# Energy Innovation and the Road to Net-Zero

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NET-ZERO AMERICA

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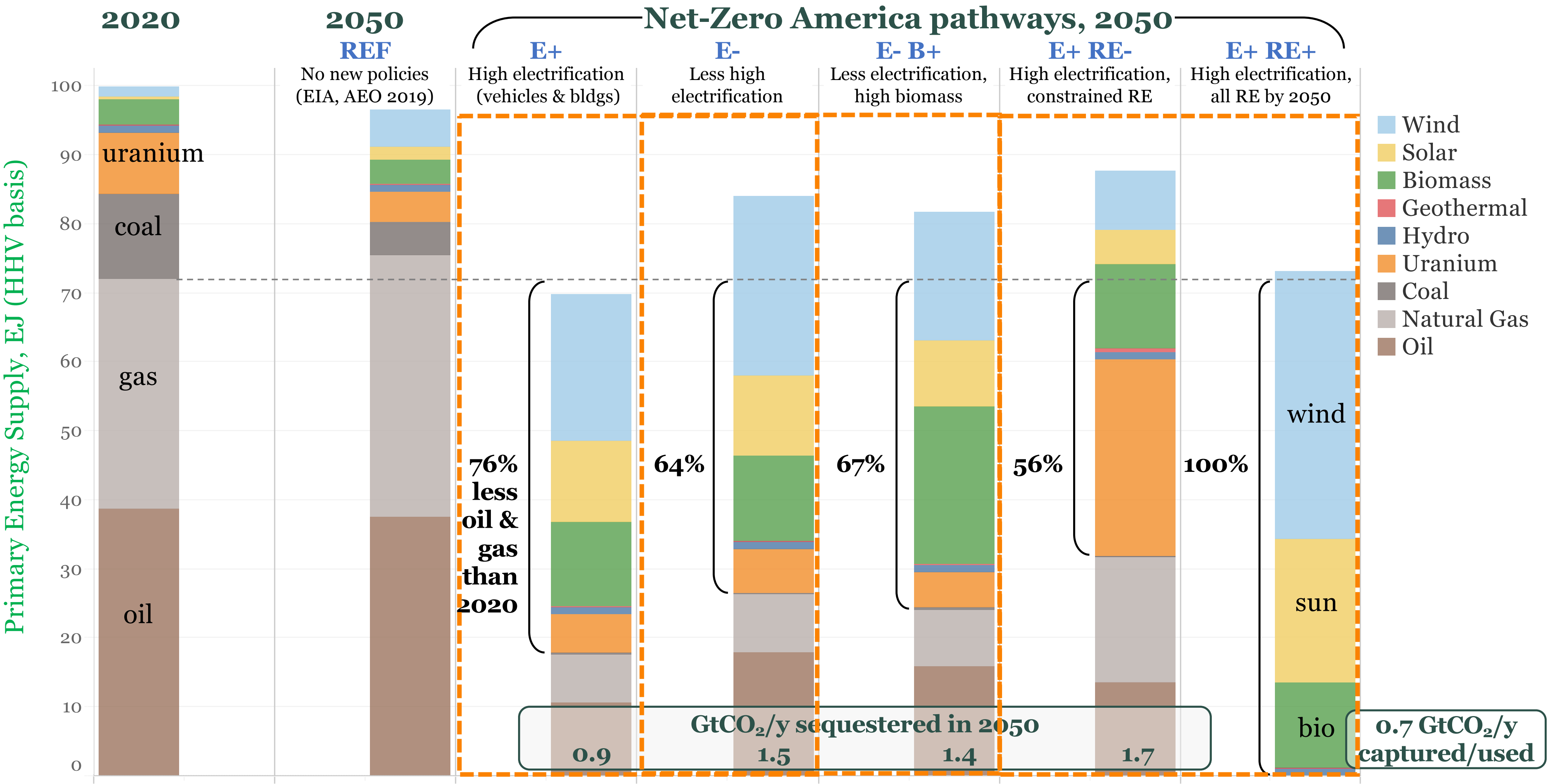
# NET-ZERO AMERICA:

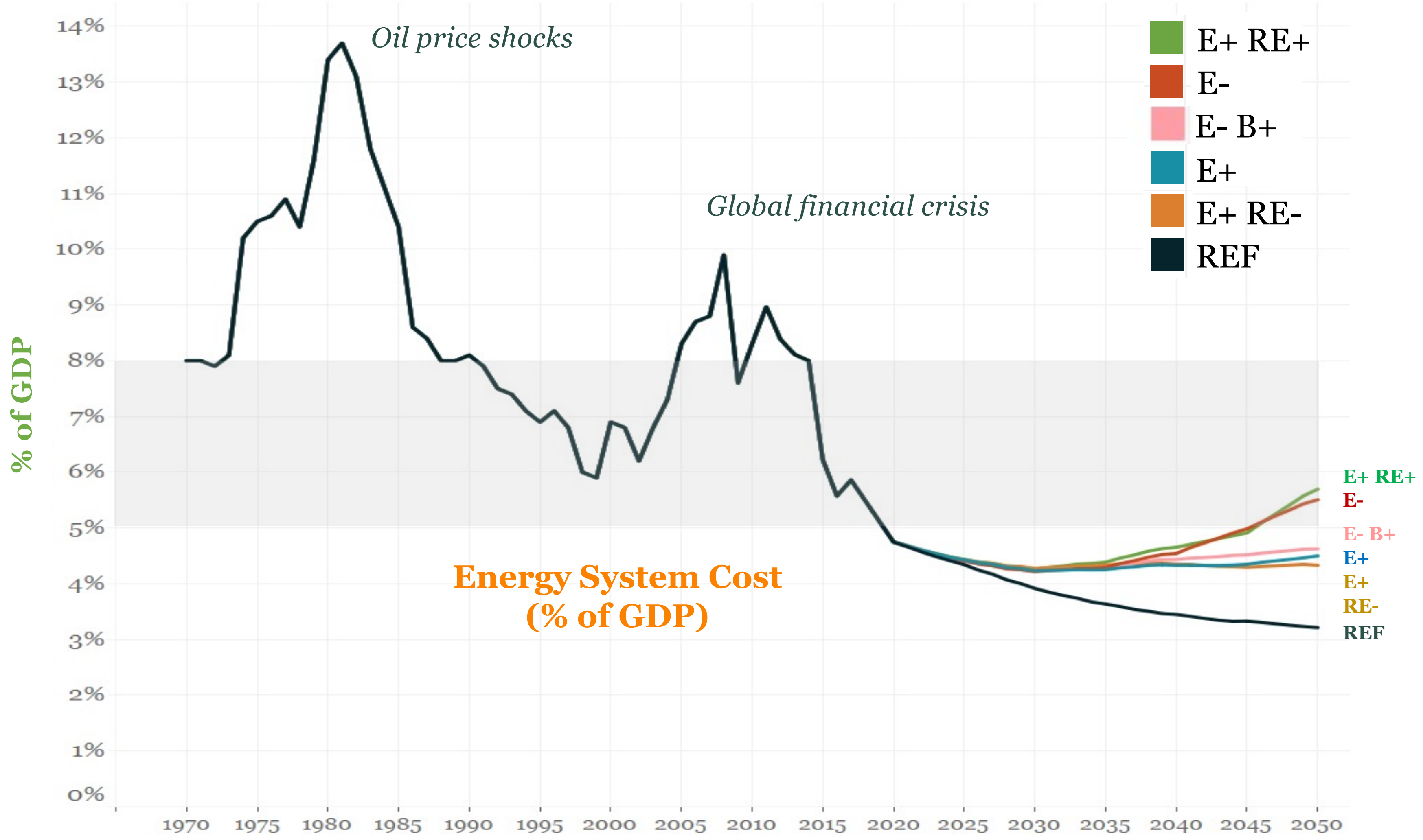
## Potential Pathways, Infrastructure, and Impacts

https://netzeroamerica.princeton.edu/

# FIVE MODELED PATHS TO NET-ZERO IN 2050



# TRANSFORMATIVE BUT AFFORDABLE



# USING SOLUTIONS AT HIGH TECHNOLOGY READINESS LEVEL


**TRL9 (Commercially mature):**
e.g. wind, solar PV, Li-ion batteries, electric vehicles, heat pumps, building efficiency

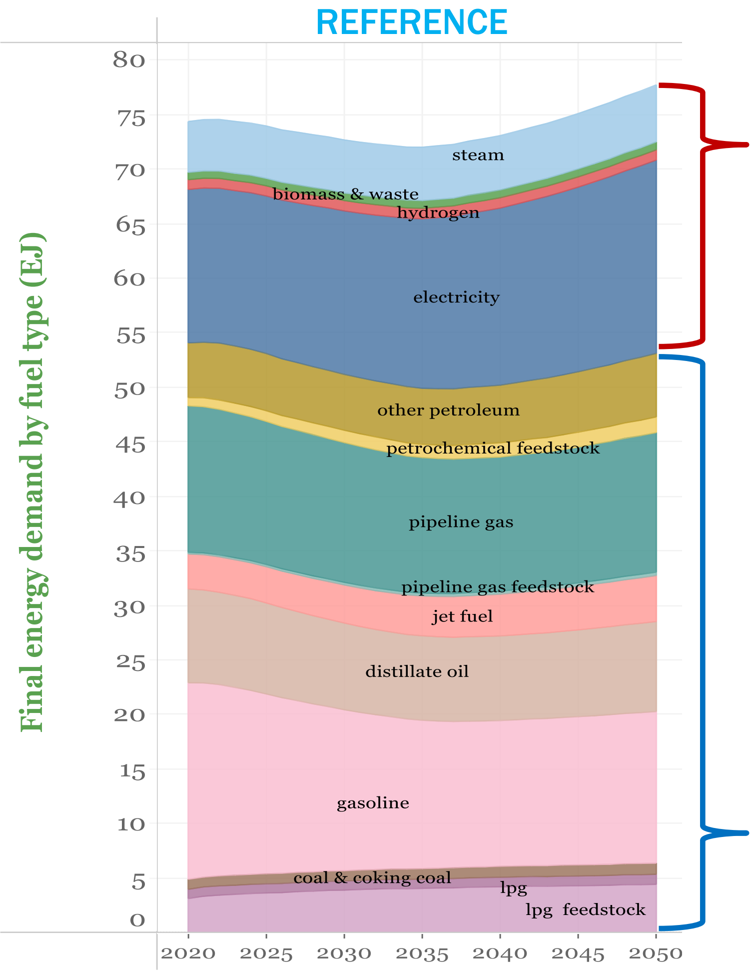
**TRL 7-8 (Commercial-scale demonstration):**
e.g. electrolysis, post-combustion $CO_2$ capture, geologic $CO_2$ storage, F-T fuels production

**TRL 6-7 (Pilot stage):**
e.g. oxyfuel Allam-cycle, biomass gasification, direct air capture, hydrogen combustion turbines

