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Nuclear Synfuels IES Use Case

FORCE Overview and Training

April 4-6, 2023

INL/MIS-23-71825

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Contents

- What are synfuels?
- Why synfuels?
- How synfuels could be made using nuclear energy
  - Fischer-Tropsch Synfuel Production Process
  - Hydrogen Production
  - Carbon Source(s)
- Dispatch analysis and economic evaluation
- Conclusions

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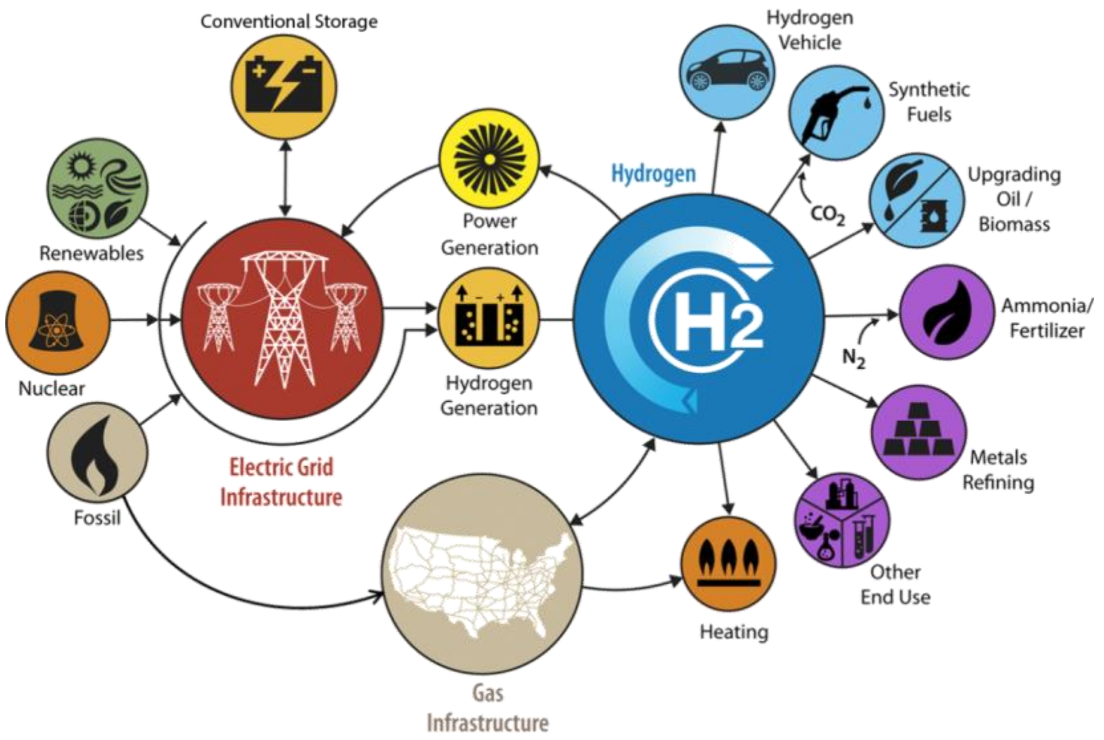
Synfuels as part of a hydrogen economy

- Synthetic fuel production is one of the hydrogen utilization pathways identified by the DOE H2@Scale initiative
- Synthetic fuels are a pathway for large-scale hydrogen utilization
- Nuclear energy can be used to provide the energy for synfuel production
  - Low GHG emissions
  - Synfuel production as a dispatchable load



U.S. Department of Energy H2@Scale Initiative
https://www.energy.gov/eere/fuelcells/h2scale

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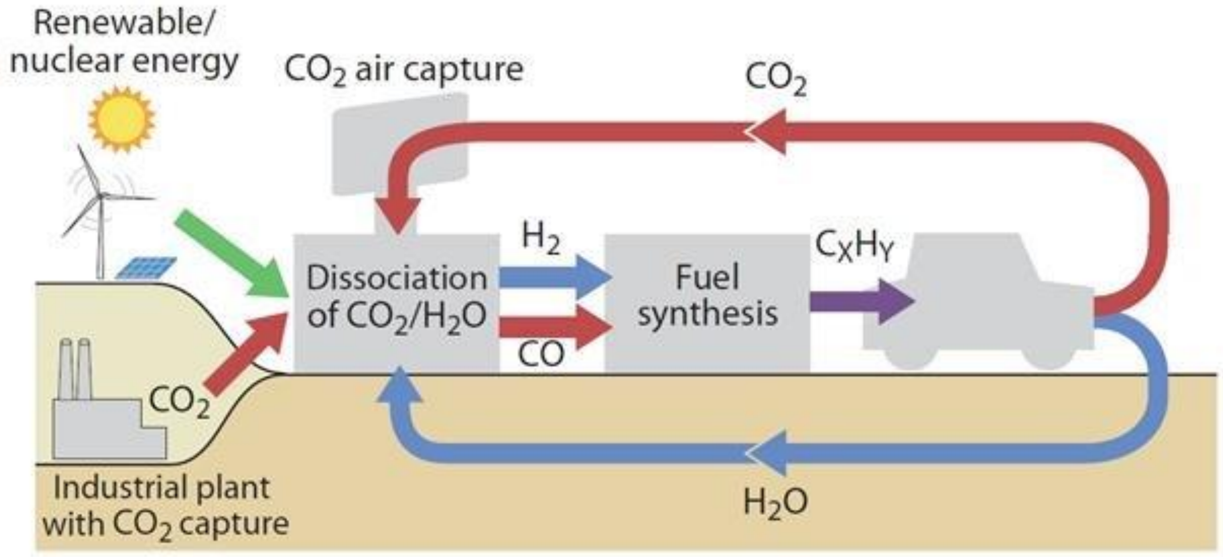
What are Nuclear Synfuels?

- Synthetic liquid hydrocarbon fuels, e.g., diesel fuel, jet fuel, gasoline
- Produced from carbon dioxide and hydrogen with energy input
- Nuclear energy used for hydrogen production (via electrolysis) and to power the synthetic fuel production plant



Source: Escobar (2015)
http://dx.doi.org/10.13140/RG.2.1.4250.7360

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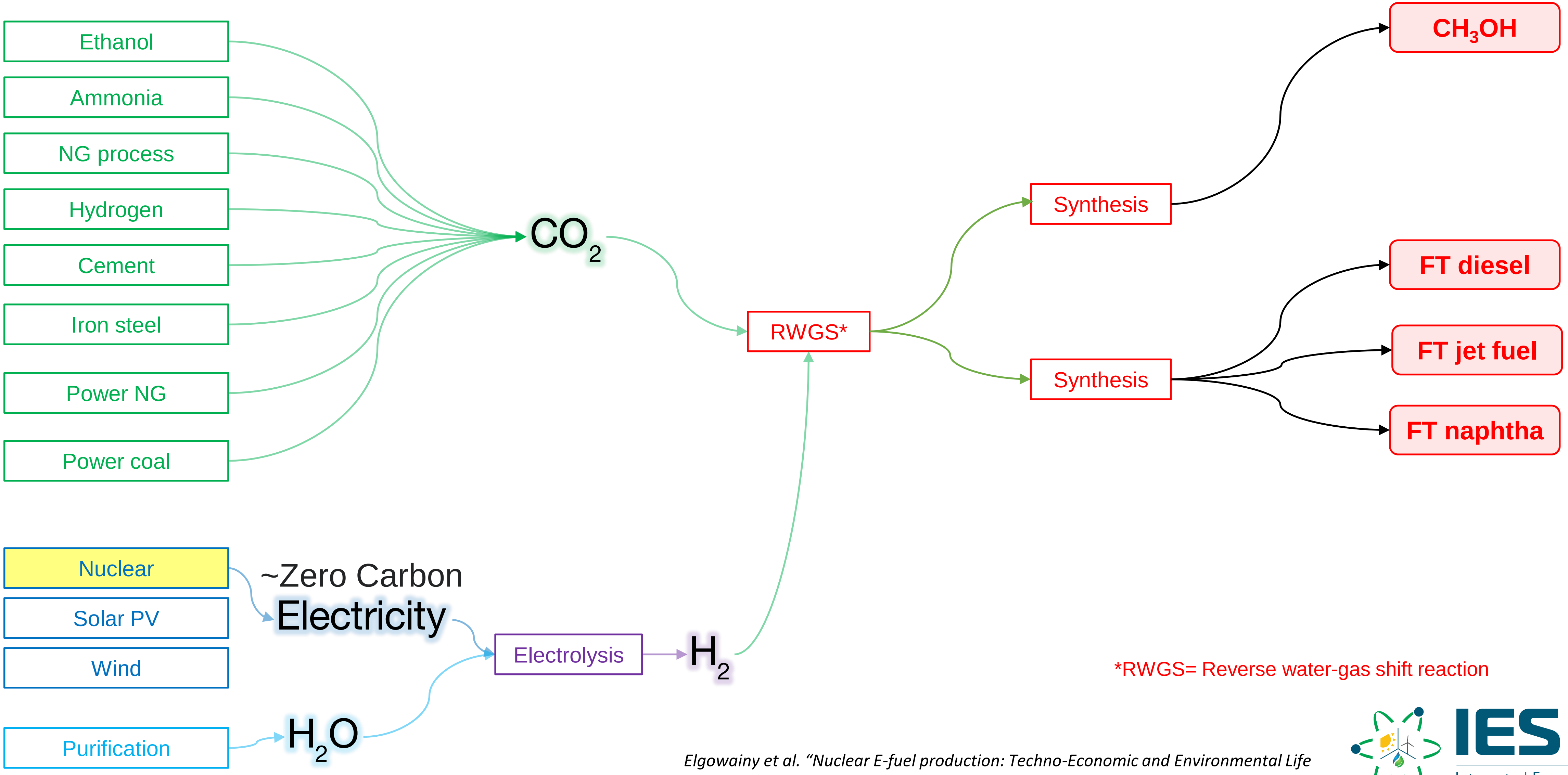
Conversion processes for synthetic FT fuels



