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CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS)

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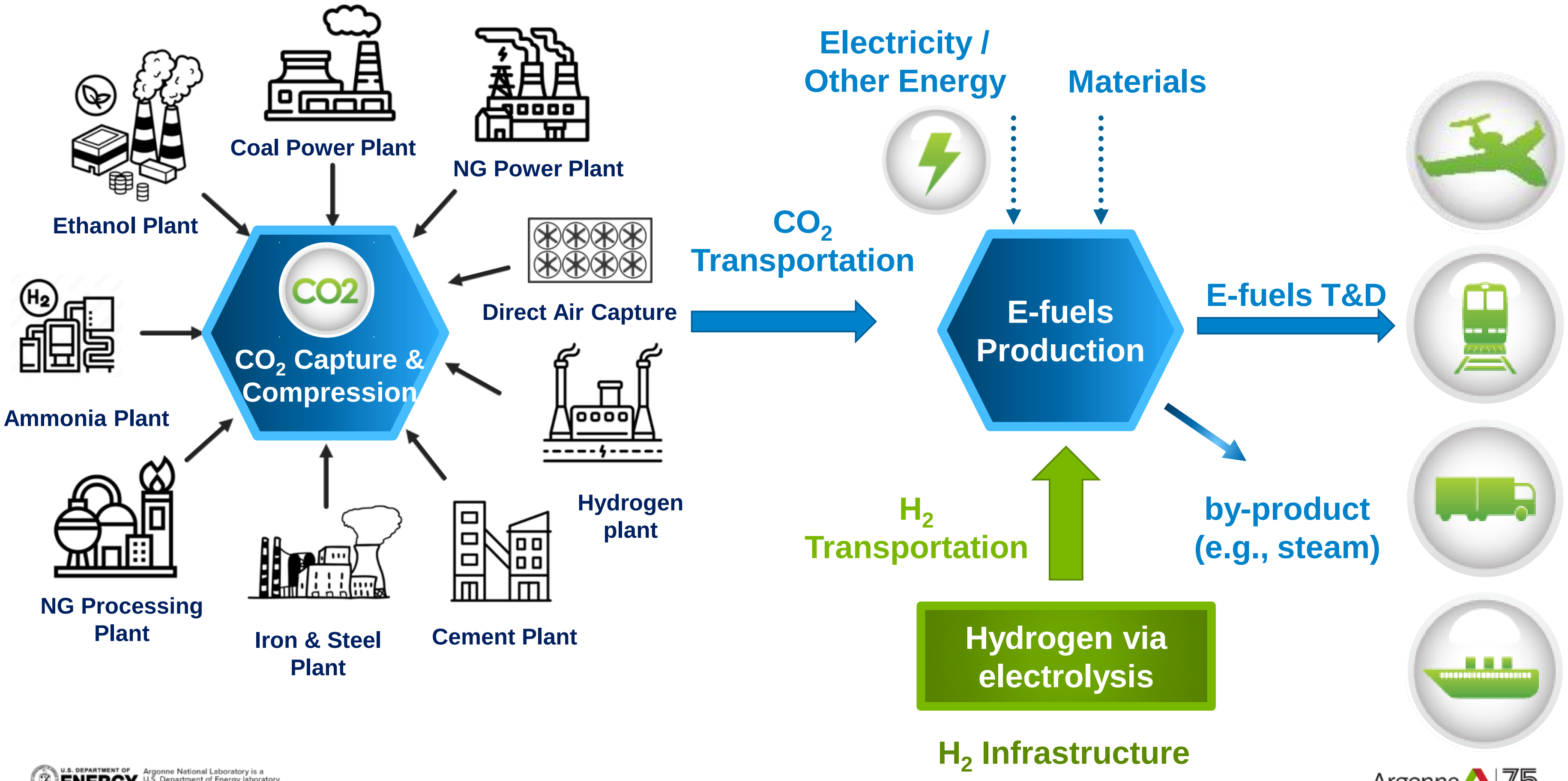
CO_2 Sources for Electro-Fuels Production



GREET CCUS Flowchart (E-fuel Tab)

● ***Select CO_2 sources***

1. Ethanol Plant
2. Ammonia Plant
3. NG Processing Plant
4. Hydrogen (SMR) Plant
5. Cement Plant
6. Iron/Steel Plant
7. NGCC Power Plant
8. Coal Power Plant
9. DAC (Direct Air Capture)

CO_2 Capture & Compression

CO_2 Pipeline Transportation

● ***Select electricity & heat sources***

Electricity Sources

1. US Grid Mix
2. NGCC
3. Coal IGCC
4. Biomass IGCC
5. Renewable (Wind)
6. Nuclear

Heat Sources

1. North American NG
2. Non-North American NG
3. RNG
4. Waste heat

● ***Select H_2 production technology***

1. Solar Electrolysis
2. Nuclear (HTGR) Electrolysis
3. Fossil NG SMR
4. Nuclear (Thermo-cracking)
5. Nuclear LWR
   (High Temperature
   Electrolysis with SOEC)

Hydrogen Production

H_2 Pipeline Transportation

● ***Select E-fuel pathway***

E-fuel Pathways (FT fuel, Methanol, and Ethanol)

E-fuel Production (& by-product) → **e-fuel Storage** → **e-fuel Distribution** → **Combustion (for combustible products)**

1. FT fuel production with RWGS with H_2 recycle
2. MeOH production with RWGS with H_2 recycle
3. EtOH production via gas fermentation (Waste heat)
4. FT fuel production using Nuclear LWR

CO_2 Capture and Compression (Industrial CO_2 Sources)

- **CO_2 purity is the key**
  - High-purity CO_2 does not require capture, but only compression stage
  - CO_2 capture (MDEA*) and compression processes for med- and low-purity sources

(*) Methyl diethanolamine CO_2 capture

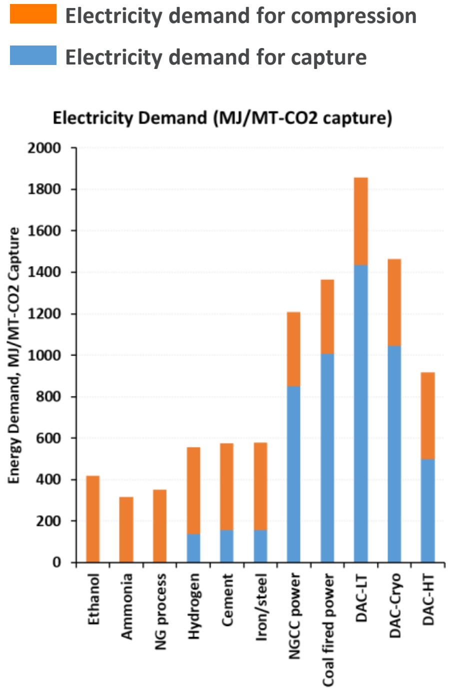
CO_2 Sources	CO_2 Capture & Compression Energy		Reference
	Electricity (MJ/MT-CO_2)	Natural Gas Input (MJ/MT-CO_2)	
Ethanol Plant	420	0	▪ CO_2 Capture Energy - DOE/NETL-2013/1602 (2014) - DOE/NETL-2015/1723 (2015) ▪ CO_2 Compression Energy - GREET compression module
Ammonia Plant	318	0	
NG Processing Plant	352	0	
Hydrogen (SMR) Plant	558	4454	
Cement Plant	577	4441	
Iron/steel Plant	579	4459	
NGCC Power Plant	1207	0	
Coal Power Plant	1365	0	

CO_2 Capture Energy for Direct Air Capture (DAC)

