Aurora Energy Research

CCS Impacts to System Level Emissions for 45V IRS Comments

Prepared for Calpine

February 2024

Agenda

Aurora provides market leading forecasts & data-driven intelligence for the global energy transition

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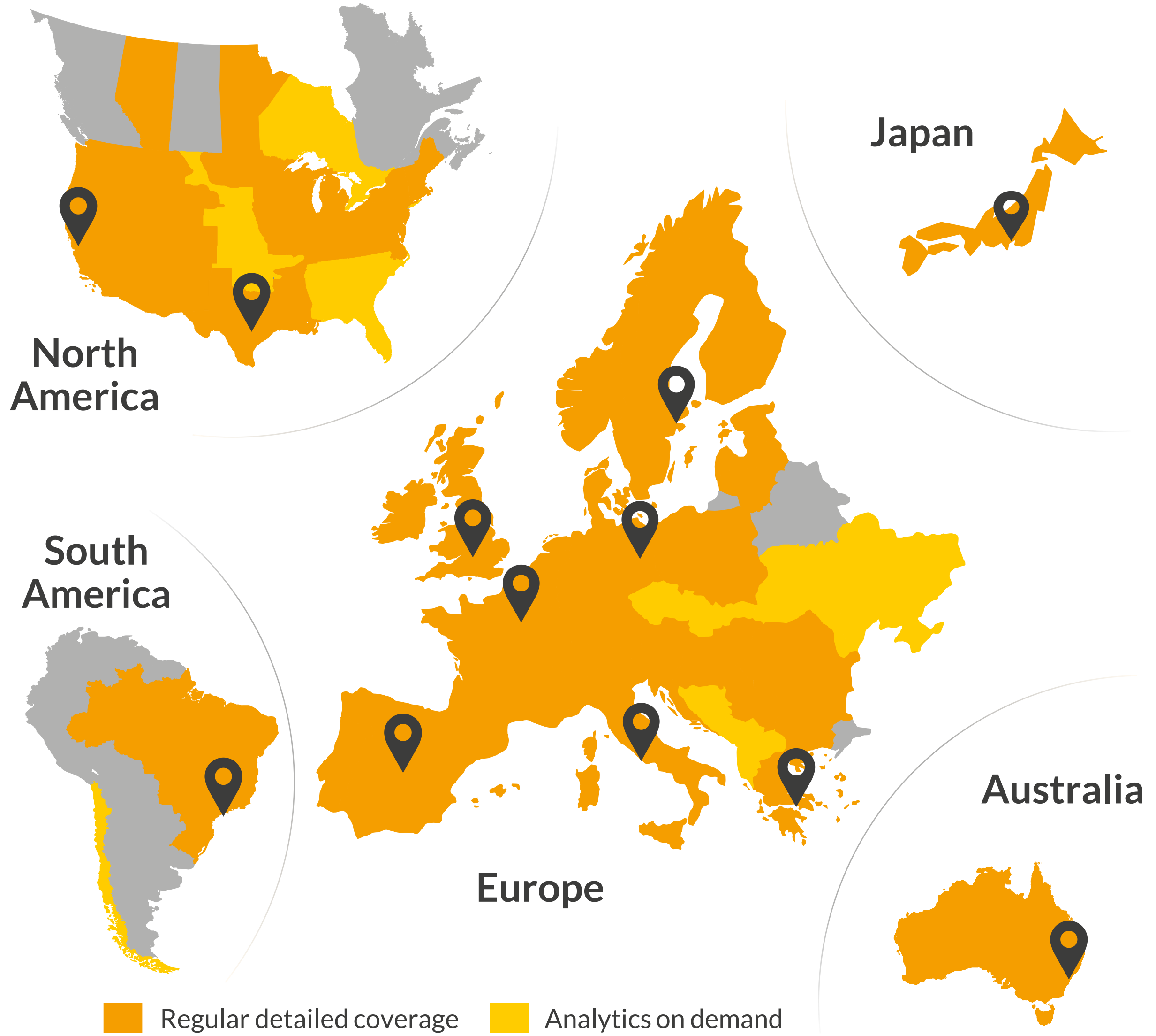
- Power markets
- Renewables
- Storage
- Electric vehicles
- Hydrogen H_2
- Carbon CO_2
- Natural gas



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market experts (75+ in USA)

750+
subscribing companies

150+
transactions supported in 2022

Source: Aurora Energy Research

Our market leading models underpin a comprehensive range of seamlessly integrated services to best suit your needs

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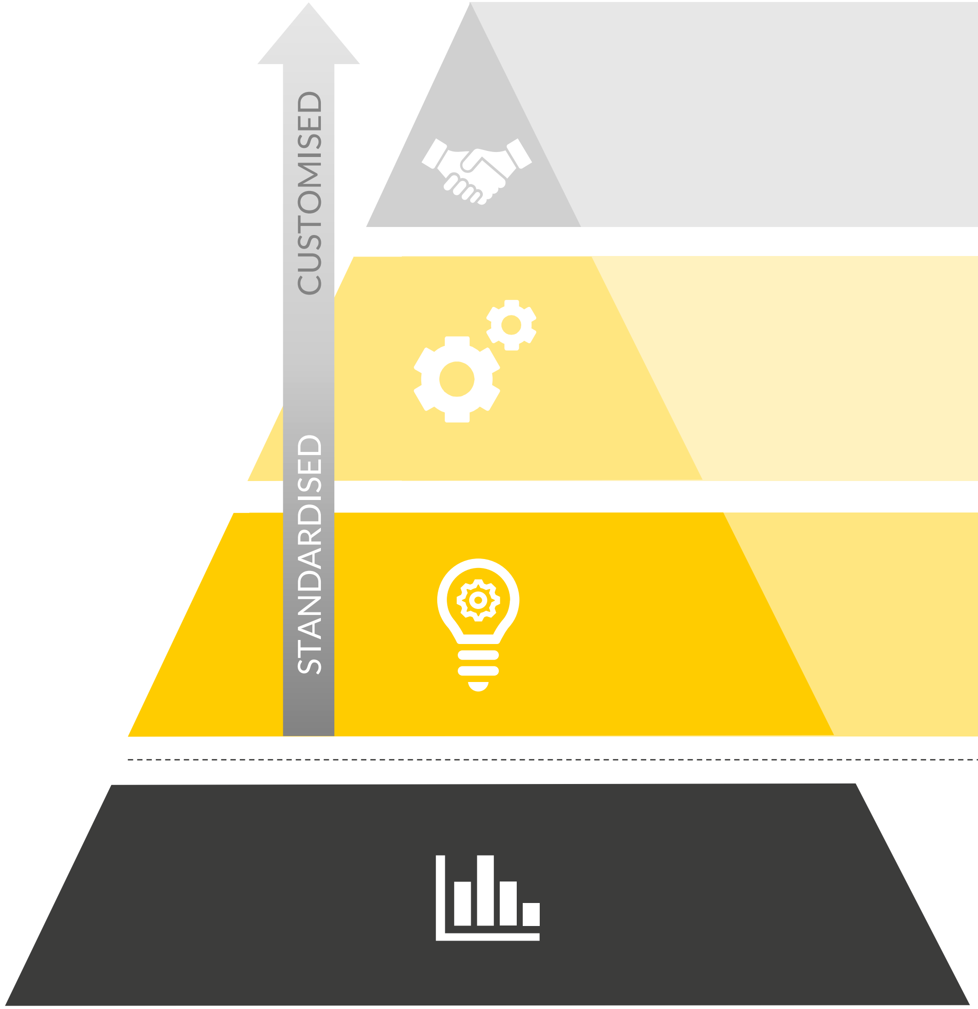

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Proprietary and continuously updated cutting-edge models populated with highest quality curated datasets

Developed over 10 years, 50+ dedicated modellers

Source: Aurora Energy Research

We are working with key US and international utilities, investors, lenders, developers and government

"Part of our policy role is to understand the data behind the system and reading your documents and getting insight from y'all at Aurora is fantastic. Thank you." – Jimmy Glotfelty, PUCT Commissioner

Sources: Aurora Energy Research

Aurora is trusted as a bankable lender's advisor across US and European power markets

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Aurora's price forecasts have been relied upon by lenders in recently completed transactions:

- 471 MW solar financing in ERCOT leveraging our market forecast and transmission modelling
- $568MM debt financing of a 350MW Storage portfolio in CAISO
- $650MM debt financing of a 215MW Solar + Storage facility in CAISO
- $130MM debt financing of a 150MW Solar project in ERCOT
- Market advisor for debt financing of Gresham House's 400+MW battery storage portfolio
- Debt financing of a 826MW CCGT asset
- €28MM debt financing
  First subsidy-free wind financing in Poland
- £192MM debt financing
  Saltend CCGT with CHP. LMA for regular forecasts
- Market advisor for the financing of a portfolio of hydro and PV assets
- Sell side advisor for the largest operational battery storage portfolio within the frequency containment reserve in Europe (90 MW)
- Market advisor for first project financing of battery storage in the UK
- €48MM debt financing
  220MW Potegowo onshore wind farm of Israel Infrastructure Fund

Ongoing financing projects:

- Market advisor for debt financing of a 600 MW onshore wind farm in ERCOT for a global Canadian developer
- Debt financing of a solar/storage asset in ERCOT for a global European developer
- Market Advisor for Debt financing providing structural floor pricing for term loans

Sources: Aurora Energy Research

Our clients tell us there are five areas in particular where we distinguish ourselves from our competitors

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Analytical rigour and objectivity

- Independence is hard wired into our operation: we give the balanced answer, not the convenient one
- Our business combines industry-standard subscription reports with cutting edge bespoke consultancy services, providing all-encompassing analyses

Dedication to energy markets

- We are the largest dedicated wholesale power market analytics company
- Executive and board level commitment to this strategy means no distractions from the core business

In-house modelling

- We own our own power and commodities models and do not rely on black box third-party models
- Our model is highly sophisticated and continuously enhanced and tested

Centre of the industry

- Our annual flagship event, the Aurora Spring Forum, is the meeting point for energy industry seniority
- Our broad subscriber base encompasses all facets of the energy Industry

Close proximity to policy

- We are well-connected with policy makers, government and industry leaders who keep us updated on upcoming and unexpected policy amendments
- Our directors are advisors to the government further strengthening our relationship

"Aurora Energy Research is, I think, one of the smartest energy modelling companies around, and helped us on this Energy Outlook and continue to help us"

Spencer Dale, Chief Economist, BP

bp

"We have worked with Aurora in various occasions and value their in-depth forecasts and analysis. It helped to support our understanding of the UK electricity market."

Guillaume Leprieur, Director, MUFG

MUFG

Source: Aurora Energy Research

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Background

- On December 22nd, 2023, the Treasury Department and the IRS released long-awaited guidance on eligibility and implementation for the 45V hydrogen production tax credit.

- This guidance specified requirements along the “three pillars” of incrementality, deliverability, and temporal matching.

  Incrementality: Requires use of newly constructed clean electricity generation for hydrogen production.

  Deliverability: Requires electricity generated from within the same region as the hydrogen production.

  Temporal matching: Requires time matching of hydrogen production with new clean electricity generation.

- The IRS is seeking comments on these proposed regulations, due February 26th, 2024, with a public hearing planned for March 25th, 2024.

- This study seeks to contextualize the “incrementality” requirement for an existing CCGT asset with plans to reduce operational emissions through an upgrade using carbon capture.

- The analysis involves modeling of total system-level emissions for varying configurations of thermal generation with and without carbon capture, combined with hydrogen electrolysis, to be used to support IRS comments submission.

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III. Modeling results

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Without carbon capture, each additional 150MW of electrolyzer load adds an average of 6.5 mn tons of additional emissions to the system from 2027 to 2038

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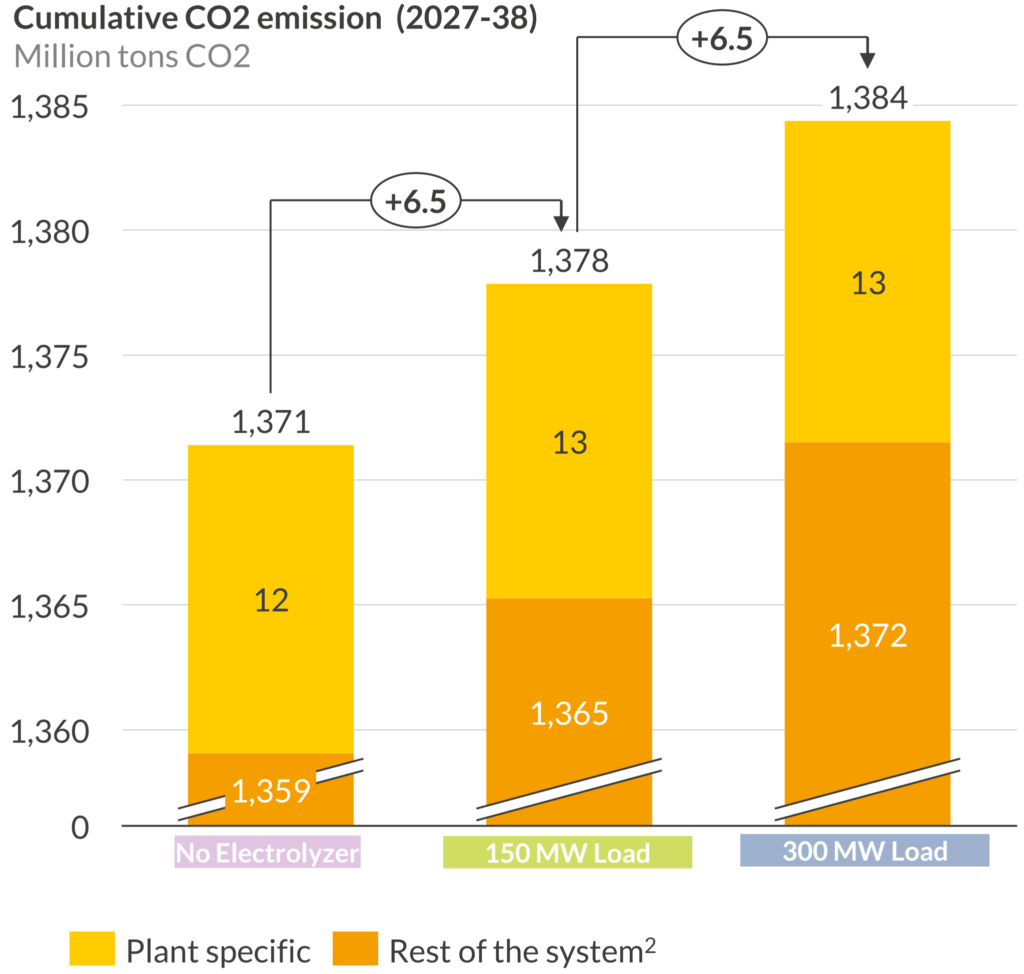
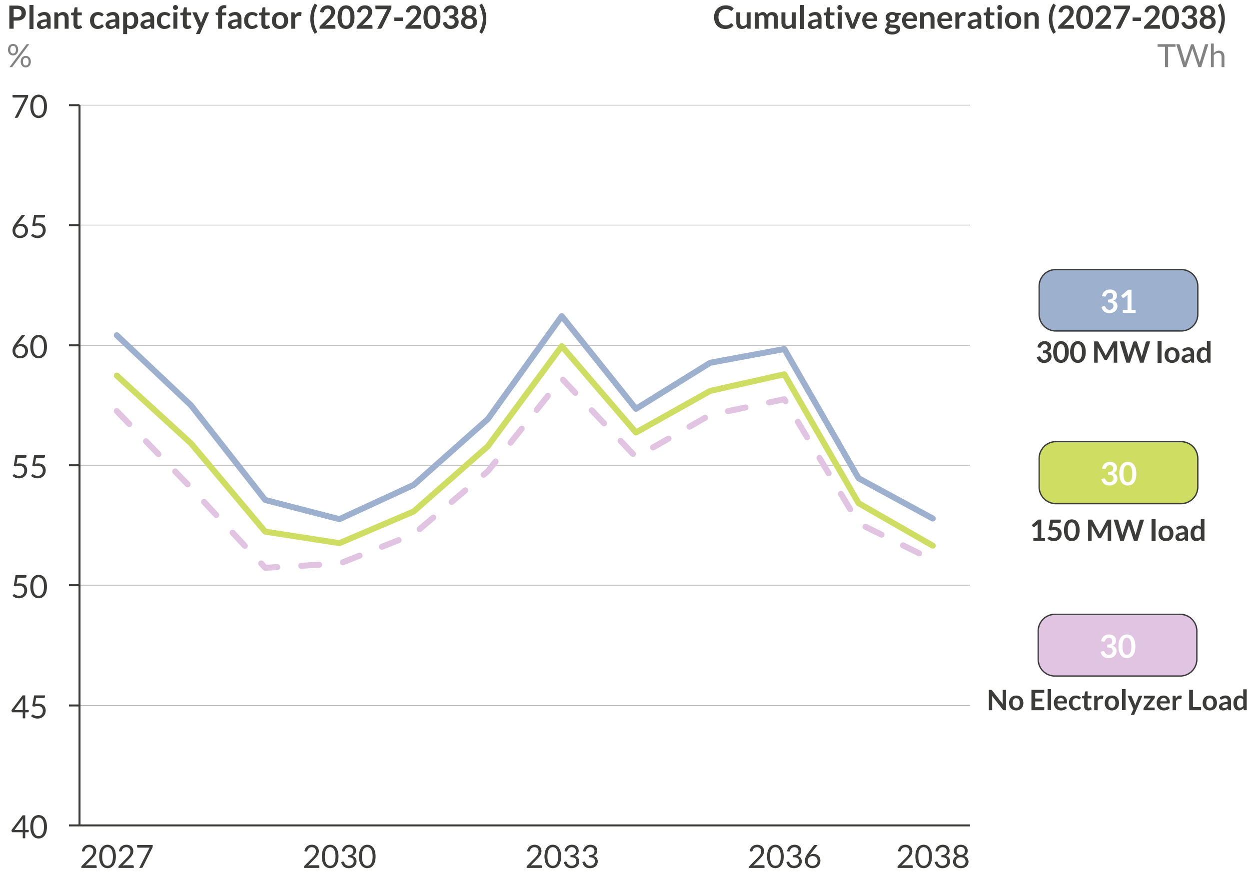
CO2 emissions increase due to increased load



