LIFE CYCLE ANALYSIS OF HEAVY-DUTY TRUCKS

An environmental impact study comparing alternative fuels/drivetrains

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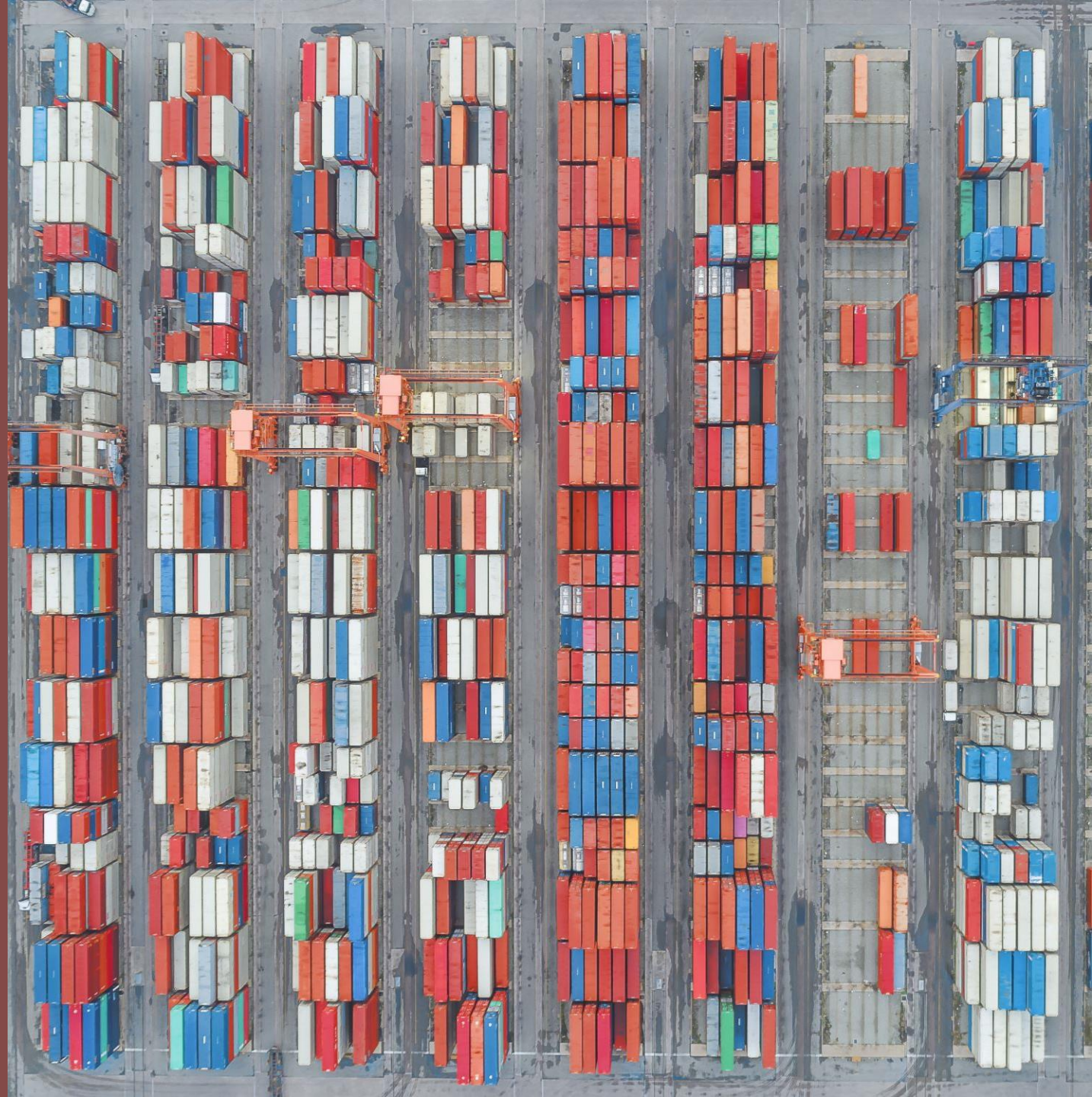
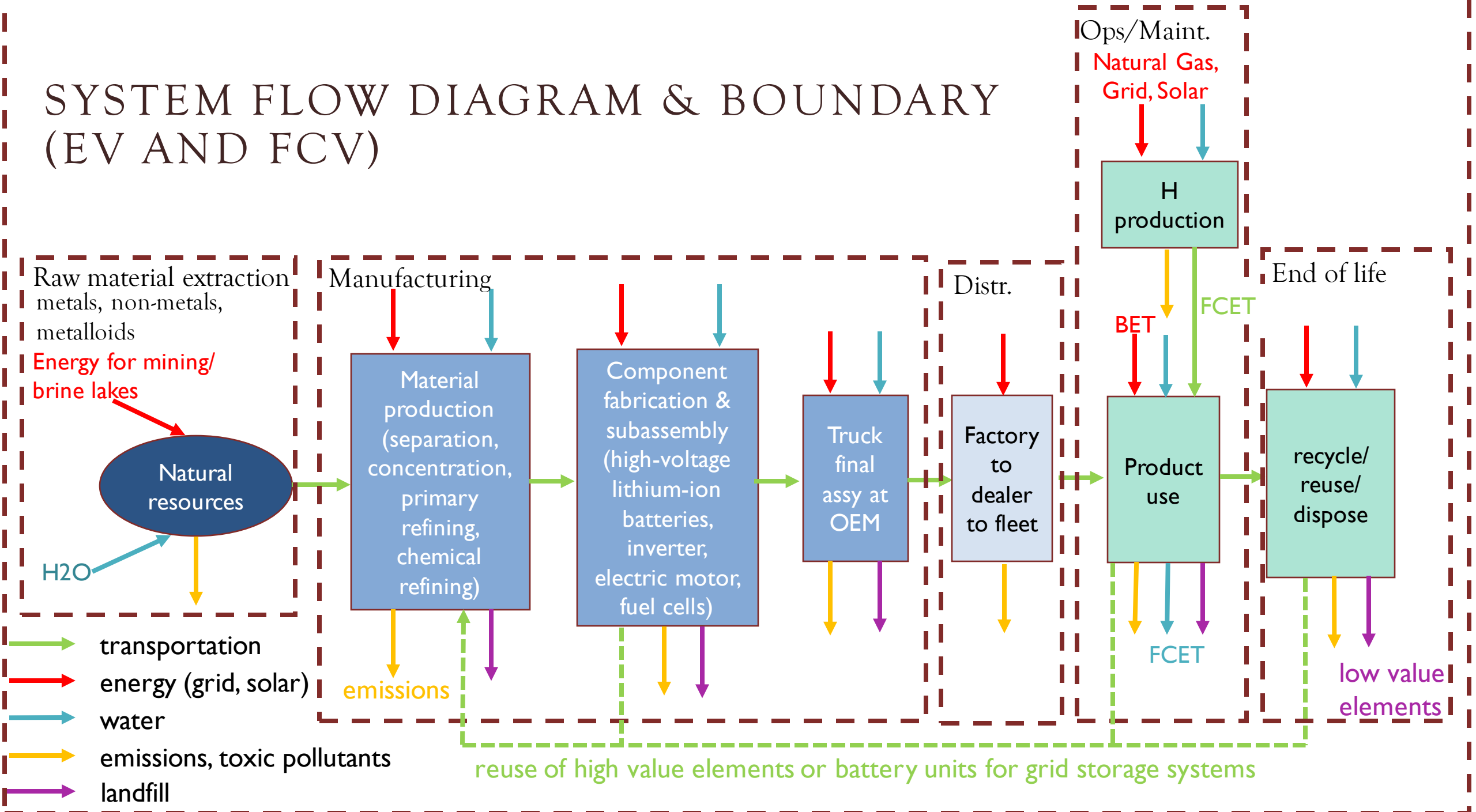


