Options to Decarbonize our Energy System

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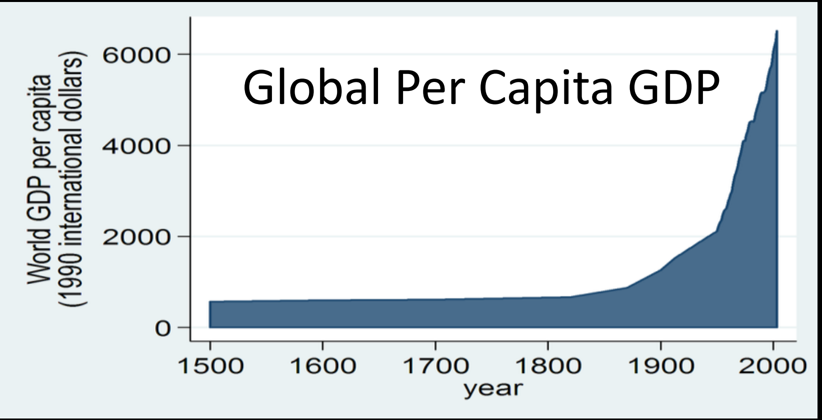
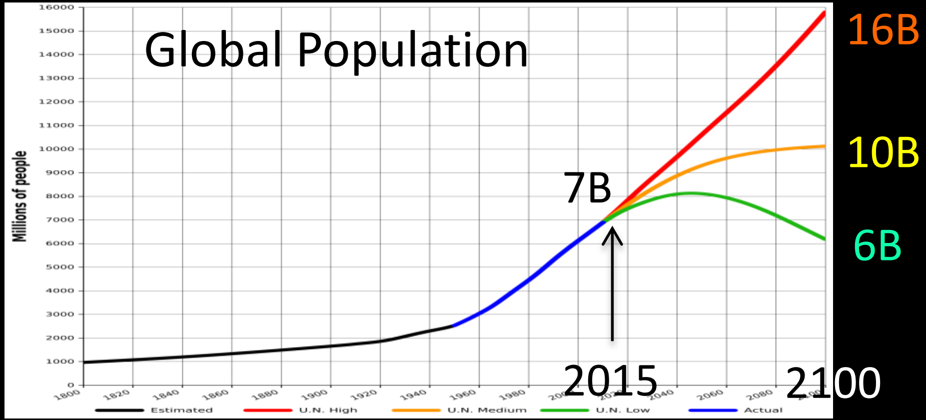
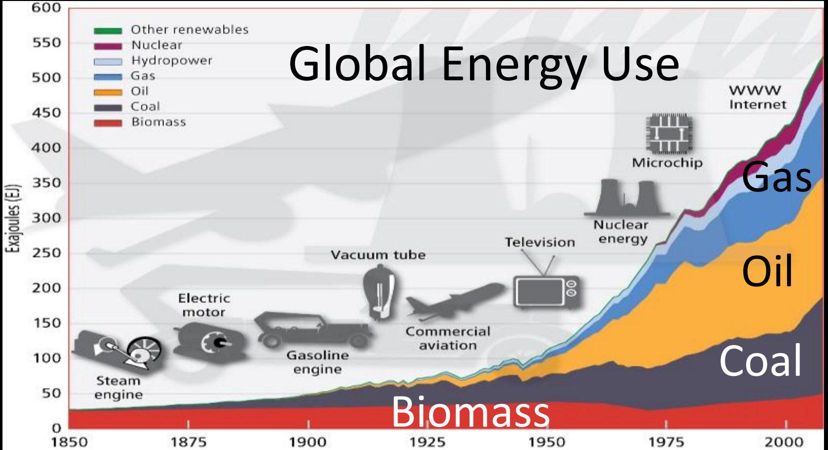
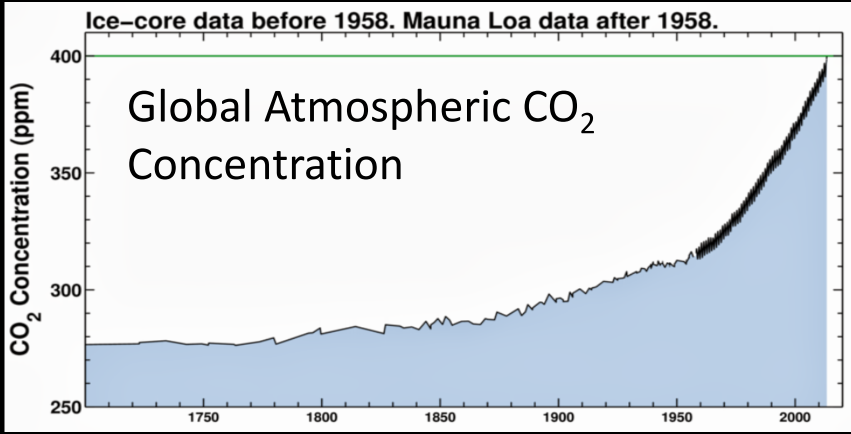
Global Exponentials