The additional load is fulfilled by the entire system, including the studied CCGT plant[1] that will be retrofitted with carbon capture technology in 2027



1) The plant is a 500 MW CCGT in Houston. 2) Carbon emissions from the rest of the system come from all gas, coal, and lignite fueled plants. 3) The electrolyzer is placed in Houston and runs at 90% load factor starting 2027. At 67% efficiency, the electrolyzer pulls 150MW of electricity from the grid to produce 100MW of hydrogen. Assume perfect time-matching with CCGT-CCS.

Sources: Aurora Energy Research

The IRA tax credit pushes down the marginal cost of a CCGT-CCS plant from $41 to ~$17-24/MWh, making it cheaper than most thermal generation

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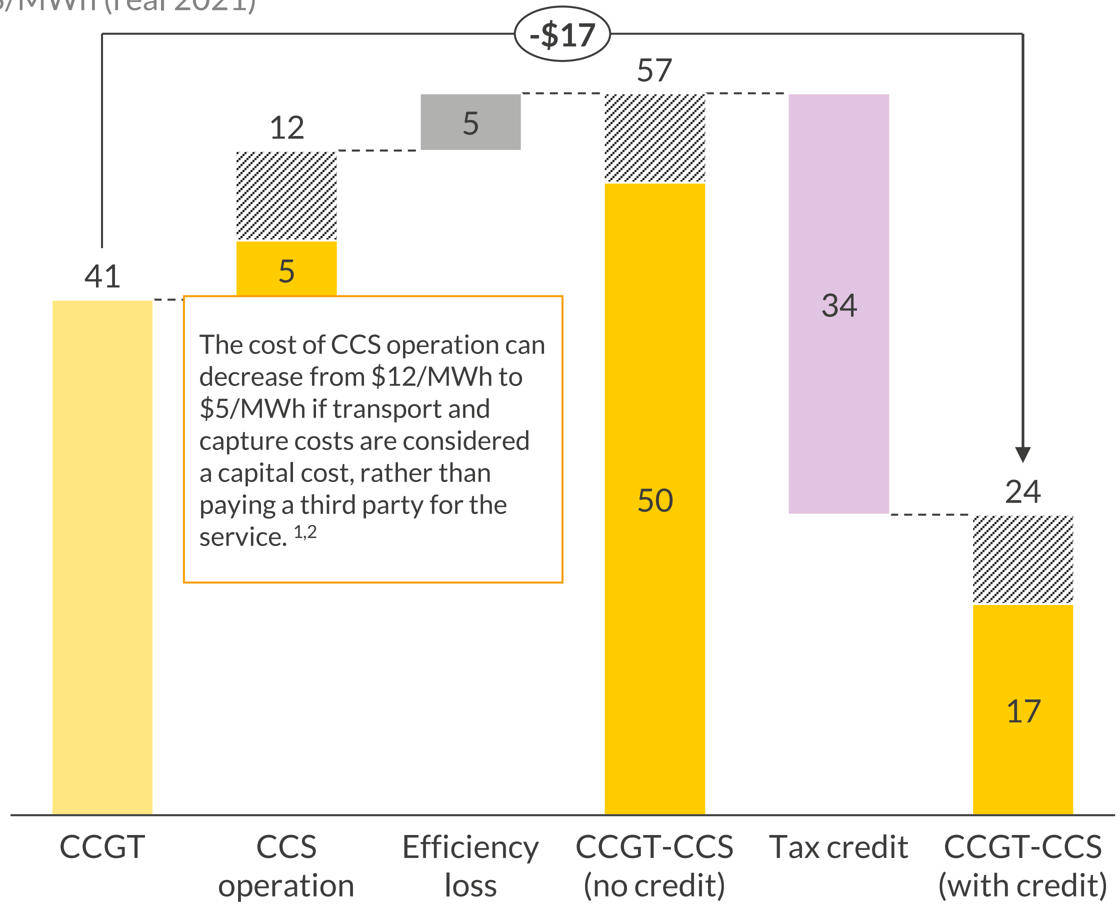
1 CCS tax credits make CCGT-CCS units ~$20/MWh cheaper than CCGTs

IRA tax credit impact on short-run marginal costs of CCGT-CCS[1] (2030, South)

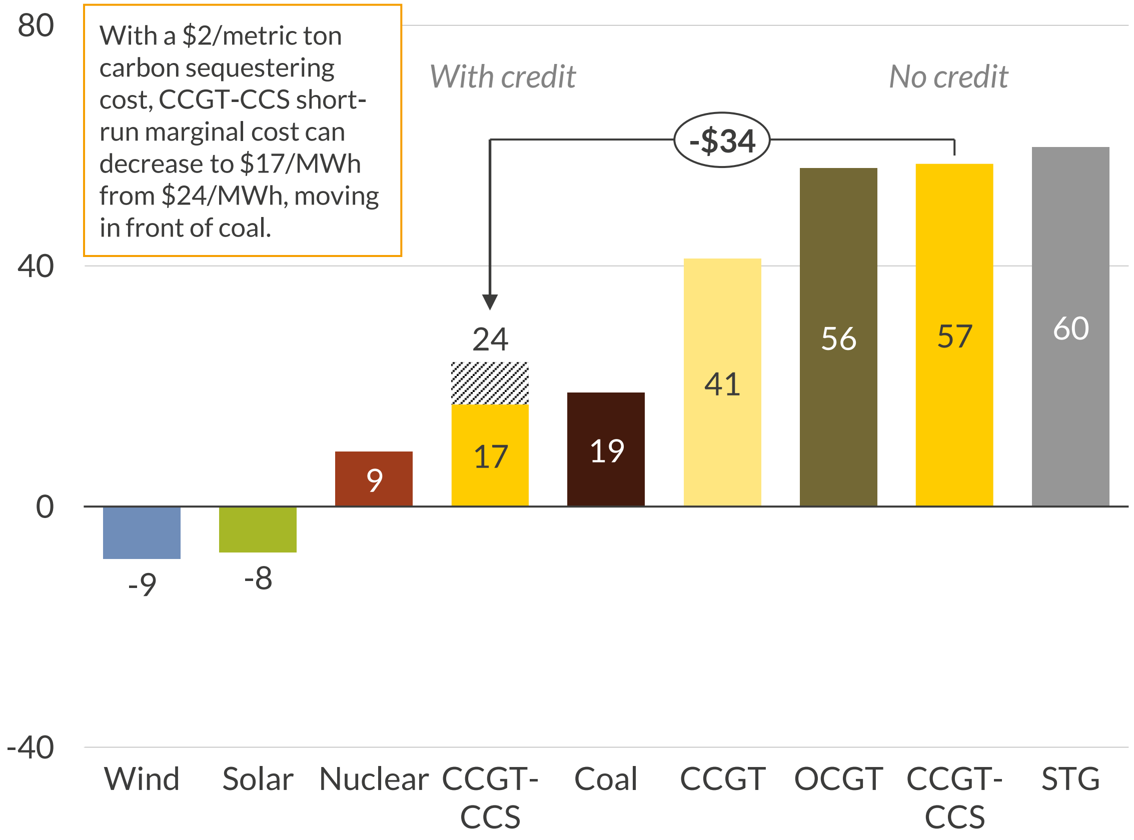
$/MWh (real 2021)



