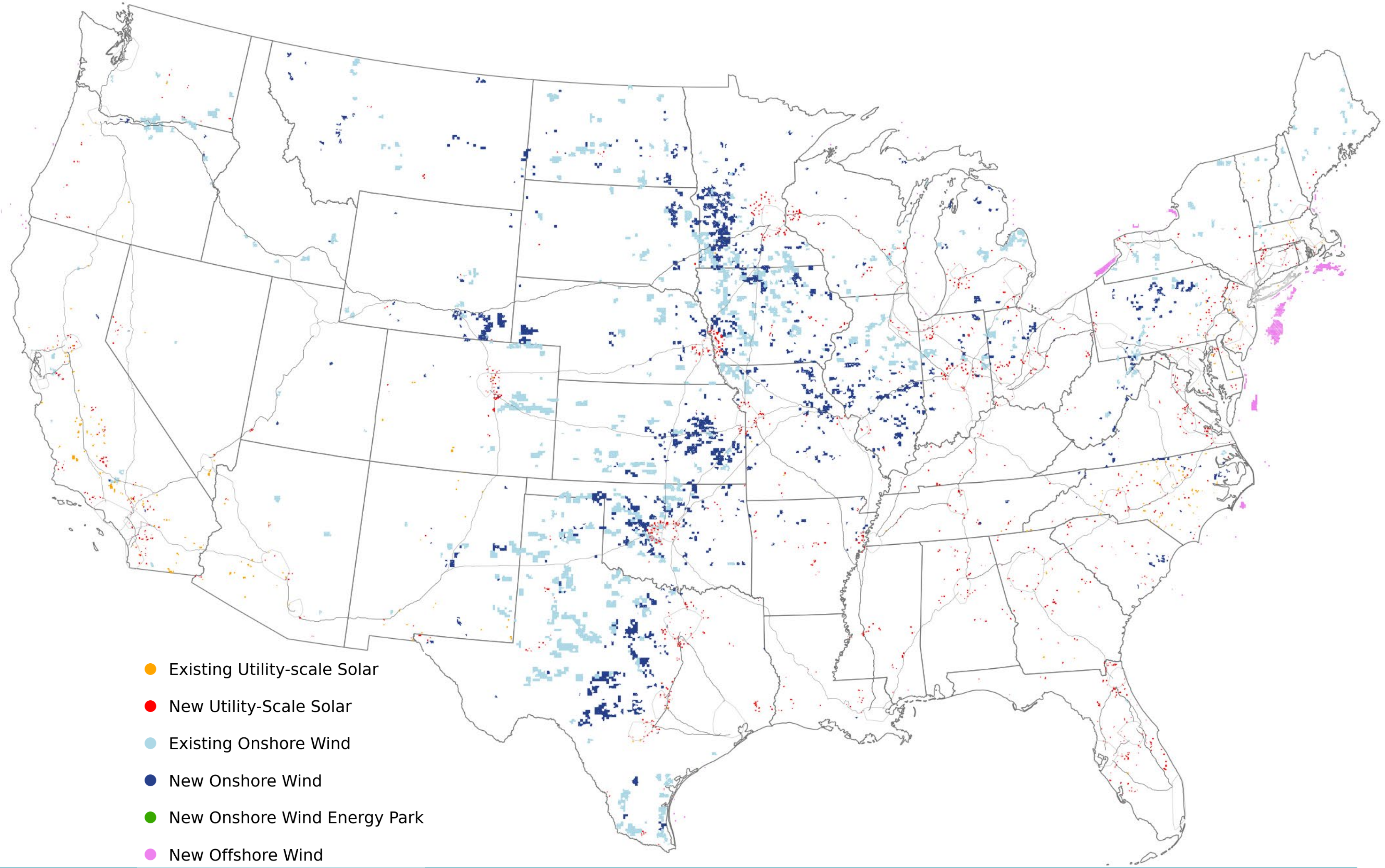
Metric	Installed (GW)
Large PV	806
Customer-sited PV	206
Onshore Wind	539
Offshore Wind	44
Wind energy parks	0
Nuclear	94
Gas w/cc	94



Central Scenario, 2050

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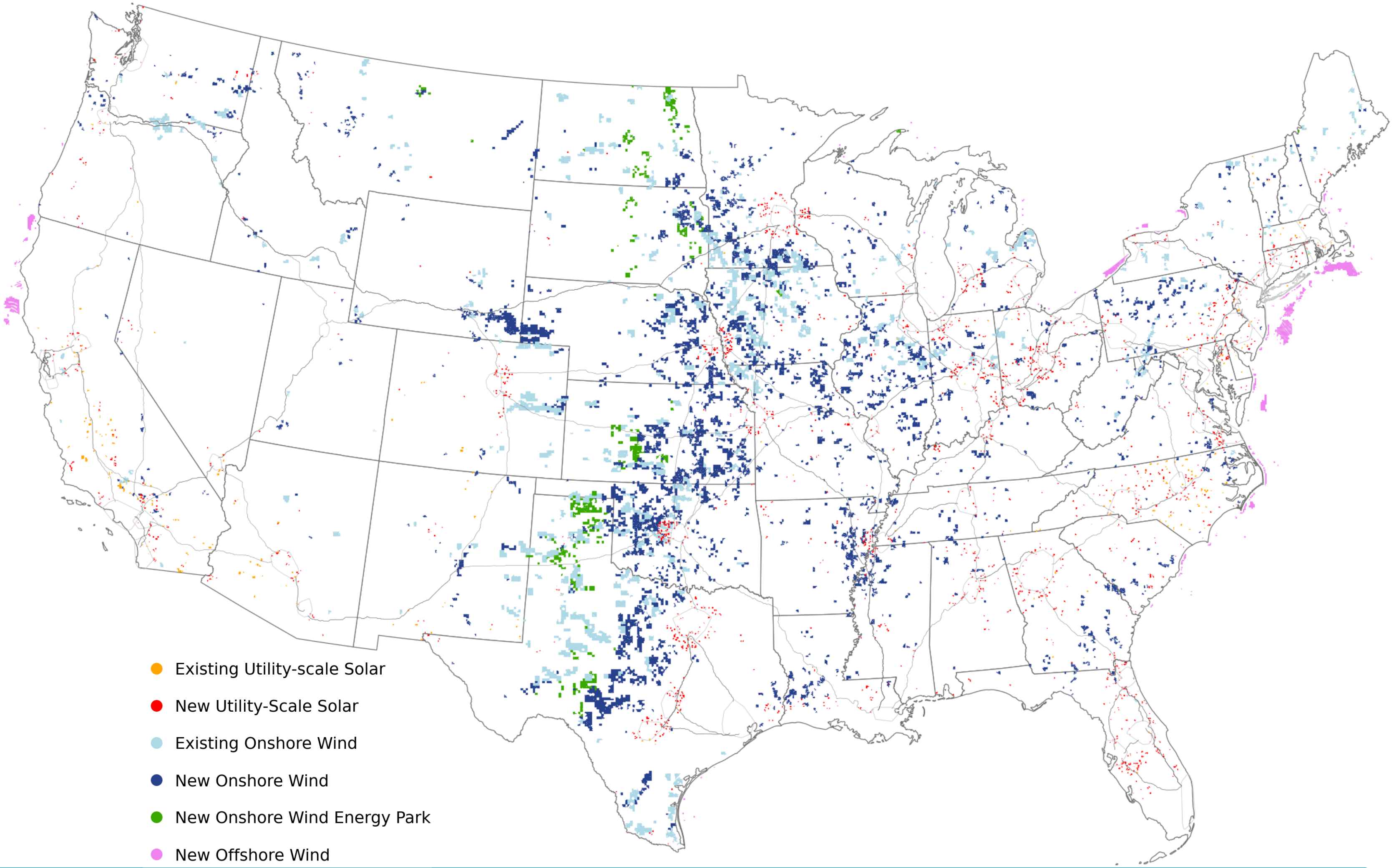
Metric	Installed (GW)
Large PV	1,070
Customer-sited PV	468
Onshore Wind	1,562
Offshore Wind	87
Wind energy parks	112
Nuclear	91
Gas w/cc	135



Drop-In Scenario, 2050

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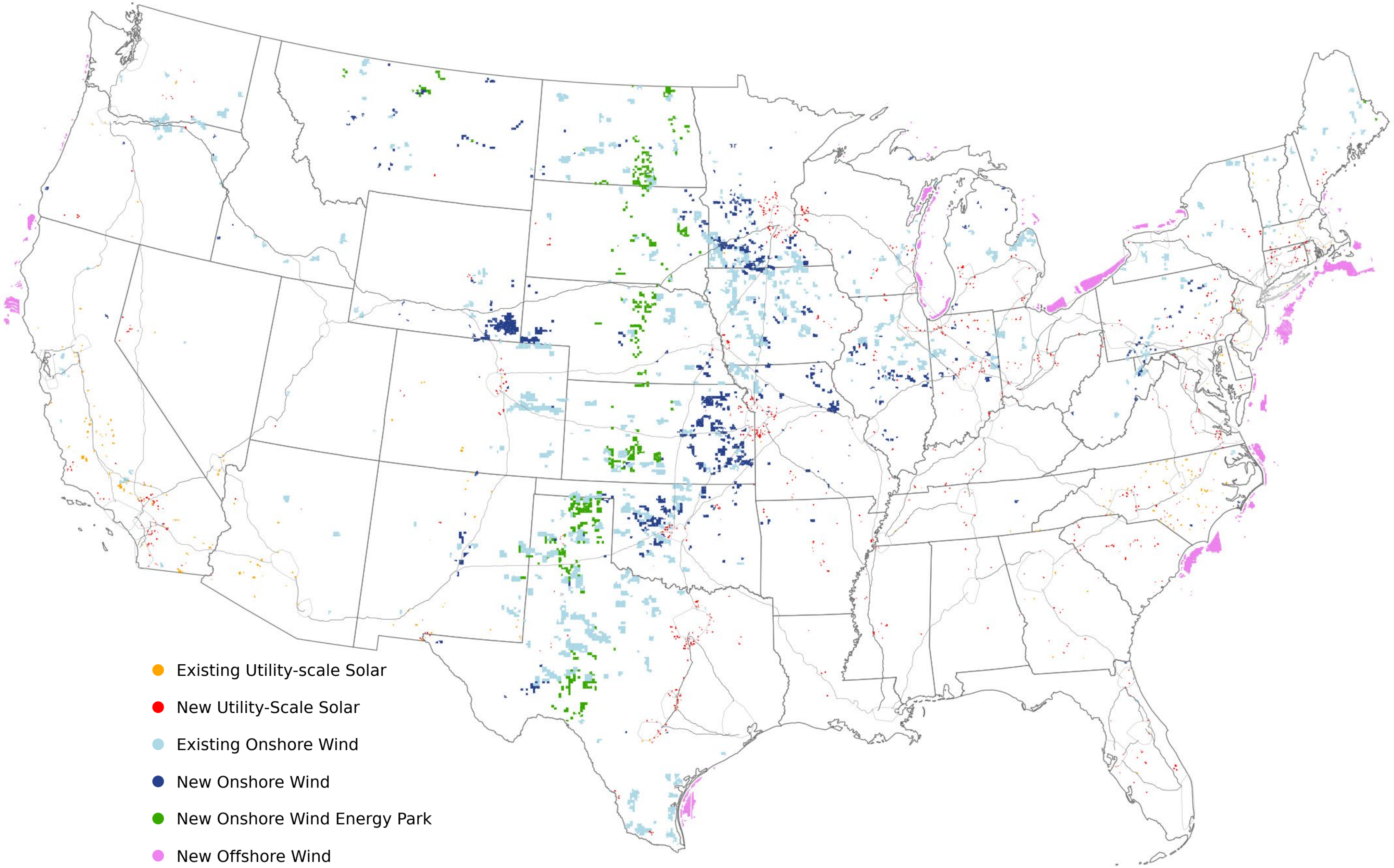
Metric	Installed (GW)
Large PV	524
Customer-sited PV	565
Onshore Wind	346
Offshore Wind	185
Wind energy parks	160
Nuclear	318
Gas w/cc	235



Low Land Scenario, 2050

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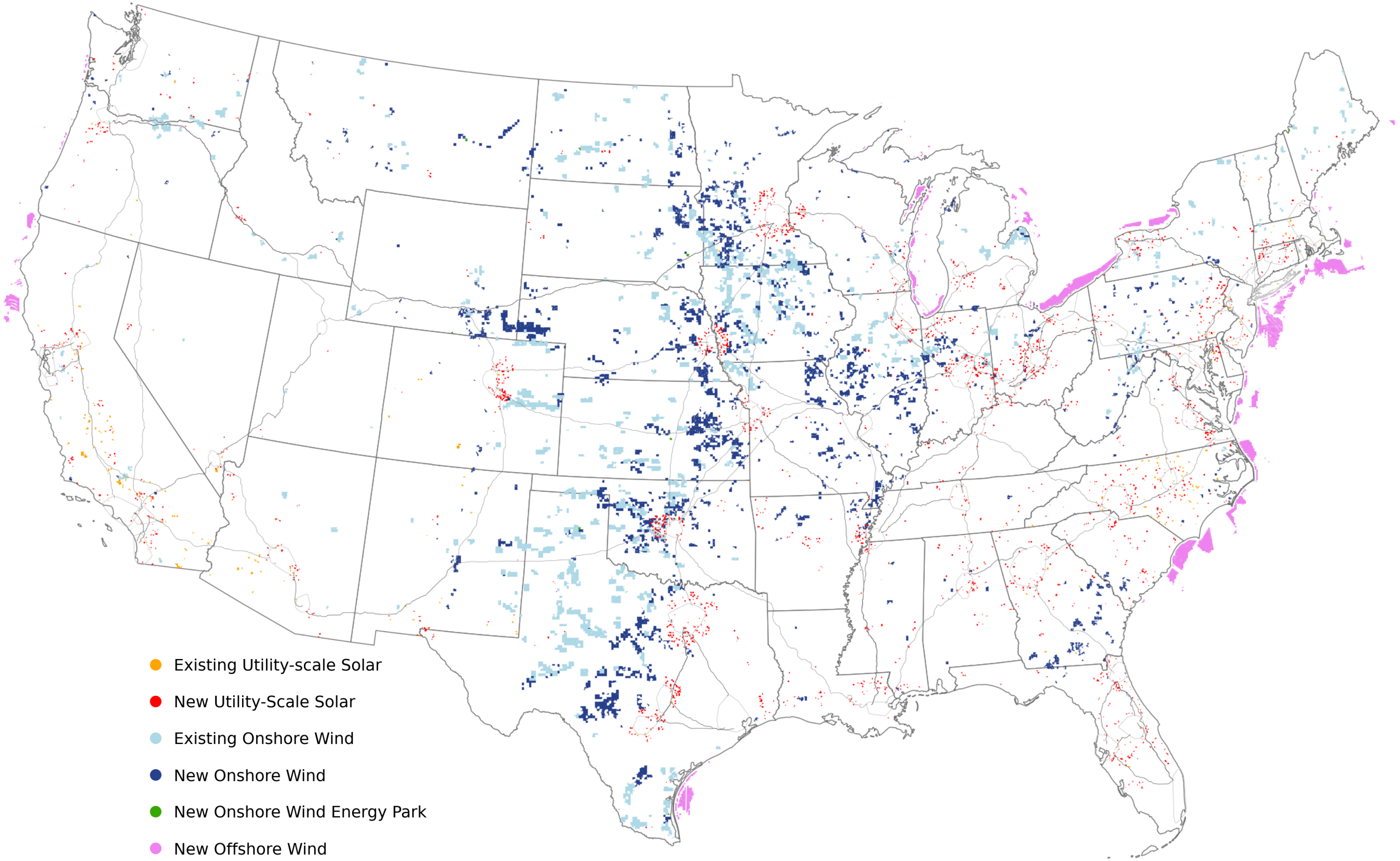
Metric	Installed (GW)
Large PV	1,287
Customer-sited PV	539
Onshore Wind	737
Offshore Wind	265
Wind energy parks	0
Nuclear	115
Gas w/cc	281



