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LOW-CARBON ELECTRICITY GRID

2020–2021 | Energy Symposium Series | *Critical Issues in Energy*

FRIDAY, OCTOBER 16TH, 2020 | 10:00AM – 11:30AM CST

VIRTUAL SYMPOSIUM

Dr. Ramanan Krishnamoorti
Chief Energy Officer
UH Energy

UNIVERSITY of **HOUSTON** | **UH ENERGY**

HOUSTON'S LOW-CARBON ENERGY FUTURE: FOUR WAYS FORWARD

2020–2021 | Energy Symposium Series | *Critical Issues in Energy*

OCTOBER 9, 16, 23, 30 | 10:00AM – 11:30AM CST

VIRTUAL SYMPOSIUM

LOW-CARBON ELECTRICITY GRID

October 23rd   **Hydrogen**

October 30th   **Circular Plastics Economy**

To learn more about the
"Houston: Low-Carbon Energy Capital –
Four Ways Forward" series visit:

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- Turner Harris

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PATHWAYS TO NET ZERO GRID

PATHWAYS TOWARD NET ZERO GRID – KEY FINDINGS

- ERCOT (the power grid representing 90% of Texas electricity demand) has already achieved a significant reduction in carbon intensity, and renewable growth trends indicate continued progress in this regard

- ERCOT is well positioned for continued growth in renewable energy supply, and Houston can be expected to play a leading role in this effort

- However, the pathway to a net zero grid faces three key challenges:
  - The mismatch between renewable production and load profiles, coupled with the physical reality that power supply must equal demand on a near-instantaneous basis

  - Seasonal and diurnal variability of renewable production, and

  - Existence of must-run CO_2 emitting generation, acting to "crowd out" renewable supply during periods of low demand

- Absent energy storage, continued addition of renewable resources will ultimately lead to extended periods of renewable curtailment, dampening financial returns on renewable investment and inhibiting further grid decarbonization

- Energy storage technologies can capture and store episodically excess renewable supply and allow carbon free supply to approach 90%, although the financial return for such technologies is inevitably diminished as storage capacity grows – ultimately constraining further investment in storage

- Adoption of green hydrogen production can provide an effective storage solution for balancing supply and demand over seasonal periods; the electrolysis process can utilize excess renewable production when it is generated, and the resulting hydrogen can be stored for multi-day and seasonal periods

- Additionally, green hydrogen would leverage both existing natural gas storage/transport/power generation infrastructure, as well as existing brown hydrogen infrastructure

- Finally, achievement of net zero carbon emissions from the power grid is technically feasible, but the law of diminishing returns ensures that the marginal cost to eliminate the last few percentages of grid carbon emissions will be very high – potentially far in excess of the cost to reduce emissions from other sectors of the economy

TEXAS WELL POSITIONED FOR EXPANSION OF RENEWABLES AND ENERGY STORAGE

Texas is well positioned for expansion of renewables and energy storage

- Top-tier wind and solar resources

- Independent power grid; ERCOT is not connected to Eastern and Western interconnections, and is largely regulated by state authority

- ERCOT's operation and optimization of ~$10 billion/year energy market is world-class

- One of the largest unregulated retail power markets in the world – over 22 million Texans can choose from over 200 retail electric providers

- Extensive pipeline, natural gas, and transmission infrastructure

- Suitable salt geology to support energy storage in the Gulf Coast, east Texas, and the Panhandle
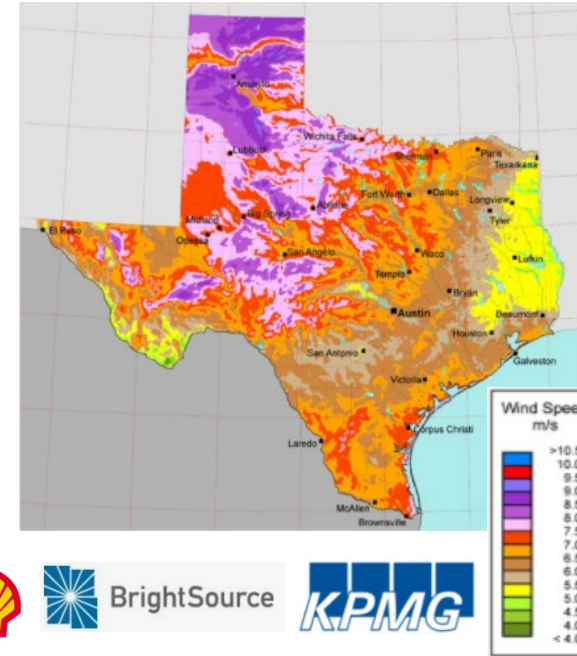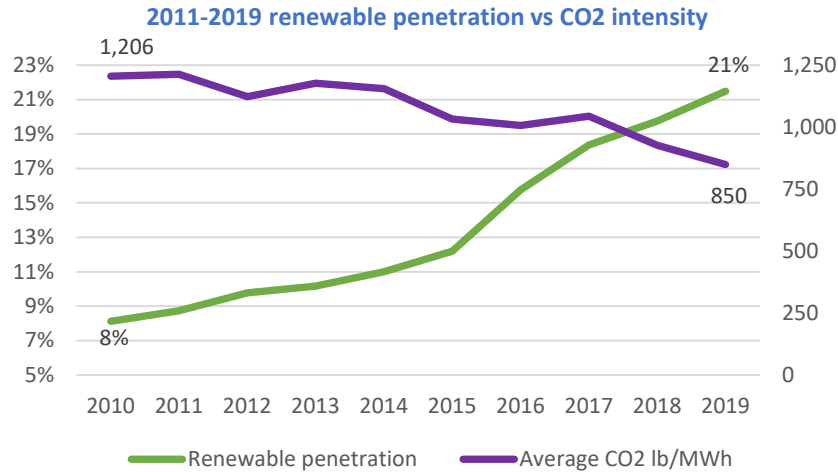
Houston community can cement a leadership role in grid decarbonization

- Cohesive leadership across political and business community

- Extensive base of sophisticated decision-makers for energy-focused capital markets

- Global-scale energy players with large Houston presence pivoting to green investment to address climate-related risks to existing business operations

- Concentration of major renewable energy developers and owners

- Headquarters to many large retail power companies

- Highly skilled and diverse energy workforce

- World-class brown hydrogen infrastructure

# TEXAS RENEWABLE GROWTH SUPPORTS PATHWAY TO NET ZERO GRID

2011-2019 renewable penetration vs CO2 intensity

— Renewable penetration   — Average CO2 lb/MWh

2015-2020 (expected) ERCOT renewable additions, MW

■ Wind additions   ■ Planned wind   ■ Solar additions   ■ Planned solar

To date, Texas has enjoyed robust renewable growth which has resulted in declining CO2 intensity