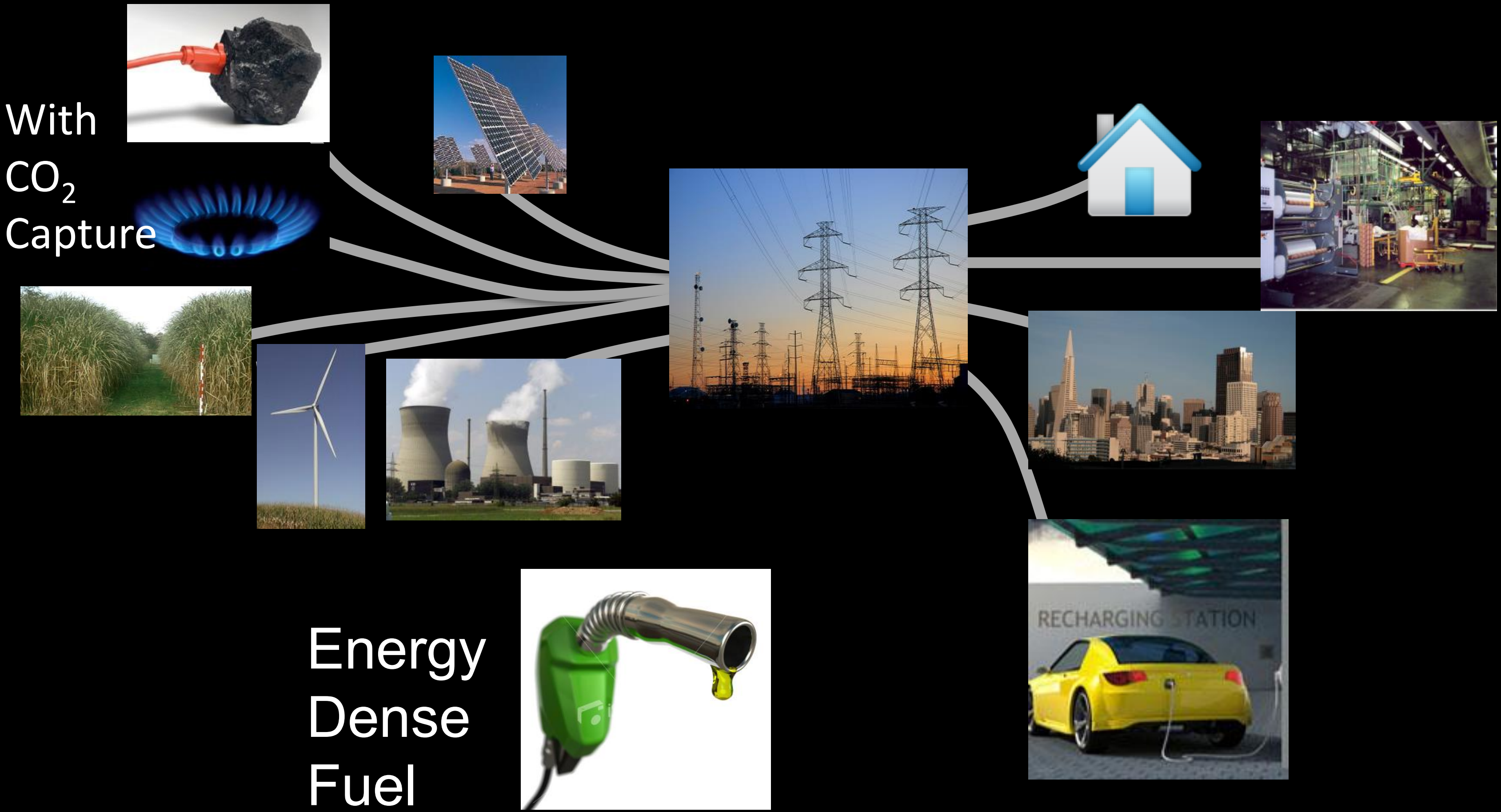






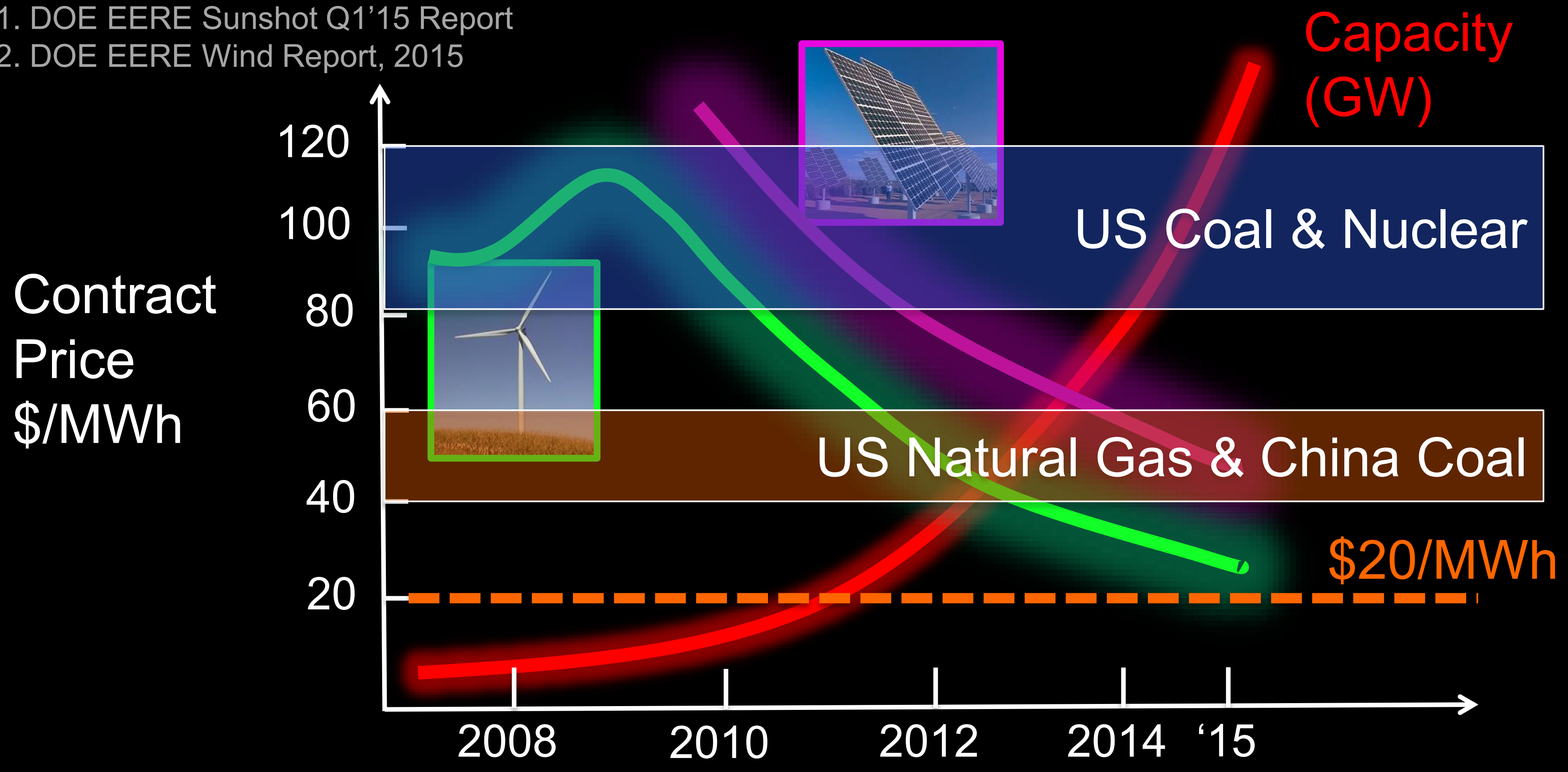


How can we decarbonize our energy system and continue economic growth?


With CO_2 Capture