100% Renewables Scenario, 2050

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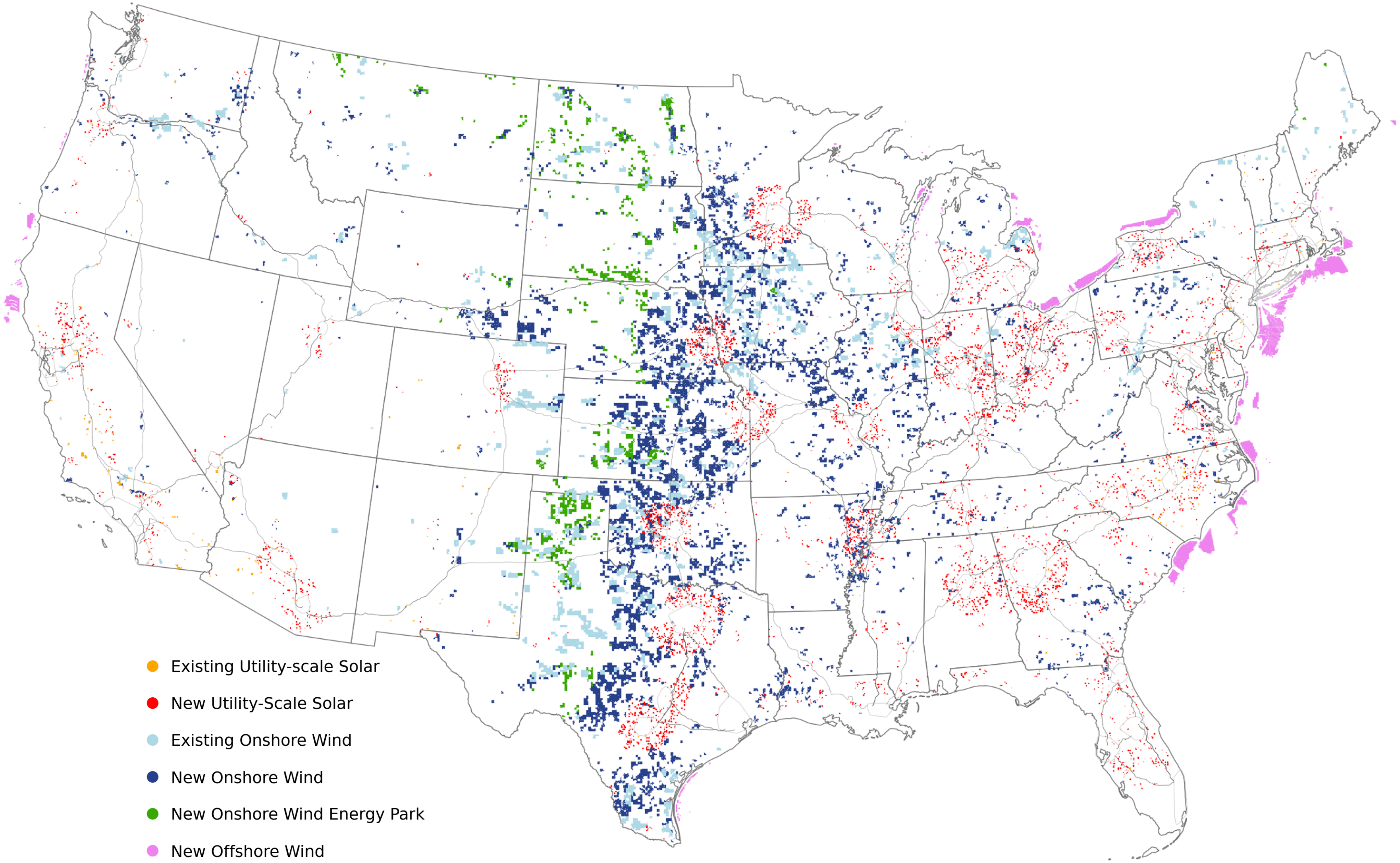
Metric	Installed (GW)
Large PV	3,241
Customer-sited PV	602
Onshore Wind	2,085
Offshore Wind	262
Wind energy parks	278
Nuclear	0
Gas w/cc	0



Current Policy, 2050

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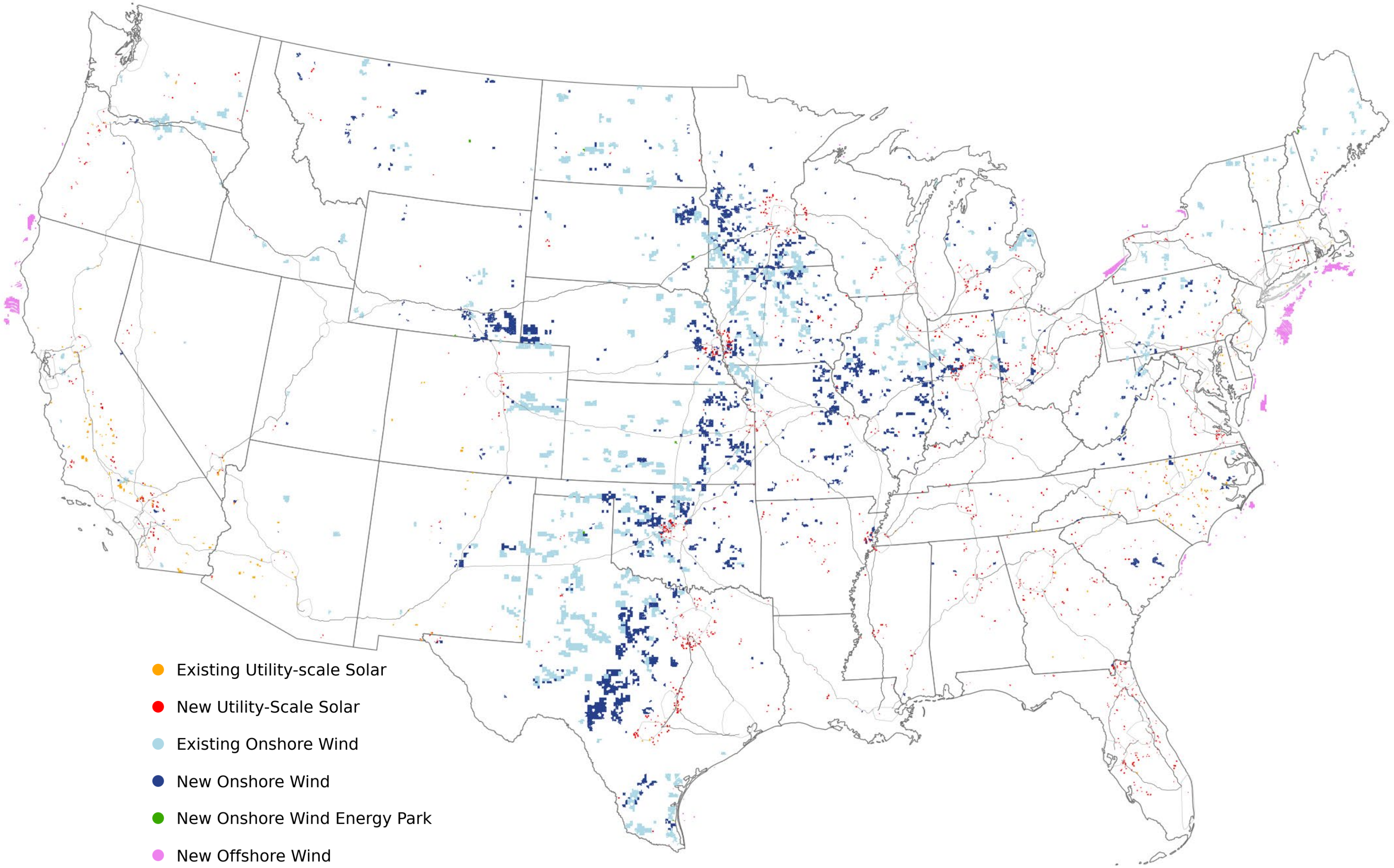
Metric	Installed (GW)
Large PV	771
Customer-sited PV	387
Onshore Wind	585
Offshore Wind	73
Wind energy parks	0
Nuclear	91
Gas w/cc	0



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Renewable Siting Sensitivities: Motivation and Methods

Research motivation

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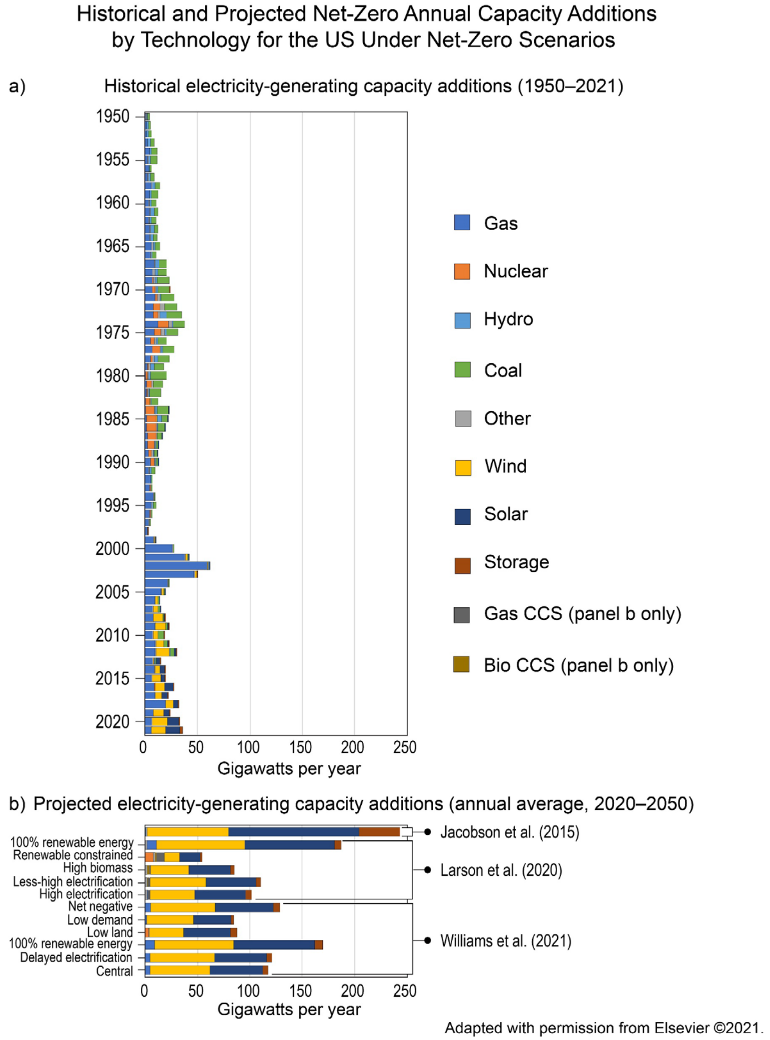
- Proposed federal legislation* looks to improve siting across the energy sector, which would also make fossil fuel extraction easier. This, in turn, would reduce the price of fossil fuels, especially natural gas, which trades in regional markets.
- Our research does not quantify a specific legislative proposal, but instead tests the impacts of constrained renewable siting, transmission siting, and low fossil fuel prices on current policy and net-zero scenarios
- Wind and solar deployment are being slowed due to a complex set of factors
  - Many of these factors are institutional and are difficult to reflect in energy models.
  - To simply assumptions, we test scenarios in which wind and utility-scale solar are constrained by their average build rate over the last five years and new inter-zonal transmission can't be completed. These scenarios are compared against default assumptions from the Annual Decarbonization Perspective.

