# Syn-Fuels Production for Hybrid Nuclear Power Facilities

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*Sustainable Energy Economy Workshop*
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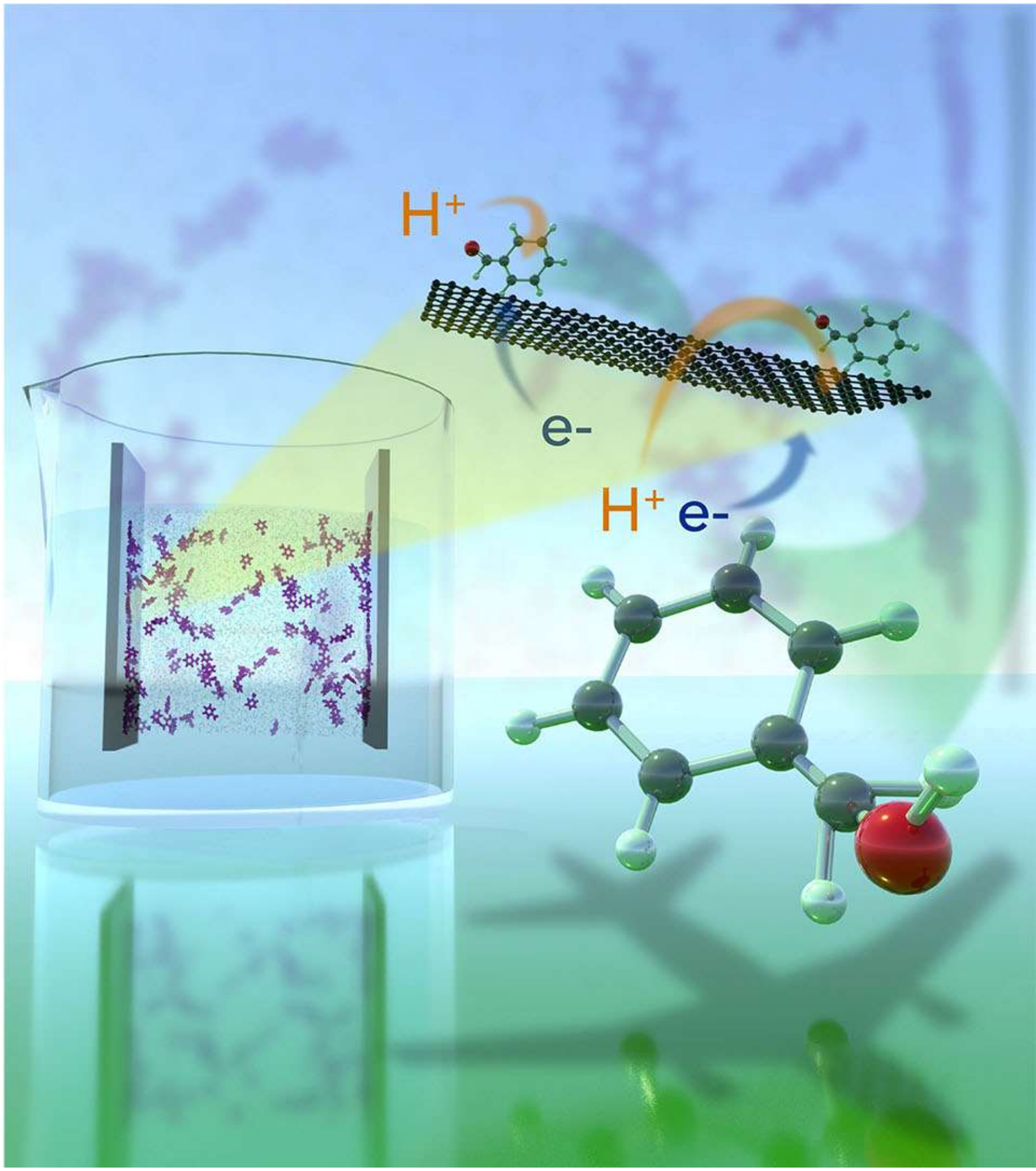

# 3 key take-aways

- $CO_2$ to fuels and products takes a tremendous amount of energy
- Nuclear power (Davis-Besse) is well positioned to make syn-fuels & products from $CO_2$
- PNNL-INL doing a techno-economic analysis to understand the business case

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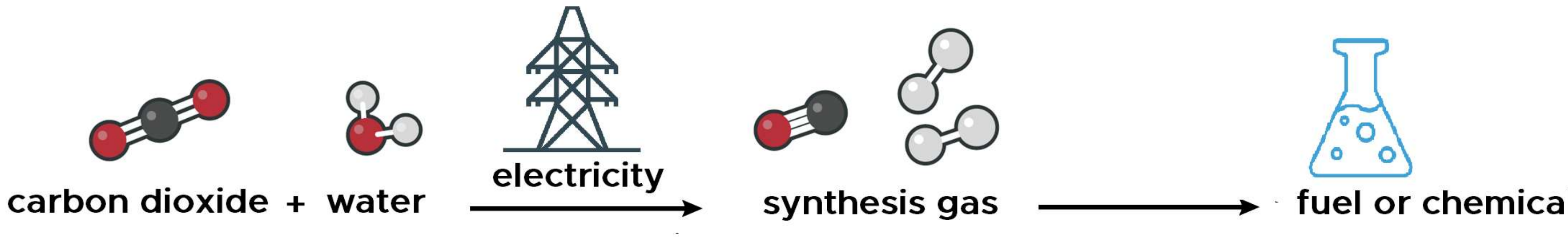
# Power-to-Liquids provides a means to recycle carbon dioxide back into fuels and chemicals




