# A US perspective on the energy transition


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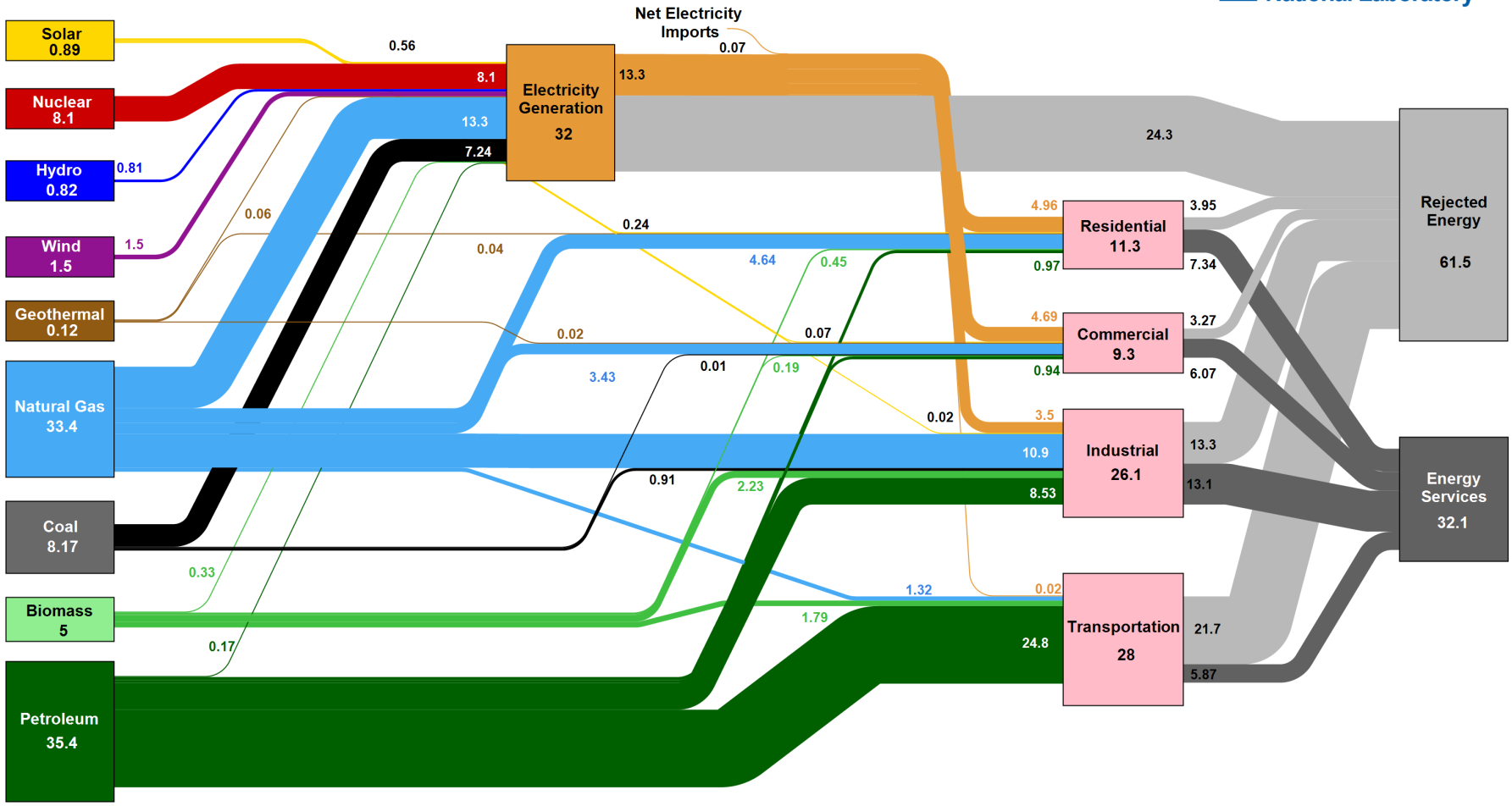
University of Colorado **Boulder**


**Sweet - PATHFNDR Conference, November 7th, 2024**
**ETH Zurich, Switzerland**

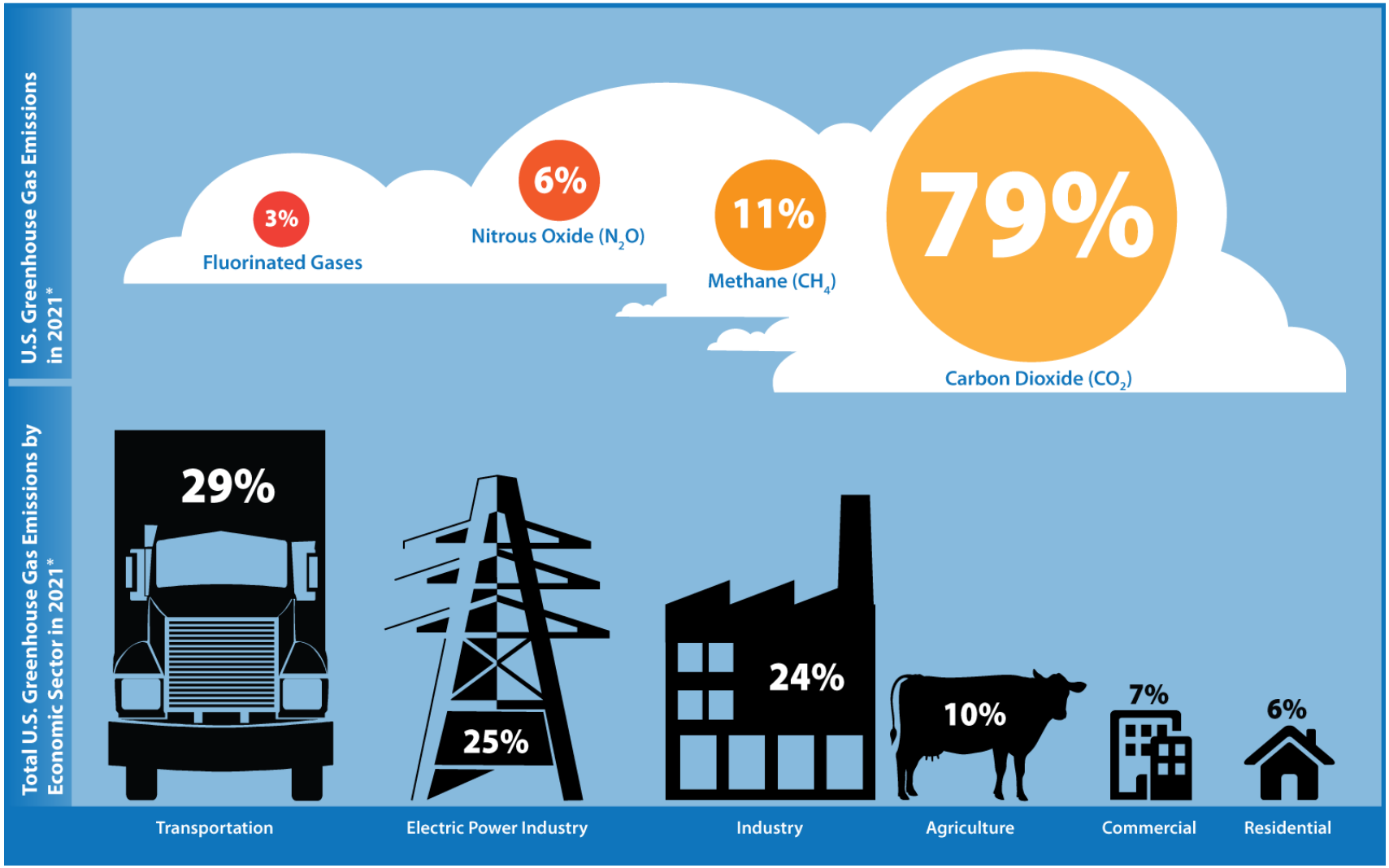
# Estimated U.S. Energy Consumption in 2023: 93.6 Quads

Lawrence Livermore National Laboratory




Source: LLNL October, 2024. Data is based on DOE/EIA SEDS (2024). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 49% for the industrial sector, and, 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

# US GHG Emissions

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Source: US EPA

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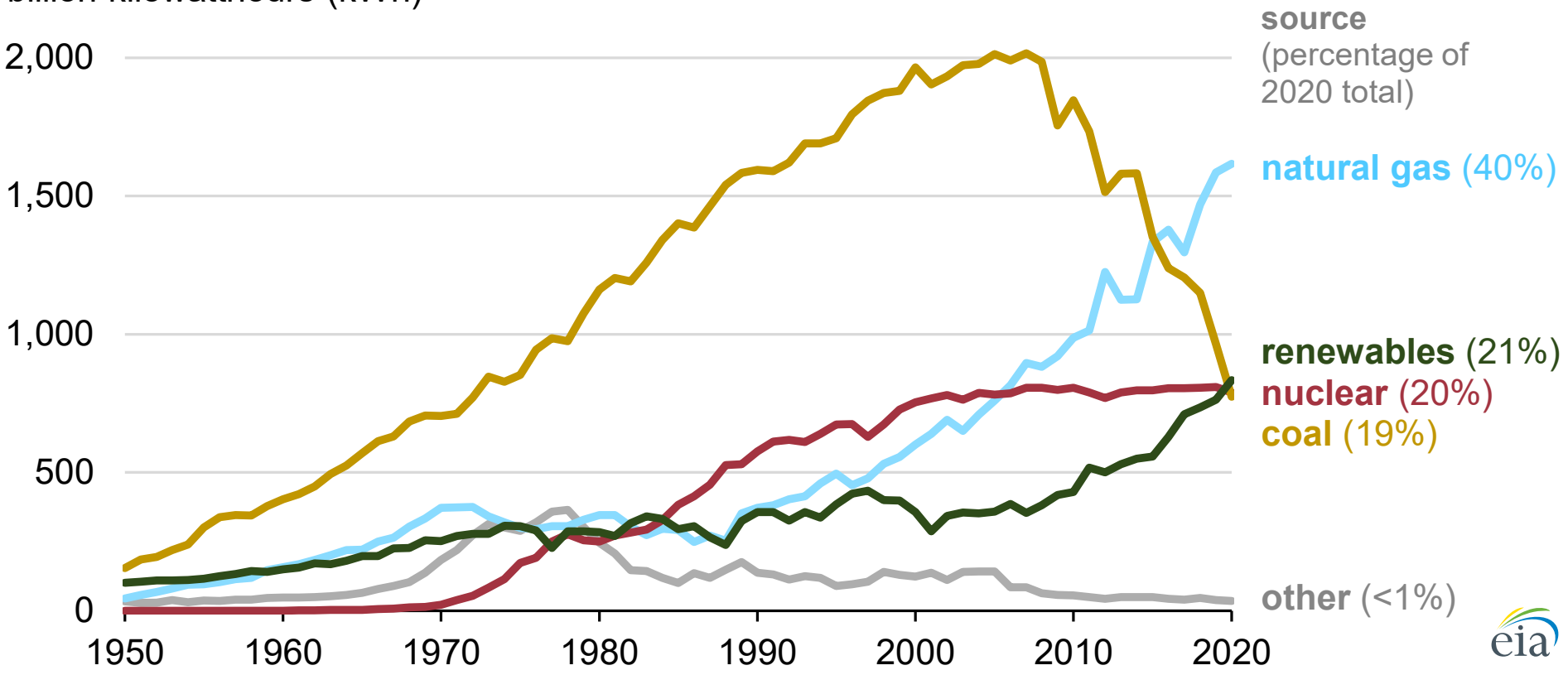
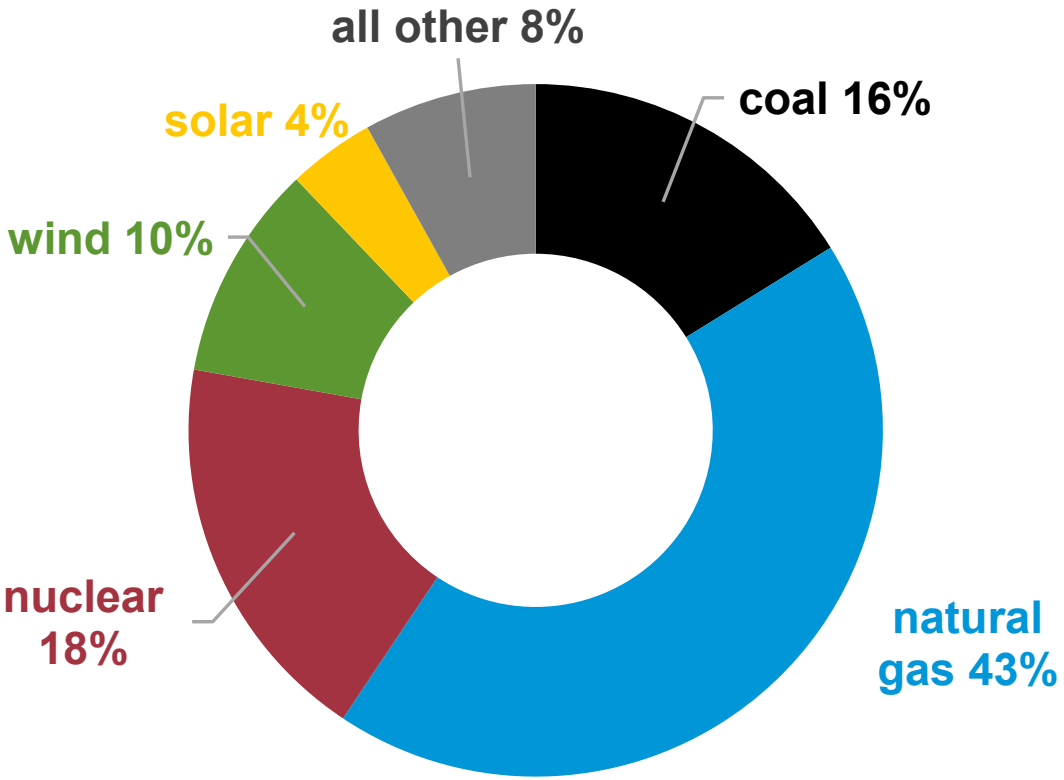
# US Electricity Generation Mixture

**Annual U.S. electricity generation from all sectors (1950–2020)**
billion kilowatthours (kWh)



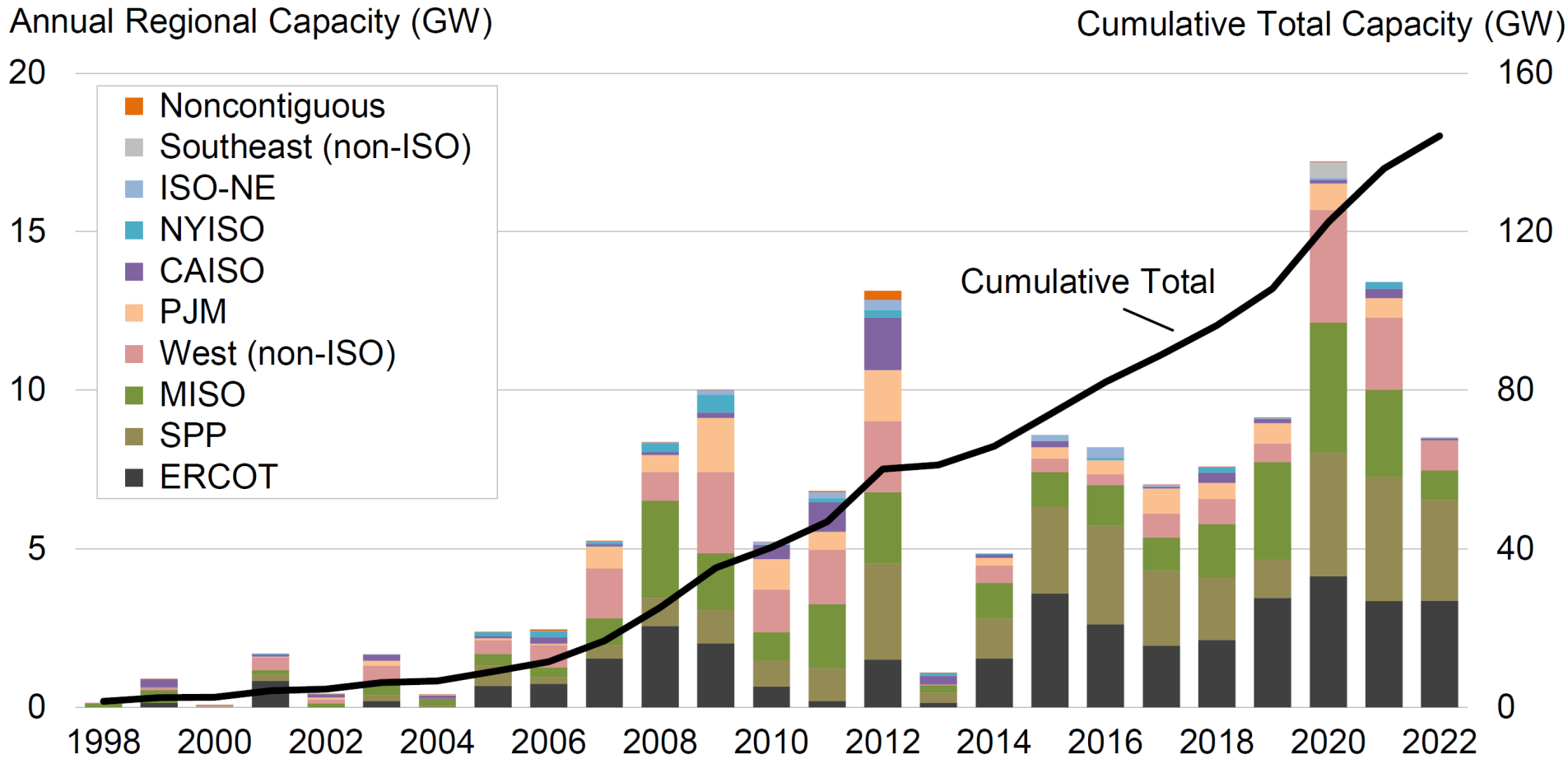
## Share of electricity generation by resource type (2023)




eia

# Wind Electricity Generation

United States: ~ 147.5 GW
Record 8.5 GW installed in 2022
~10% annual energy share in 2023




Global wind capacity end of 2022: ~ **906 GW,** Global electricity generation capacity **~ 7500 GW**

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Source: LBNL Land-Based Wind Market Report 2023

