IES Integrated Energy Systems Program

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U.S. Nuclear Energy Market Potential

Flexible Plant Operation and Generation Pathway Stakeholder Engagement Meeting

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Funding program: IES Program

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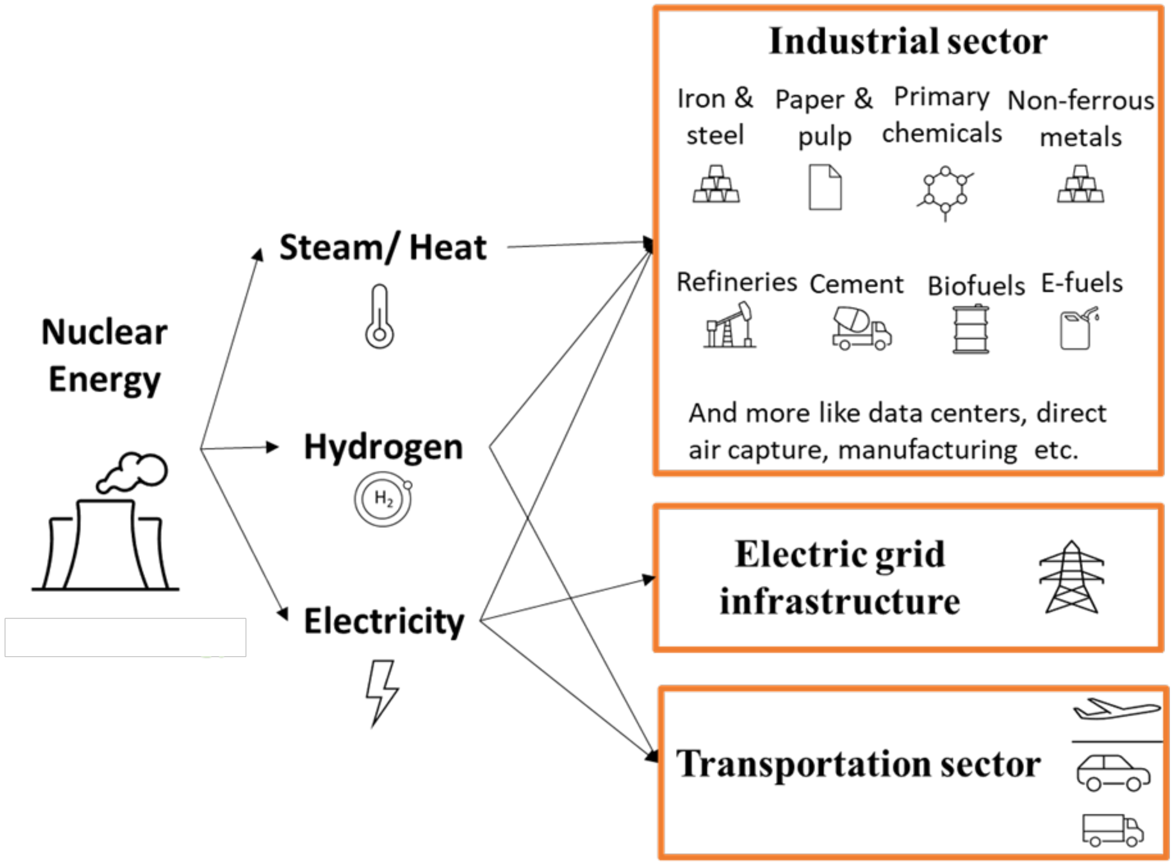
Argonne NATIONAL LABORATORY

Purpose of the national impact study

Context

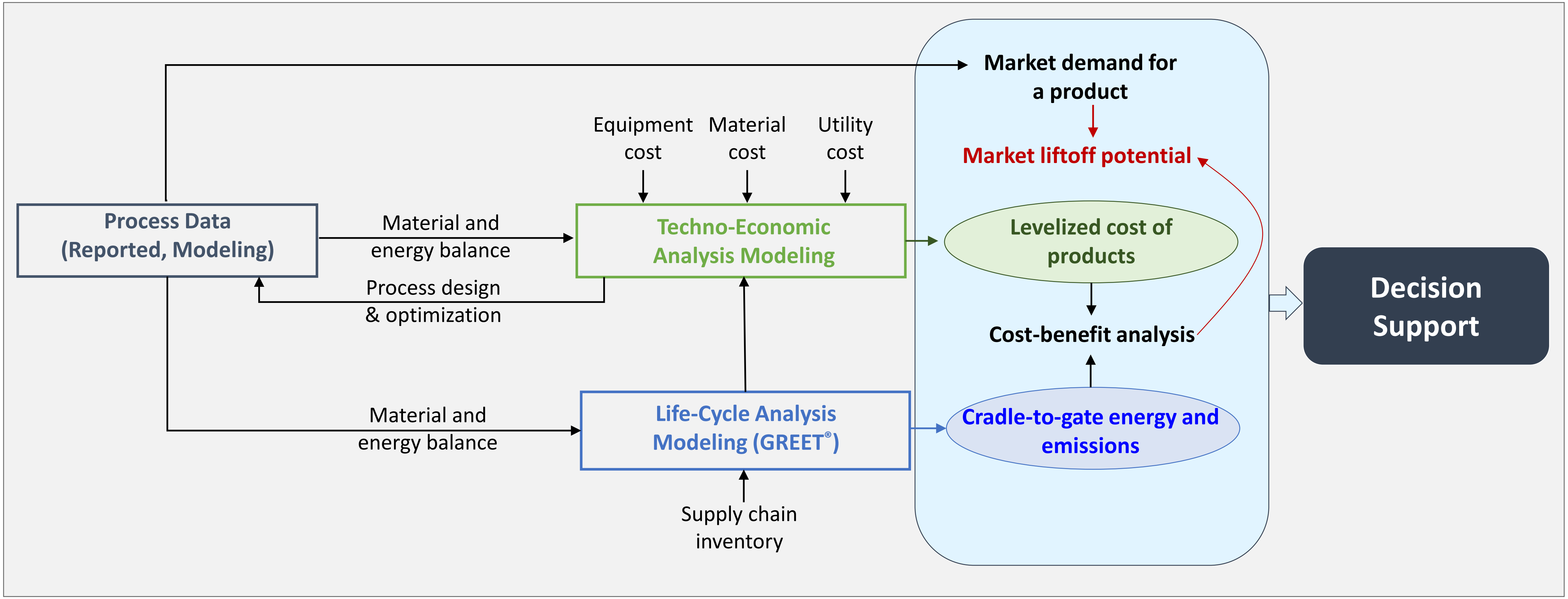
- Nuclear energy provides zero-emissions **electricity** and can produce **steam** and **hydrogen** with integrated systems like heat exchangers and electrolyzers
  - This can satisfy environmental goals of **industrial sectors** such as refineries, pulp & paper, ammonia, steel and cement production
  - Hydrogen can be used for synthetic fuels and chemicals production using available CO_2 sources
  - Achieving these goals must be **resilient** and **viable economically**



Objectives and impact

- Evaluate the **technical**, **economic** and **market** potential of nuclear energy use in industrial and transportation applications in the US
- Evaluate the **benefits** associated with nuclear energy use versus alternatives such as fossil + CCS (carbon capture and storage) and renewable energy + energy storage across these applications
- **Develop a roadmap** for potential nuclear energy deployment by region, timeframe, and application

National impact analysis framework



Approach to evaluating nuclear potential for energy applications: Marginal Abetment Cost curve (MACC)

Nuclear technologies consideration:

- ✓ Current LWR
- ✓ Future SMR, HTGR, SCFR, etc. (up to 750°C)

Focus on:

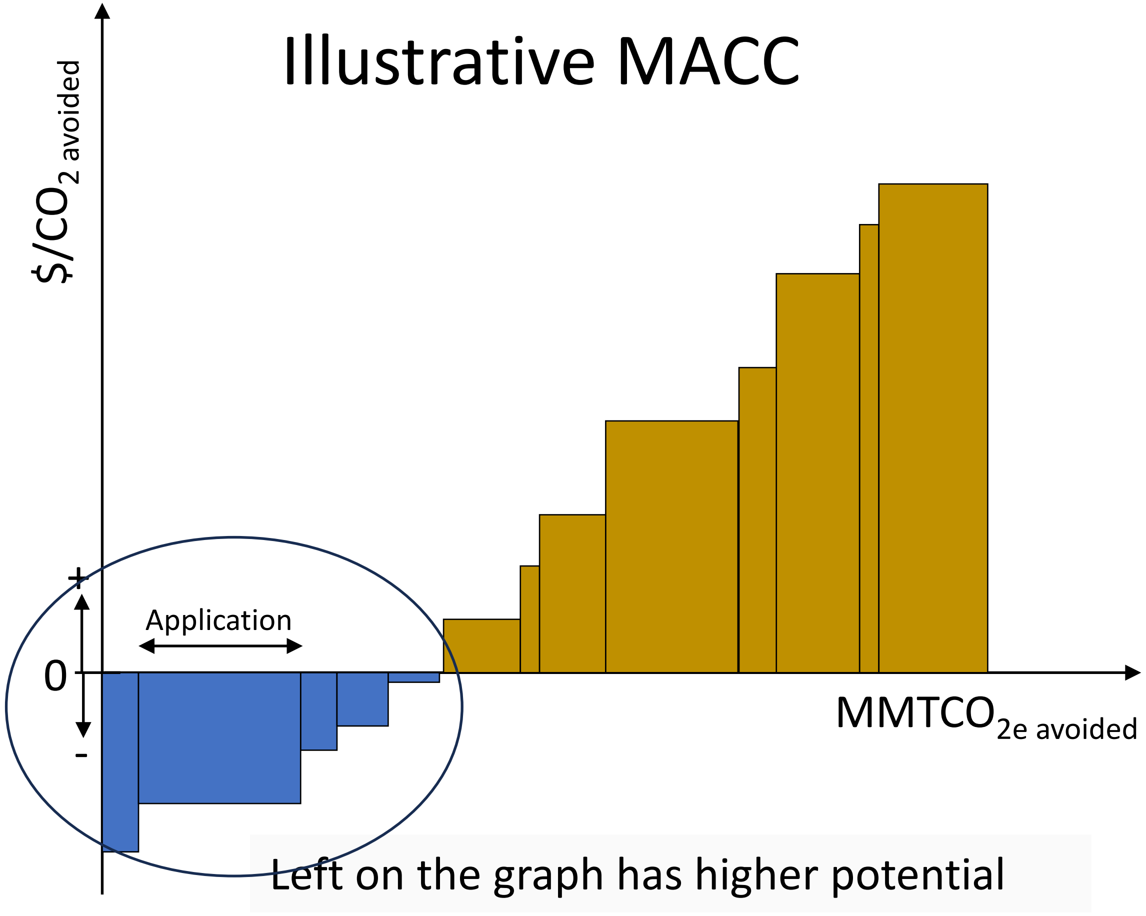
(1) **Applications with high market potential**

(2) **Negative or low cost of reduced emissions**

- → **Develop MACC** (vs. current technologies, over time)
- → **Consider other low-cost alternative** (including process waste utilization)
- → **Evaluate other constraints** (e.g., infrastructure, fleet turn over, supply chain, uranium resources, etc.)
- → **Develop Sankey diagram for NE use in energy sectors** (with time)

Criteria for application selection:

- ✓ Applications with high GHG contribution to national inventory
- ✓ Applications with high demand for one or more of:
  1. Steam (by quality)→ selective nuclear reactor
  2. Power (30% of steam)
  3. H_2 (50-80% of power)
  4. Direct or high temperature heat @1200-1400°C (80-90% of H_2)



Environmental Benefits
Argonne GREET® LCA Model

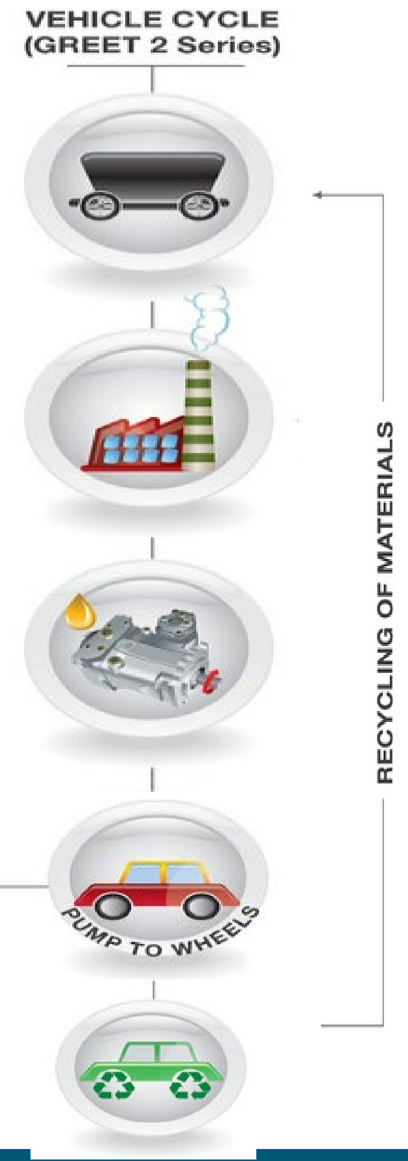
The R&D GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model