## To make syngas

1. Co-electrolysis of $CO_2$ and $H_2O$
2. Electrolysis of $H_2O$ with reverse water-gas-shift
3. Steam methane reforming
4. Dry reforming ($CH_4$ +$CO_2$)
5. Gasification of MSW or biomass

## To make sustainable aviation fuel

1. Small-scale Fischer-Tropsch
2. Methanol to olefins, upgrading
3. Fermentation and alcohol-to-jet

**Abundant low-cost $CO_2$ and electricity are needed**

BIOIN
BIOPRODUCTS INSTITUTE

# Nuclear and hydro power are excellent for syn-fuels

Annual power and energy to make syngas

100MGY ethanol plant needs 220 MW

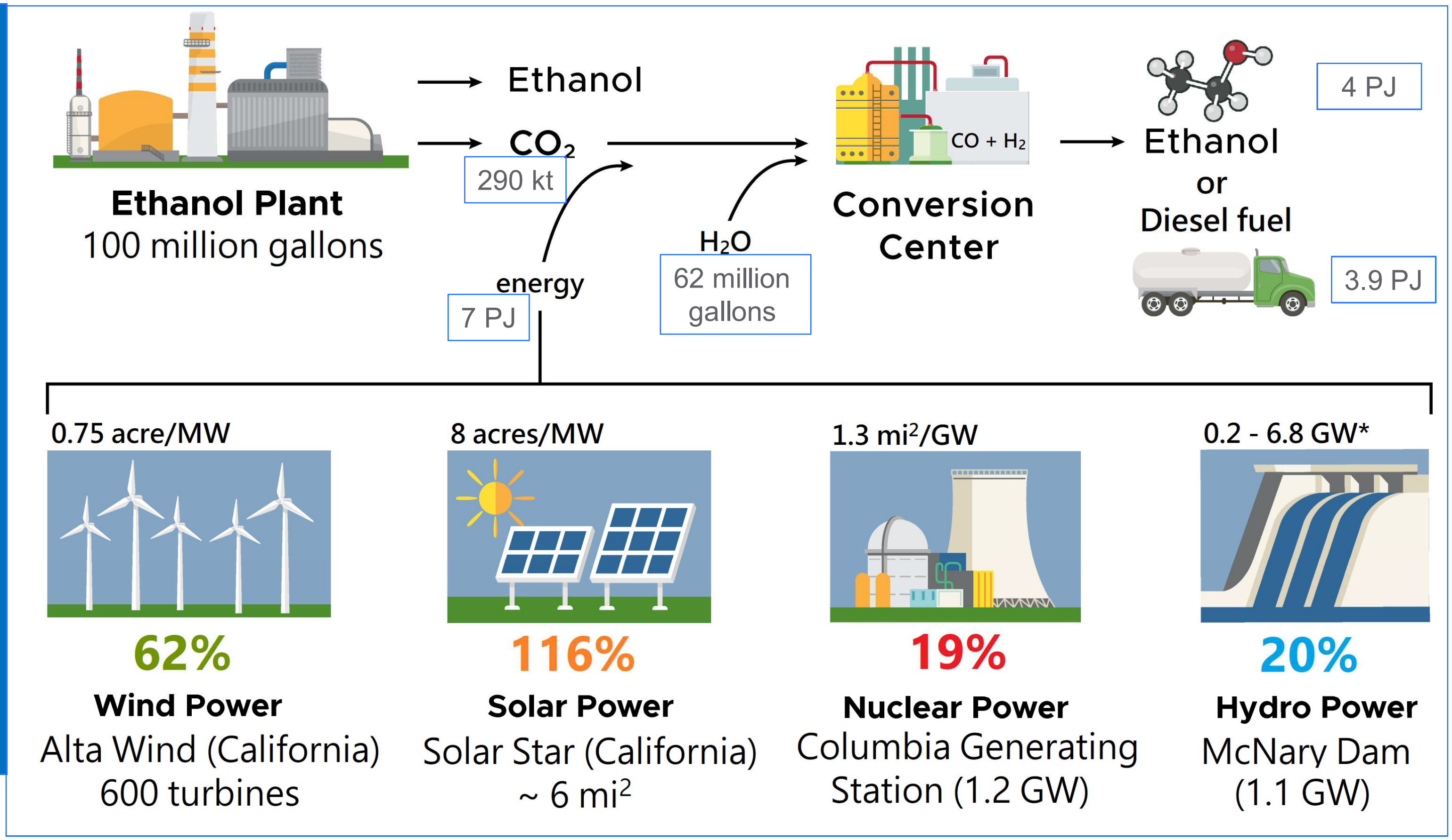
- 150 MW ($H_2$)
- 72 MW (CO)