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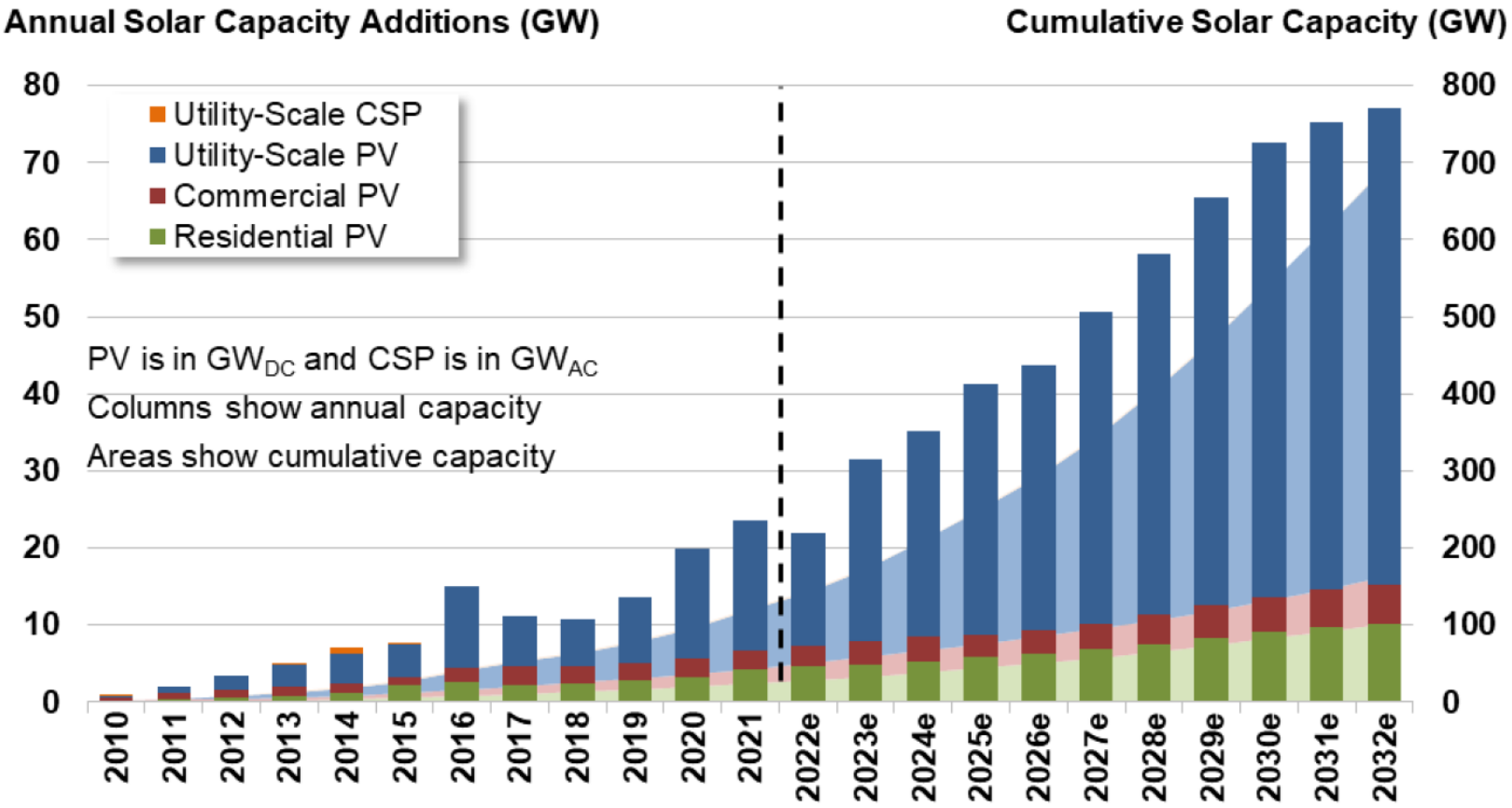
# Solar Electricity Generation

United States: ~ 170 GW
~4% annual energy share in 2023
~30 GW installed in 2023




***Sources:*** *Wood Mackenzie/SEIA Solar Market Insight Reports, Berkeley Lab*

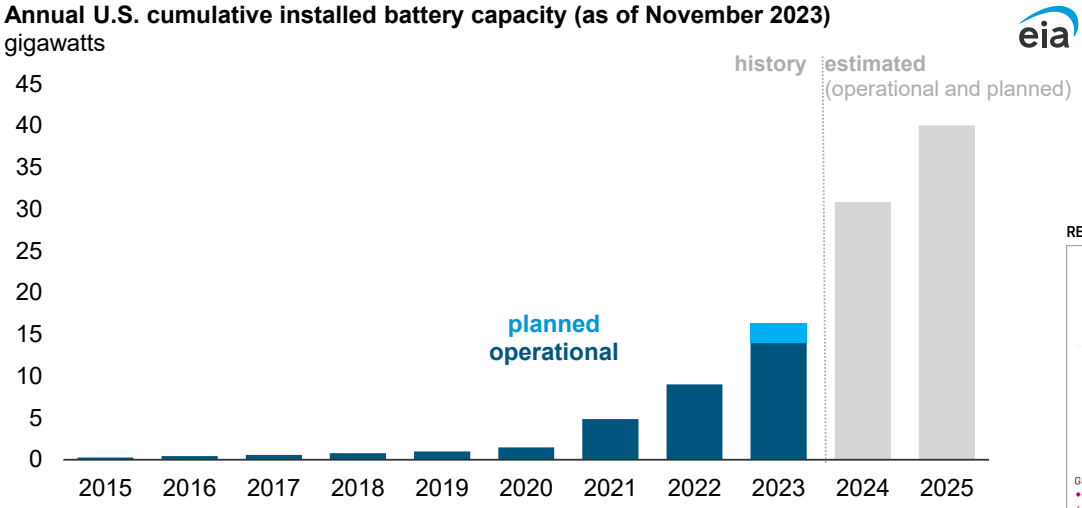
Global solar installations end of 2010: **~ 40 GW,** Global solar capacity end of 2023: **> 1,600 GW**

# Battery Storage

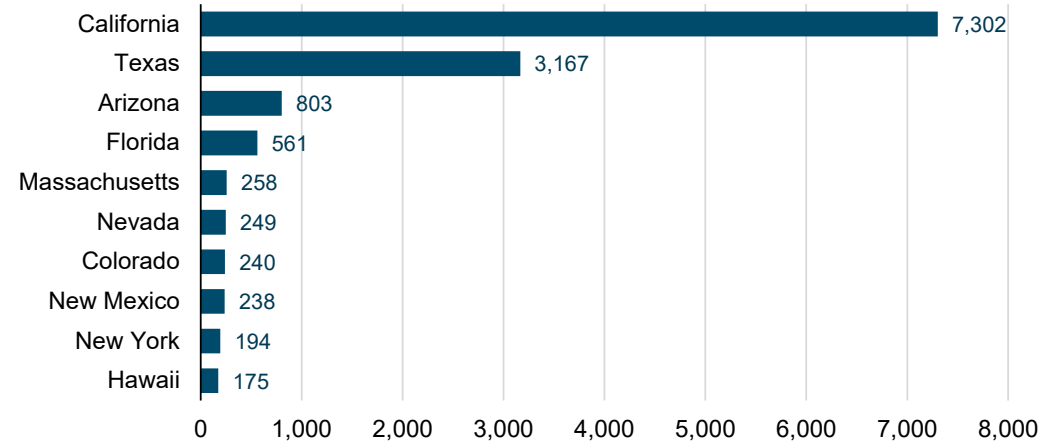
United States: ~ 30 GW
~15 GW installed in 2024

Globally: ~86 GW installed (2023), projected to 760 GW (2030)

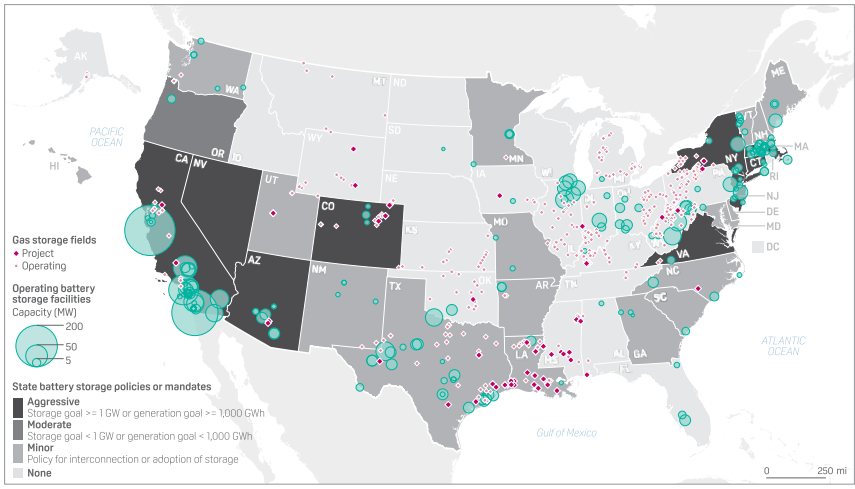
**Annual U.S. cumulative installed battery capacity (as of November 2023)**




**Top 10 U.S. states with the most installed battery capacity (as of November 2023)**




**RENEWABLES' BACKSTOPS: GAS STORAGE AND, INCREASINGLY, BATTERIES**

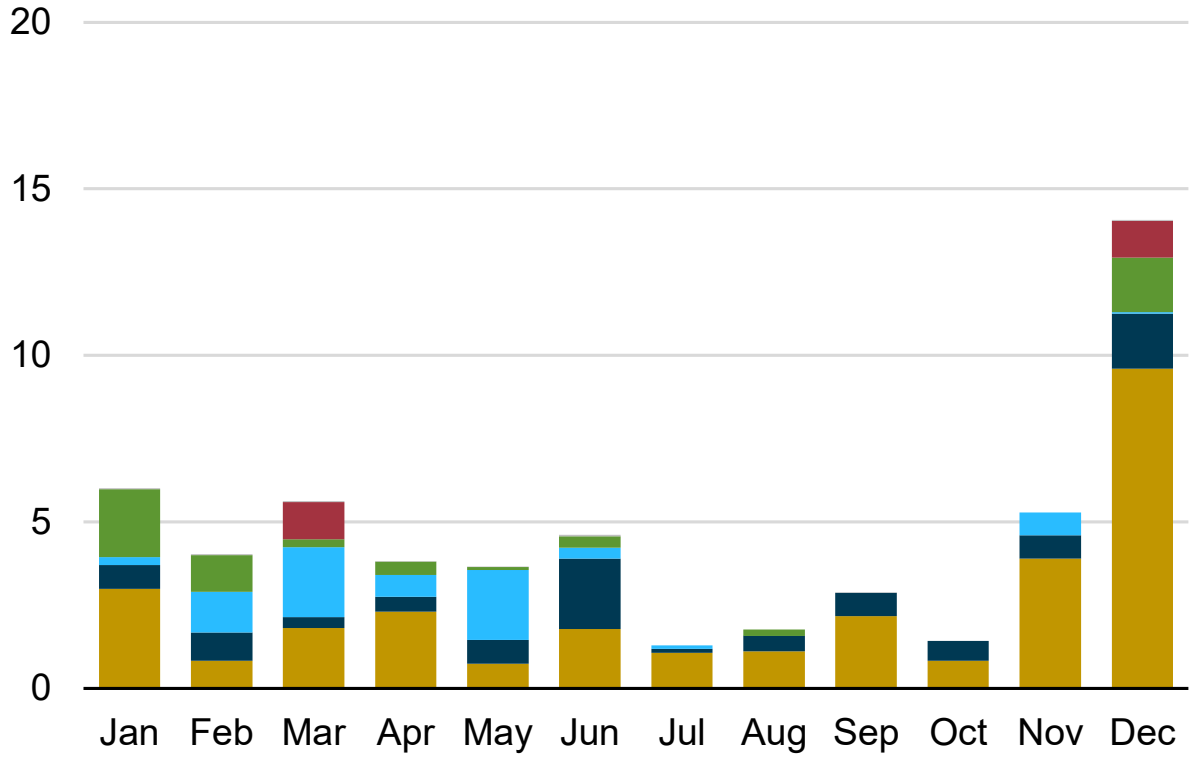


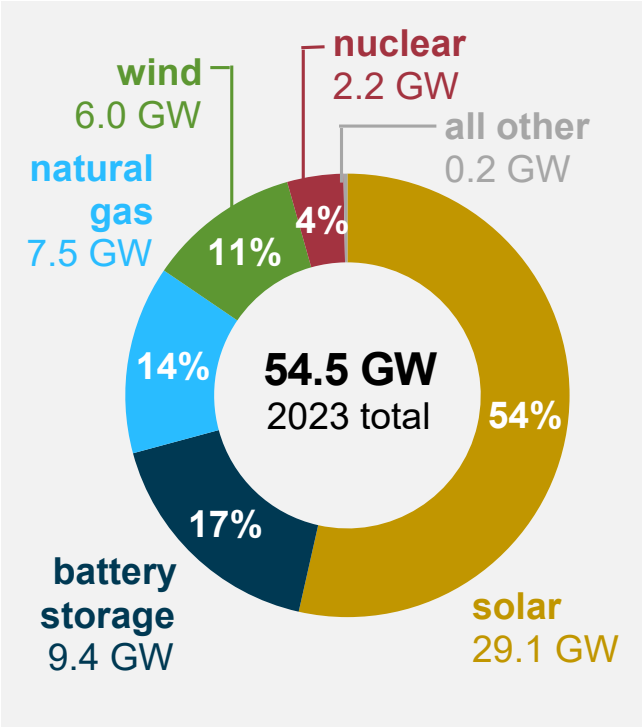

Source: S&P Global Platts, S&P Global Market Intelligence, Federal Energy Regulatory Commission

* Q2 2024: 97% of capacity additions in ERCOT, WECC & CAISO

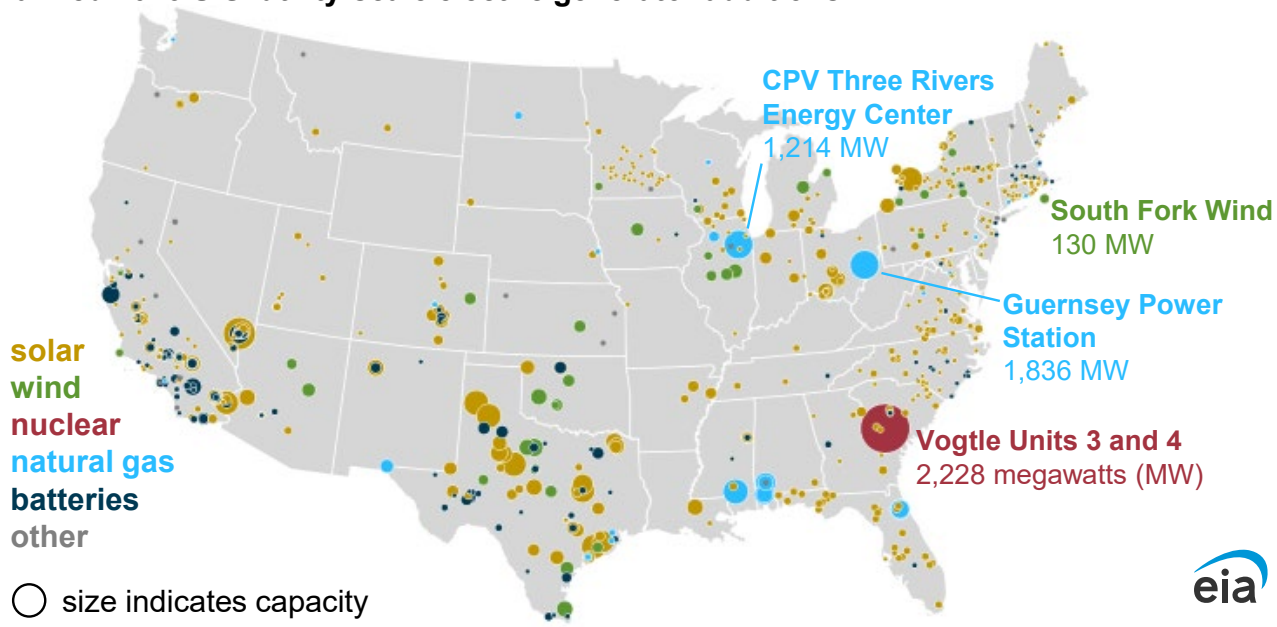
# New Power Generation

**U.S. planned utility-scale electric-generating capacity additions (2023)**
gigawatts (GW)

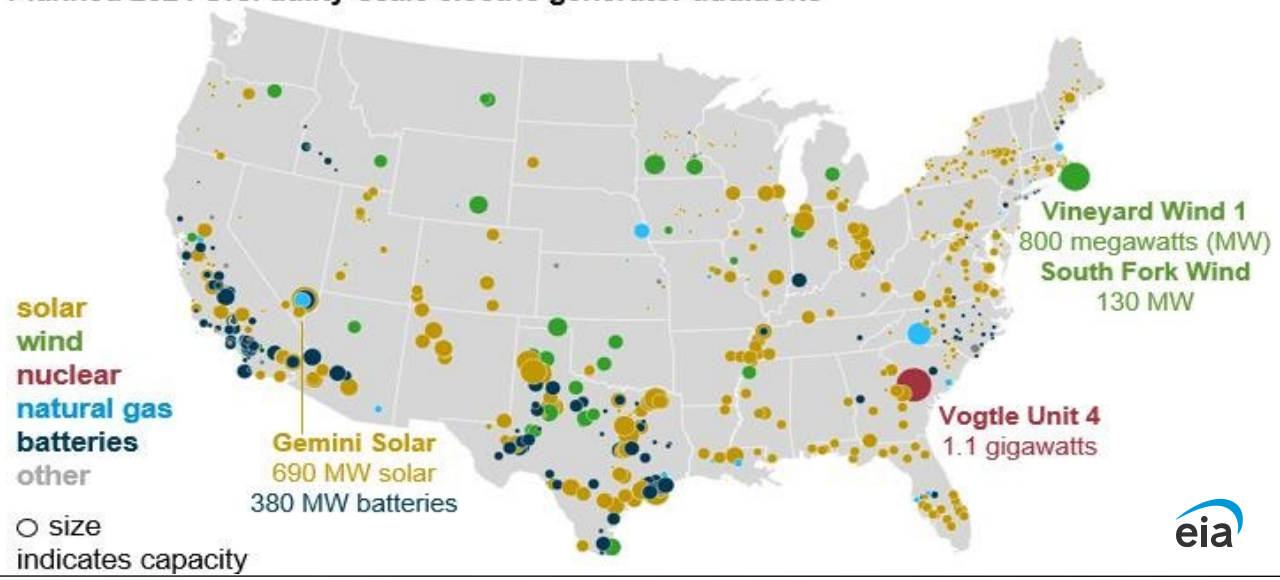


**Planned 2023 U.S. utility-scale electric generator additions**



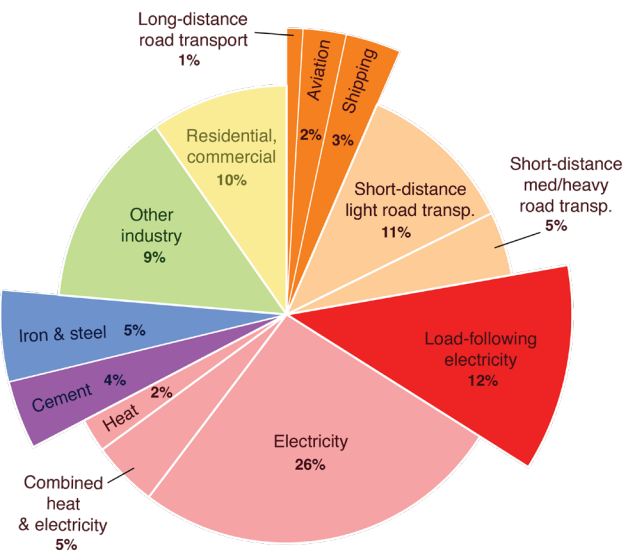

**Planned 2024 U.S. utility-scale electric generator additions**



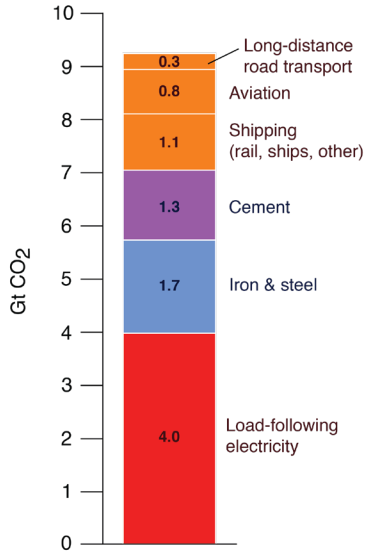
# Markets vs. Vertically Integrated Utilities