- With DOE support, Argonne has been developing the R&D GREET **life cycle analysis (LCA)** model since 1995 with annual updates and expansions
- It is available for free download and use at greet.es.anl.gov
- >65,000 registered users globally including automotive/energy industries and government agencies

Evaluates benefits of nuclear energy use across applications

R&D GREET 1 model:
Fuel-cycle (or well-to-wheels) modeling of vehicle/fuel systems

R&D GREET 2 model:
Vehicle cycle modeling of vehicles



R&D GREET sustainability metrics include energy use, criteria air pollutants, GHG, and water consumption

Energy use

- Total energy: fossil energy and renewable energy
- Fossil energy: petroleum, natural gas, and coal
- Non-fossil energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

Resource availability and energy security

Air pollutants

- VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx
- Estimated separately for total and urban (a subset of the total) emissions

Air quality, human health and environmental justice

Greenhouse gases

- CO_2, CH_4, N_2O, black carbon, and albedo
- CO_{2e} of the five (with their global warming potentials)

Global warming impacts

Water consumption

- Addressing water supply and demand (energy-water nexus)

Regional/seasonal water stress impacts

GREET covers materials, chemicals, bioproducts, and plastics

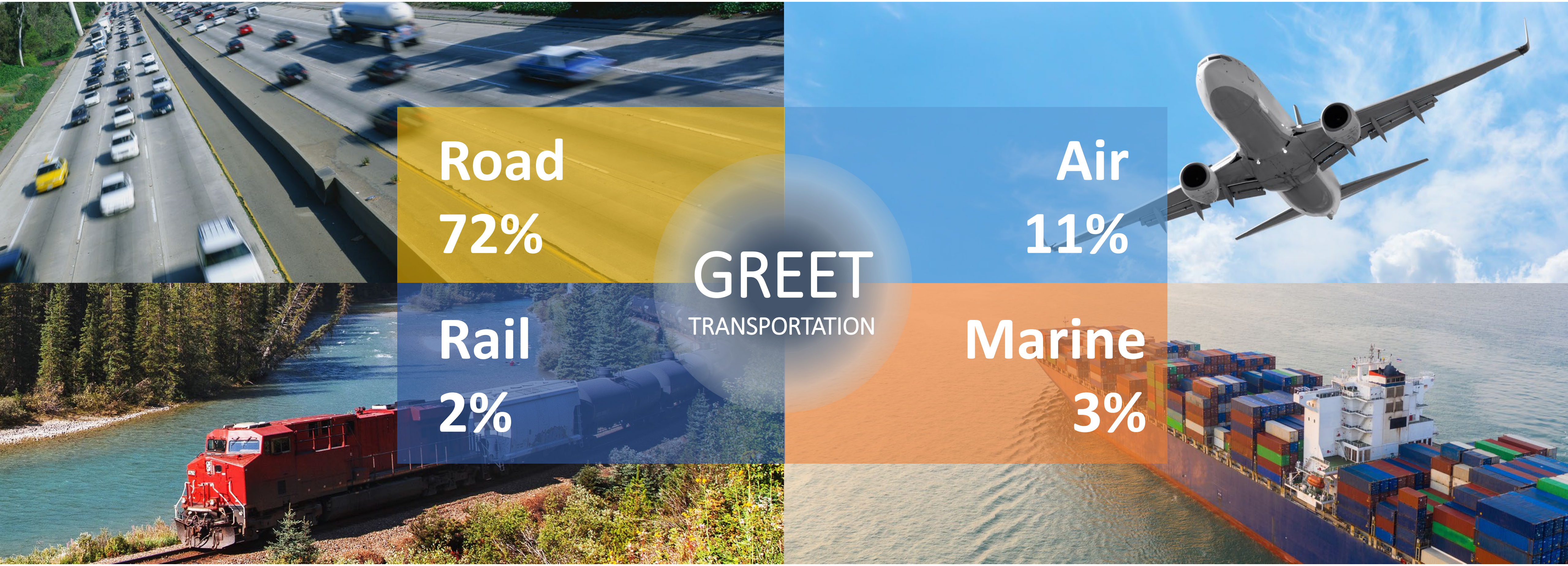
- Platform chemicals from refinery operations
- Bio-based chemicals

- Materials for vehicles
- Building and construction materials

- Major building blocks to promote and expand the U.S bioeconomy
- Integration of biorefinery process with biofuels

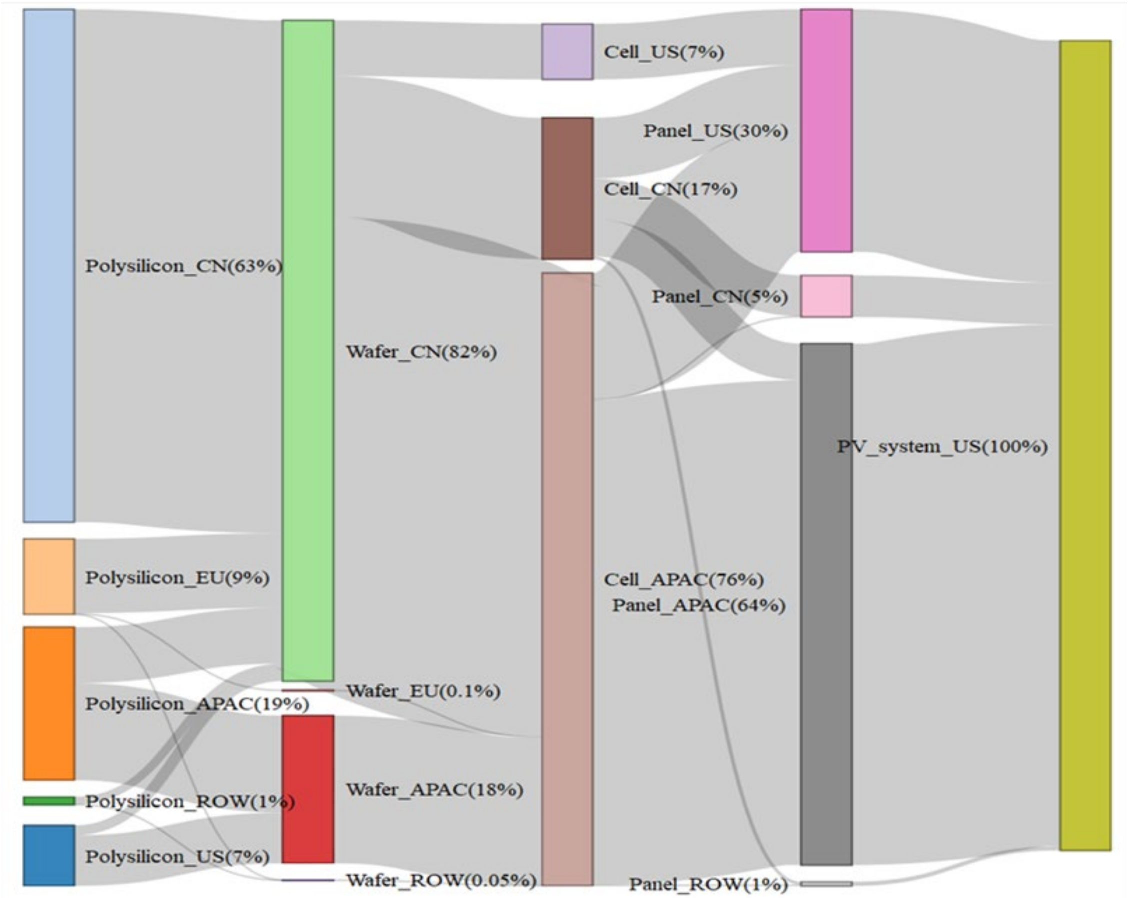
- Major fossil-based plastics
- Bioplastics,
- Plastic re-/upcycling, and plastic-to-fuels

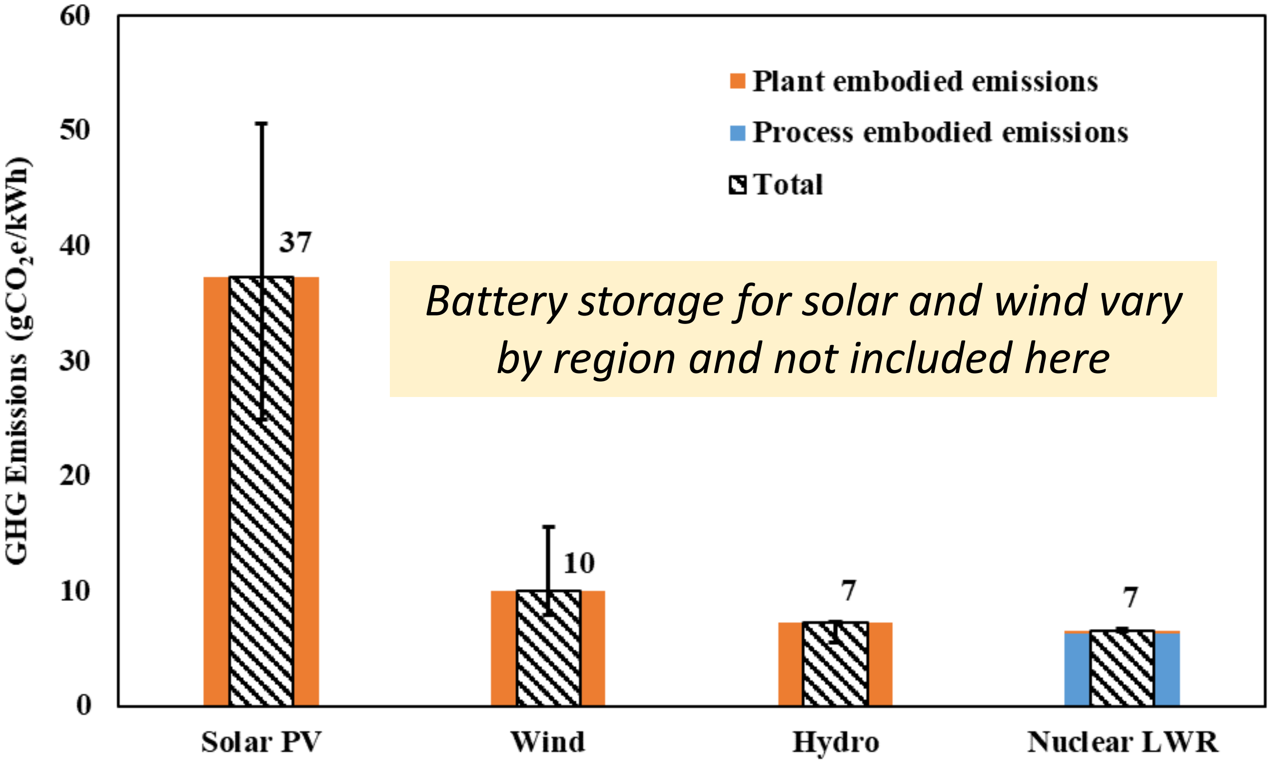
GREET covers all transportation subsectors



Numbers are shares of subsectors in US transportation GHG emissions; remaining 12% is from pipelines and offroad.