2 This brings CCGT-CCS close to the bottom of the dispatchable merit order

Appx. short-run marginal costs by generation technology (2030, South)

$/MWh (real 2021)



1) Assumes 45% CCGT efficiency, 95% carbon capturing efficiency, $20/metric ton carbon sequestering cost, and 0.181 tCO2/MWhTh carbon intensity. For the rest of the analysis, we assume $20/metric ton carbon sequestering cost as fee for service
2) Note that CCS operation includes carbon sequestering and ~$4/MWh variable cost

Sources: Aurora Energy Research

Retrofitting a CCGT to CCGT-CCS impacts carbon emissions in two ways: reduction of the plant emissions and displacement of other thermal plants

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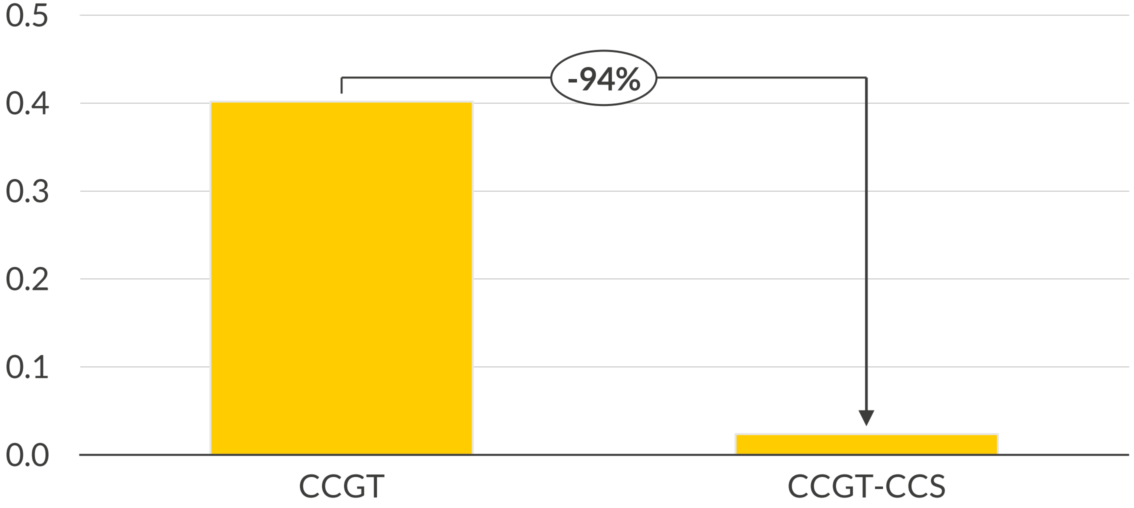
1 Reduction in individual plant's emissions

Carbon intensity before and after retrofitting, 2027
tons CO2/MWh

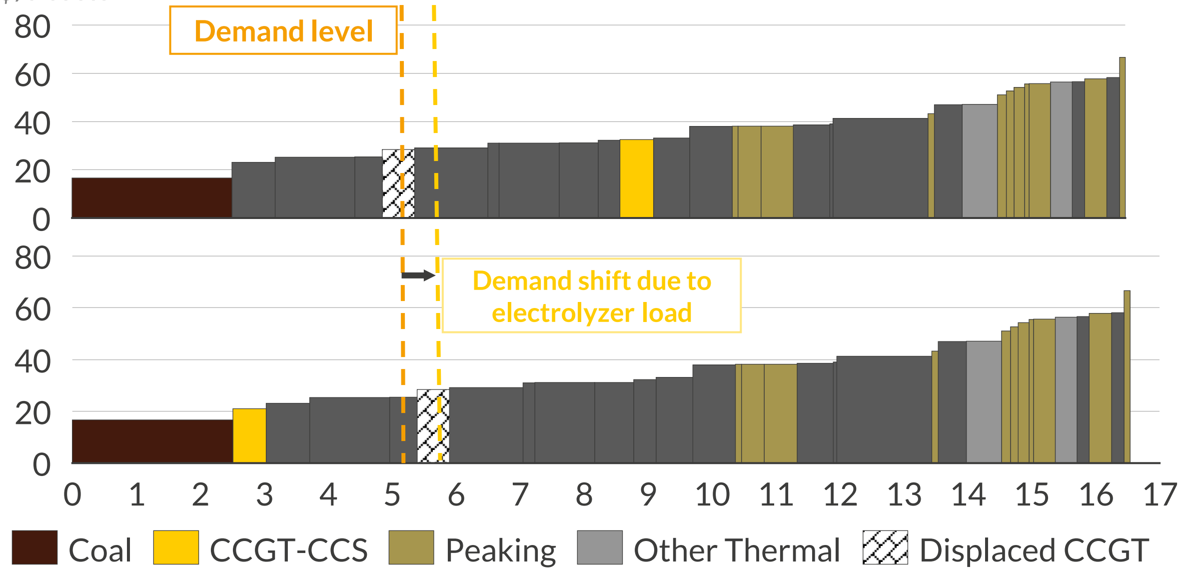


Driver	Description
A Reduction in CO2 emissions intensity (tCO2/MWh)	CCS decreases the CO2 emitted per unit of power generated
B Increased CO2 emissions due to higher capacity factor (MWh)	CO2 emissions increase slightly due to increased generation

2 System-wide emissions reduction due to displacing less efficient thermal

Illustrative thermal marginal cost stack in Houston Hub
$/MWh

Total Capacity
GW



Driver	Description
System-wide reduction due to displacement (MWh)	Additional generation from the CCGT-CCS displaces generation from other thermal plants
System-wide increase due to additional electrolyzer demand	Additional load from electrolyzer capacity shifts the demand curve, offsetting previous thermal displacement

Note: Assumes 45% CCGT efficiency, 95% carbon capturing efficiency, $20/metric ton carbon sequestering cost, and 0.181 tCO2/MWh$_{(Thermal)}$ carbon intensity. Modeled period 2027-2038 when the CCGT-CCS has the 12-year tax credit ($85/metric ton carbon captured)

Sources: Aurora Energy Research

The retrofitted CCGT-CCS[1] plant reduces the generation of more carbon-intensive plants; meanwhile, total generation remains constant