*RWGS= Reverse water-gas shift reaction

Elgowainy et al. "Nuclear E-fuel production: Techno-Economic and Environmental Life Cycle Analysis." Presentation to DOE NE Office. April 2022

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Major CO_2 and zero–carbon electricity sources to consider

Carbon Sources

Bio-derived CO_2

- Ethanol plants
- Waste streams (MSW, residues, etc.)

Fossil- derived CO_2

- Ammonia plants
- NG processing plants
- NG SMR plants
- Cement plants
- Iron & Steel mills
- Fossil power plants

Zero-Carbon Electricity Sources

- **Wind**
- **Solar**
- **Nuclear**

Elgowainy et al. "Nuclear E-fuel production: Techno-Economic and Environmental Life Cycle Analysis." Presentation to DOE NE Office. April 2022

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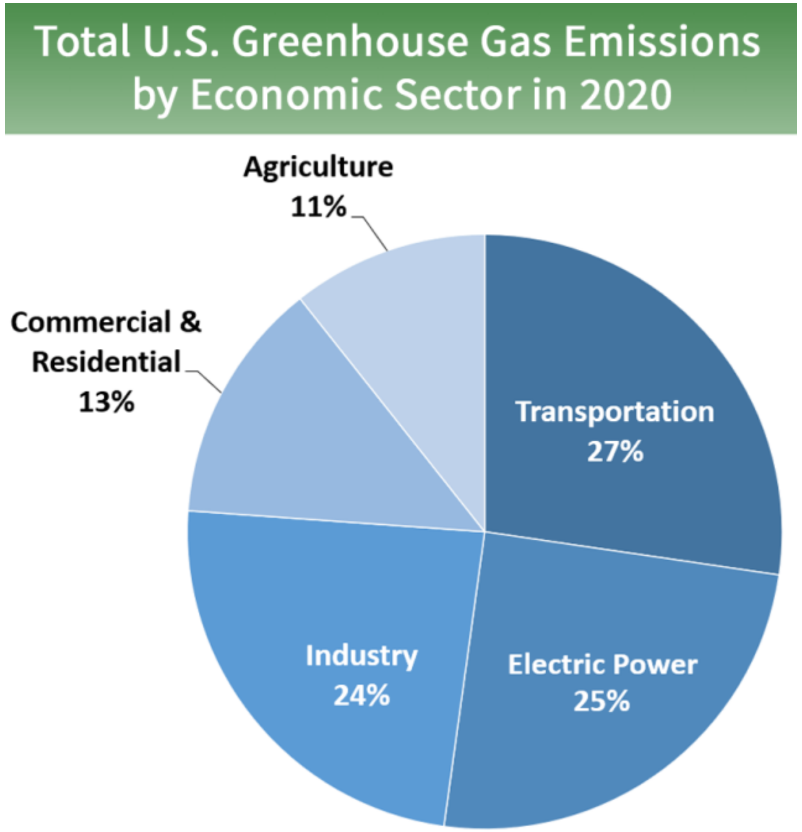
Motivation

- Transportation sector responsible for 27% of total U.S. greenhouse gas emissions
- Nuclear energy can be used to produce H_2 that could be combined with CO_2 to produce synthetic transportation fuels.
- Use of biogenic CO_2 sources could result in fuels with low life-cycle CO_2 emissions.
- Use of CO_2 derived from fossil-based sources could offset emissions associated with petroleum derived transportation fuels.



5,981 million tonnes total U.S. CO2 emissions in 2020
(EPA, 2022, Sources of Greenhouse Gas Emissions | US EPA)

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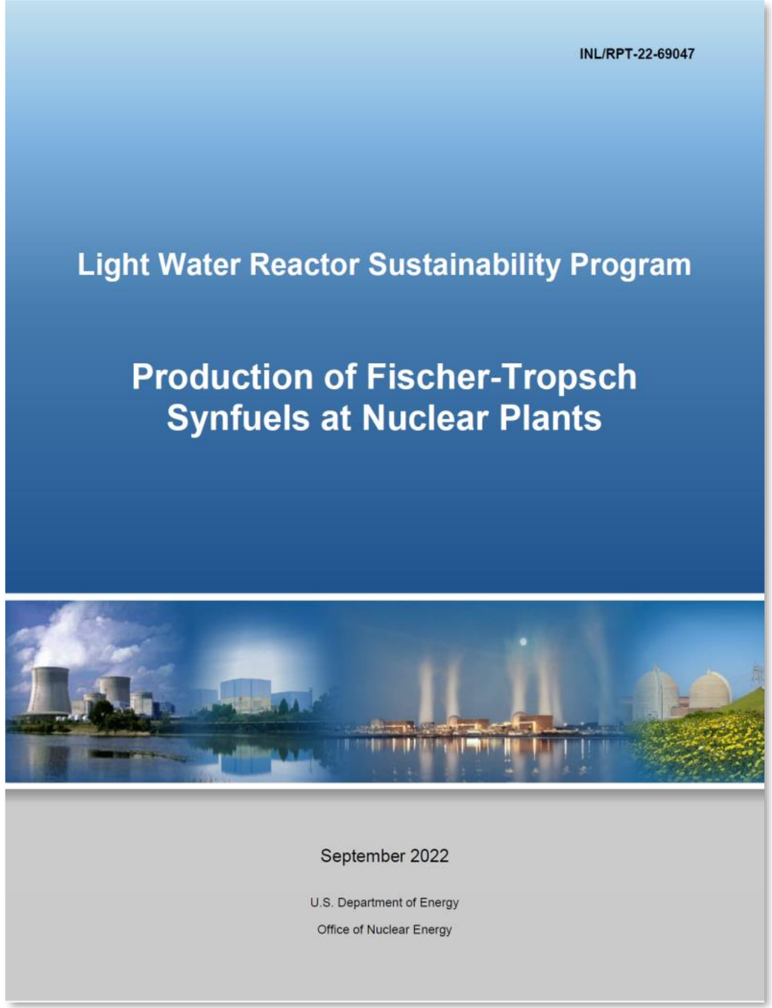
FY-22 INL/ANL Synfuel Analysis

- Evaluate the business case for producing synthetic fuels for the transportation market using CO_2 and energy from existing light water reactors
- Fischer-Tropsch synfuel production process considered. Naphtha, jet, and diesel fuel products specified.
- Hydrogen required for synfuel production to be obtained from a future Nth-of-a-kind high temperature electrolysis plant using nuclear heat and power


INL/RPT-22-69047

Light Water Reactor Sustainability Program

Production of Fischer-Tropsch Synfuels at Nuclear Plants

September 2022

U.S. Department of Energy

Office of Nuclear Energy

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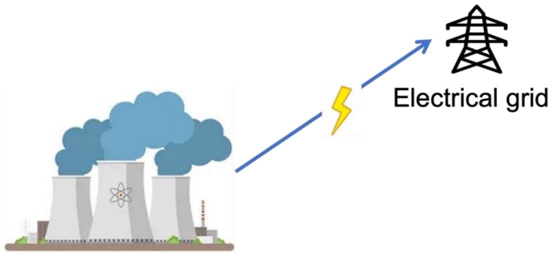
HERON Optimization Analysis