* https://www.utilitydive.com/news/manchin-barrasso-permitting-reform-bill-demand-hearing-aep/716809/

Wind and solar build rates in net-zero scenarios

- Across many U.S. net-zero studies, solar and wind build rates have each averaged 40-60 GW/year
  - In contrast, renewable build over the last five years has averaged 1/3 of this required rate
- Reaching net-zero by mid-century is possible without rapid increases in renewable build rates, but at higher cost, and by relying more on other resources that will also be difficult to site (e.g., nuclear) or will also have large land footprints (e.g., biomass)
- The Inflation Reduction Act raises the stakes when it comes to slowing down renewable build rates
  - Historic climate legislation provides an unprecedented window for accelerated clean energy deployment

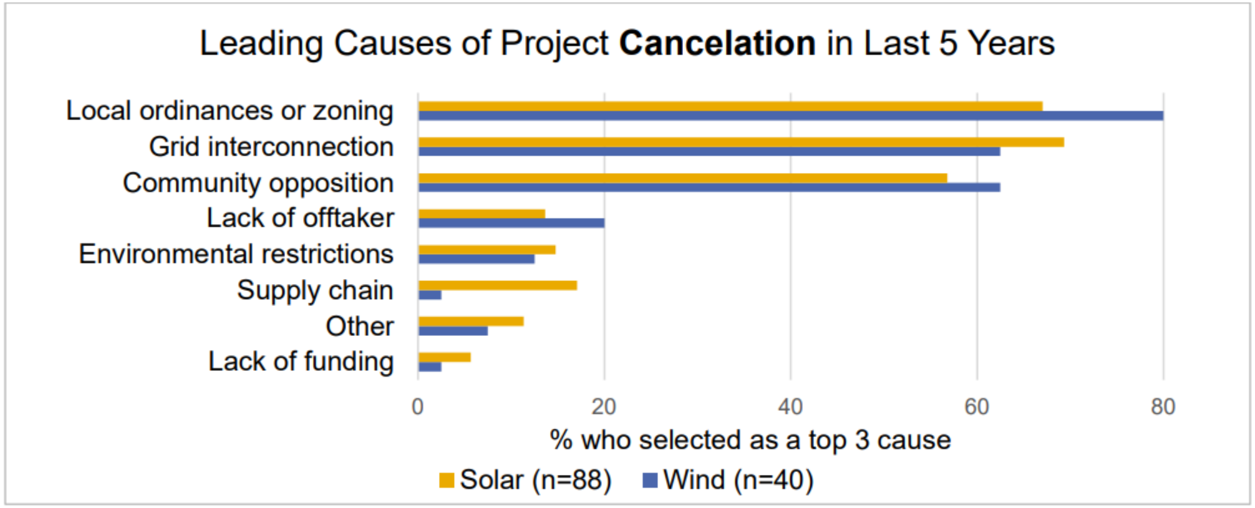


Source: National Climate Assessment
https://nca2023.globalchange.gov/all-figures/#32

Recent developer experience

- Approximately one-third of wind and solar siting applications submitted in the last five years were canceled, while about half experience delays of 6 months or more
  - Project delays added $200/kW in capital cost for both wind and solar
  - Developers expect wind to be somewhat more difficult to site than solar, leading to a shift in focus

Figure 1. Developer reported leading causes of project cancelation in last five years.



Survey of Utility-Scale Wind and Solar Developers, Robi Nilson, Ben Hoen, Joe Rand, Lawrence Berkeley National Laboratory
w3s_developer_survey_summary_-_011724.pdf (lbl.gov)

What do the current trends look like?

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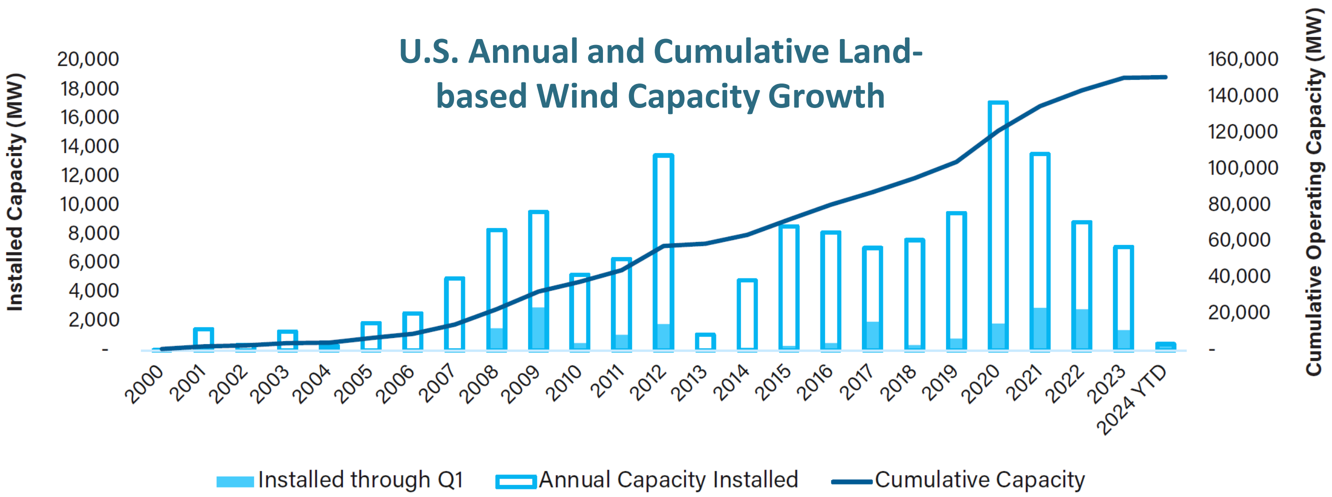
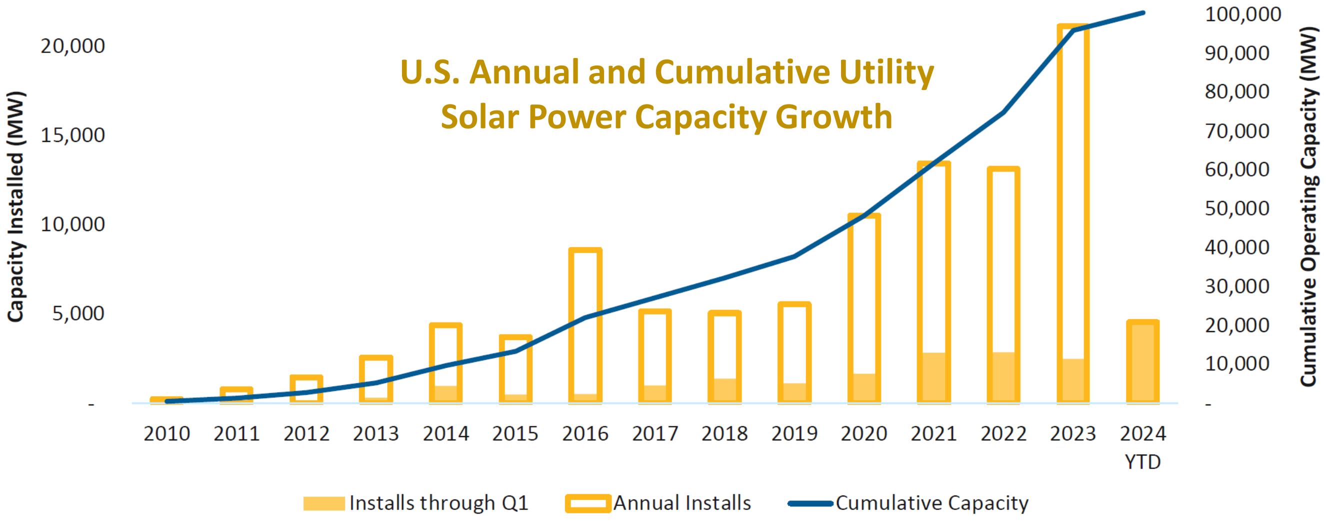
- Solar PV had a record-breaking year in 2023 and the EIA near-term energy outlook expects similar deployments in 2024 and 2025
- In contrast, wind installations have slowed from a peak in 2020 due to supply chain, siting/permitting, and transmission queues
- Solar build is 60% of what is needed* for net-zero, but wind build is only 20% of the required rate





* Based on past net-zero studies from EER and others, see slide 19

Source: American Clean Power Association | Clean Power Quarterly 2024 Q1

Scenarios to explore renewable build and transmission

Starting Assumptions	Scenario Name	Renewable Build Rates	Renewable Siting Restrictions	Inter-zonal Transmission	Fossil Fuel Price	Research question
ADP 2023 Current Policy	Current Policy: Growth	Growth	NREL 2023 Reference Access	Least-cost solution	AEO 2023 Reference	
	Current Policy: Frozen	Frozen	NREL 2023 Limited Access	No new transmission	AEO 2023 Reference	How do emissions reduction from IRA change when wind and solar are frozen at recent rates?
	Current Policy: Growth + High Fossil Supply	Growth	NREL 2023 Reference Access	Least-cost solution	AEO 2023 High Oil & Gas Supply	How do emissions change if renewables grow, but fossil fuels are also lower price?
ADP 2023 Central Scenario	Net-Zero: Growth	Growth	NREL 2023 Reference Access	Least-cost solution	AEO 2023 Reference	
	Net-Zero: Frozen	Frozen	NREL 2023 Limited Access	No new transmission	AEO 2023 Reference	How does the cost of net-zero change when wind and solar are frozen at recent rates?
	CO2 Price: Frozen	Frozen	NREL 2023 Limited Access	No new transmission	AEO 2023 Reference	How do emissions change when wind and solar are frozen at recent rates and policies are implemented that would otherwise reach net zero?

A limited but important set of updates are implemented that reflect incremental updates on the way to ADP 2024. Among them, the IRA tax credits for electricity generation have been extended to 2040 from 2035 and RPS/CES policies have been updated.

Renewable build rates

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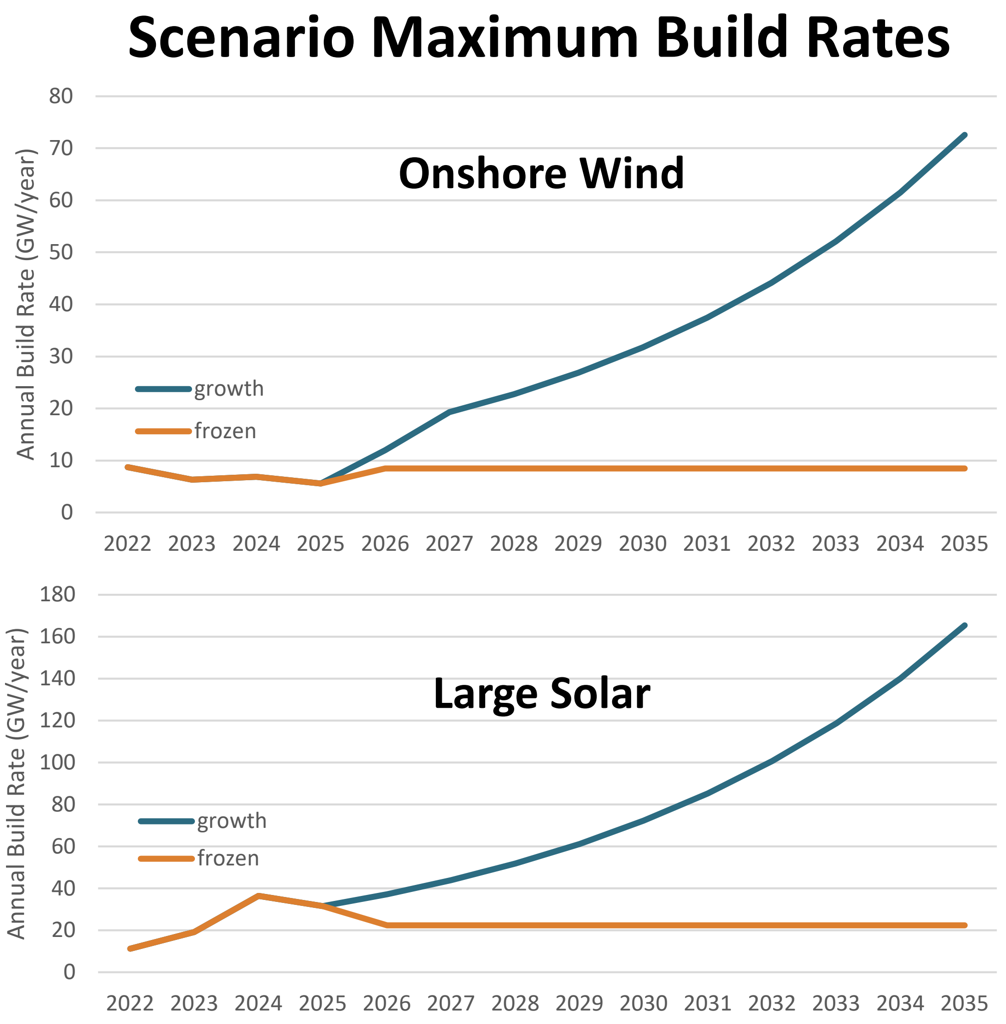
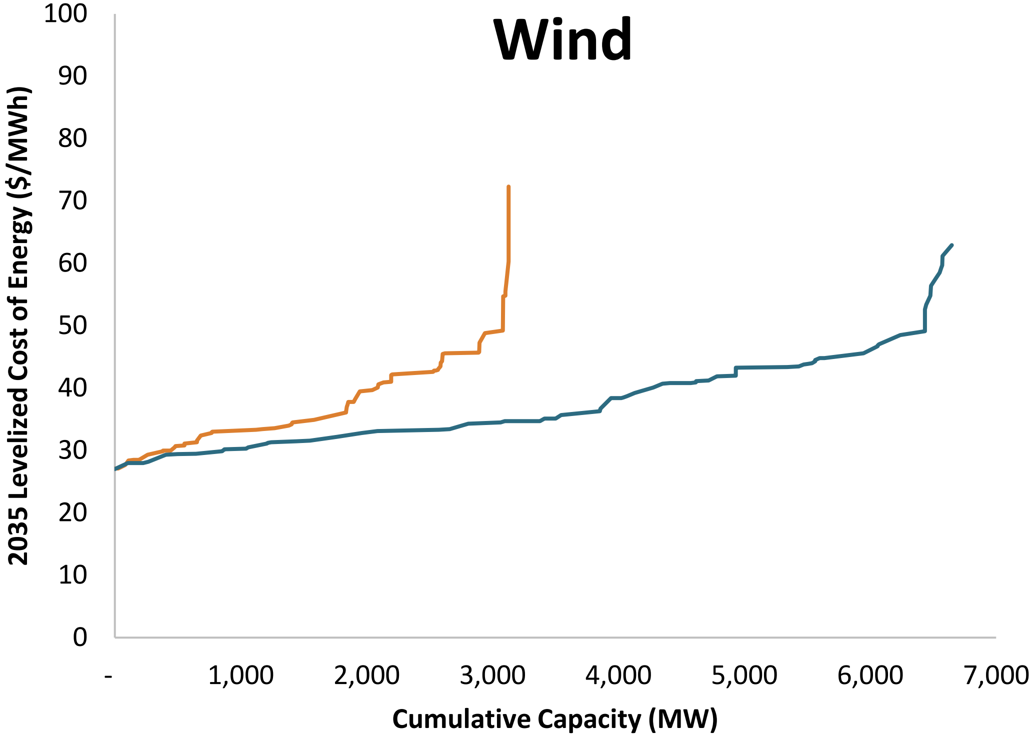
- Wind and solar deployment are being slowed due to a complex set of factors
  - Many of these reasons are institutional and are difficult or impossible to reflect in energy models.
  - Rather that attempting to capture the myriad factors analytically, we compare a "frozen" scenario in which wind and utility-scale solar are constrained by their average build rate over the last five years with a "growth" scenario from ADP 2023
  - Federal policy alone is unlikely to fully bridge the gap between "frozen" and "growth" but can accomplish part of the difference