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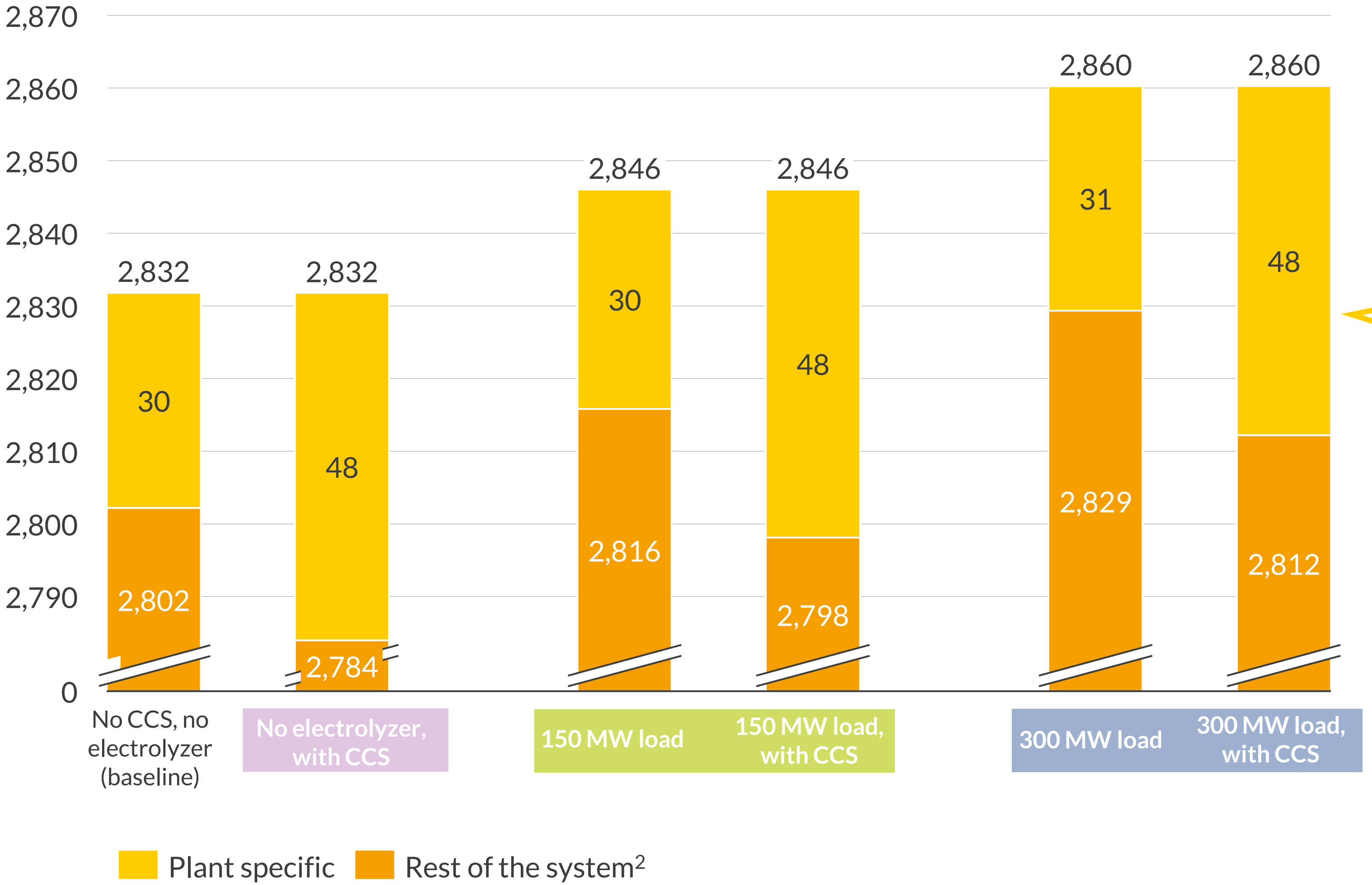
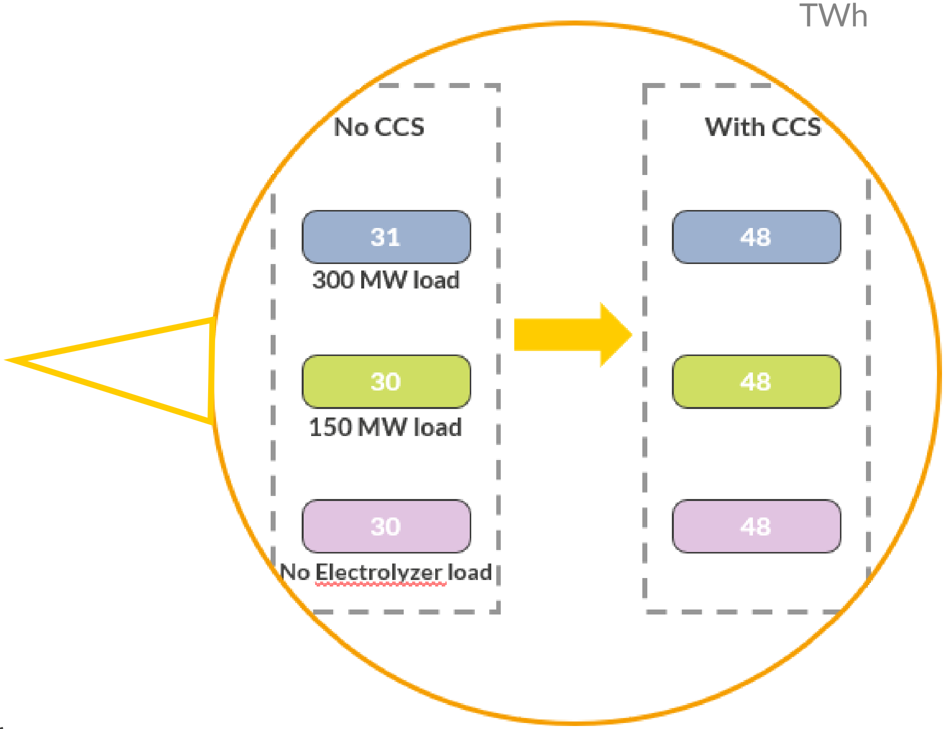
Cumulative Thermal generation (2027-38)
TWh



Plant-wide cumulative generation (2027-2038)
TWh



- The more the CCGT-CCS plant runs, the more generation from less efficient thermal it replaces, due to their later placement in the merit order

1) Assumes 45% CCGT efficiency, 95% carbon capturing efficiency, $20/metric ton carbon sequestering cost, and 0.181 tCO2/MWh $_{(Thermal)}$ carbon intensity. Modeled period 2027-2038 when the CCGT-CCS has the 12-year tax credit ($85/metric ton carbon captured) 2) the rest of the system includes only carbon emitting technologies: gas, coal, and lignite 3) At 67% efficiency, the electrolyzer pulls 150MW of electricity from the grid to produce 100MW of hydrogen. Assume perfect time-matching with CCGT-CCS

Sources: Aurora Energy Research

From 2027 to 2038, 405 MW of electrolyzer load can be added to the system without an increase of total emissions vs baseline with a CCS retrofit

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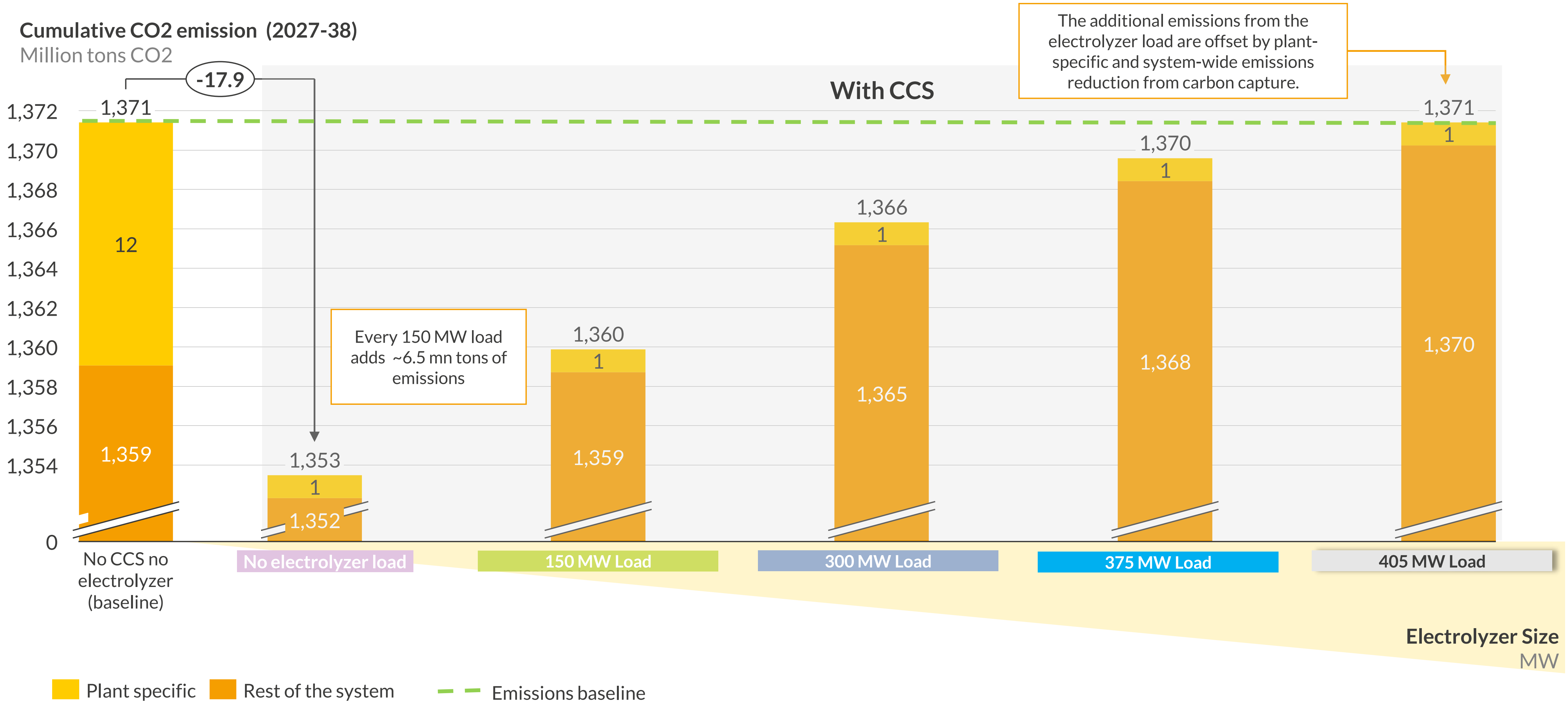
Cumulative CO2 emission (2027-38)
Million tons CO2