- Texas leads the nation in wind installations, with 27,219 MW installed in the ERCOT market at year end 2019, and another 7,910 MW expected to be in service by year-end 2020

- In less than a decade, the fraction of energy supplied by renewables has more than doubled

- The growth in renewables and a dramatic reduction in coal generation has resulted in ERCOT CO2 intensity declining 30% from 1,206 lb/MWh in 2010 to 850 lb/MWh in 2019

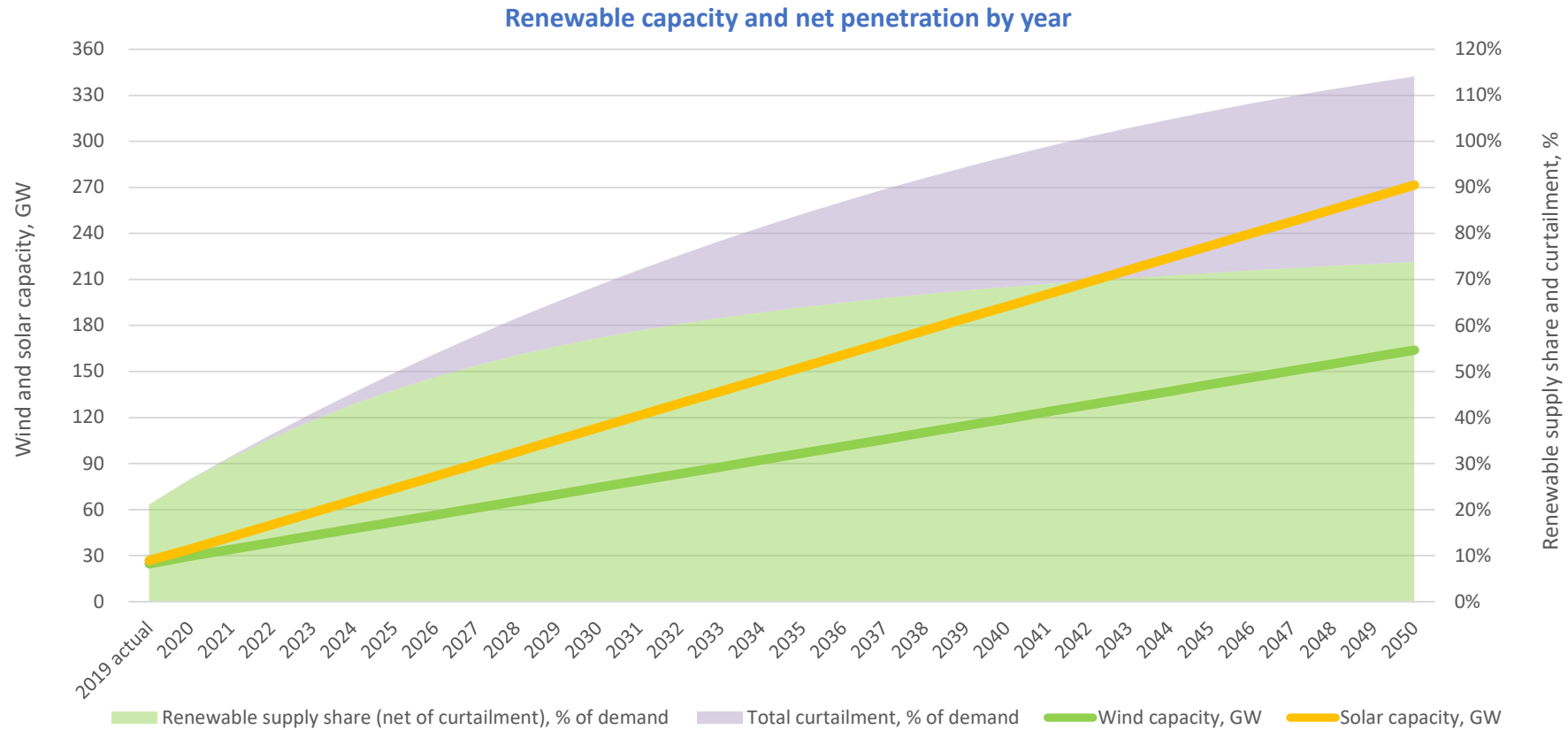**Texas pathway to sufficient renewables for a net zero grid by 2050**

- As a result of numerous factors, including declining installation costs, improved conversion efficiencies, federal tax incentives, and corporate renewable energy purchases, renewable resources are expected to dominate ERCOT supply additions for the foreseeable future

- The vast scale of the potential ERCOT renewable resource base is demonstrated by examination of the ERCOT interconnection queue, listing wind development projects totaling 23,427 MW and solar projects of 59,205 MW

- By 2050 renewable capacity of 200 to 250 GW, along with the exiting carbon-free nuclear capacity and a requisite level of energy storage, could meet nearly all ERCOT demand on an hourly basis

- Achieving this level of renewable capacity equates to additions of 5,500 to 7,000 MW/year – in-line with 2020 expected renewable additions of 7,910 MW
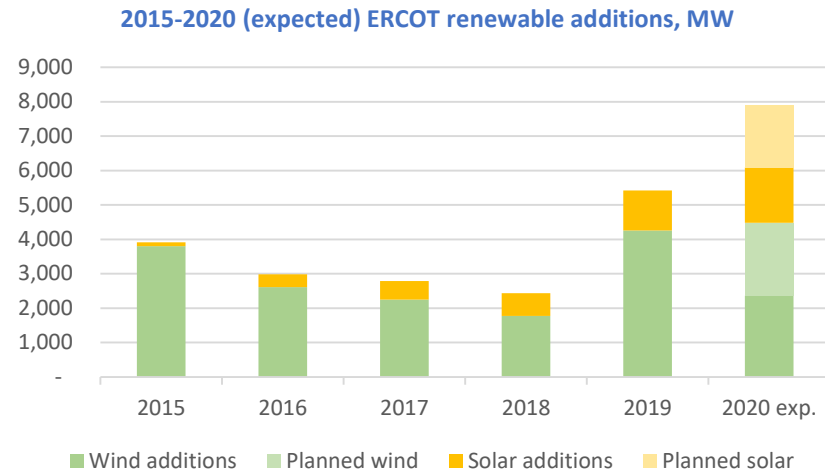
Source: ERCOT GIS reports 2010-2020; US EIA; ERCOT Generation by Fuel Type Reports 2010-2019

