DOE Hydrogen Program

2022 Annual Merit Review and Peer Evaluation Meeting

Nuclear Hydrogen and Synthetic Diesel and Jet Fuel

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Project ID: NE002

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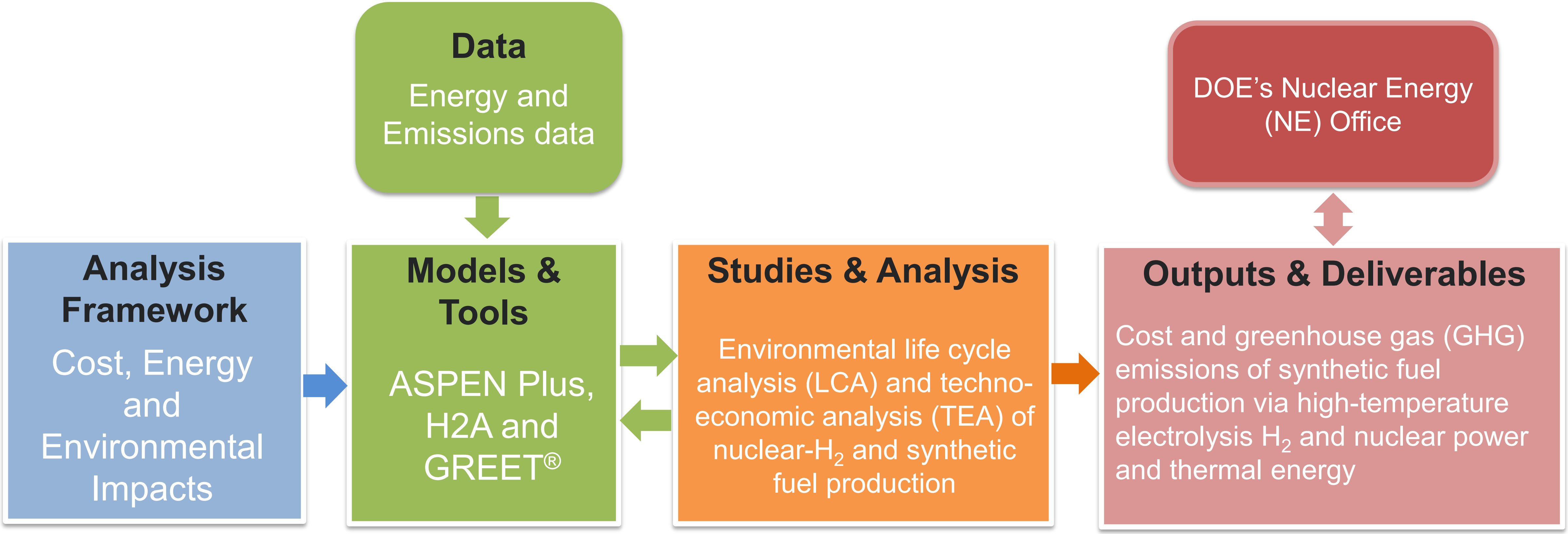
Project GOAL: Evaluate cost and greenhouse gas (GHG) emissions of synthetic fuel production using nuclear power and thermal energy



Overview

Timeline

- Start: October 2021
- End: Determined by DOE
- % complete (FY22): 70%

Barriers to Address

- Insufficient suite of models and tools
- Indicators and methodology for evaluating economic and environmental sustainability
- Overcome inconsistent data, assumptions, and guidelines