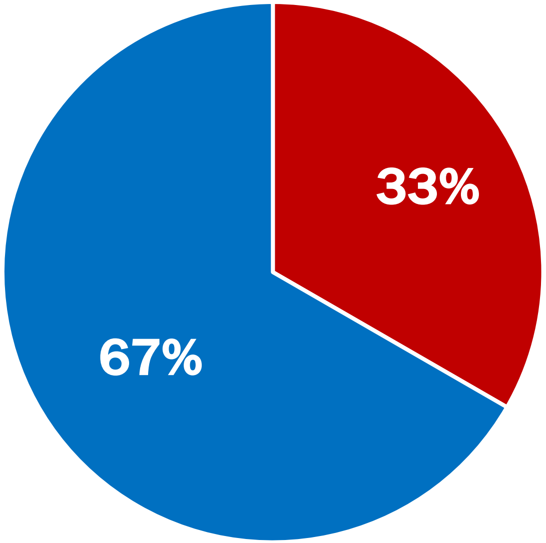
# BUILDING BLOCKS OF A NET-ZERO EMISSIONS ECONOMY

1. Efficiency & Electrification
2. Clean Electricity
3. Net-Zero Carbon Fuels
4. $CO_2$ Capture, Use & Storage

# SIZING UP THE CHALLENGE

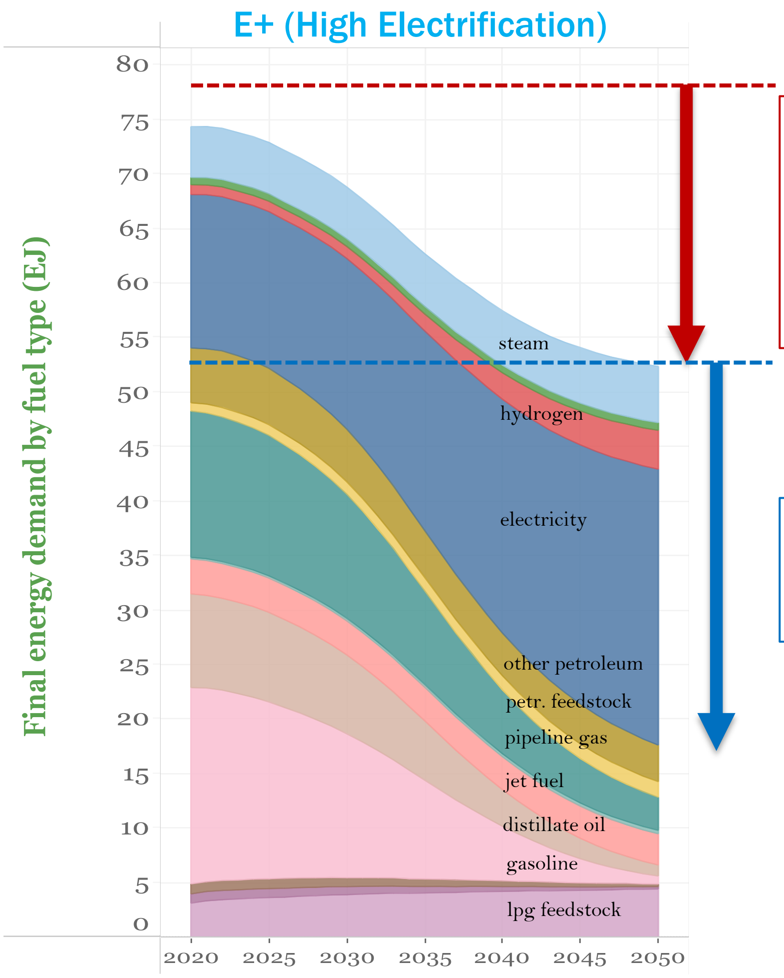



Demand for non-hydrocarbon final energy demands could be satisfied with **zero carbon electricity**