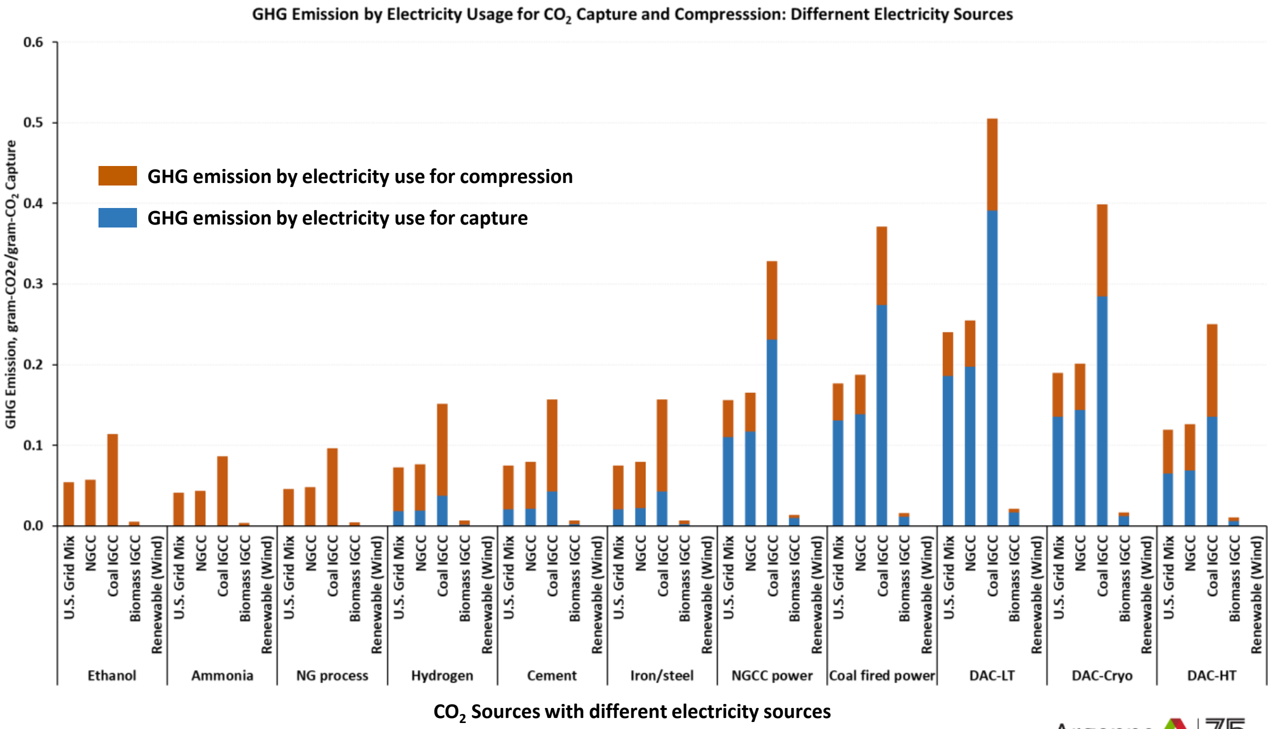
DAC Technology	CO_2 Capture & Compression Energy		Reference
	Electricity (MJ/MT-CO_2)	Natural Gas Input (MJ/MT-CO_2)	
Low temperature (LT) adsorption	1856	6750	▪ CO_2 Capture Energy - Deutz and Bardow, Nature Energy vol 6, 203–213 (2021) (DAC-LT) - Baxter et al. GHGT-15 (2021) (DAC-Cryogenic) - Keith et al. Joule vol 2(8), 15, 1573-1594 (2018) (DAC-HT) ▪ CO_2 Compression Energy: GREET compression module
Cryogenic carbon capture	1465	0	
High temperature (HT) absorption	918	8805	

- The energy consumption varies greatly among different DAC technologies.

Electricity Demand and GHG Emission: CO_2 Capture and Compression



- **GHG emission by electricity sources**
  - Coal > NGCC > U.S Grid Mix >> Biomass IGCC
- **Zero GHG emission with renewable (Wind) electricity**



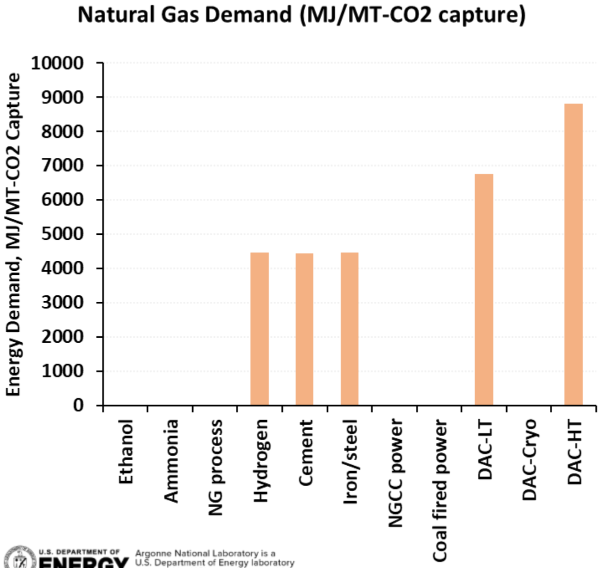
CO_2 compression work

$$\text{Compression work} = \left(\frac{mzRT}{\eta M_w}\right)\left(\frac{K_s}{K_s - 1}\right)\left[\left(\frac{P_2}{P_1}\right)^{1-\frac{1}{K_s}} - 1\right]$$

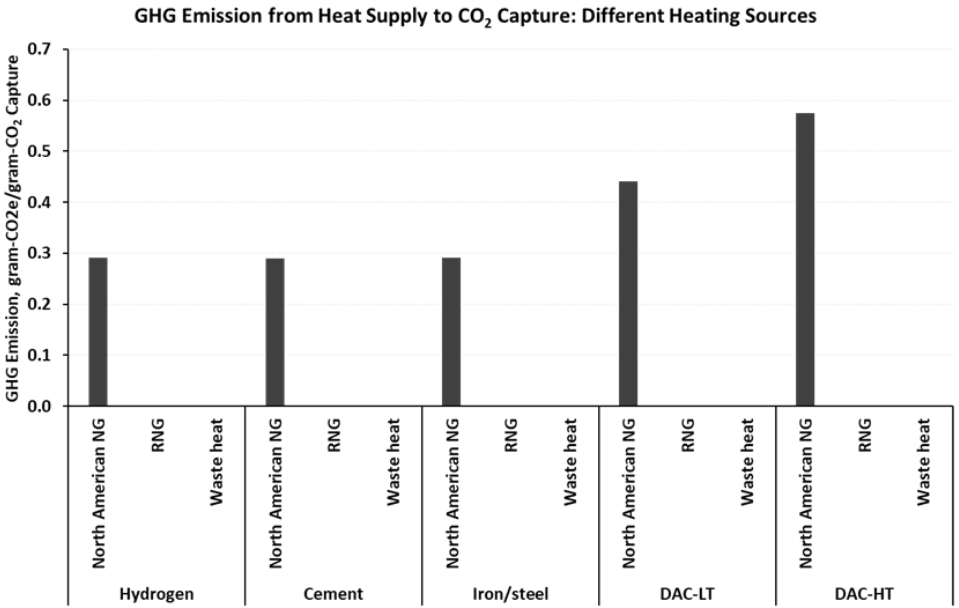
m	CO_2 mass rate	R	Universal gas constant
P	Pressure	T	Temperature
η	Compressor efficiency	K_s	CO_2 specific heat ratio
ρ	CO_2 density	M_w	CO_2 molecular weight
z	Compressibility factor		

Heat Demand and GHG Emission: CO_2 Capture

- **Natural gas for CO_2 capture from:**
  - Hydrogen SMR
  - Cement
  - Iron/Steel
  - DAC (LT)
  - DAC (HT)