Source: FERC

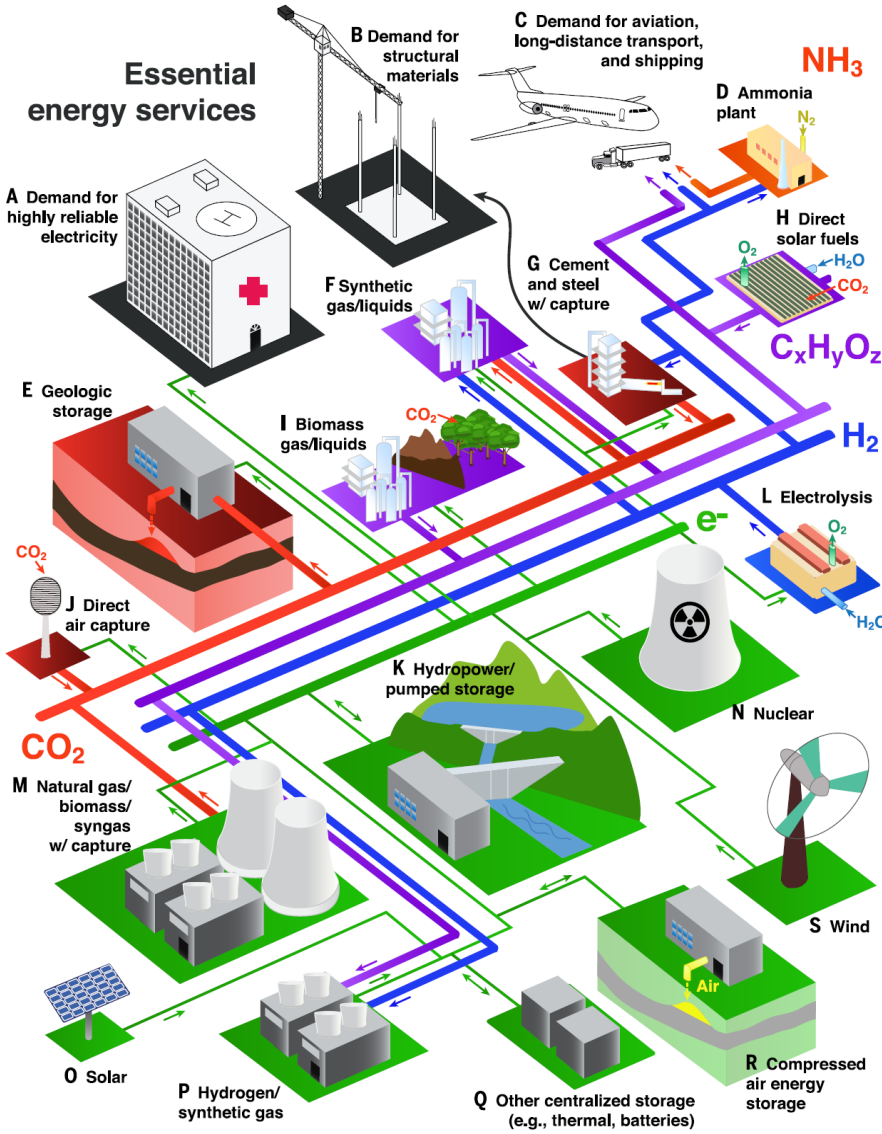
# Sector Coupling




**A** Global fossil fuel & industry emissions, 2014 (33.9 Gt $CO_2$)




**B** Difficult-to-eliminate emissions, 2014 (9.2 Gt $CO_2$)

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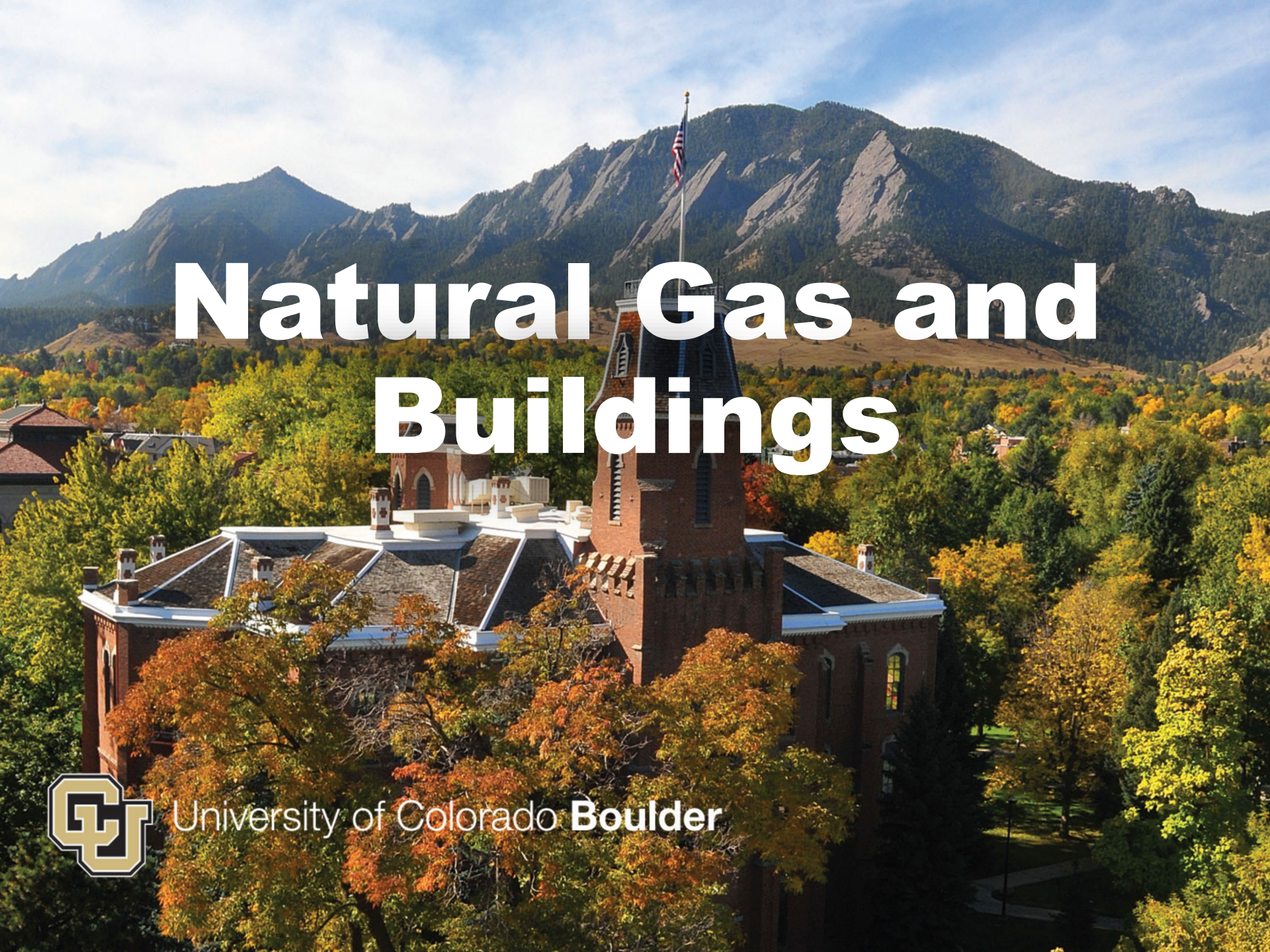
Source: Davis et al., Science, 2018


Natural Gas and Buildings
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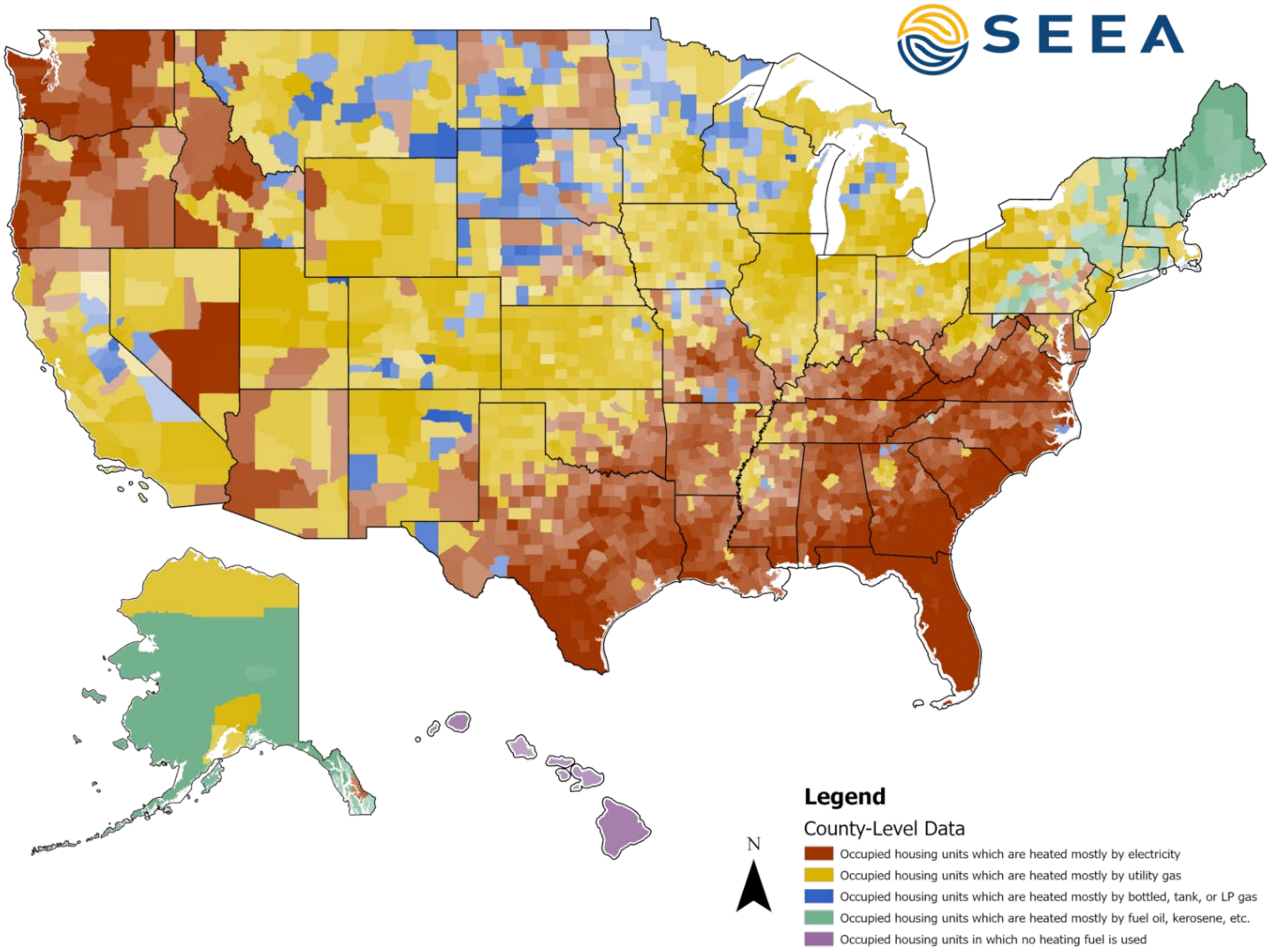
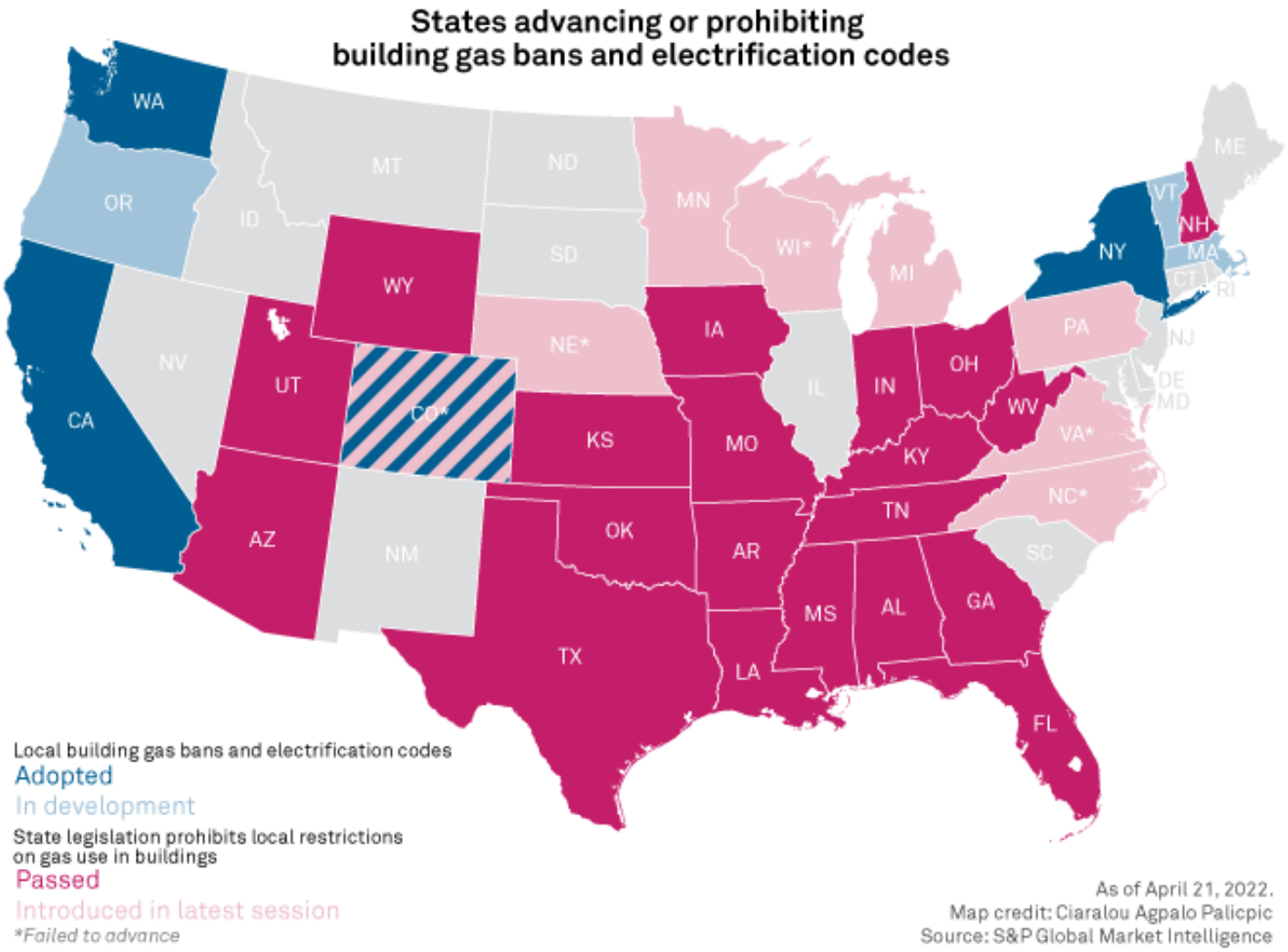
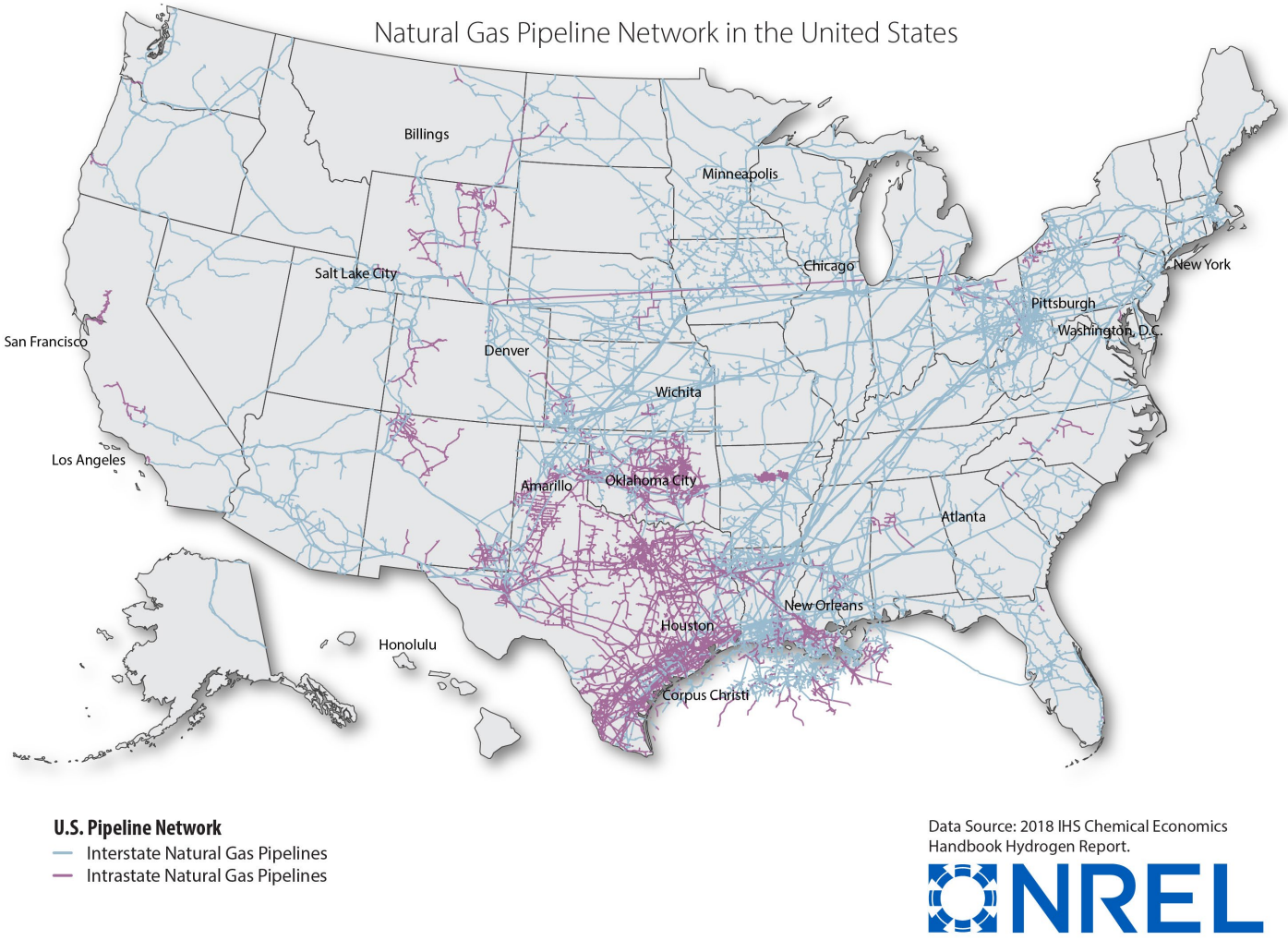
# Residential Heating by Source