U.S. ethanol will need

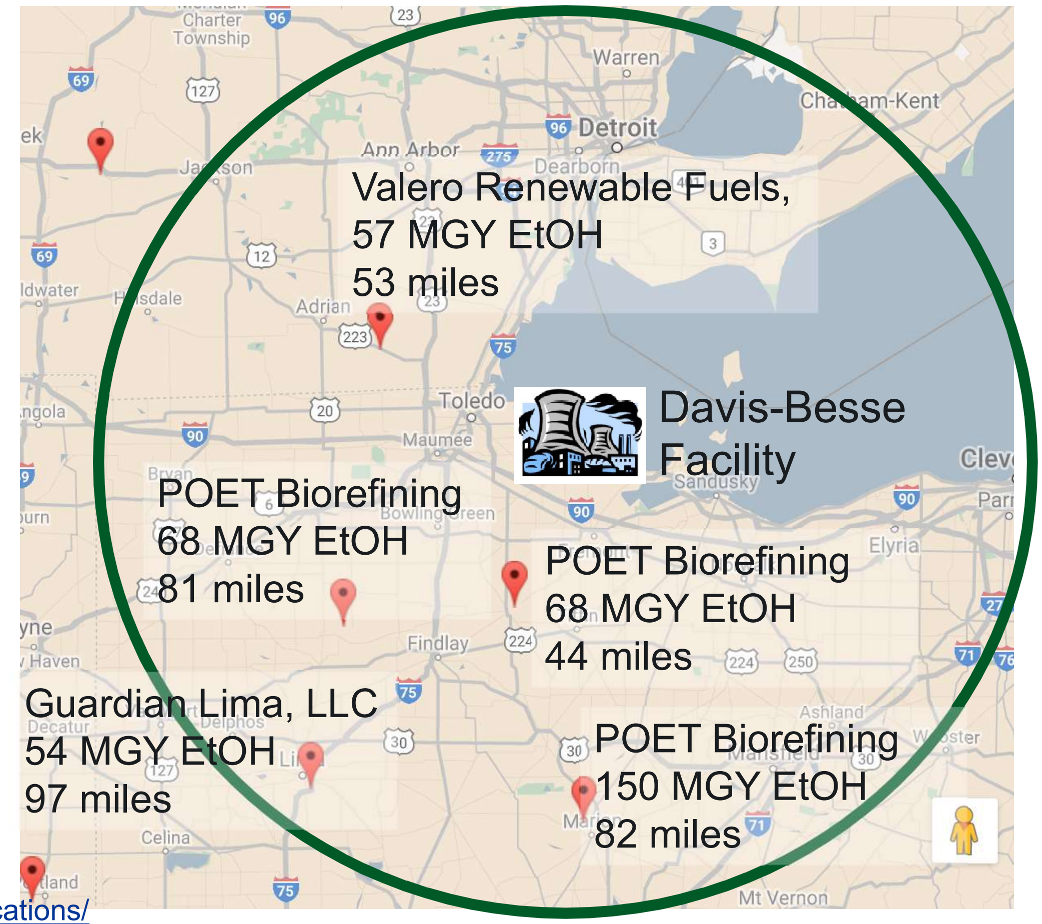
- 33 GW (1EJ)