Nuclear electricity emissions < solar PV and wind electricity: cradle to grave (C2G) greenhouse gas (GHG) emissions



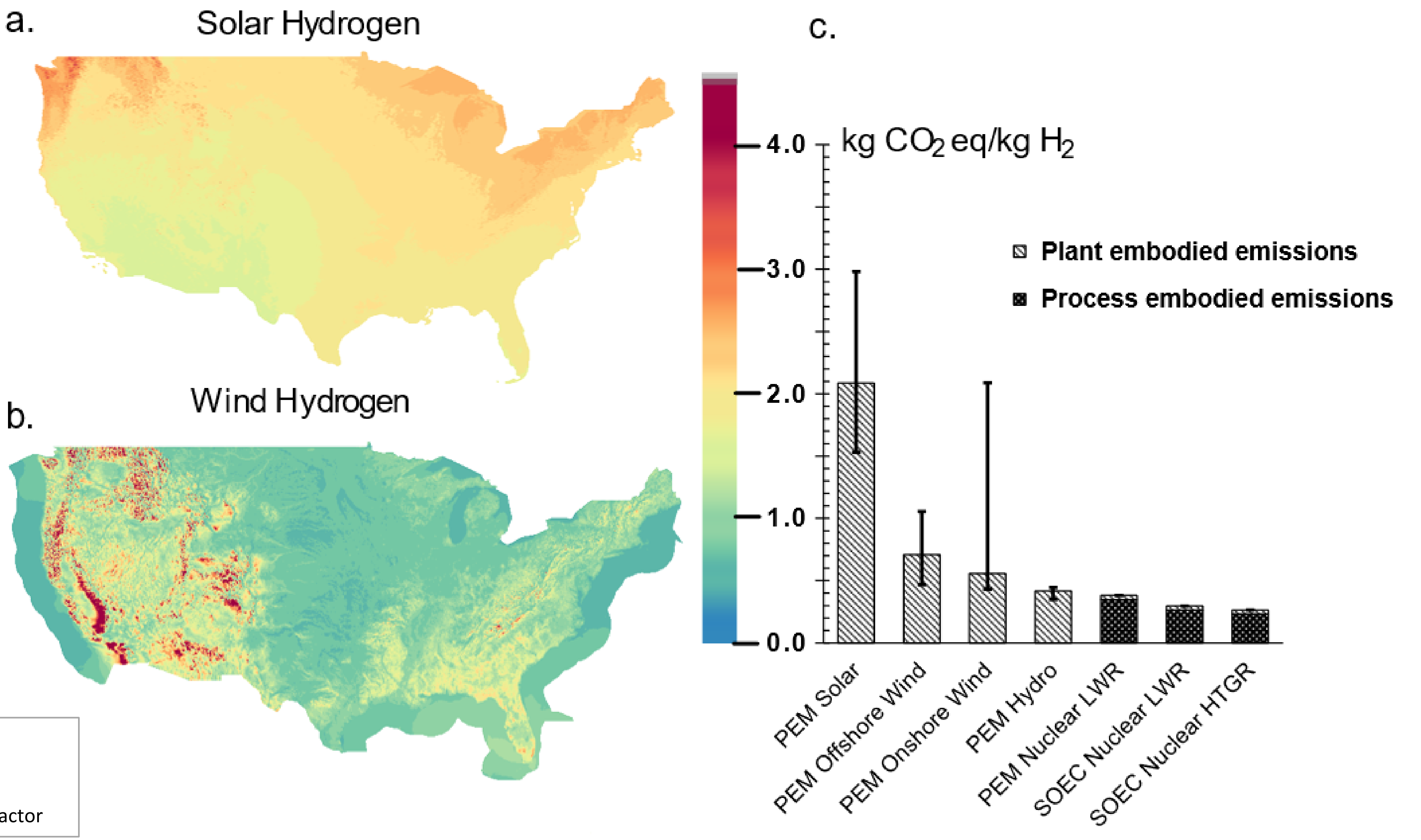


Battery storage for solar and wind vary by region and not included here

- Yu Gan *et al* 2023 *Environ. Res. Lett.*, DOI 10.1088/1748-9326/acf50d
- Yu Gan *et al* 2024, ES&T, *https://doi.org/10.1021/acs.est.3c06769*
- Ng et al. 2025, *Journal of Industrial Ecology, https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.70008*

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

C2G GHG emissions of H_2 production via water electrolysis is lowest with nuclear power



SOEC = solid oxide electrolysis cell
PEM = proton exchange membrane
LWR: light water reactor
HTGR: High temperature gas cooled reactor

- Yu Gan *et al* 2024, ES&T, *https://doi.org/10.1021/acs.est.3c06769*

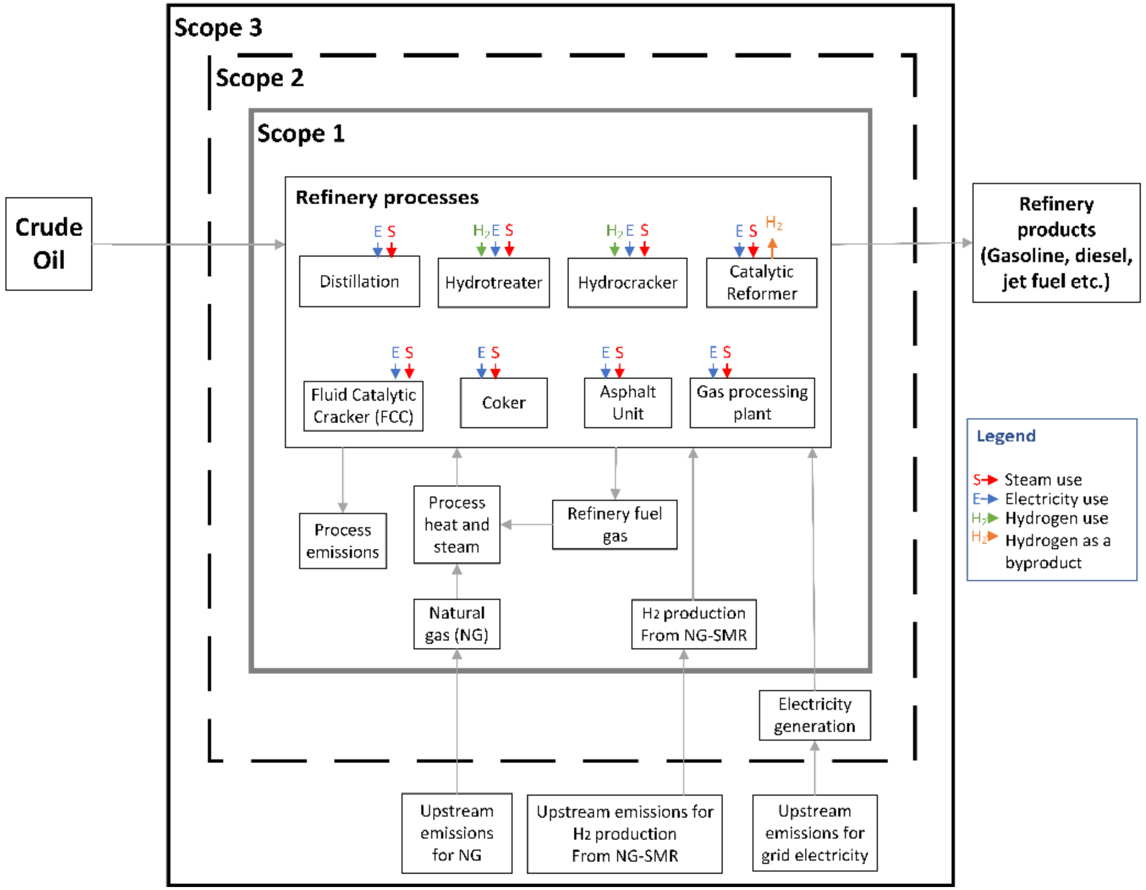
➢ *Impact of solar and wind power infrastructure CAPEX emissions vary due to resource energy intensity and capacity factor*

Nuclear Energy
for Industrial Applications

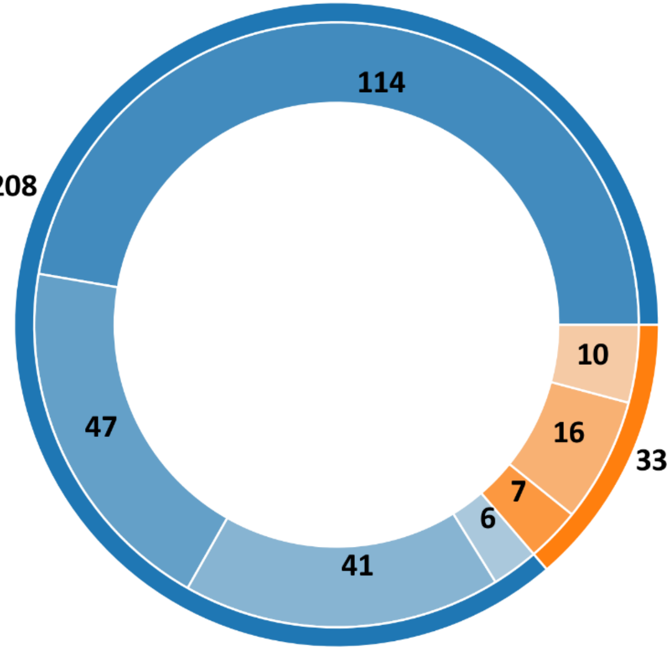
Petroleum refining sector potential use of nuclear energy

Methodology and results

- Estimated well to gate (WTG) emissions for petroleum refineries for (business-as-usual and nuclear integration scenario), using energy and fuel use estimates from EIA, GHGRP, EPA database and GREET for facility level and aggregated to regional and national level



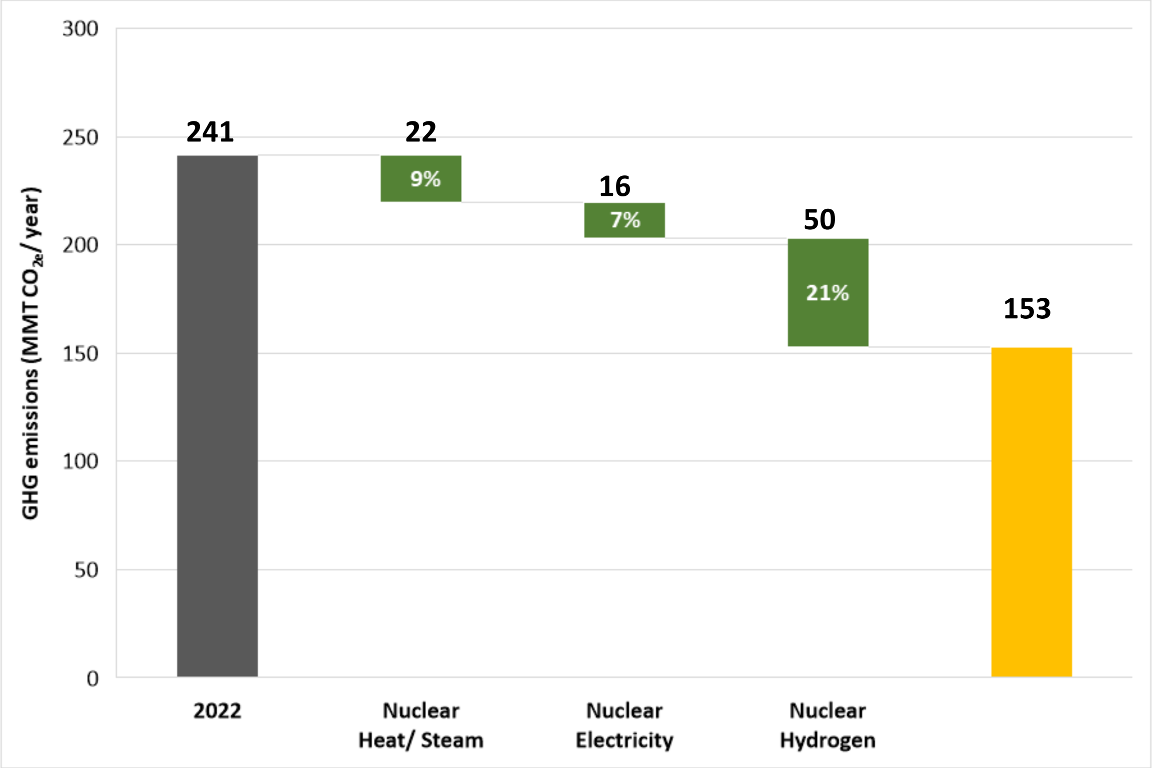
Well to Gate (WTG) System boundary for emissions analysis



GHG Emissions for U.S. petroleum refineries sector (MMT CO_{2e}/ year)

Petroleum refining sector using nuclear energy
Emissions Results

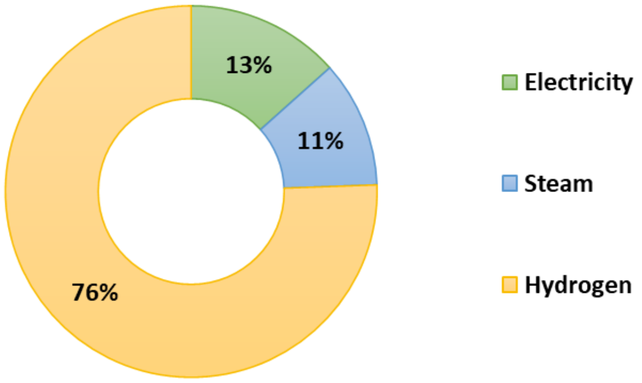
- Well to Gate emissions estimated for BAU case are about 241 MMT CO_{2e}/ year for the petroleum refineries sector
- Potential emissions avoided by nuclear energy by petroleum refineries sector could be about 88 MMT CO_{2e}/ year
- Avoided emissions can reduce the petroleum refinery sector emissions are as follows:
  - Electricity: 7%
  - Steam: 9 %
  - Hydrogen: 21%
- High impact refinery facilities were identified where emission reduction potential is high in absolute and relative terms