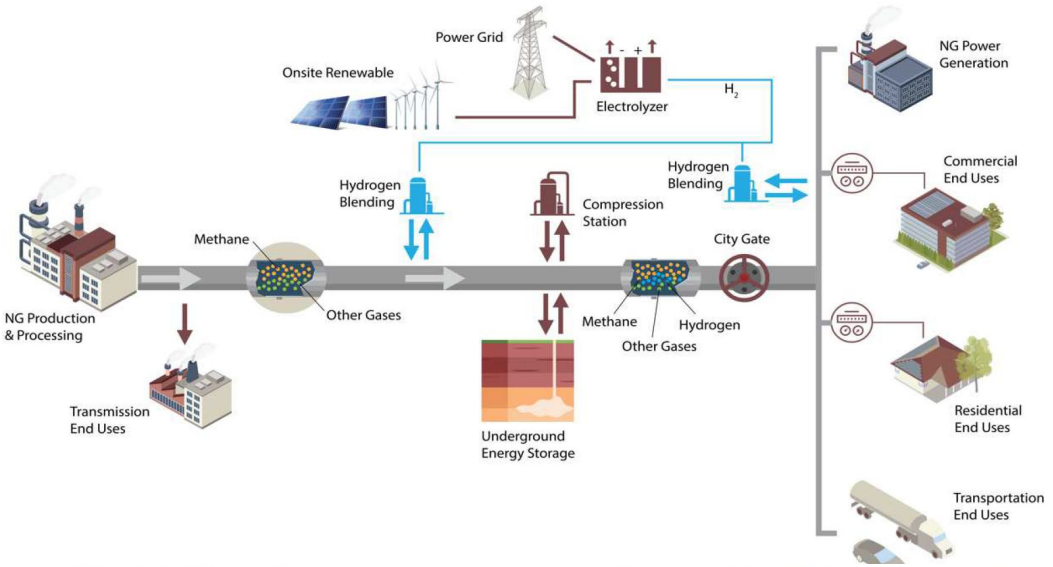
# State-level Policy

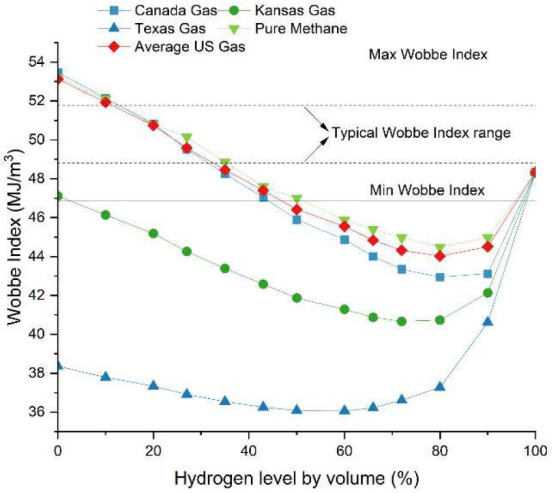


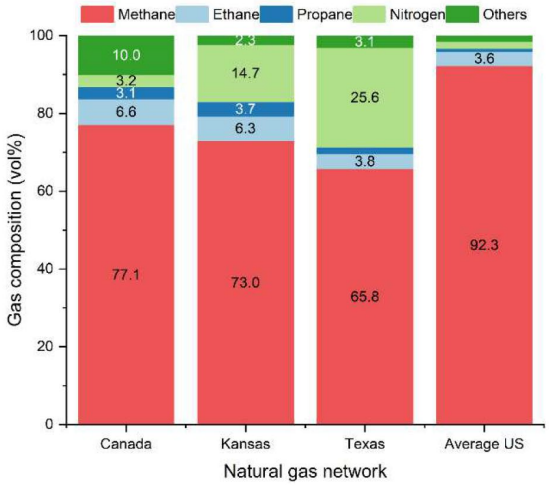
# Natural Gas Networks



# Hydrogen Blending






Source: Cakir Erdener et al., International Journal of Hydrogen Production, 2023


Transportation
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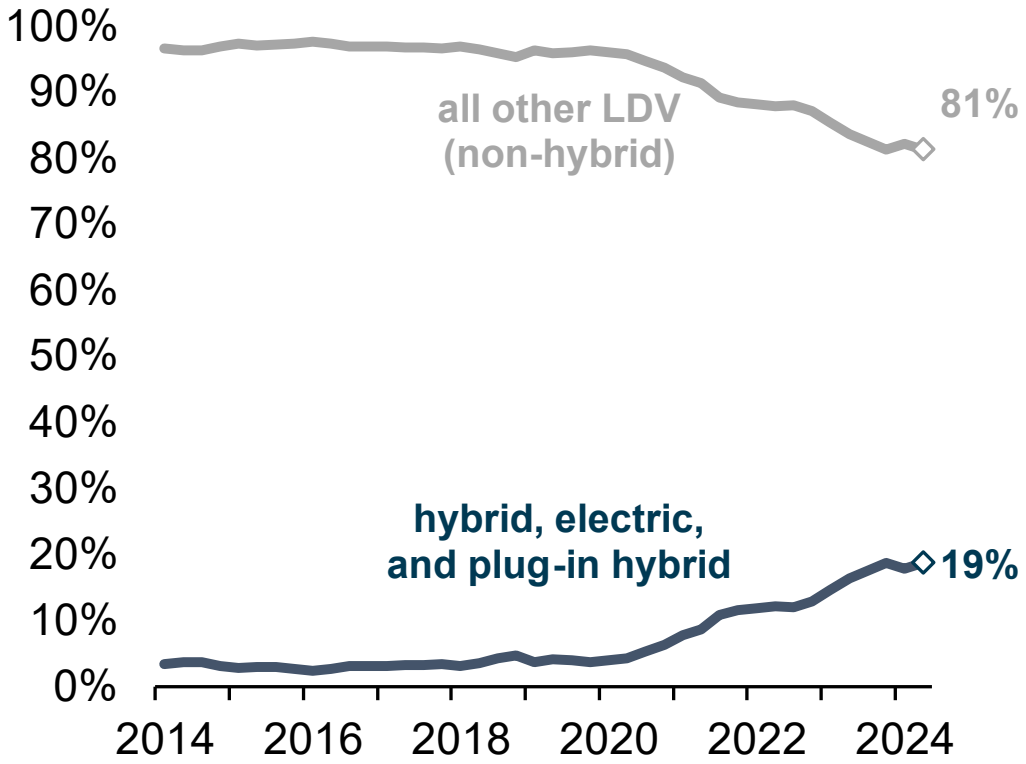
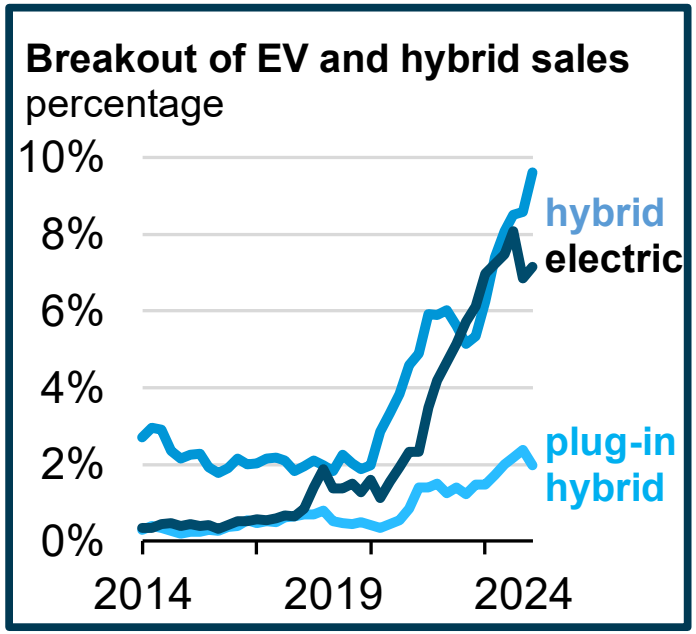
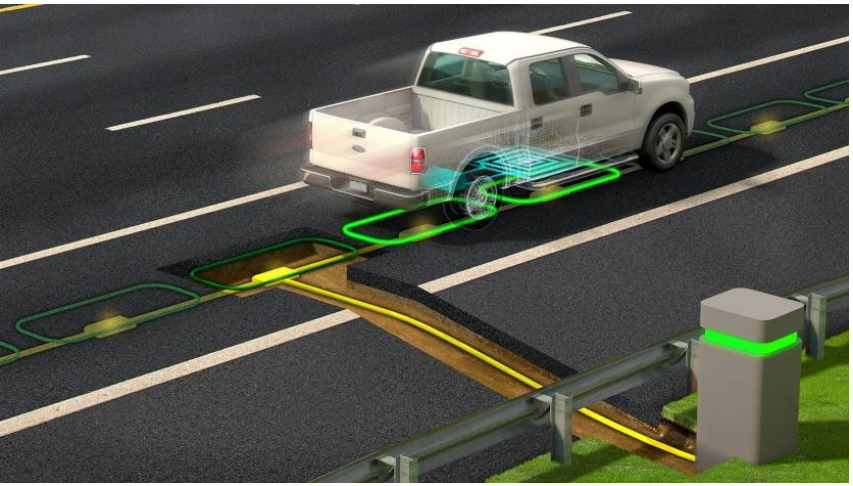
# US Electric Vehicle Sales

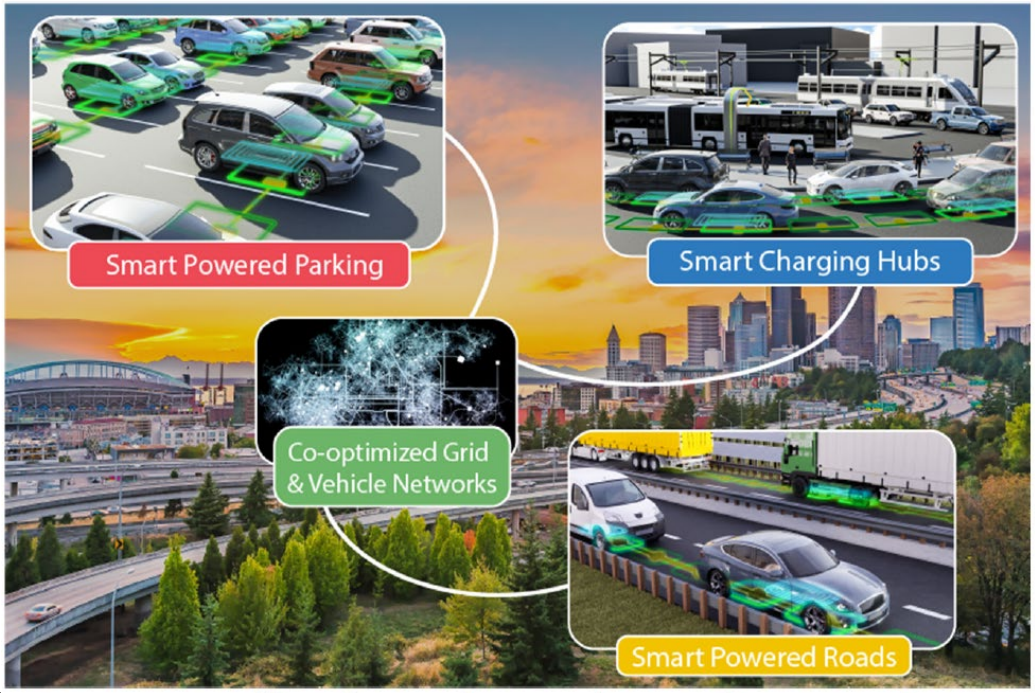
**Quarterly U.S. light-duty vehicle (LDV) sales by powertrain (Jan 2014–June 2024)**
percentage of sales



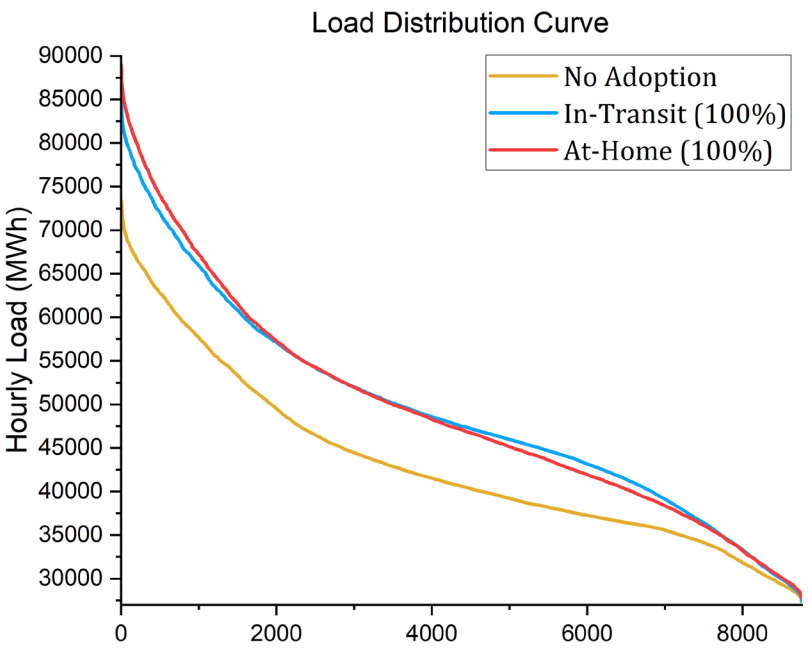
# ASPIRE – Engineering Research Center

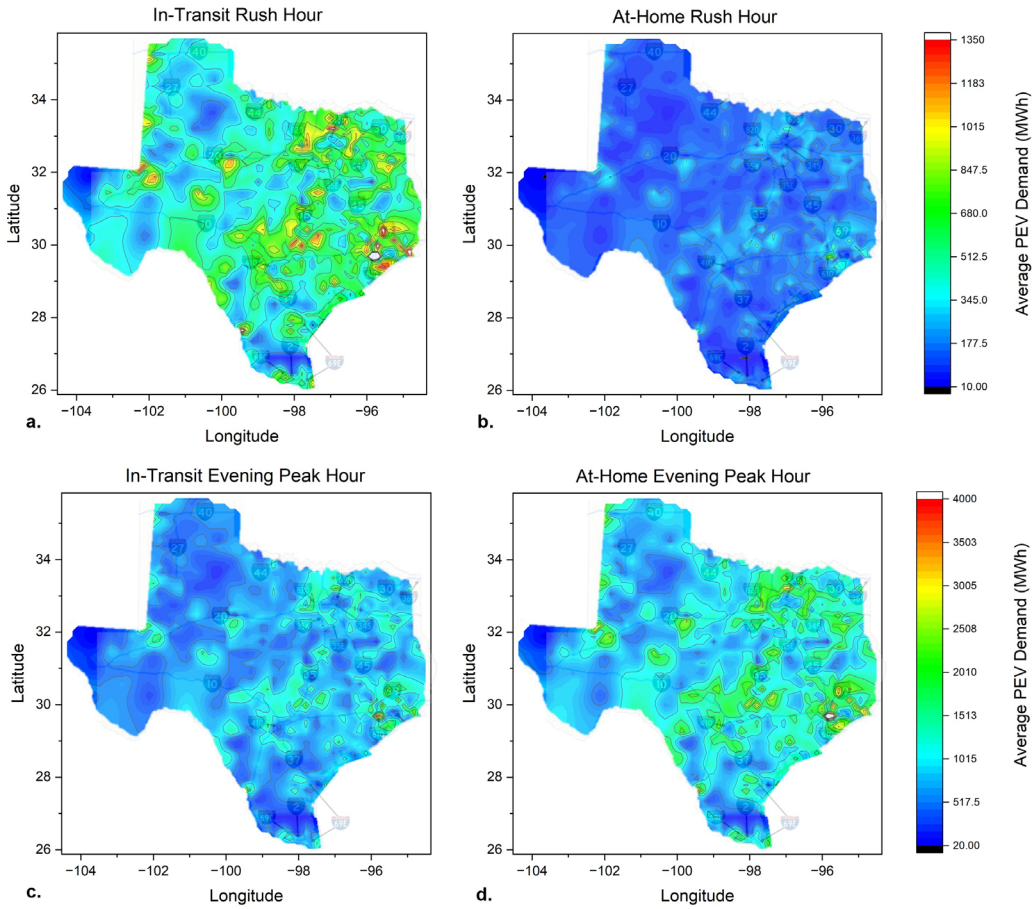





# EV Demand Analysis

LDEV consumption rate = **0.32 kWh/mi**

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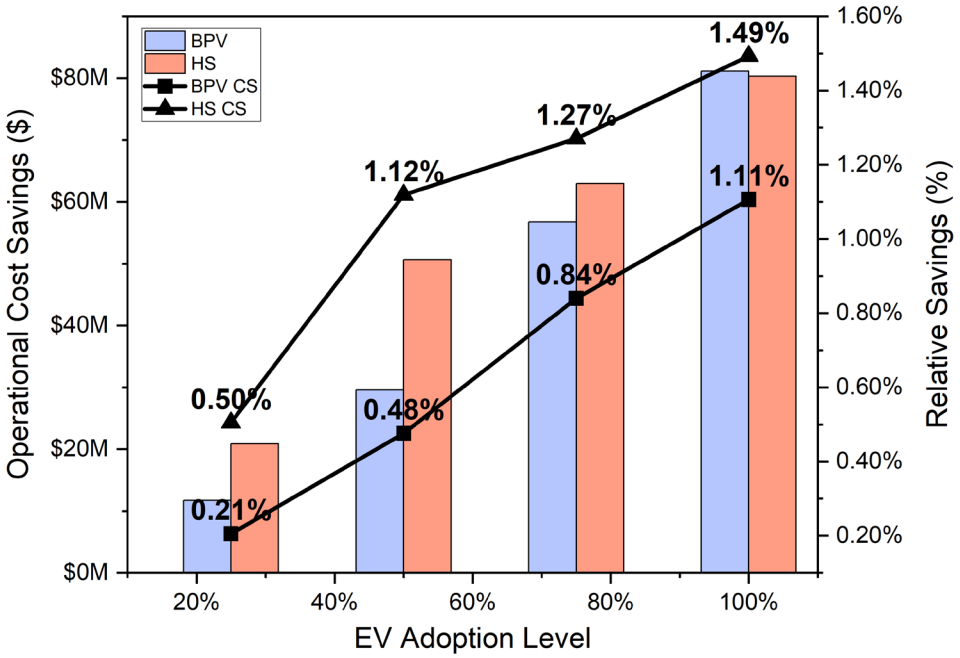
Source: Sauter, Lara, Turk, Milford, and Hodge, Applied Energy, 2024

# Research Takeaways

- Results from this study highlight advantages to in-road charging, including 1.49% in additional system cost savings and reduced cost to consumers when charged via additional renewable resources. In ERCOT, this equates to ~$80M per year in electricity system cost savings

| Network Provider | EV Charging Rate ($/kWh) | Retail Rate Increase |
|---|---|---|
| EVgo PlusMax | 0.220 | 196% |
| Tesla Supercharging | 0.250 | 223% |
| EVgo Basic | 0.280 | 250% |
| Electrify America Member | 0.310 | 277% |
| Electrify America Guest | 0.430 | 384% |

| Additive Cost | None - Parity | 200% | 300% | 400% |
|---|---|---|---|---|
| Wholesale Rate ($/kWh) | 0.085 | 0.170 | 0.255 | 0.340 |
| HH Cost Savings | $1,655 | $1,113 | $570 | $28 |
| Retail Rate ($/kWh) | 0.112 | 0.224 | 0.336 | 0.448 |
| HH Cost Savings | $1,482 | $766 | $50 | -$665 |






Source: Sauter, Lara, Turk, Milford, and Hodge, Applied Energy, 2024


Computing
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# Nuclear Renaissance?