WITHOUT STORAGE, BENEFITS FROM RENEWABLE ADDITIONS PLATEAU

- The chart below shows the impact of increasing renewable capacity (absent energy storage) on renewable penetration and curtailment
- This chart assumes that renewable capacity is added every year from 2021 to 2050 at the 2020 expected rate (4,479 MW wind and 3,431 MW solar per year)
- Renewable supply share increases quickly in the early years, but realizes diminishing returns as renewable capacity continues to grow
- Investors are not likely to find returns from renewable projects attractive at levels of curtailment beyond 15 to 20% - the Production Tax Credit of~$25/MWh for wind is lost when curtailment occurs

Renewable capacity and net penetration by year

Legend: Renewable supply share (net of curtailment), % of demand · Total curtailment, % of demand · Wind capacity, GW · Solar capacity, GW

THREE KEY CHALLENGES ON THE PATHWAY TO NET ZERO GRID

Challenge 1: **Renewable production is intermittent, and varies across hours of the day, months of the year, and across years, creating uncertainty of supply**

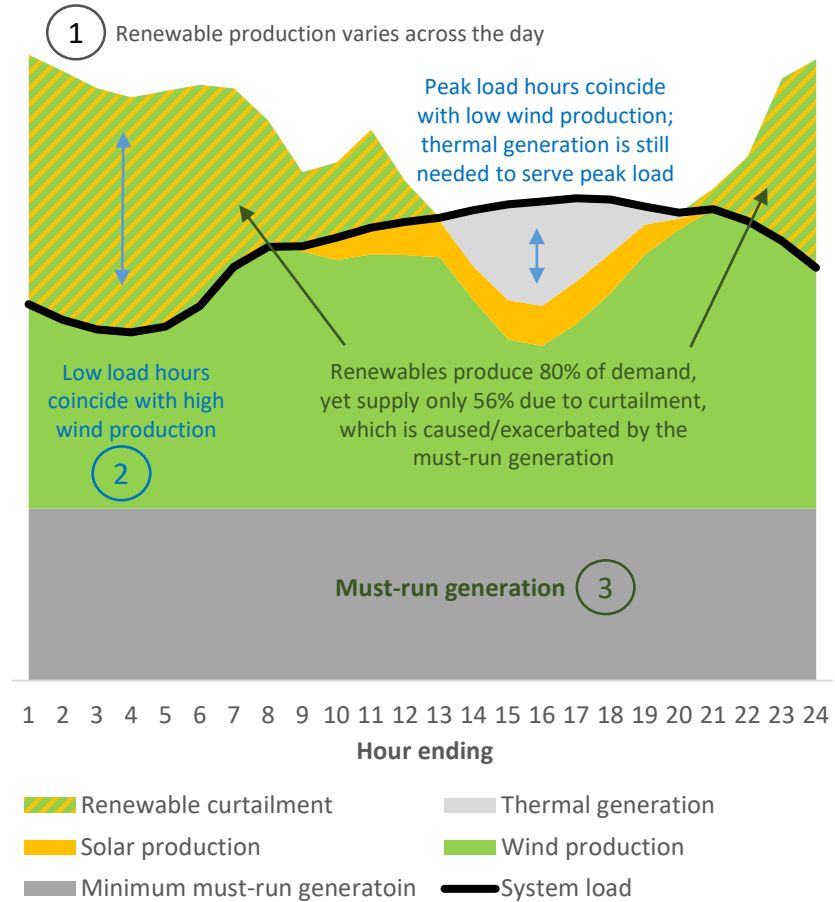- The variation in wind and solar production is evident in the chart on the right

Challenge 2: **Renewable production patterns do not align well with ERCOT load (particularly with regard to West Texas wind), creating periods of under/over supply**

- Current mix of renewable production is lowest in the highest load hours, and highest when load is low

- While renewables can materially contribute to meeting demand during morning and evening hours, thermal generation is needed to serve load during peak hours

Challenge 3: **Renewable production displaced by must-run generation during low-demand hours**

- Must-run capacity includes nuclear units, cogeneration units, minimum output from online coal units, and units online to provide Ancillary Services

- Must-run units are price-taking – they will offer energy at very low/negative prices, at times displacing wind and solar generation in hours when high renewable output coincides with low demand

- Future challenge is mainly cogen must-run – nuclear is carbon-free, coal is likely to be retired, and new energy storage can provide Ancillary Services with minimal associated must-run energy

Illustrative diurnal load and production on a Spring day

This chart reflects the diurnal load and renewable production patterns on March 29, 2019 – renewables have been scaled up to produce 80% of total energy demand on this day

① Renewable production varies across the day

Peak load hours coincide with low wind production; thermal generation is still needed to serve peak load

Low load hours coincide with high wind production ②

Renewables produce 80% of demand, yet supply only 56% due to curtailment, which is caused/exacerbated by the must-run generation

Must-run generation ③

Hour ending: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Legend:
- Renewable curtailment
- Thermal generation
- Solar production
- Wind production
- Minimum must-run generatoin
- System load

PATHWAYS TOWARD NET ZERO GRID – STUDY APPROACH/METHODOLOGY

Intent of study

- Provide an understanding of the implications of very high renewable penetration and the role storage can play in enabling reliable, economic operation of a decarbonized grid

Study approach & scope

- Determine a suitable mix of wind and solar additions that minimizes over-supply/curtailment at high penetration levels
- Test supply-side solutions for relieving renewable over-supply, reducing CO2 intensity, and provided necessary firm back-up for renewable under-supply
    - Lithium-ion batteries
    - Compressed air energy storage (CAES)
    - Green hydrogen conversion for existing cogeneration (cogen) plants, existing, combined-cycle gas turbine (CCGT) plants, and CAES

Not in study scope

- Demand-side solutions or adjustments included in evaluation
- Increased electrification (beyond vehicles) or end-use efficiency improvements
- Improvements in renewable/storage performance or costs
- Other storage technologies that could become available over the study period were not evaluated
- Opportunity to push green hydrogen to markets other than power
- Economic impact of additional transmission needed to support high renewable penetration

Hourly market modeling methodology

- Start with actual 2019 hourly load, wind production, solar production, and prices for energy – grow hourly load, wind, and solar production to match future expectations
- Calculate hourly renewable over/under-supply and dispatch storage
- For each hour, use change in "net load" (system load less renewable production) to adjust the market heat rate (dt/MWh) up or down – net load represent the residual demand served by dispatchable generation and energy storage
- Energy price and spark spread found by multiplying adjusted heat rate by forward natural gas price in each hour
- ORDC & RTORDPA price adders calculated for each hour