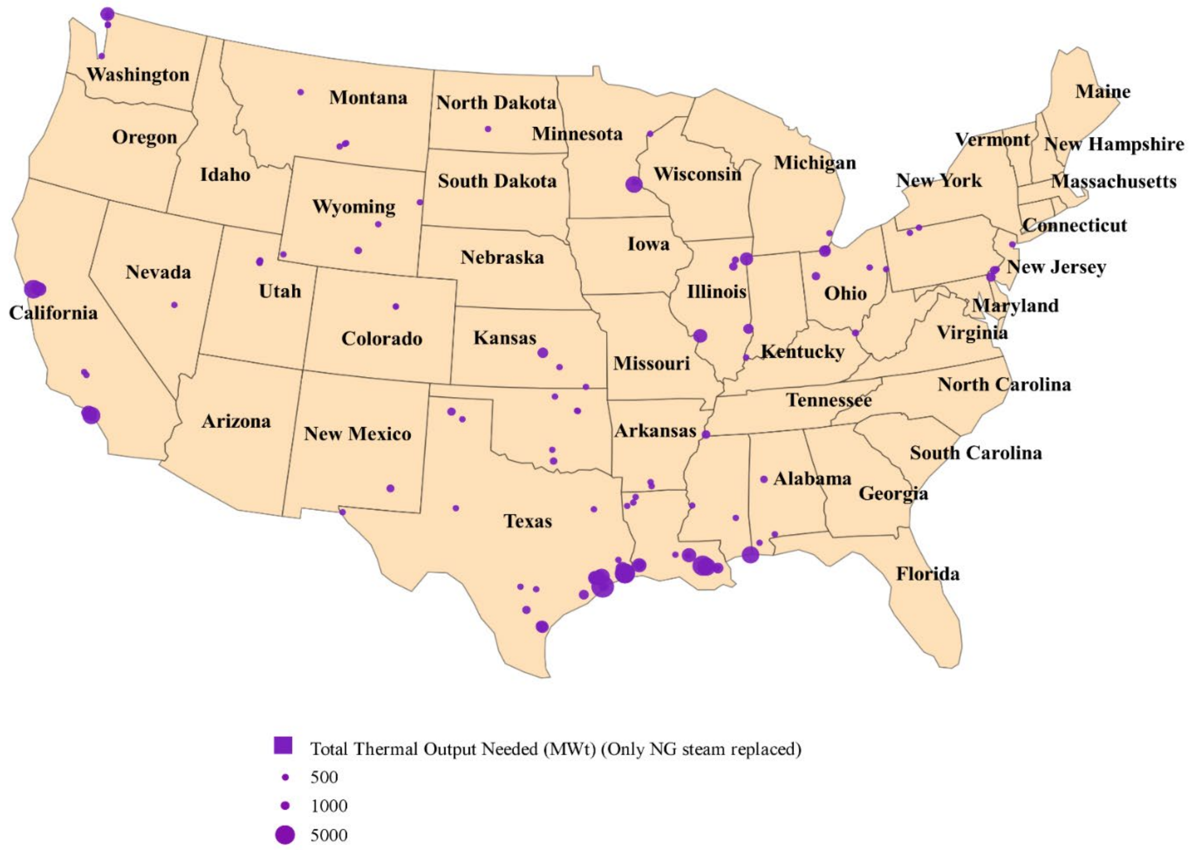
- Conservative: no internal product displacement or repurposing is assumed (e.g., fuel gas in refineries)

Petroleum Refineries
Results

Nuclear energy potential for refineries (replacing NG steam, NG SMR-H_2, and electricity)



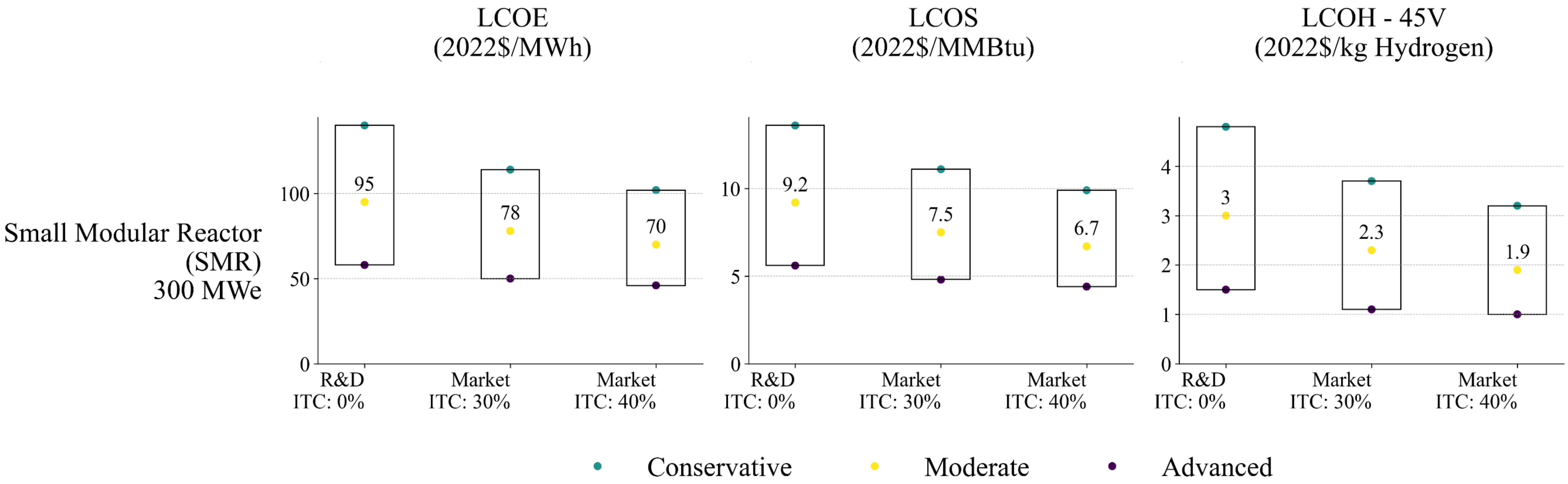
Type of demand	MW_t	MW_e
Steam	10,662	3,519
Electricity	12,938	4,269
Hydrogen	73,021	24,097
Total	96,622	31,885



- Our conservative estimates for Nuclear energy potential for all refineries to be about 97 GW_t or 32 GW_e, with potential of hydrogen production is the highest, close to 24 GW_e
- Large demand centers are observed on the Gulf coast of the US

Cost Analysis

Levelized cost analysis for nuclear electricity (LCOE), steam (LCOS) and hydrogen (LCOH) in 2035

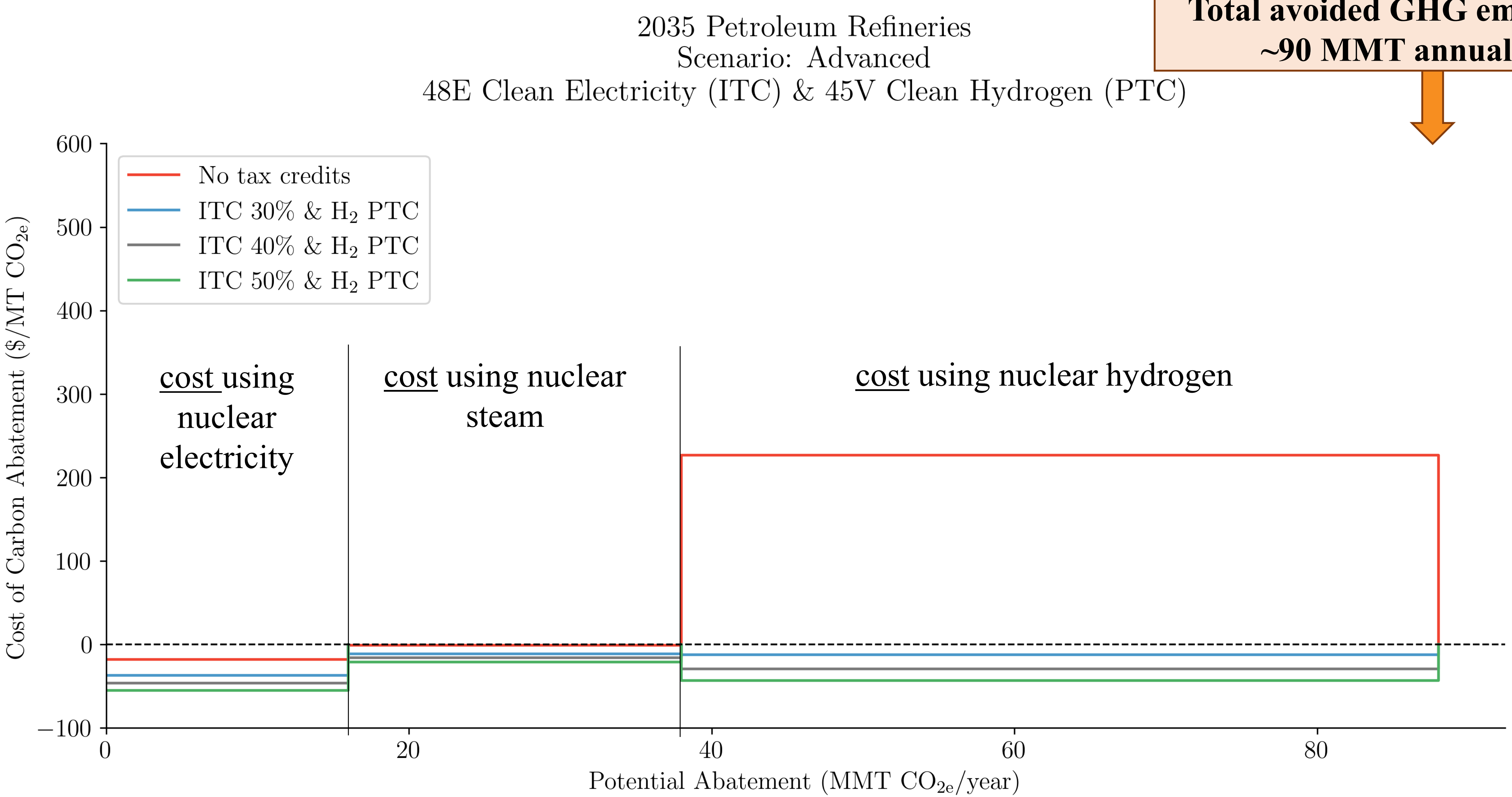


Conservative: Business as usual innovation; Moderate: Intermediate technology innovation progress, Advanced: Optimistic progress
ITC: Investment Tax Credit; PTC: Production Tax Credit