RESEARCH PROBLEM & FUNCTIONAL UNIT

- **THE question: which type of engine/powertrain has the lowest carbon footprint? Electric (EV) or hydrogen fuel cell (FCV)?**
- Understand the life cycle impacts from all phases of alternative technology heavy-duty trucks
  - Compare all phases of the lifecycle including the manufacturing, distribution, operation, and retirement/recycling of truck components which are different between models, not those items which are the same (e.g., a tire is a tire) → changed to entire vehicle comparison
- Functional unit = 1 mile driven
- Main assumptions
  - Both class-8 trucks used in same region with same number of miles (48,360/yr., 10-year life, 300-mile range)
  - Information on vehicles gleamed from various sources since not in production
    - Kenworth/Toyota T680 in demonstration (CARB grant)
    - Tesla running tests, but access to test Semi not available to outside entities

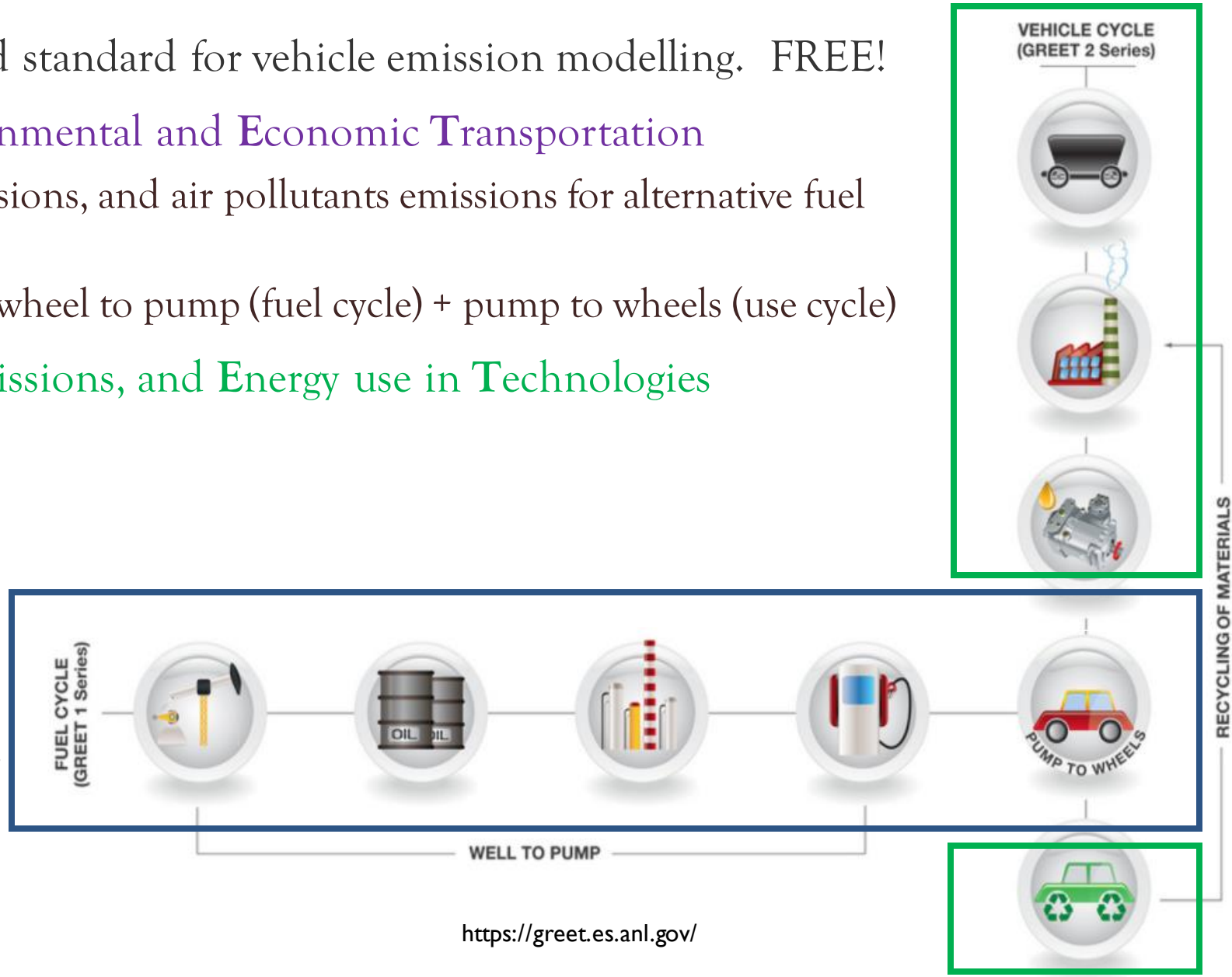
EV Tesla Semi
vs.
FCV Kenworth/Toyota T680