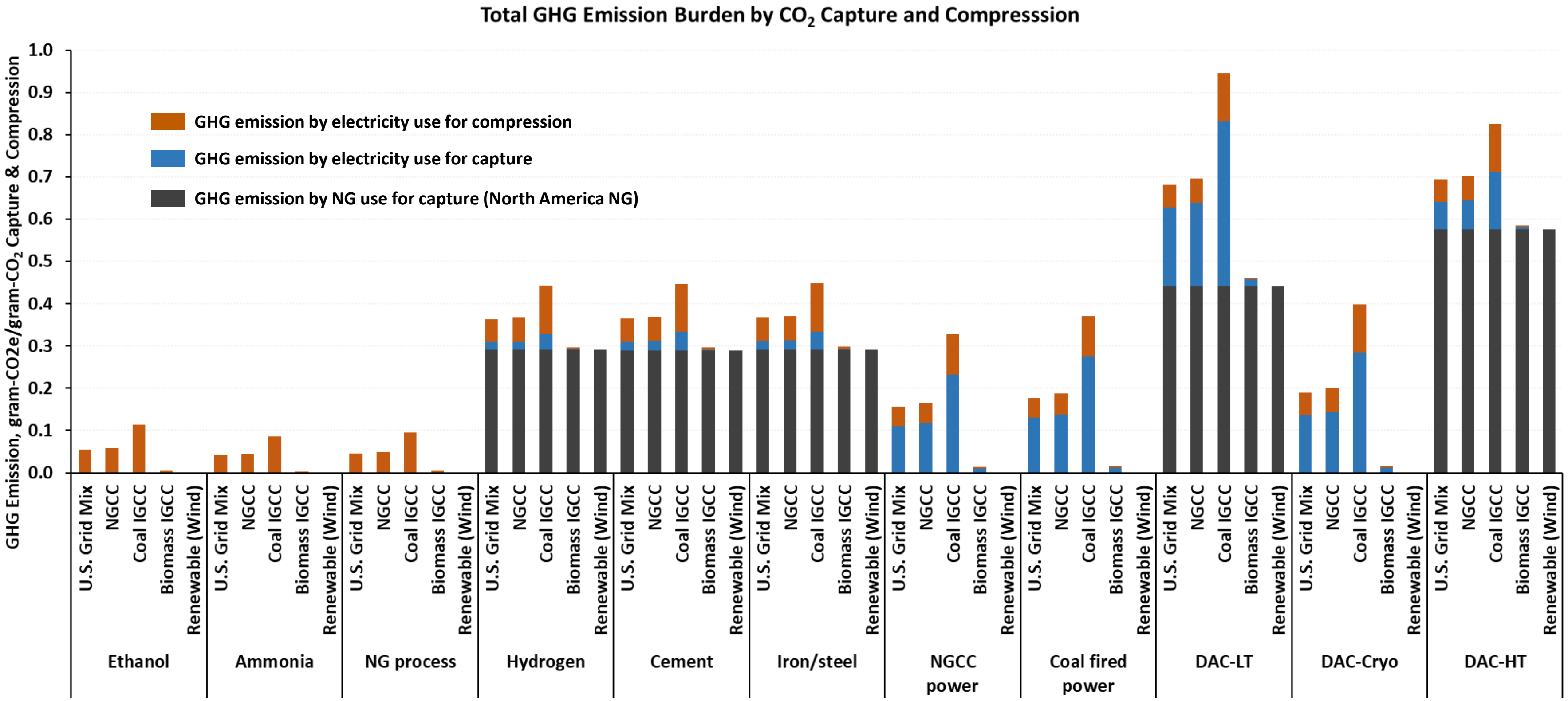


- **Using NG, GHG emission is significant**
- **Using RNG or waste heat, the GHG is close to zero or zero.**



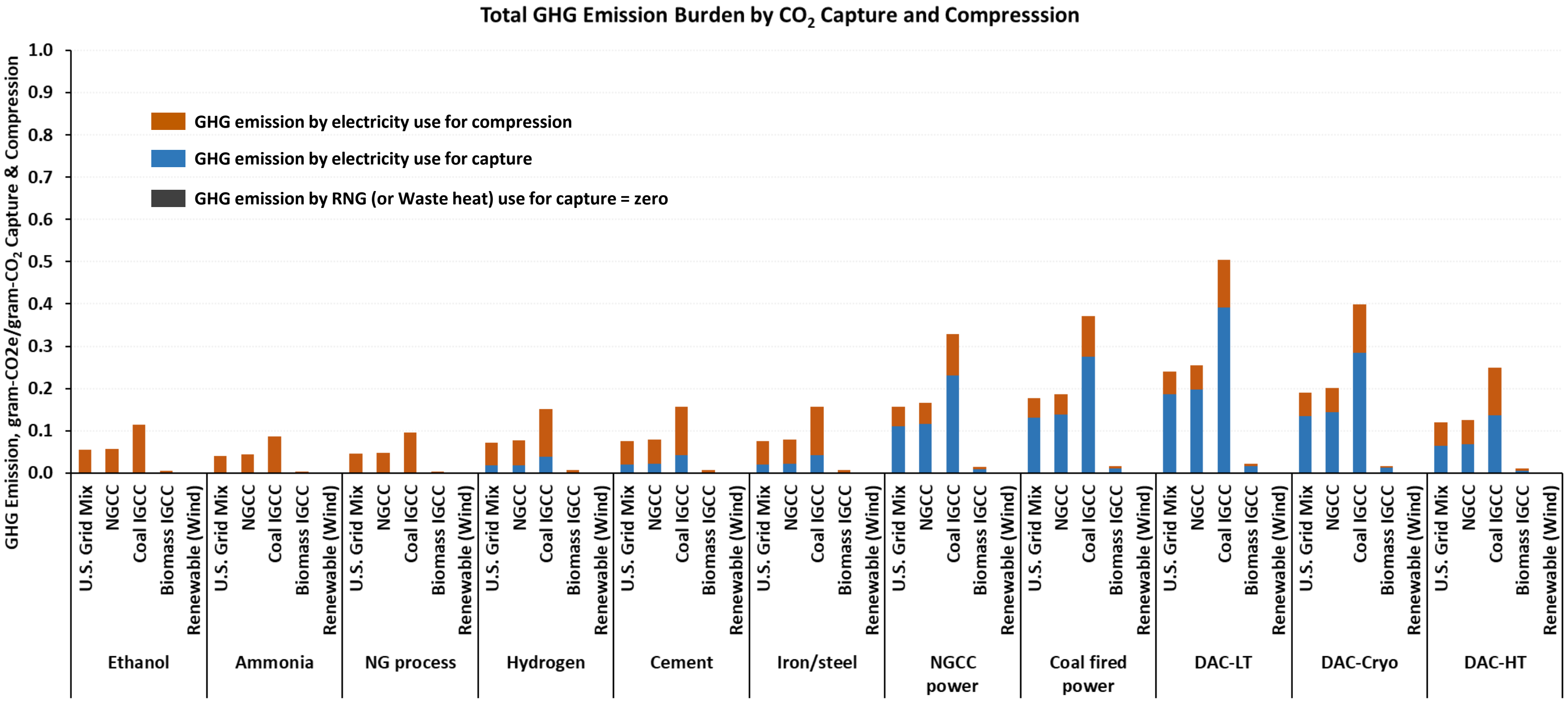
CO_2 Capture and Compression: Total Emission Burden

Different Electricity Sources with North America NG for Capture Process Heat

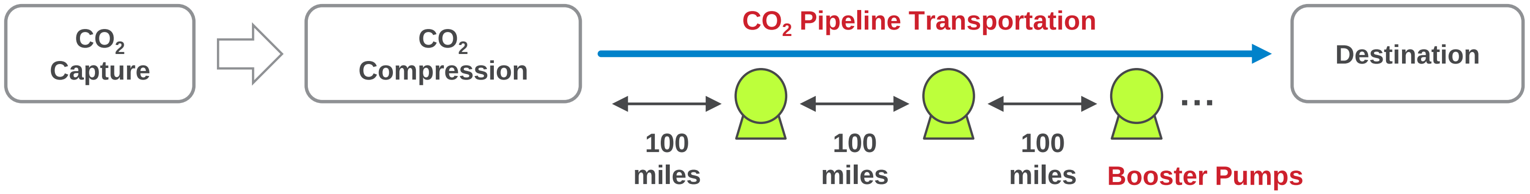


CO_2 Capture and Compression: Total Emission Burden

Different Electricity Sources with RNG (or Waste Heat) for Capture Process Heat



CO_2 Pipeline Transportation – Electricity Demand for Booster Pumps (beyond Initial Compression)