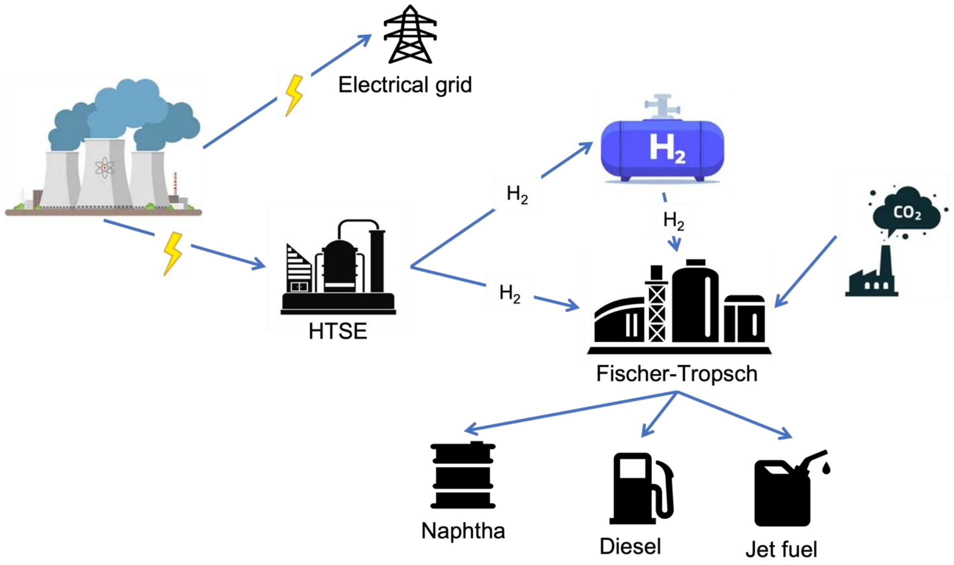
- Business-As-Usual Operations
  - Price-taker model based on synthetic electricity pricing data derived from historical pricing data
  - Constant sale of electrical power to grid

- Grid-Integrated Nuclear Synfuel IES Operations
  - Price-taker model based on synthetic electricity pricing data derived from historical pricing data
  - Dispatch of electrical power to most profitable application (power sales vs. hydrogen production)
  - Steady-state FT synfuel production
  - H2 storage used to allow continued operation of FT plant when NPP dispatches electric power to grid
  - Optimization performed to determine synfuel production capacity, H2 storage capacity, and dispatch schedule that maximize NPV

Business-As-Usual Operations



Grid-Integrated Nuclear Synfuel IES Operations



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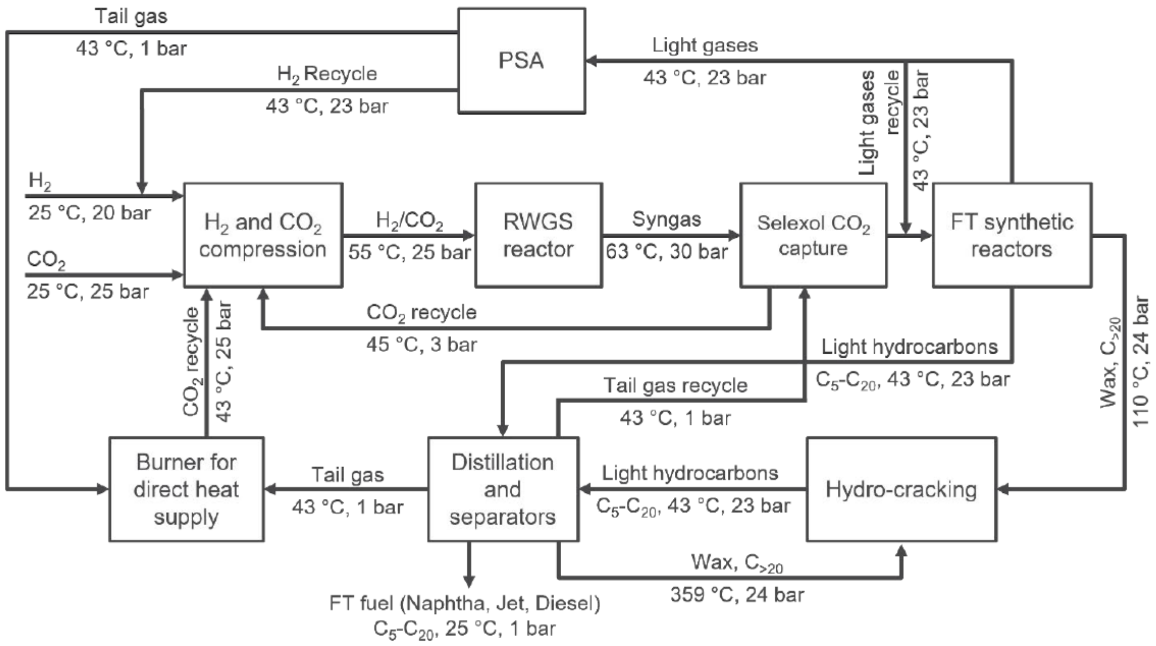
FT Synfuel production

- FT process model developed by ANL used as basis for process performance and cost estimates
- FT process assumed to operate at steady state

$$(2n+1)\,H_2 + n\,CO \rightarrow C_nH_{2n+2} + n\,H_2O \qquad (1)$$

$$2n\,H_2 + n\,CO \rightarrow C_nH_{2n} + n\,H_2O \qquad (2)$$



		FT-100	FT-400	FT-1000
Feedstock	H_2 (MT/d)	56	255	601
	CO_2 (MT/d)	348	1,580	3,724
Products	Naphtha (MT/d)	39	176	414
	Jet fuel (MT/d)	47	213	502
	Diesel (MT/d)	26	118	278
	Total FT fuel (gal/d)	40,430	183,030	431,050
Carbon conversion		99%	99%	99%

		FT-100	FT-400	FT-1000
Input	Electric power (H_2 prod.)	86.2	390.9	922.2
	Thermal power (H_2 prod.)	15.0	68.0	160.4
	Electric power	3.4	15.5	36.6
Output	Naphtha	19.7	89.6	210.4
	Jet fuel	24.0	108.7	256.4
	Diesel	13.2	59.9	141.3
	Steam	16.1	73.0	174.6
Total energy efficiency		69.8%	69.8%	69.8%

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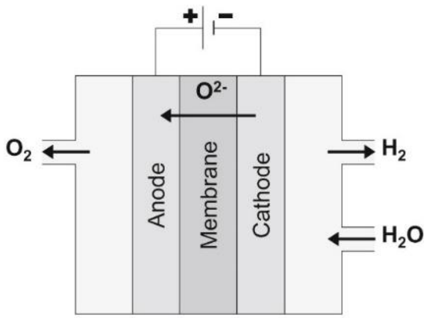
Nuclear-Based High Temperature Steam Electrolysis