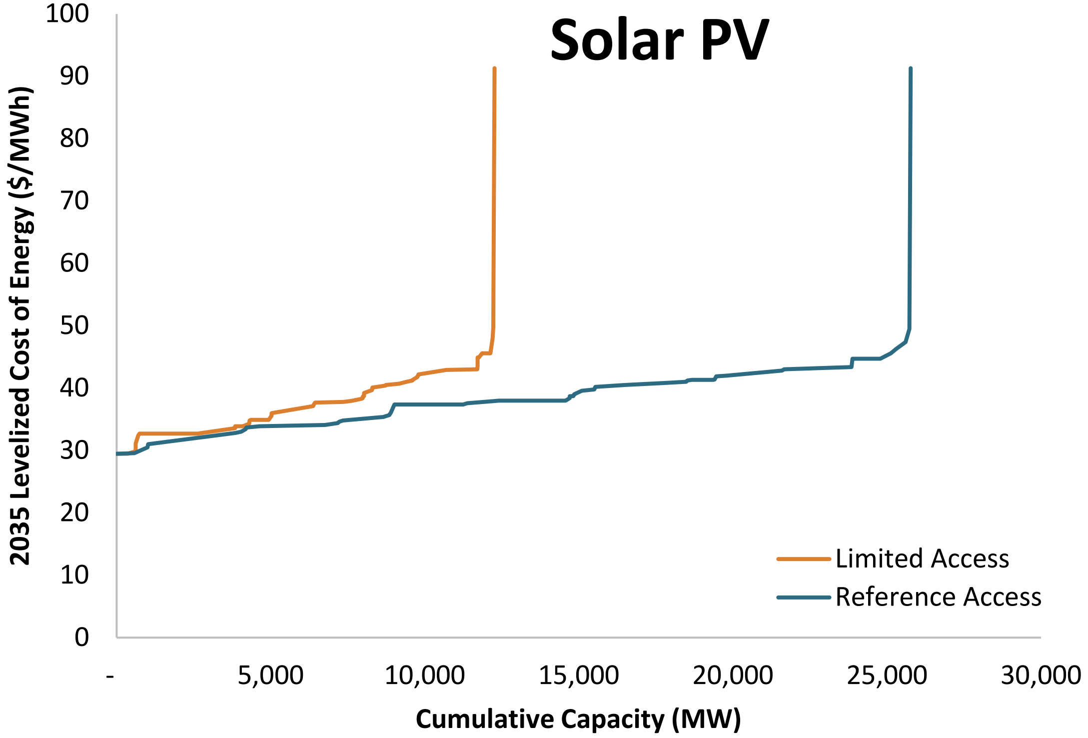


The build rates in the "Growth" scenario are the product of compound annual growth constraints in RIO and the displayed values are reflective of the model building the maximum possible in each year. To build 72.5 GW of wind in 2035, the model must also build 61.5 GW of wind in 2034, and so on. Actual build from RIO is shown on the appendix.

Renewable siting restrictions

- The frozen scenario uses NREL's Limited Access supply curves for wind and solar.
  - Applies the most restrictive land area exclusions, capturing potential increased setback requirements and difficulties facing deployment on federally managed lands

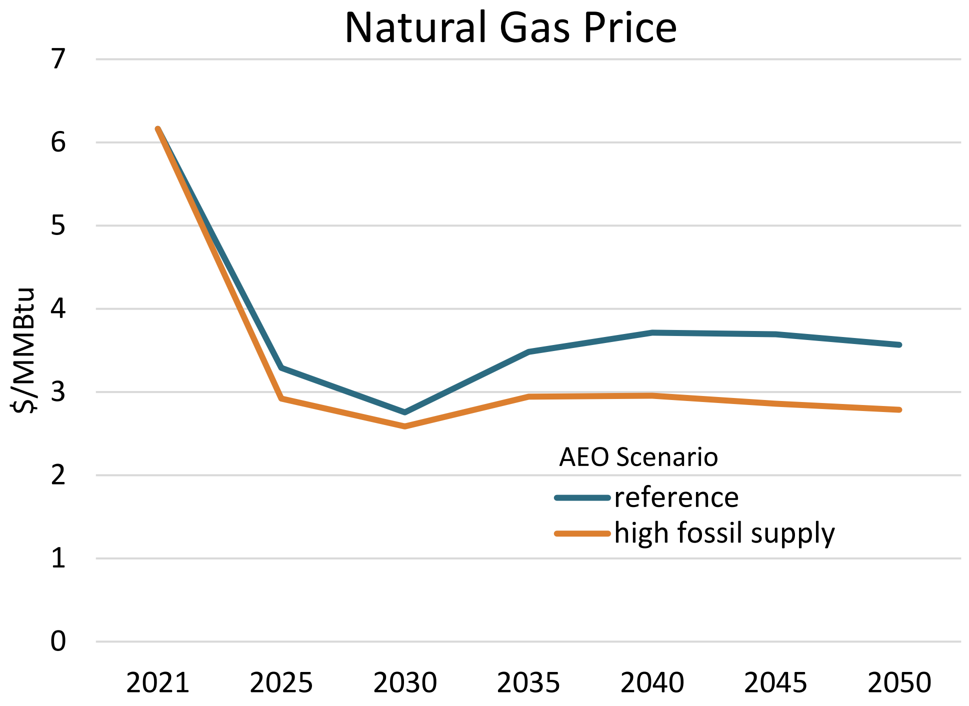


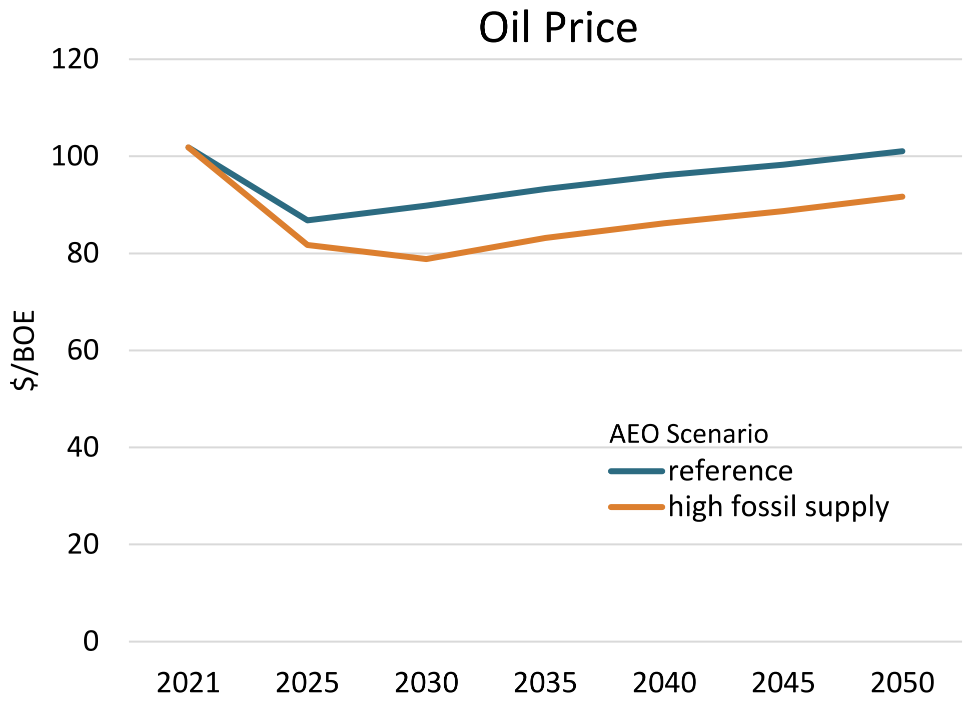


*Lopez Et Al. 2023. https://www.nrel.gov/gis/wind-supply-curves.html, https://www.nrel.gov/gis/solar-supply-curves.html

Fossil fuel price scenarios

- Price scenarios are derived from the 2023 Annual Energy Outlook scenarios
- It is unlikely that policy alone can impact natural gas, and especially oil, prices to this extent, making the price spread between scenarios larger than what new policy is likely to cause





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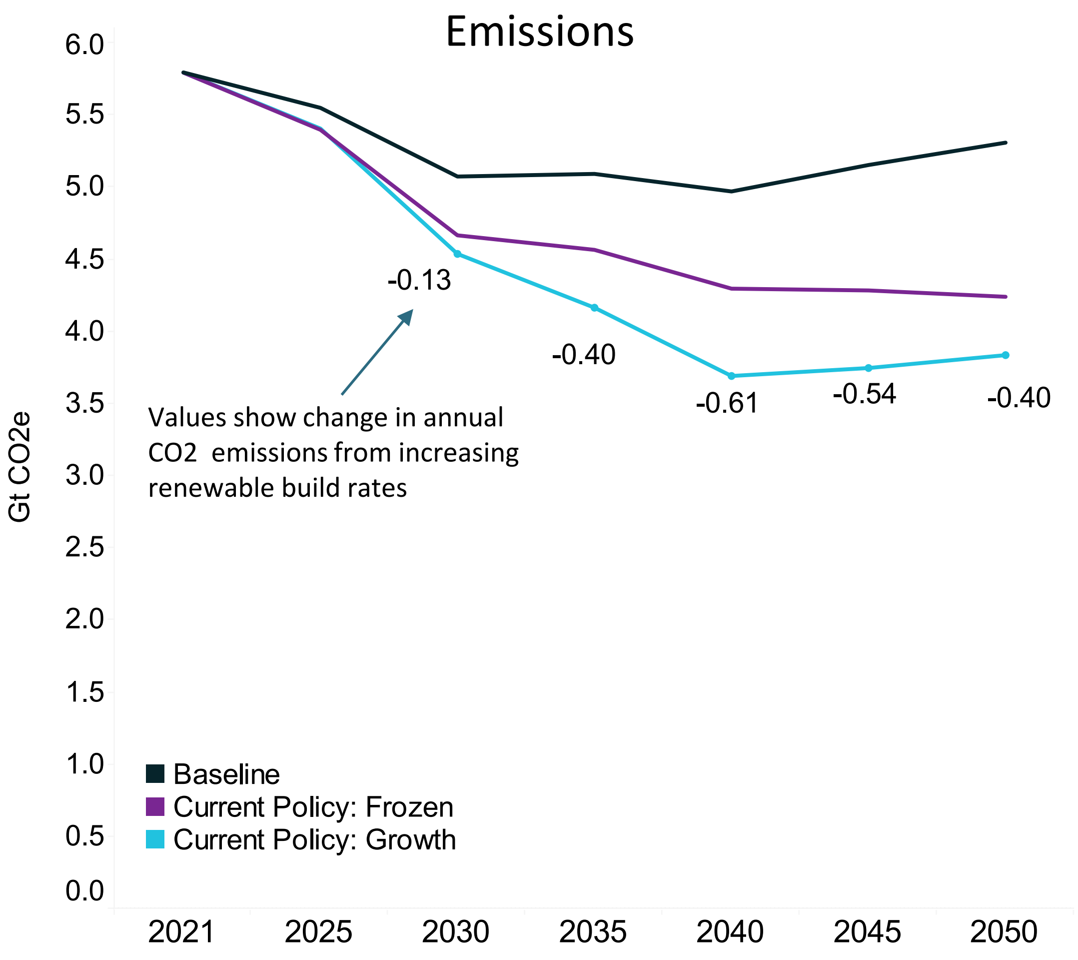
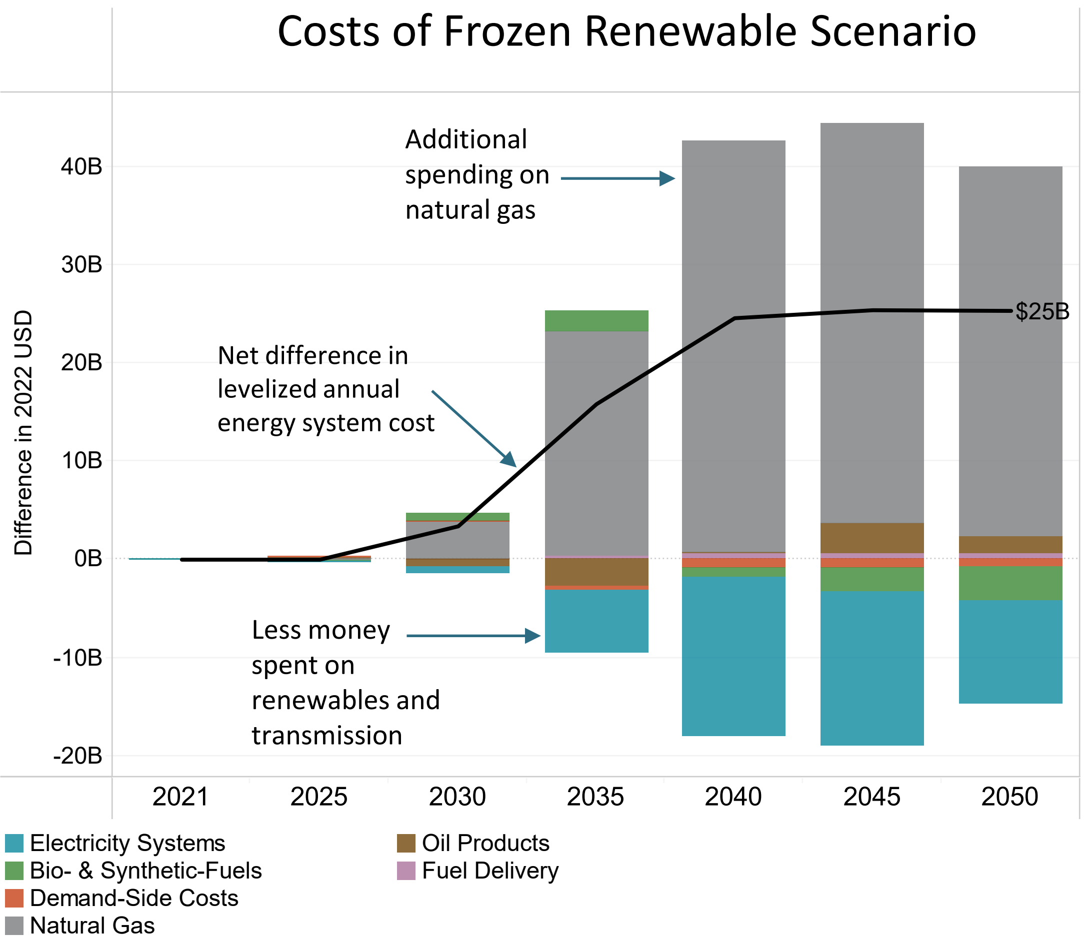
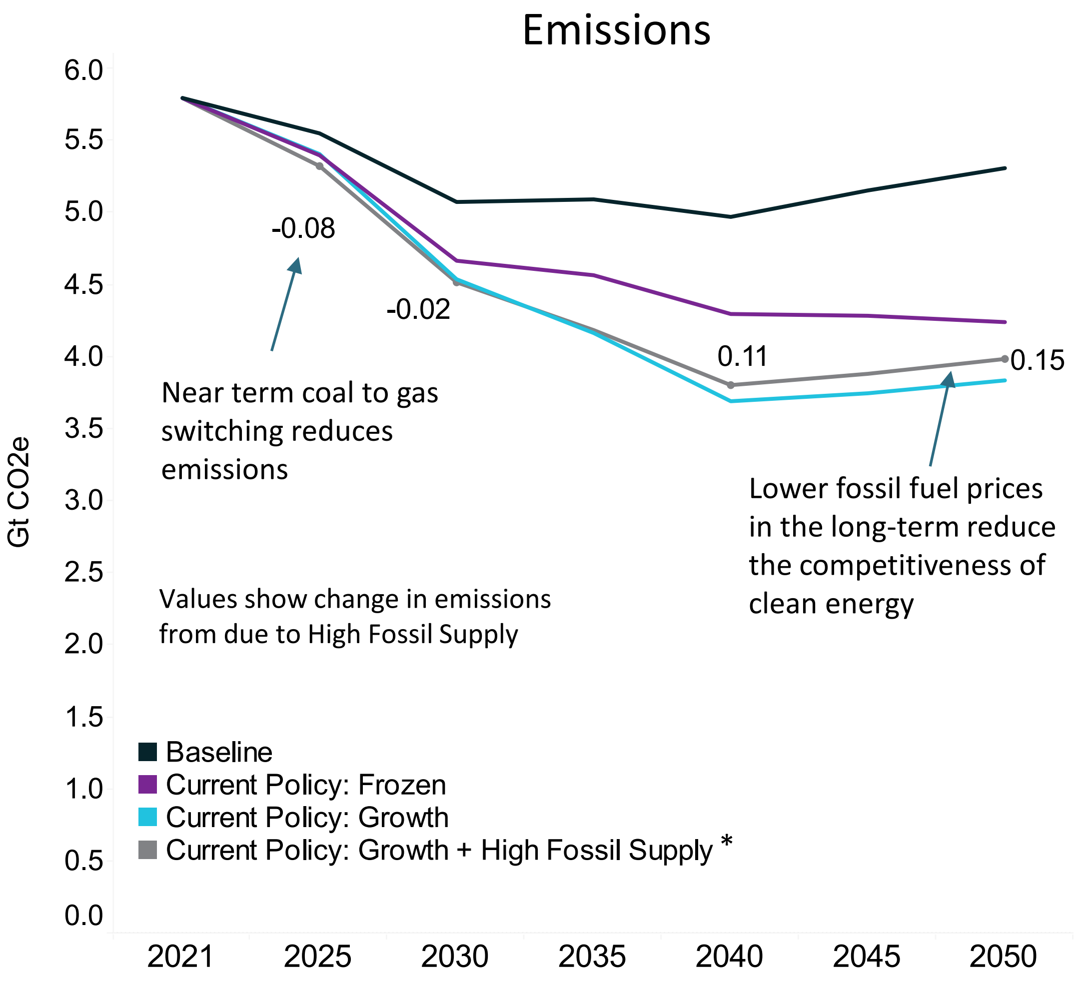
Renewable Siting Sensitivities: Results for Current Policy Scenario