- **Electricity demand for one booster pump = 7.7 MJ/MT-CO_2**
- **Assumptions**
  - Pump pressures from 1500 psia to 2200 psia
  - Temperature = 25°C
  - Booster pump efficiency = 75%
  - Placing boosters at every 100 miles (e.g., there will be three boosters when the pipeline distance is 400 miles)
- **Default pipeline distance**
  - 200 miles (i.e., one booster) for all industrial sources except DAC (zero mile)
  - A user can manually change the pipeline distance

CO_2 pipeline transportation distance

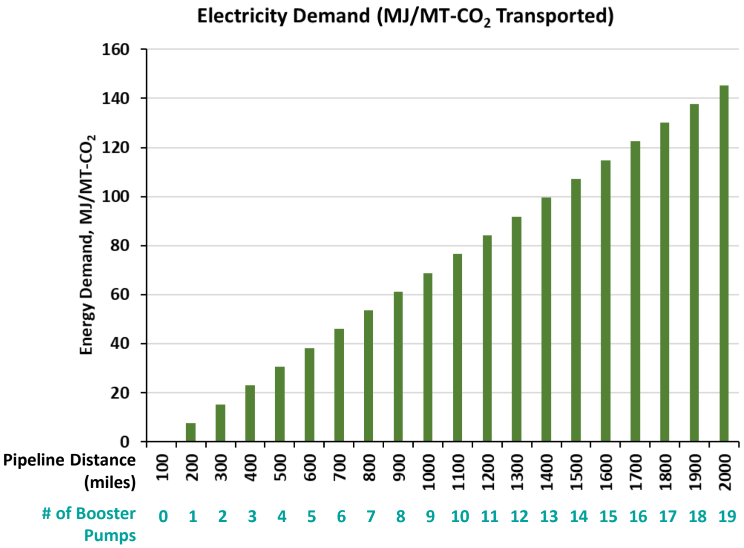
Energy requirements for CO2 capture and transportation

Selected:	Ethanol	Ethanol	Ammonia	NG process	Hydrogen	Cement	Iron/steel	NGCC power	Coal fired power	DAC
CO2 transportation distance (miles)		200	200	200	200	200	200	200	200	0
Electricity for CO2 capture (MJ/MT-CO2)	0	0	0	0	138	157	158	850	1,008	1,436
Natural gas for CO2 capture (MJ/MT-CO2)	0	0	0	0	4,454	4,441	4,459	0	0	6,750
Electricity for CO2 compression at the CO2 source (MJ/MT-CO2)	420	420	318	352	420	420	420	357	357	420
Electricity for CO2 transportation (booster pumps) (MJ/MT-CO2)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0.0

Electricity demand for booster pump(s)

Electricity Demand and CO_2 Emission of Booster Pumps: CO_2 Pipeline Transportation

- **Electricity demand is determined by the number of booster pumps** (as a function of pipeline distance)

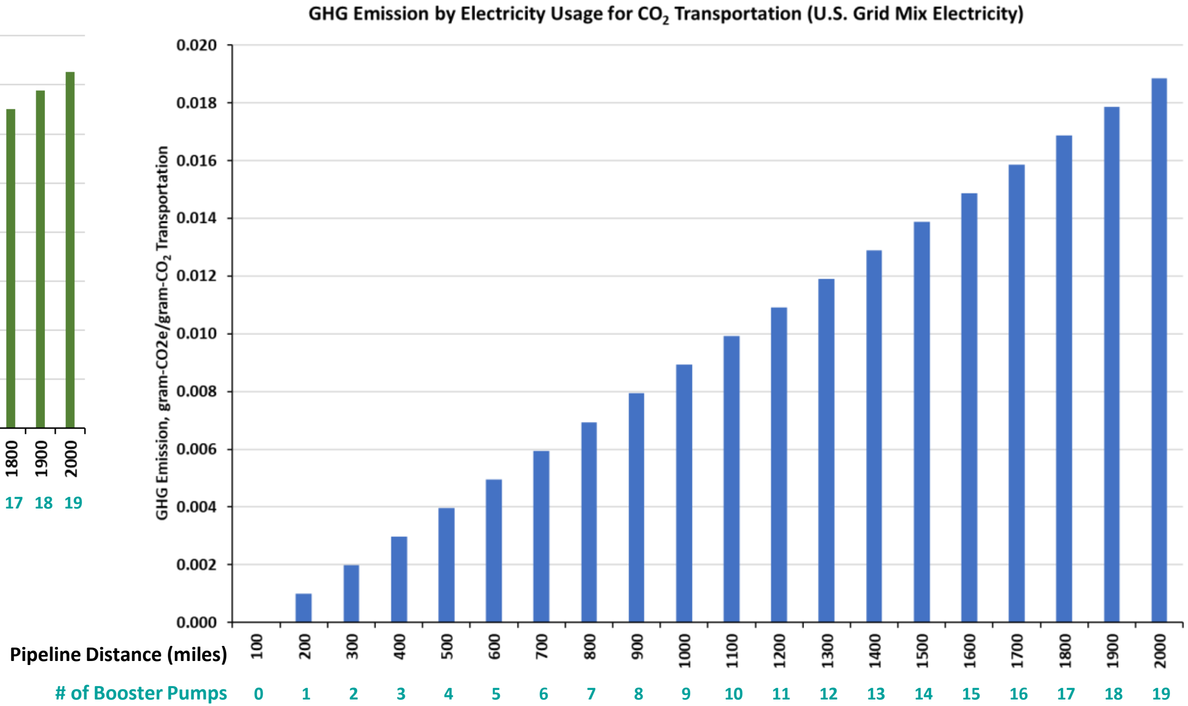


CO_2 booster pump work (transportation)

$$\text{Pump work} = \frac{m \times \Delta P}{\eta \times \rho}$$

m	CO_2 mass compressed
P	Pressure
η	Pump efficiency
ρ	CO_2 density

- **GHG emission by using U.S. Grid mix**
- **Zero GHG emission with renewable (Wind) electricity**



CO_2 Capture and Transportation Energy for Each e-fuel Pathway (CCU)

- **Calculation**
  - (CO_2 capture energy + CO_2 compression energy + CO_2 transportation energy) x (Total CO_2 input mass per mmBtu of fuel throughput)
  - Unit: Btu/mmBtu of fuel throughput

- **e.g., FT fuel production with RWSG with hydrogen recycle - CO_2 source from the hydrogen (SMR) plant**

131	**3) Calculations of Energy Consumption, Water Consumption, and Emissions for Each Stage**					
132		**FT fuel production with RWGS with H2 recycle**				
133		**FT Fuel Production**	**Intermediate combustion**	**FT Fuel Transportation and Distribution**	**FT Fuel Storage**	**CO2 capture and transport**
134	**Share of feedstock input as feed (the remaining input as proce**	96.27%				
135	**Energy efficiency**	57.47%				
136	**Urban emission share**		10.0%	67.00%	70.00%	
137	**Loss factor**	1.000		1.000	1.000	
138	**Steam exported: Btu/mmBtu of fuel produced**	0.000				
139	**Electricity exported: KWh/mmBtu of fuel produced**	0.000				
140	**CO2 input: grams per mmBtu FT fuel product**	162,251				
141	**Shares of hydrogen as process fuels**	3.73%				
142	Natural gas	0%				
143	Hydrogen	76.05%				
144	Electricity	23.95%				
145	Natural gas					684,955.06
146	Feed loss	0.00%				
147	**Energy use: Btu/mmBtu of fuel throughput (except as noted)**					
148	Hydrogen	64,204				
149	Electricity	20,219				86,917
150	Natural gas	0				
151	Fuel gas		449,333			
152	Feedstock loss	0		46	0	

Natural Gas Demand

Total CO_2 input = 162,251 g/mmBtu-fuel

CO_2 capture = 4,454 MJ/MT-CO_2

Electricity Demand

Total CO_2 input = 162,251 g/mmBtu-fuel

CO_2 capture = 138 MJ/MT-CO_2
CO_2 compression = 420 MJ/MT-CO_2
CO_2 transportation = 7.7 MJ/MT-CO_2

Overview of Pathways

FT Fuel

- **Fischer-Tropsch reaction**
- **Feedstock**
  - Captured CO_2
  - H2
  - Electricity