**Demand for hydrocarbons;** too large to meet with biofuels or offset with negative emissions.

# 1. KNOCKING IT DOWN TO SIZE: EFFICIENCY & ELECTRIFICATION




**32% reduction in total final energy demand**

Same-fuel efficiency: 8 EJ

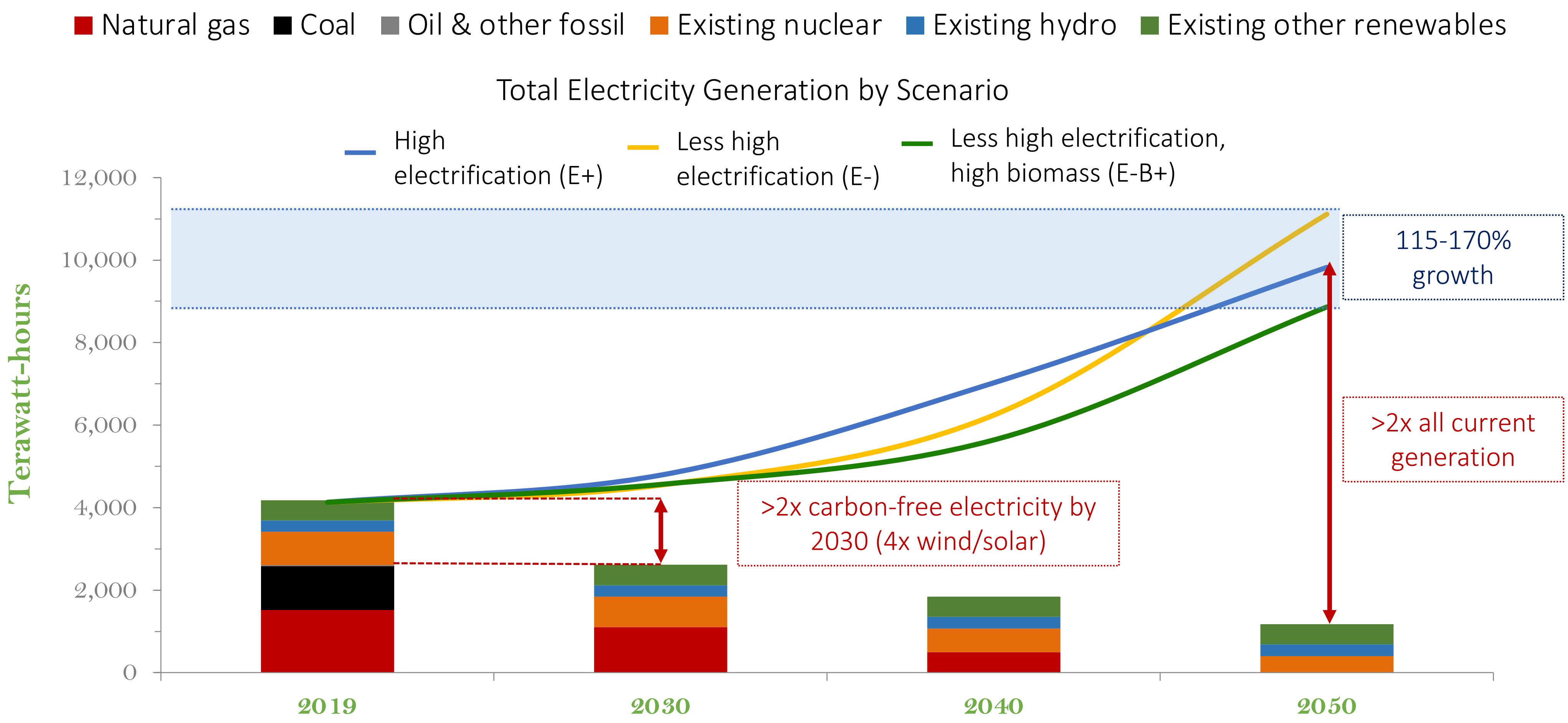
Electrification: 13 EJ

Oil refining (demand reduction): 4 EJ

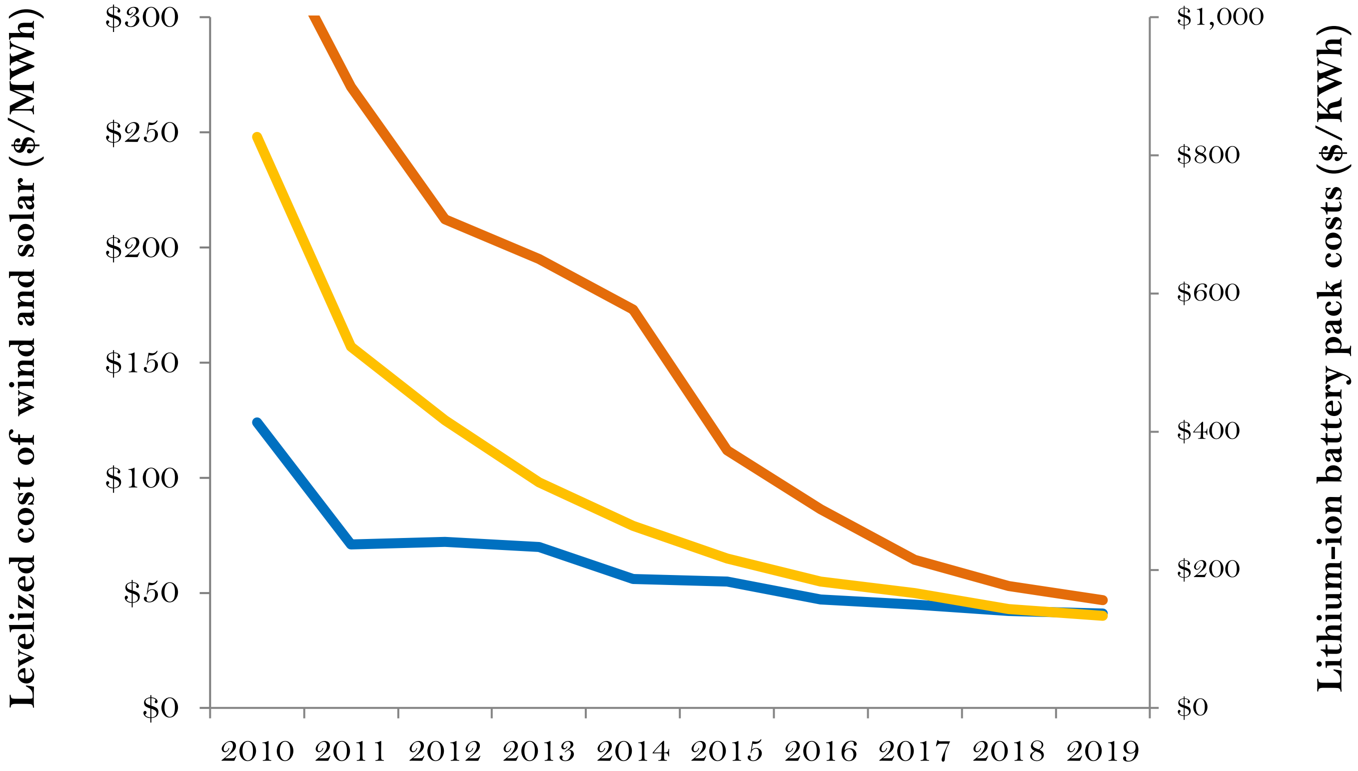
**68% reduction in hydrocarbon fuel demand**