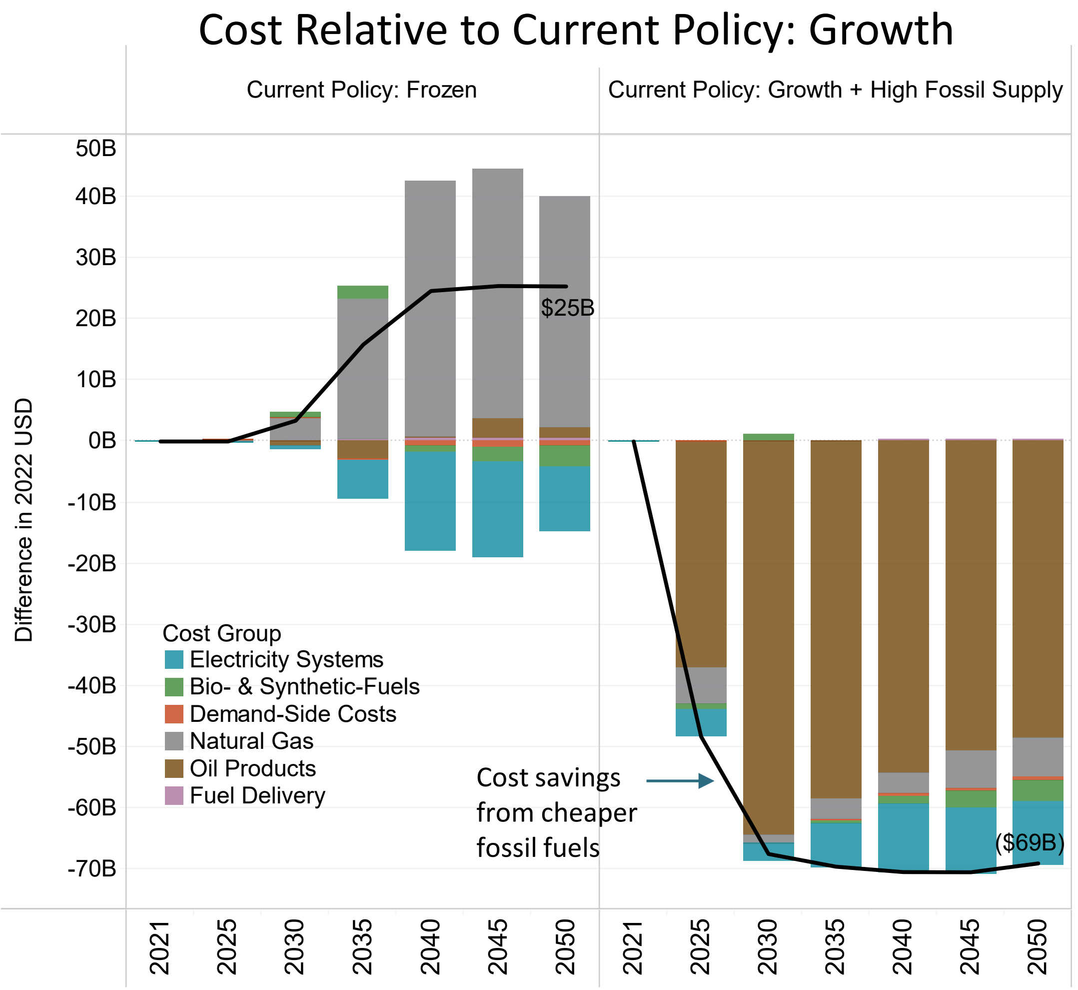
How do emissions reductions from IRA change when wind and solar build is frozen at recent rates?





How do emissions change if renewables grow, but fossil fuel prices are also lower?





* Assumes inelastic final energy demand

Difference in levelized annual energy system cost

Summary: Impact of frozen renewable growth and no new transmission on current policy

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- Approximately half of the emissions reductions benefits from IRA in the medium-term are dependent on being able to install wind, solar, and transmission faster than today
  - 300 wind and 600 solar projects need to be completed every year by the mid-2030s*
  - Inter-zonal transmission capacity increases by 58% by 2050 in Current Policy scenario
- Lower fossil fuel prices prices decrease emissions modestly in the near-term (by accelerating coal-to-gas switching) and increase emissions in the long term**
  - With the assumptions made here, lower fossil fuel prices combined with fast renewable growth leads to lower emissions than higher fossil fuel prices with no renewable growth
- Faster renewable growth saves significant cost to energy consumers – annual cost savings ramp up to $25B per year by 2040
  - Frozen renewable growth reduces the cumulative tax credits claimed by IRA by $300B***

* Assumes a median project size of 180 MW for wind and 50 MW for solar
** Our analysis did not explore the impact of low oil prices on EV adoption. However, given the global nature oil markets, it's more likely that U.S. policy can impact domestic gas prices but that oil prices don't change significantly.
*** Tax credits are not a societal savings because such tax credits do need to be funded. However, this analysis focuses on energy system costs where tax credits do decrease expenditures.

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Renewable Siting Sensitivities: Results for Net Zero Scenario

How does the cost of net-zero change when wind and solar are frozen at recent rates?

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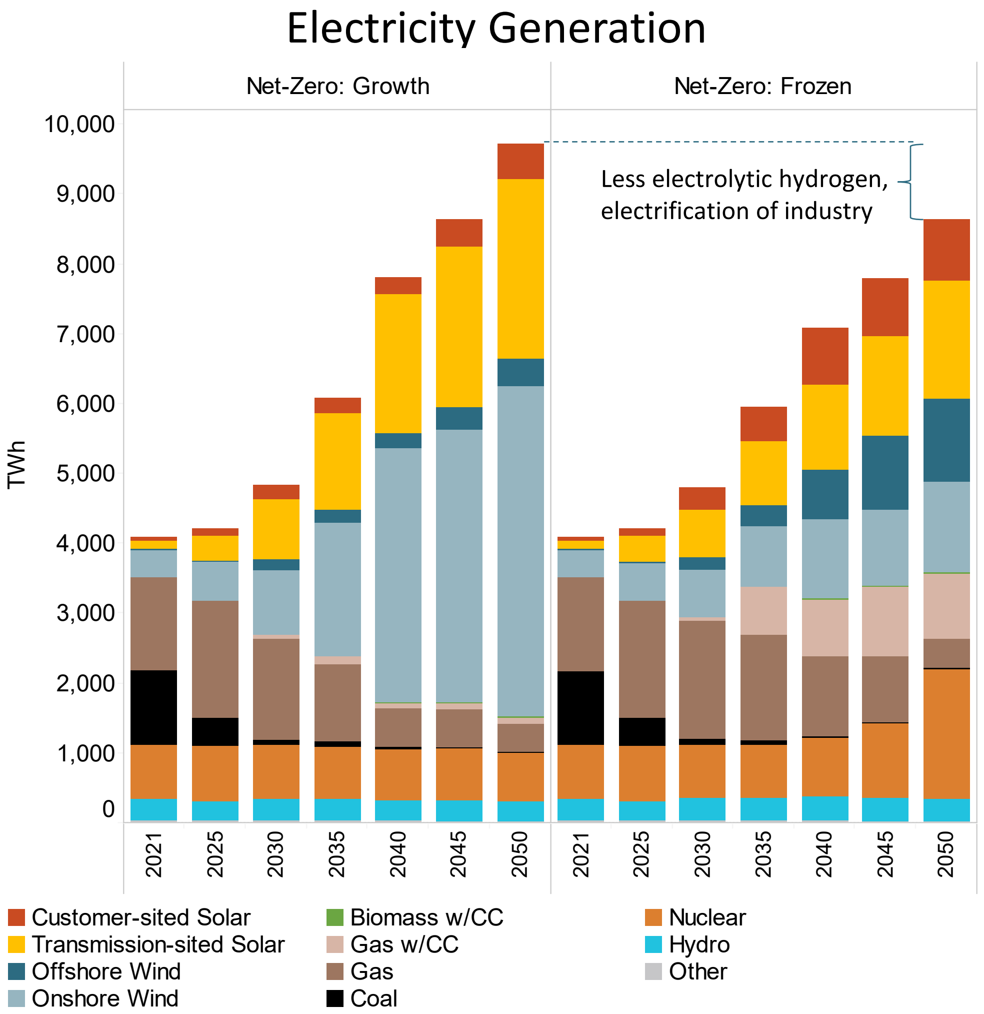

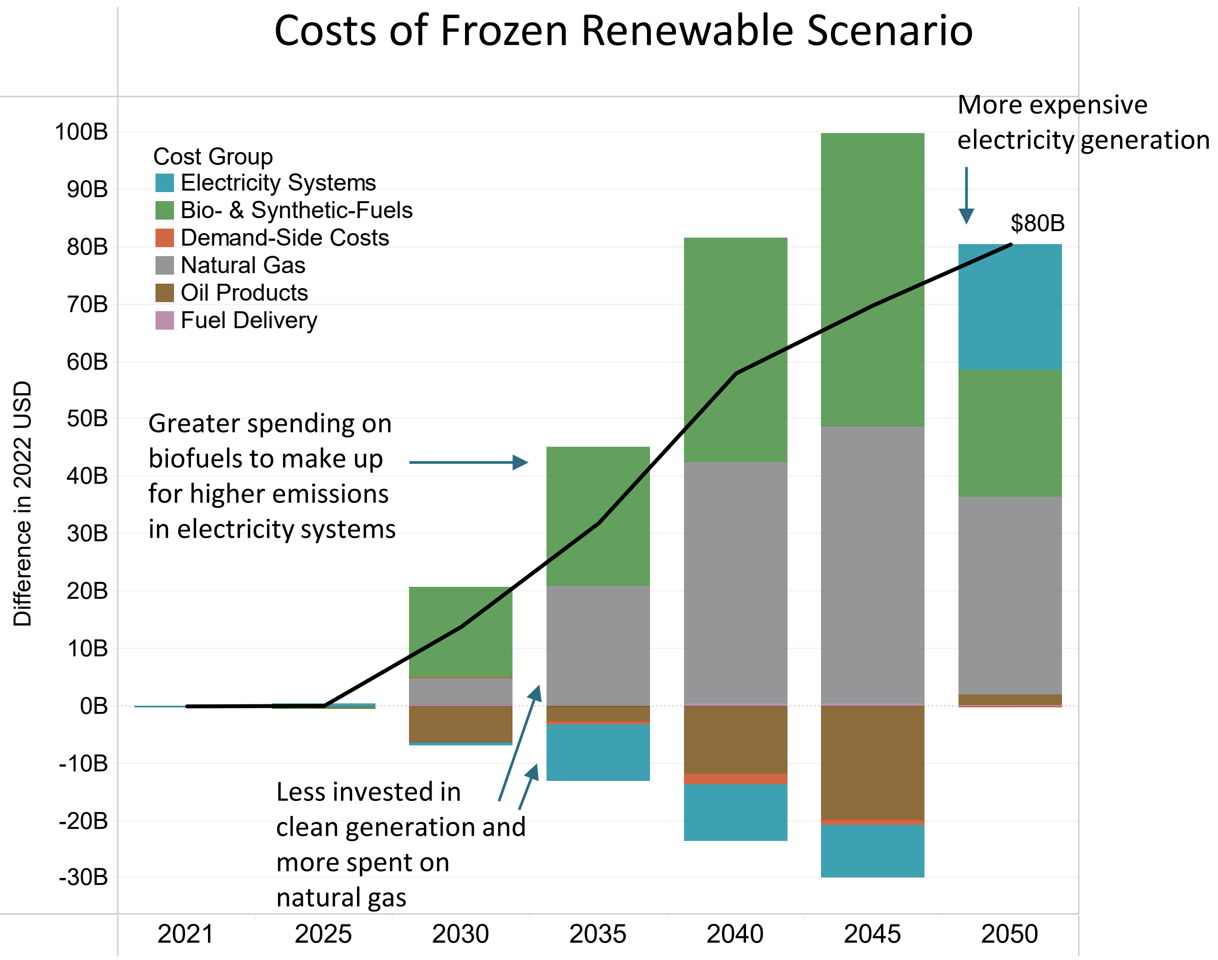

How do emissions change when wind and solar are frozen at recent rates and policies are implemented that would otherwise reach net zero?