Energy Dense Fuel
RECHARGING STATION

Carbon-Free Electricity

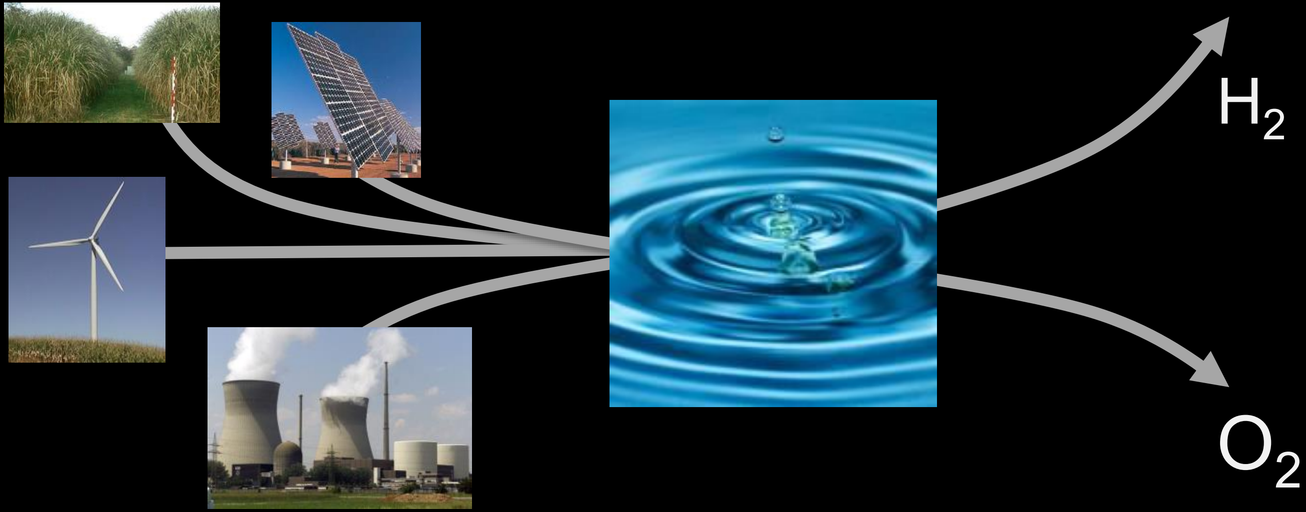
Source
1. DOE EERE Sunshot Q1'15 Report
2. DOE EERE Wind Report, 2015



Why Hydrogen?