36 EJ less demand for liquids & gaseous fuels

# 2. CLEAN ELECTRICITY: LINCHPIN FOR A NET-ZERO ECONOMY



# THE GOOD NEWS: WIND, SOLAR, BATTERY COSTS PLUMET




**Total cost declines (2010-2019)**

Utility Solar PV $/MWh -84%

Onshore Wind $/MWh -67%

Li-ion packs $/KWh -87%

Data Sources: Wind & solar costs from Lazard (2019), Lazard's Levelized Cost of Energy Analysis – Version 13.0.
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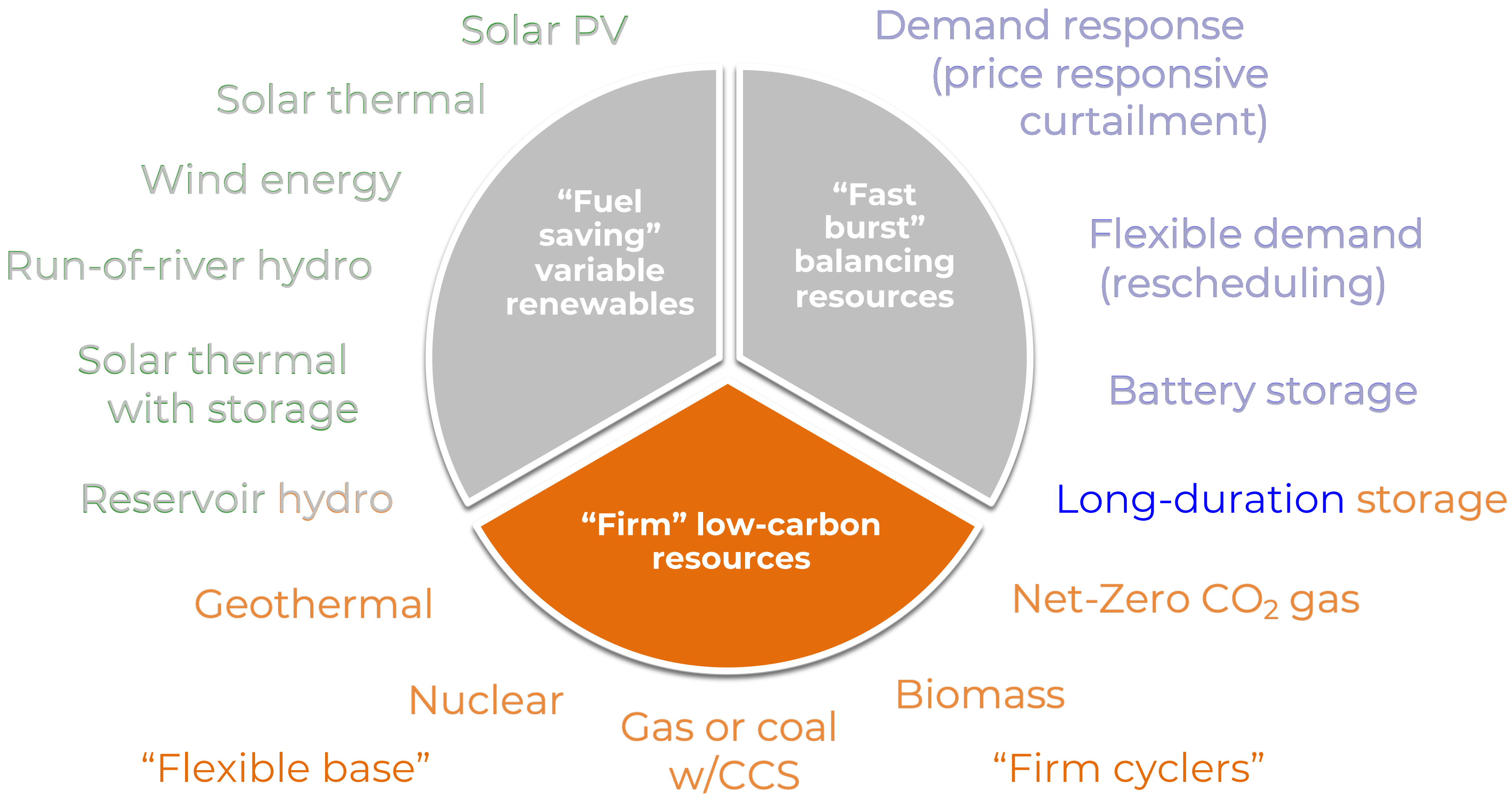
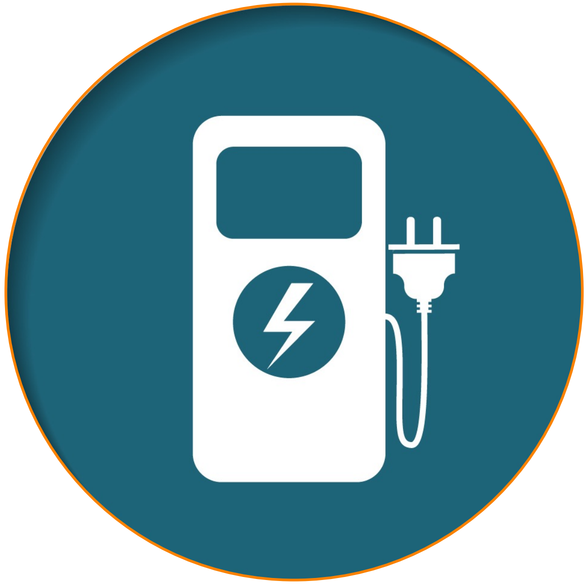
# WE NEED TO COMPLETE THE BALANCED DIET