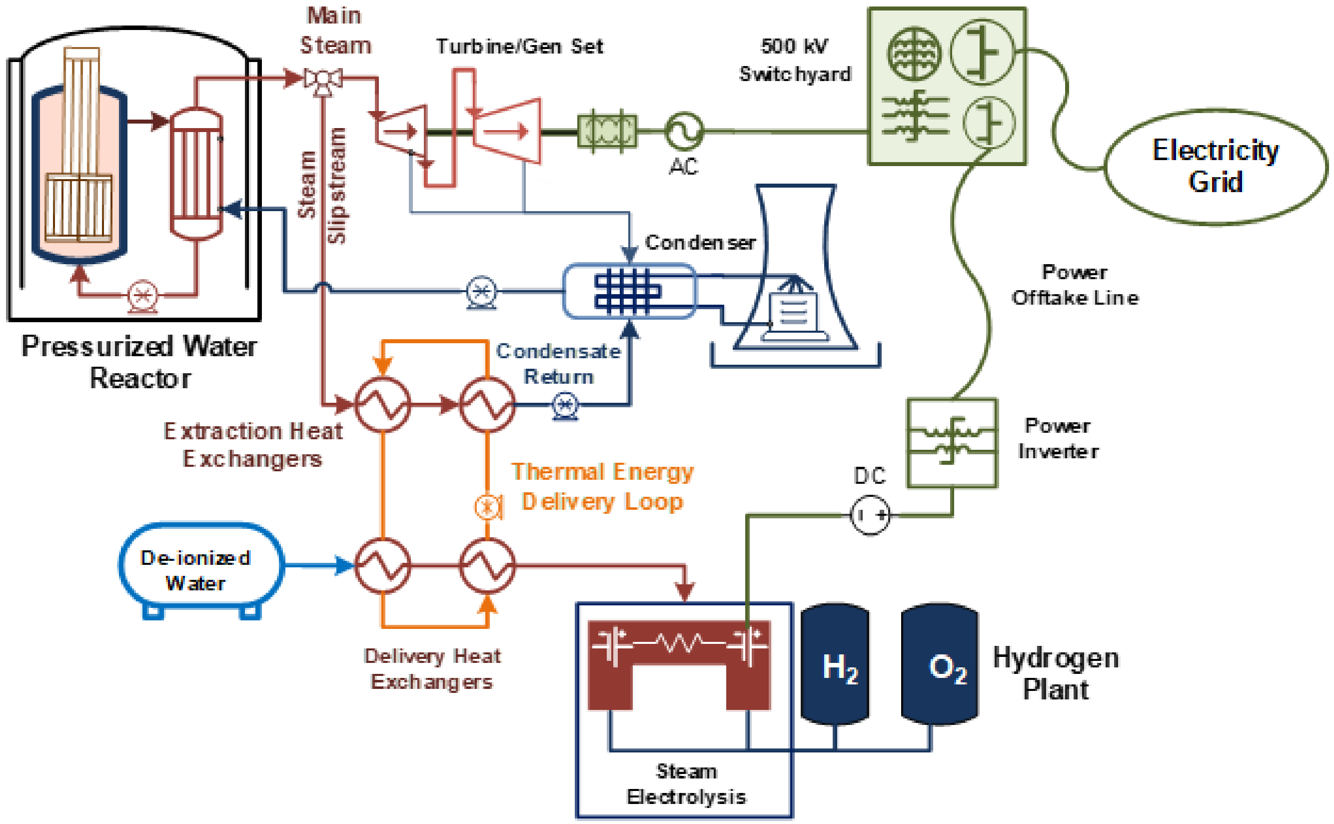
High Temperature Steam Electrolysis

- HTE has reduced energy requirements relative to LTE
- Use of heat input decreases HTE electrical power requirement
- When low-cost source of heat is available, HTE can reduce energy costs of hydrogen production
- NPP steam used for vaporization of HTSE process feedwater
- Recuperation and electrical topping heat used to achieve 700-800°C stack operating temperature
- Modular construction design basis
- Oxygen byproduct vented to atmosphere using air sweep gas; process schemes that recover oxygen possible.
- Hot standby mode used to minimize ramp times



Cathode: $H_2O(g) + 2e^- \rightarrow H_2(g) + O^{2-}$ (3)

Anode: $O^{2-} \rightarrow \frac{1}{2}O_2(g) + 2e^-$ (4)



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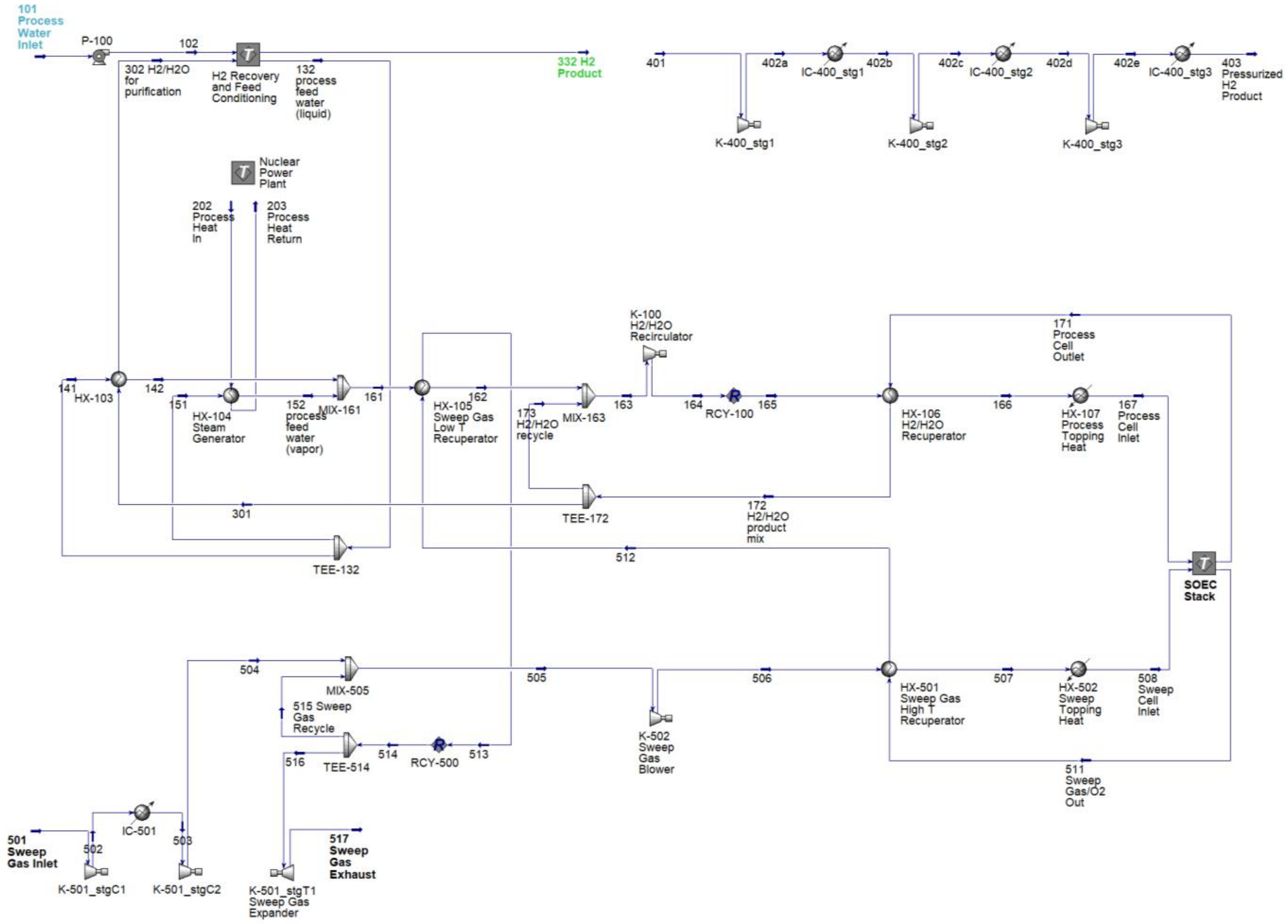
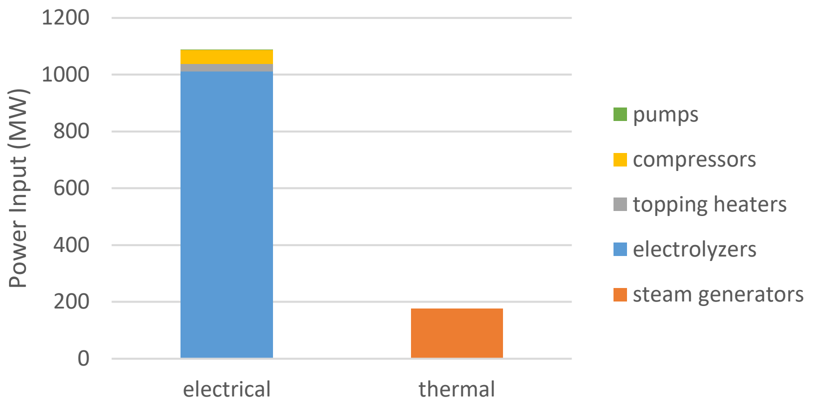
Nuclear-Based HTSE Process Analysis





	Large Scale H_2 Production Design Basis
Plant Design Capacity	1087 MW-e
Nominal Hydrogen Production Capacity**	697 tpd
Process Power Requirement, Normal** Electrical Thermal	 1087 MW-e 177 MW-t
Process Power Requirement, Hot Standby** Electrical Thermal	 10 MW-e 13 MW-t
Specific Energy Consumption Electrical Thermal	 37.4 kWh-e/kg H_2 6.1 kWh-t/kg H_2
System H_2 Production Efficiency (energy content of product H_2 divided by electrical energy equivalent input)	89.6% HHV basis
Utilities** Process Water Feed Rate Cooling Water Circulation Rate	 72.1 kg/s [1.1 k gpm] 1057 kg/s [17 k gpm]

Wendt et al. HTSE Process Performance and Cost Estimates. INL-RPT-22-66117, 2022.