About $100B industry

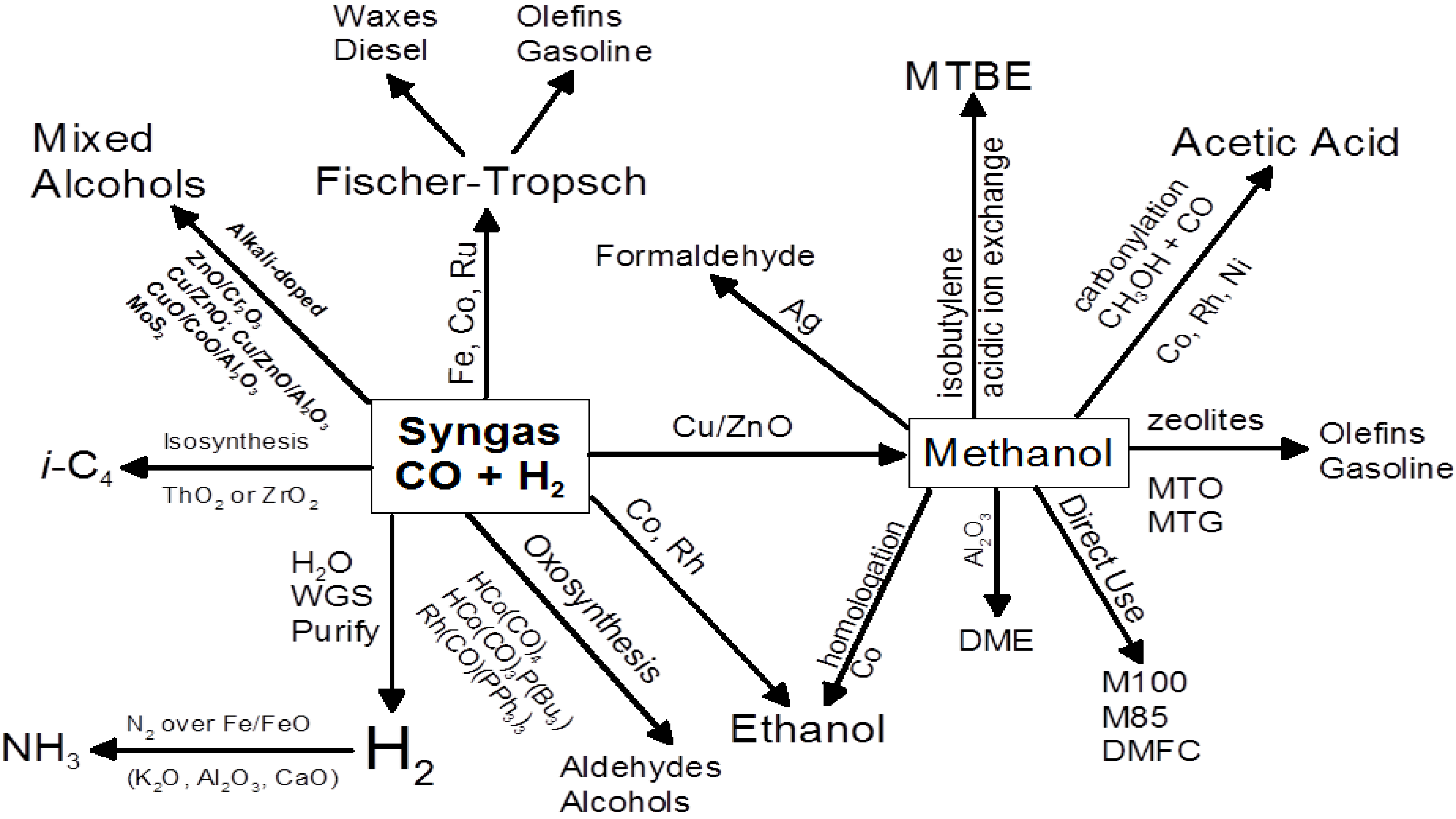
45 million tons worldwide production



- Displace fossil fuels - direct use in vehicles using fuels cells
- Reducing CO_2 into chemicals and fuels
- Electricity storage and generation
- **NH_3**
- **Refinery hydrogenation**