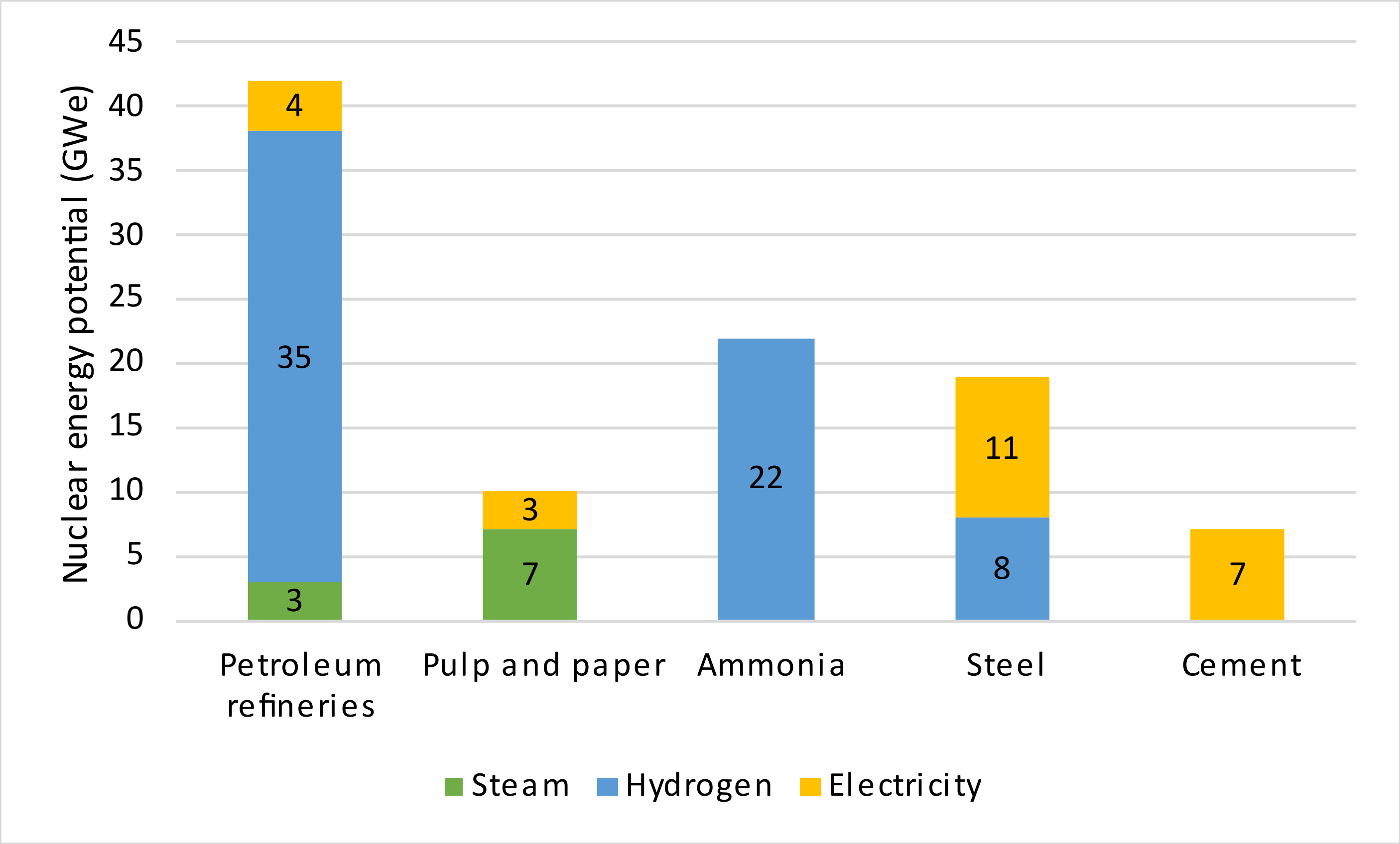
Cost-Benefit Analysis

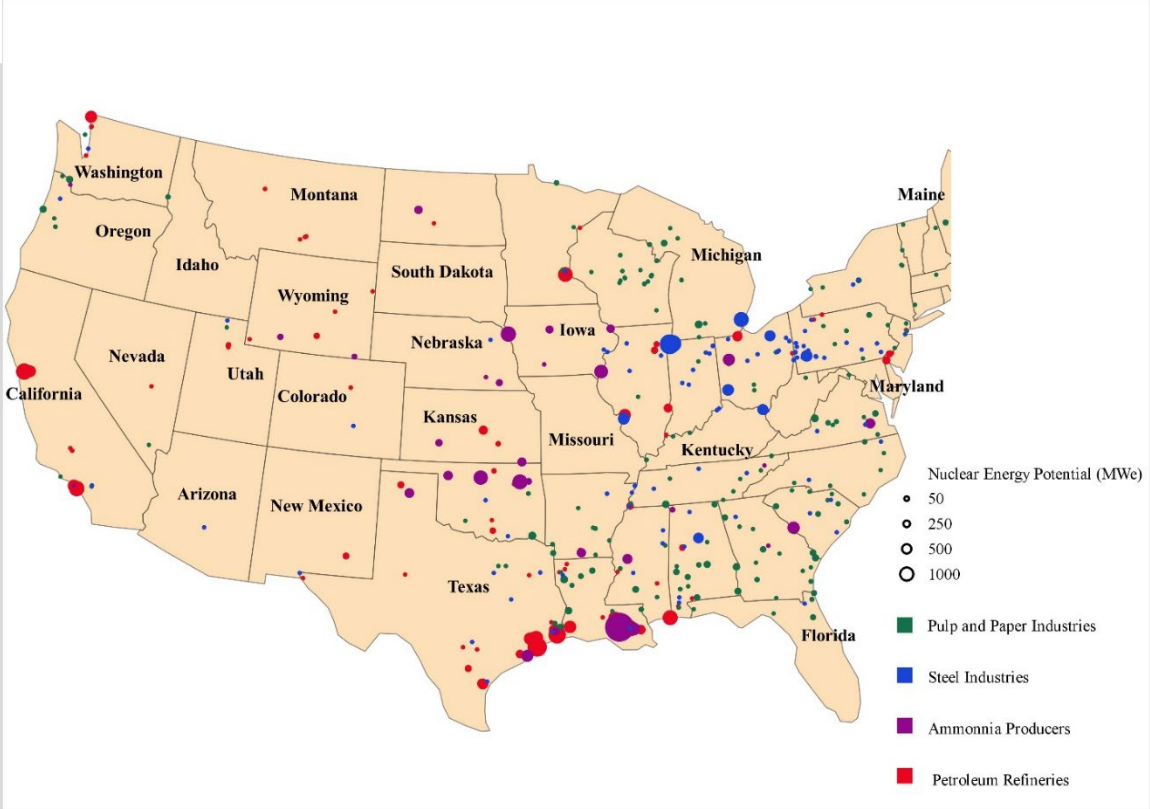
Petroleum refineries avoided GHG emissions using nuclear electricity, steam and hydrogen: negative cost in 2035

Total avoided GHG emissions ~90 MMT annually



Nuclear energy potential for just 5 industrial sectors is ~100 GWe



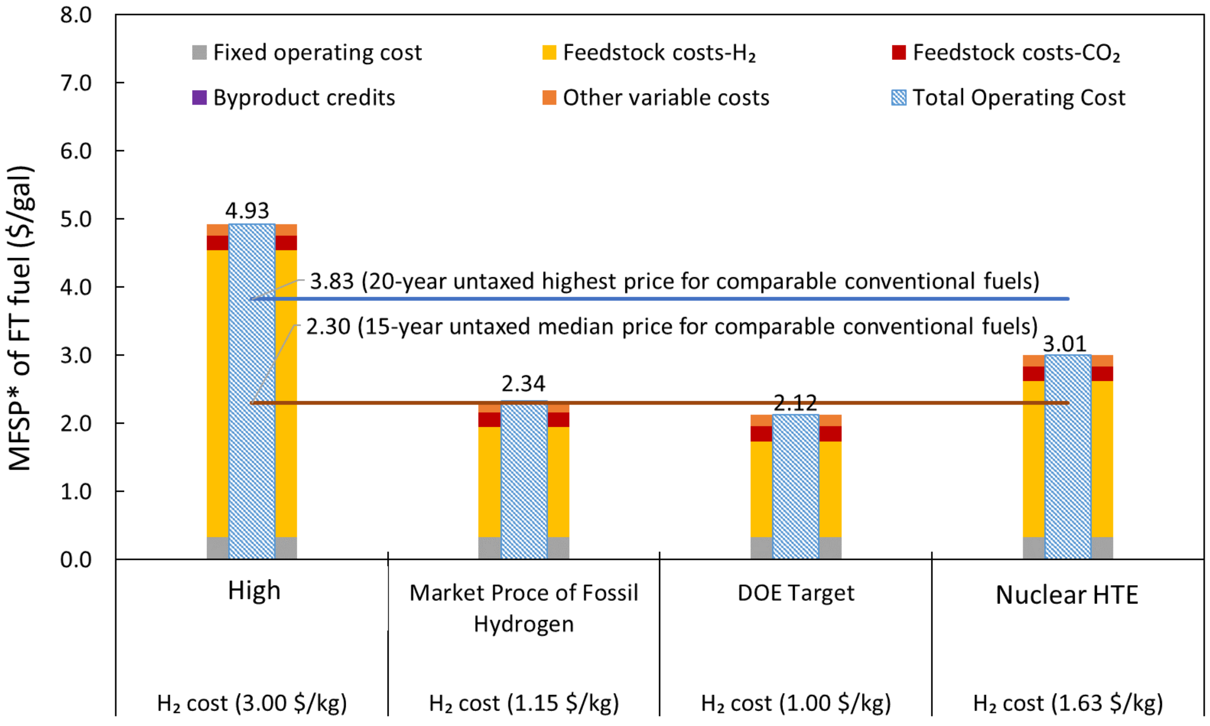


Nuclear Energy for Transportation Applications (e-fuels)

E-fuels via Fischer-Tropsch (FT) process using $H_2 + CO_2$

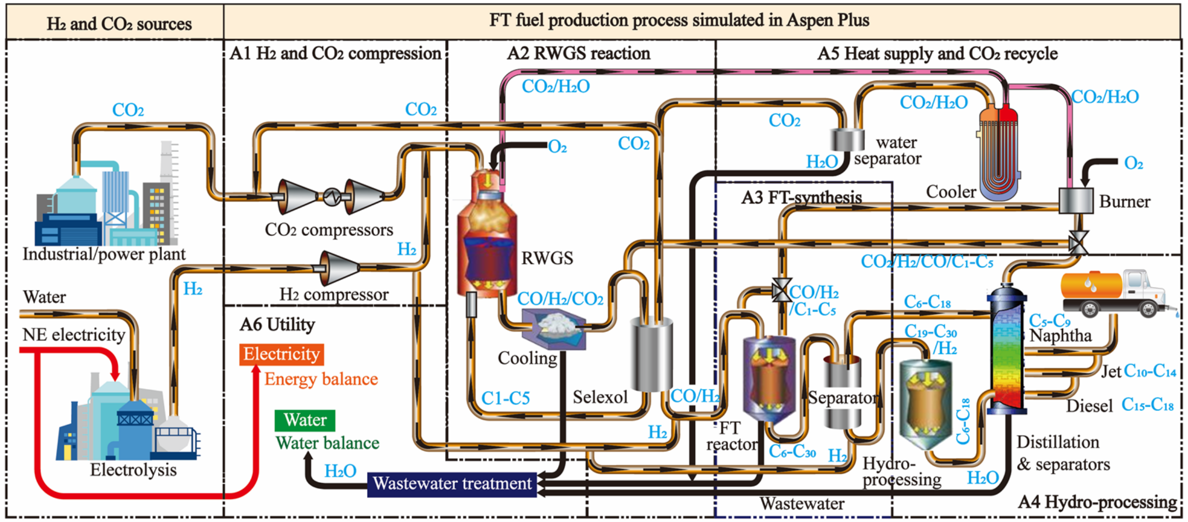
- FT fuels can be synthesized by using CO_2 and H_2 via RWGS and FT reaction
- $CO_2 + H_2 \rightarrow$ syngas $\rightarrow$ FT fuels