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Sources: Aurora Energy Research

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Technology assumptions – 150-375MW of electrolyzer and 500 MW of CCGT-CCS in Houston starting 2027, perfect time-matching

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Electrolyzers and CCGT-CCS in Aurora model

	Flexibility	Load Factor	Demand	Capacity	Efficiency	Implied Additional demand/supply
Electrolyzer	Price responsive subject to fulfilling hydrogen demand and perfect time-matching with CCGT-CCS	90%	Fulfils hydrogen demand which is back-calculated from installed capacity and load factor	150, 300, and 375 MW of load	67% Proton exchange membrane (PEM)	100MW-> 0.1*8760*0.90 = 0.79 TWh Extra power demand per year
CCGT-CCS	Economic Dispatch	55% before retrofit; 90% after retrofit	Fulfils electrolyzer's (via perfect time-matching) and system-wide power demand	500	45% before retrofit; 38% after retrofit	500MW-> 0.5*8760*(0.90 - 0.55)[1] = 1.53 TWh Extra power supply per year

Additional CCGT-CCS assumption

- Capture rate: Gas CCGT + CCS has a capture efficiency of 95%. Therefore 5% of carbon will be emitted.
- 45 Q: Valid for first 12 years of at $85/ton
- Carbon sequestering cost: $20/ton
- CCGT-CCS efficiency derating: 15% (Additional fuel consumption by CCGT to produce equivalent electricity)

Carbon intensity assumption

- 0.181 tCO2/MWh for natural gas
- At 45% plant efficiency, the plant carbon intensity is 0.4 tCO2/MWh; At 95% capture rate, CCUS captures 0.38 tCO2/MWh

- Added electrolyzer with load of **150 MW, 300 MW, and 375 MW** to produce hydrogen
- The electrolyzer production profile has perfect time matching with the CCGT-CCS dispatch.

1) CCGT capacity factor increases from 55% to 90% after retrofitting

Sources: Aurora Energy Research

System-wide carbon emissions: CCS reduces emissions under the same or even higher levels of load

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CO2 emissions (2027-38)
Million tons CO2

Year	No electrolyzer no CCS	No electrolyzer with CCS	150 MW electrolyzer load with CCS	405 MW electrolyzer load with CCS
2027	143	142	142	143
2028	131	130	130	131
2029	129	127	128	129
2030	122	121	122	122
2031	116	115	115	116
2032	108	107	107	108
2033	104	102	103	104
2034	100	99	99	100
2035	102	100	101	102
2036	104	102	103	104
2037	105	104	104	105
2038	106	105	105	106
Total	**1371**	**1353**	**1360**	**1371**

1) Capacity in 2023 2) retirement is not applicable when assets retire partial capacity

Sources: Aurora Energy Research, ERCOT

2027 – 2038, wind and solar capacities increase by 44 GW; conventional thermal capacity declines by 10 GW

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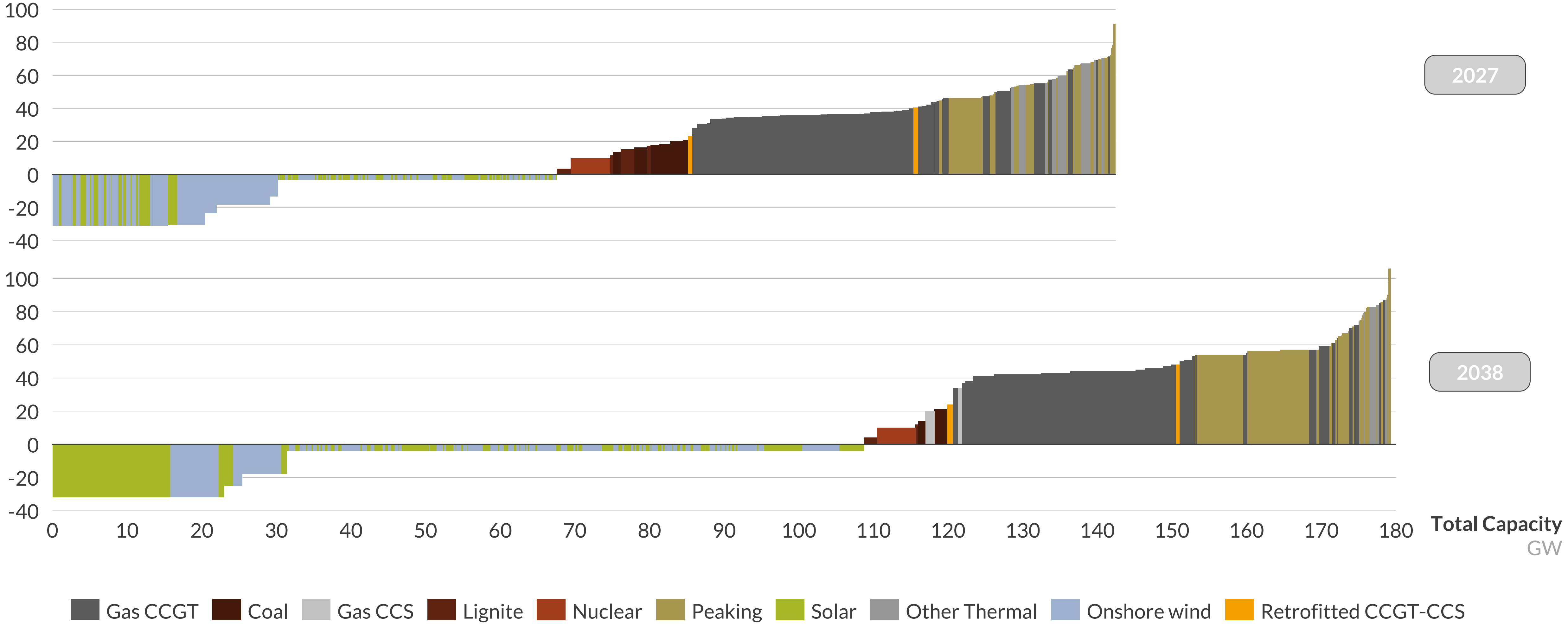
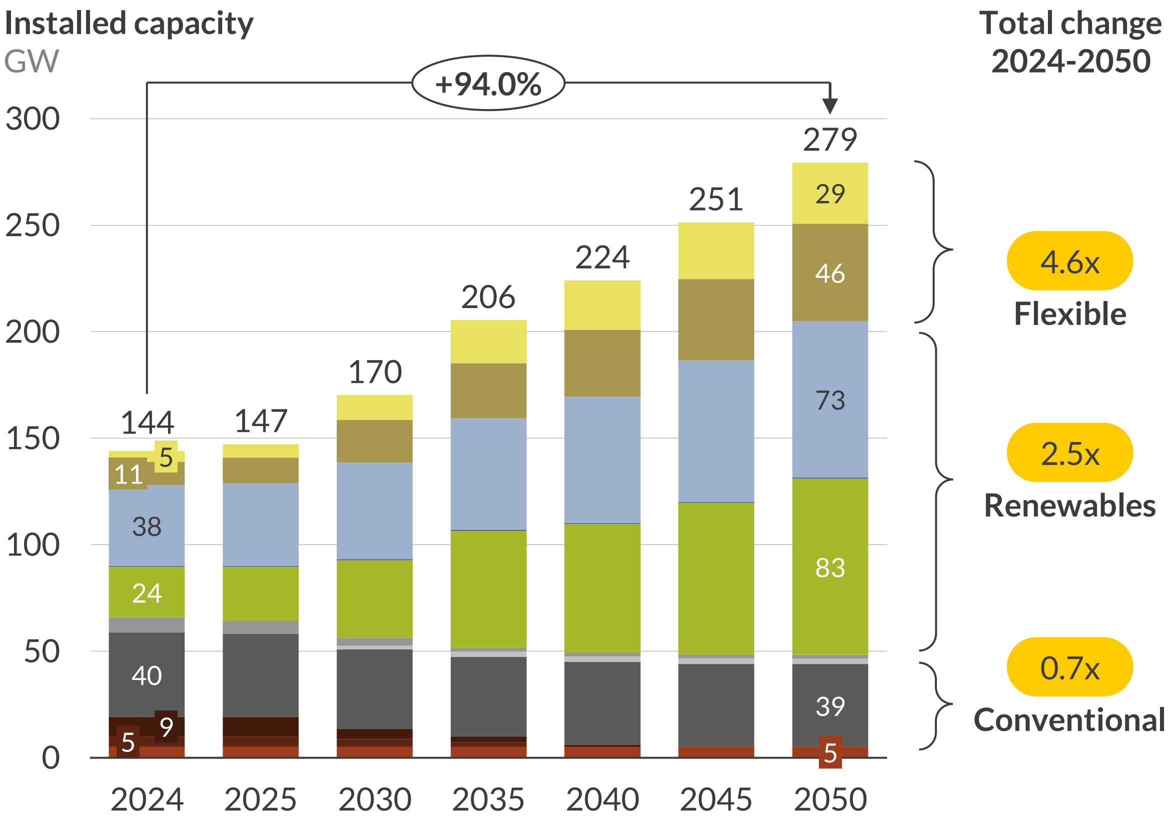
Illustrative merit order in ERCOT
$/MWh