Budget

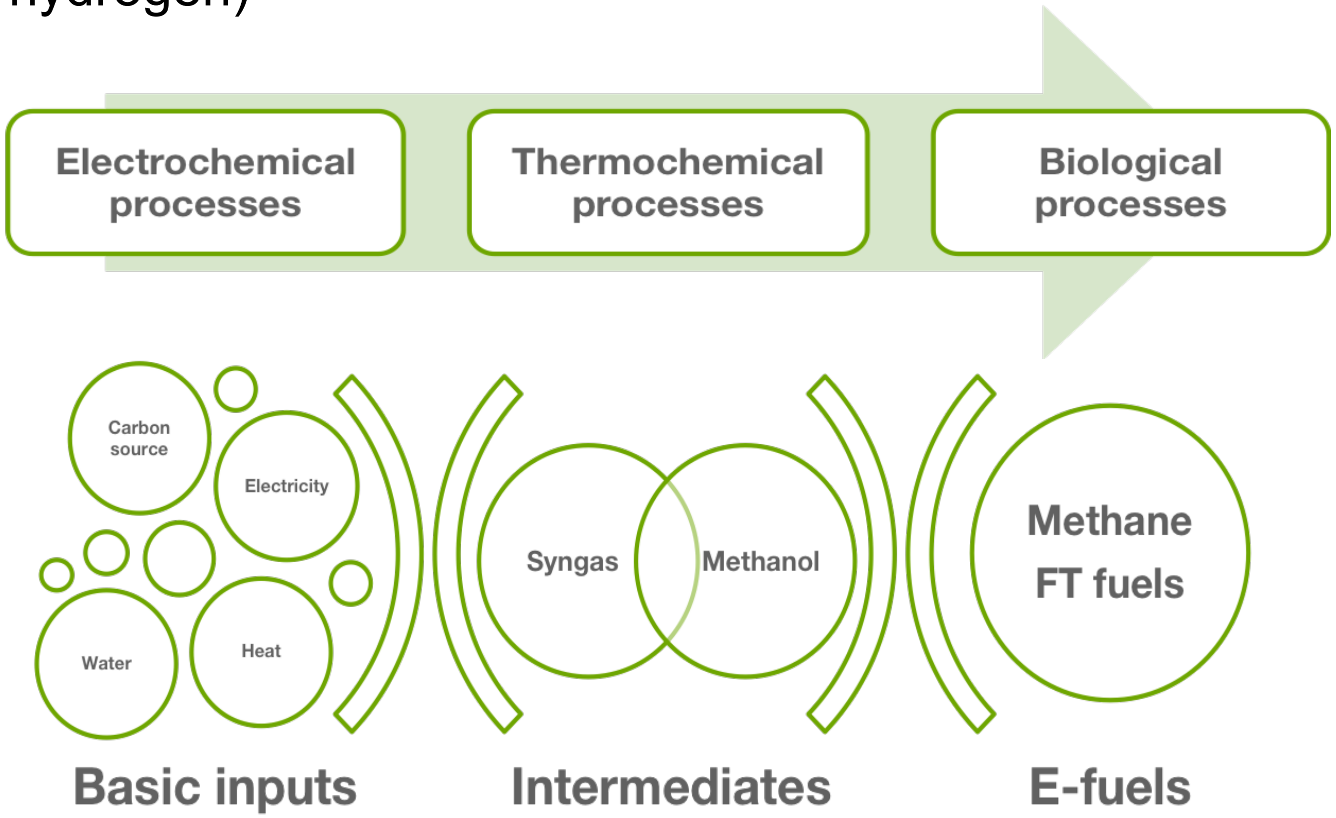
- Funding for FY22: $563K

Partners/Collaborators

- Idaho National Laboratory
- Industry collaborators

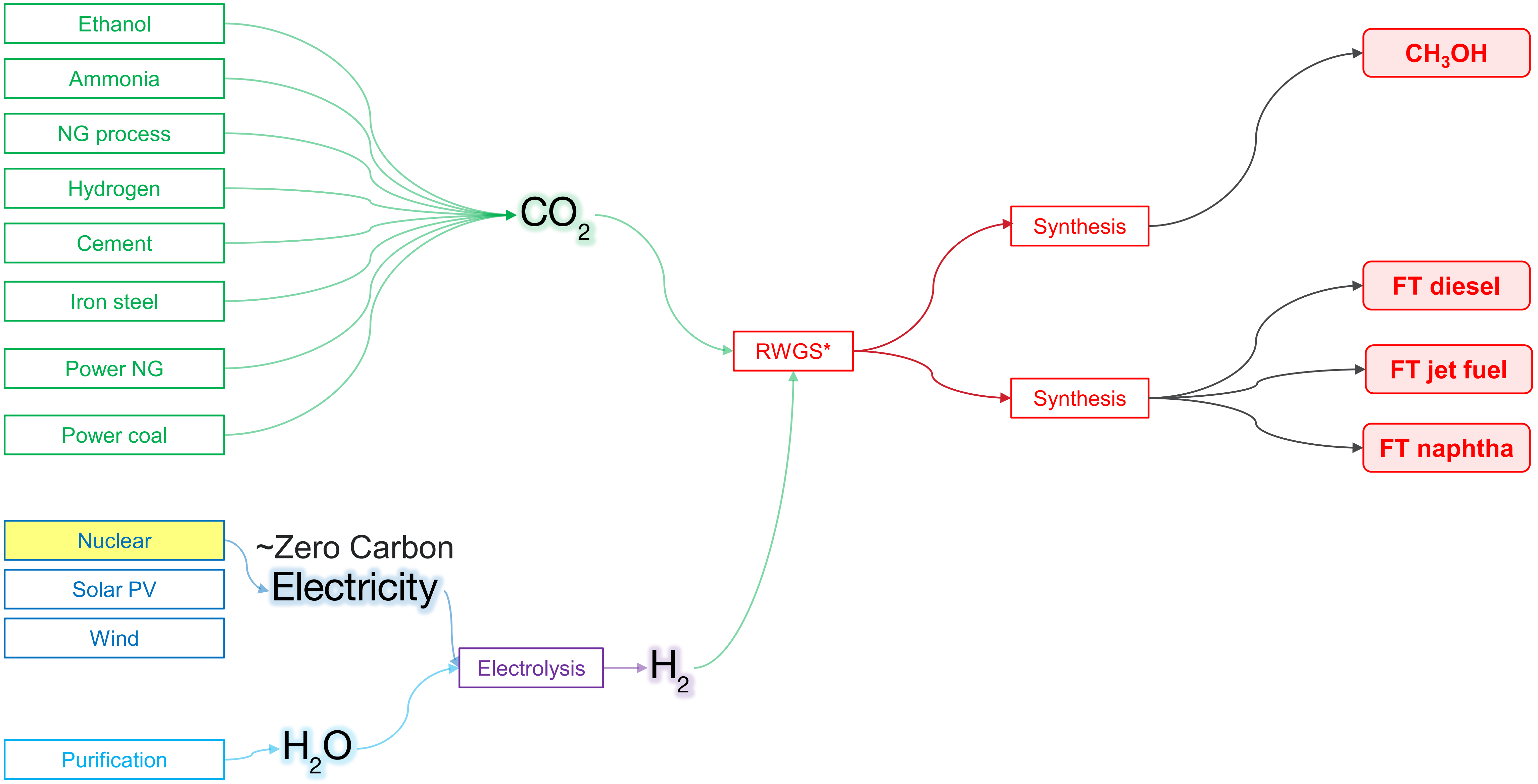
H_2+CO_2 → Liquid hydrocarbon fuels and chemicals

- Synthetic fuels or electrofuels "e-fuels" are liquid hydrocarbons, e.g., Fischer-Tropsch (FT) fuels, that encompass energy carriers (and their intermediates) primarily using a carbon source and electricity (for hydrogen)



Conversion processes for synthetic FT fuels

Approach/Strategy



*RWGS= Reverse water-gas shift reaction

Potential synfuel production by nuclear power capacity

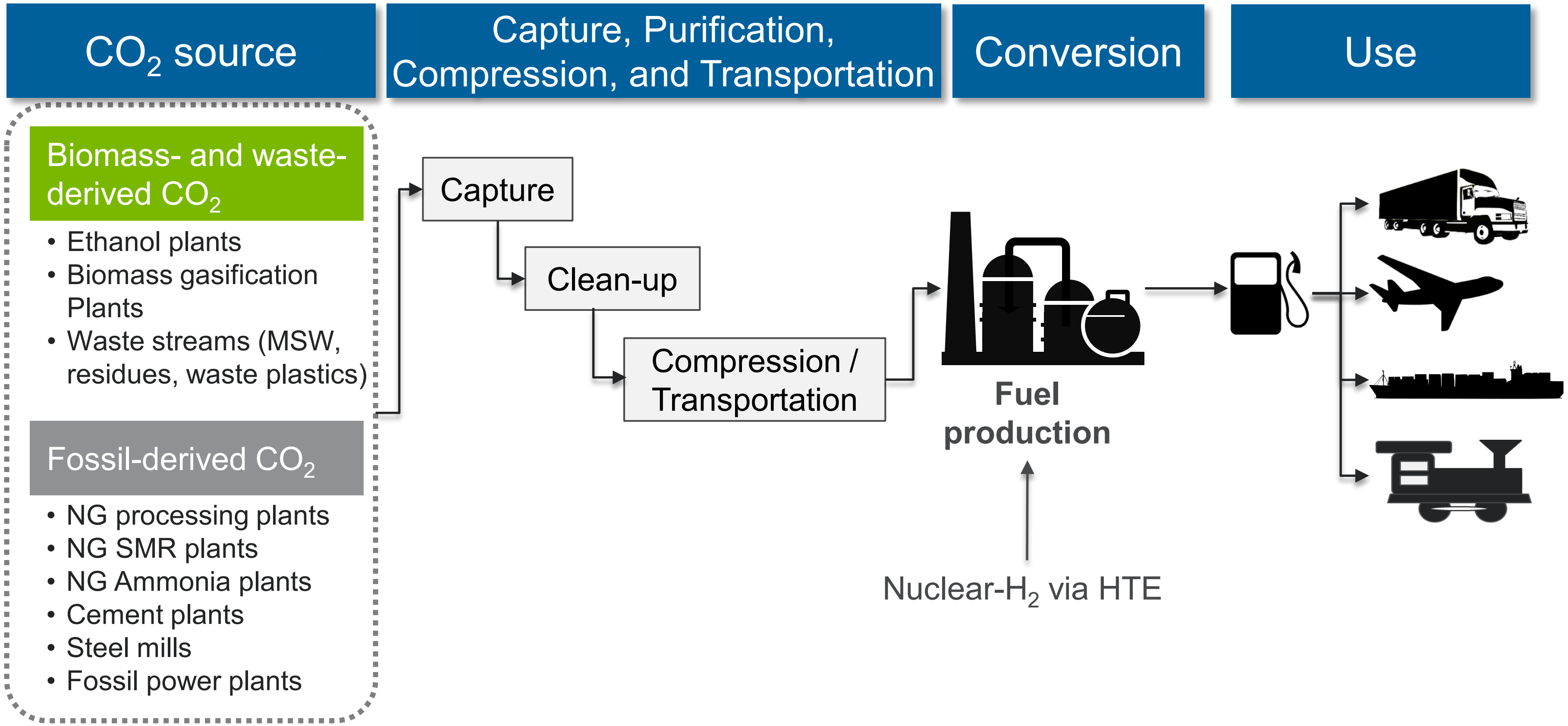
Nuclear reactor scale	Large (300~1,000+MW)	Small (20~300MW)	Micro (1~20MW)
			