SYSTEM FLOW DIAGRAM & BOUNDARY (EV AND FCV)



TOOLS: AFLEET 2020 & GREET 2020

- By Argonne National Library; gold standard for vehicle emission modelling. FREE!
- Alternative Fuel Life-Cycle Environmental and Economic Transportation
  - Estimates energy use, GHG emissions, and air pollutants emissions for alternative fuel light and **heavy-duty vehicles**
  - Well-to-wheels (WTW) phases = wheel to pump (fuel cycle) + pump to wheels (use cycle)
- Greenhouse Gases, Regulated Emissions, and Energy use in Technologies
  - Estimates energy use, GHG emissions, and air pollutants emissions for **passenger vehicles**
  - Vehicle cycle + recycling phases
    - Raw material recovery/ transport/processing
    - Material production/processing
    - Vehicle assembly
    - Disposal/recycling of vehicle; battery recycling (new addition)



https://greet.es.anl.gov/

LCA PROCESS

Inventory Analysis

- Obtain data for major component systems with differences
- Determine scale up ratios for car to truck conversion

AFLEET

- Heavy-duty truck app
- Well to pump (fuel cycle) & pump to wheel (use cycle) modeling

GREET

- Passenger vehicle app
- Cradle to gate phases + recycling/disposal modeling
- "Factor up" for trucks