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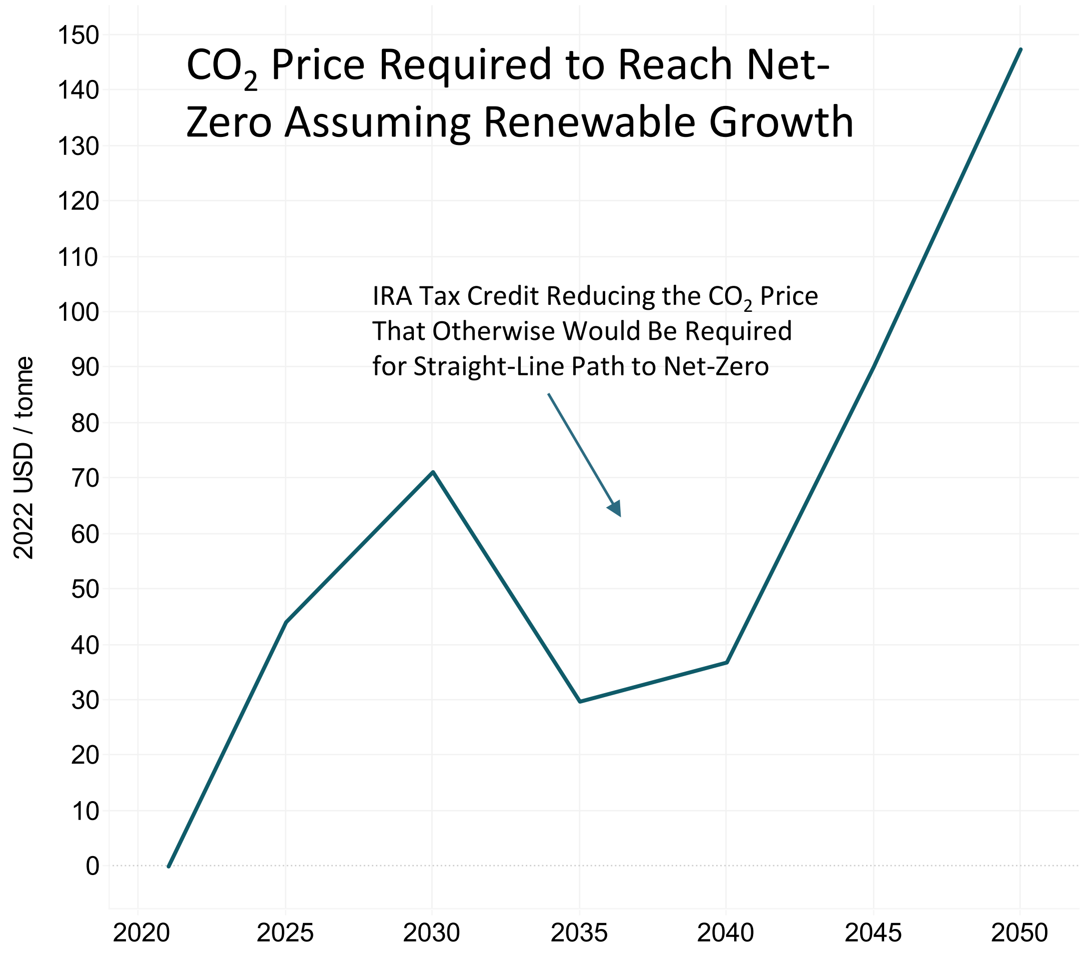

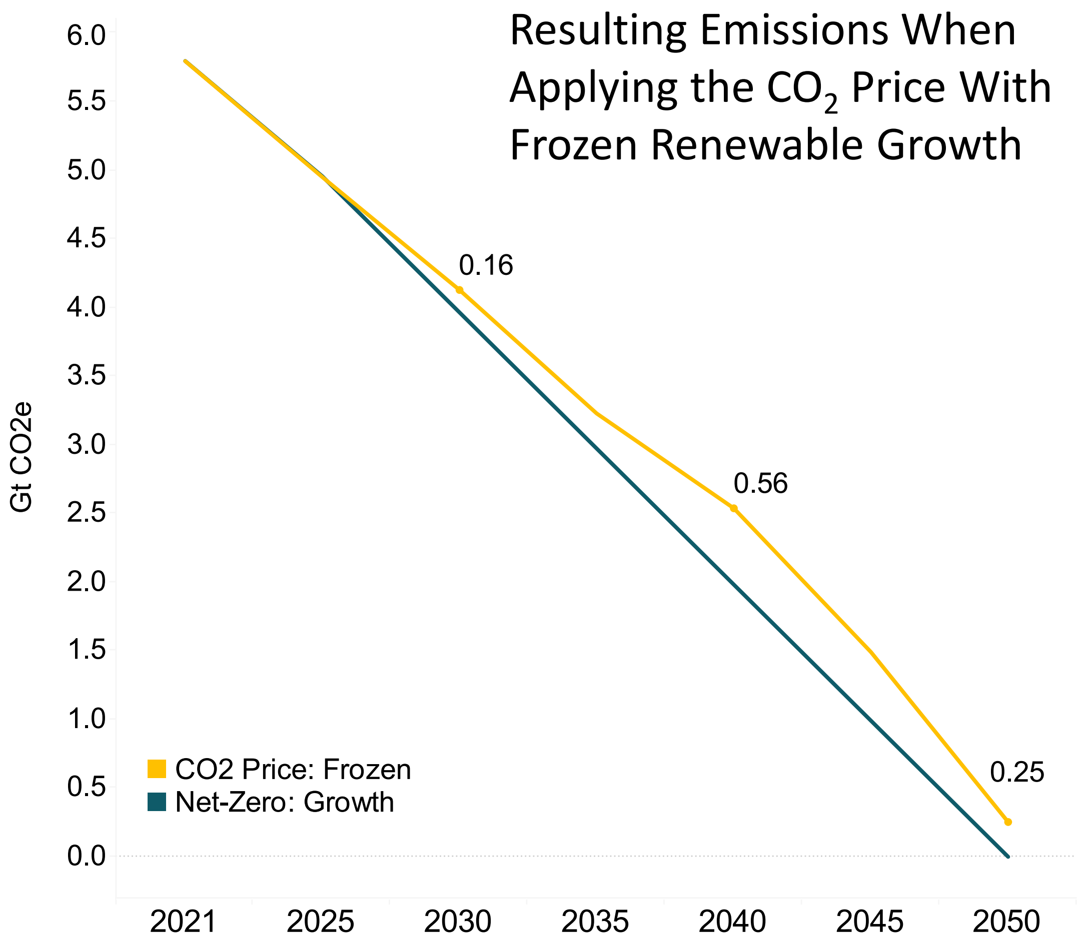

Summary: Impact of frozen renewable growth and no new transmission on net-zero

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- Frozen renewable growth and no new inter-zonal transmission will increase the annual cost of a net-zero system by $80B in 2050
- Policy mechanisms that, assuming renewable growth, are enough to incentivize a straight-line path to net-zero in 2050, would, with frozen renewable growth, have increased emissions by 560 Mt in 2040 and 250 Mt in 2050.
- If new primary energy from faster growth of wind and large-scale solar is not achieved, and new inter-zonal transmission cannot be built, the net-zero energy system changes in the following ways:
  - In the power sector, 140 GW new nuclear, 160 GW gas with carbon capture, 190 GW additional offshore wind, and 190 GW additional rooftop PV.
    - If these alternative resources cannot be sited (e.g., nuclear is difficult to site for reasons similar to those for wind) then net-zero cannot be achieved
  - 475 Mt additional carbon capture in 2050 (roughly a doubling)
  - 2 EJ of additional biomass in 2050, roughly the same scale as all corn ethanol today (2.4 EJ)

THANK YOU

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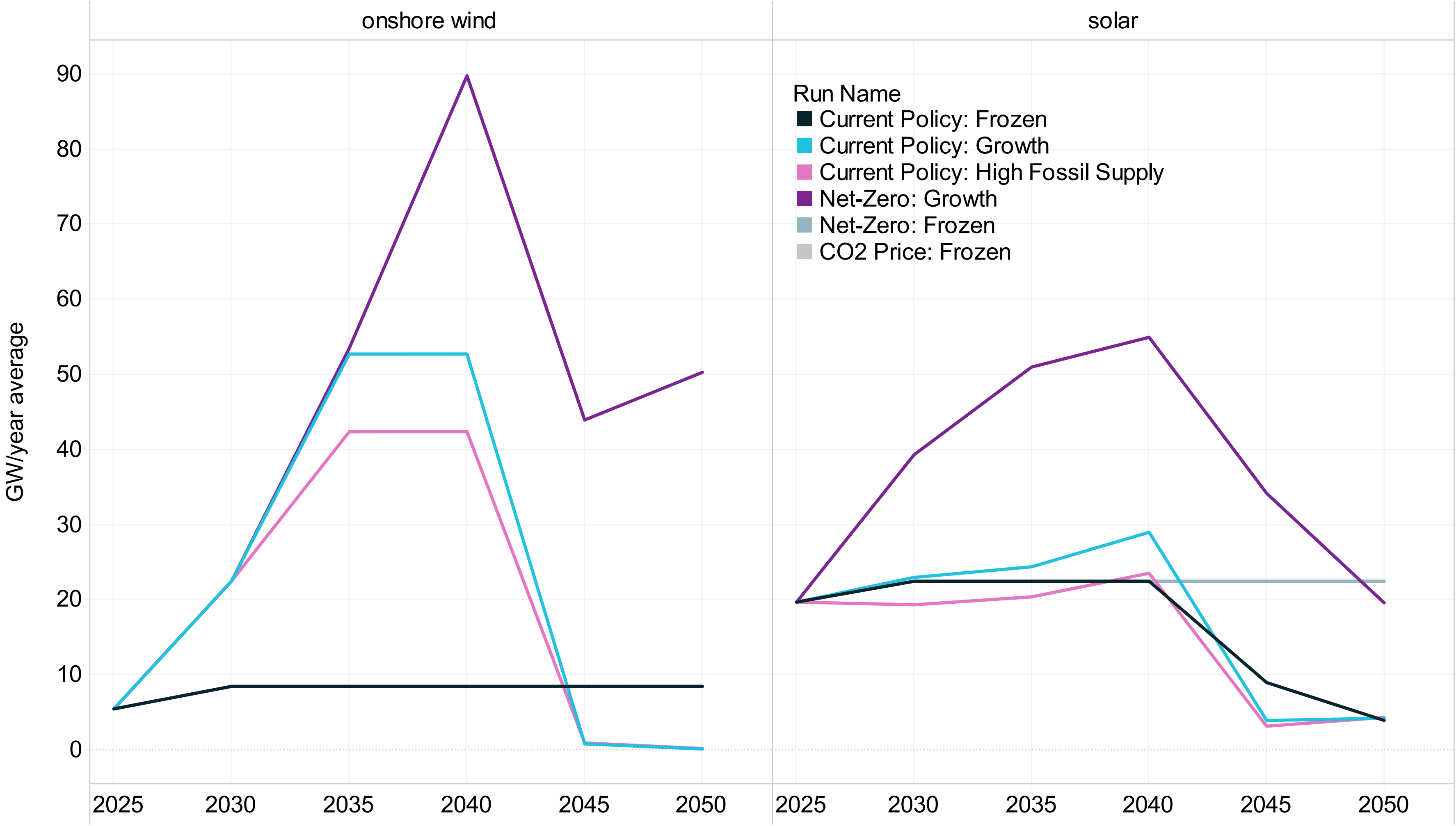
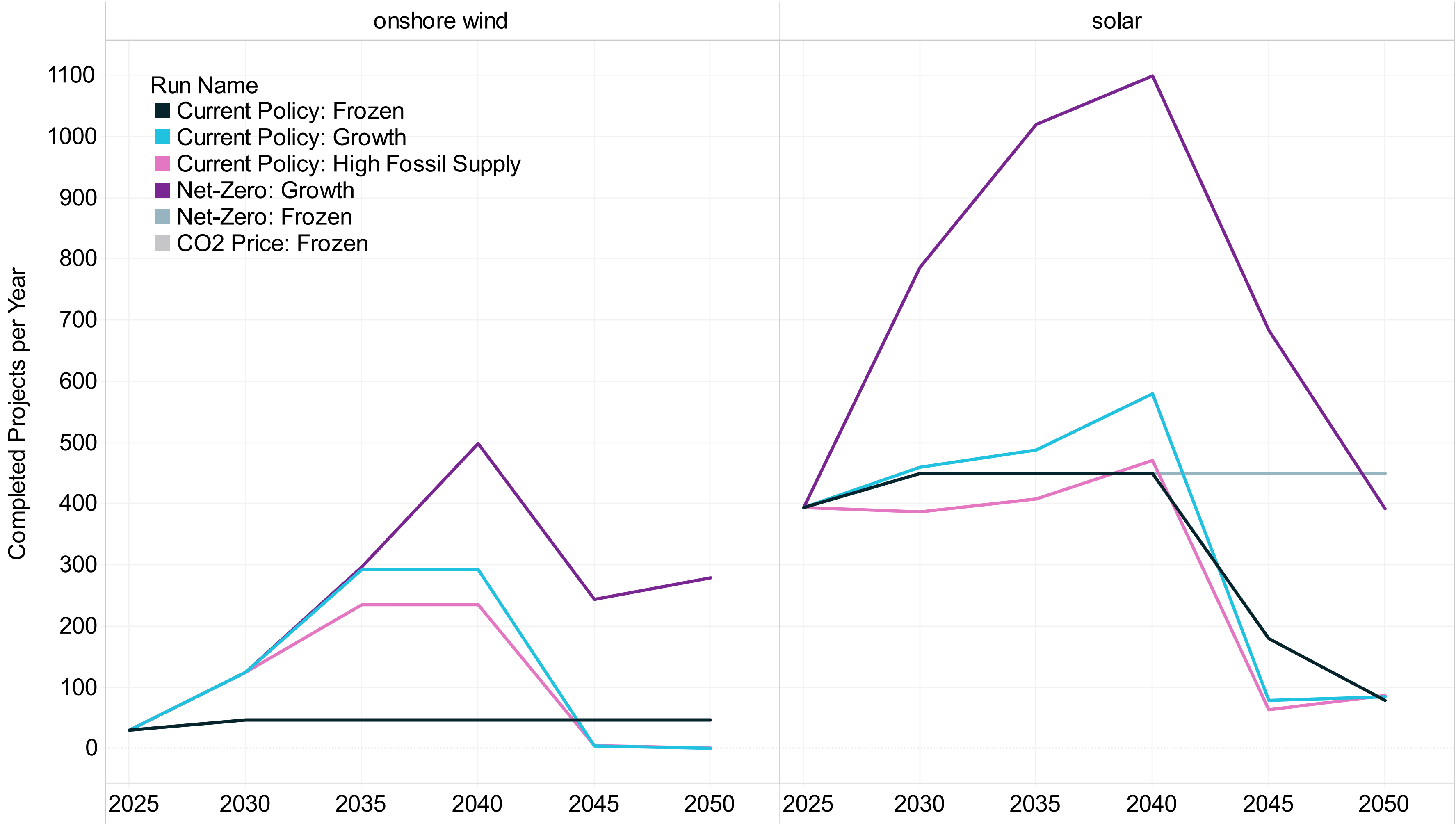
Renewable build rate by scenario