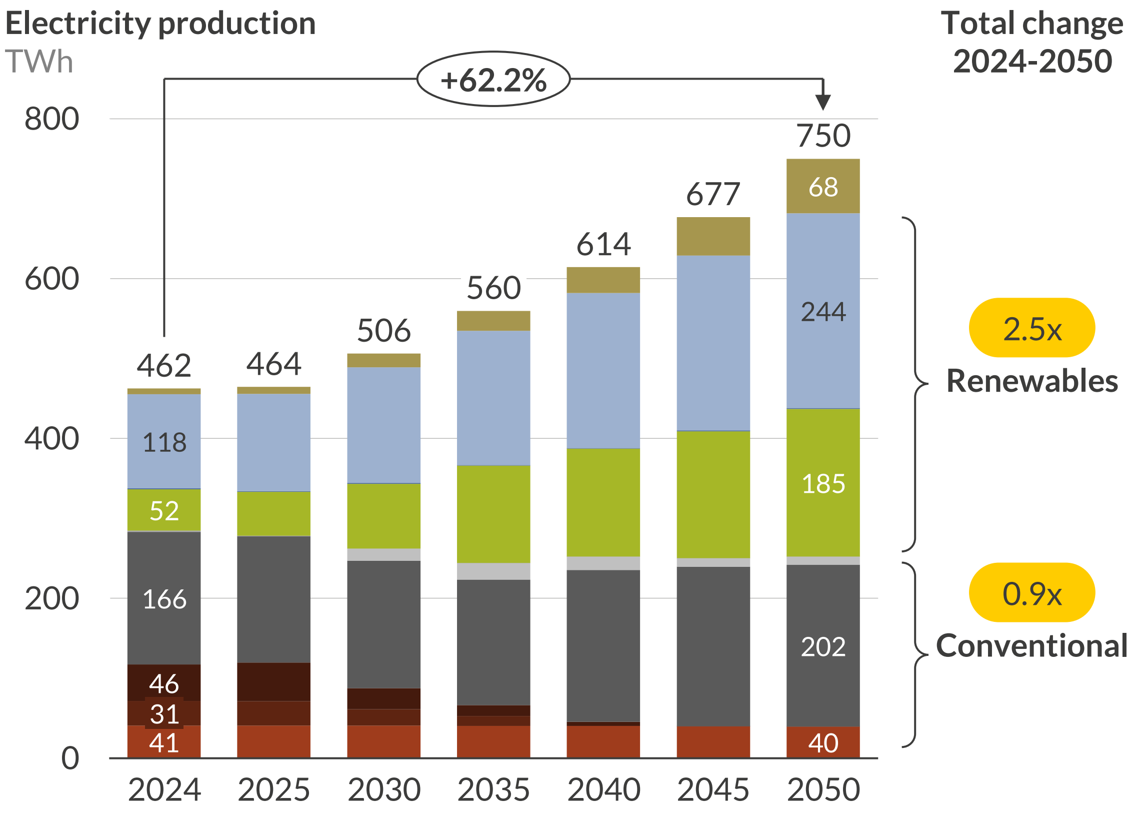


Note: Excludes battery, hydro, and biofuel

Sources: Aurora Energy Research

Wind and solar capacities reach 156GW in 2050; batteries grow to 29GW; conventional thermal capacity declines to less than 50GW





- Installed capacity more than doubles across the horizon, driven by the growth of renewables, peaking, and battery capacities.
- Conventional capacity declines by 17.6GW from now to 2050 as coal, lignite and steam gas turbine capacity retires with no new build replacement.
- In line with capacity increases, renewables generation increases by 152% between 2024 and 2050. Peaking technologies will increase to 46GW of capacity in 2050 but run relatively few hours.
- Peaking production increases almost 10x from 2024 to 2050. Battery production isn't shown; net production is negative due to efficiency losses.

Nuclear | Lignite | Coal | Gas CCGT[1] | Gas CCS | Other thermal | Solar | Other renewables[2] | Hydro | Onshore wind | Gas / oil peaker[3] | Battery storage

1) CC. 2) Includes biomass. 3) Gas / oil peaker includes OCGT (CT).

Sources: Aurora Energy Research

The ERCOT IQ[1] is used to determine near term capacity additions; long term capacity expansion is determined by in-model economic build decisions

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In the short term (<5 years) projects from the ERCOT interconnection queue are chosen to be included in the forecast based on a detailed selection process

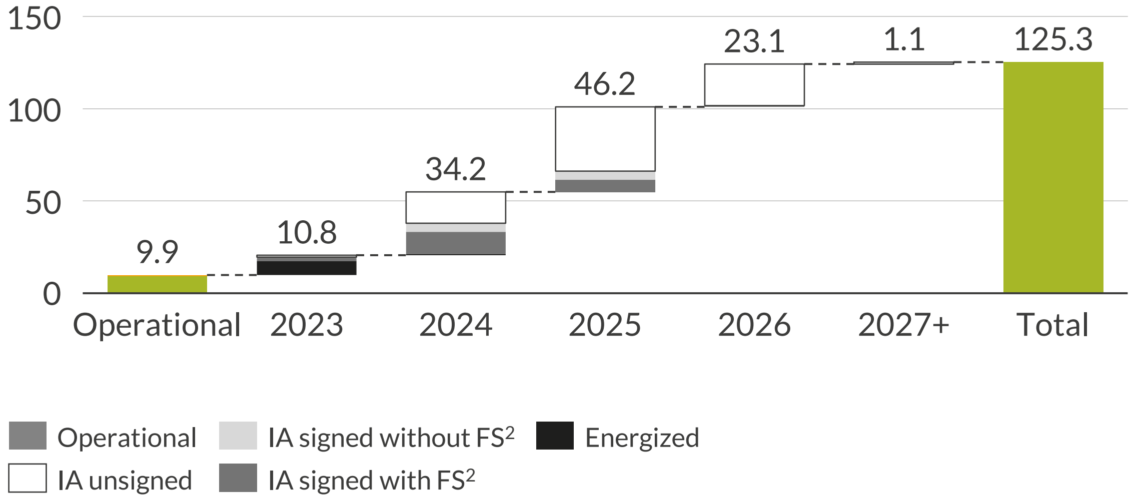
- The ERCOT interconnection queue for wind, solar and batteries includes more projects and capacity than could be realized given economic and practical constraints. For this reason, Aurora chooses a subset of projects to include in the forecast
- Selection criteria is based on project development stage, planned commercial operation date, resource type and historic success rates
- Assumptions are updated on a quarterly basis as the queue evolves