Synthesize/ Normalize

- Combine all phases in Excel
- Adjust to functional unit

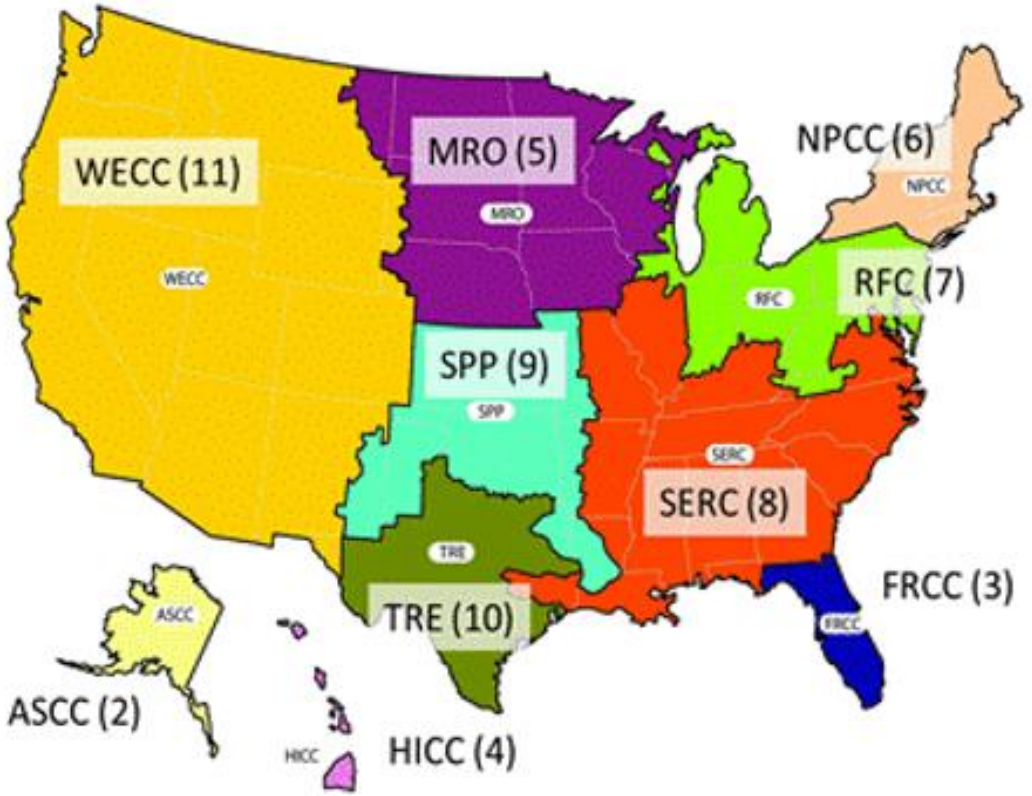
MODEL DATA INPUTS

type	component	car	truck	factor	factor based on	references/notes
diesel	model	GREET default	Kenworth/Toyota T680			
	vehicle weight	3184 lbs.	14200 lbs.	4.46	weight	GREET, Truckinginf
EV	model	Tesla Model S (2021 model)	Tesla Semi			
	vehicle weight	4766 lbs.	26909 lbs.	5.64	weight	Tesla, Teslarati
	lithium-ion battery NCA	85 kWh, 1200 lbs. (7104 cells)	500 kWh, 5622 lbs.	5.88	kWh	Electrek, Insideevs.news, Teslarati
	motor	2 ea. (70 lbs./140 lbs.)	4 ea.	2	quantity	Tesla
	power converter	--	--	5.64	overall weight	no specific data found
FCV	model	Mirai (2021 model)	Kenworth/Toyota T680 FCV			
	vehicle weight	4255 lbs. (XLE 4 dr model)	22000 lbs.	5.17	weight	Autolog, CCJ Digital
	fuel cell stack	1 ea. 128 kw, 172 hp; 25.5 kg	2 ea. 153 hp	1.779	hp	Fuelcellworks, Toyota, Greencar Reports
	fuel tanks	3 ea.; 5.6 kg capacity; 131 kg	6 ea.; 60kg capacity (no wt)	10.714	capacity*	Fuelcellworks, Greencar Reports
	lithium-ion battery NCA	1.24 kWh (84 cells); 44.6 kg	12 kWh; 907 kg	9.677	kWh	Car & Driver, CCJ Digital, Greencar Reports
	tractor motor	1325 torque, 670 hp	221 torque, 182 hp	3.68	hp	Motortrend, Fleet Equipment
	electronic controller	--	--	5.17	overall weight	no specific data found
	power converter	25.5 kg	--	5.17	overall weight	Fuelcellworks
	*Factor adjusted to overall weight since % of tank to vehicle allocaton > than calculated					