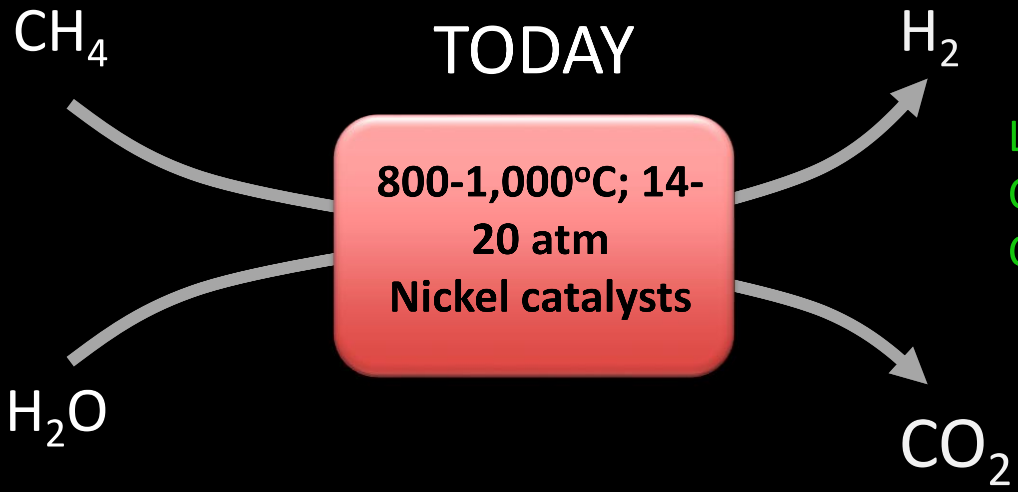
$CO_2 + H_2$ -> $CO + H_2O$

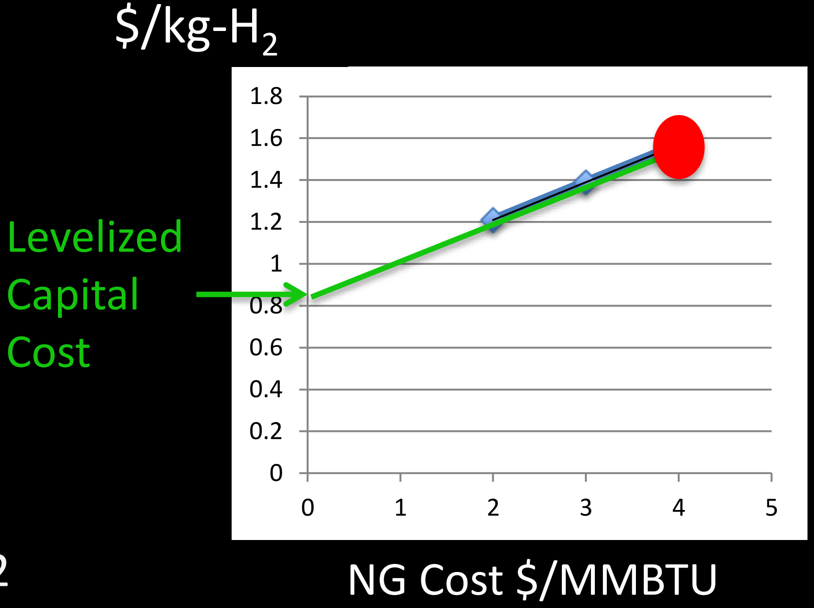
Reverse Water Gas Shift Reaction



Waxes
Diesel
Olefins
Gasoline
MTBE
Mixed Alcohols
Fischer-Tropsch
Acetic Acid
Alkali-doped
ZnO/Cr2O3
Cu/ZnO; Cu/ZnO/Al2O3
CuO/CoO/Al2O3
MoS2
Fe, Co, Ru
Formaldehyde
Ag
isobutylene
acidic ion exchange
carbonylation
CH3OH + CO
Co, Rh, Ni
Syngas
CO + H2
Cu/ZnO
Methanol
zeolites
Olefins
Gasoline
MTO
MTG
Isosynthesis
i-C4
ThO2 or ZrO2
H2O
WGS
Purify
HCo(CO)4
HCo(CO)3P(Bu3)
Rh(CO)(PPh3)3
Oxosynthesis
Co, Rh
homologation
Co
Al2O3
DME
Direct Use
M100
M85
DMFC
N2 over Fe/FeO
NH3
H2
(K2O, Al2O3, CaO)
Aldehydes
Alcohols
Ethanol