▪ Techno-economic analysis

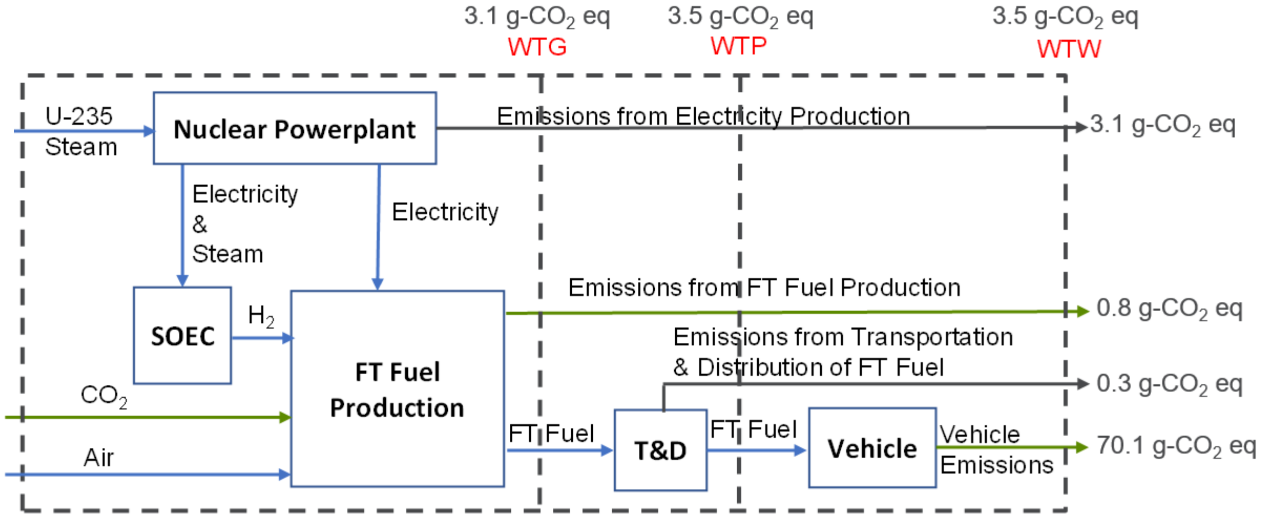


*MSFP=minimum fuel selling price

▪ Conversion process modeling



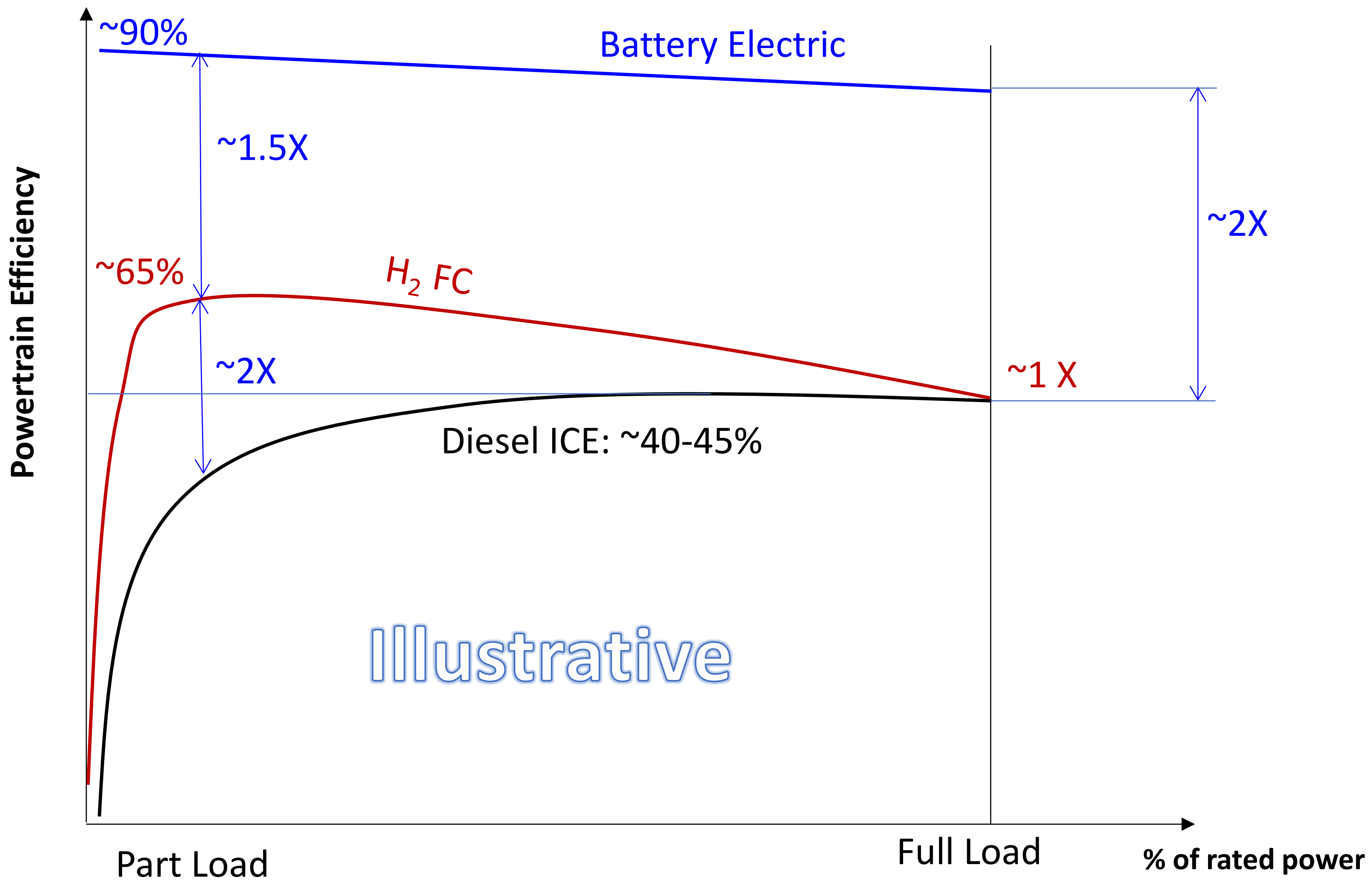
▪ Well-to-gate emissions



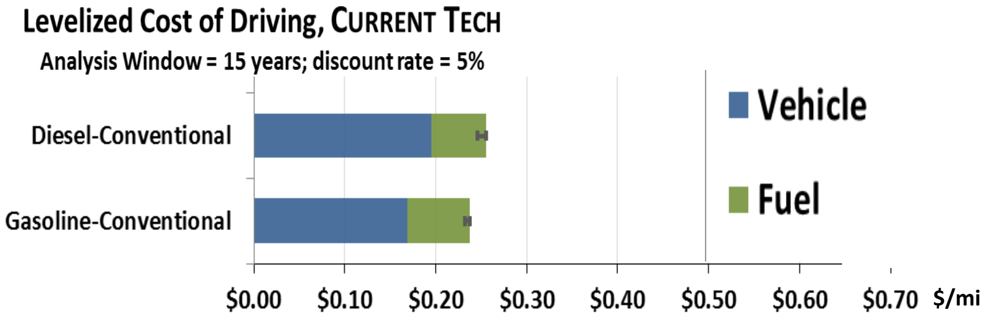
Numbers in per MJ FT Fuel

https://www.osti.gov/biblio/1868524

Energy efficiency of alternative powertrain relative to incumbent (e.g., diesel ICE) is key in enabling lower operation cost and life cycle GHG emissions

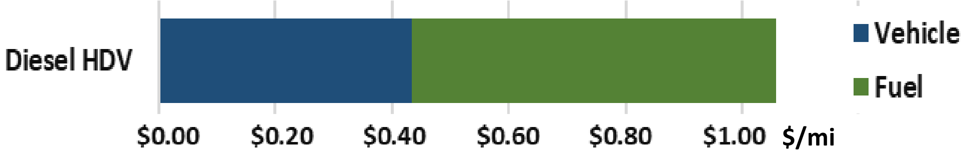


Breakeven H_2 fueling depends strongly on fuel economy ratio with conventional ICEV (fuel cost perspective)



LDVs, https://greet.es.anl.gov/publication-c2g-2016-report

Average Marginal Costs in 2018	[$/mi]
Fuel Costs [$3.18/gal in 2018]	$0.433
Truck/Trailer Lease or Purchase Payments	$0.265

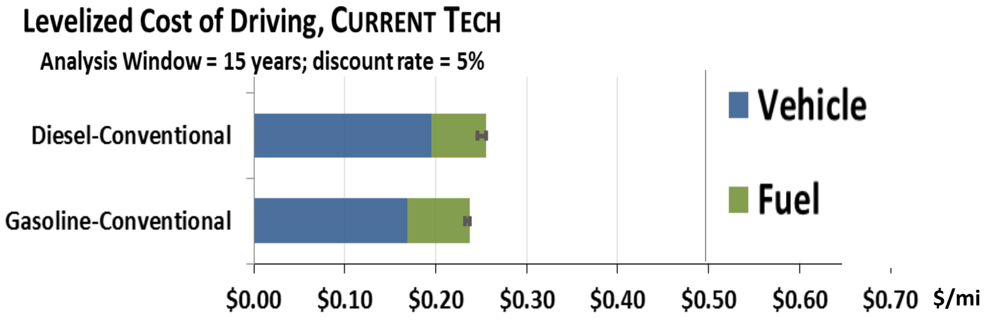


https://truckingresearch.org/atri-research/operational-costs-of-trucking/

	Class 6 PnD Box Truck		Class 8 Line Haul Truck	
	Diesel ICEV	**H_2 FCEV**	**Diesel ICEV**	**H_2 FCEV**
Fuel Economy	8 mpgd	17 mi/kg (~16 mpgde)	7 mpgd	9 mi/kg (~8 mpgde)
Fuel Economy Ratio	**~2**		**~1.1**	
Equivalent Fuel Cost	**$3/gal**	**$6/kg**	**$3/gal**	**$3/kg**
	$4/gal	**$8/kg**	**$4/gal**	**$4/kg**
	$6/gal	**$12/kg**	**$6/gal**	**$6/kg**

✓LCOD: Levelized Cost of Driving
✓M/HDV: Medium- and Heavy-Duty Vehicle
✓VMT: Vehicle Miles Travelled
✓LDV: Light-Duty Vehicle
✓PnD: Pickup and Delivery
✓FCEV: Fuel Cell Electric Vehicle

Breakeven BEV charging cost depends strongly on fuel economy ratio with conventional ICEV (fuel cost perspective)



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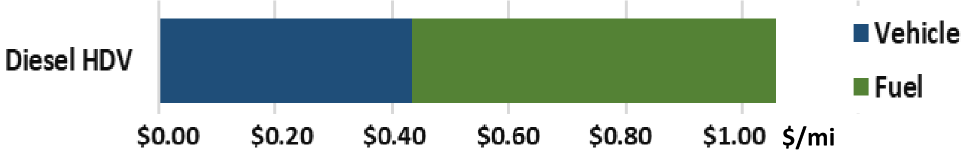
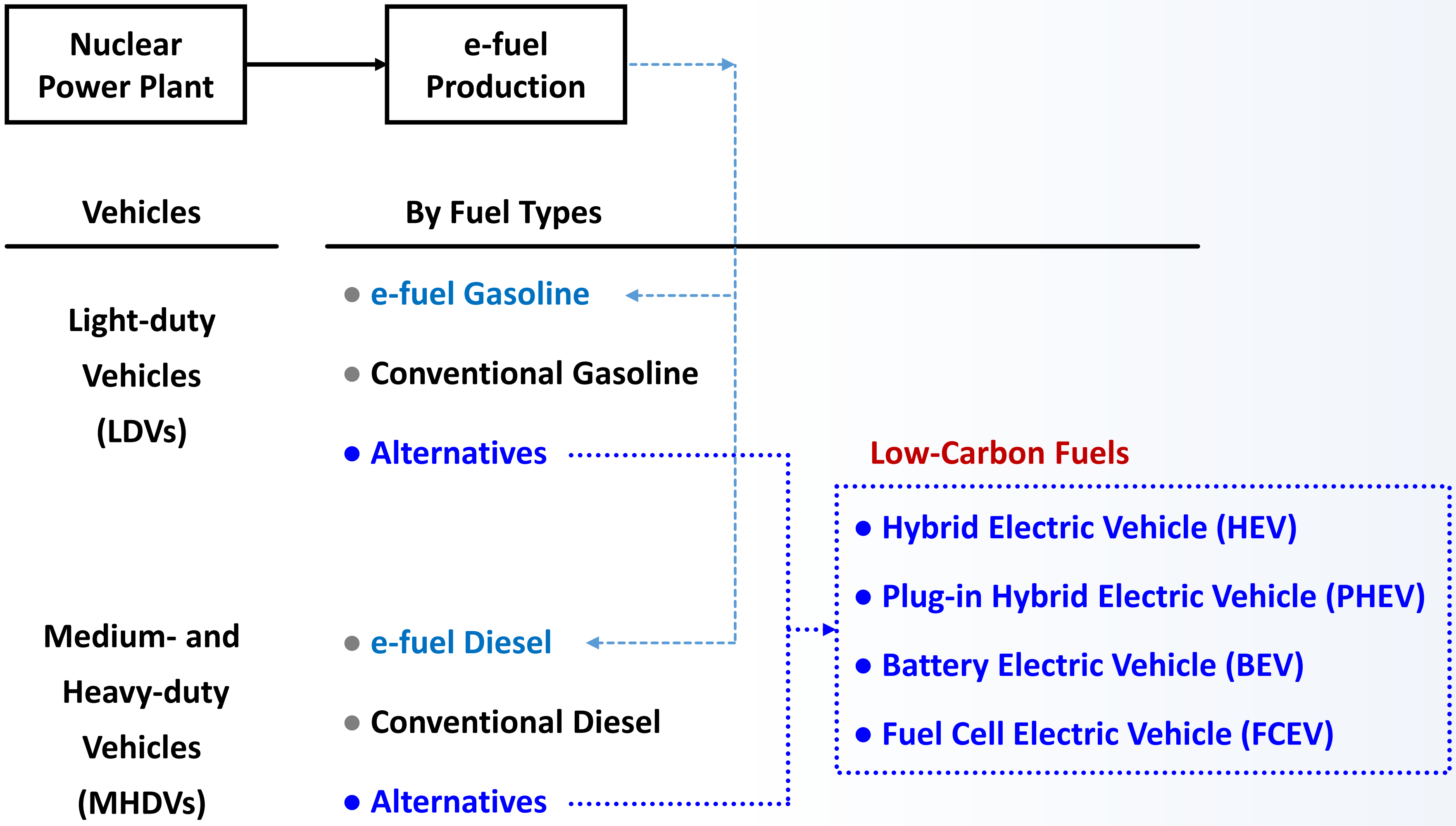


https://truckingresearch.org/atri-research/operational-costs-of-trucking/

	Class 6 PnD Box Truck		Class 8 Line Haul Truck	
	Diesel ICEV	BEV	Diesel ICEV	BEV
Fuel Economy	8 mpgd	~30 mpgde	7 mpgd	~15 mpgde
Fuel Economy Ratio	~4		~2	
Equivalent Fuel Cost	$3/gal	$0.32/kWh	$3/gal	$0.16/kWh
	$4/gal	$0.43/kWh	$4/gal	$0.21/kWh
	$6/gal	$0.64/kWh	$6/gal	$0.32/kWh

✓LCOD: Levelized Cost of Driving
✓M/HDV: Medium- and Heavy-Duty Vehicle
✓VMT: Vehicle Miles Travelled
✓LDV: Light-Duty Vehicle
✓PnD: Pickup and Delivery
✓FCEV: Fuel Cell Electric Vehicle