← Model S

Mirai→

MODEL DATA INPUTS

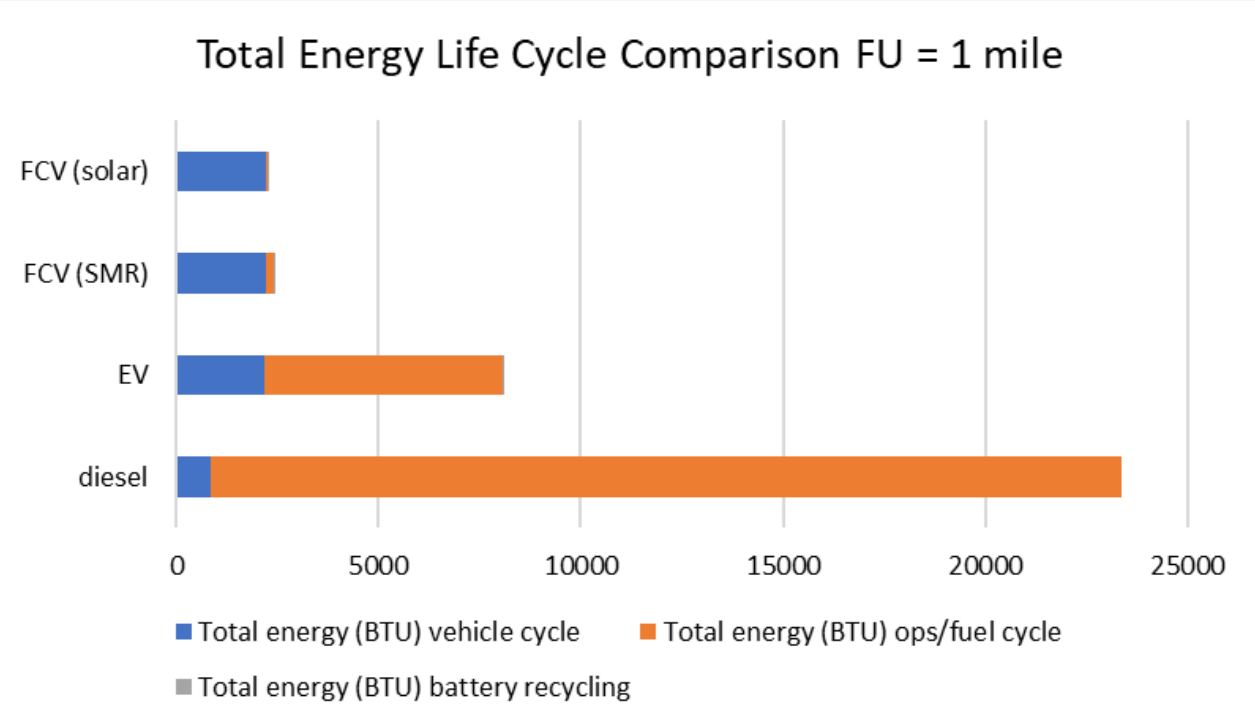


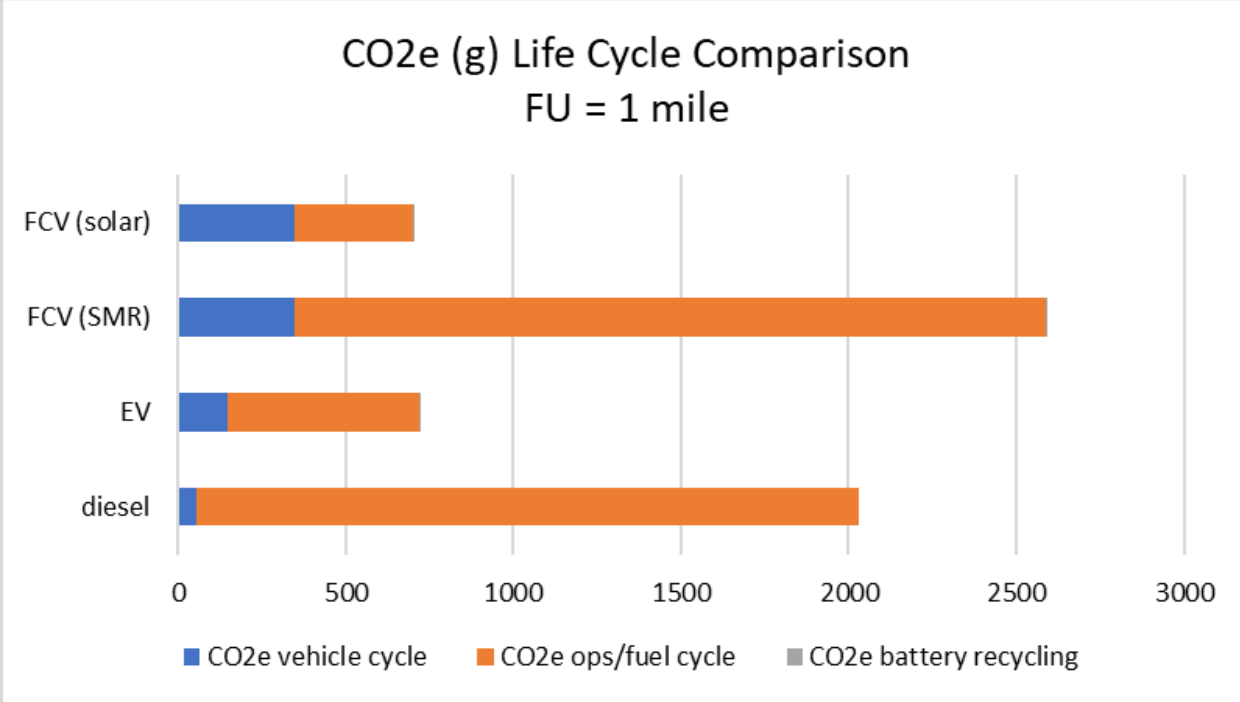
CO2e calculation (per IPCC 2nd assessment Rpt)	
CO2	1
CH4	21
N2O	310

- GREET presents data for total life of vehicle
- AFLEET presents data for yearly and total life of vehicle
- Adjusted to functional unit (1 mile) for all

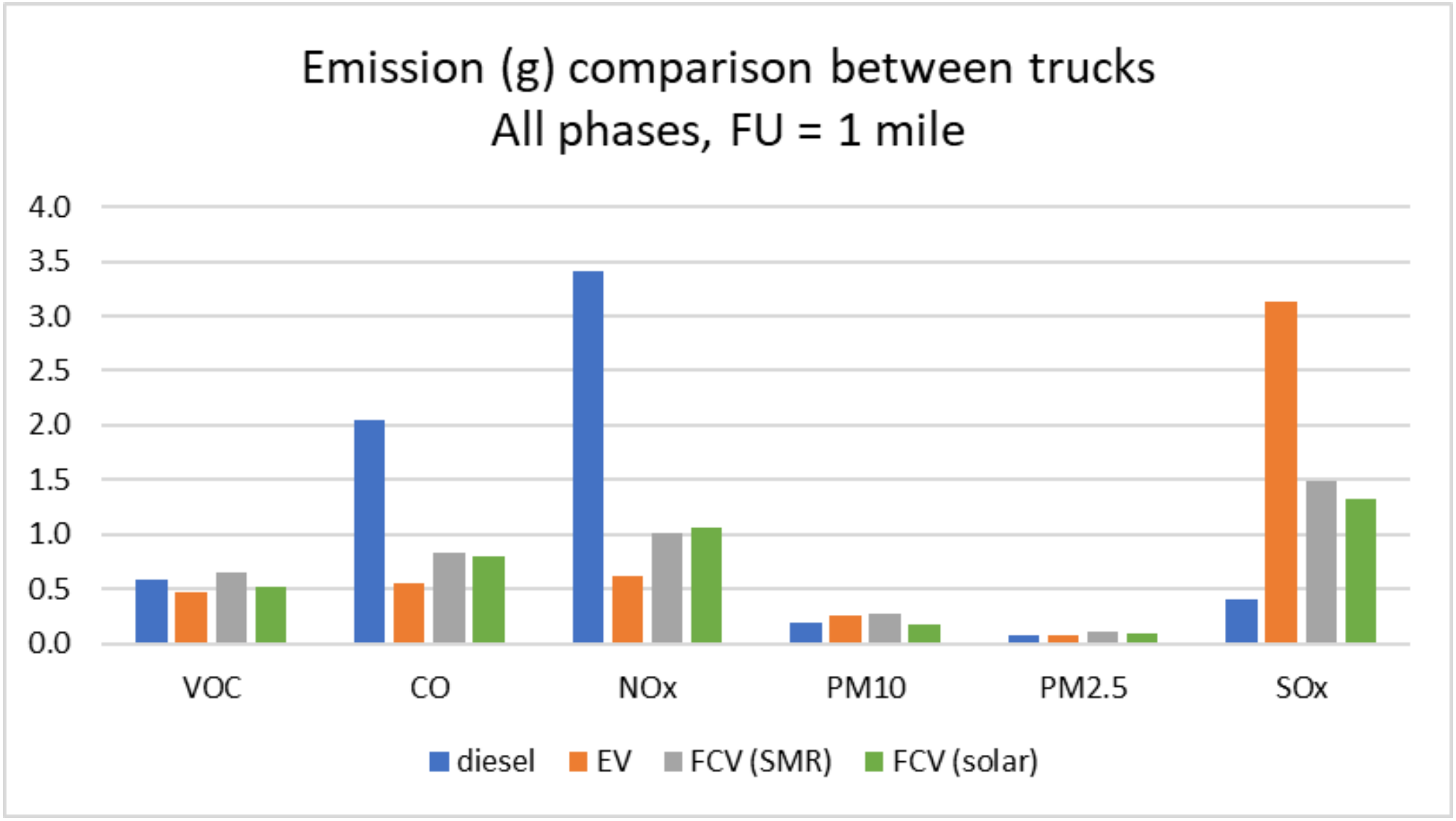
Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Western Electricity Coordinating Council (WECC) Mix										
2019	0.14%	31.24%	17.38%	8.40%	0.45%	25.58%	2.26%	7.65%	6.50%	0.40%

