H_2ICE Impact on Medium and Heavy Duty Truck Applications

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"Hydrogen Internal Combustion Engines and Their Use in Trucks"

These are preliminary results from ongoing study on H_2ICE evaluations for trucks

Executive Summary

H_2ICEs De-risk H_2 Infrastructure Investments While Offering a Viable Option for Freight Decarbonization.

- Assuming **HFTO & VTO[1] targets** are achieved, FCHEVs will be economically competitive by 2030, against diesel and H_2ICE vehicles.
- Freight decarbonization solutions remain highly uncertain: Energy cost (diesel, electricity, H_2), powertrain requirements, component durability, thermal management, performance degradation, fueling/charging infrastructure, CAPEX…
- Hydrogen Earth Shot is critical for any H_2 fueled vehicle competitiveness.

While meeting HFTO H_2 cost targets remain critical, H_2ICEs could de-risk some of the investments, jump-starting the H_2 economy.

(1) HFTO: Hydrogen and Fuel Cell Technologies Office; VTO: Vehicle Technologies Office

Overview

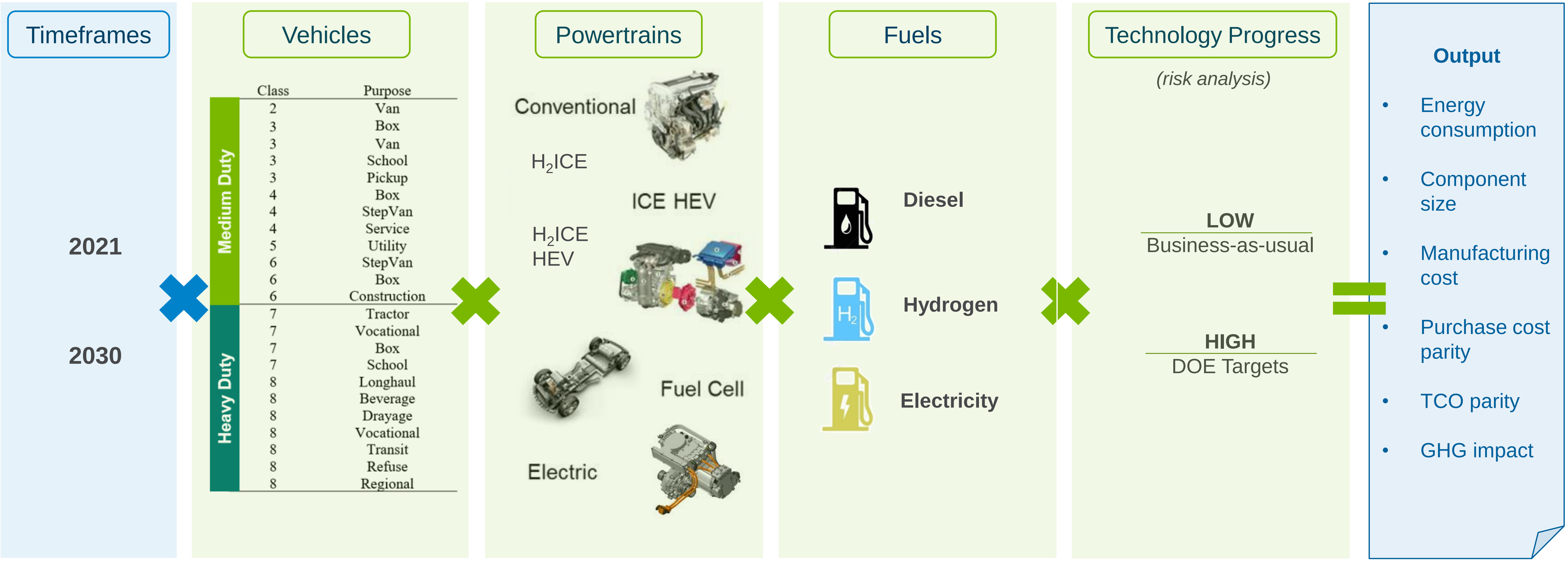
- **Background**
  - Diesel engines can be adapted to burn H_2, potentially accelerating adoption of hydrogen as a fuel
  - State-of-the-art H_2ICE engine test data is not readily available. H_2ICE potential was evaluated using information from publications and inputs from industry partners

- **Questions**
  - Under which conditions can H_2ICE vehicles compete against other powertrains including diesel ICE vehicles, FCHEVs & BEVs?
    - Factors considered: vehicle cost, energy consumption & TCO
  - How will hydrogen cost uncertainties impact the overall results?
  - Which medium and heavy duty truck applications show the most promise?