and could provide

- ~7 billion gallons



# ~1,150kt $CO_2$ is available from ethanol produced within 100 miles of Davis-Besse



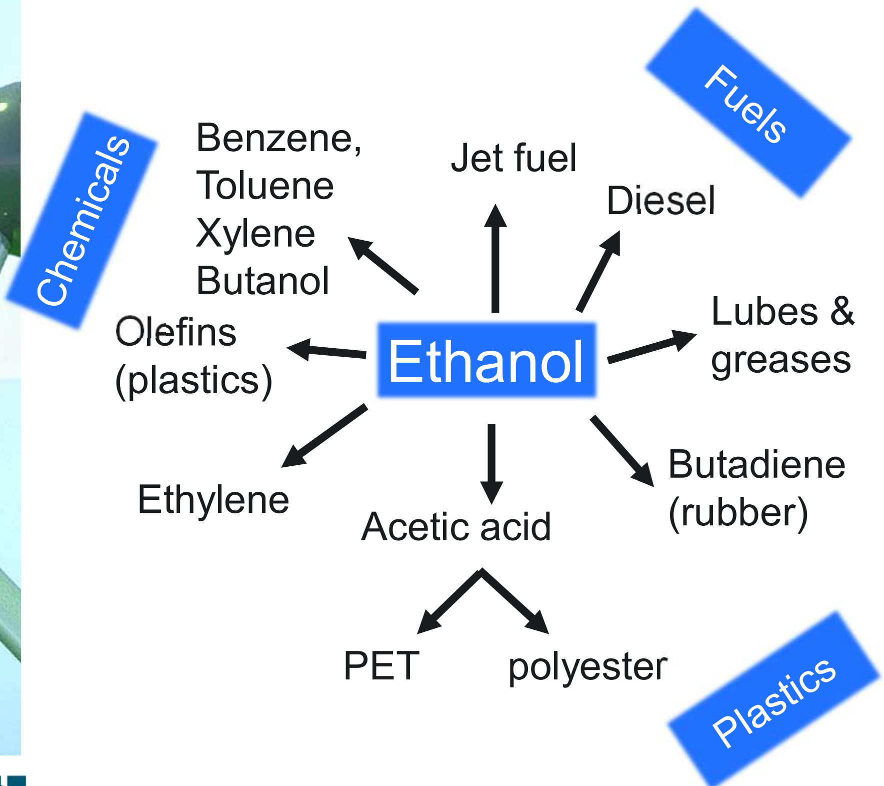

*https://ethanolrfa.org/biorefinery-locations/

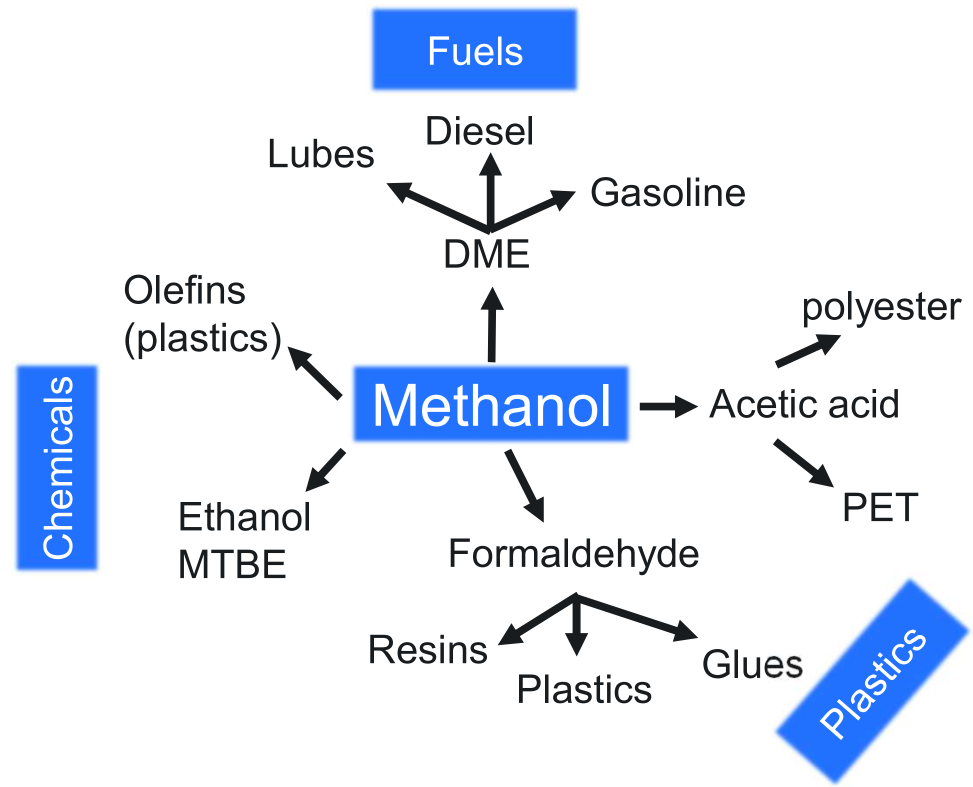
# Davis-Besse (~900MW$_e$) power plant can make a significant amount of syn-products/fuels

- $CO_2$ conversion to products, lubes and fuels
- Assumed 1,150 kt/yr of $CO_2$ from 5 ethanol plants* is within 100 miles of DB
  - Ethanol production ~ 400 MGY
  - 290 kt $CO_2$/100 MGY ethanol
- $CO_2$ conversion to formic acid – OCO to discuss
  - 1,200 kt/yr formic acid
- $CO_2$ conversion to syn-gas (building block)
  - ~870 MW needed
- Syn-gas could be converted to methanol ethanol, diesel, lubes, chemicals, etc.
  - 160- 200 MGY ethanol
  - 100-120 MGY jet or diesel fuel
  - US uses ~18 BGY jet fuel

*https://ethanolrfa.org/biorefinery-locations/

# Ethanol and methanol can be converted to many high value chemicals and fuels



# Electricity cost must be low for any process making jet fuel (or other product) to be practical

Low temperature electrolysis energy required for producing synthesis gas needed for jet fuel is based on ΔG° (ideal boundary condition)

| At $0.02/kWh<br>electricity cost $1.3/gal | | | | | At $0.04/kWh<br>Electricity cost adds $2.6/gal | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $CO$ | | $2\ H_2$ | | | $CO$ | | $2\ H_2$ | | |
| $0.42/gal | + | $0.86/gal | = | ~$1.3/gal | $0.86/gal | + | $1.7/gal | = | $2.6/gal |

…a carbon tax can help make up the difference ($90/t equates to less than $0.50 per gallon)

Energy required to make syn gas based on $\Delta G = nFE$, where n=2, F = 96,485 C/mol, E = 1.83 V (CO) or E = 1.82 V $H_2$ which comes to 12.6 MJ/kg CO and 175.6 MJ/kg $H_2$

This is only the ideal electricity cost. Does not include other costs like capital, operations, etc.