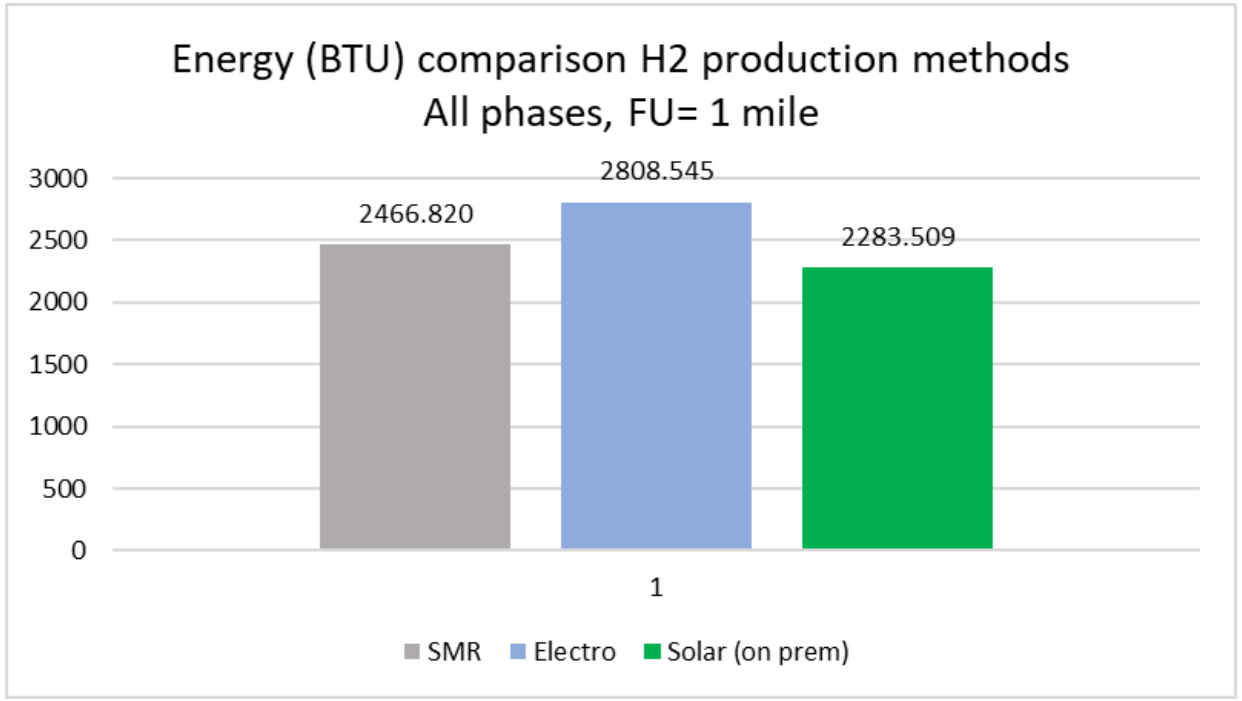
RESULTS: ENERGY & CO2e COMPARISONS

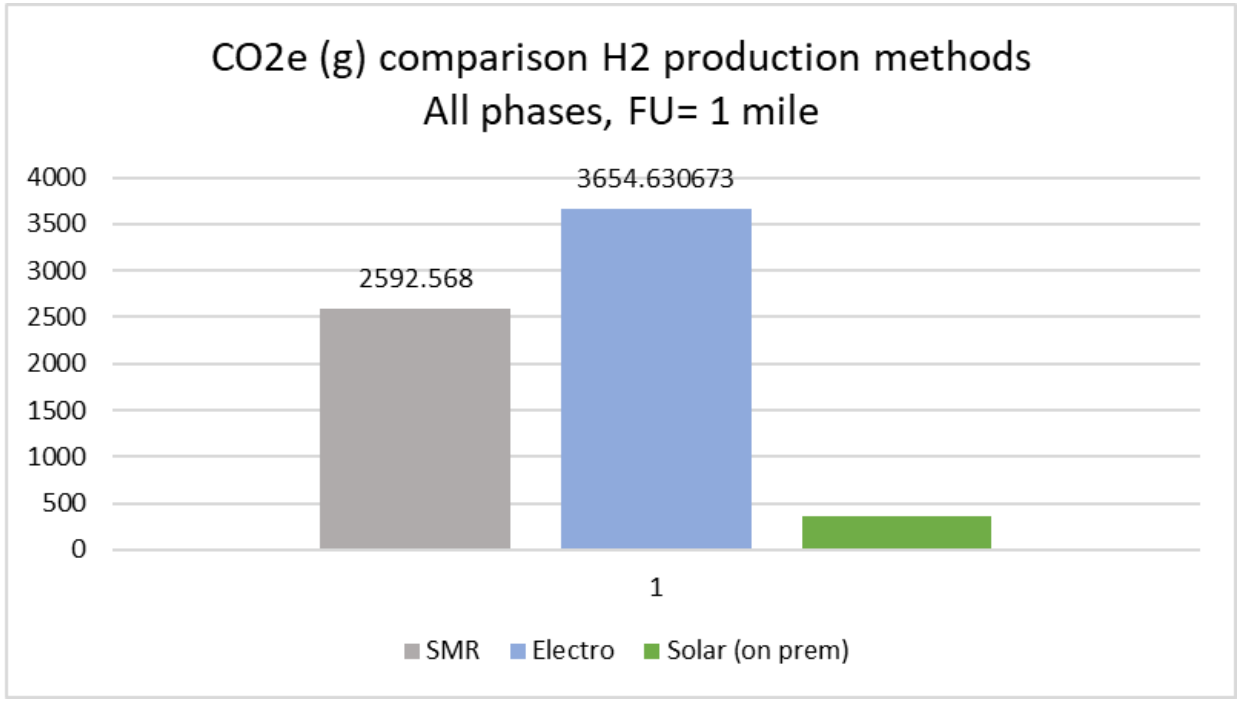




RESULTS: VOC, CO, NOx, PM, SOx COMPARISONS







COMPARE DIFFERENCE FOR ALTERNATIVE METHOD OF H2 PRODUCTION

NORMALIZATION

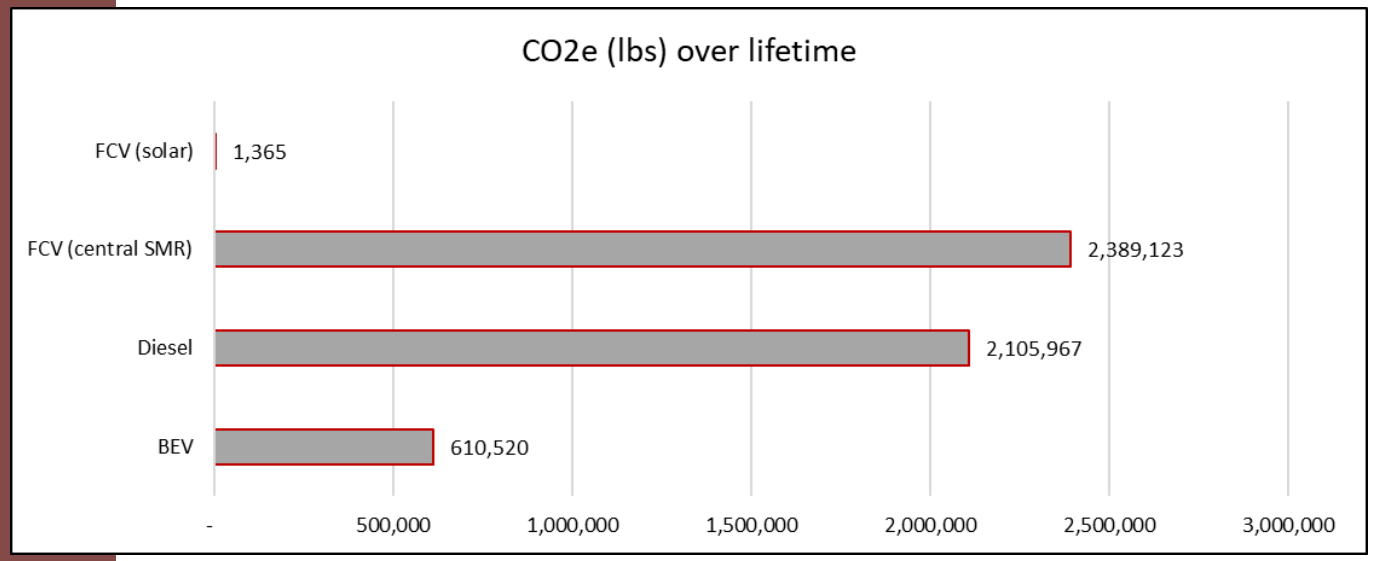
Impact categories	impact factor	emission/use	notes
climate change	21.5	CO2e (CO2, CH4, N2O)	
photochemical ozone formation	2.4	VOC, NOx, CO	
acidification	1.5	NOx, SOx	
terrestrial eutrophication	1.0	NOx	
particulate matter	0.1	PM2.5 (PM10 excluded)	