H_2 production from HTE (efficiency 80%)	170~580 metric ton/day	12~170 metric ton/day	0.6~12 metric ton/day
FT fuel production	270~910 metric ton/day	18~270 metric ton/day	0.9~18 metric ton/day
FT fuel production	**98,000~330,000 gal/day**	**6,500~98,000 gal/day**	**330~6,500 gal/day**

Nuclear reactor scale information from Shannon Bragg-Sitton and Richard Boardman 08/12/2021 Next Generation Nuclear Energy -Advanced, Small and Micro-Modular Reactors (SMRs and MMRs)

Synfuel synthetic plant evaluated by ANL

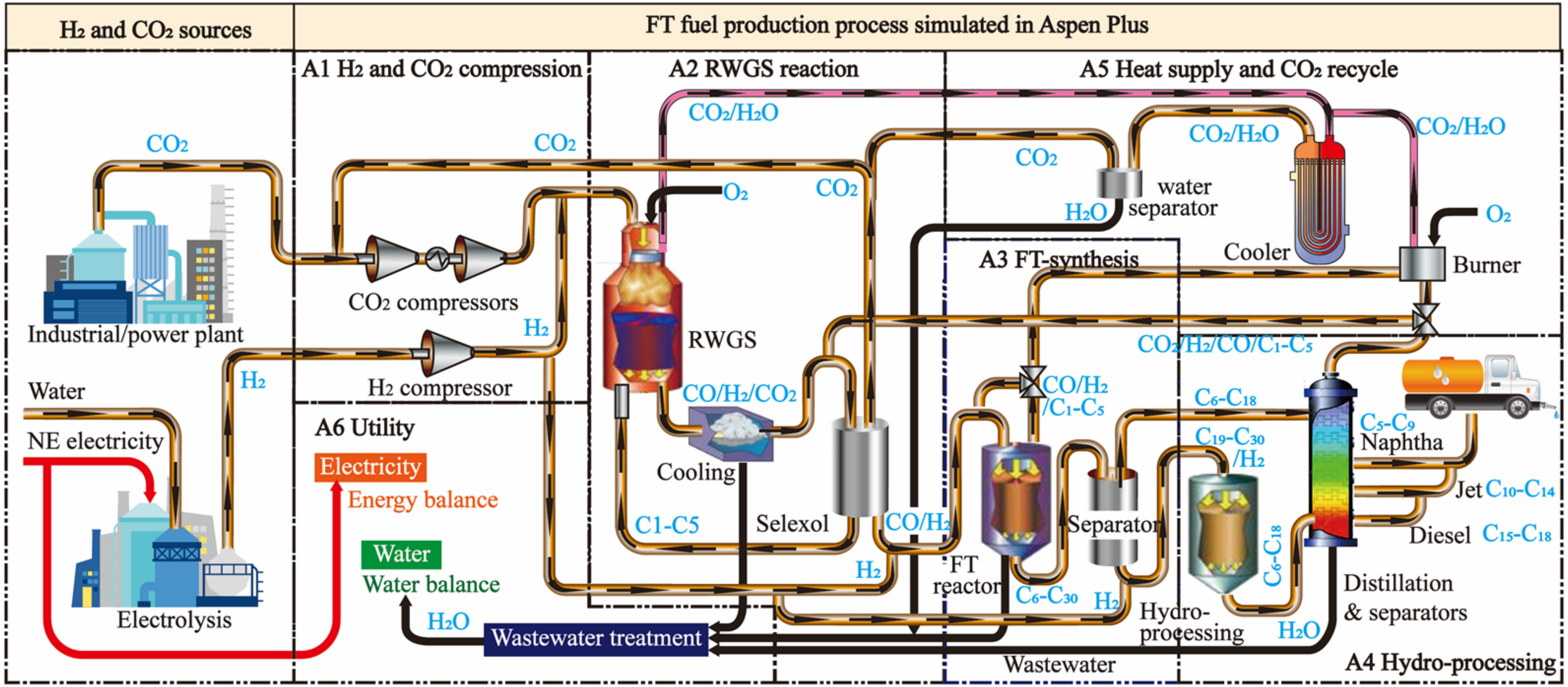
Nuclear power	H_2 production	FT fuel production
440 MW	255 metric ton/day	185,000 gal/day