Key inputs & assumptions

- Energy demand growth = 1.7%/year
- 2050 electric vehicle demand of 3.1 MM MWh
- Carbon price = $24-40/metric ton
- Retirement of today's coal capacity of 14 GW prior to 2050
- Gas-fired generation added as needed to maintain min. reserves
- Must-run capacity for Ancillary Services displaced by energy storage
- ERCOT congestion unchanged

Output

- Hourly volumetric balance between renewable production and system demand accounting for must-run nuclear and cogen
- Hourly energy storage and hydrogen electrolyzer dispatch to meet balancing needs, as well as hourly storage inventory
- CO2 emissions from must-run and back-up generation
- Estimates of capital investment based on today's technology costs

CURTAILMENT AND RENEWABLE PENETRATION VARY WITH MIX OF WIND AND SOLAR, BUT MIX CANNOT ELIMINATE OVER-SUPPLY

- To illustrate the challenge of matching energy supply to demand with high levels of renewable penetration, five scenarios were created:
  - 2019 ERCOT hourly load profile was adjusted to the year 2050, assuming a growth rate of 1.75% across all hours of the year
  - Renewable penetration scenarios under which unconstrained renewable (nameplate renewable resource capacity multiplied by 2019 hourly capacity factor) equaled the annual 2050 ERCOT demand not served by nuclear generation
- The figure on the left displays the nameplate wind and solar capacity for each of the five scenarios
- The middle figure displays the renewable supply share after curtailment; even the best apparent mix of ERCOT wind and solar results in substantial over-supply that would be "wasted" in the absence of energy storage (as shown in the figure on the right)
- Higher levels of solar additions result in particularly severe curtailment levels
- To evaluate the potential pathways to a net zero grid, the heavy wind scenario was chosen as the Base Case for further study

2050 renewable capacity, GW
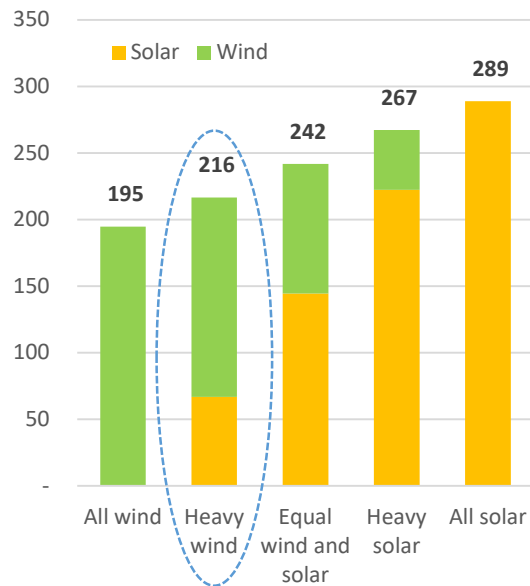
**Renewable supply after curtailment , % of load**
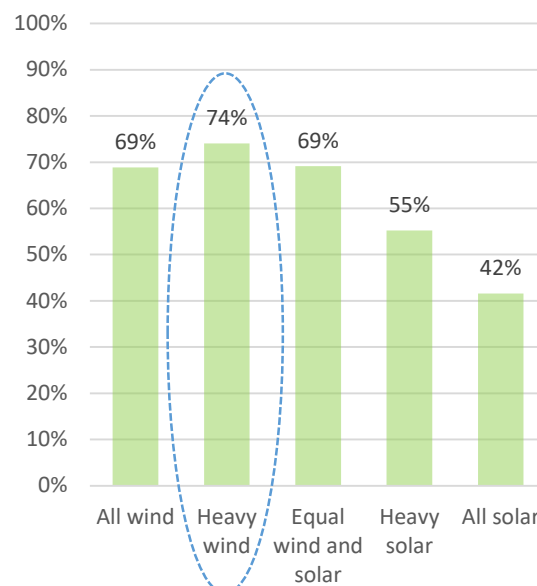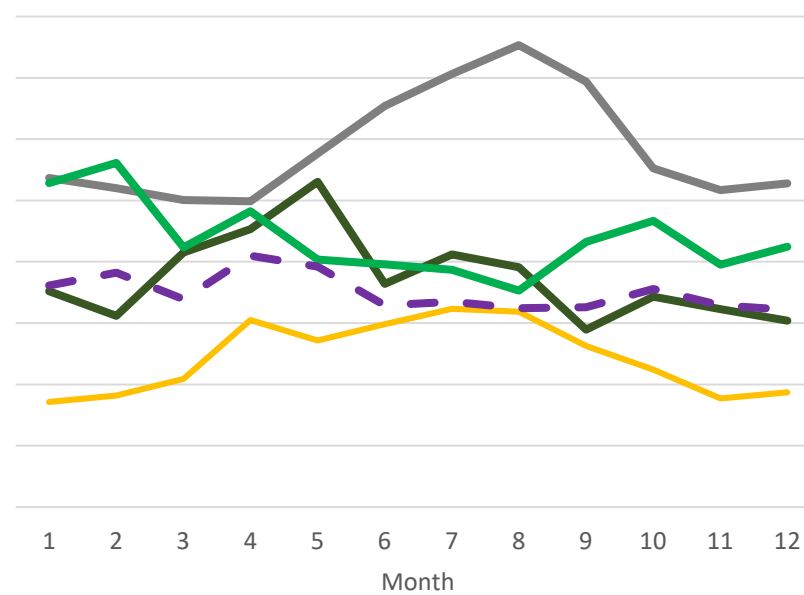
Renewable over-supply, % of potential production
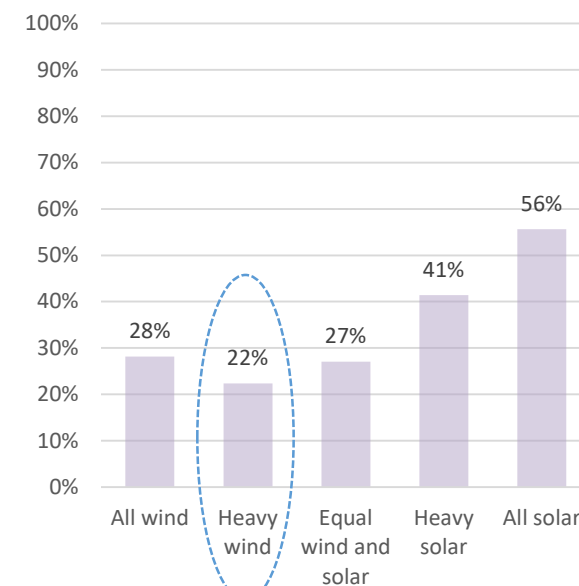
2050 BASE CASE RENEWABLE SCENARIO