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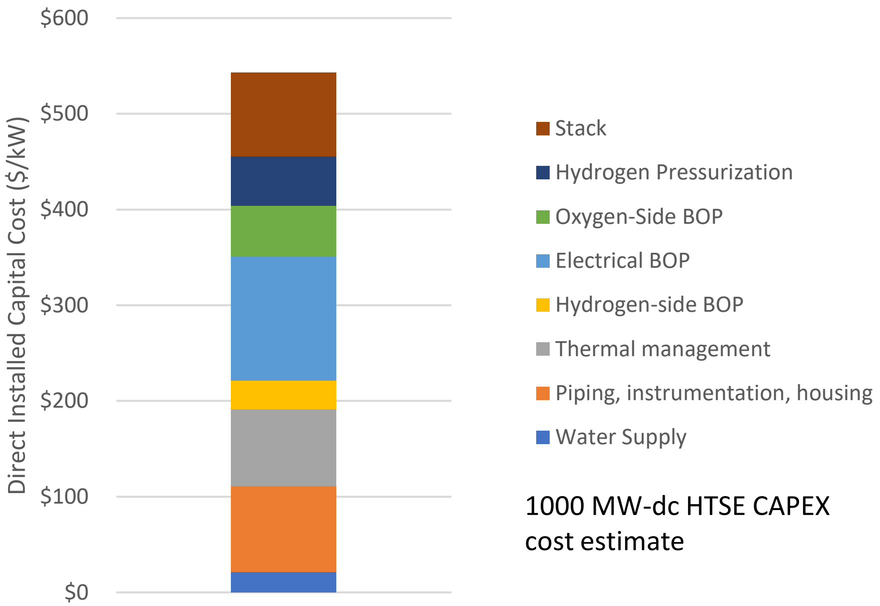
Nuclear-Based HTSE Economic Analysis

Parameter	Value	Reference or Note
Stack operating temperature	800°C	O'Brien et al. 2020
Stack operating pressure	5 bars	See Section 2.2.1 of INL/RPT-22-66117
Operating mode	Constant V	
Cell voltage	1.29 V/cell	Thermoneutral stack operating point.
Current density	1.5 A/cm²	James and Murphy 2021
Stack inlet H_2O composition	90 mol%	O'Brien et al. 2020
Steam utilization	80%	See Section 2.2.1 of INL/RPT-22-66117
HTSE modular block capacity	25 MW-dc	1000x capacity increase over O'Brien et al. 2020
Sweep gas	Air	O'Brien et al. 2020
Sweep gas inlet flow rate	Flow set to achieve 40 mol% O_2 in anode outlet stream	
Stack service life	4 years	HFTO Hydrogen Production Record 20006
Stack degradation rate	0.856%/1000 hr.	HFTO Hydrogen Production Record 20006
Stack replacement schedule	Annual stack replacements completed to restore design production capacity	Based on H2A model stack replacement cost calculations.

Cost of nuclear plant modification (plant shutdown, permitting, piping/equipment retrofits, etc.) not included in analysis

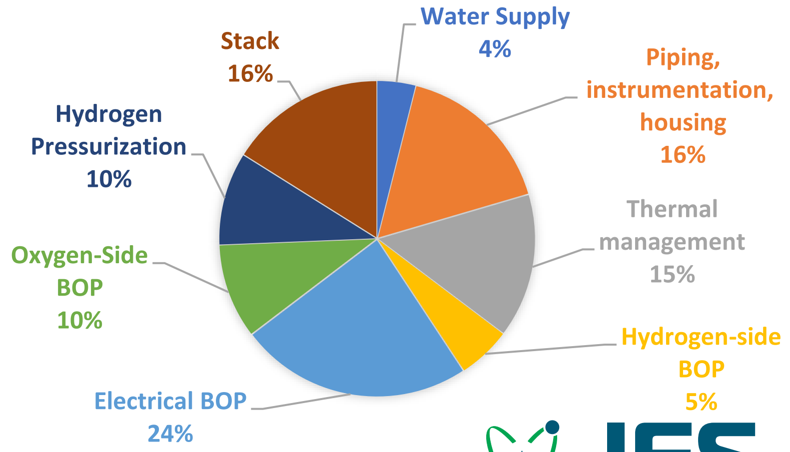
	FT-100	FT-400	FT-1000
H_2 Production Rate (MT/day)	56	255	601
Energy Consumption Electric (MWe) Thermal (MWth)	 86.2 15.0	 390.9 68.0	 922.2 160.4
Direct Capital Cost ($/kW-dc)	665	573	547
Total Capital Investment ($/kW-dc)	861	742	708
Fixed Operating Cost ($/kW-dc-yr)	61	38	33
Variable Operating Cost, excluding energy costs ($/MW-dc-hr)	3.4	3.4	3.4

Wendt et al. HTSE Process Performance and Cost Estimates. INL-RPT-22-66117, 2022.



1000 MW-dc HTSE CAPEX cost estimate

SOEC SYSTEM COST BREAKDOWN



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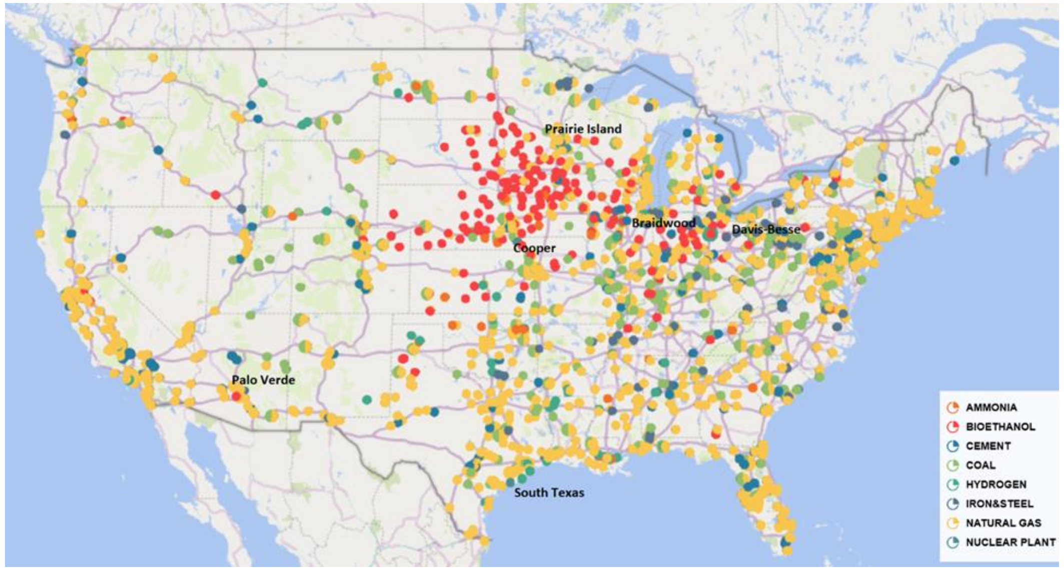
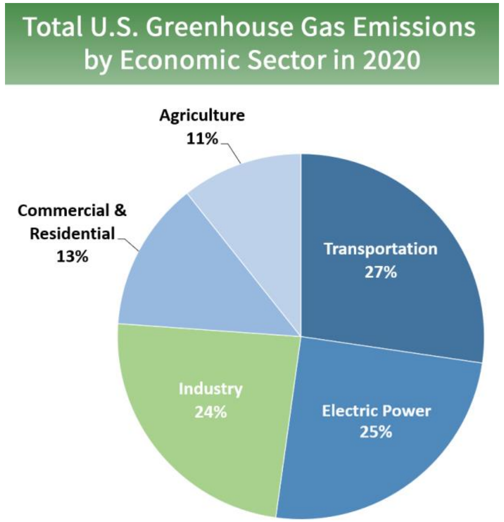
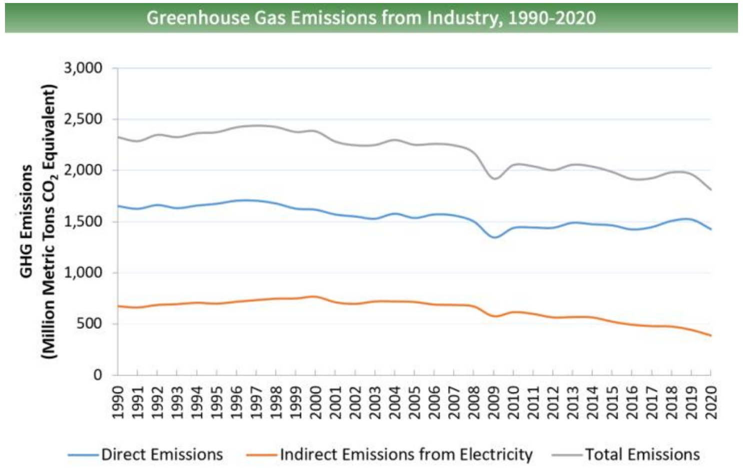
Industrial Sector CO_2 emissions