# High temperature electrolysis can decrease the electricity cost ~30%, but low cost electricity is still needed

High temperature electrolysis energy required for producing synthesis gas needed for jet fuel is based on ΔG° (ideal boundary condition)

**High temperature electrolysis at \$0.02/kWh**
**electricity cost \$0.9/gal**

| CO | | $2\ H_2$ | | |
|---|---|---|---|---|
| \$0.30/gal | + | \$0.60/gal | = | \$0.90/gal |

**Low temperature electrolysis at \$0.02/kWh**
**Electricity cost adds \$1.3/gal**

| CO | | $2\ H_2$ | | |
|---|---|---|---|---|
| \$0.42/gal | + | \$0.86/gal | = | ~\$1.3/gal |

…a carbon tax can help make up the difference (\$90/t equates to less than \$0.50 per gallon)

Energy required to make syn gas based on $\Delta G = nFE$, where n=2, F = 96,485 C/mol, E = 1.28 V (CO) or E = 1.28 V $H_2$ which comes to ~8.8 MJ/kg CO and ~123 MJ/kg $H_2$

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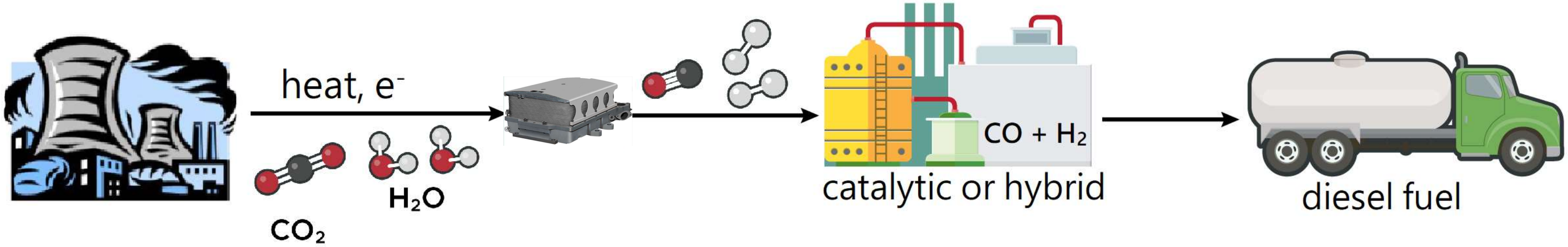
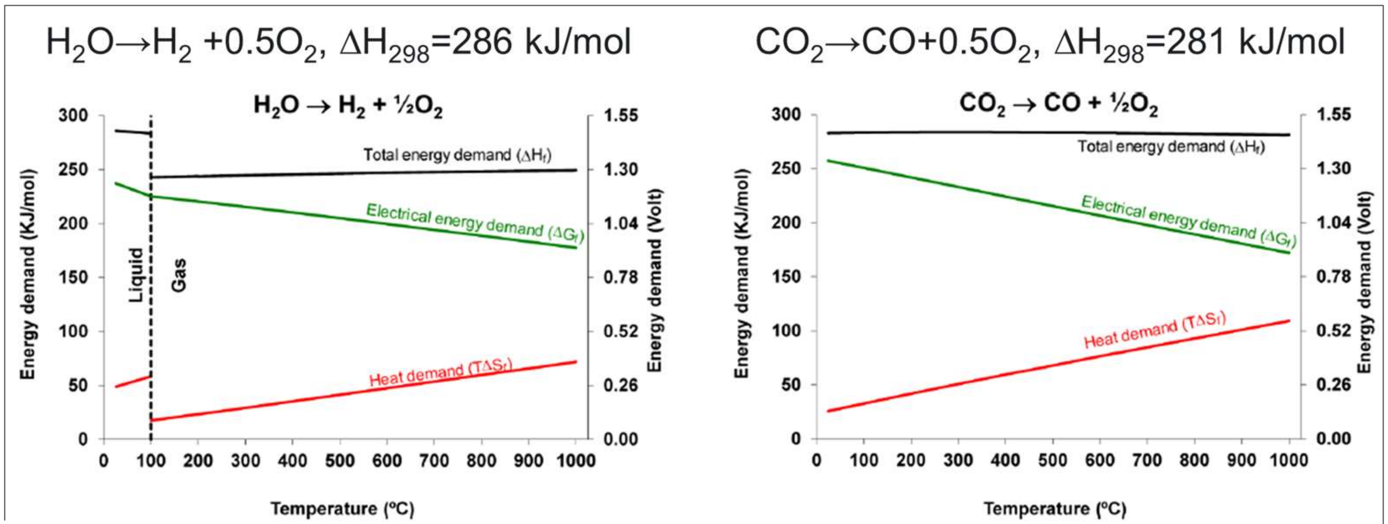
# PNNL and INL are examining the economics: using thermal +electrical energy and renewable credits may be keys