- **Two pathways**
  - *Low conversion*
  - *High conversion*

    (by integrating with nuclear)
- **Product**
  - Jet fuel
  - Diesel
  - Gasoline

Electro-Methanol

- **Catalyzed reaction between CO and H_2**
- **Feedstock**
  - Captured CO_2
  - H_2
  - Electricity
- **Product**
  - Methanol

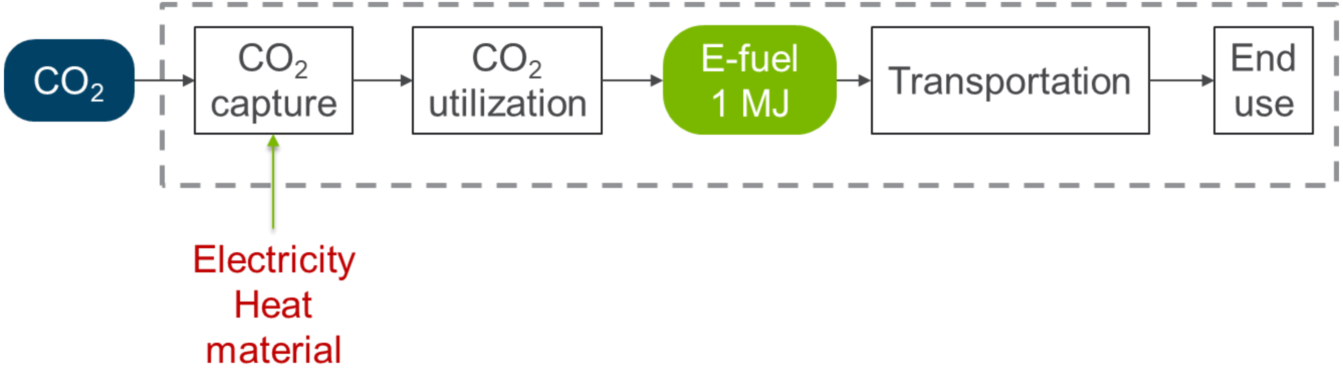
Ethanol

- **Produced using gas fermentation**
- **Feedstock**
  - Captured CO_2
  - H_2
  - Electricity
- **Product**
  - Ethanol

GREET Methods for CO_2 Utilization

Incremental Approach

E-fuels Production Boundary

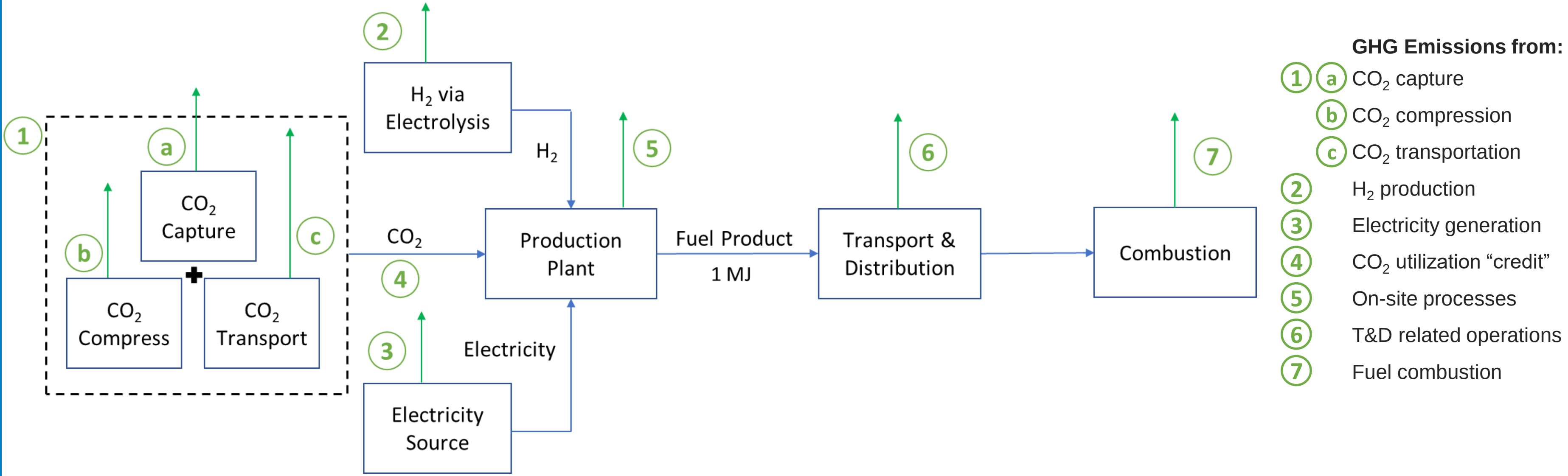


$$CI_{e-fuel} = GHG_{capture} + GHG_{conversion} + GHG_{transportation} + GHG_{fuel\ use}$$

$$= m_{CO_2} \times CI_{CO_2\ feedstock} + \left[\Sigma\left(X_{input} \times CI_{input}\right) + m_{unconverted\ CO_2}\right] + GHG_{transportation} + GHG_{fuel\ use}$$

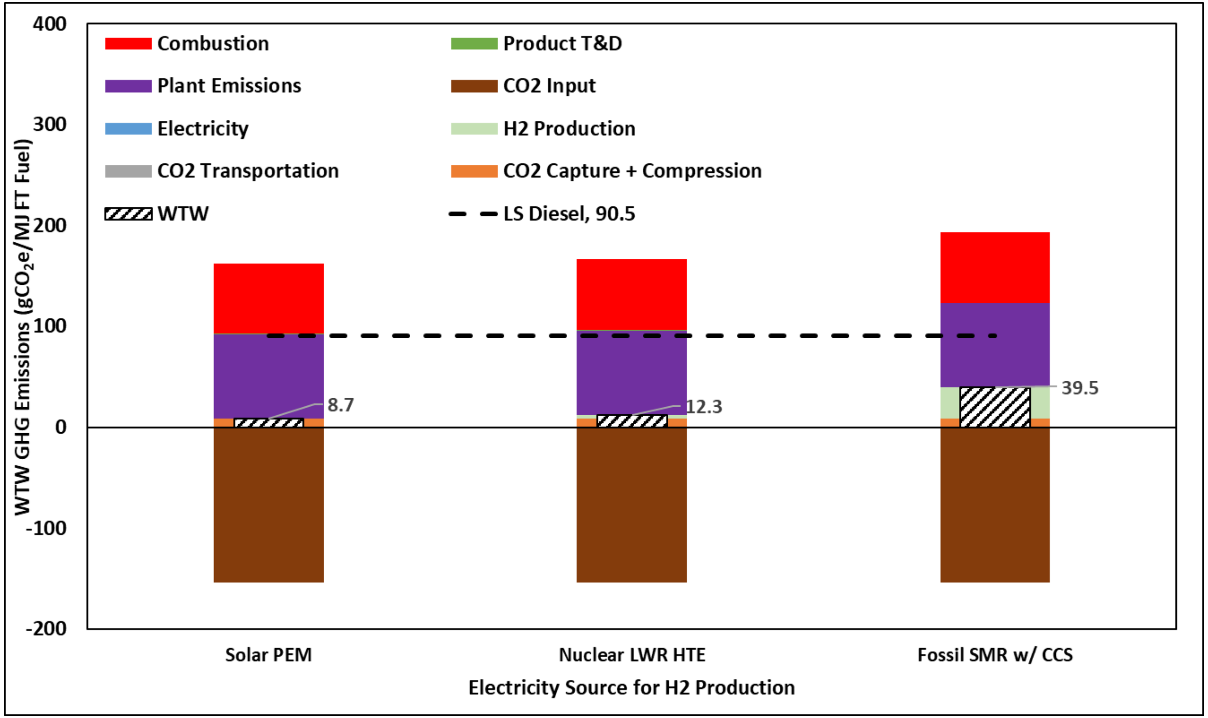
- Method: the CI of the CO_2 feedstock is estimated from the separated CO_2 capture process.
- Pros: the CI of e-fuel is defined; the upstream that releases CO2 does not need to be analyzed.
- Note: GHG credit is only issued to the CO2U facility.