# 3. NET-ZERO CARBON FUELS

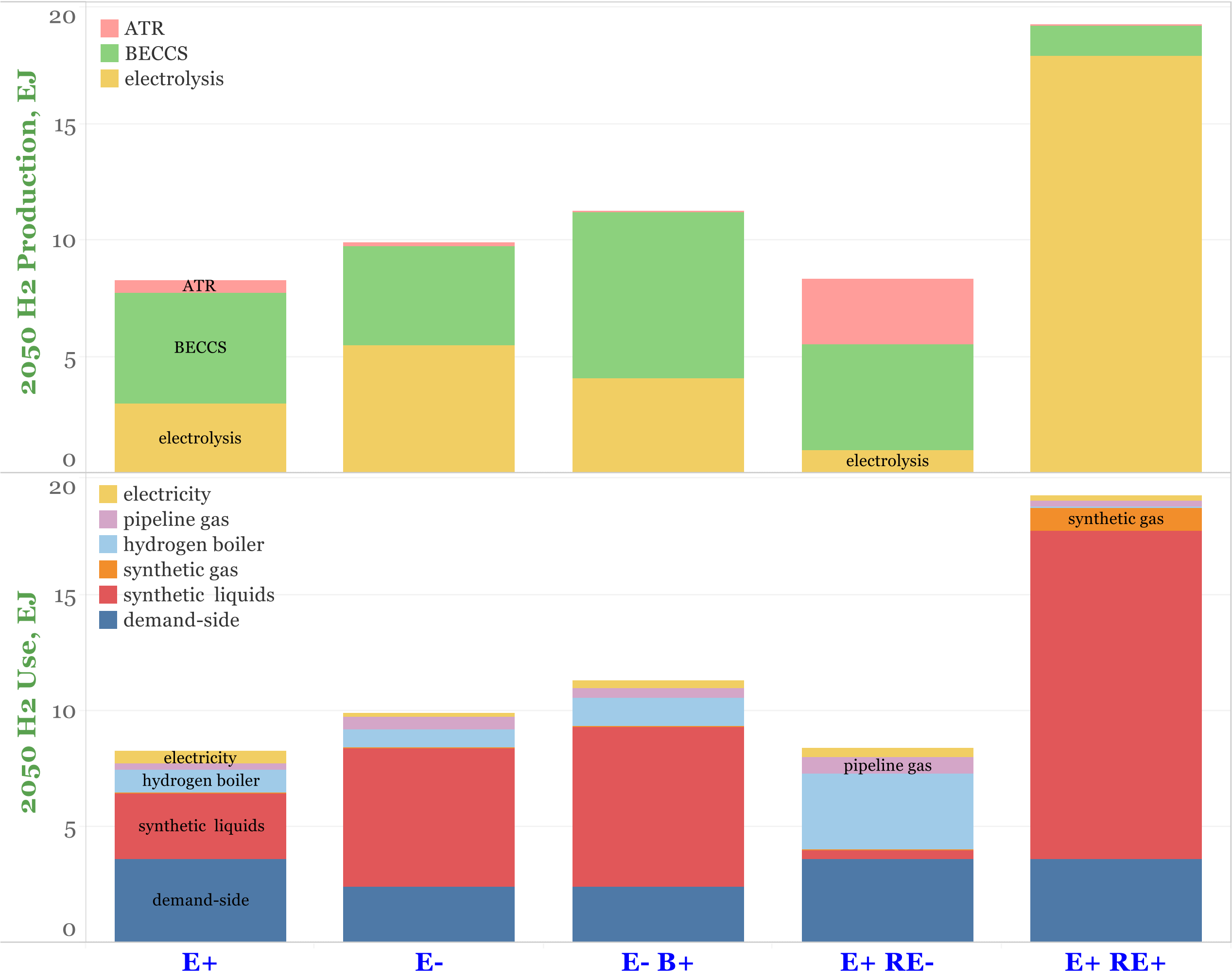
1. **Hydrogen made from a variety of sources**: biomass, NG w/CCS, or electrolysis and used directly or as hythane (blend of $H_2$ + $CH_4$)



2. **Drop-in synthetic liquid & gaseous fuels** made from biomass or synthesized from $H_2$ + captured $CO_2$

3. **Fossil-derived fuels with negative emissions offsets** from biomass w/CCS or direct air capture