resource depletion	18.6 (m3)	water resource depletion	* gallons by 0.00378541178
mineral resource depletion	12.7	<did not include>	

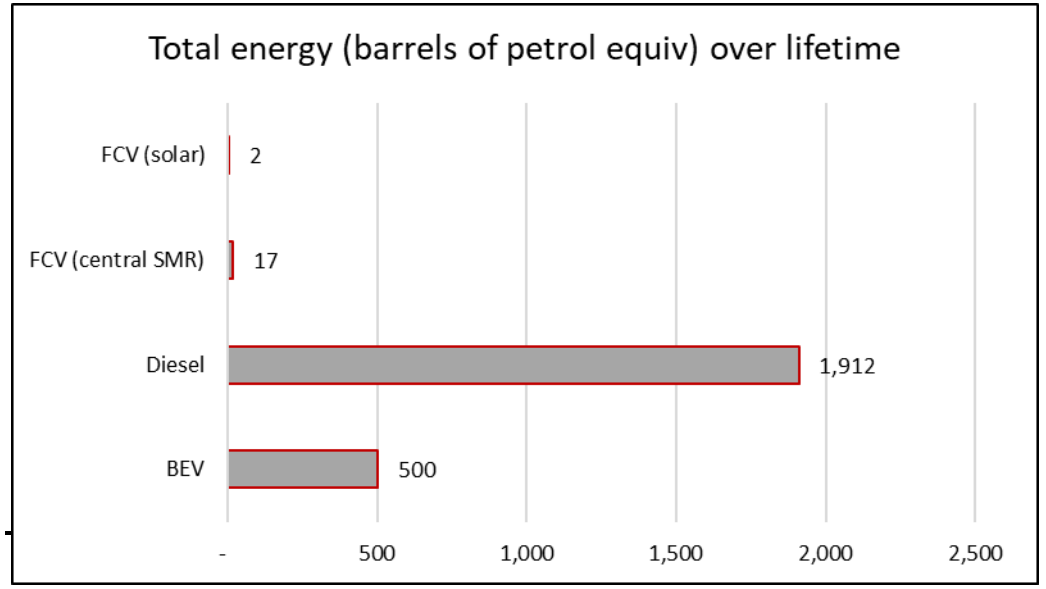
Impact categories	Diesel	EV	FVC (SMR)
climate change	43,655.568	15,481.854	55,740.216
photochemical ozone formation	14.507	3.941	5.943
acidification	5.733	5.613	3.729
terrestrial eutrophication	3.414	0.610	1.005
particulate matter	0.008	0.008	0.012
resource depletion	0.000	0.001	0.001
mineral resource depletion			
total	43,679.230	15,492.026	55,750.906