System boundary for synthetic (FT) fuel economic and environmental analysis



HTE=High Temperature Electrolysis

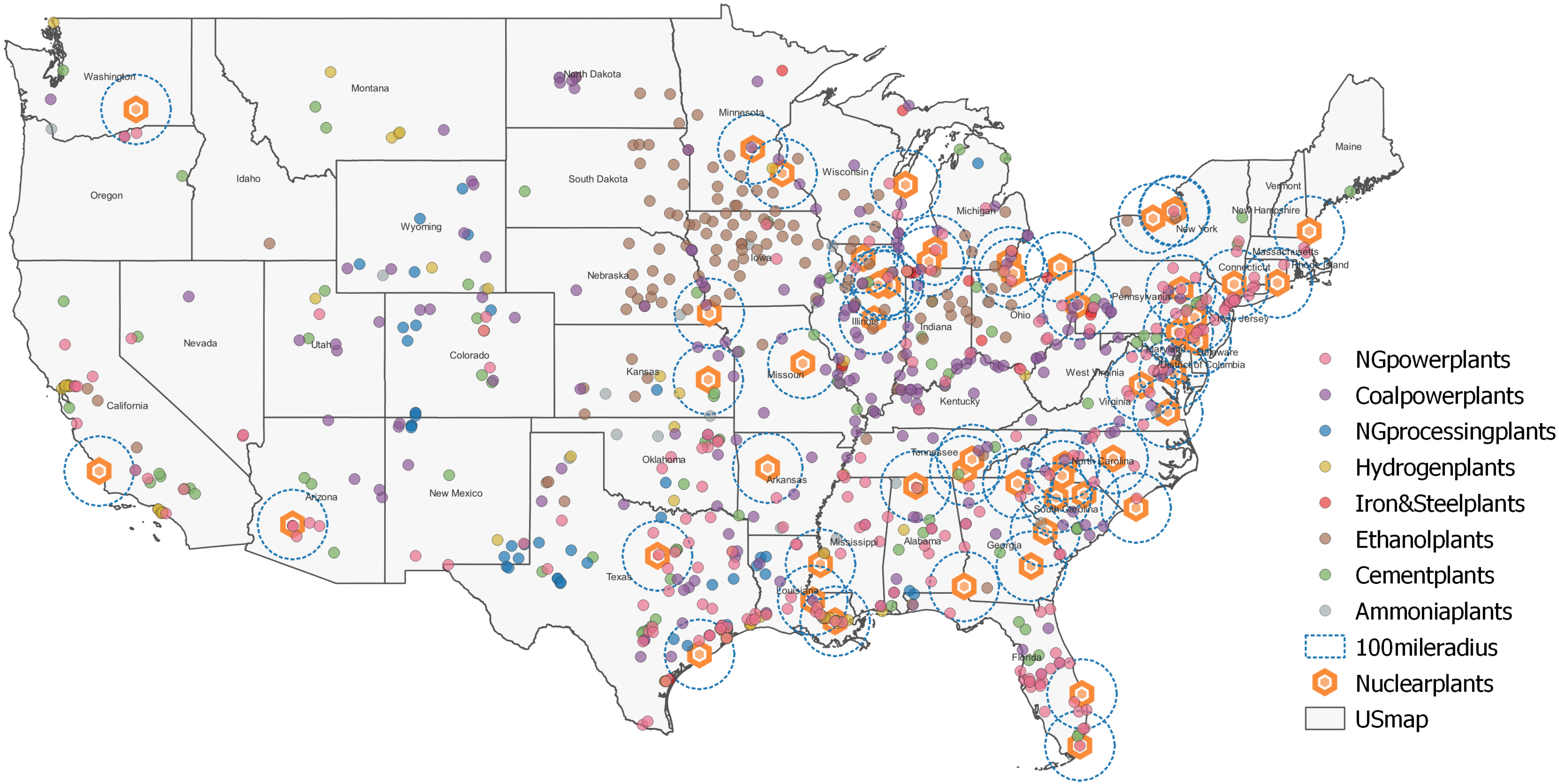
Process modeling of FT fuel production using Aspen-Plus



- **System boundary-new baseline**
  - ✓ H_2 and electricity from NE plant
  - ✓ Tail gases are combusted for direct heating and generating steam
  - ✓ Low quality steam (151°C) can be used for H_2 electrolysis or CO_2 capture from industrial/power plant

- **Chemical equations of C1-C30 carbon chain**
  - ✓ The Fischer–Tropsch (FT) process involves a series of chemical reactions that produce a variety of hydrocarbons C_nH_{2n+2} (alkanes)
  - ✓ The more useful products are C_5–C_{18}

Large number of CO_2 sources exist within 100-mile radius from nuclear power plants



Potential CO_2 supply from various sources (2020)

Sector	CO_2 Purity	Subgroup	Number of Facilities (Process CO_2 emission above 0.1 MMT/yr)	CO_2 annual production [million ton-CO_2]
Industries	High	Ethanol Plant[(a)]	134	25.9
		Ammonia[(b)]	25	21.2
		Natural Gas Processing[(b)]	44	9.8
Industries	Medium	Hydrogen[(b)]	76	38.3
		Cement[(b)]	89	64.6
		Iron and Steel[(c)]	56	38.0
Power Plants	Low	Coal Power Plant	195	720
		Natural Gas Power Plant	602	629
		Co-firing of Coal/NG at the Same Location	34	97.1
		Total	1,255	1,618

(a) Biogenic CO_2 emission (calculation based on ethanol production)

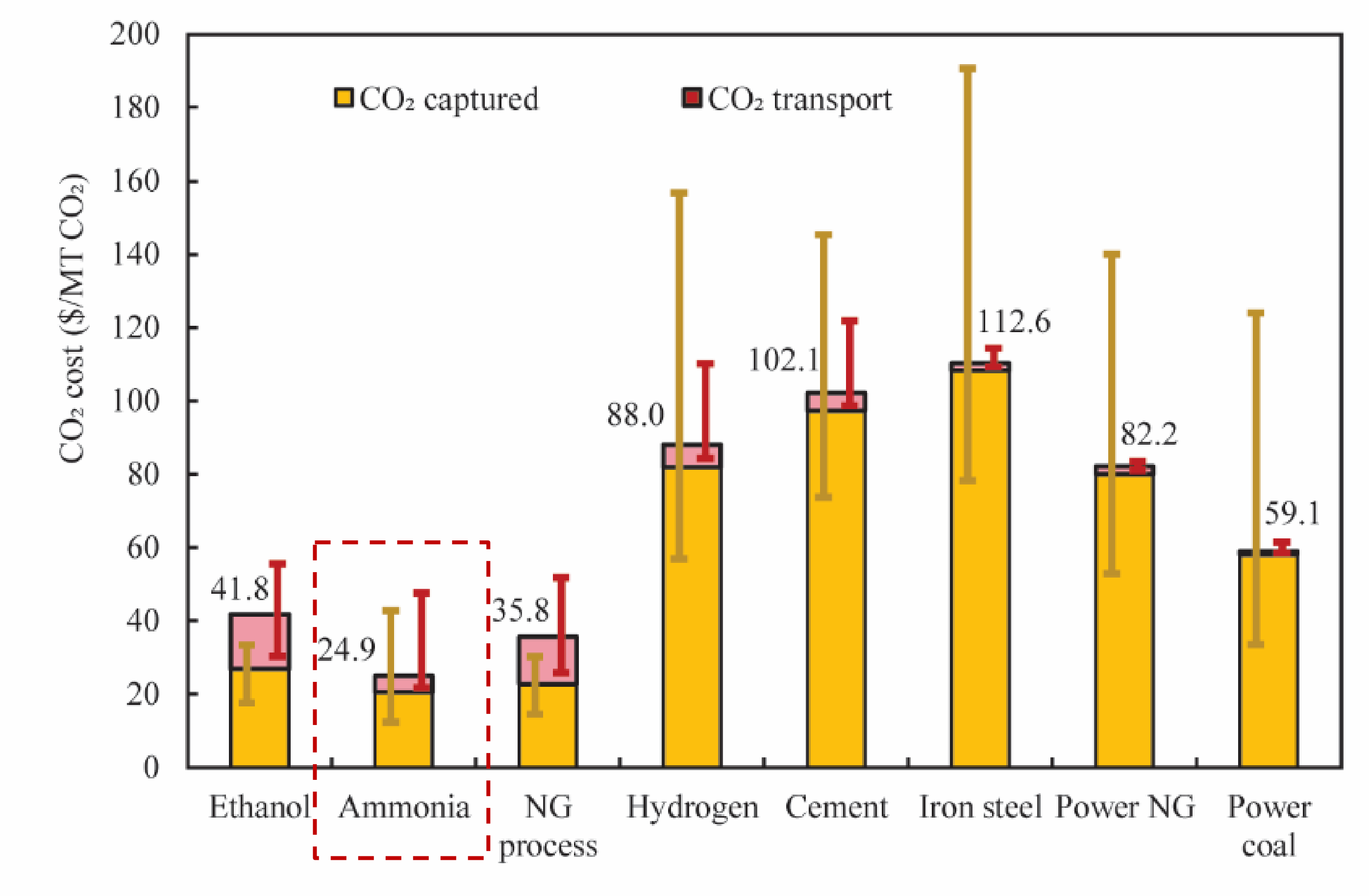
(b) CO_2 Emission from processes (exclude combustion emissions)