H_2 production: Steam Reforming of Natural Gas

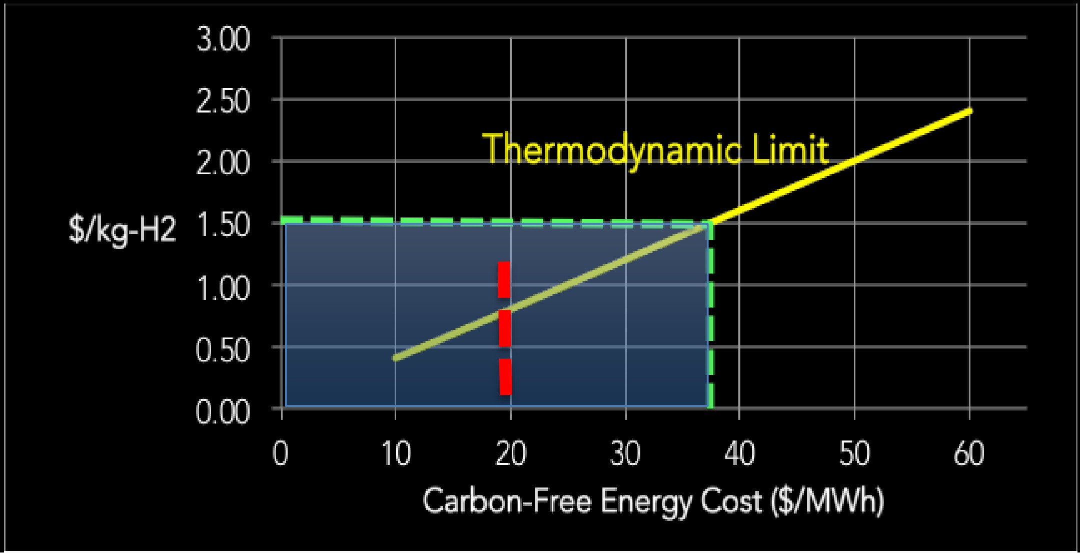


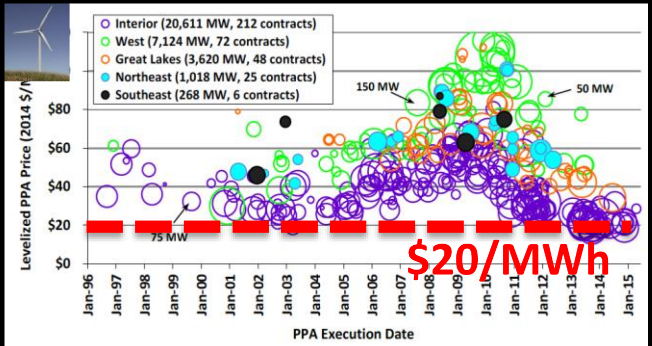


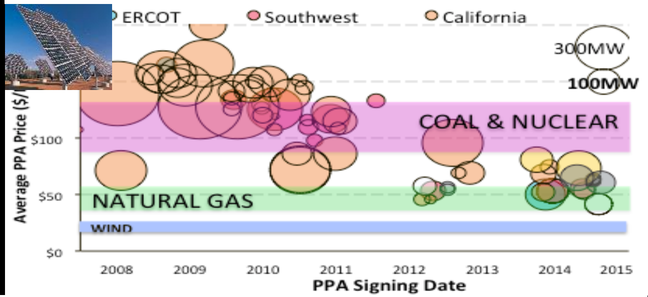
How do we produce carbon-neutral H_2 at <$2/kg at scale?

Thermodynamics & Cost Limits

$H_20 = H_2 + ½ O_2$; $ΔH$ = 286 KJ/mol = 40 kWh/kg-H_2







Biomass

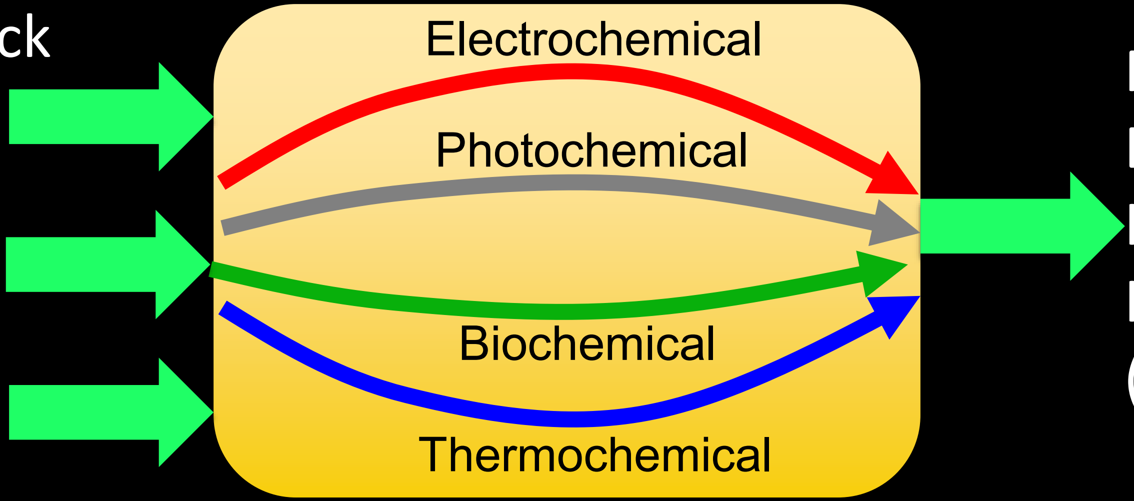
- Calorific Value: 7000 BTU/lb = 15400 BTU/kg = 4.50 kWh/kg-bm
- Cost = $65/ton = $0.065/kg-bm
- Energy Cost = $15/MWh

A grand challenge in decarbonization…

CO_2 feedstock at \$/tC

H_2O

Carbon-free energy at \$/kWh



Methanol
Ethanol
Hydrogen
Hydrocarbon
(\$/kg; \$/L)

Can we combine pathways?