- To develop an understanding of the implications of high renewable penetration without energy storage, a Base Case scenario incorporating sufficient renewable capacity to produce (assuming 2019 annual average average capacity factors) an amount of energy equal to the projected 2050 ERCOT annual demand (net of carbon-free nuclear generation) was created

    - Wind capacity is 149.8 GW, reflecting additions of 121.0 GW 2021-2050

    - Solar capacity is 66.7 GW, representing additions of 61.9 GW 2021-2050

- The lack of coincidence between the aggregate renewable output and system demand (less nuclear generation) inevitably leads to a high frequency of over or under-supply from the renewables

Diurnal capacity factor of load and renewable resources (2019 actual)
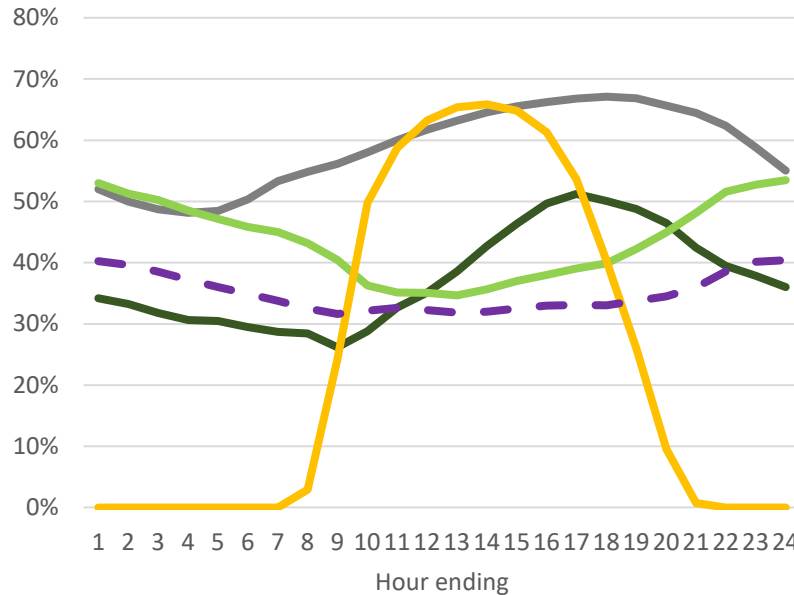
Monthly capacity factor of load and renewable resources (2019 actual)

ERCOT load — Coastal wind — Panhandle wind — ERCOT solar — 2019 renewable mix

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2050 BASE CASE* RENEWABLE OVER/UNDER-SUPPLY IN THE ABSENCE OF LARGE-SCALE ENERGY STORAGE SOLUTIONS

Absent energy storage, 22% of potential renewable production is curtailed
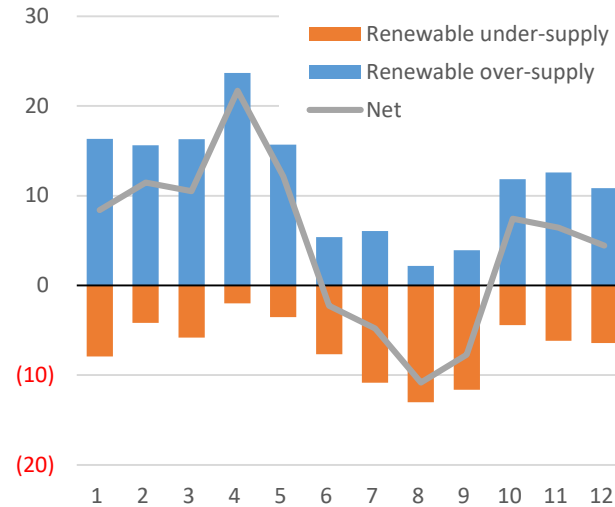
Daily/inter-day imbalances

2050 (under)/ over-supply by hour, MW*
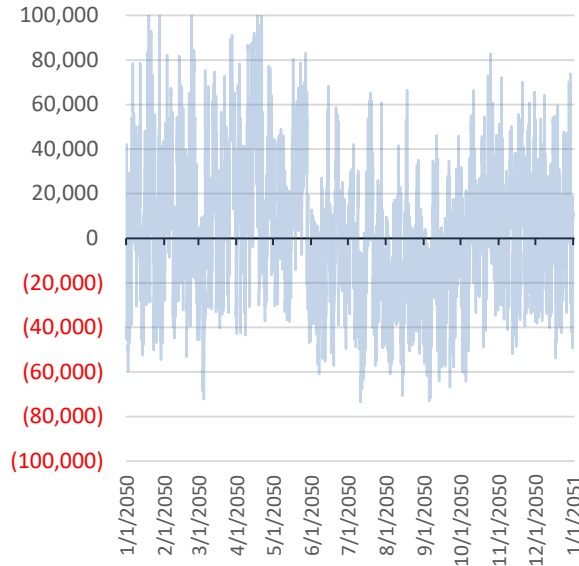
- Daily occurrences of significant over/under-supply
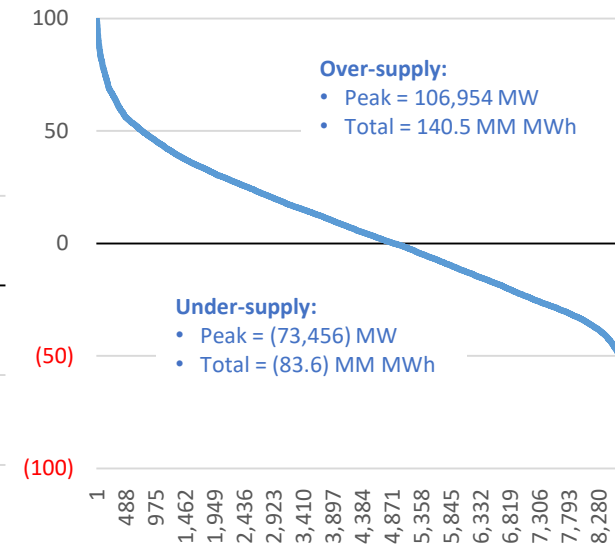- Daily pattern is random

Seasonal imbalances

2050 renewable over and under-supply by month, MM MWh*

- High net over-supply in the spring season
- High net under-supply in the summer season

Size of over/under-supply

2050 ranked (under)/ over-supply by hour of the year, '000 MWh*

Over-supply:
- Peak = 106,954 MW
- Total = 140.5 MM MWh

Under-supply:
- Peak = (73,456) MW
- Total = (83.6) MM MWh

- Over-supply is larger than under-supply due to must-run capacity
- Approximately 10% of imbalances are greater than 50,000 MW