General Scheme of E-fuel Pathways



- Electro- fuel : FT fuels, MeOH, EtOH
- CO_2 : Industrial sources, power plant, DAC
- Electricity for CO_2 capture + compression: Grid, NG, coal, biomass, wind, nuclear
- H_2 source: solar electrolysis, nuclear electrolysis, fossil SMR
- Electricity for e-fuels production: Grid, NG, coal, biomass, wind, nuclear

FT Fuel – Low Conversion: H_2 Source Impact

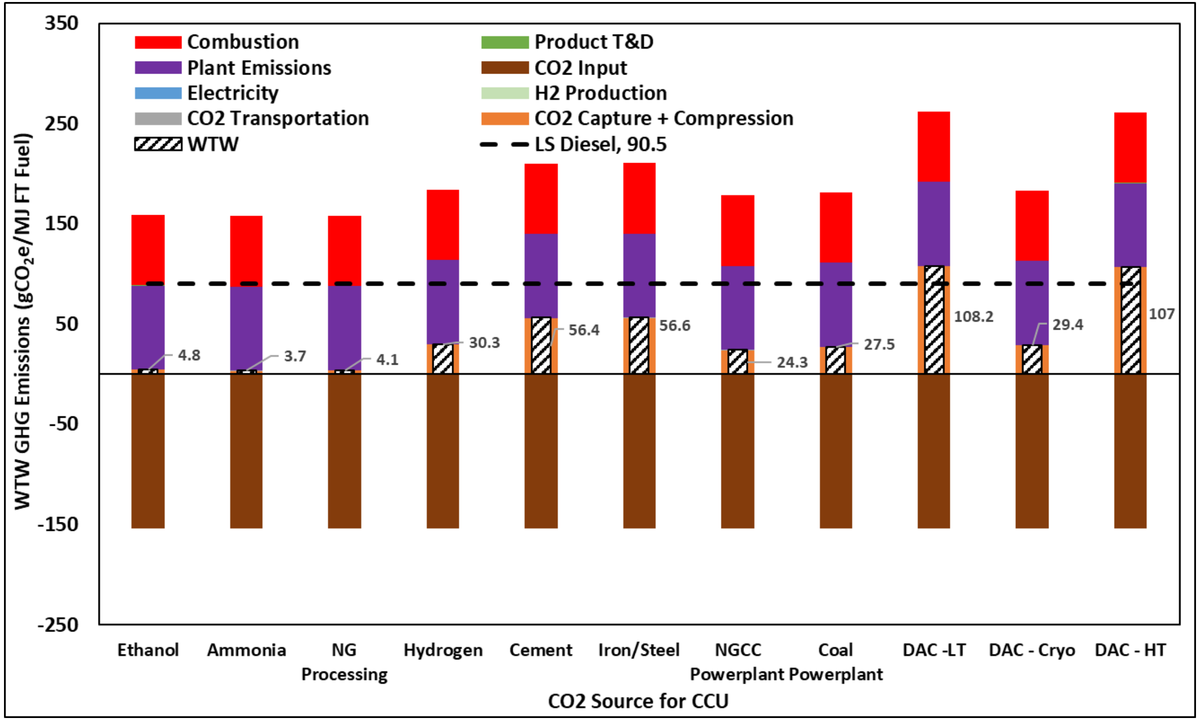


Assumptions

- CO_2 is from ethanol plant
- CO_2 capture & compression from grid electricity
- CO_2 transportation → 200 mi w/ grid electricity

- Collecting CO_2 from ethanol plant does not need capture unit, only needs compression.
- Using H_2 from renewable or nuclear electricity can reduce e-fuels GHG emission significantly relative to petroleum counterpart.

FT Fuel – Low Conversion: CO_2 Source Impact

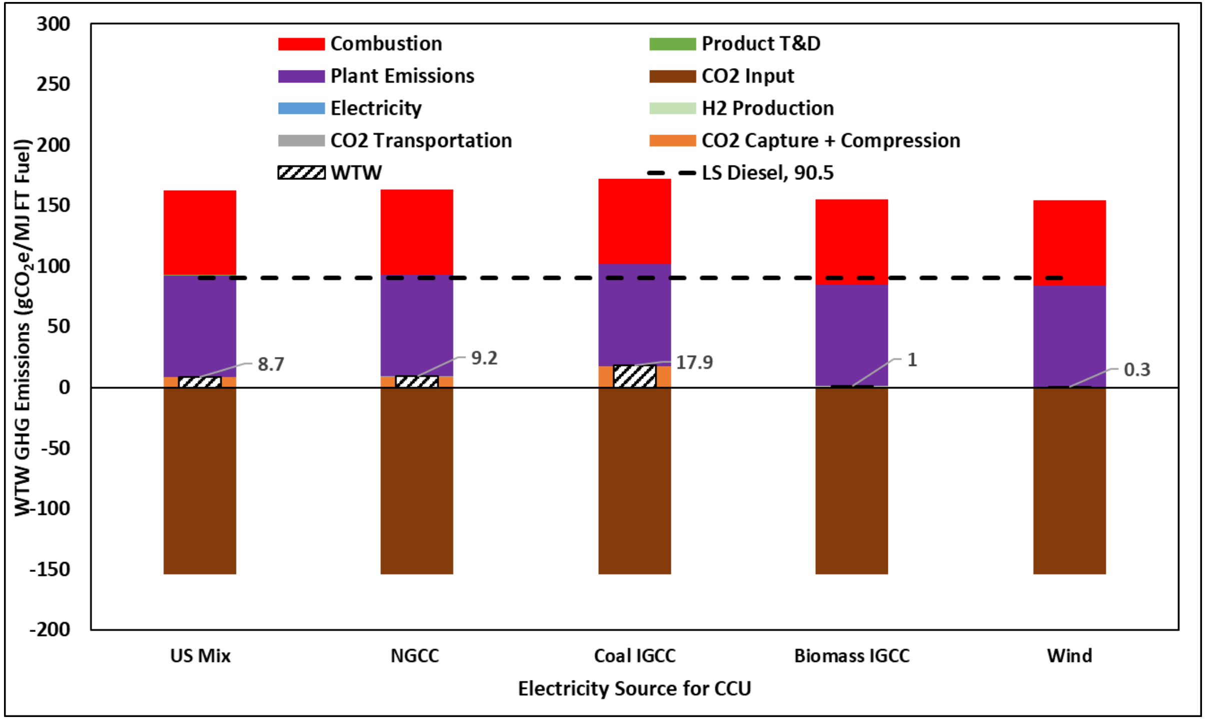


Assumptions

- H_2 from solar/wind PEM
- Electricity for CO_2 capture & compression is from U.S. grid (except for power plant)
- The heat for CO_2 capture is from natural gas
- CO_2 transportation → 200 mi w/ grid electricity

- Using high purity CO_2 sources (EtOH, Ammonia, NG processing) for e- FT fuels production can reduce GHG emission by 90% relative to petroleum baseline, when low carbon H2 and electricity are used.