Path-Independent Techno-Economics

Energy Cost (Energy Efficiency)

Thermodynamic Limit

= 40 kWh/kg-H_2

Realistic ≈ 50 kWh/kg-H_2 (within 80% of limit)

Energy cost =

50 kWh/kg x \$0.02/kWh = \$1/kg-H_2

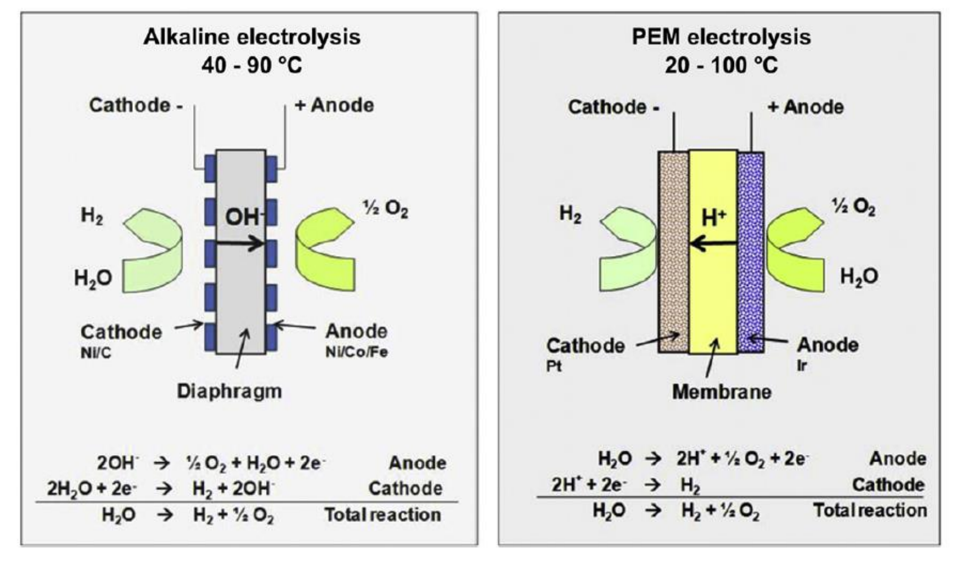
Levelized Non-Energy Cost

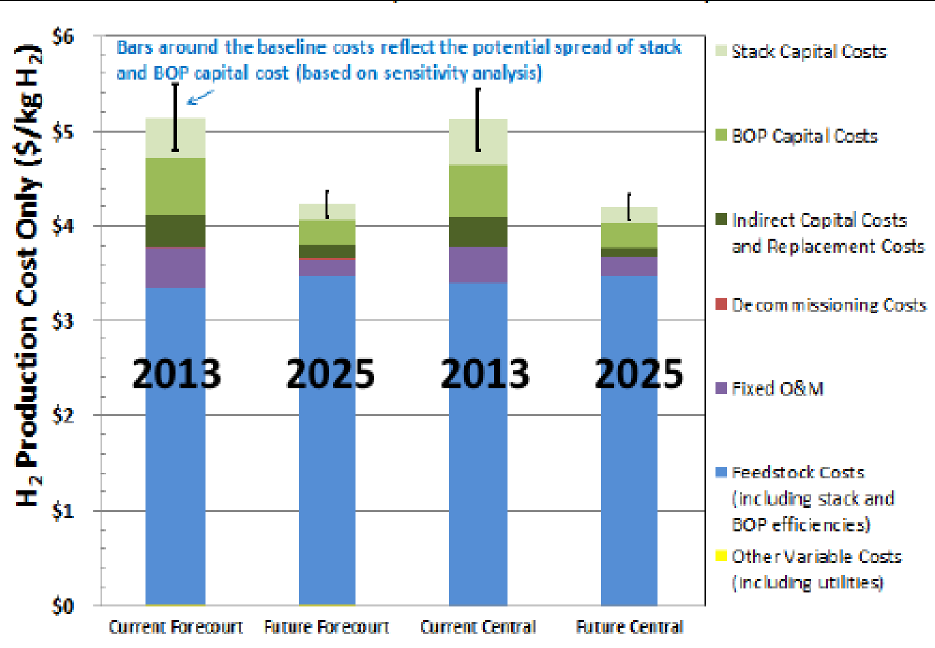
- Capital cost for plant
- O&M
- Cost of capital
- Depreciation

- \$0.50/kg-H_2 at scale

Electrochemical Pathway

Can one achieve economies of scale in non-energy cost





ΔH = 55 kWh/kg-H_2

500-1500 kg/day 50,000 kg/day

TODAY: $5/kg-$H_2$

OPTIMISTIC LIMIT: $2/kg-$H_2$

How can one achieve $1.50/kg-$H_2$ limit at scale with new system design?