Total cost of ownership (TSO) – Work Scope



MHDV TCO Analysis – Fuel Price

- Basic data = Annual Energy Outlook 2023 (AEO 2023) reference case

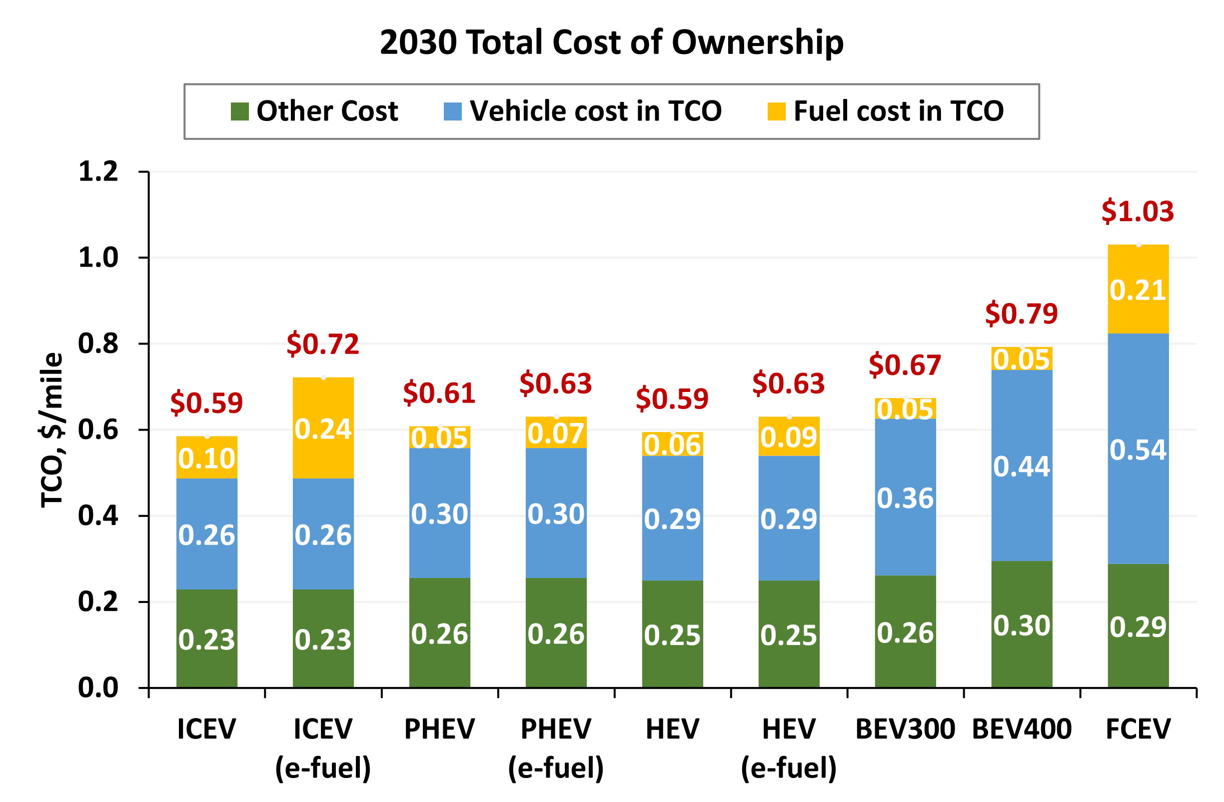
- Fuel prices
  - Diesel (AEO 2023)
    - Untaxed: price without federal and state taxes
  - Hydrogen and e-fuel price
    - Argonne's internal analysis

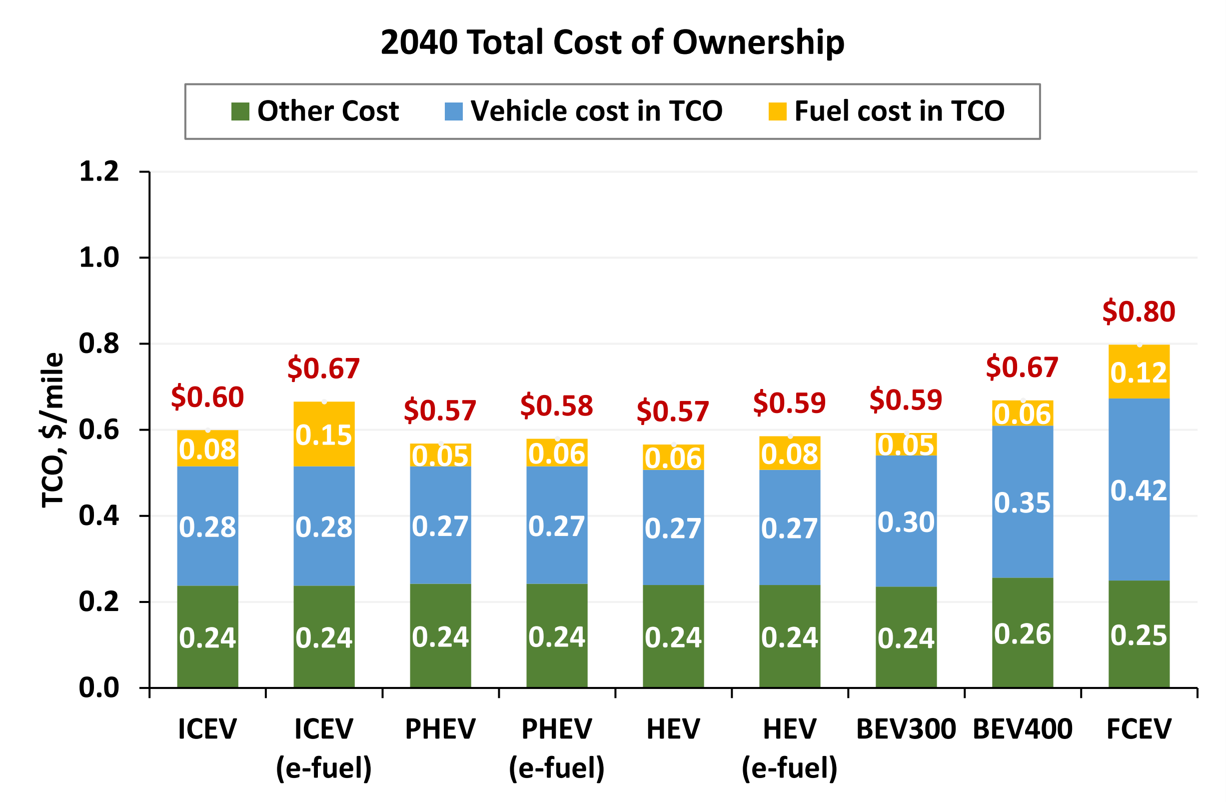
Year	Diesel price ($/gallon)		Nuclear e-fuel price ($/gallon)	Hydrogen price ($/kg)
	U.S. Average	Regional Variation		
2030	3.06	2.95 – 3.62	6.11	10
2040	3.19	3.12 – 3.81	4.75	7

- **Electricity for MHDV charging**
  - Argonne's internal analysis

Year	MHDV BEV charging cost (cent/kWh)
2030	40
2040	30

TCO Results (Small SUV): *relatively small contribution of fuel cost*



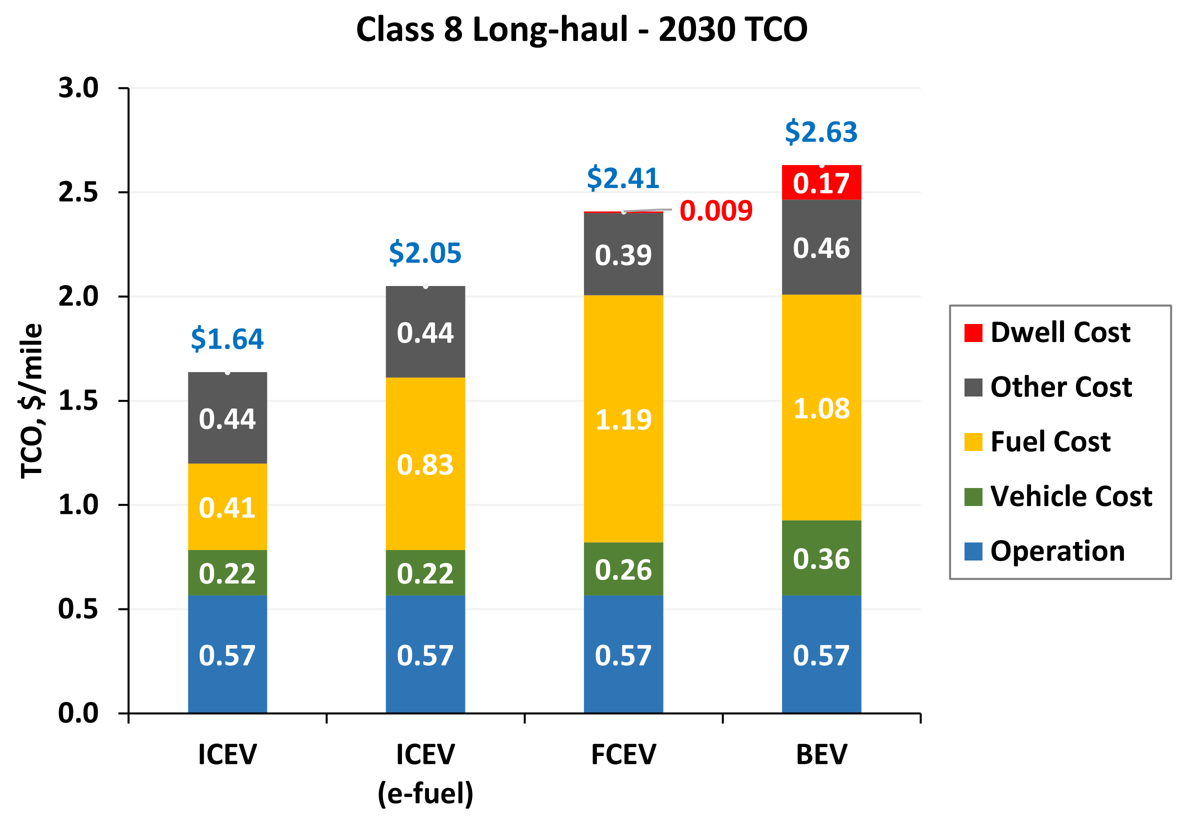


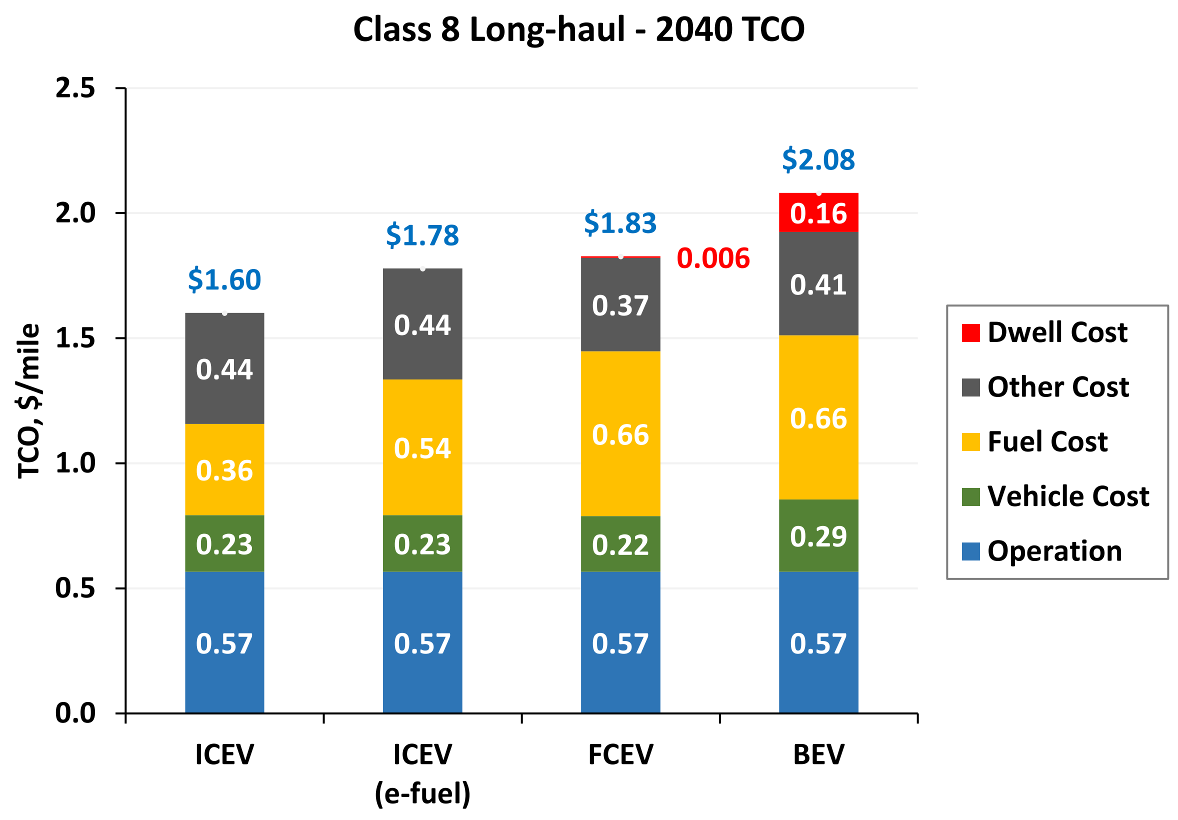
* Other Cost: Financing, Insurance, Tax, Fees, Maintenance