Longer term (>5years), in-model build decisions are based on economics; a plant will only build if its net present value (NPV) is greater than zero

- Beginning with forecasted year 2025, the model will begin to build new projects if they are determined be NPV positive
- This process is iterative, with each new round of build decisions being used to forecast a price series that is fed back into the model to recalculate the NPV of new plants and retire plants which are NPV negative
- Additionally, practical constraints around interconnection and grid reliability are considered and may restrict the buildout of a new project even if it is NPV positive

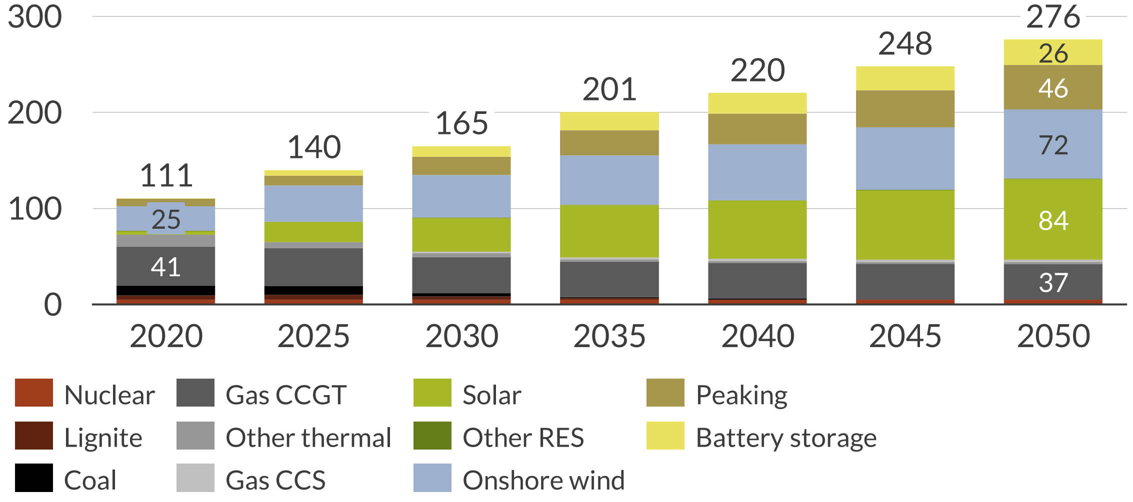
Illustrative capacity of solar queue

GW



Illustrative capacity expansion based on economic build decisions

GW



1) Interconnection queue. 2) Financial security.

Sources: Aurora Energy Research

During each 5-minute period, the real-time market clears based on the capacity offered by various technologies and their respective bids

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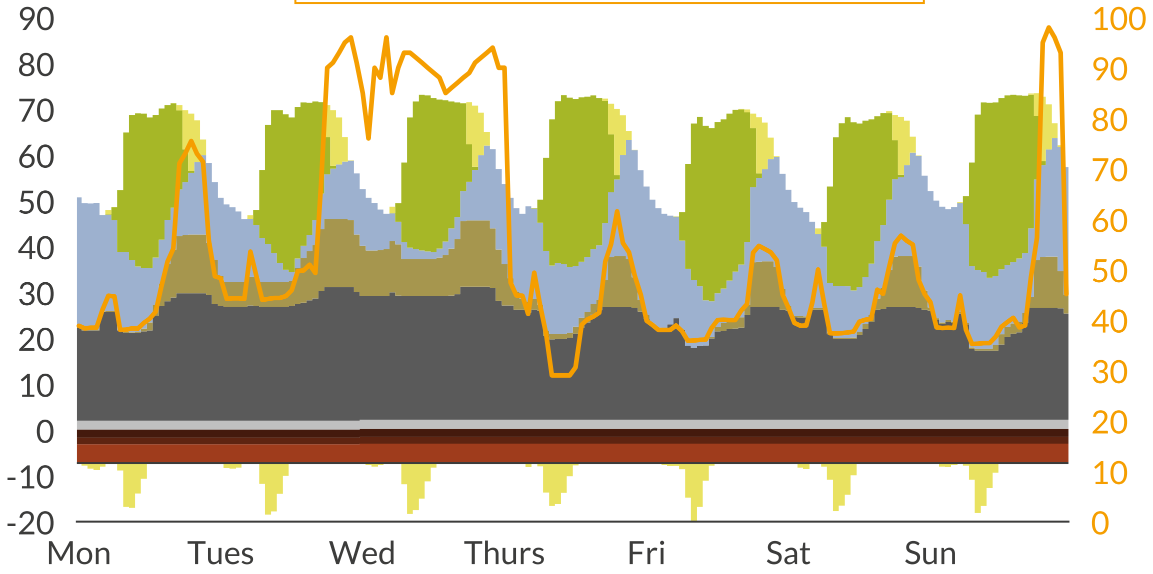
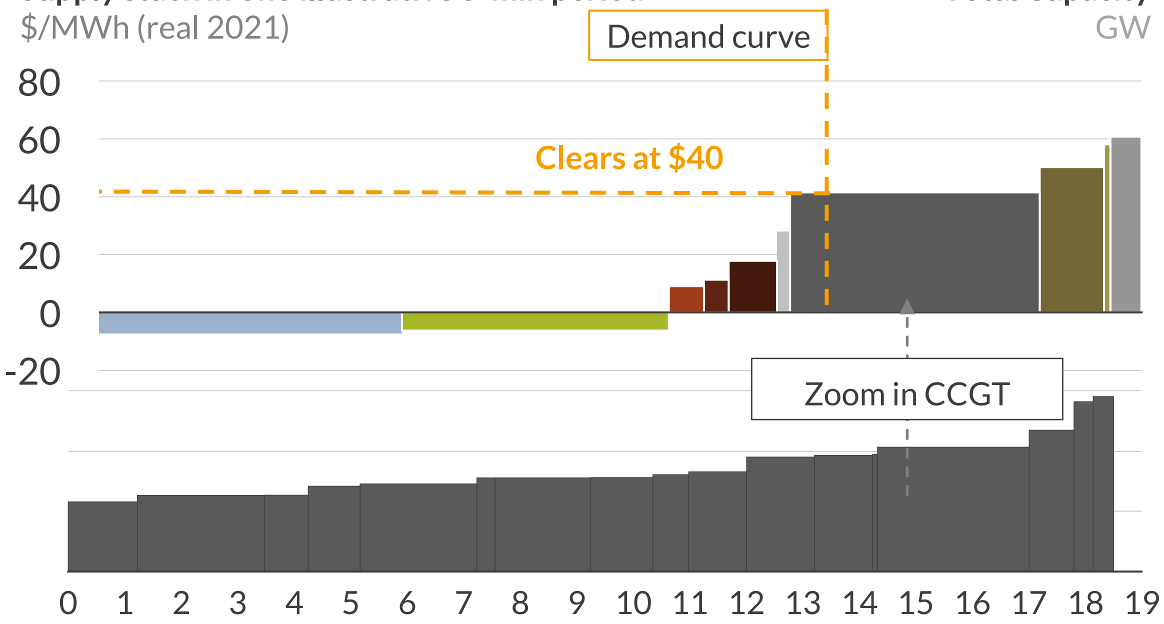
Generation during a particular period depends on the technologies available and bidding



Each available generator bids into the market at its marginal cost; market uses pay-as-clear auction



Onshore wind | Solar PV | Nuclear | Lignite | Coal | Gas CCS | Gas CCGT | OCGT | Other thermal | Battery storage

- Renewables generation depends on the weather
- ERCOT procures as much of cheap renewables as possible. Conventional capacities such as natural gas, nuclear, and coal are procured after renewables.
- Any remaining demand is met by more expensive "flexible" capacities that can ramp up and down as needed.
- The price is determined by the most expensive technology that must run to meet total demand

- In a pay-as-clear auction:
  - Each plant submits its short-run marginal cost (SRMC) as the bid
  - SRMC : fuel cost + variable cost for plant operation - tax credit
- The vertical demand curve depends on the hour of day and time of the year
- Pay-as-clear means that plants in front of the demand curve are paid the same market clearing price; they must run or face a hefty penalty

Sources: Aurora Energy Research

Details and disclaimer

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