Computing sector additions to dwarf other sectors?


## *Hungry for Energy, Amazon, Google and Microsoft Turn to Nuclear Power*

Large technology companies are investing billions of dollars in nuclear energy as an emissions-free source of electricity for artificial intelligence and other businesses.

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## DOE, USDA announce over $2.8B for Palisades nuclear plant restart

A $1.5 billion loan guarantee and $1.3 billion in awards will support site work and power purchase agreements for the 800-MW Michigan plant, the Biden-Harris administration said Monday.

Published Oct. 1, 2024

## New nuclear clean energy agreement with Kairos Power

Oct 14, 2024
3 min read

To accelerate the clean energy transition across the U.S., we're signing the world's first corporate agreement to purchase nuclear energy from multiple small modular reactors (SMR) to be developed by Kairos Power.

Michael Terrell
Senior Director, Energy and Climate

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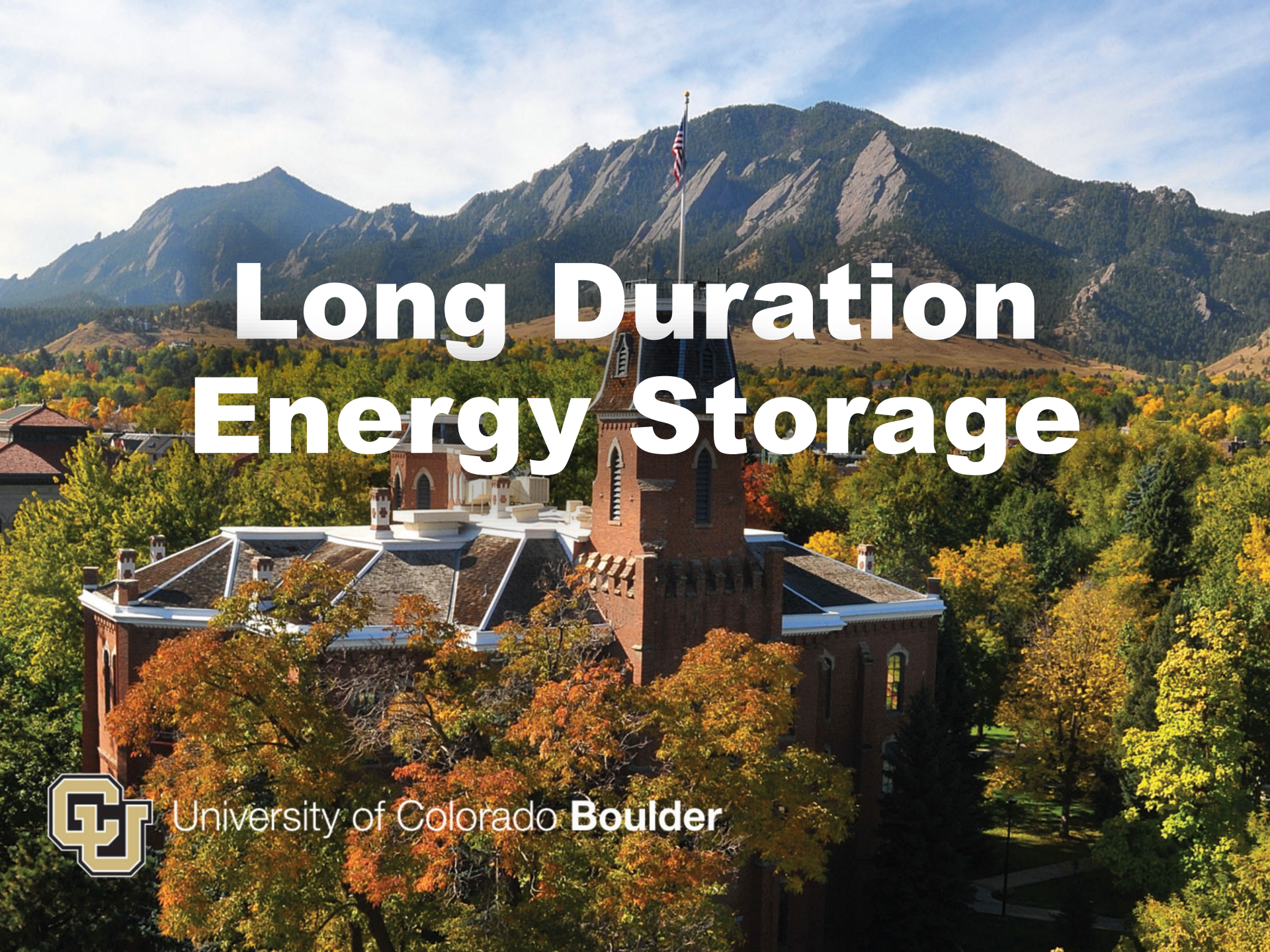
3 min

October 16, 2024

## Amazon signs agreements for innovative nuclear energy projects to address growing energy demands

Written by Amazon Staff


Long Duration
Energy Storage
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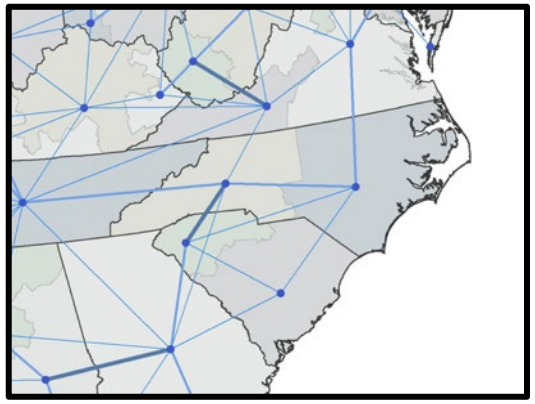
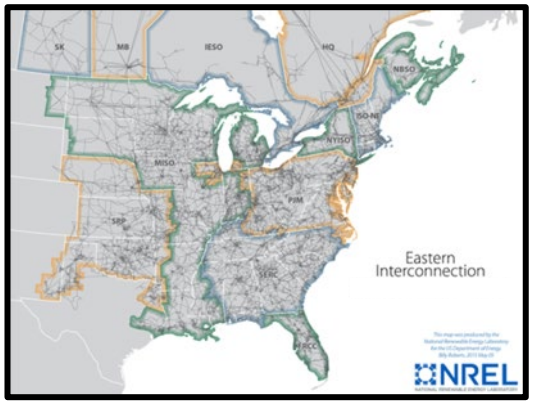
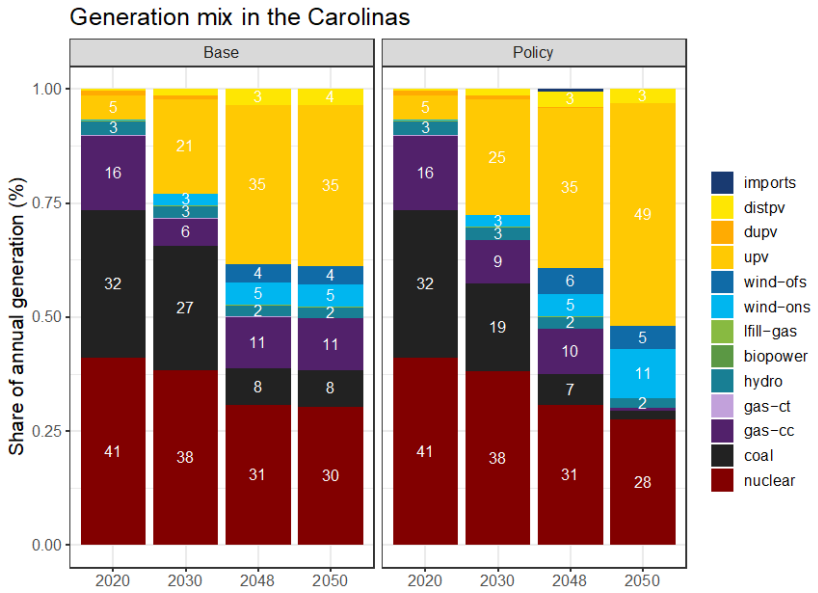
# Duke Energy – Zero Carbon Study

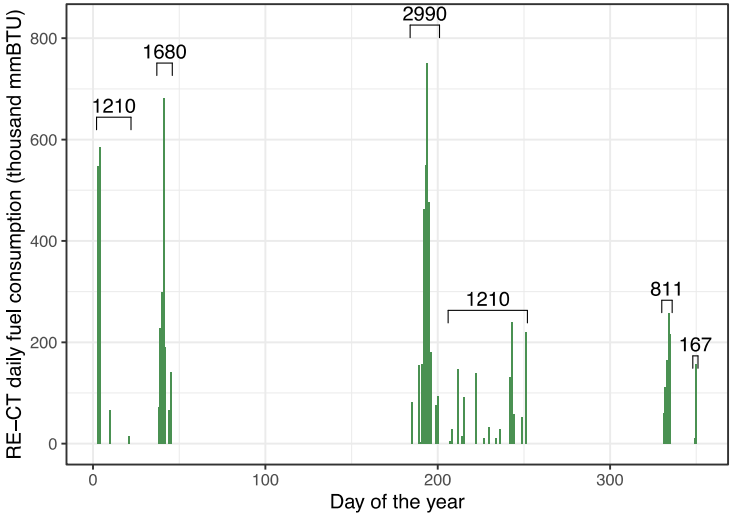


**Capacity expansion in ReEDS**




**Production Cost Modeling in PLEXOS**

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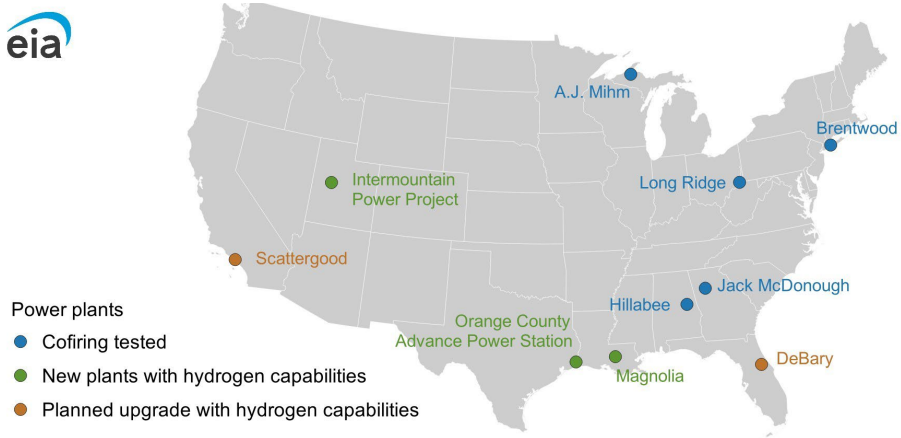
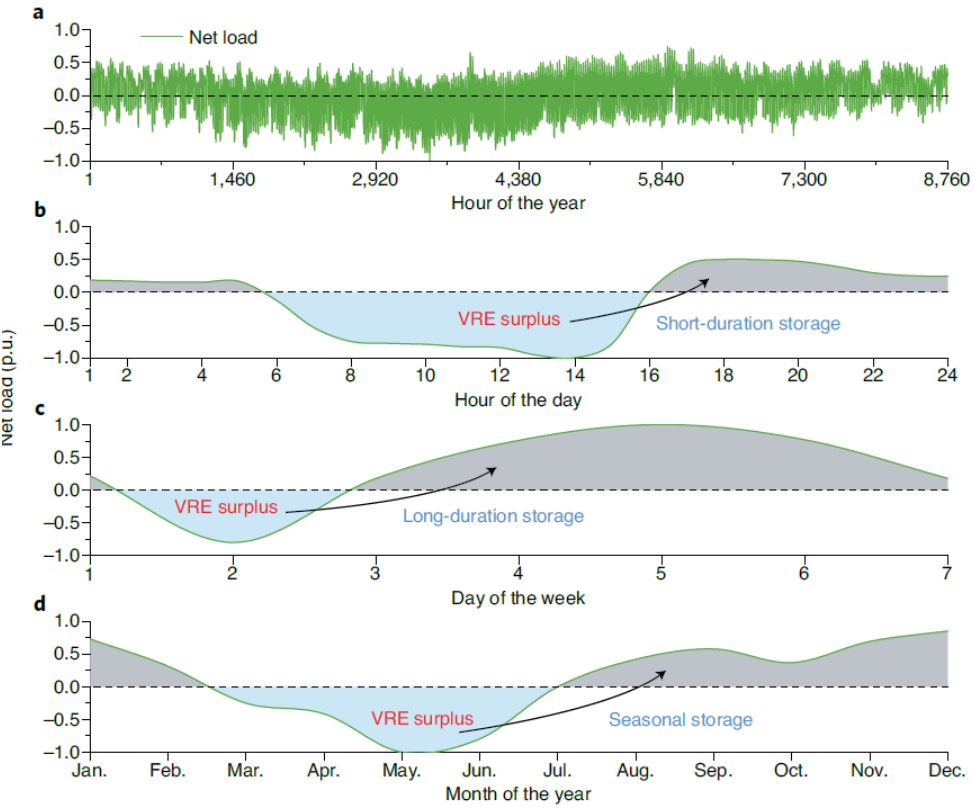
# Hydrogen Hubs

- Total of $7B possible, funded through the Bipartisan Infrastructure Law, very deployment focused, mainly heavy transportation
- Almost 1 year since announcement, many sub-project cancelations, partners leaving


**Hydrogen plans or tests at U.S. power plants (2024)**



# Long Duration Energy Storage




CAES

Breeze · HYDROSTOR · AUGWIND

Closed loop PHS and run of river

Rye Development

Gravity-based

ENERGY VAULT

Liquid Air Energy Storage

Sumitomo SHI FW

Liquid C02

ENERGYDOME

PHS

Quidnet Energy · AECOR

Latent heat (solid-liquid)

MGA THERMAL · Ice Energy

Sensible Heat

BRENMILLER

Sensible heat (solids / liquids)

KYOTO · MALTA · BUILD TO ZERO · hyme

Sensible heat (solids)

ECHOGEN power systems · ENERGYNEST · KRAFT BLOCK · MAGALDI · ANTORA · RONDO

cellcube · ENLIGHTEN · ESS · INVINITY · redflow · voltstorage · STRYTEN ENERGY

Metal anode

CATL

Metal Anode

e-zinc · ENERVENUE · eos · Form energy · slb

Non-Metal Chemical Storage

ceres · noon ENERGY

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Source: Guerra, Nature Energy, 2021

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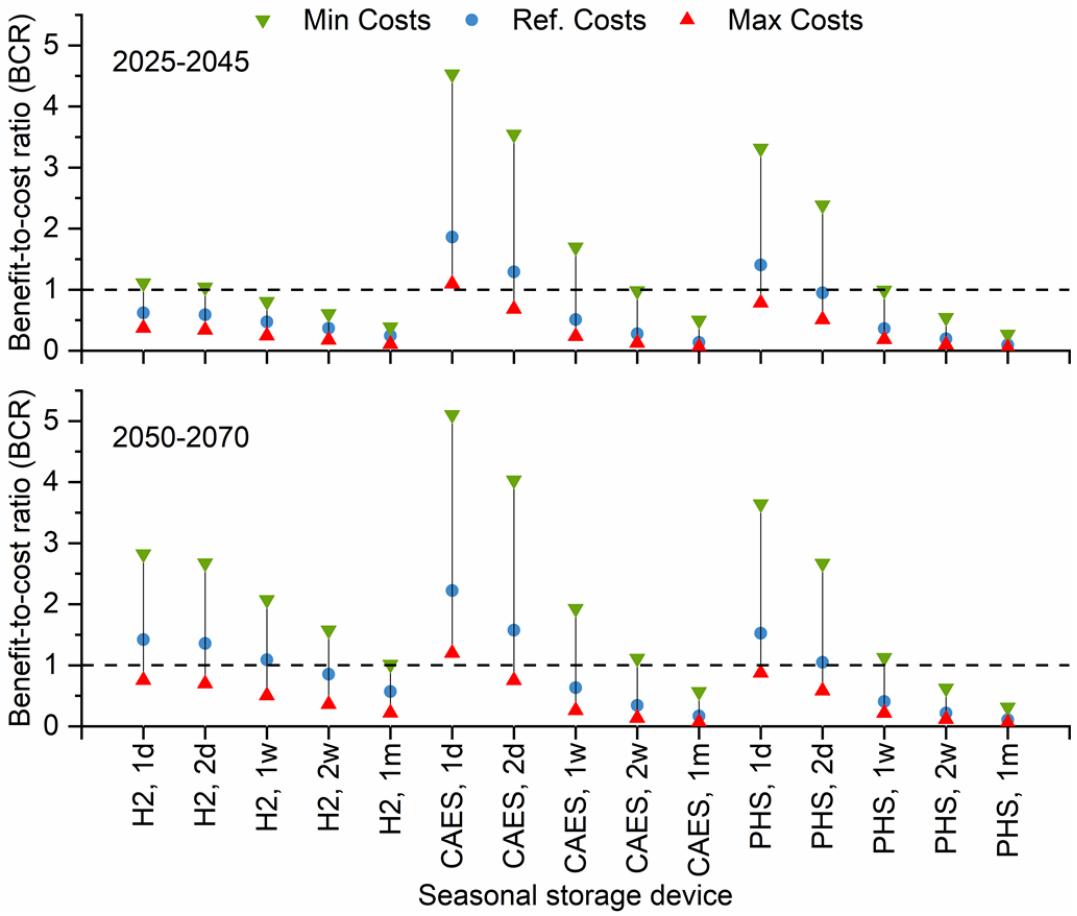
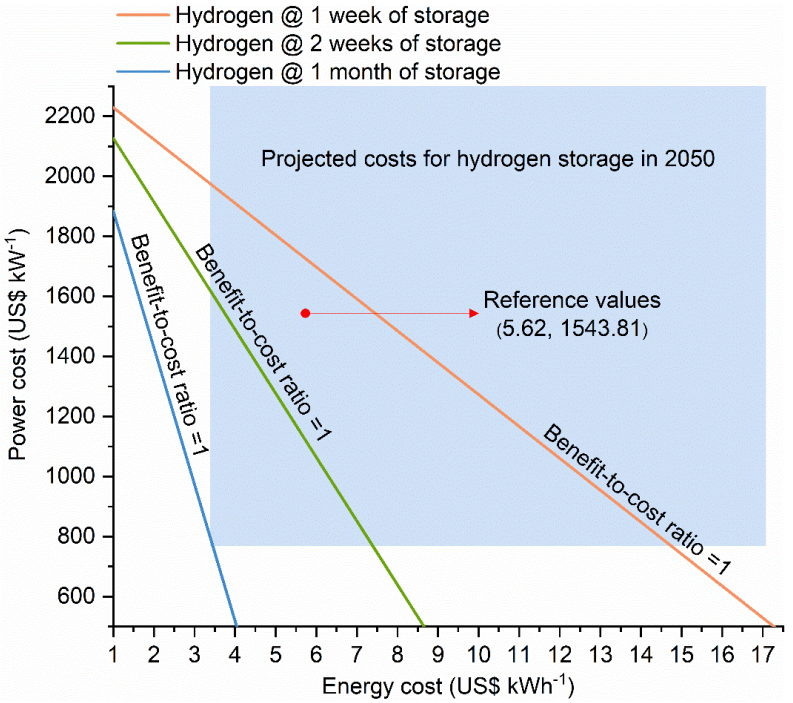
# LDES: Benefits and Costs