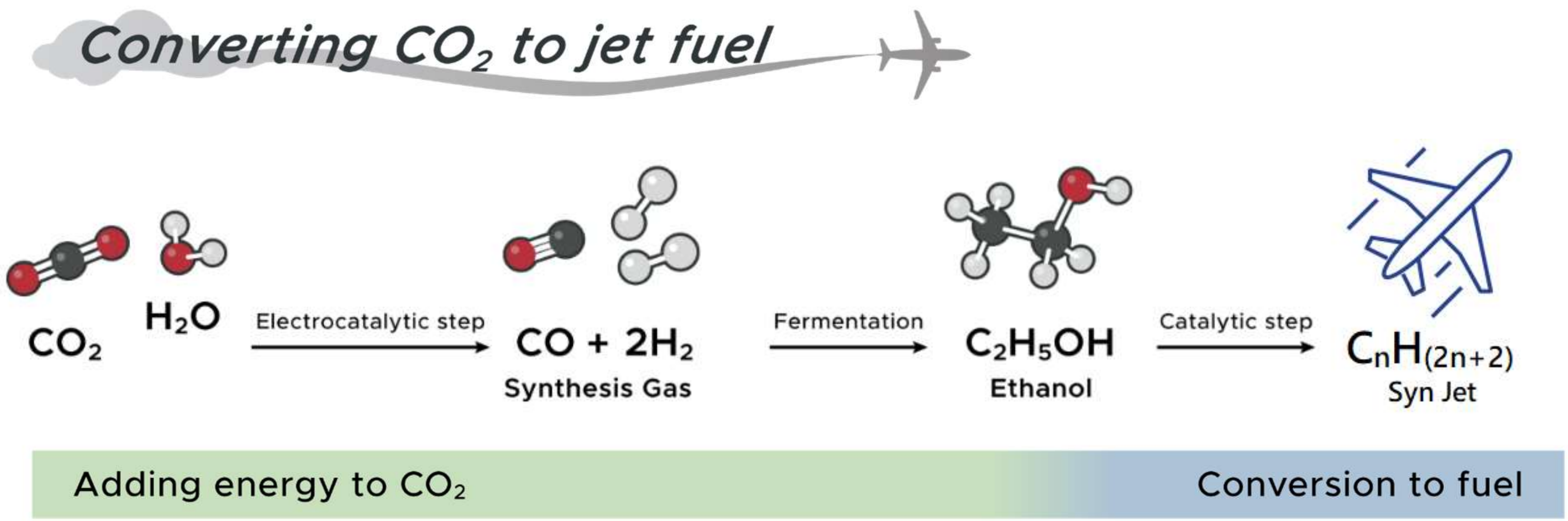




**Solid Oxide co-electrolysis of $H_2O$ and $CO_2$**

- Same materials, catalysts and designs as water electrolysis
- Syn gas electric power demand slightly higher than water electrolysis
- Near 100% electricity to syn-gas efficiency

30% less electricity compared to low temperature electrolysis and nuclear heat could provide 65% of thermal energy reducing $H_2$ cost by 10%

# We have a process nearly shovel ready to make jet fuel from syn-gas with high carbon efficiency




1. Add energy
   - $CO_2$ to CO (electrolysis) 353 kJ/mol CO
   - $H_2O$ to $H_2$ (electrolysis) 351 kJ/mol $H_2$
2. Convert gases into liquids
   - Commercial
   - Low temperature
   - Highly energy efficient
   - Highly carbon efficient
3. Concentrate the energy and adjust the carbon structure (PNNL Ethanol-to-Jet")
   - Final pilot stage
   - High Energy return on investment
   - High carbon efficiency

# 3 key take-aways

- $CO_2$ to fuels and products takes a tremendous amount of energy
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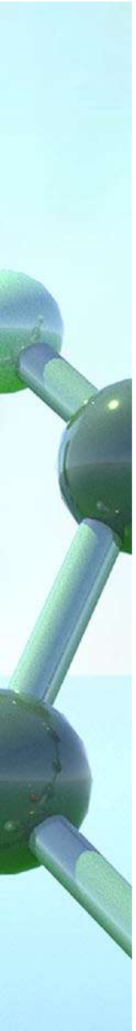

# Thank you

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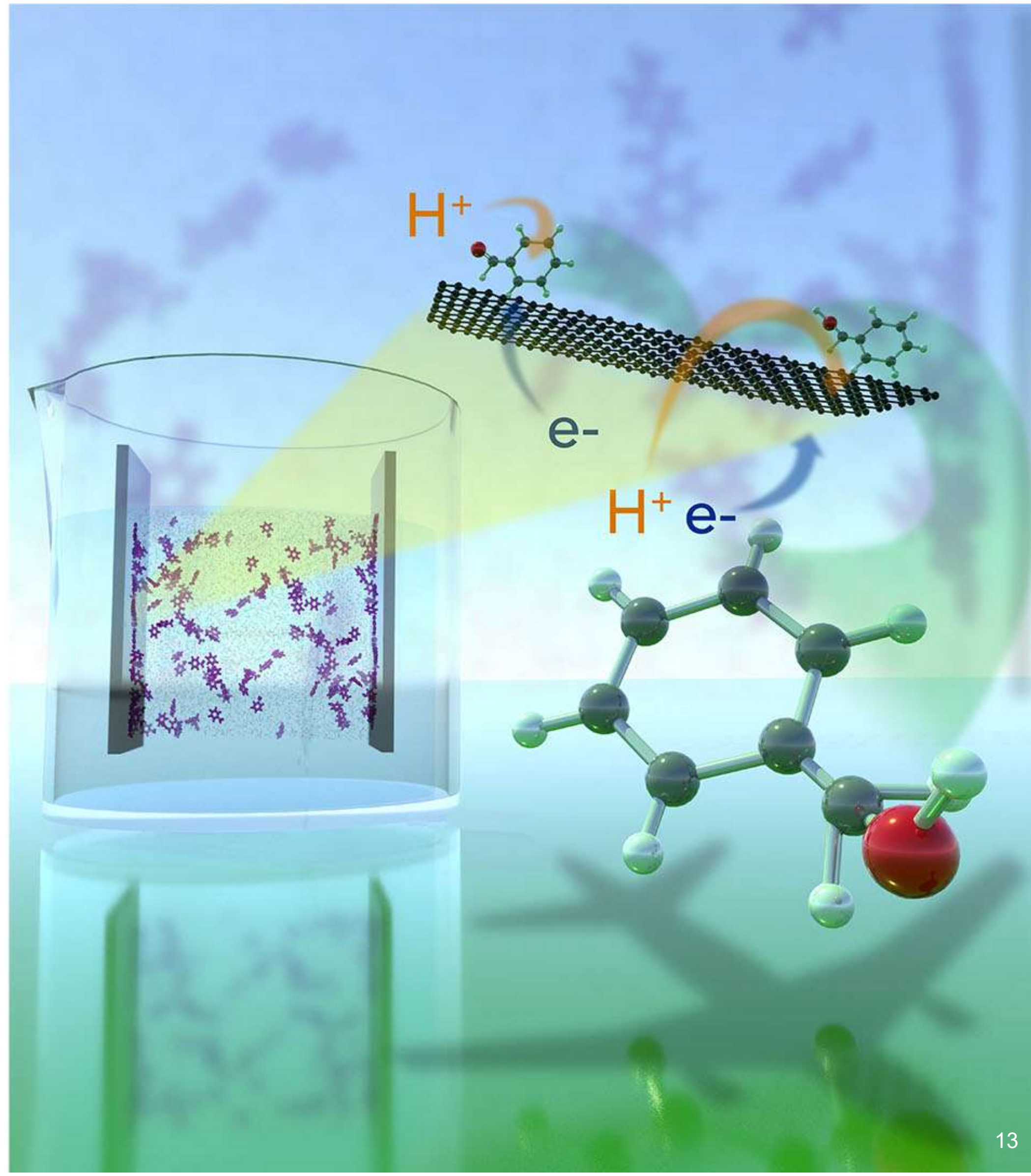