Reference: Crenna et al 2018, Zampori et al, 2016

JUST TO PUT THINGS IN CONTEXT…

FOR USE PHASE INCLUDING FUEL CYCLE



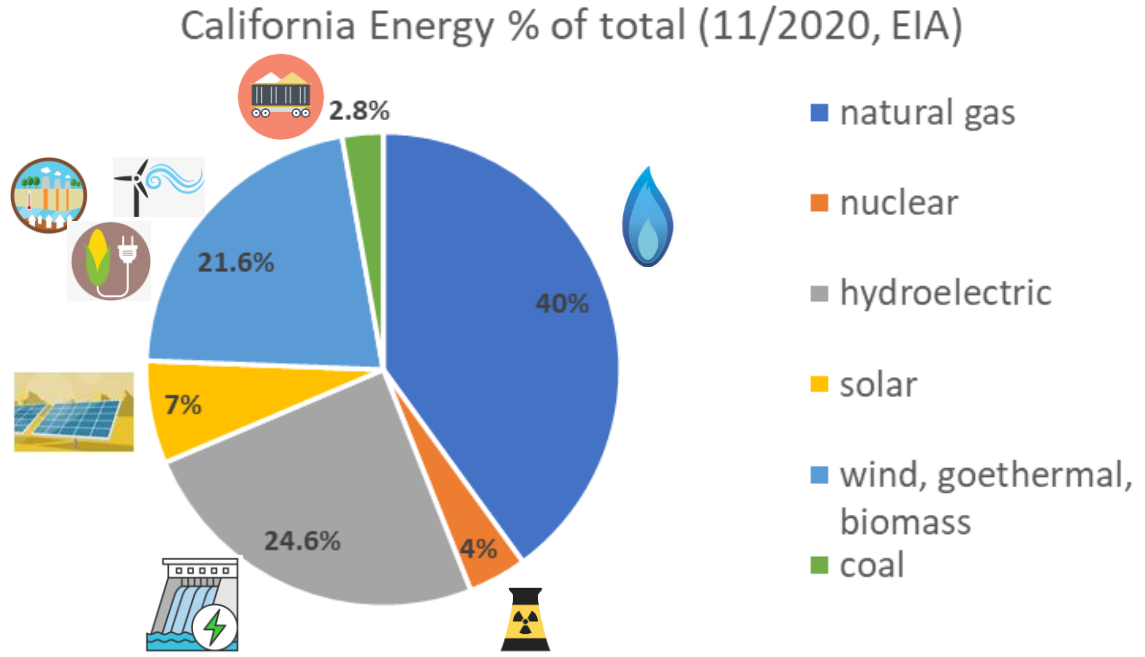


LIMITATIONS

- Manufacturing info not available for these new technologies
- “Black boxes” at their finest
- Highly complex, but did allow for one to customize inputs (if you had that level of detail)
- Did not provide references consistently where information was obtained from
- The manuals/user guides are lacking but getting better!
- EOL recycling of batteries is still in its infancy; only high value elements are extracted and reused. The battery recycling is new for 2020 and needs work.
- Wanted to compare just those components of interest; this tool does not allow for that since materials are spread among all categories
- Would like to have further breakdown of phases – this is possible, but will take a lot of manipulation of the tool
- Did not include charging infrastructure at site but tool supports doing it
- CO2e I found was not current in the tools, so I adjusted to IPCC 100 yrs.
- H2O consumption for hydrogen production needs more study
- Raw materials or components – could not specify source

NEXT STEPS

- Recheck hydrogen scale up by talking with experts; adjust as necessary
- Run model with current & future CA grid, EIA region mix with more fossil fuels
- Add natural gas truck to mix



Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
California Mix										
2019	0.00%	42.53%	0.00%	10.26%	1.17%	14.06%	4.53%	8.09%	18.30%	1.06%
2020	0.00%	35.00%	0.00%	10.87%	1.25%	15.15%	4.83%	9.01%	22.74%	1.14%
2025	0.00%	34.10%	0.00%	5.96%	1.38%	16.12%	6.28%	9.69%	24.92%	1.54%
2030	0.00%	24.99%	0.00%	0.00%	1.61%	17.24%	10.35%	10.33%	33.61%	1.87%
2035	0.00%	20.00%	0.00%	0.00%	1.56%	16.45%	14.28%	10.05%	35.77%	1.87%
2040	0.00%	17.29%	0.00%	0.00%	1.40%	14.17%	15.54%	9.18%	40.53%	1.89%
2045	0.00%	15.34%	0.00%	0.00%	1.27%	12.36%	15.89%	8.34%	44.92%	1.88%
2050	0.00%	15.59%	0.00%	0.00%	1.21%	10.58%	15.07%	7.77%	47.97%	1.80%

Source: GREET

https://www.pngkit.com/view/u2t4t4i1i1t4e6t4_banner-library-stock-natural-gas-pptx-burn-to/, https://cliparts.zone/natural-gas-cliparts, http://clipart-library.com/nuclear-power-symbol.html https://www.dreamstime.com/illustration/hydroelectric-dam.html, http://www.clubscikidzmd.com/march-break-resources-activities/thursday-5-7-lego-challenge-3-build-a-wind-car/attachment/480-4808057_wind-energy-wind-turbine-clipart-png/, https://depositphotos.com/vector-images/solar-panels.html, https://www.enbridge.com/energy-matters/energy-school/geothermal, https://www.clipartkey.com/view/iRTbxbh_biomass-energy-png/, https://www.electricchoice.com/kids/coal/, https://www.eia.gov/state/?sid=CA

Thank you!