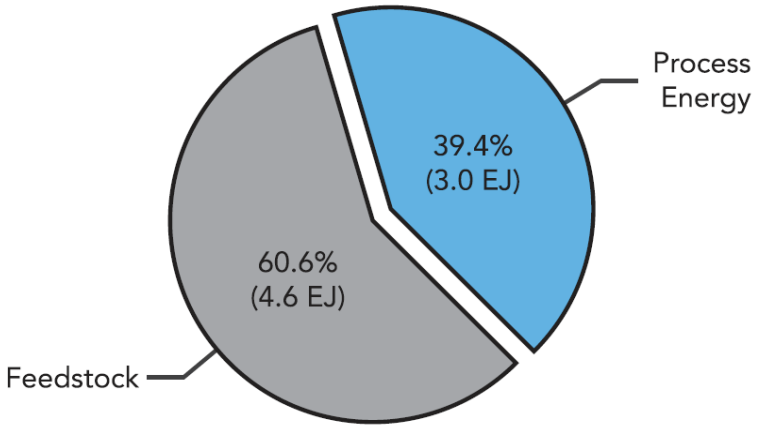



Source: Guerra, et al., Energy & Environmental Science, 2020

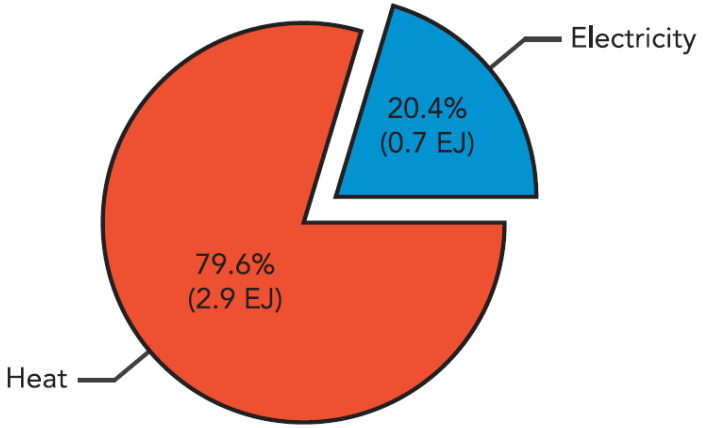

Chemical Industry
University of Colorado Boulder

# US Chemical Industry Overview

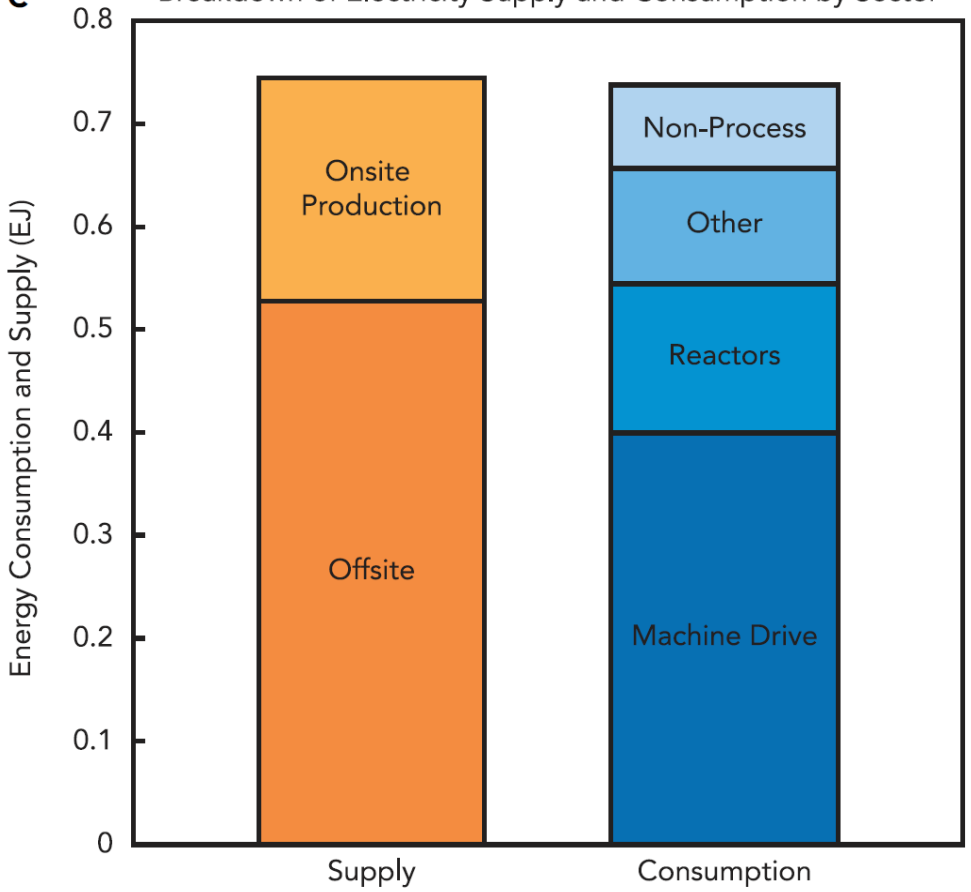
**A** Distribution of Fossil Fuel Use for Energy and Feedstock Applications




**B** Role of Electricity and Heat in Sectoral Energy Consumption




**C** Breakdown of Electricity Supply and Consumption by Sector

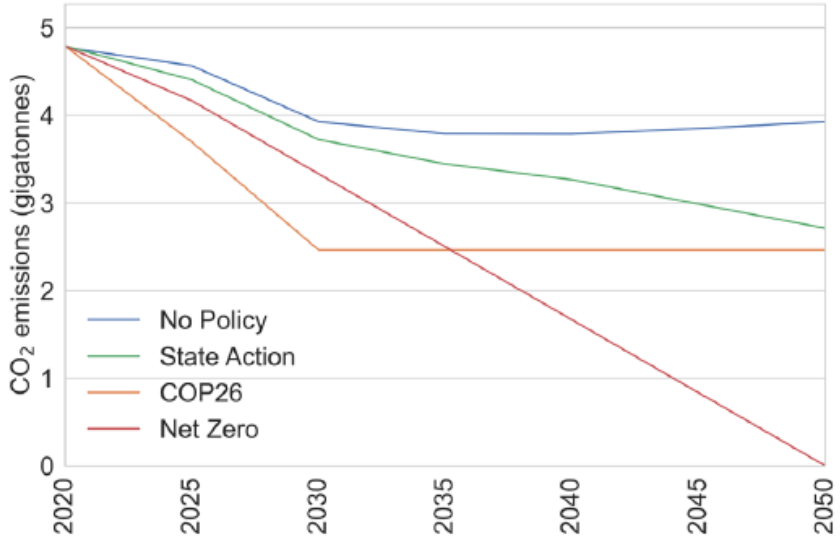


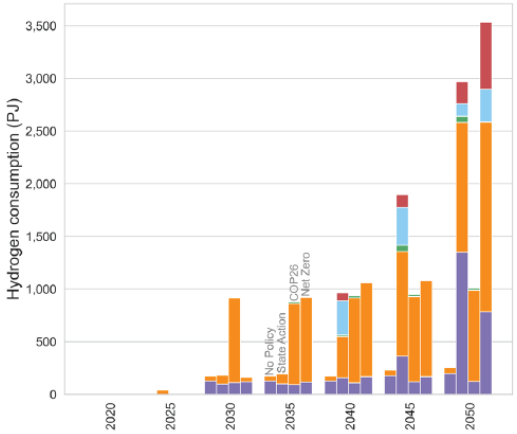


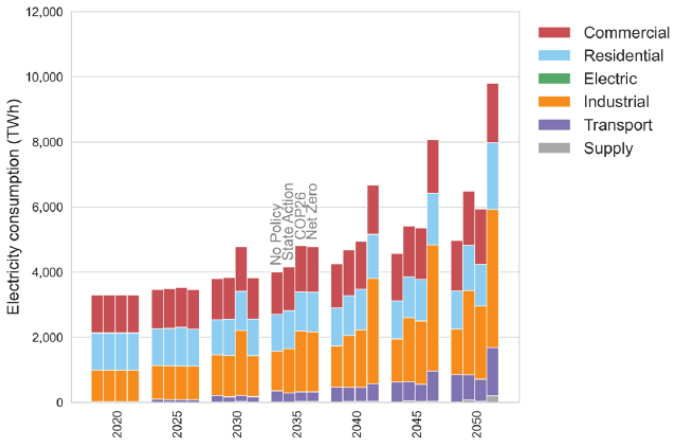

Source: Mallapragada et al., Joule, 2023

# Energy Carriers for Other Sectors

- Multi-sector models, such as the Open Energy Outlook, project the need for hydrogen, carbon capture and sequestration, and limited amounts of carbon-to-fuels
- Hydrogen usage largely for industrial decarbonization, very little for electricity (long-duration energy storage)
- Relatively small demand for carbon-to-fuels, cost projections higher than DAC with sequestration

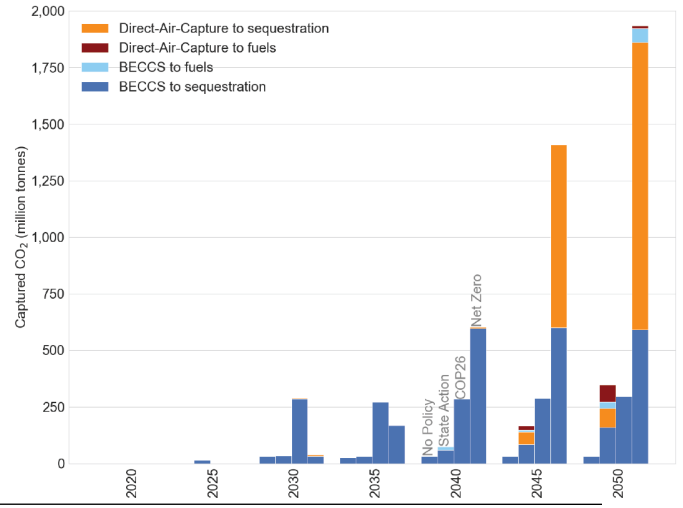


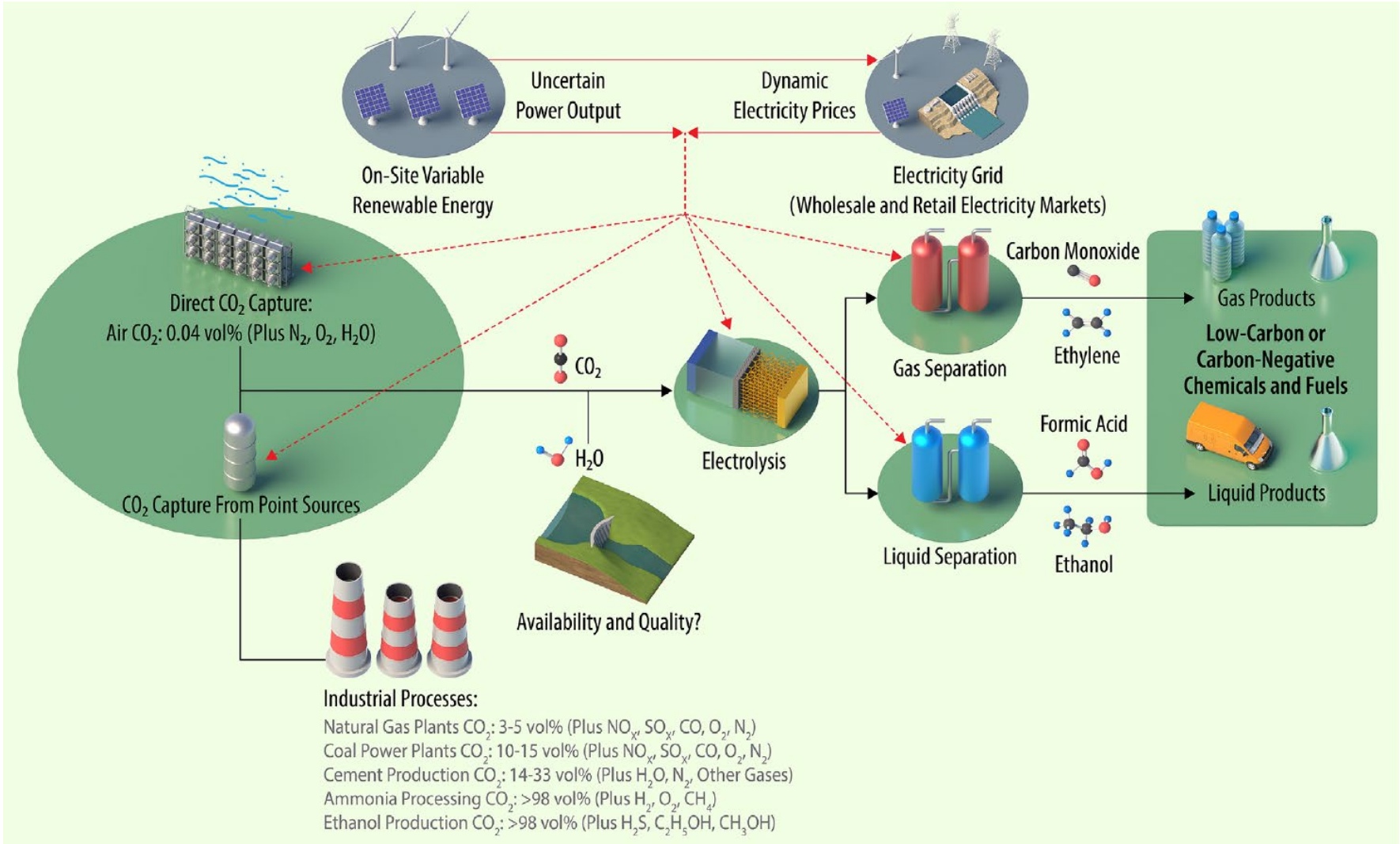





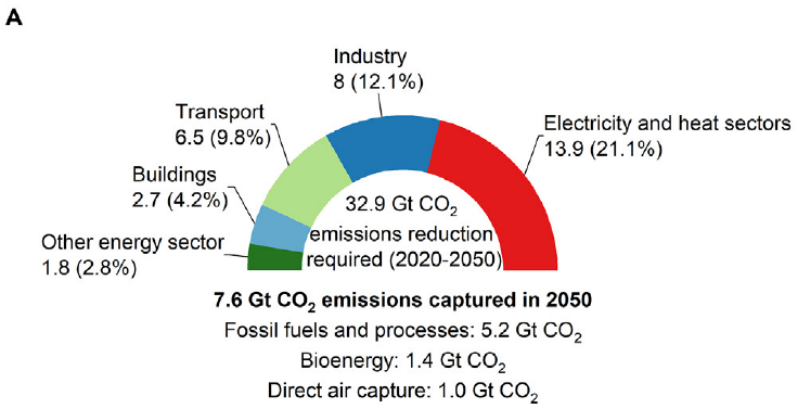


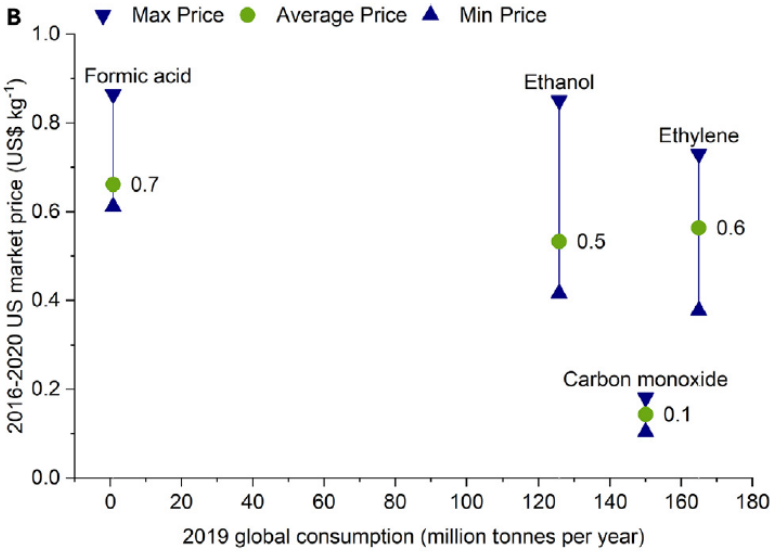


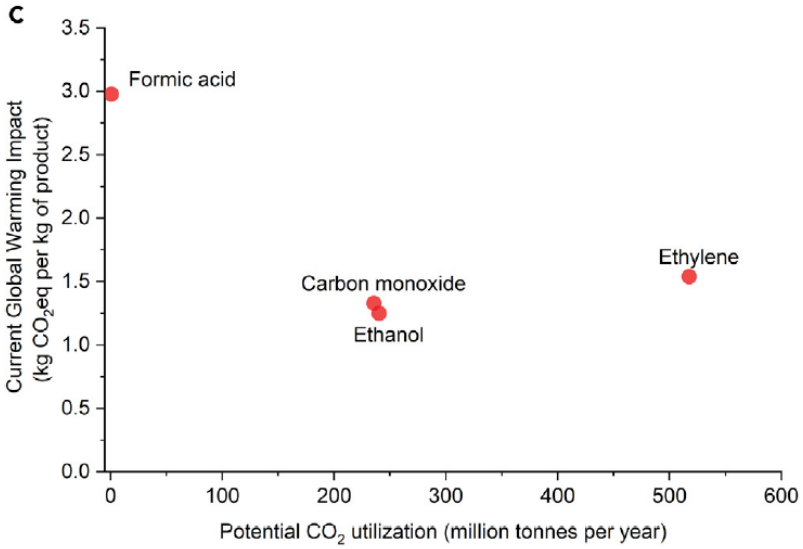
# Potential for $CO_2$ Electrolysis

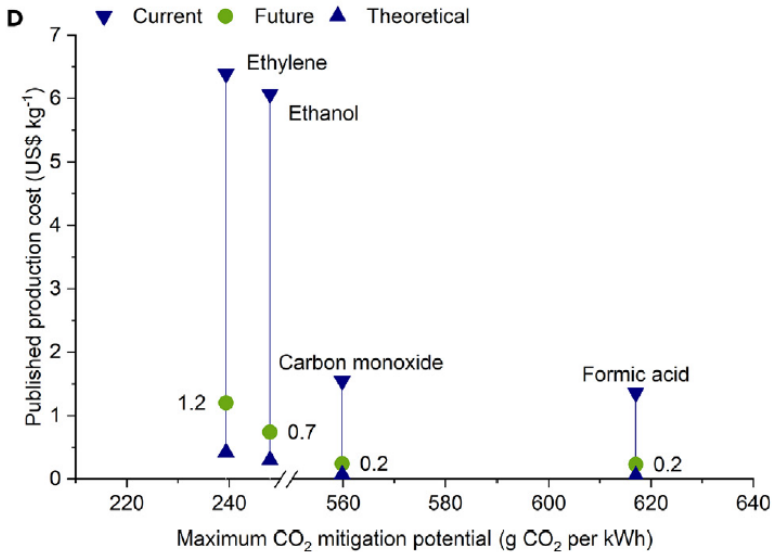


# $CO_2$ Electrolysis: Markets and Potential

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Source: Guerra, Almajed, Smith, Somoza-Tornos, and Hodge, Joule 2023