# Backup Slides

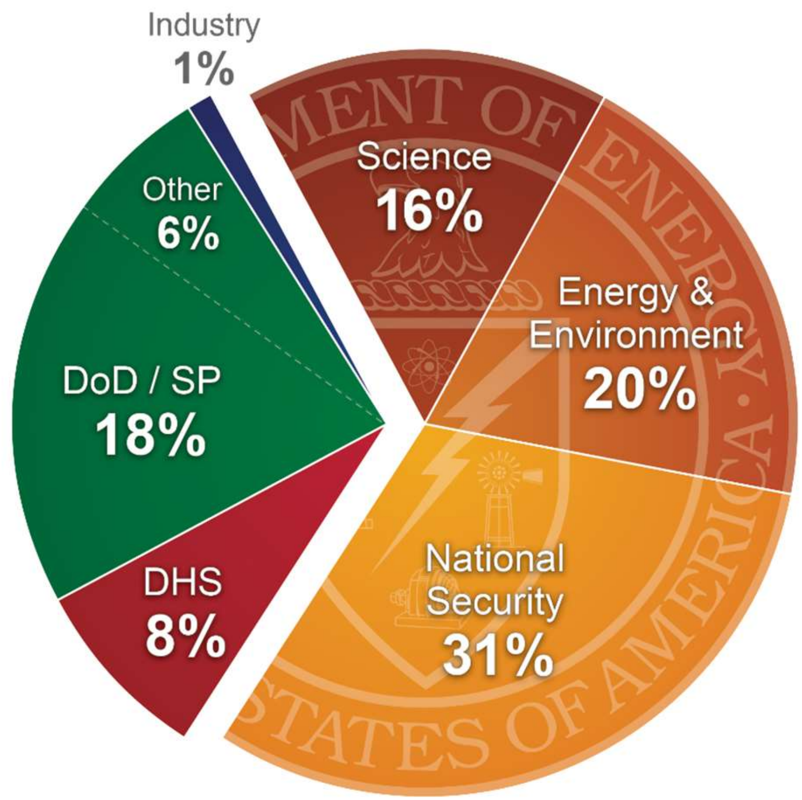
# PNNL supports a wide **breadth of sponsor missions**

**4,400** Staff

**$960M** Budget

**1,124** Peer-reviewed publications

**208** Invention disclosures




**FY2018 Budget**

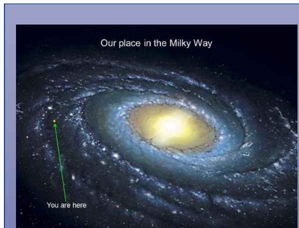
# Energy is the ability to do work, Power is energy over time

Energy

- Energy is the ability to do work
- SI unit of energy is joule (J) and is kg $m^2/s^2$
- The U.S. uses roughly 100 exajoules of energy yearly

Power

- Power is energy over time
- SI unit of Power is watt (W) and is kg/$m^2/s^3$




How can I relate exa (E)?