FT Fuel – Low Conversion: Electricity Impact

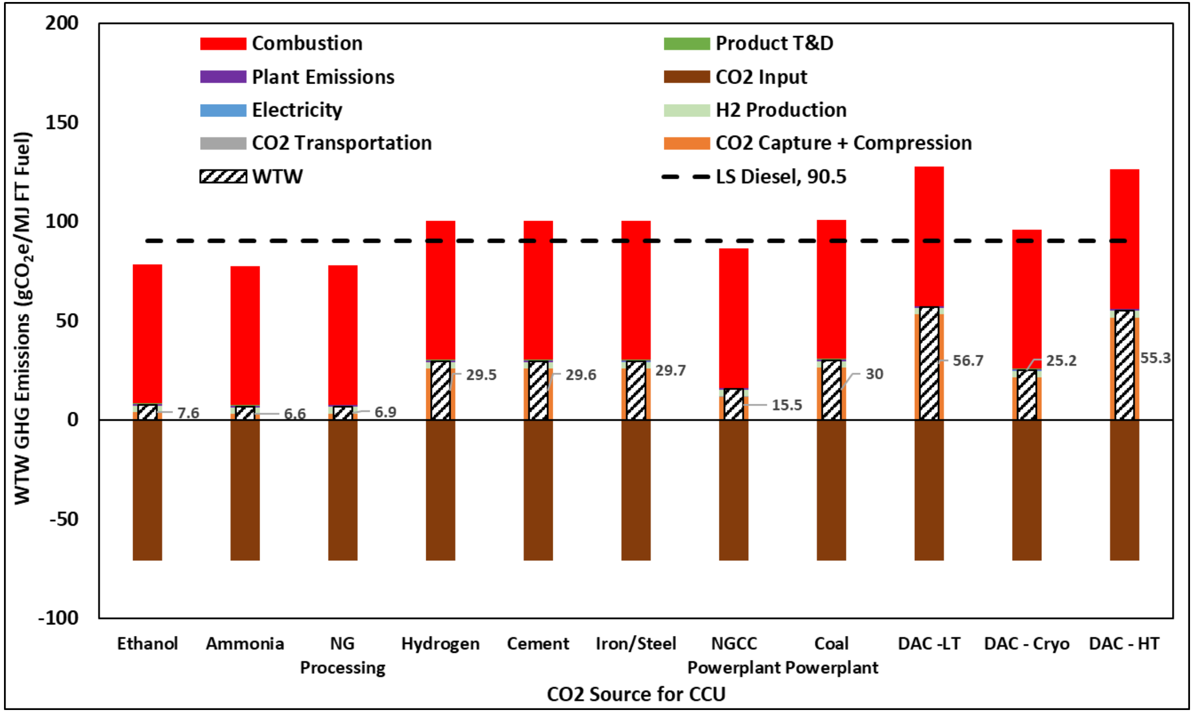


Assumptions

- H_2 from solar/wind PEM
- CO_2 is from ethanol plant, thus there is only energy consumption for compression.
- CO_2 transportation → 200 mi w/ grid electricity

- Excluding the electricity consumption for H_2 production, the onsite electricity consumption for FT production is relatively small, thus the impact of electricity source is not significant.

FT Fuel – High Conversion: CO_2 Source Impact

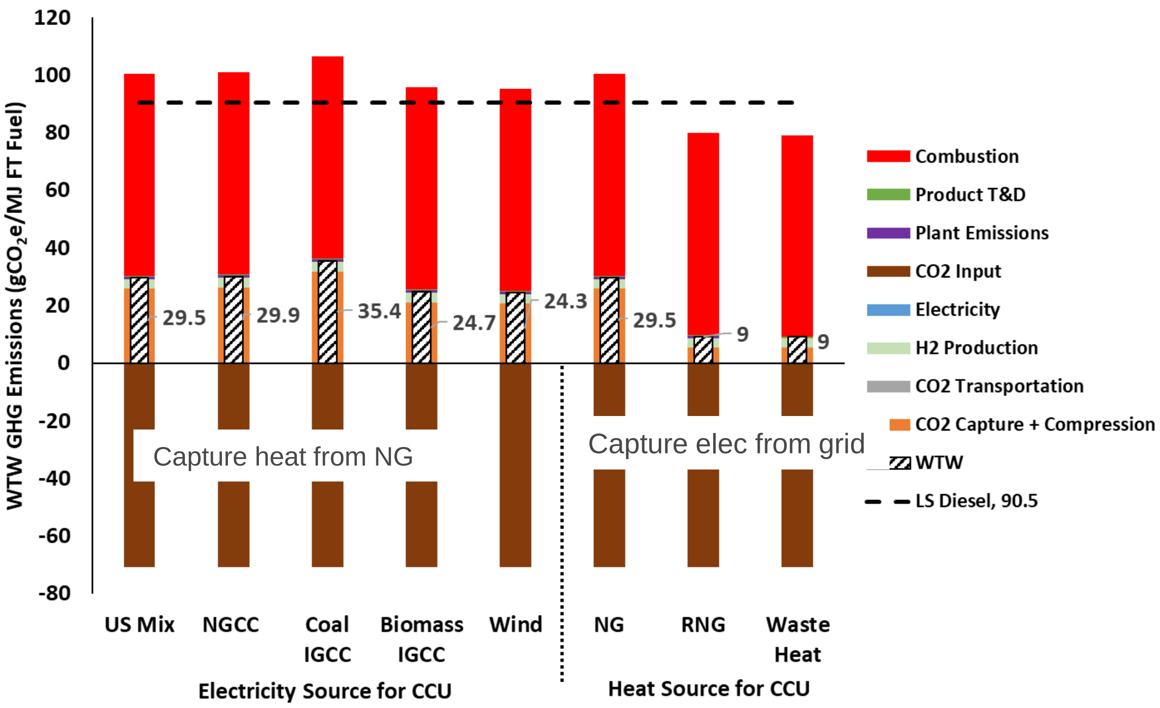


Assumptions

- H_2 from nuclear HTE
- CO_2 capture & compression from grid or powerplant electricity
- The heat for CO_2 capture is from natural gas
- CO_2 transportation → 200 mi w/ grid electricity

- Using high purity CO_2 sources (EtOH, Ammonia, NG processing) for e- FT fuels production can reduce GHG emission by 90% relative to petroleum baseline.

FT Fuel – High Conversion: Impact of CO2 Capture Energy Sources

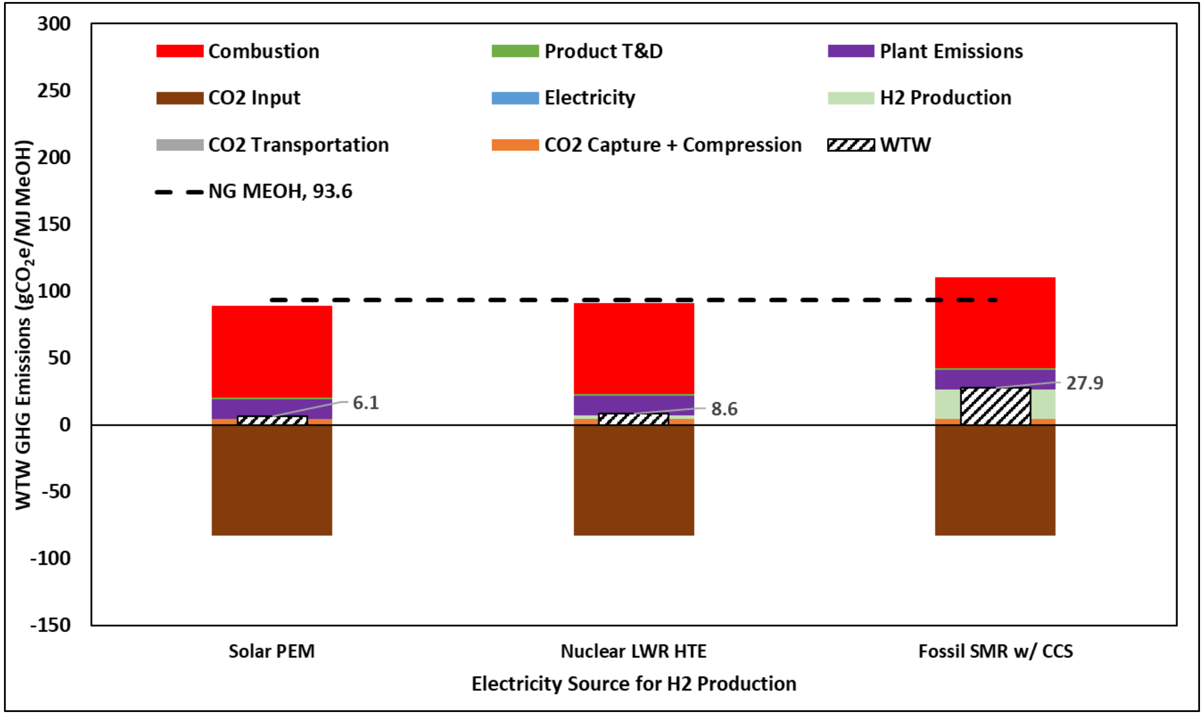


<u>Assumptions</u>

- H_2 from nuclear HTE
- CO_2 is from **cement plant**, while electricity and heat sources vary
- CO_2 transportation → 200 mi w/ grid electricity

- Similarly, excluding the electricity consumption for H_2 production, the impact of electricity source on FT production emission is relatively small.