* Based on 2050 scenario with average load of 75,308 MW, 150 GW of wind capacity, 67 GW of solar capacity, 74% renewable penetration (prior to storage), and renewable curtailment equal to 22% of potential renewable production (before storage)

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# TODAY'S TECHNOLOGY SOLUTIONS FOR TEXAS RENEWABLE INTEGRATION

Although the storage technologies reflected in this analysis were limited to lithium-ion batteries, CAES, and green hydrogen conversion, other storage technologies can be expected to become available over the time frame of the study period

	How it works	Ratio of MWh-in to MWh-out	Storage duration	Today's installation cost*	Key advantages (+) & disadvantages (-)
Lithium-ion batteries	Power is absorbed by the battery and stored for later use via an electro-chemical process	0.85	1-4 hours	$1,137/kW @ 4 hours	(+) Bankable equipment from many reputable suppliers (-) Storage adequate for <10% of over-supply events
Compressed Air Energy Storage (CAES)	Electricity is used to compress air, which is then stored and later used to run a turbine generator	1.69	+48 hours	$1,295/kW @ 48 hours	(+) Bankable equipment from Siemens (+) Storage adequate for >50% of over-supply events (-) CAES uses a small amount of natural gas in the expansion process
CAES converted to green H2	Electrolysis uses electricity to separate water into hydrogen and oxygen; the hydrogen can be stored and later used as fuel in existing natural gas-fired turbines	0.63	Multi-day/ seasonal	H2 electrolysis = $1,000/kW H2 storage = $16.25/Bbl CCGT = $1,000/kW	(+) Better fuel efficiency than cogen/CCGT (+) Suited to co-location of H2 storage (-) Requires incr. renewable additions
Cogen converted to green H2		0.52			(+) Reduce must-run CO2 emitting supply (+) Utilize existing cogen capacity (-) Requires incr. renewable additions
NG generation converted to green H2		0.33			(+) Power industry standard technology (+) 45 GW existing CCGT fleet in ERCOT (-) Low ratio of MWH-in to MWh-out (-) requires large incr. renewable additions

* Lithium-ion installation costs based on Lazard Levelized Cost of Storage Report, Nov. 2019; 100 MW scale with $232/kW-hour lithium-ion module cost (storage media); CAES based on Apex ERCOT estimate; H2 electrolyzer based on estimate of utility-scale (Hydrogen Council, Path to Hydrogen Competitiveness, January, 2020); H2 cavern cost assumed to be ~16.25/Bbl

48-HOUR STORAGE REDUCES MORE CARBON, BUT ALL STORAGE REALIZES DIMINISHING BENEFITS AS CAPACITY GROWS

- CAES longer storage duration allows for more charging and greater utilization of renewable production
- Incremental benefits of CAES diminish at capacity additions greater than ~30,000 MW
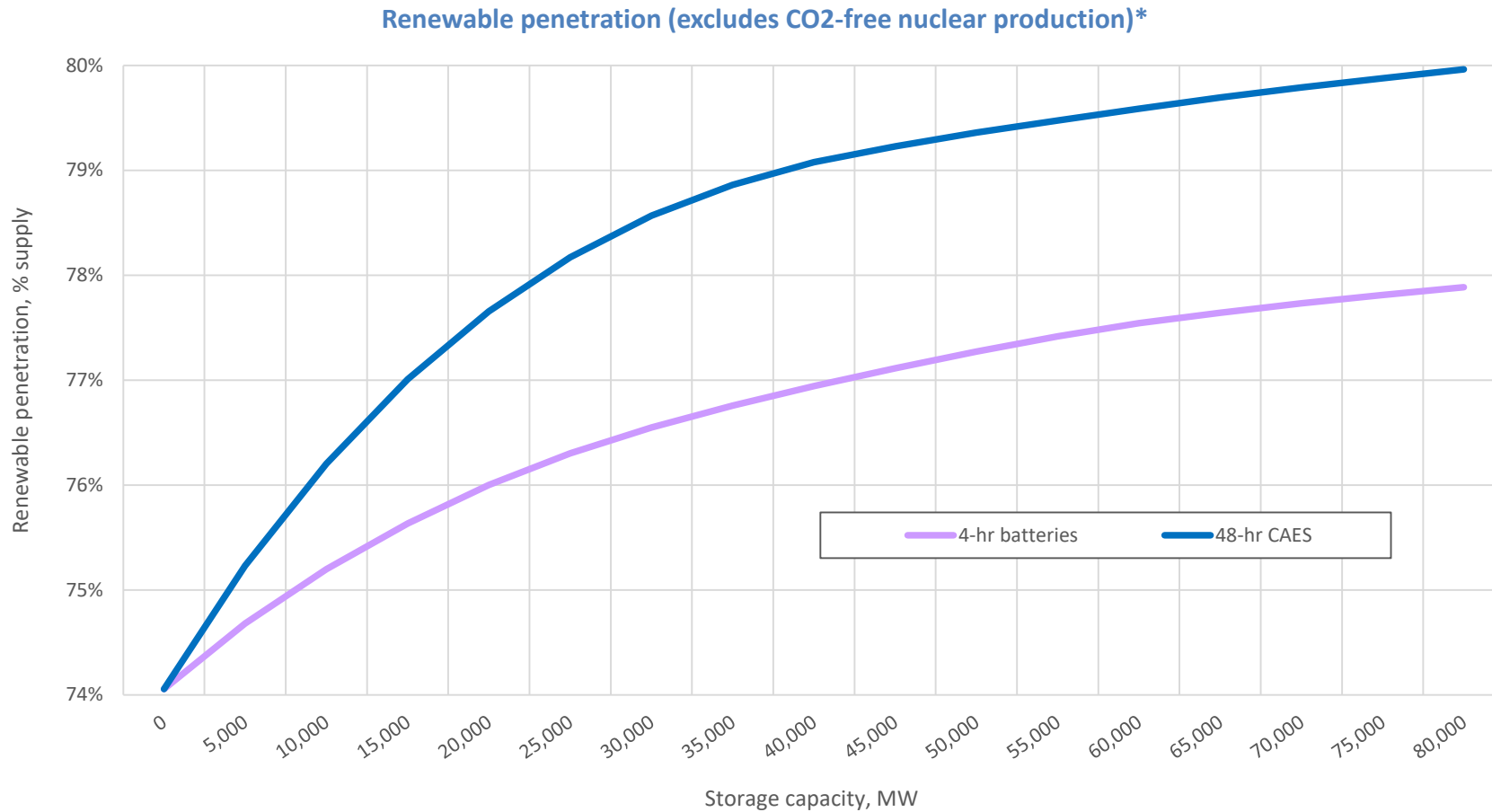
Renewable penetration (excludes CO2-free nuclear production)*