(c) 66% of the total CO_2 emission: 66% of mid-purity CO_2 emission facilities

Reference:

- EPA GHGRP, RFA Ethanol Production 2020
- Zang et al. 2021. Environnemental Science & Technology 2021, 55, 7595-7604

CO_2 cost vary by source



- **CO_2 cost**
  - ✓ Includes captured cost and transportation cost
  - ✓ CO_2 captured cost is impacted by CO_2 concentration and scale
  - ✓ CO_2 transportation cost is impacted by transportation distance and CO_2 daily demand
  - ✓ The CO_2 transportation distance is assumed to be 50 miles

Process modeling for synthetic FT fuel production: product yield

Feedstock Input				
Feedstock	**Mass flow (MT/day)**		**Cost ($/kg)**	**Cost ($/day)**
H_2	**255**		1.63*	414,954
CO_2	**1,580**		0.0249	39,342
Total				454,296
FT fuel output				
Fuel type	**Mass/volume flow**			
	MT/day	**gal/day**		
Naphtha	176	67,495		
Jet fuel	213	76,287		
Diesel	118	40,723		
Total	507	**184,505**		
Total FT fuel conversion				
Carbon conversion ratio (%)			99%	
H_2 consumption (kg/gal-FT fuel)			**1.38**	
CO_2 consumption (kg/gal-FT fuel)			**8.56**	

*H_2 cost scenarios: baseline natural gas H_2 $1.15/kg, nuclear HTE $1.63/kg, DOE targets $1/kg and $2/kg, high $3/kg

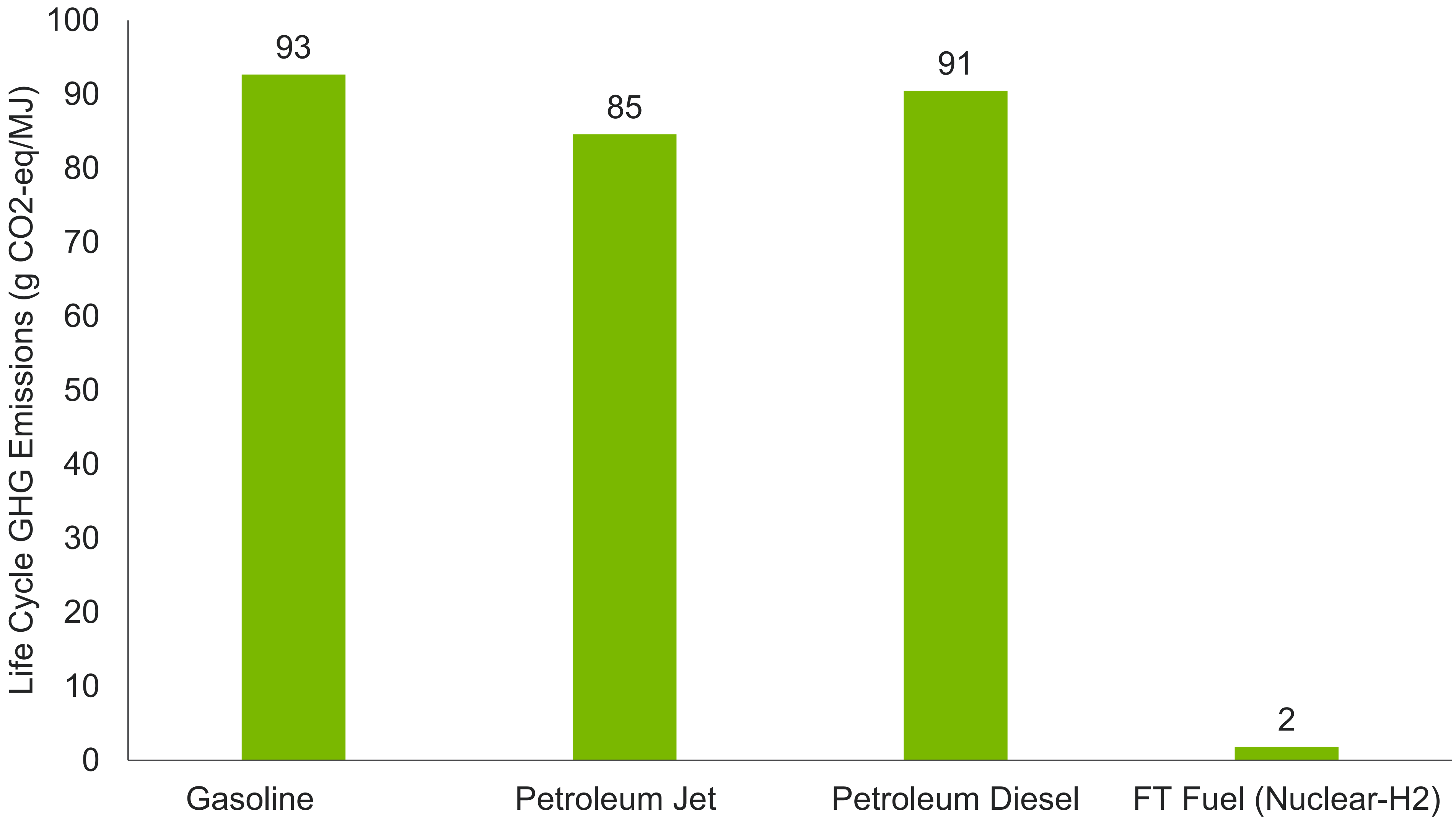
Energy Efficiency of FT fuel production is ~50%

Energy conversion efficiency (including nuclear energy for H_2 production)

Energy balance	Energy type	MW (LHV*)
Rate of energy inputs	Nuclear electricity for H_2 production	422
	Nuclear thermal energy for H_2 production	72.9
	Electricity for FT process	14.9
Rate of energy outputs	Naphtha	90.2
	Jet fuel	108
	Diesel	59.5
	Byproduct steam from FT reactor	79.8
FT-fuel production efficiency from nuclear electricity and thermal energy		**51%**
Total energy efficiency (including energy in byproduct steam)		66%

*LHV=Lower Heating Value

Nuclear-based e-fuels virtually eliminate life-cycle GHG emissions of conventional fuels



Using Argonne's GREET® model (https://greet.es.anl.gov)

Life-cycle emission analysis of power generation facilities

--Estimating embodied emissions from facilities installation, operation, and associated upstream processes of material production and manufacturing

--Compare the embodied emissions of different power generation facilities in the functional unit of per kWh of electricity generated:

- Solar photovoltaic (PV) system
- Wind turbine
- Nuclear power plant

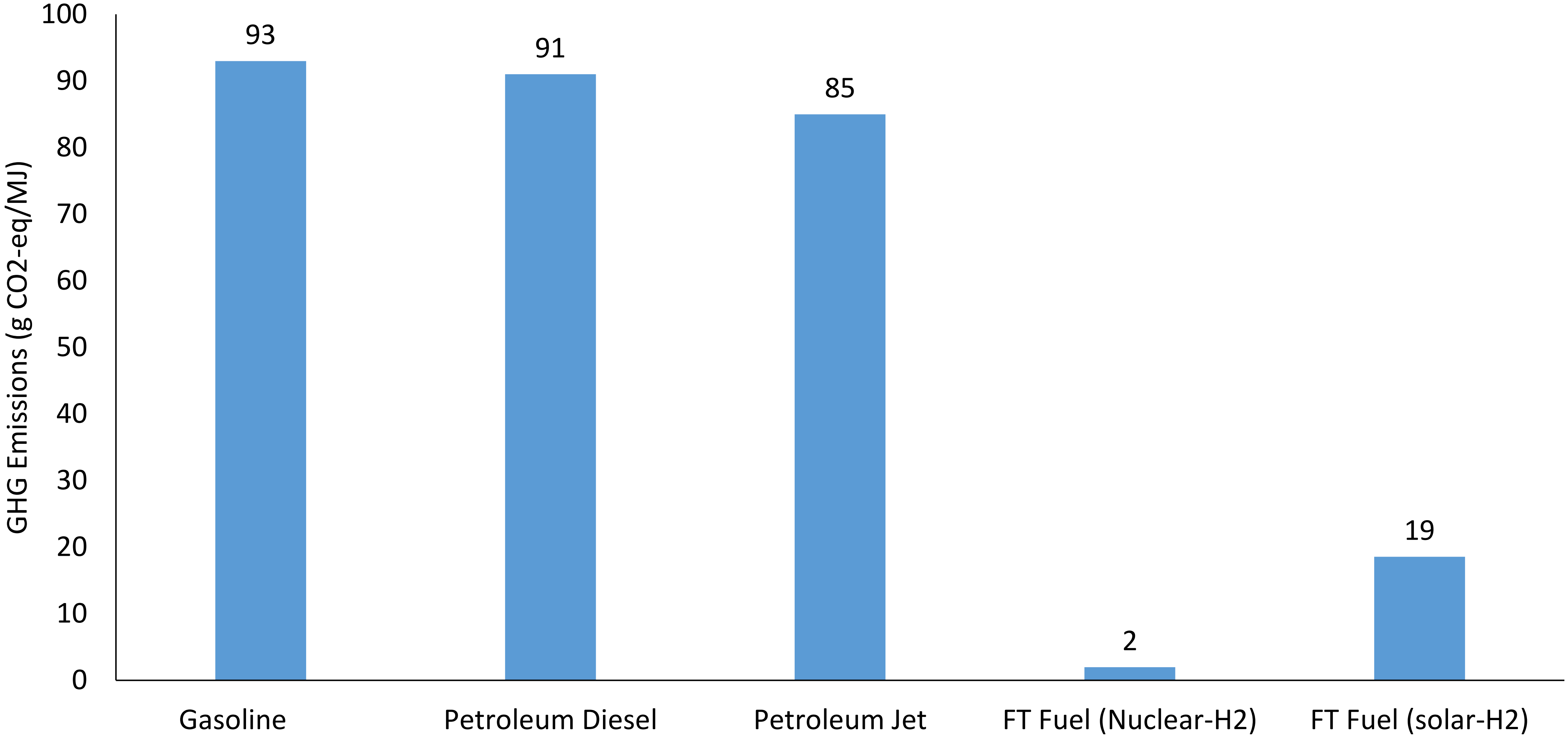
Embodied GHG emissions of electricity generating facility (gCO_{2e}/kWh)

	Solar PV	Wind	Nuclear power plant
Average	**28.5**	**9.68**	**0.29**
High	66.5	15.5	0.43
Low	19.2	7.73	0.24

Preliminary

Row material extraction **Material processing** **Manufacturing** **Installation, operation and maintenance**

Life-cycle GHG emissions of e-fuels and conventional fuels, including CAPEX emissions



Using Argonne's GREET® model

Historic retail prices for conventional fuels (untaxed) as baseline for comparison with FT cost*

Gasoline	15 Years	20 Years
Average	$2.42	$2.23
Stdev	$0.50	$0.59
Lowest	$1.45	$ 0.95
Highest	$3.48	$3.48
90th	$3.13	$3.08
80th	$2.96	$2.80
20th	$1.94	$1.75
10th	$1.82	$1.42

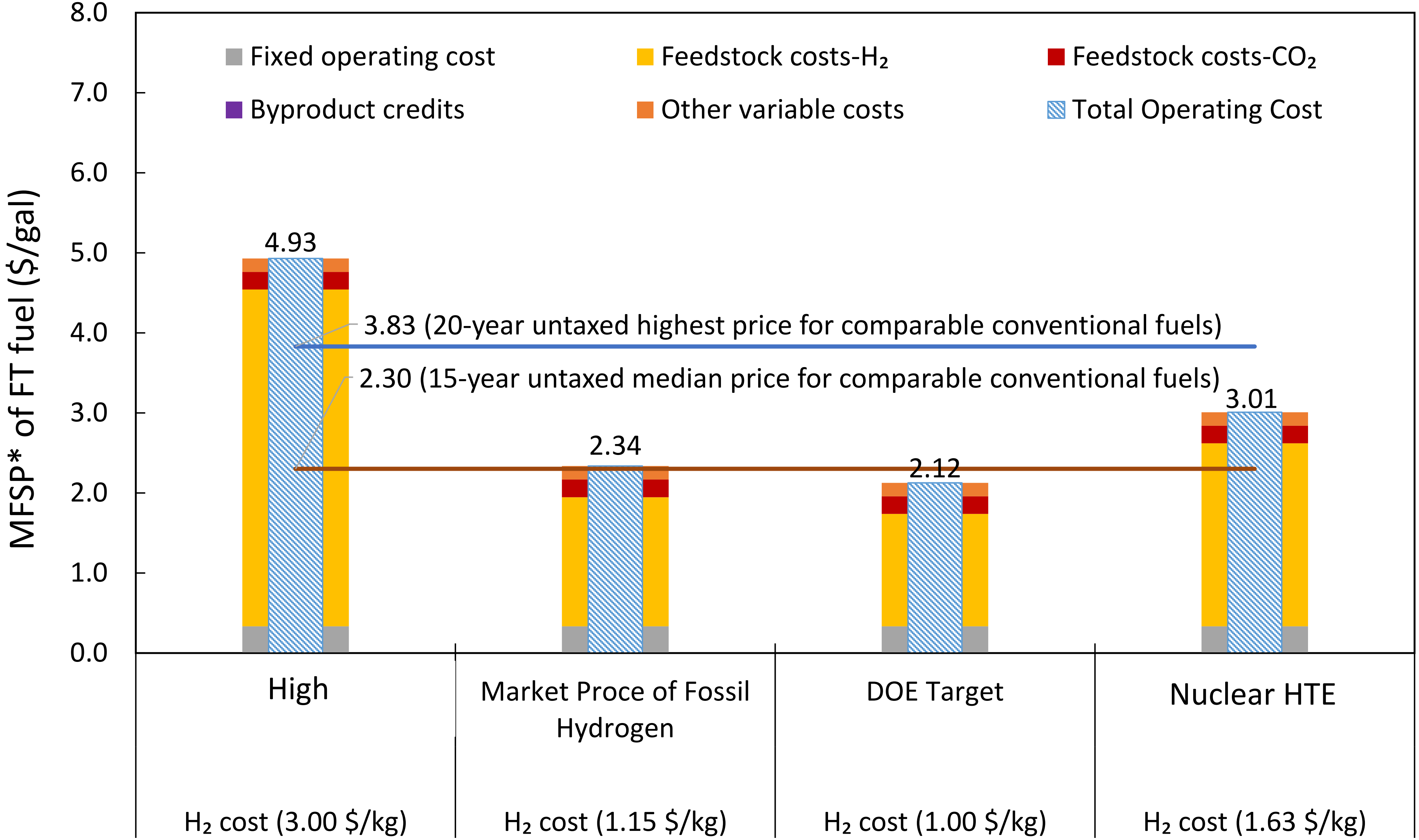
Jet Fuel	15 Years	20 Years
Average	$2.19	$1.96
Stdev	$0.69	$0.76
Lowest	$0.73	$0.56
Highest	$4.01	$4.01
90th	$3.12	$3.06
80th	$2.95	$2.81
20th	$1.54	$1.31
10th	$1.39	$0.93