Thermochemical Pathway – Materials & Systems

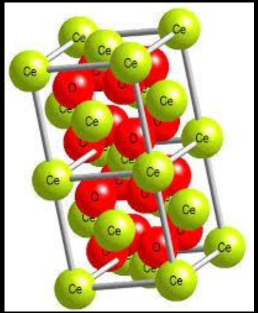
STATE-OF-THE-ART

Medium = 600 °C

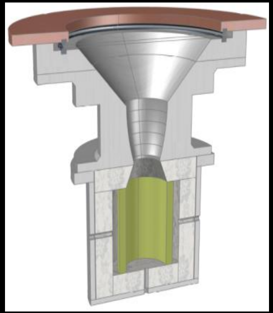
Hot = 1,500 °C

CeO_2

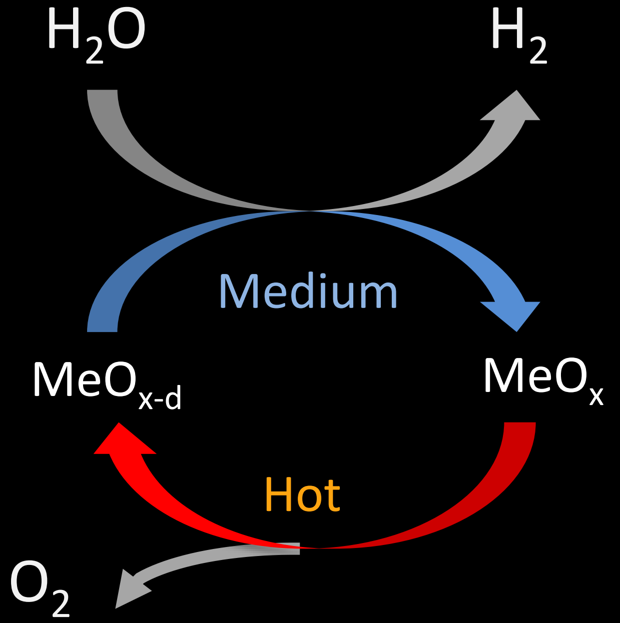
< 1% η_{Carnot}



Material



Reactor



$$\Delta T = \frac{-2\Delta G^{H_2O}_{f,T_{GS}} - T_{GS}\Delta S}{S^{O_2}_{T_{TR}} + 2\Delta S_{reduction}}$$

FUTURE

Medium = 600 °C

Hot = 800 °C

Fluidized bed reactor?

- Matching heat input to chemistry
- Heat recuperation

Non-Energy System Cost = \$0.50/kg-H_2 at scale doable?

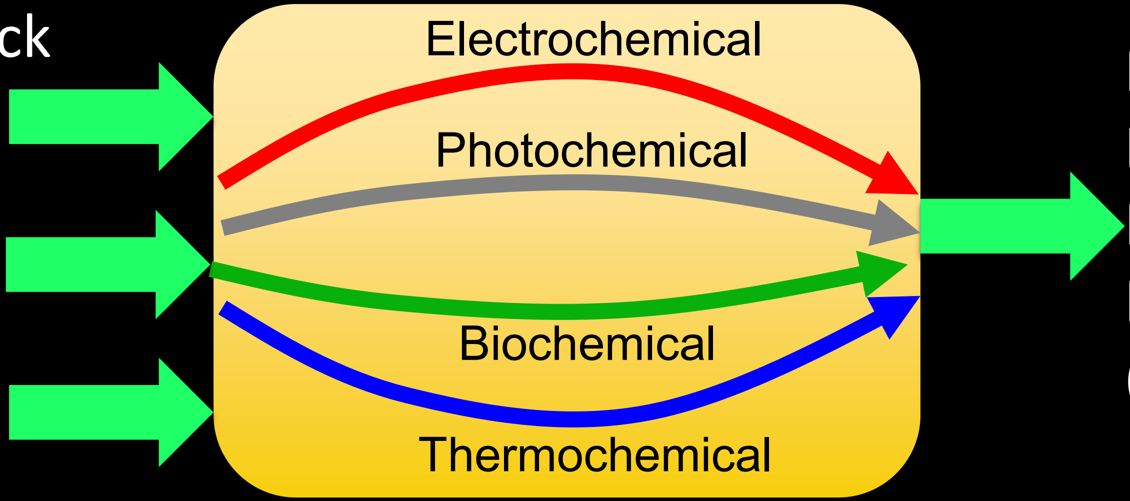
How can we achieve 50 kWh/kg-H_2 in energy efficiency?

Zero-Net Carbon Fuels – Science to Systems

CO_2 feedstock at \$/tC

H_2O

Carbon-free energy at \$/kWh



Methanol
Ethanol
Hydrogen
Hydrocarbon
(\$/kg; \$/L)

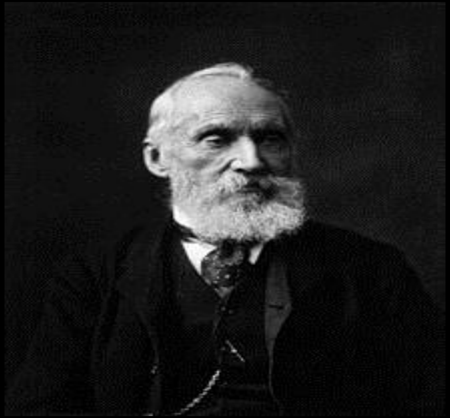
(In)Famous Predictions from the Past

“Radio has no future”

“X-rays will prove to be a hoax.”

“Heavier-than-air flying machines are impossible”

Lord Kelvin in 1890s



(In)Famous Predictions from the Past

“Man will not fly for 50 years.”

Wilbur Wright in 1901

Any sufficiently advanced technology is indistinguishable from magic.

Arthur C. Clarke