- An Exa second is 32 billion years (more than 2x the age of the universe)
- The radius of the Milky Way Galaxy is 500 Em
- An EJ is the energy intake for about a 100 billion people (2,400 kcal/person)

## Energy units

1 kJ = 0.95 Btu

1 kJ = 0.278 Wh

1kJ = 0.239 kcal

1 EJ = 0.95 Quad ($10^{15}$ Btu)

1 Btu = 1.055 kJ

1 kWh = 3.6 MJ

1 kcal = 4.184 kJ

1 Quad = 1.055 EJ

Kilo (k) = $10^3$ (thousand)
Mega (M) = $10^6$ (million)
Giga (G) = $10^9$ (billion)
Tera (T) = $10^{12}$ (trillion)
Peta (P) = $10^{15}$ (quadrillion)
Exa (E) = $10^{18}$ (quintillion)

# High temperature electrolysis can decrease the electricity cost ~30%, but low cost electricity is still needed

High temperature electrolysis energy required for producing synthesis gas needed for jet fuel is based on ΔG° (ideal boundary condition)

**At $0.02/kWh**
**electricity cost $1.3/gal**

| CO | | $2 H_2$ | | |
|---|---|---|---|---|
| $0.30/gal | + | $0.60/gal | = | $0.90/gal |

**At $0.04/kWh**
**Electricity cost adds $2.6/gal**

| CO | | $2 H_2$ | | |
|---|---|---|---|---|
| $0.60/gal | + | $1.2/gal | = | $1.8/gal |

…a carbon tax can help make up the difference ($90/t equates to less than $0.50 per gallon)

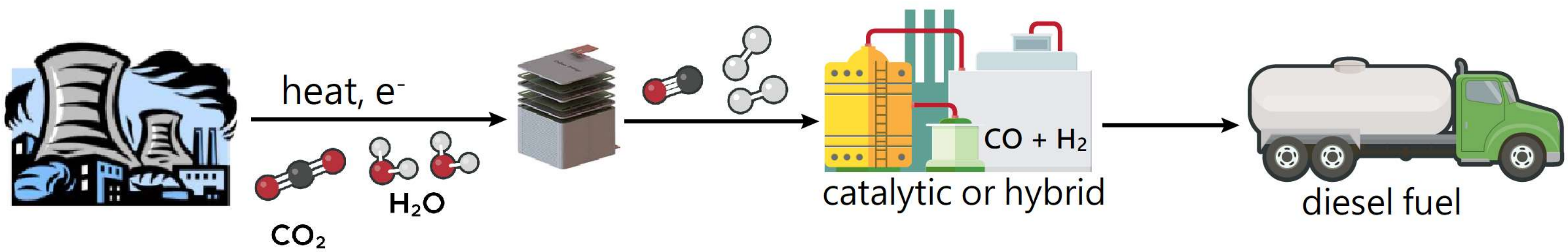
Energy required to make syn gas based on $\Delta G = nFE$, where n=2, F = 96,485 C/mol, E = 1.28 V (CO) or E = 1.28 V $H_2$ which comes to ~8.8 MJ/kg CO and ~123 MJ/kg $H_2$

This is only the ideal electricity cost. Does not include other costs like capital, operations, etc.

# Syn-gas can be transformed to many fuels or products

- Ethanol $2CO + 4H_2 \rightarrow C_2H_5OH + H_2O$
- Methanol $CO + 2H_2 \rightarrow CH_3OH$
- Fischer-Tropsch $CO + 3H_2 \rightarrow CH_4 + H_2O$

$$CO + 2H_2 \rightarrow (1/n)(C_nH_{2n}) + H_2O$$
$$CO + H_2O \rightarrow CO_2 + H_2$$



# Based on chemical equations co-electrolysis and water electrolysis followed by reverse water gas shift have similar energy needs

$26H_2O + 24CO_2 \;=\; 2C_{12}H_{26} + 37O_2$

| Co-electrolysis | | $H_2O$ electrolysis with RWGS | |
|---|---|---|---|
| $25H_2O + 50e^- \;=\; 25H_2 + 25/2\ O_2$ | (electrolysis) | $37H_2O + 74e^- \;=\; 37H_2 + 37/2\ O_2$ | (electrolysis) |
| $12CO_2 + 24e^- \;=\; 12CO + 6O_2$ | (electrolysis) | $36H_2 + 12CO_2 \;=\; 12CO + 24H_2 + 12H_2O$ | (reverse water gas shift) |
| $12CO + 24H_2 \;=\; 6C_2H_6O + 6H_2O$ | (fermentation) | $12CO + 24H_2 \;=\; 6C_2H_6O + 6H_2O$ | (fermentation) |
| $6CH_6O \;=\; 6C_2H_4 + 6H_20$ | (dehydration) | $6CH_6O \;=\; 6C_2H_4 + 6H_2O$ | (dehydration) |
| $6C_2H_4 \;=\; C_{12}H_{24}$ | (oligomerization) | $6C_2H_4 \;=\; C_{12}H_{24}$ | (oligomerization) |
| $6C_2H_4 + H_2 \;=\; C_{12}H_{24}$ | (hydrogenation) | $6C_2H_4 + H_2 \;=\; C_{12}H_{24}$ | (hydrogenation) |
| $13H_2O + 12CO_2 + 74e^- \;=\; C_{12}H_{26} + 37/2O_2$ | | $13H_2O + 12CO_2 + 74e^- \;=\; C_{12}H_{26} + 37/2O_2$ | |

On a mole bases the thermodynamics requirements for $H_2O$ and $CO_2$electrolysis step are similar 257 vs 237 kJ/mol (minimum); 353 kJ/mol vs 351 kJ/mol (practicable)

# 90% of U.S. ethanol production is in the Midwest