# HYDROGEN: A CRITICAL ZERO-CARBON ENERGY CARRIER & FUEL




## $H_2$ sources

**ATR** = autothermal reforming of natural gas with $CO_2$ capture.

**BECCS** = biomass gasification to $H_2$ with $CO_2$ capture (negative net emissions).

**Electrolysis** = water splitting using electricity.

## $H_2$ uses

**Electricity** = $H_2$ burned in gas turbines in high "hythane" blend with $CH_4$ (60% limit by energy).

**Pipeline gas** = $H_2$ used for "hythane" blend in $CH_4$ pipelines (7% limit by energy).

**$H_2$ boiler** = industrial steam generation.

**Synthetic gas** = $CH_4$ synthesis from $H_2$ and $CO_2$.

**Synthetic liquids** = Fischer Tropsch fuels from $H_2$ + $CO_2$.

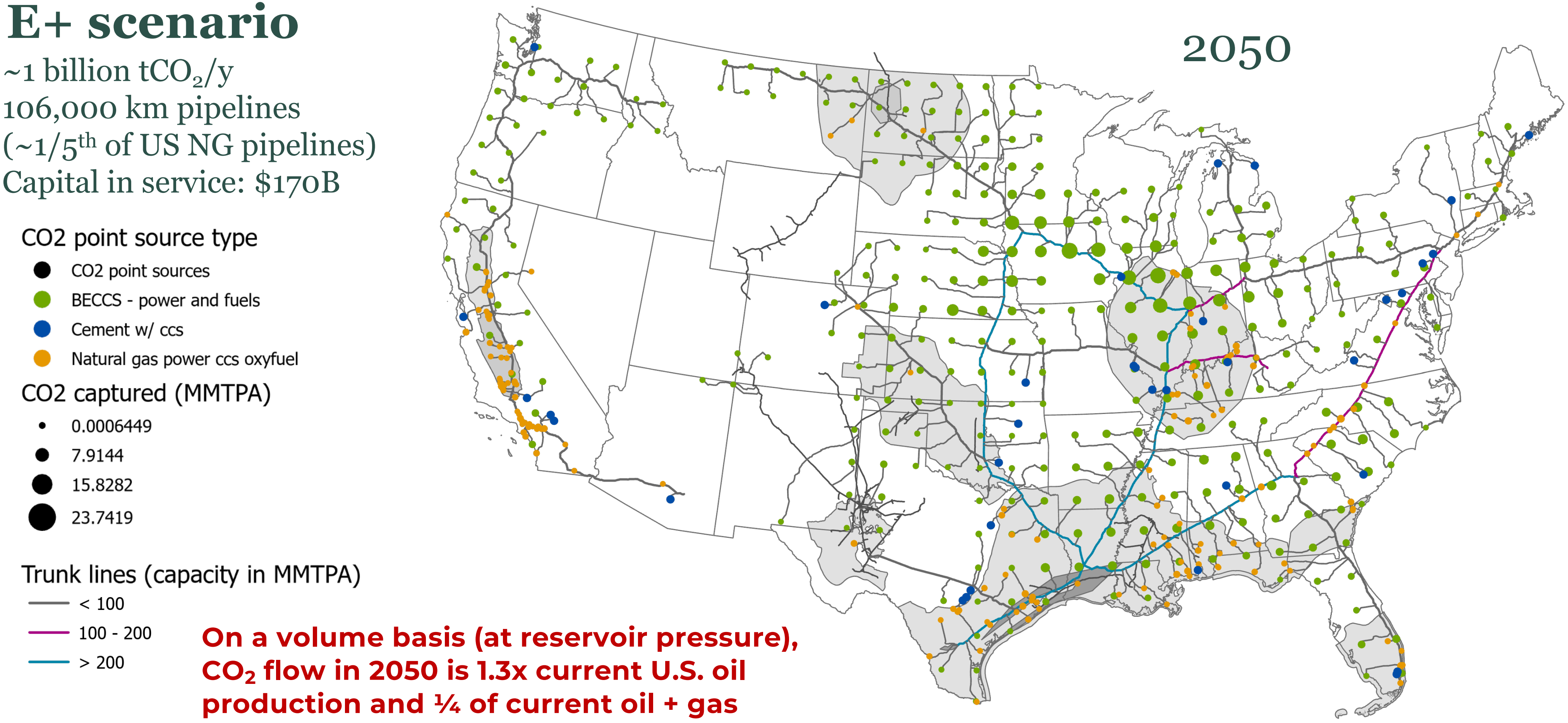
**Demand side** = $H_2$ used in transport and for production of chemicals, direct-reduced iron, and process heat in various industries.

*Note*: All fuel values reported in this slide pack are on HHV basis.