5,981 million tonnes total U.S. CO2 emissions in 2020 (EPA, 2022, [Sources of Greenhouse Gas Emissions | US EPA](https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions))





	Total CO2 Emission (MMT/year)	Concentration CO2 (%vol)	Lower CO2 Capture Cost ($/ton)	Upper CO2 Capture Cost ($/ton)	Average Capture Cost ($/ton)
Bioethanol	31	99.8%	17.6	33.4	27
Ammonia	35	97.1%	12.4	42.8	20.5
Natural Gas (Power Plant)	645	3.9%	52.9	140	80.0
Coal (Power Plant)	979	12.9%	33.6	124	58.0
Hydrogen	44	44.5%	56.9	156.8	81.9
Iron/Steel	72	23.2%-26.4%	80.0	194.8	110.7
Cement	67	22.4%	67.1	195.2	107.9
Total CO2	1,872				
Total FT fuel (Mgal/year)	217,537				

Zang, G. et al., Environ Sci Technol, vol. 55, no. 11, pp. 7595-7604, 2021. https://www.ncbi.nlm.nih.gov/pubmed/33979128

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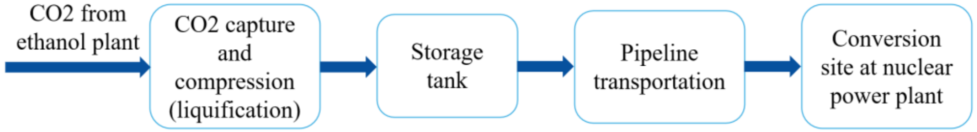
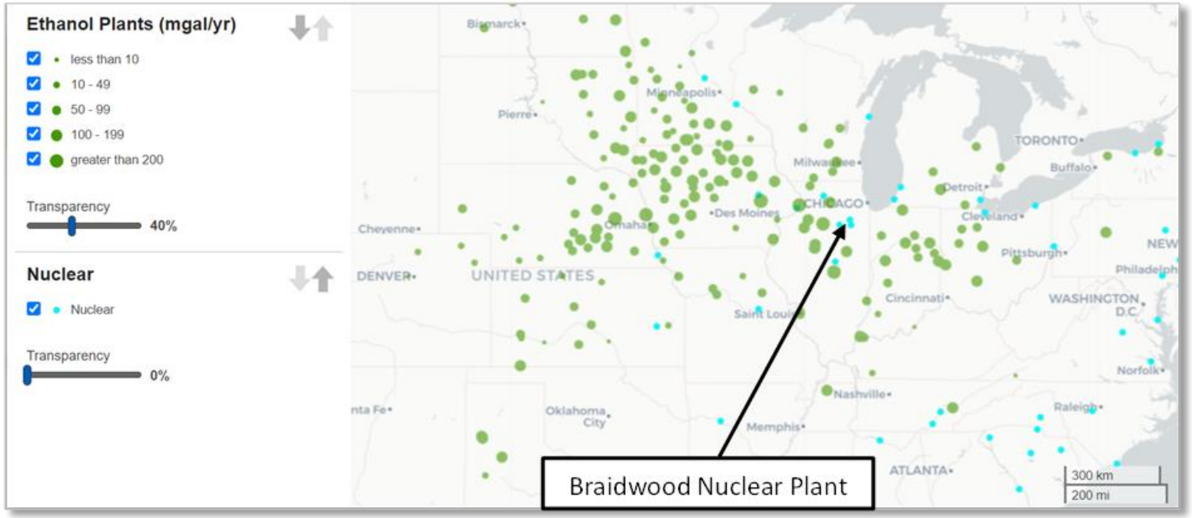
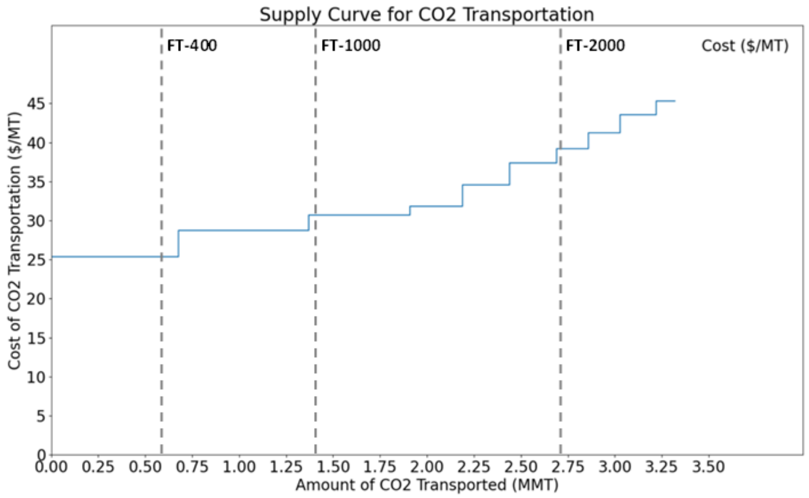
CO2 feedstock supply

- CO_2 from bioethanol plants considered as carbon feedstock
- CO_2 pipeline transport costs calculated using NETL CO_2 Transport Cost Model

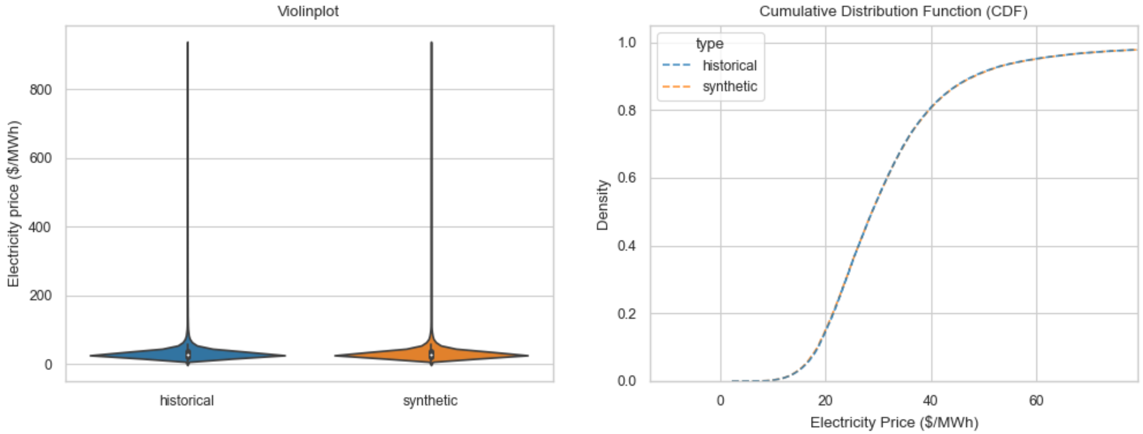






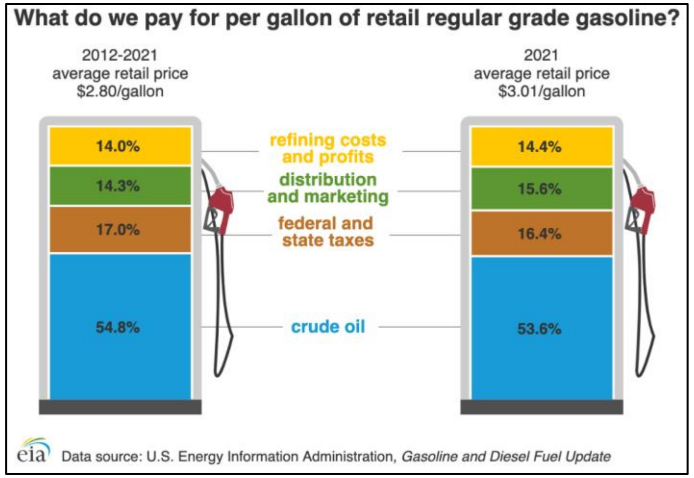
Electricity Pricing Data

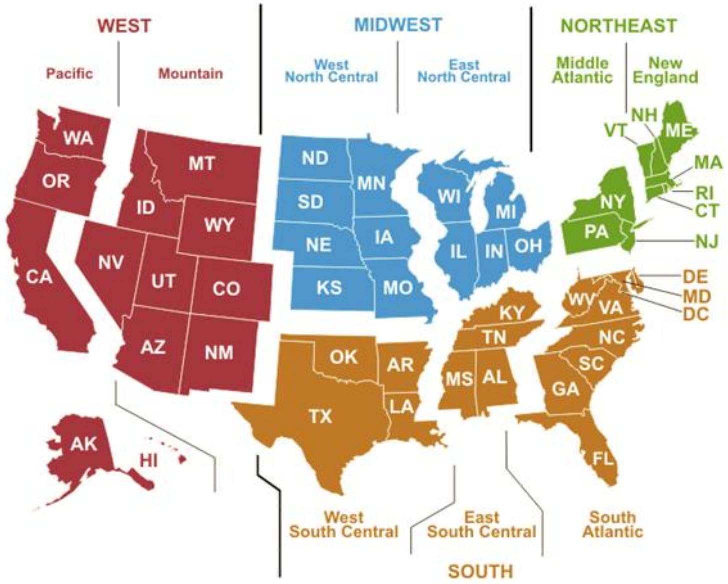
Historical Electricity Pricing Data at the Braidwood NPP location:
10 year, 2 year, 3 month, and 2 week timeframes