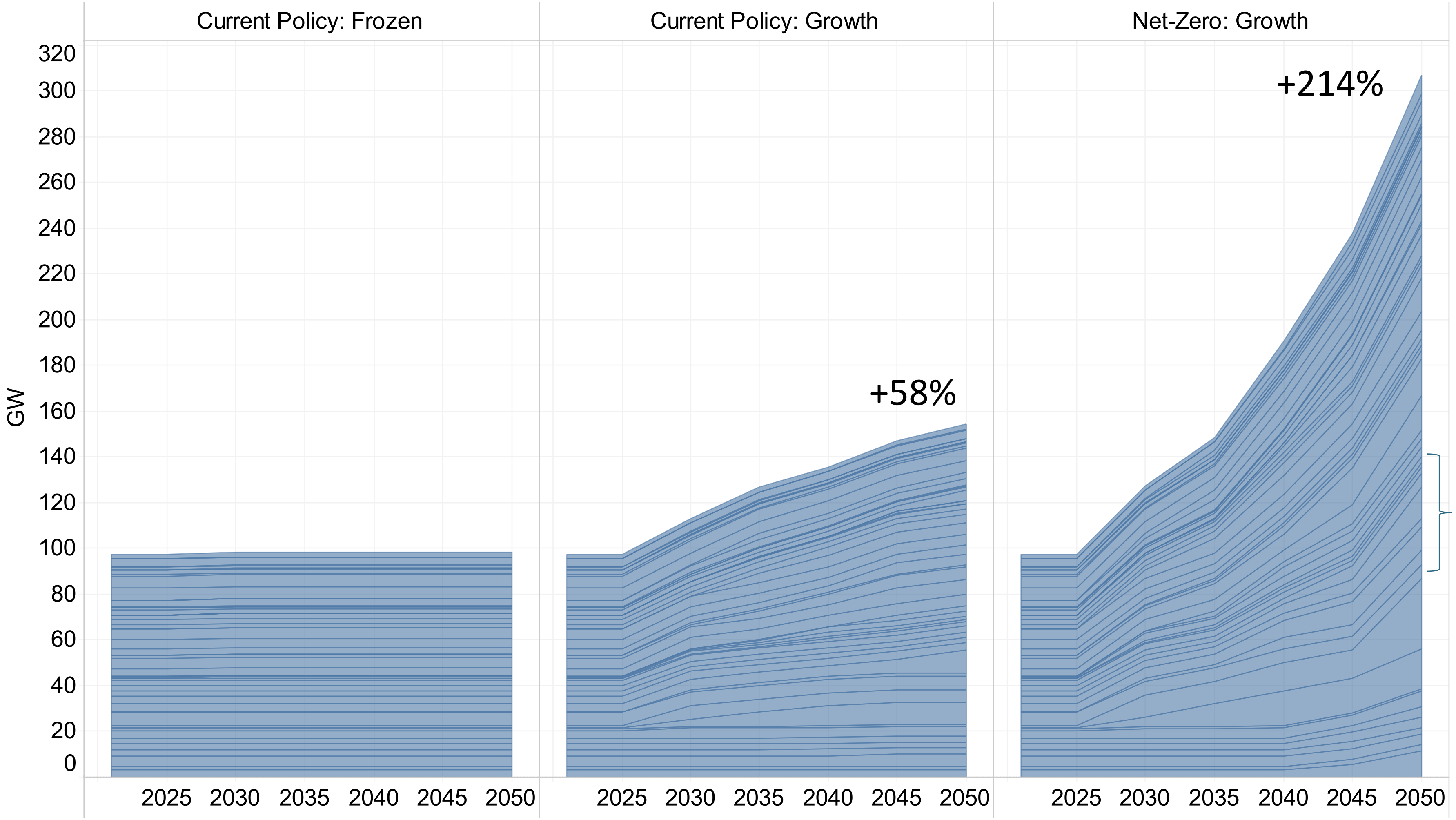


Estimated number of projects by scenario



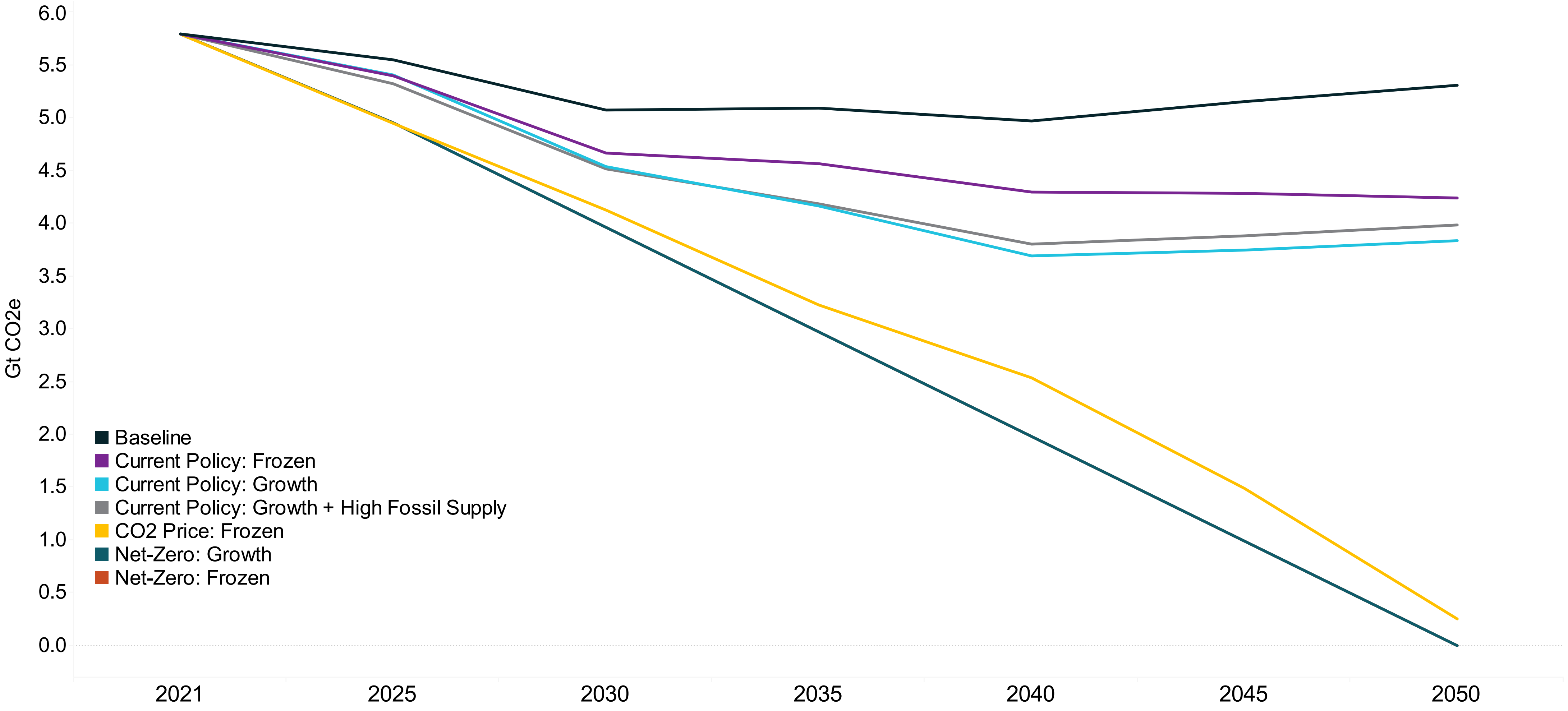
Assumes a median wind project size of 180 MW (NREL), and a median solar project size of 50 MW (LBNL)

Inter-zonal transmission capacity

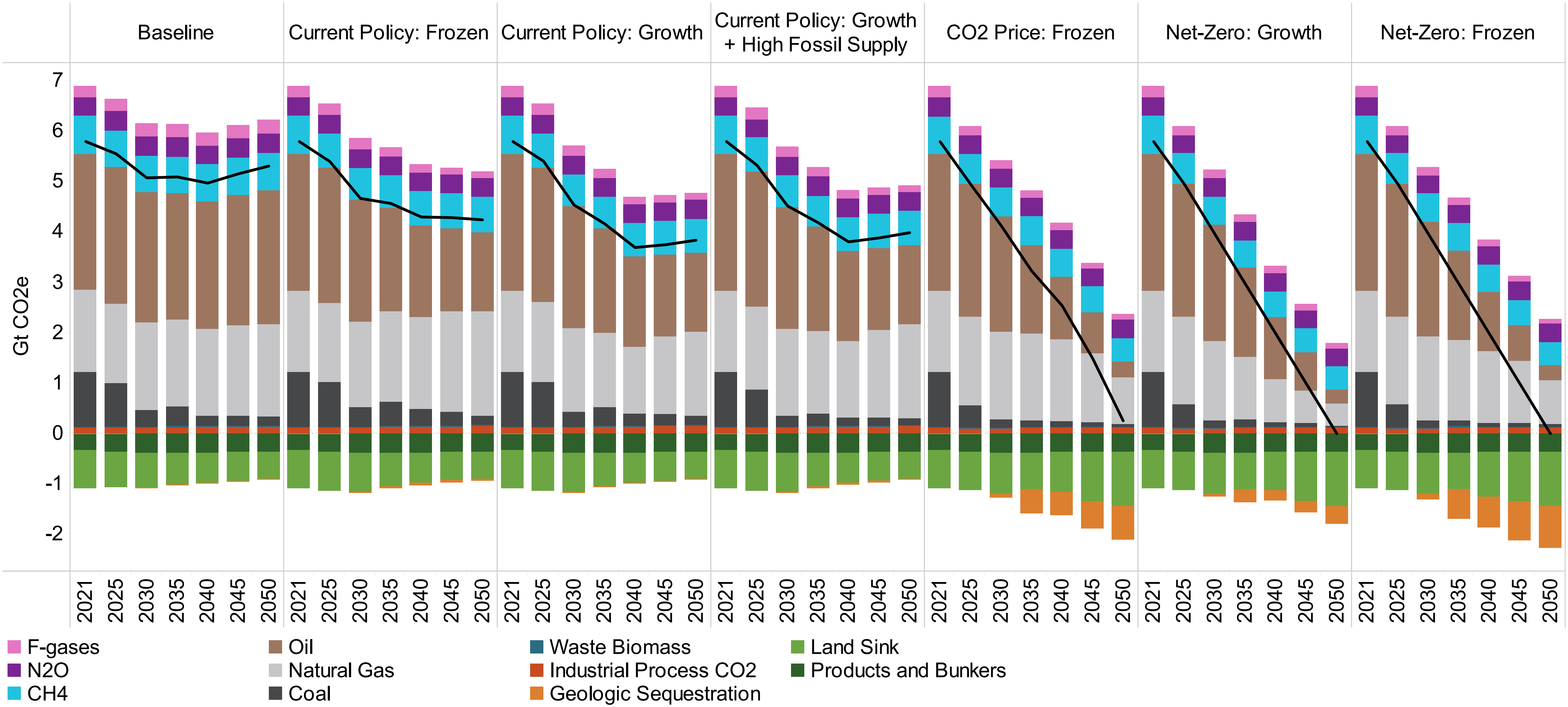


Each line represents a separate inter-zonal path in RIO between EIA Electricity Market Module Regions