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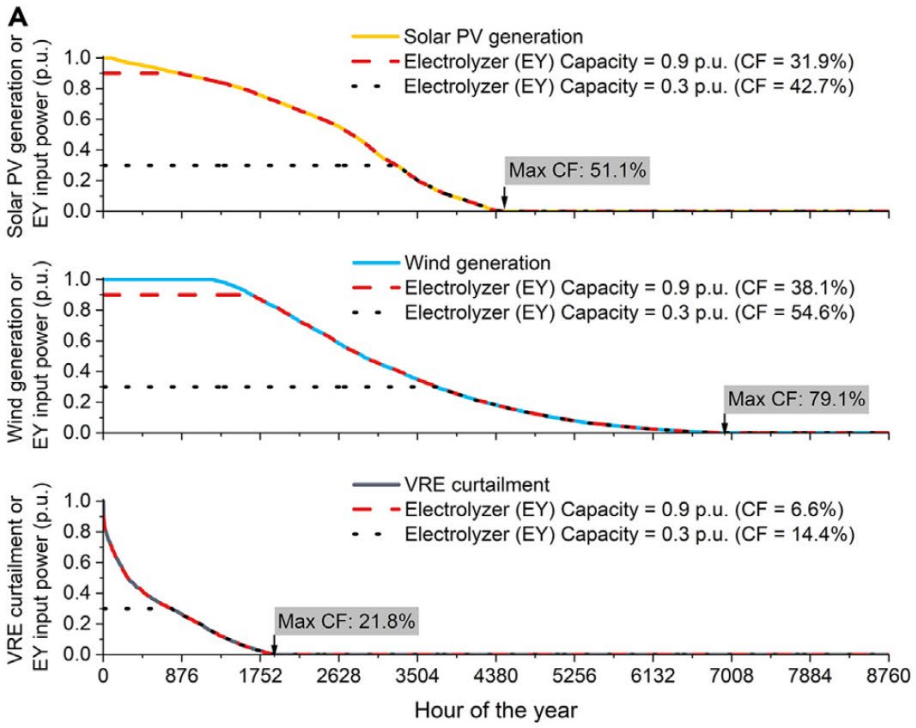
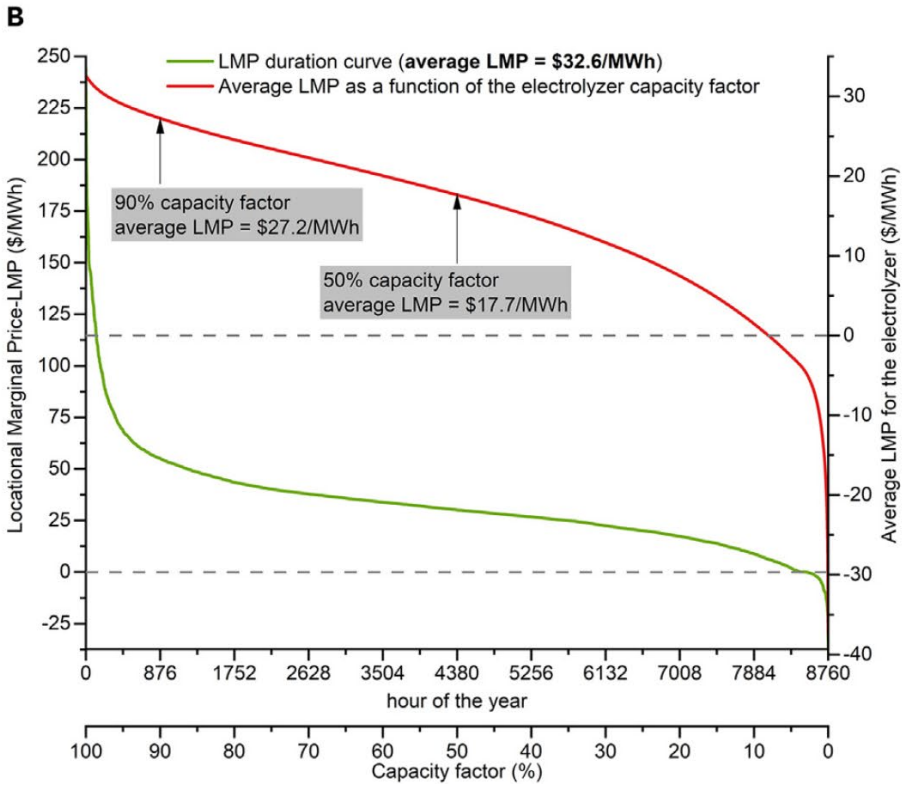
# Variable Renewables and Electrolysis

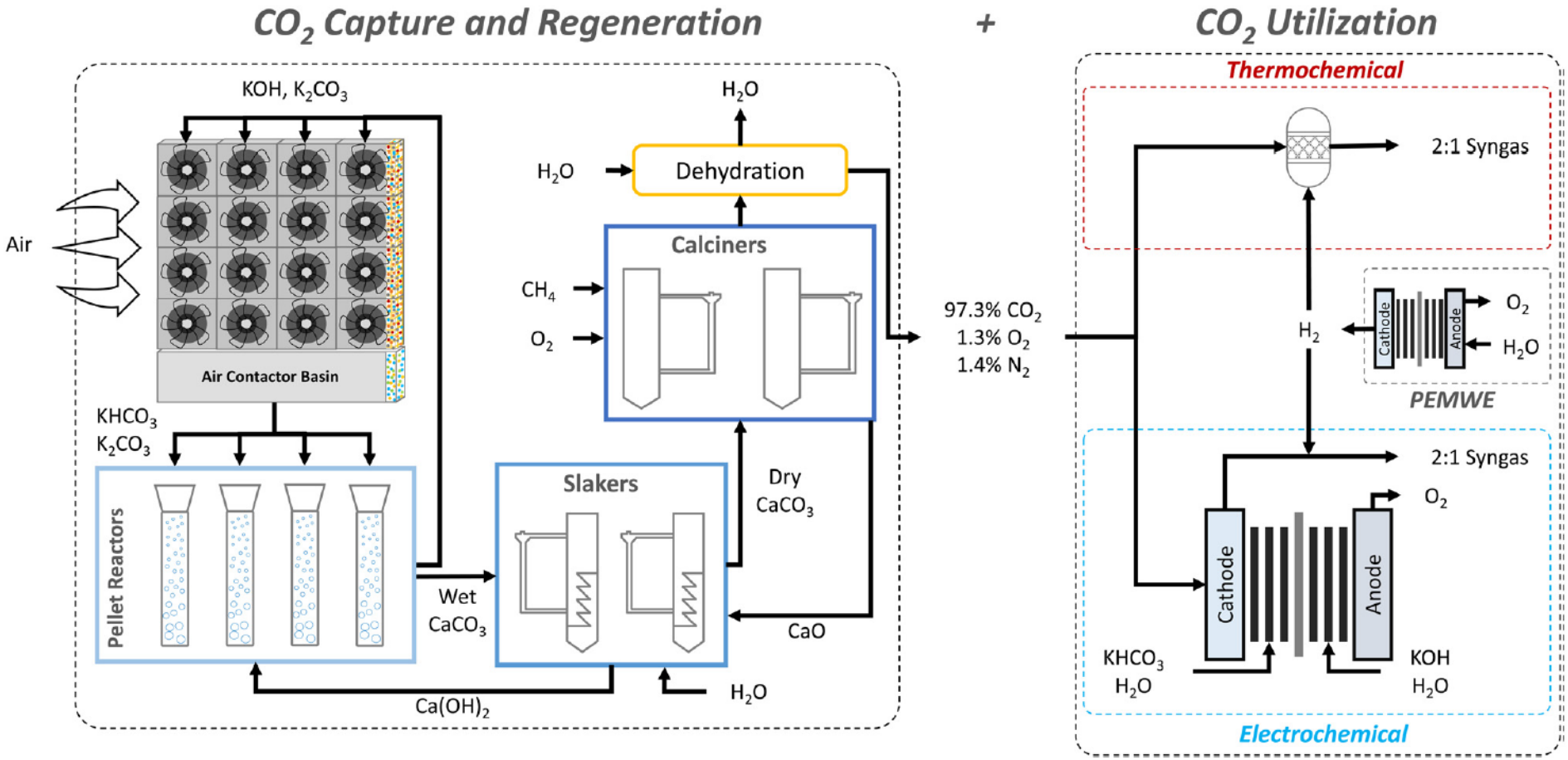





Source: Guerra, Almajed, Smith, Somoza-Tornos, and Hodge, Joule 2023

# Full Syngas Process Flowsheets

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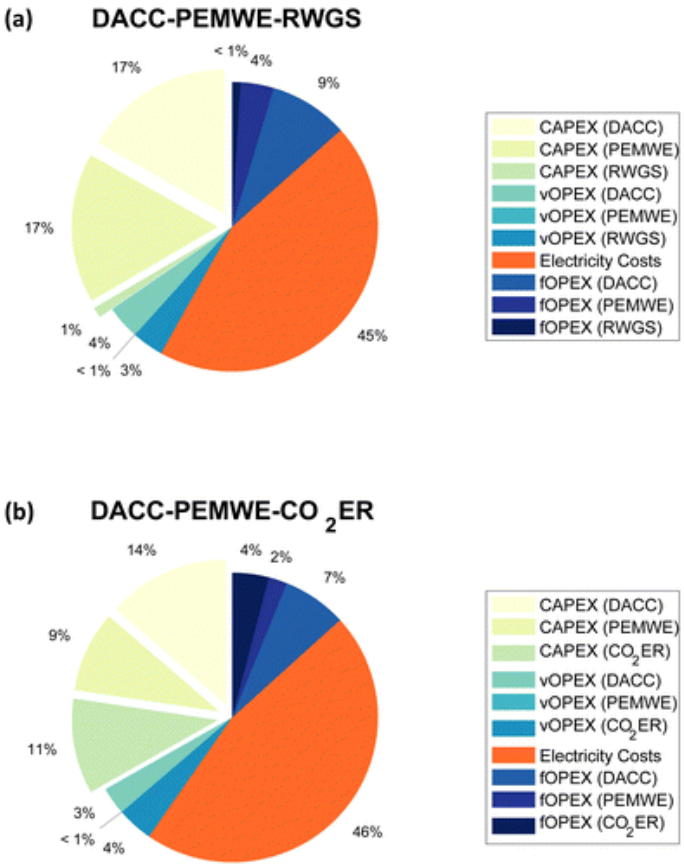
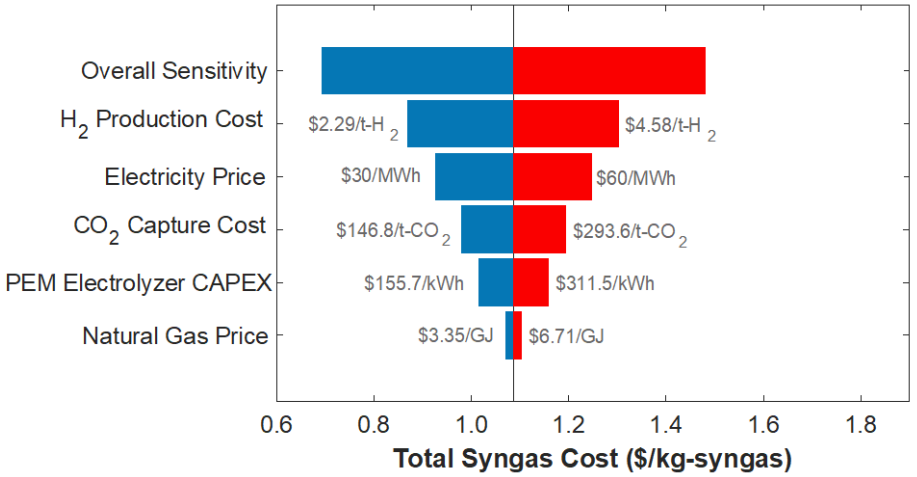
Source: Almajed, Guerra, Smith, Hodge, and Somoza-Tornos, Energy & Environmental Science, 2023

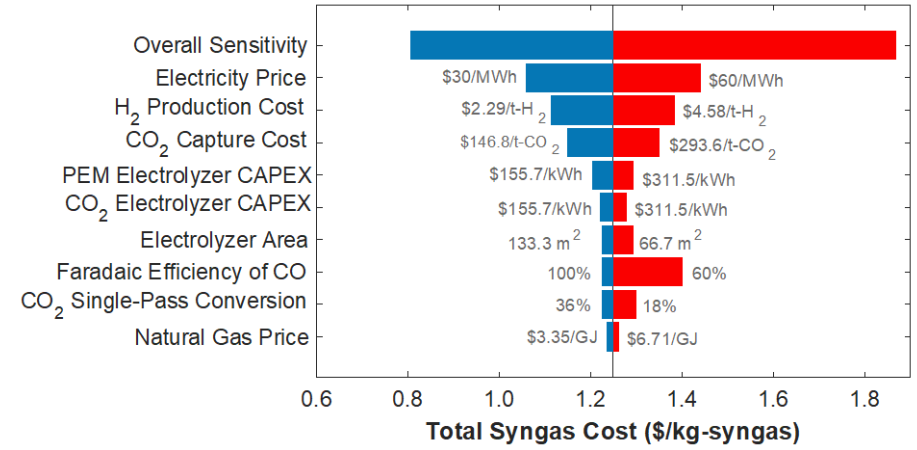
# Cost Comparison vs. RWGS










- **Average annual electricity price** and **electrolytic hydrogen production cost** influence the production cost of air-sourced 2:1 syngas the most

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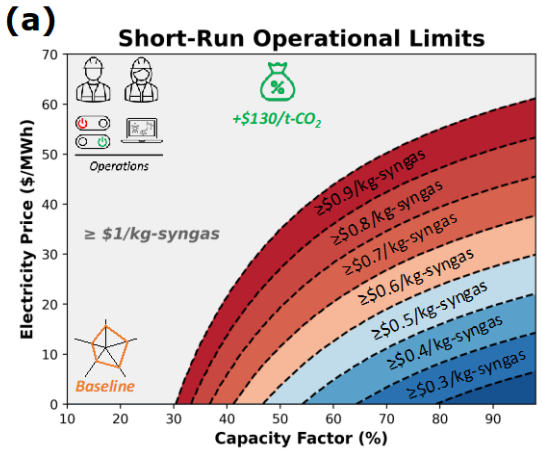
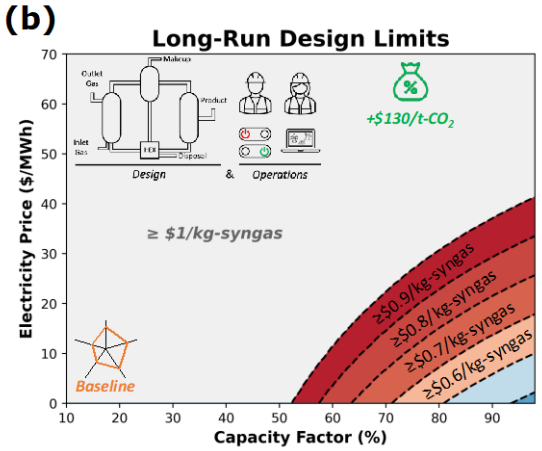
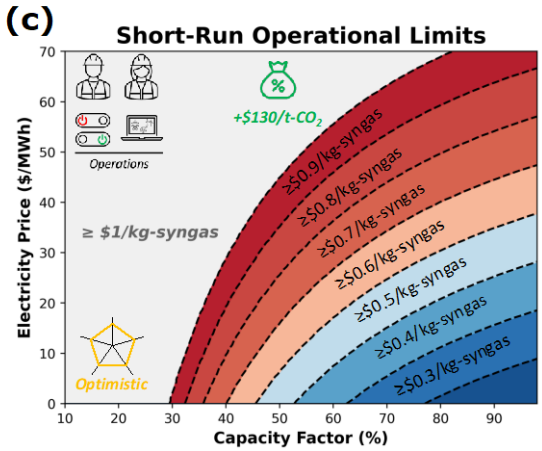
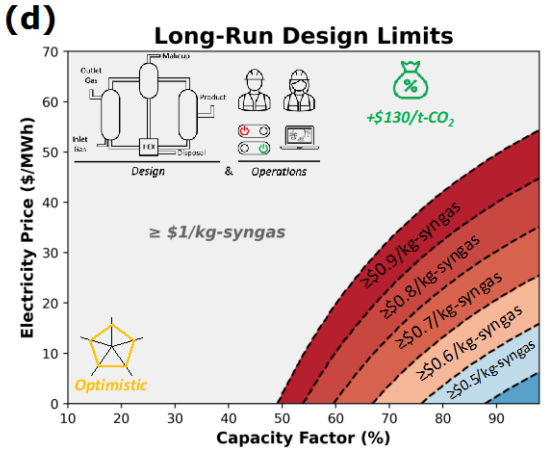
Source: Almajed, Guerra, Smith, Hodge, and Somoza-Tornos, Energy & Environmental Science, 2023

# Air-to-syngas production assessment



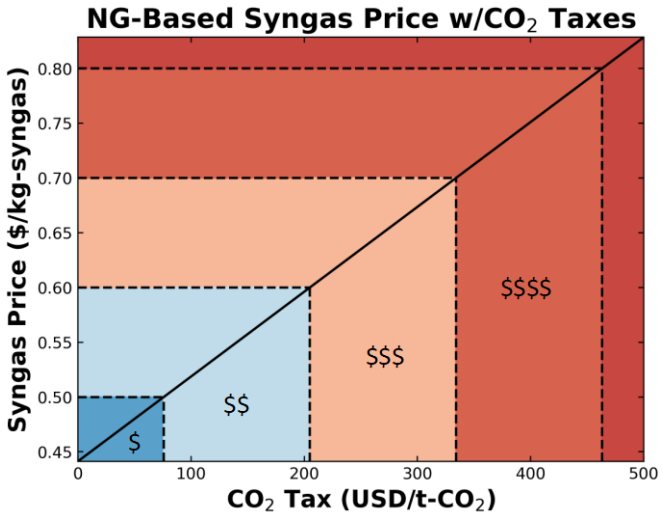




- $CO_2$ taxes on conventional syngas methods
- $CO_2$ tax credits for air-to-syngas pathways

**At $0.6/kg-syngas (*baseline*):**

- Capacity factor of **≥ 48%** (**81%**) *and*
- Average electricity price of **≤ $30/MWh** (**≤ $10/MWh**)