Diesel Fuel	15 Years	20 Years
Average	$2.76	$2.50
Stdev	$0.54	$0.69
Lowest	$1.74	$1.00
Highest	$4.09	$4.09
90th	$3.46	$3.44
80th	$3.38	$3.30
20th	$2.23	$1.99
10th	$2.11	$1.44

	FT Fuel Production (gal/d)	Share in FT pool	15 Yr P50	20 Yr P50	20 Yr Highest
Naphtha	67,495	37%	$0.87	$0.80	$1.27
Jet Fuel	76,287	41%	$0.84	$0.79	$1.66
Diesel	40,723	22%	$0.59	$0.55	$0.90
Total	184,505	100%	**$2.30**	**$2.14**	**$3.83**

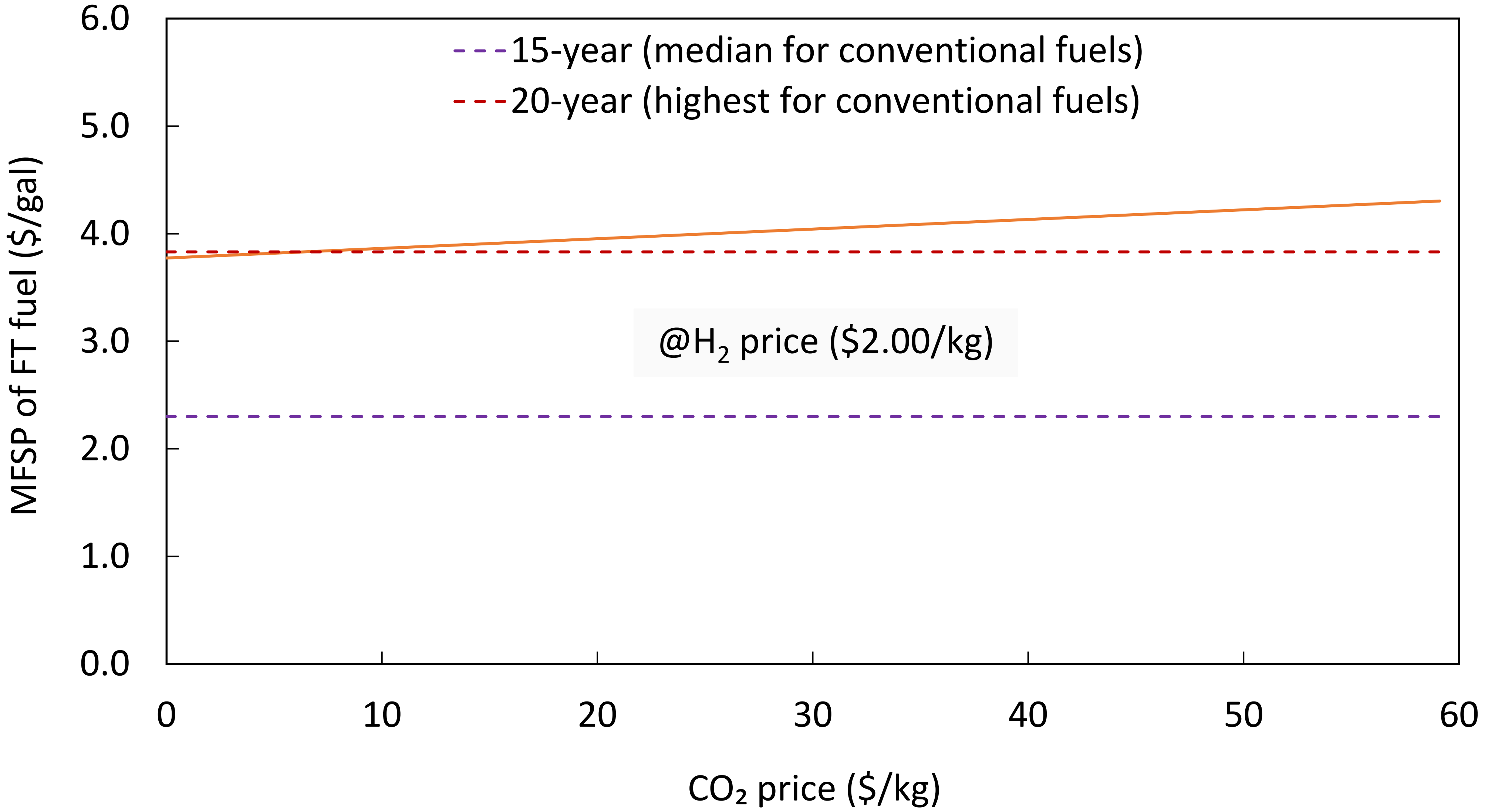
*as of March 14, 2022

H_2 cost dominates FT fuel cost

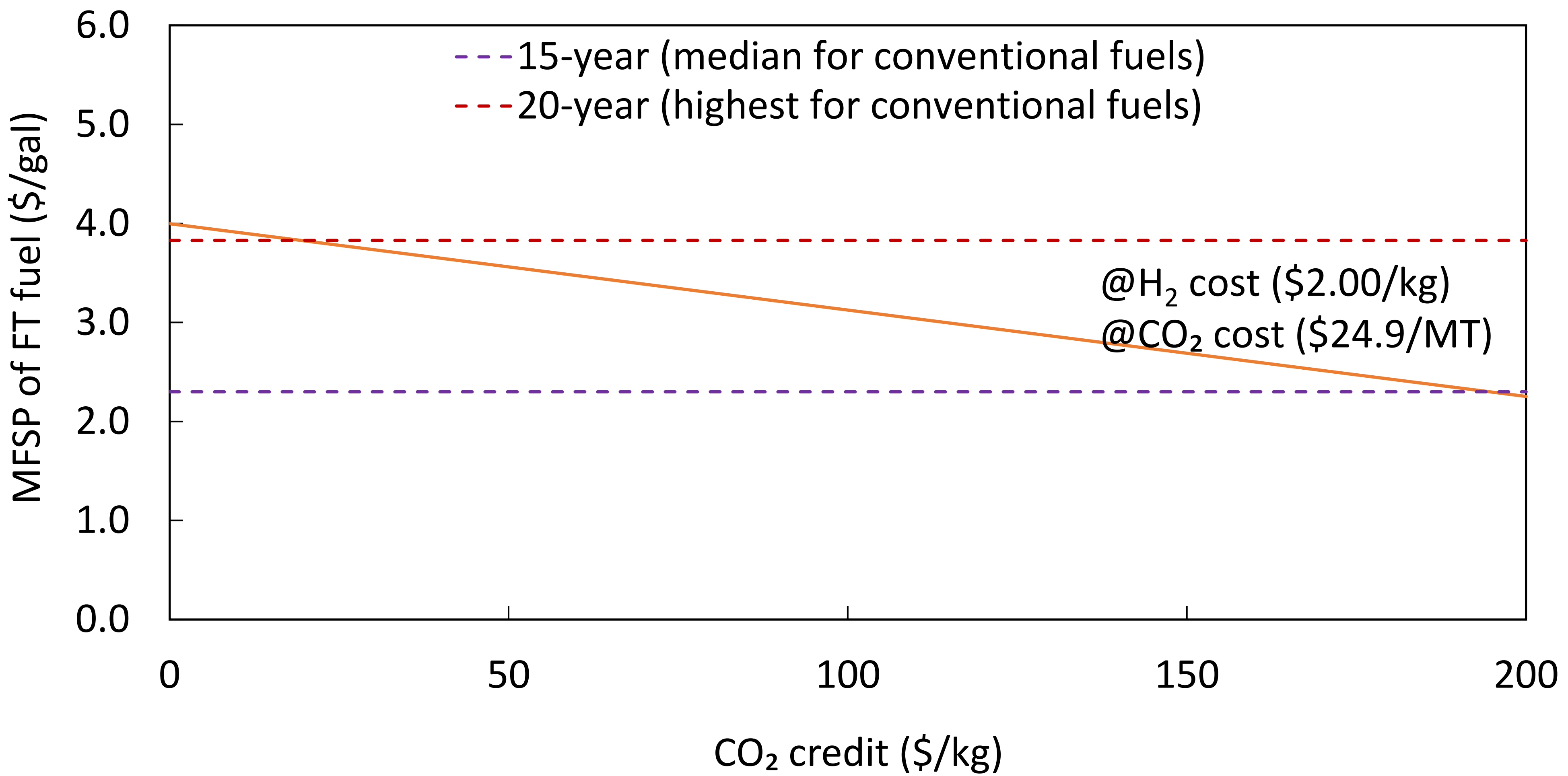


*MSFP= Minimum fuel selling price

CO_2 cost also impacts FT fuel cost



CO_2 avoidance credits can improve market competitiveness of FT fuels



External collaboration

- ❑ Idaho National Laboratory (nuclear high-temperature electrolysis modeling) and hydrogen techno-economic analysis
- ❑ Argonne National Laboratory (FT process modeling, life cycle analysis and techno-economic analysis)

Planned/proposed future work

- ❑ Document analysis in peer-reviewed publications
- ❑ Publish GREET suite of models along with documentation by end of FY22
- ❑ Update nuclear fuel cycle for various reactor technologies in GREET
- ❑ Expand life cycle analysis and GREET model to include small modular reactors and micro-reactors (both fuel cycle and CAPEX embodied emissions)
- ❑ Expand techno-economic and life cycle analysis to include other nuclear-based energy systems across energy sectors (e.g., ammonia production, oil refining, direct air capture of CO_2, etc.)
- ❑ Expand techno-economic and life cycle analysis to include energy storage systems (e.g., batteries)
- ❑ Continue evaluation of emerging technologies of interest to DOE

Any proposed future work is subject to change based on funding levels.

Summary

- **Relevance**: cost and greenhouse gas (GHG) emissions of synthetic fuel production using nuclear power and thermal energy
- **Approach**: Engineering process modeling (ASPEN Plus), life cycle analysis (GREET), and techno-economic analysis (H2A)
- **Collaborations**: collaborated with Idaho National Laboratory researchers, who modeled nuclear high-temperature electrolysis and provided hydrogen techno-economic analysis
- **Technical accomplishments**
  - Conducted CO_2 supply chain analysis from industrial and power sources, including scale and cost of CO_2 by scale, purity level and transportation distance
  - Developed and optimized ASPEN Plus model for integrated HTE-FT process to evaluate process efficiency, product yield and associated CAPEX/OPEX