Net emissions comparison



Emissions by source



Net-cost by category

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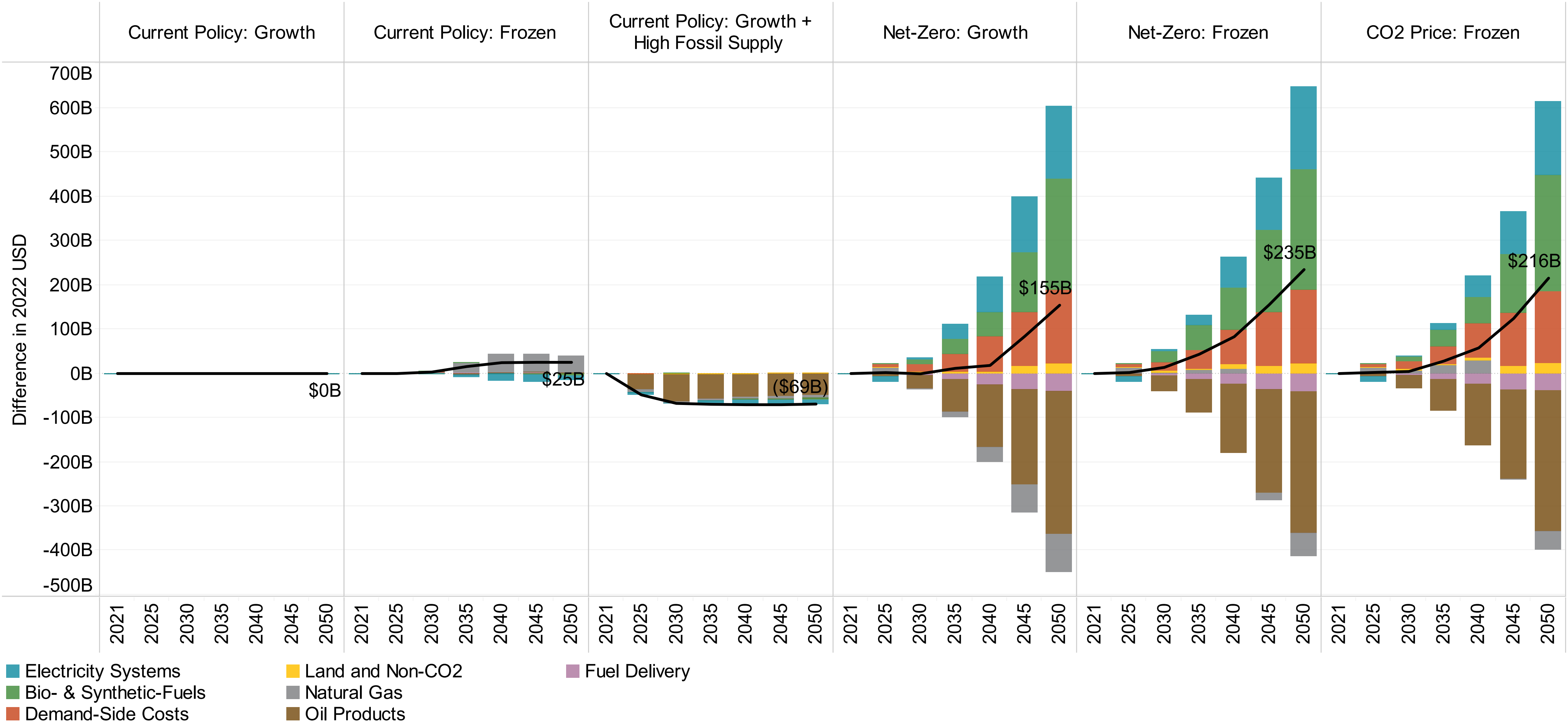
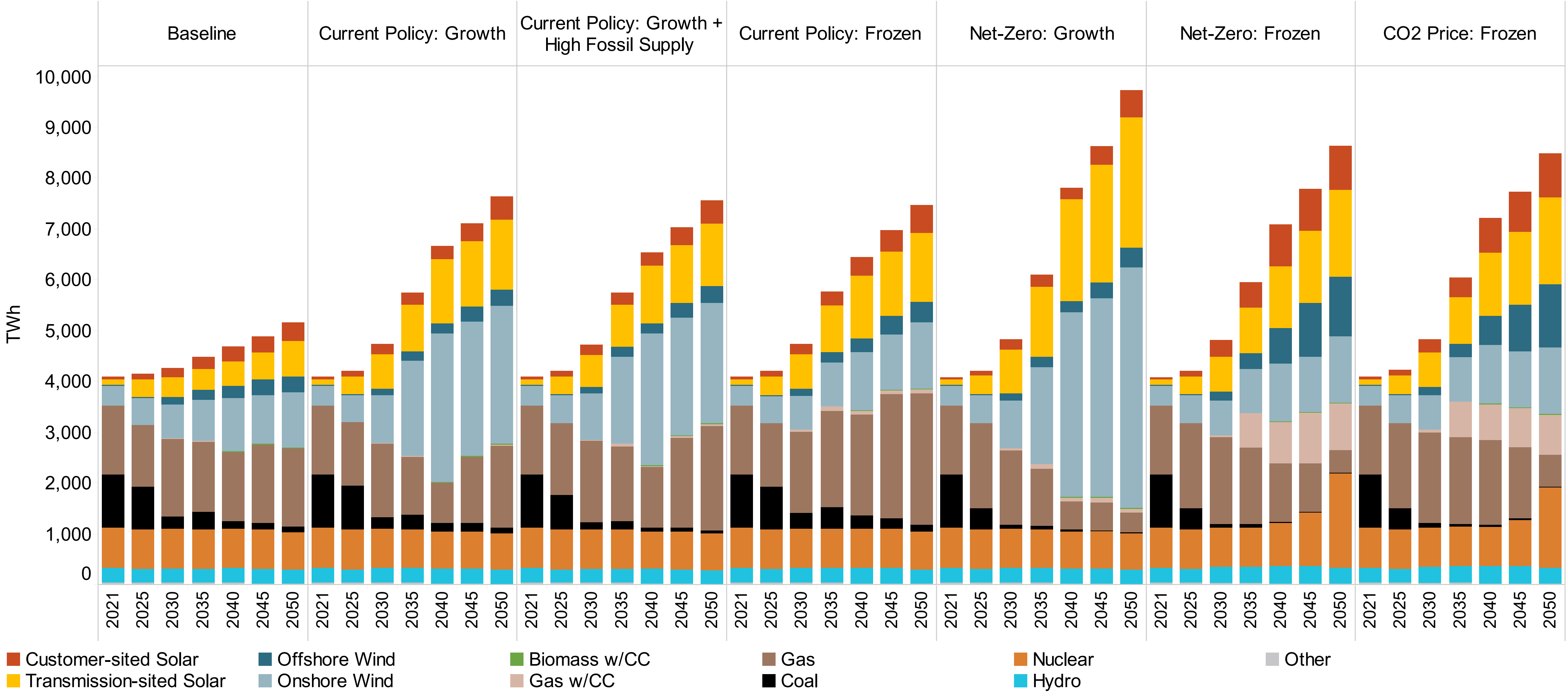
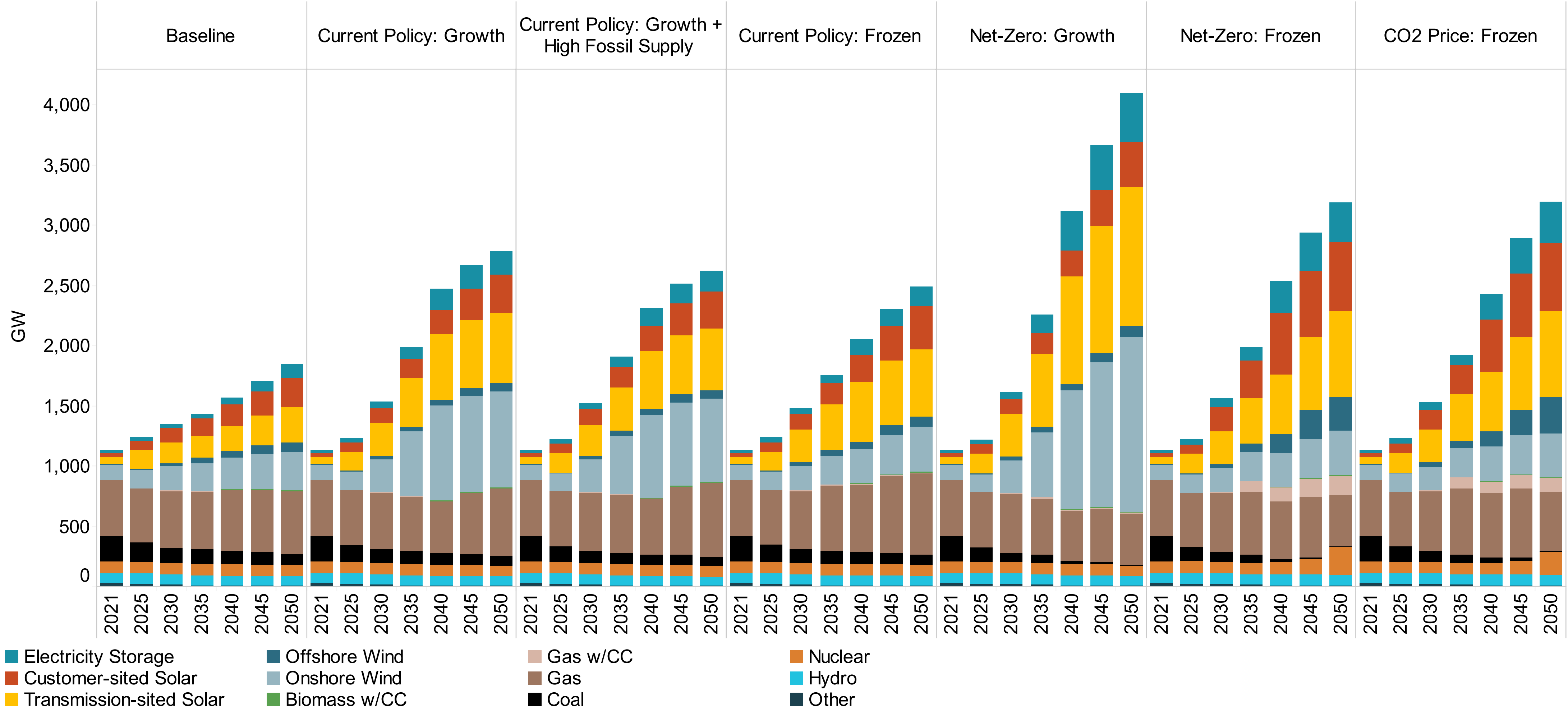


Electricity generation

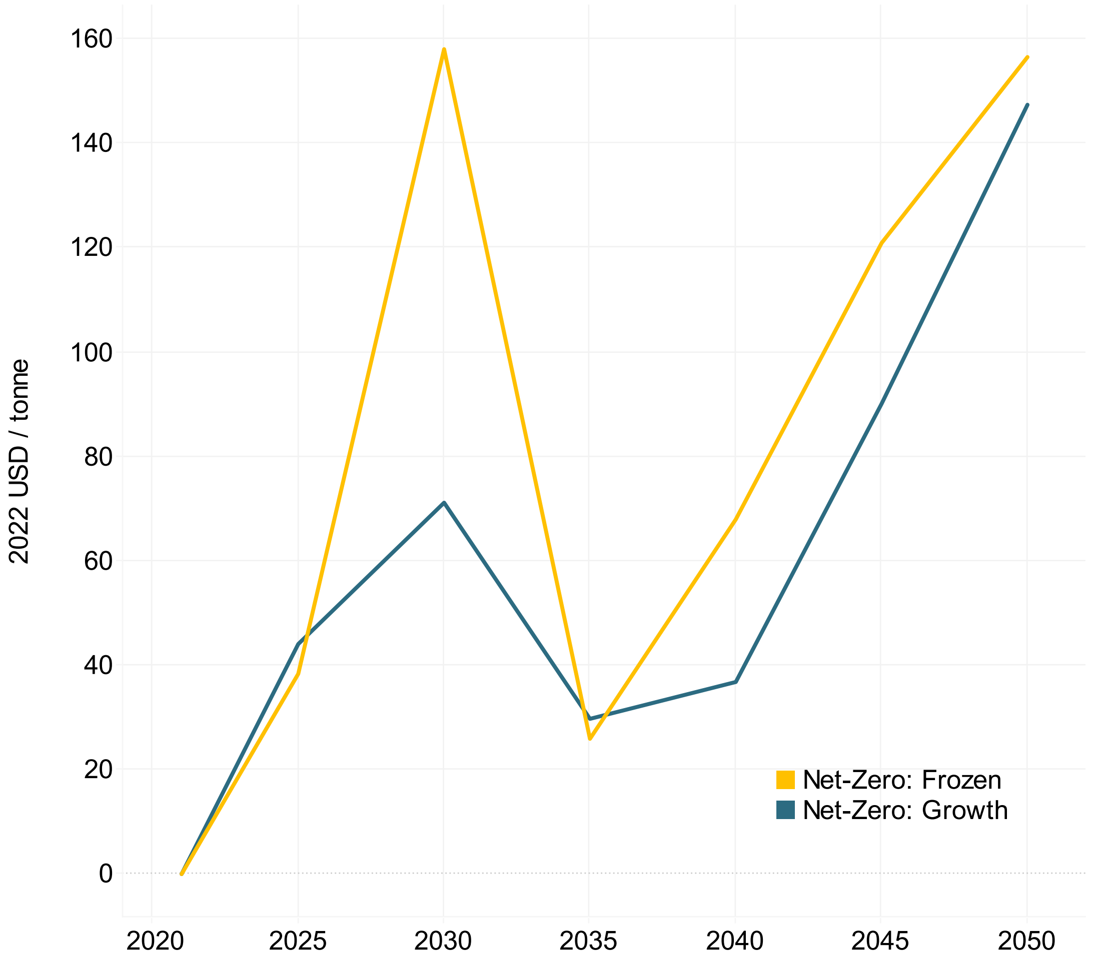


Electricity capacity



Emissions shadow price w/wo frozen renewables

- Emissions shadow price shows the near-term difficulty of staying on a straight-line path to net-zero if renewable growth is frozen ($158/tonne in 2030)
- Long-term emissions price increases $10-30/tonne to reach net-zero



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