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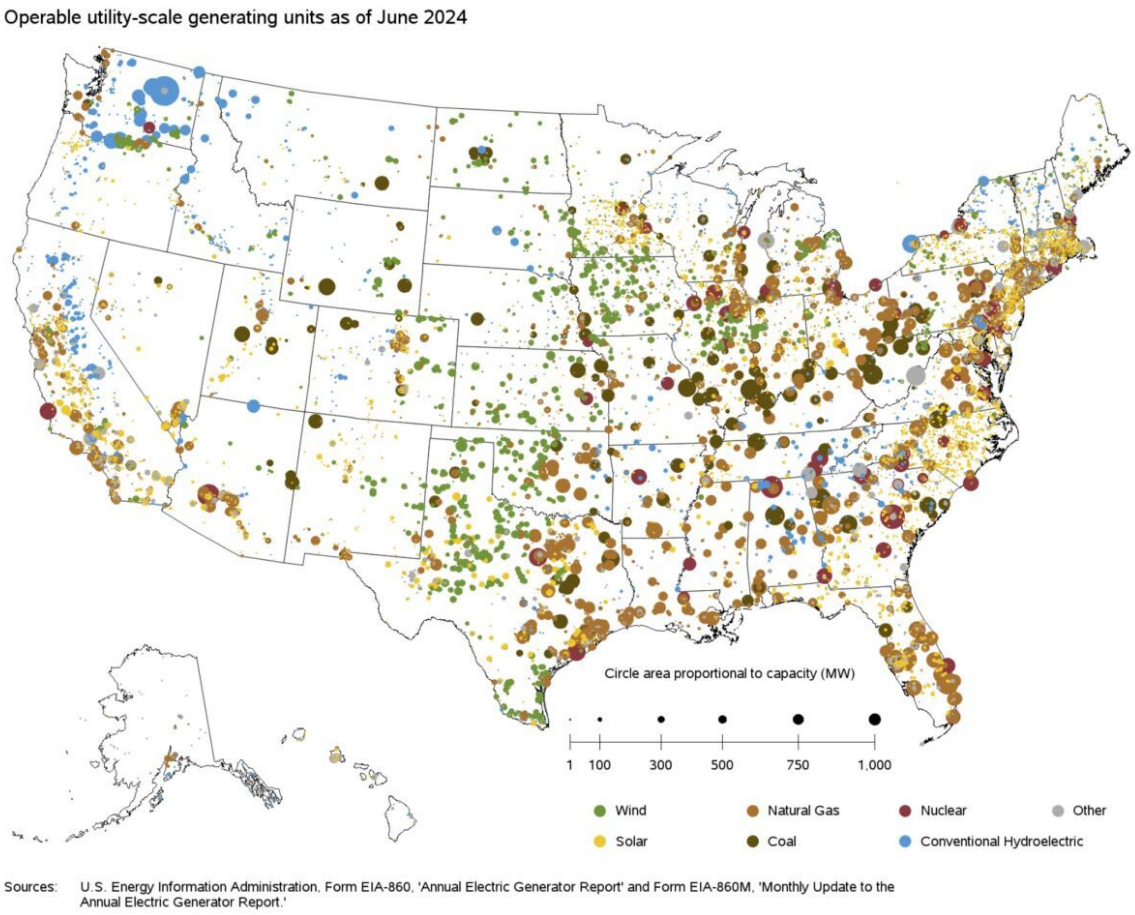
Almajed, Guerra, Somoza-Tornos, Smith, and Hodge. *Sys. & Cont. Trans.*, 2024

# Conclusions

- The energy transition is extremely variable: very advanced in Hawaii and negligible progress in the Southeast
- Suffers from lack of consistent national policy and non-market environments
- Interesting parallels with Europe, re: coordination, lack of clear technological winners for certain sectors




Sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

# Acknowledgments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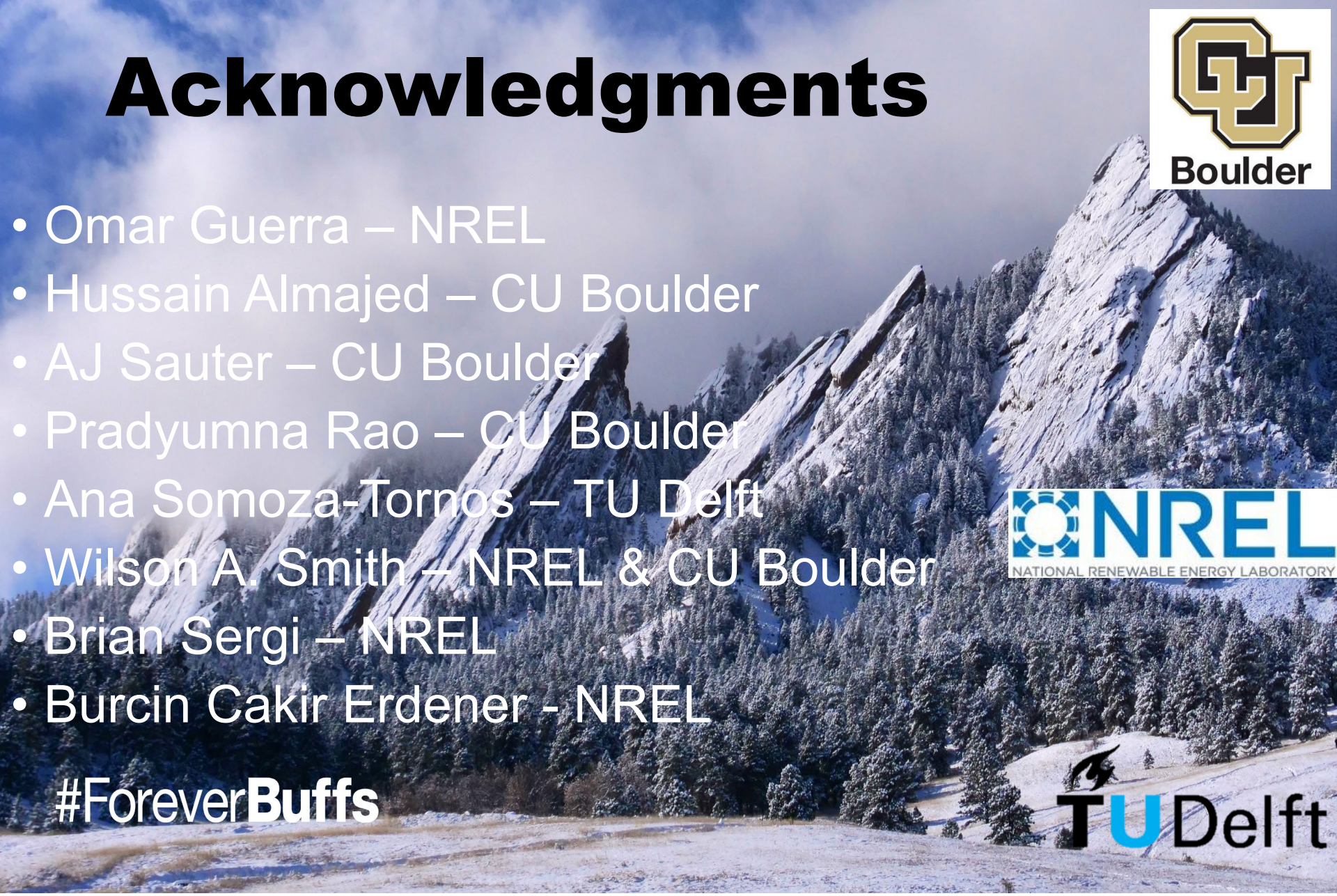
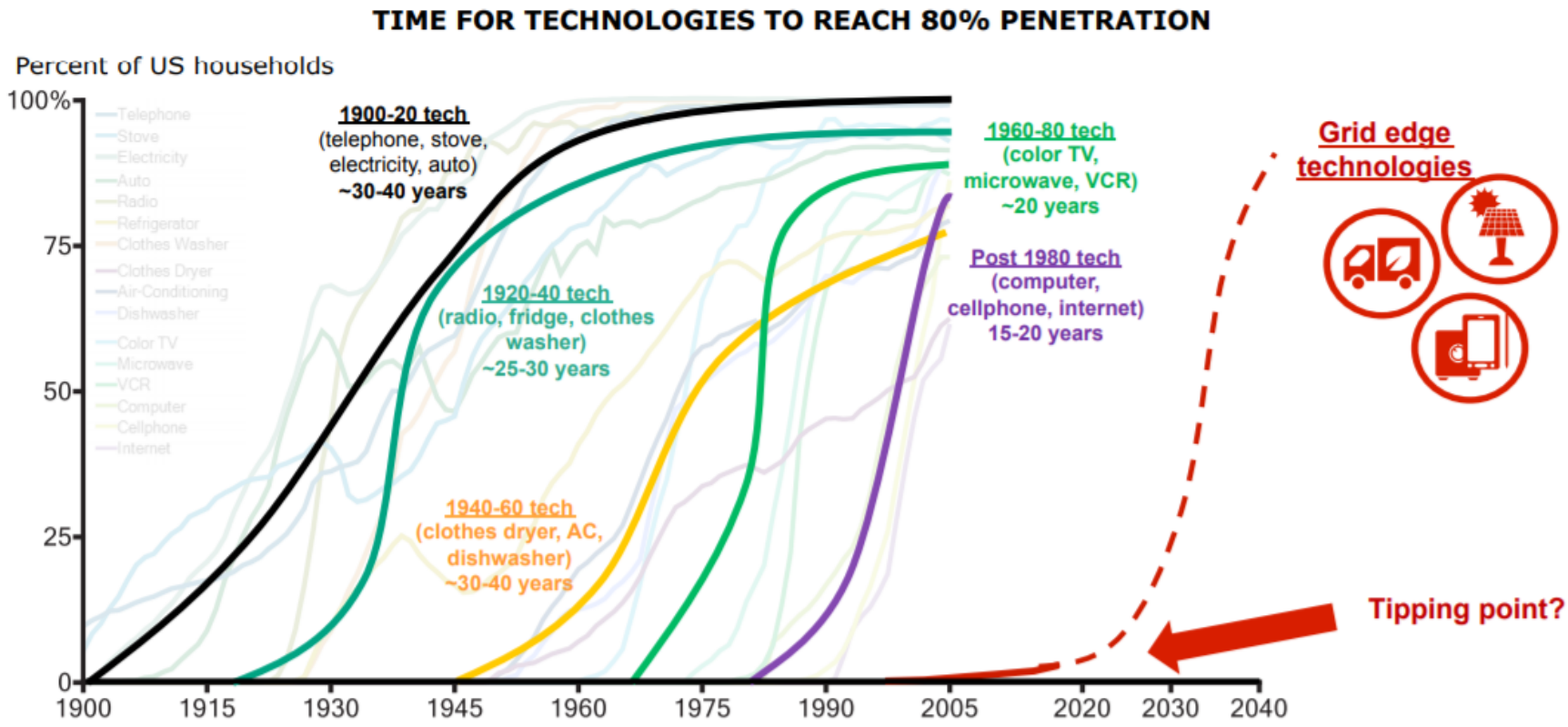
- Ana Somoza-Tornos – TU Delft
- Wilson A. Smith – NREL & CU Boulder
- Brian Sergi – NREL
- Burcin Cakir Erdener - NREL


#ForeverBuffs



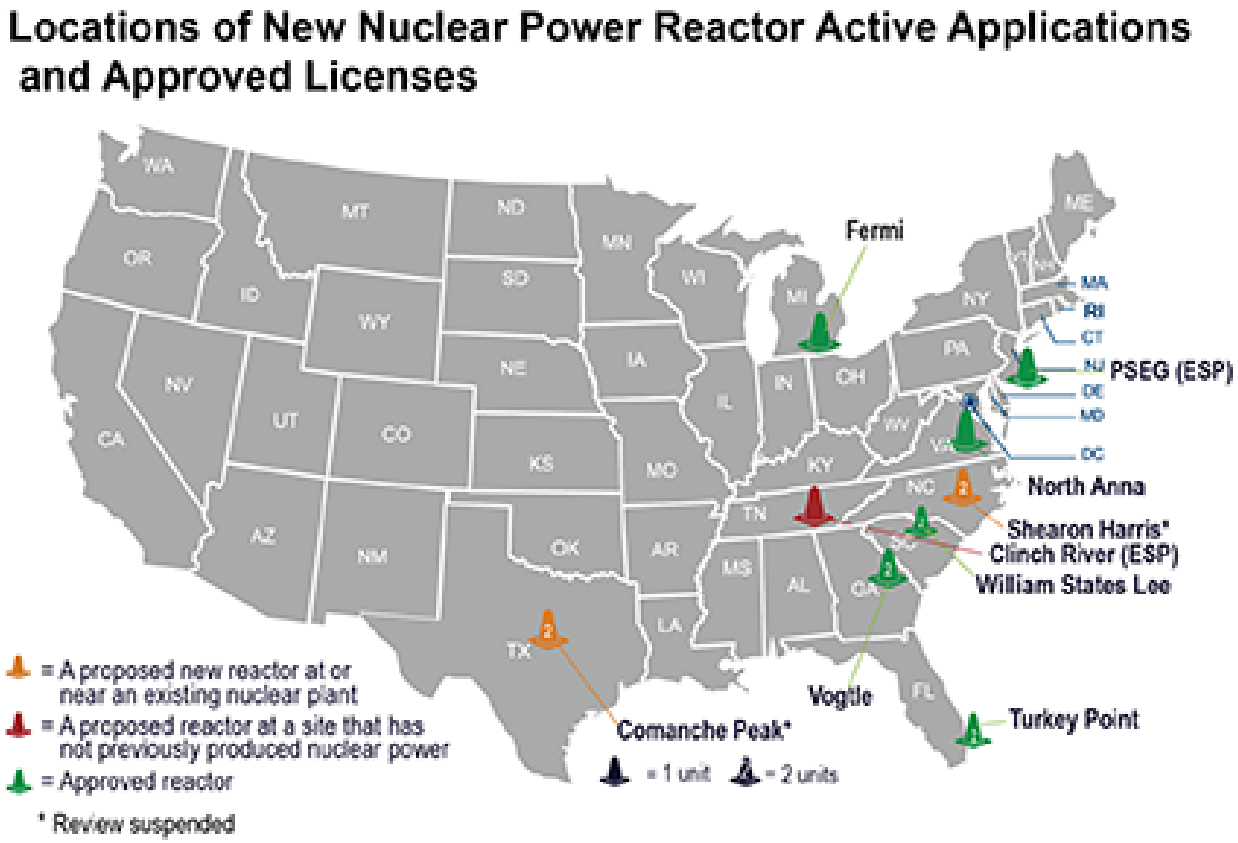

Questions?
#ForeverBuffs

# Tipping Point?

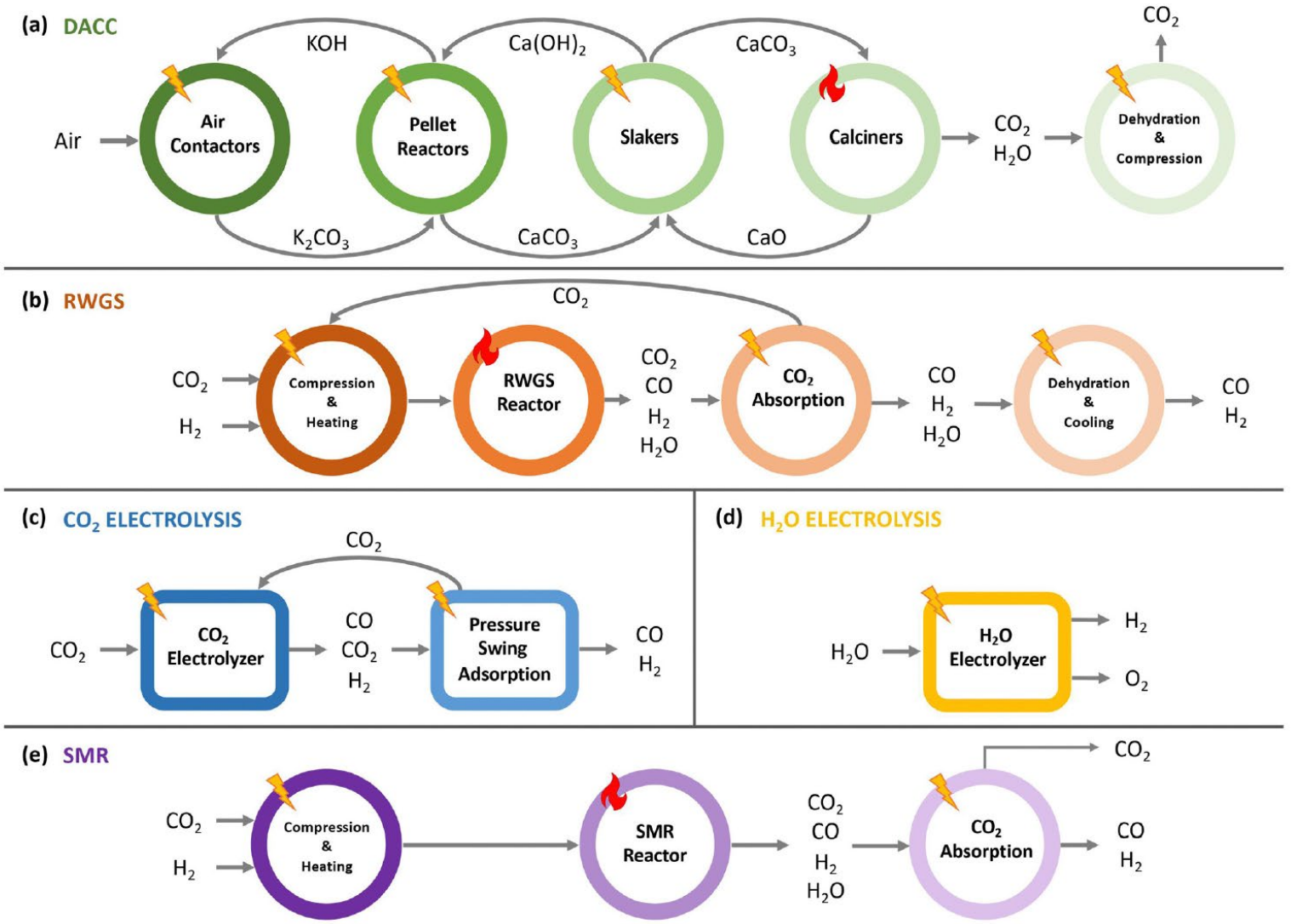



*Source: World Economic Forum and New York Times*

# New Nuclear?


Locations of New Nuclear Power Reactor Active Applications and Approved Licenses
WA
OR
CA
ID
NV
MT
WY
UT
AZ
CO
NM
ND
SD
NE
KS
OK
TX
MN
IA
MO
AR
LA
WI
IL
MS
MI
IN
KY
TN
AL
OH
WV
GA
FL
SC
NC
VA
PA
NY
ME
VT
NH
MA
RI
CT
NJ
DE
MD
DC
Fermi
PSEG (ESP)
North Anna
Shearon Harris*
Clinch River (ESP)
William States Lee
Vogtle
Turkey Point
Comanche Peak*
= A proposed new reactor at or near an existing nuclear plant
= A proposed reactor at a site that has not previously produced nuclear power
= Approved reactor
= 1 unit
= 2 units
* Review suspended
Note: Alaska and Hawaii are not pictured but have no sites. On July 31, 2017, South Carolina Electric and Gas announced its decision to cease construction on V.C. Summer Units 2 and 3, and the licensee has requested that the COLs be withdrawn. As of October 2017, Duke Energy has announced plans to cancel reactors at Levy County, Florida, and William States Lee, South Carolina. Applications were withdrawn for Calvert Cliffs, Grand Gulf, Nine Mile Point, Victoria County, and Callaway (COL and ESP). In June 2018, Nuclear Innovation North America submitted a letter requesting that the COLs for South Texas Project Units 3 and 4 be withdrawn. NRC-abbreviated reactor names are listed.
Data are current as of September 2022. For the most recent information, go to the NRC website at https://www.nrc.gov.
Source: U.S. Nuclear Regulatory Commission - As of February 2023

# $CO_2$ Electrolysis vs. Traditional Route

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Source: Almajed, Guerra, Smith, Hodge, and Somoza-Tornos, Energy & Environmental Science, 2023