  - Evaluated and compared cost and GHG emissions associated with nuclear-based FT fuels to conventional fuels
  - Evaluated embodied carbon in solar PV, wind turbines, and light-water nuclear plants
  - Documented modeling and analysis in reports
- **Future Work**:
  - Update nuclear fuel cycle for various reactor technologies in GREET
  - Expand GREET model to include small modular reactors and micro-reactors (both fuel cycle and CAPEX embodied emissions)
  - Expand techno-economic and life cycle analysis to include other nuclear-based energy systems
  - Expand techno-economic and life cycle analysis to include energy storage systems

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TECHNICAL BACKUP AND ADDITIONAL INFORMATION

ACCOMPLISHMENTS AND PROGRESS:
RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

This is a new project inFY22, and thus has not been previously reviewed

TECHNOLOGY TRANSFER ACTIVITIES

- Not applicable to this project

SPECIAL RECOGNITIONS AND AWARDS

- None for this project

PUBLICATIONS AND PRESENTATIONS

- Zang, G., Sun, P., Delgado, H.E., Cappello, V., Ng, C., Elgowainy, A. (2022) “The modeling of Synfuel Production Process: Process models of FT production with electricity and hydrogen provided by various scales of nuclear plants,” ANL/ESD-22/8.
- Zang, G., Sun, P., Elgowainy, A. (2022) “The modeling of Synfuel Production Process: Process models of FT production with electricity demand provided at LWR scale,” ANL/ESD-22/1.
- Zang, G., Sun, P., Yoo, E., Elgowainy, A., Bafana, A., Lee, U., Wang, M. and S. Supekar (2021) “Synthesis Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO_2 from Industrial and Power Plants in the United States,” Environmental Science & Technology Article ASAP. DOI: 10.1021/acs.est.0c08674.

PROGRESS TOWARDS DOE TARGETS OR MILESTONES

Progress towards analysis targets / milestones can be assessed through our contributions to relevant barriers:

1. Barrier: *Insufficient suite of models and tools*
   - Developed ASPEN Plus process model for integration of HTE-H_2 with FT process
   - Updated and expanded the GREET suite of models to evaluate environmental impacts of nuclear FT production
2. Barrier: *Indicators and methodology for evaluating economic and environmental sustainability*
   - Evaluated life cycle cost and GHG emissions using consistent modeling frameworks and assumptions
3. Barrier: *Inconsistent data, assumptions, and guidelines*
   - Collected data from literature, models, and industry sources
   - Harmonized assumptions across various modeling platforms
   - Vetted model inputs and analysis outputs