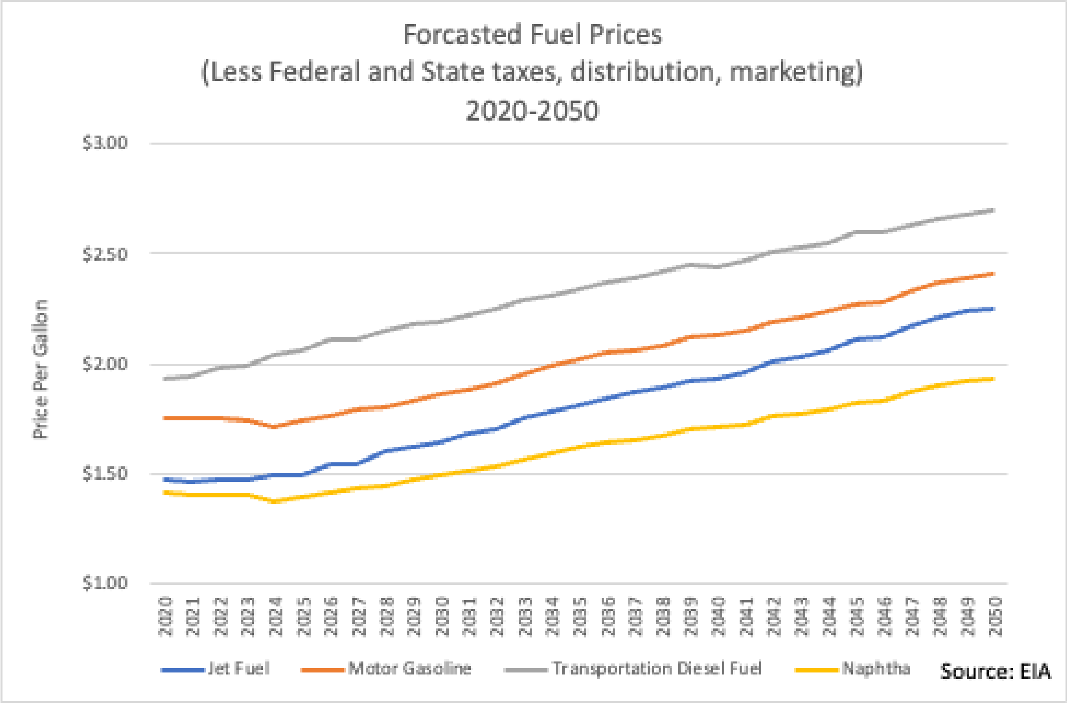


Comparison of historical and synthetic electricity pricing data sets for Braidwood Generating Station

East North Central Region Forecasted Fuel Prices (e.g., prospective Braidwood NPP synfuel plant market)







East North Central Region

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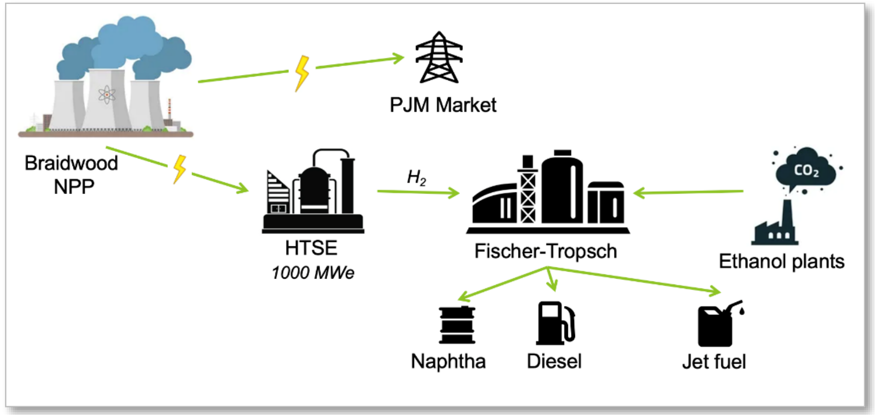
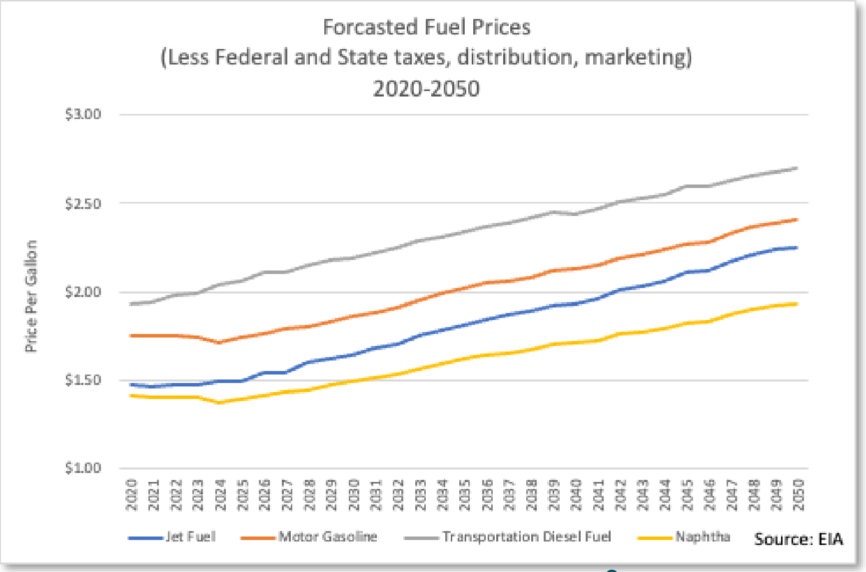
TEA of Nuclear Based Synfuel Production

- Case study of nuclear synfuel IES located at Braidwood NPP completed
- Hydrogen and FT synfuels produced in steady state operating mode
- HERON model used to perform TEA and calculate differential NPV relative to business-as-usual NPP electricity generation
- Reference Case considered a scenario in which the electrolysis and synfuel plants utilized a combined electrical load of 1000 MW-e from one unit of the NPP with the balance of the NPP power output being sold to the electric grid. Power sent to the grid is sold at prices based on historical 2018–2021 PJM LMP at the NPP node.
- The Reference Case specified synthetic fuel pricing equal to that projected for conventional petroleum-based fuels in the U.S. EIA 2021 AEO minus federal taxes and state taxes, as well as marketing and distribution costs.
- The Reference Case incorporates the 2022 IRA clean hydrogen production credits of $3.00/kg into the revenue stream for the first ten years of operation.