* Based on 2050 scenario with average load of 75,308 MW, 150 GW of wind capacity, 67 GW of solar capacity, 74% renewable penetration (prior to storage), and renewable curtailment equal to 22% of potential renewable production (before storage)

APPROACHING A NET ZERO GRID – FIVE STORAGE SCENARIOS

**Investment in capacity additions 2021-2050, $BN**
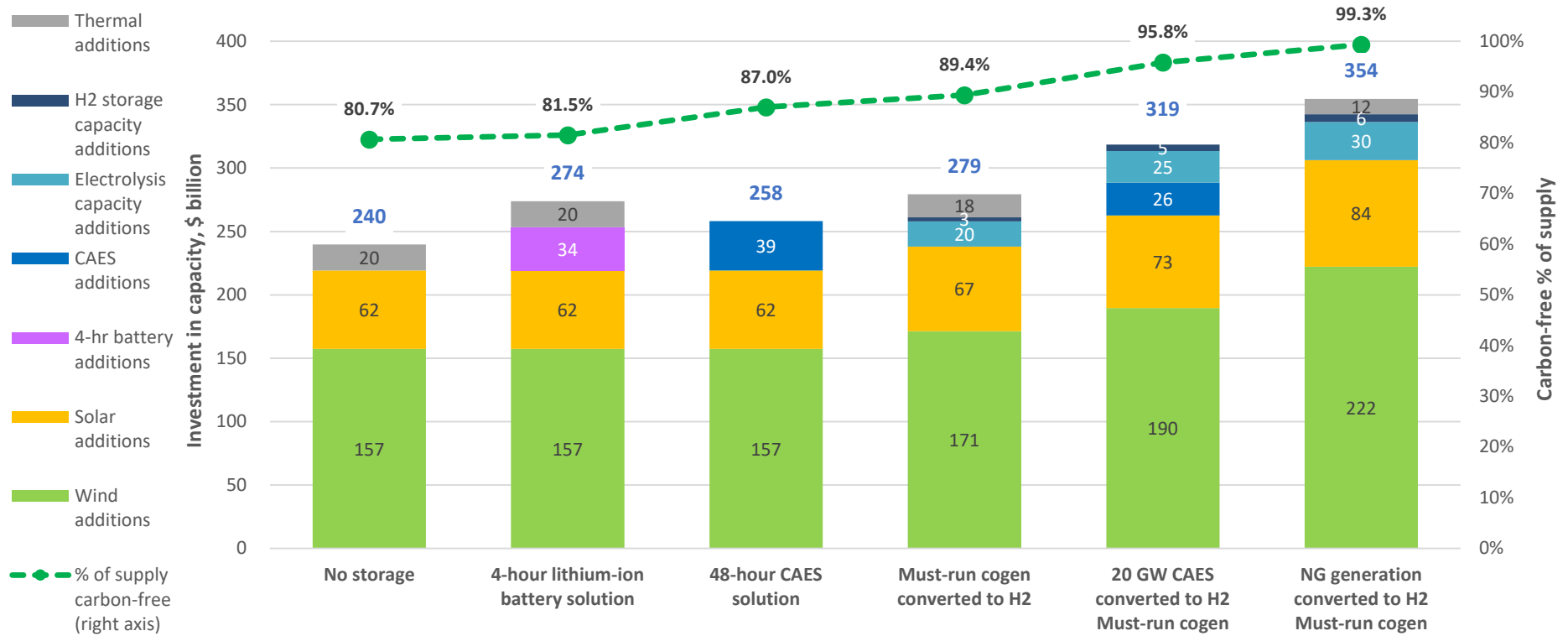
2021-2050 incremental additions, MW				(50% cogen retired)	(50% cogen retired)
Wind capacity, MW	121,048	121,048	121,048	131,779	145,839	170,917
Solar capacity, MW	61,895	61,895	61,895	66,670	72,926	84,085
Storage capacity, MW	0	30,000	30,000	0	20,000	0
H2 electrolysis capacity, MW	0	0	0	20,000	25,000	30,000
NG capacity, MW	20,432	20,432	0	18,032	0	11,932
H2 storage capacity, MMBbl*	0	0	0	200	316	384

* Some portion of necessary hydrogen storage capacity may be repurposed natural gas storage capacity

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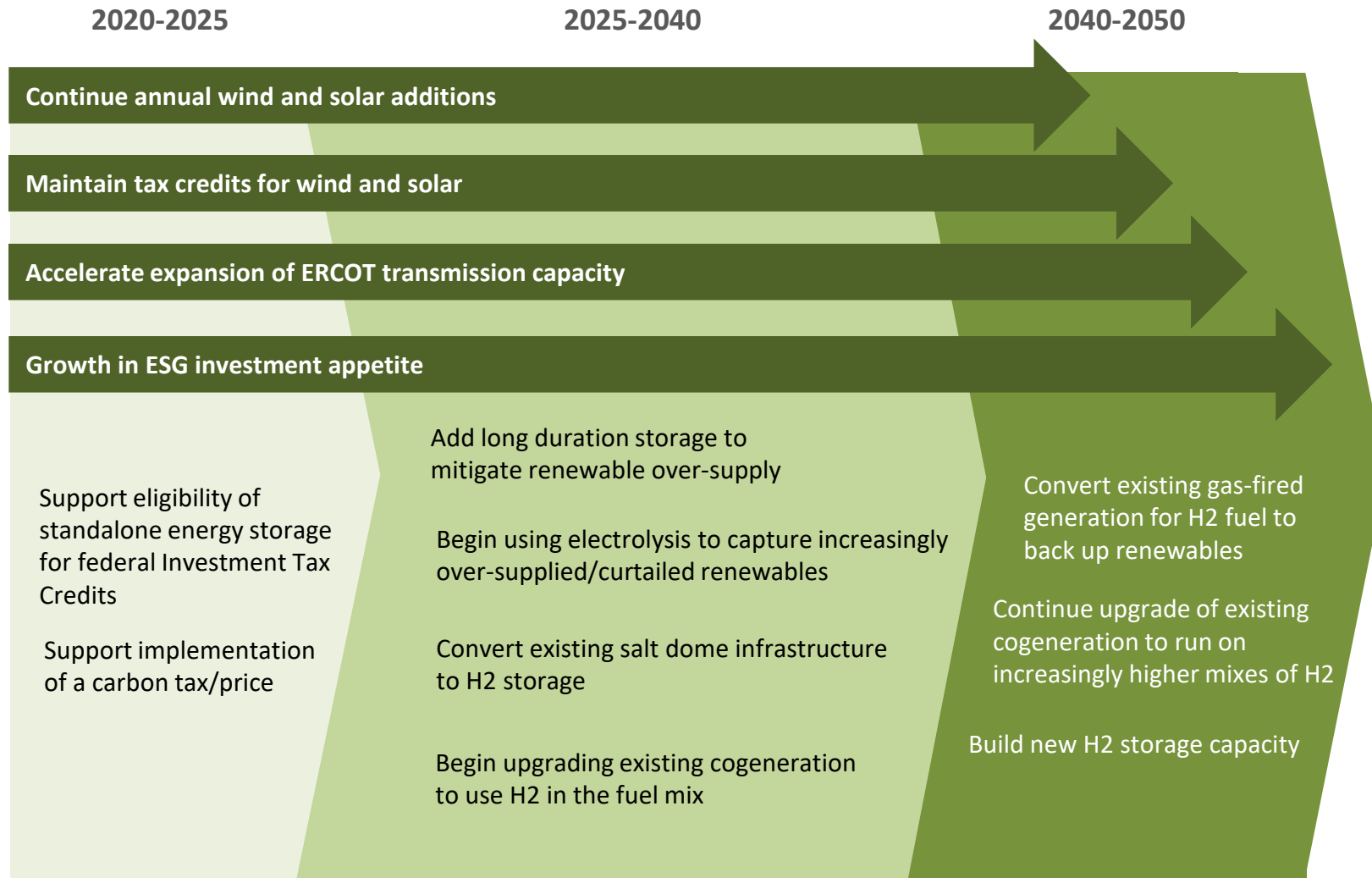# SUMMARY FINDINGS - FIVE STORAGE SCENARIOS