Total Cost of Ownership (TCO), $/mile

Year	Conventional SI		PHEV		HEV		BEV300	BEV400	FCEV
	Gasoline	*e-fuel*	*Gasoline*	*e-fuel & Electricity*	*Gasoline*	*e-fuel*	*Electricity*	*Electricity*	*Hydrogen*
2030	0.59	0.72	0.61	0.63	0.59	0.63	0.67	0.79	1.03
2040	0.60	0.67	0.57	0.58	0.57	0.59	0.59	0.67	0.80

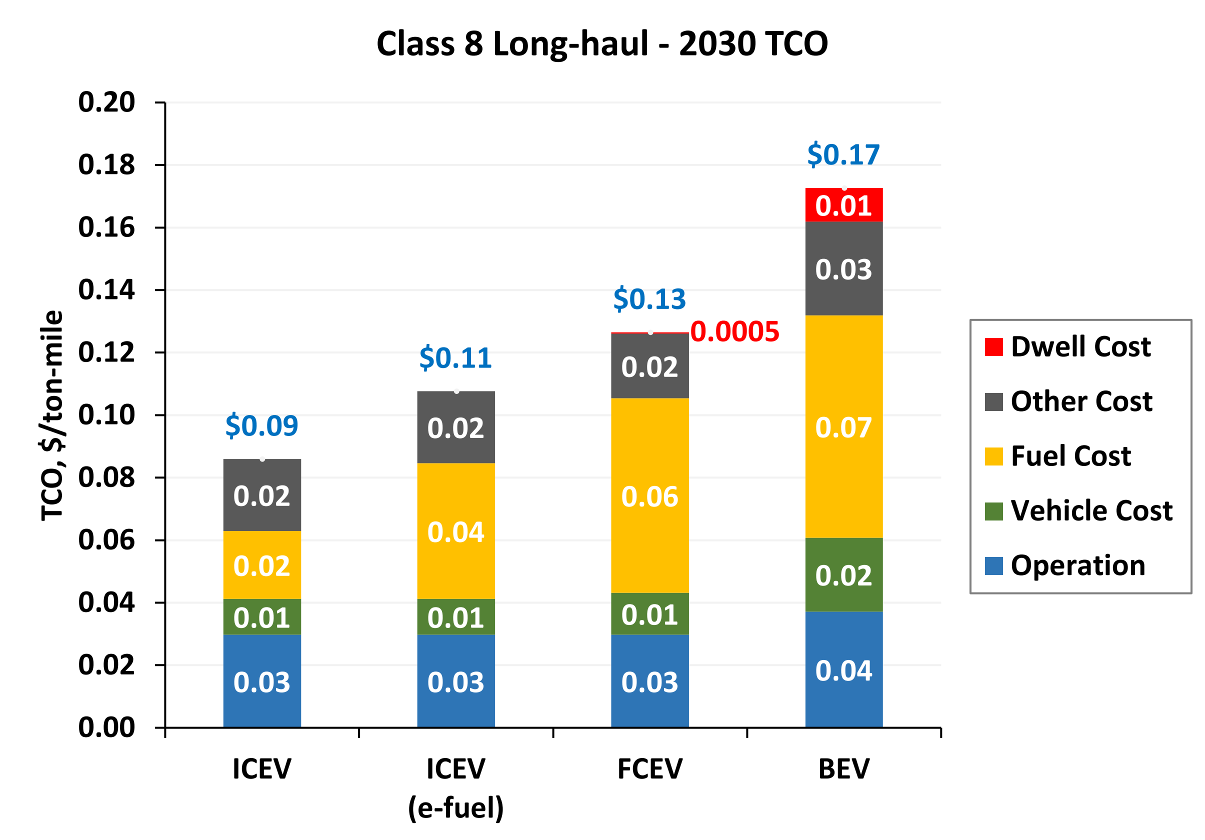
TCO Results - Class 8 Long-haul: *relatively large contribution of fuel cost*

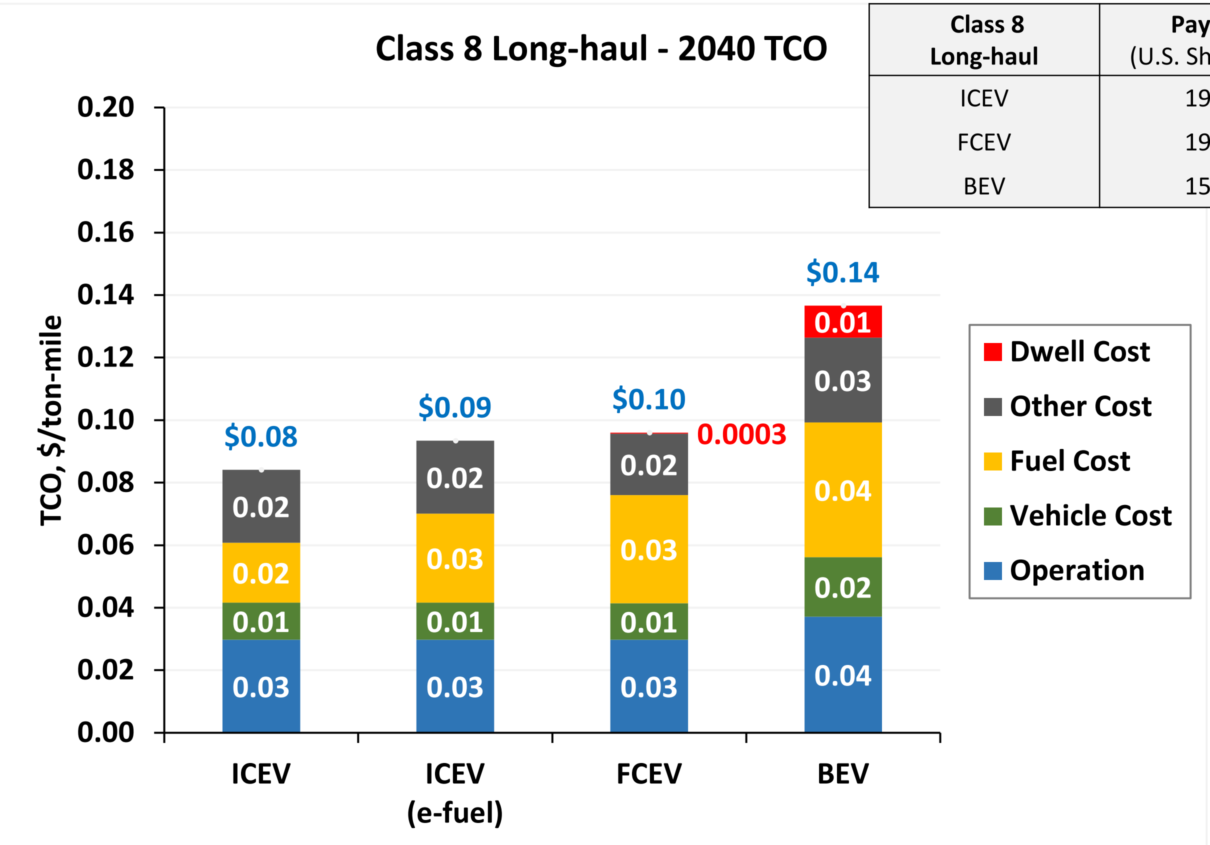




- Operation cost = labor cost for a truck driver
- Dwell cost = extra labor cost when a driver is spending time for charging (BEV) or refueling (FCEV)
  - This may be avoided by the optimum operation such as overnight charging, batter swap, etc.
- Other Cost: Financing, Insurance, Tax, Fees, Maintenance

TCO Results - Class 8 Long-haul ($/ton-mile)



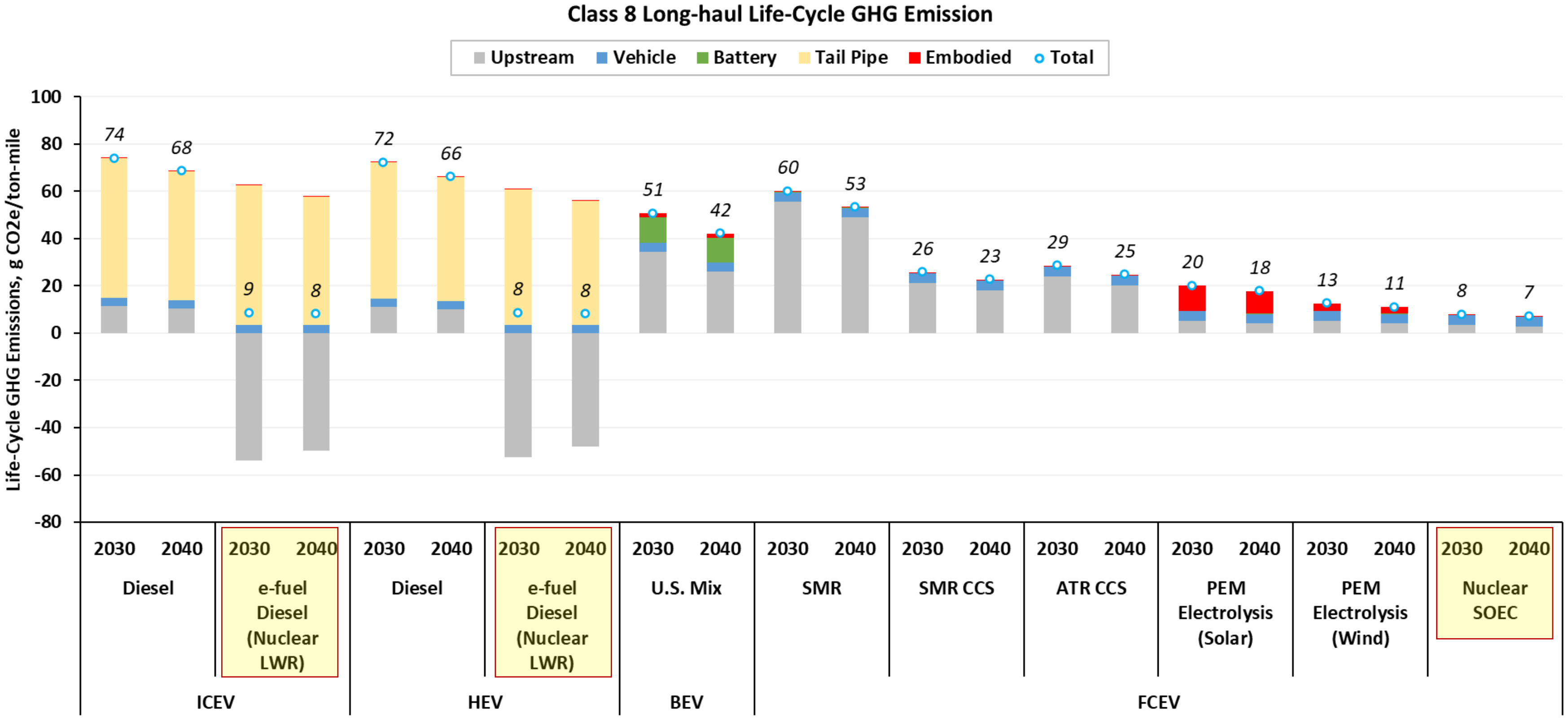


Class 8 Long-haul	Payload (U.S. Short Ton)
ICEV	19.04
FCEV	19.04
BEV	15.23

- ICEV (diesel) is the most economical option followed by ICEV with e-fuel and FCEV
- BEV has less payload due to large on-board battery
  - The relative TCO to ICEV (diesel) is increased with payload consideration

GHG Emissions : MHDV – Class 8 Long-haul

Emission by gCO_{2e}/ton-mile



● MPDGE (miles per diesel equivalent gallon)

Year	2030	2040
ICEV	9.1	9.9
HEV	9.4	10.3
BEV	16.5	18.5
FCEV	11.1	12.4

No weather effect. i.e., 100% performance

● Payload (U.S short ton)

Year	Class 8 Long-haul
ICEV	19.04
HEV	19.04
BEV	15.23
FCEV	19.04

- Consider the payload of trucks on the GHG emissions (i.e., gram of GHG emission per ton-mile).
- FCEV with green hydrogen supplied by nuclear SOEC shows the lowest GHG emission among all cases.
- e-fuel diesel with nuclear power is the 2nd lowest emissions (ICEV and HEV).
- Among three MHDVs, with payload consideration (g CO2e/ton-mile), Class 6 box delivery shows the highest GHG emission and Class 8 long-haul shows the lowest GHG emission.

Acknowledgment

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- ANL team: Adarsh Bafana, Kwang Hoon Baek, Sheik Tanveer and Neeraj Hanumante

Thank you!

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