Electro - MeOH: H_2 Source Impact

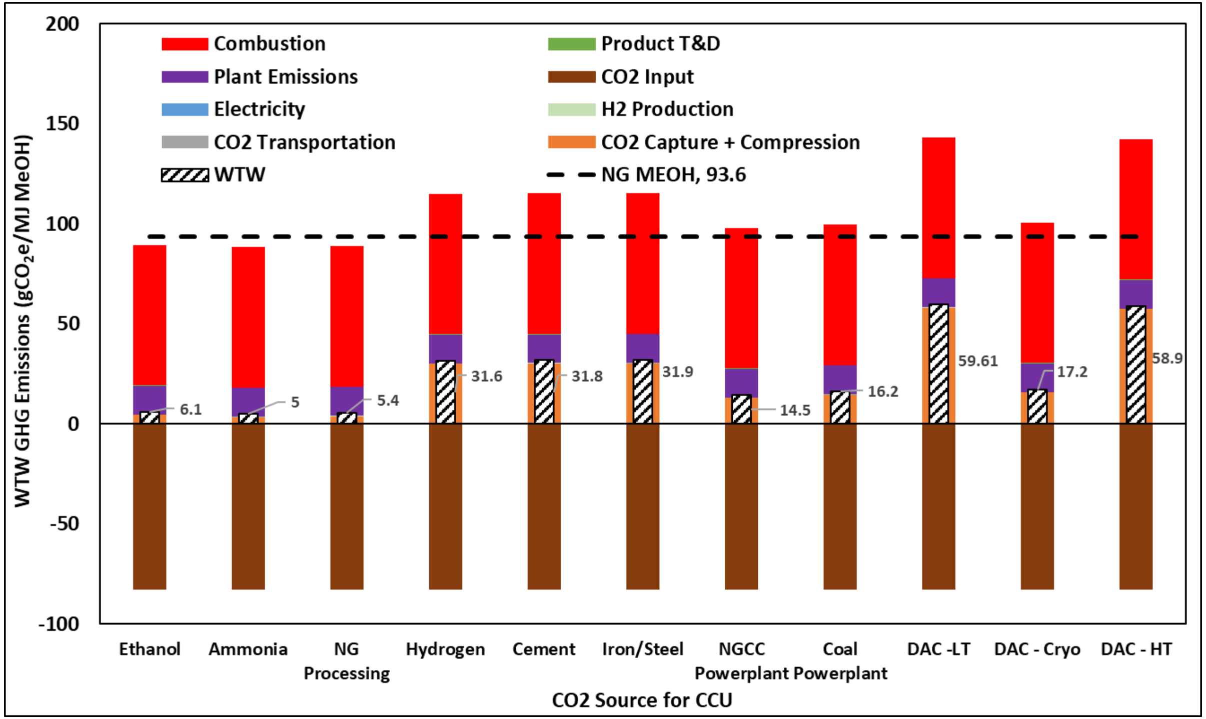


Assumptions

- CO_2 is from ethanol plant
- CO_2 capture & compression from grid electricity
- CO_2 transportation → 200 mi w/ grid electricity

- Using H_2 from renewable electricity or nuclear electricity is the key for e-fuels production to decarbonize transportation.

Electro - MeOH: CO_2 Source Impact

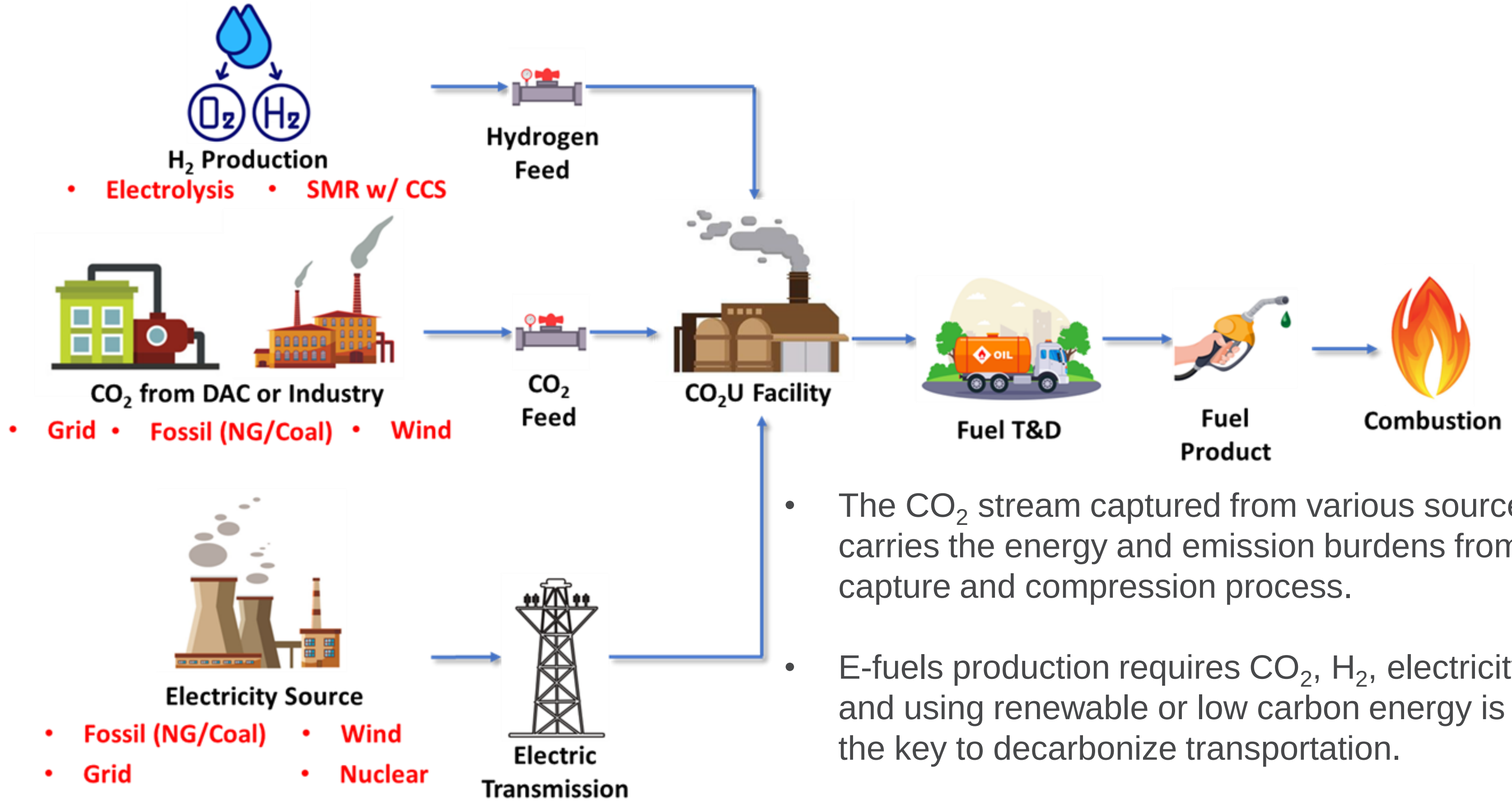


Assumptions

- H_2 from solar/wind PEM
- CO_2 capture & compression from grid or powerplant electricity
- The heat for CO_2 capture is from natural gas
- CO_2 transportation → 200 mi w/ grid electricity

- Using high purity CO_2 sources (EtOH, Ammonia, NG processing) for e-methanol production can reduce the GHG emission by more than 90% relative to fossil counterpart produced from NG.

Key Messages



- The CO_2 stream captured from various sources carries the energy and emission burdens from capture and compression process.
- E-fuels production requires CO_2, H_2, electricity and using renewable or low carbon energy is the key to decarbonize transportation.

Acknowledgement

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