% of supply CO2-free
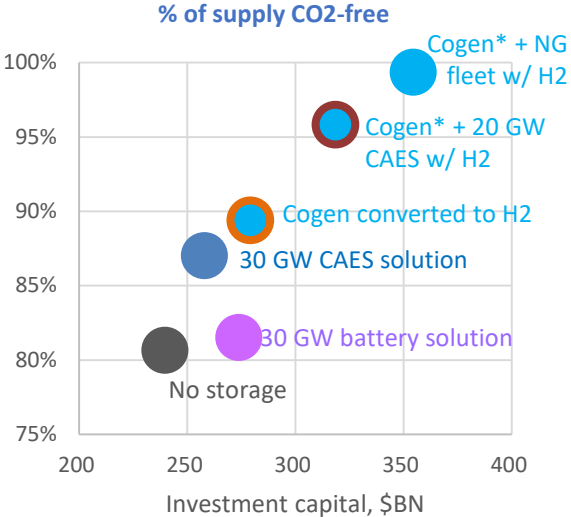
- Renewables, absent energy storage, can support only ~80% CO2-free supply before over-supply is greater than 20%, assuming a CO2 price of $24/ton

- Long duration energy storage (CAES) can support closer to 90% CO2-free supply before storage additions begin to suffer diminishing benefits

- Greater than 90% CO2-free supply is possible with green H2 conversion of cogen and existing NG-fired resources, but investment costs are materially higher due to the additional renewable capacity needed for green H2 production, as well as H2 electrolysis and storage capacity additions

Necessary CO2 price, $/ton

Demand weighted ERCOT price, $/MWh
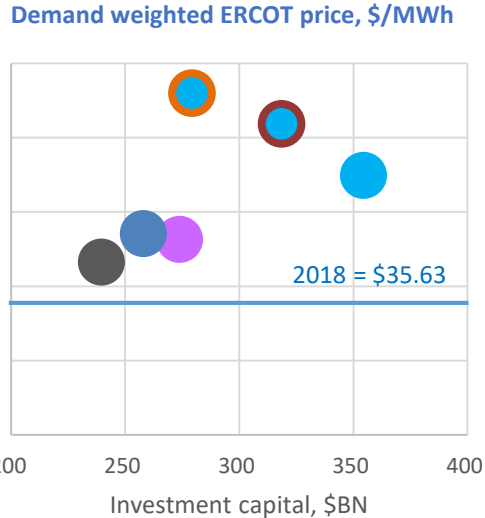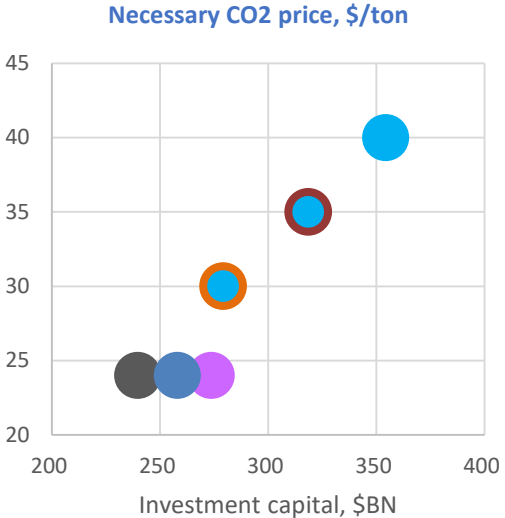
- Green H2 conversion requires a higher CO2 price to maintain the returns for additional renewable investment

- Greater renewable capacity in the hydrogen scenarios results in more hours in which renewables are on the margin – carbon pricing will have no impact on clearing prices in these hours

- The higher CO2 price needed to support H2 conversion results in an increase in ERCOT wholesale pricing of $2 to 5/MWh or $1.3 to 3.3 billion/year

* Assumes 50% of cogen capacity retired

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ROADMAP TOWARD NET ZERO GRID BY 2050

2020-2025 **2025-2040** **2040-2050**

Continue annual wind and solar additions

Maintain tax credits for wind and solar

Accelerate expansion of ERCOT transmission capacity

Growth in ESG investment appetite

Support eligibility of standalone energy storage for federal Investment Tax Credits

Support implementation of a carbon tax/price

Add long duration storage to mitigate renewable over-supply

Begin using electrolysis to capture increasingly over-supplied/curtailed renewables

Convert existing salt dome infrastructure to H2 storage

Begin upgrading existing cogeneration to use H2 in the fuel mix

Convert existing gas-fired generation for H2 fuel to back up renewables

Continue upgrade of existing cogeneration to run on increasingly higher mixes of H2

Build new H2 storage capacity

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Vijay Betanbhatla
Associate Director
Guidehouse

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