# 4. CO2 CAPTURE, STORAGE & USE: AT THE GIGATON SCALE

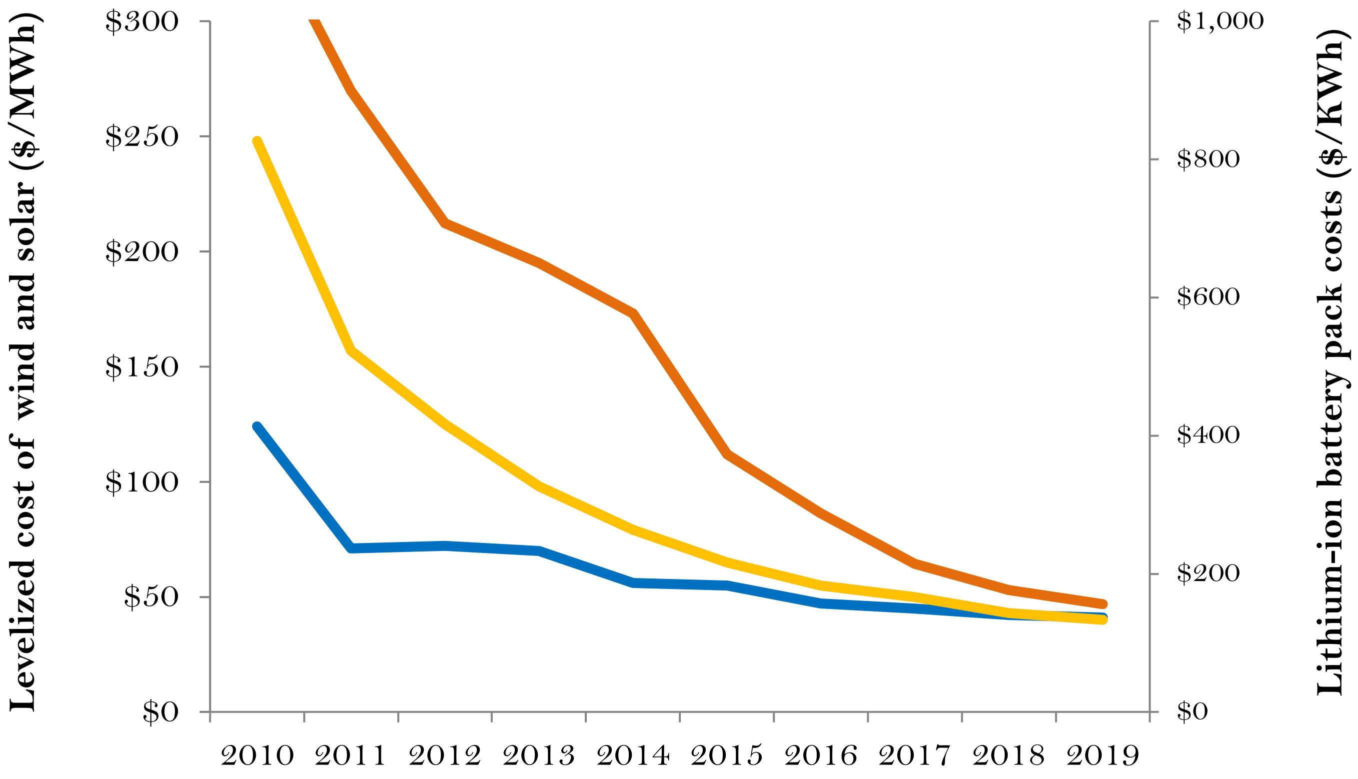
## E+ scenario

~1 billion $tCO_2/y$
106,000 km pipelines
(~1/5th of US NG pipelines)
Capital in service: $170B




**On a volume basis (at reservoir pressure), $CO_2$ flow in 2050 is 1.3x current U.S. oil production and ¼ of current oil + gas production.**

# FROM “ALTERNATIVE ENERGY” TO *REAL* OPTIONS

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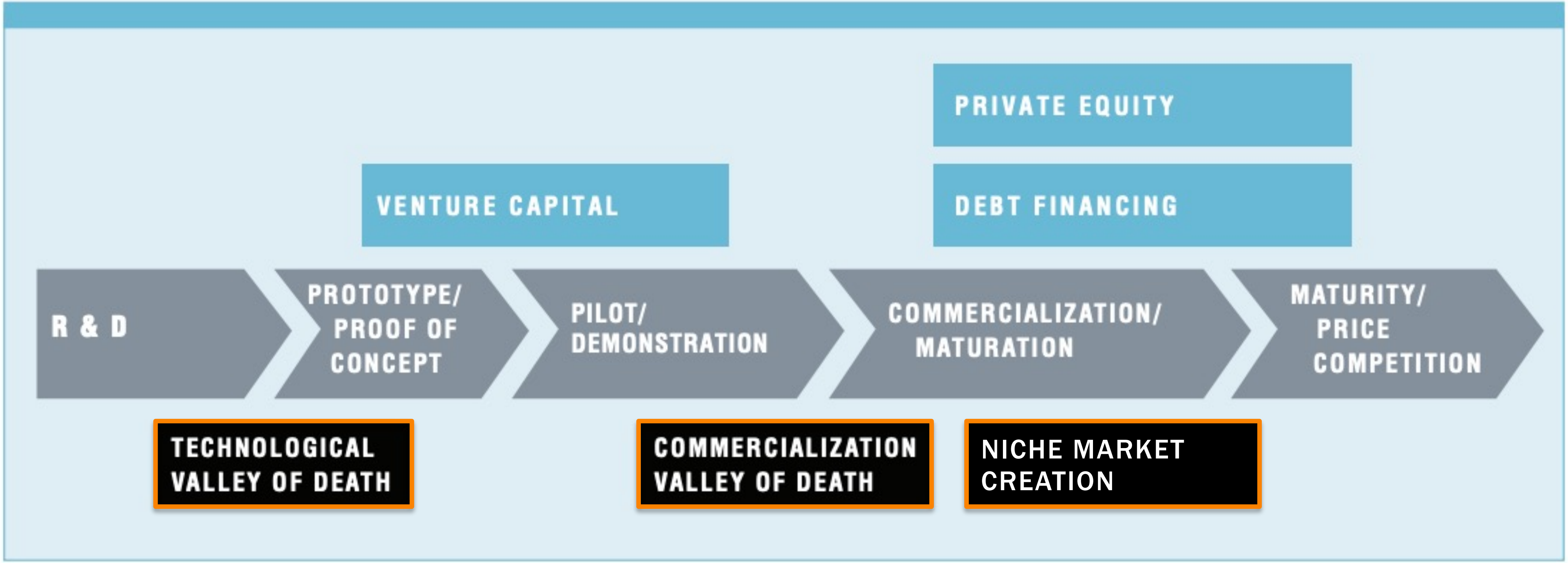
# THE 2020s: A DECADE TO COMPLETE THE NET-ZERO TOOLKIT

- ❑ **Clean firm electricity resources**: advanced nuclear, advanced geothermal, fossil and biomass with $CO_2$ capture (especially Allam cycle), low-NOx 100% hydrogen combustion turbines & fuel cells; long duration energy storage.
- ❑ **Hydrogen production** via electrolysis, natural gas reforming with $CO_2$ capture, and biomass gasification with $CO_2$ capture.
- ❑ **$CO_2$ capture** in a range of industrial applications, including cement, ammonia, biofuels, and hydrogen.
- ❑ **Synthesis of fuels from biomass and $H_2$ + $CO_2$**, including methane and liquid hydrocarbons (e.g., Fischer-Tropsch fuels).
- ❑ **Direct hydrogen-reduced iron** and other carbon-free alternatives for primary steel production.
- ❑ **High-yield bioenergy crops** such as miscanthus.
- ❑ **Direct air capture** methods.
- ❑ **Technology innovation to reduce siting challenges**.

# THE FORMULA FOR AMERICAN INNOVATION




See Jenkins & Mansur (2011), "Bridging the Clean Energy Valleys of Death: Helping American Entrepreneurs Meeting the Energy Innovation Imperative"
https://thebreakthrough.org/articles/bridging-the-clean-energy-vall

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# RESOURCES


- Princeton University *Net-Zero America* Study: http://netzeroamerica.princeton.edu
- Jenkins & Sepulveda (2021), "Long duration energy storage: a blueprint for research and innovation," *Joule*, 5(9): 2241-2246 https://bit.ly/LDES_Joule
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