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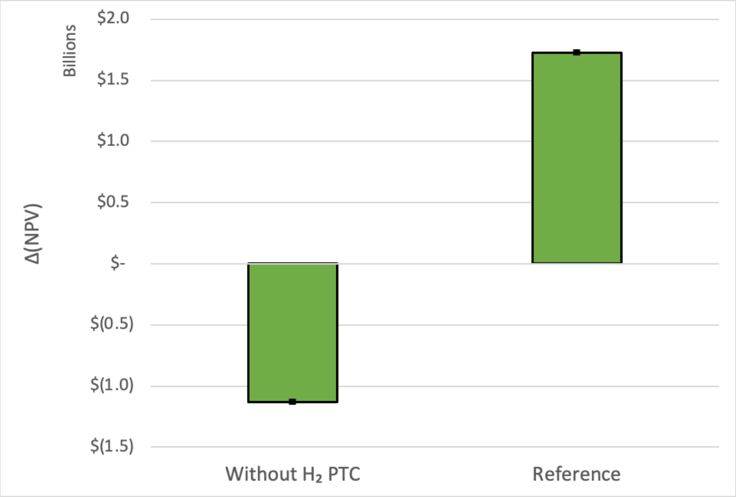
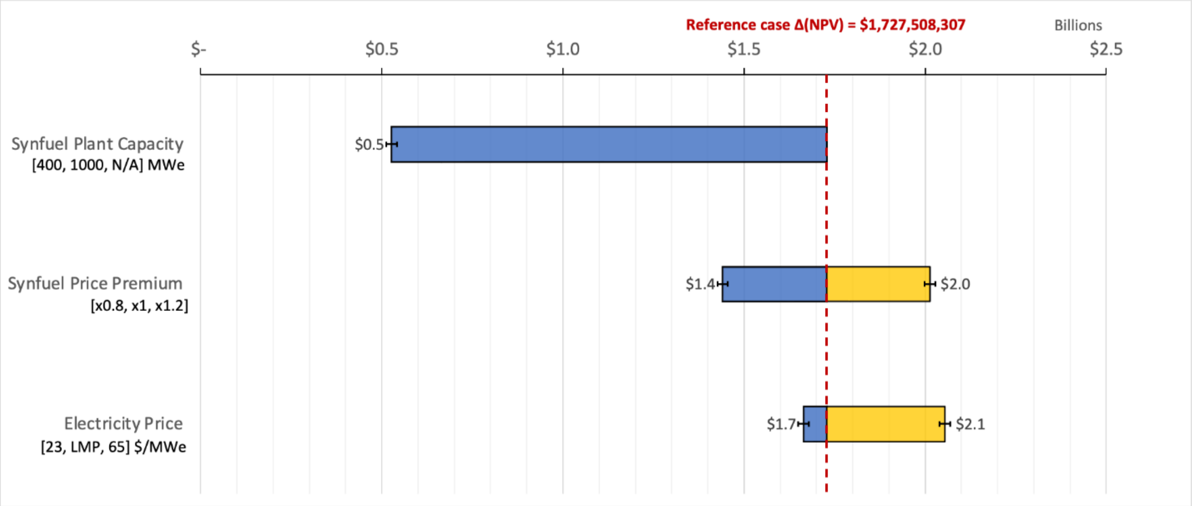
TEA of Nuclear Based Synfuel Production

- The analysis predicts that a 1000 MW nuclear-powered synfuel plant could result in a NPV increase of approximately $1.7 billion when accounting for the additional revenues from the 2022 IRA clean hydrogen PTCs of $3/kg.
- Exclusion of the 2022 IRA clean hydrogen PTCs results in a negative NPV relative to the Business-As-Usual Case
- Sensitivity analysis indicates that:
    - Decreasing the synfuel production capacity decreases the NPV of the nuclear synfuel IES
    - A synfuel price premium increases the NPV
    - The Nuclear-Synfuel IES would have a greater NPV than the business-as-usual case when electricity market prices are low, suggesting that synfuel production could provide a strategy for decreasing the economic risks to NPPs posed by a loss of revenues attributed to falling electricity market prices.

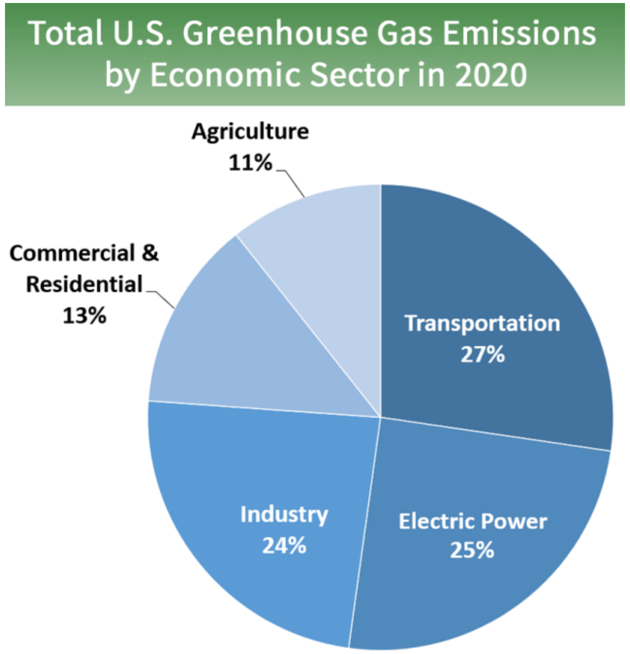




Preliminary Results – Subject to Change

US CO2 Emissions, Transportation Fuel Use, and Generation Capacity

- Nuclear energy can be used to produce H2 that could be combined with CO2 to produce synthetic transportation fuels. Use of biogenic CO2 sources could result in low life-cycle CO2 emissions. Use of CO2 derived from fossil-based sources could offset emissions associated with petroleum derived transportation fuels.



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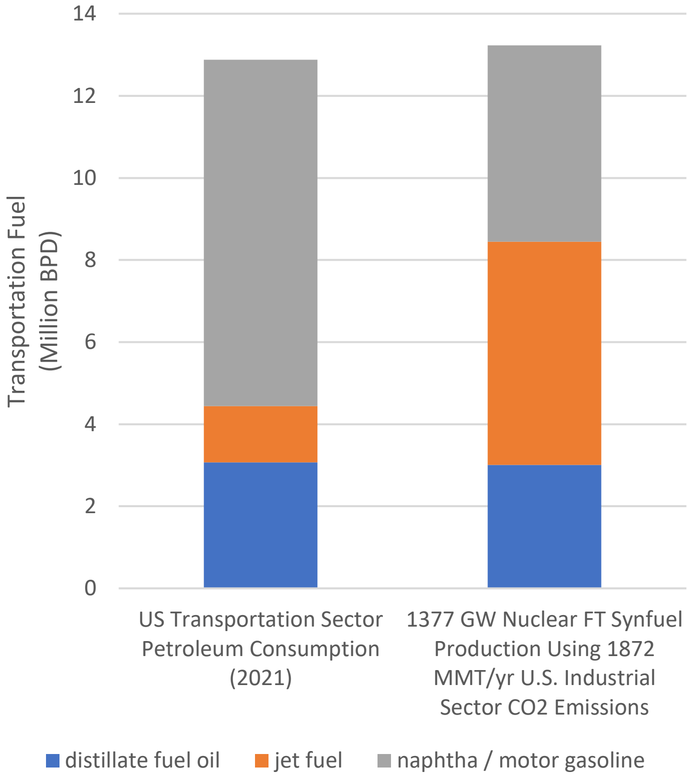

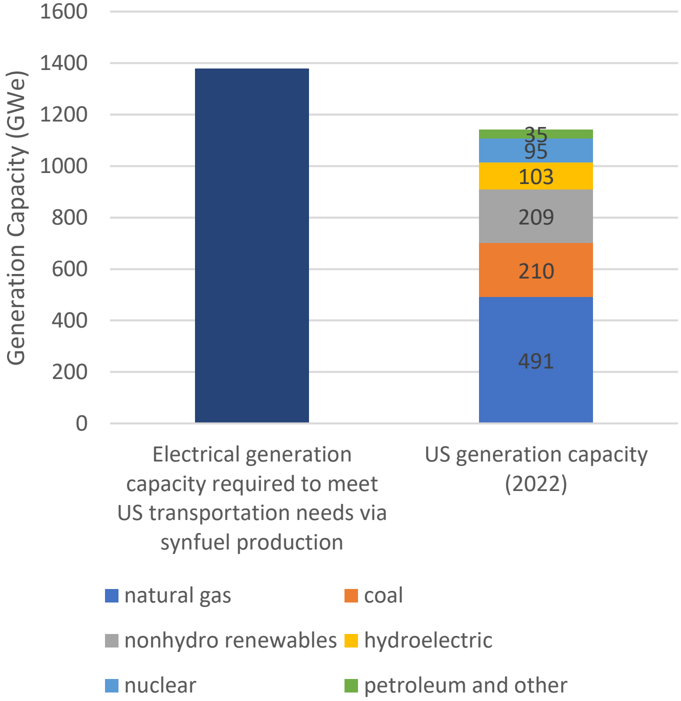

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Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Grid Integrated Analysis

- Build upon steady state FT process analysis reported on in September 2022
- Evaluate grid-integrated nuclear-synfuel IES
  - Dynamic operation of electrolysis plant
  - Use of hydrogen storage to maintain steady state synfuel plant operations
  - Additional case study locations (different electricity and fuels market pricing; different CO2 sources and transport infrastructure)