- **Timeframes** Current & 2030

Approach

Quantify the impact of technologies on energy consumption, performance, and cost of advanced vehicles



	Class	Purpose
Medium Duty	2	Van
	3	Box
	3	Van
	3	School
	3	Pickup
	4	Box
	4	StepVan
	4	Service
	5	Utility
	6	StepVan
	6	Box
	6	Construction
Heavy Duty	7	Tractor
	7	Vocational
	7	Box
	7	School
	8	Longhaul
	8	Beverage
	8	Drayage
	8	Vocational
	8	Transit
	8	Refuse
	8	Regional

- Automated large-scale simulation process developed to handle hundreds of combinations in the case of this study, to inform on consumption, characteristics, costs, and emissions of current and future MDHD vehicles.

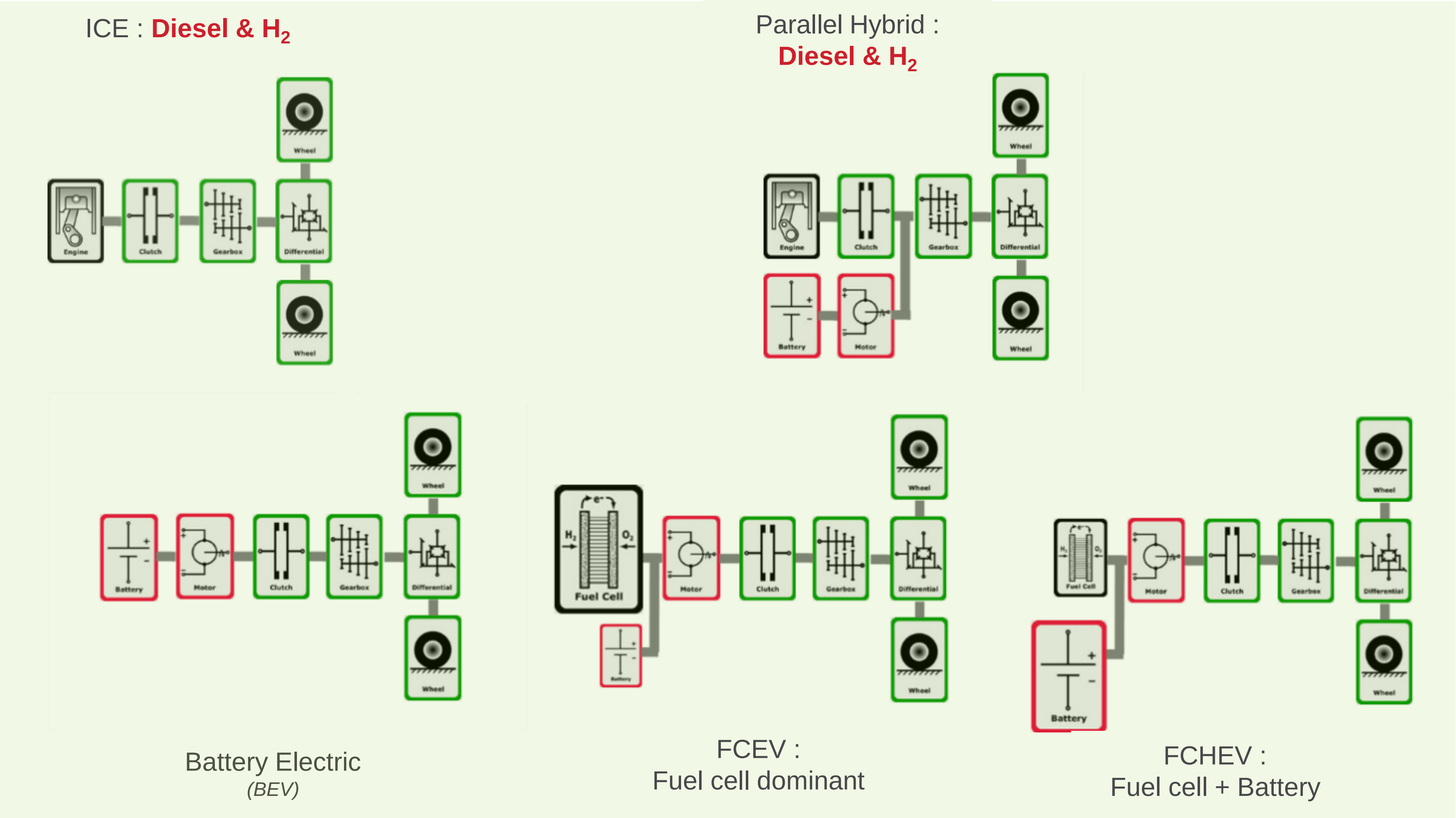
Powertrain Configurations and Fuels Considered

New technologies (H_2ICE, ICE HEVs, FCHEVs and BEVs) will compete with Diesel trucks

Long haul truck is the first evaluation candidate.

Designed for 500 mile range.

Longer range trucks are possible with FC & H_2ICE systems.



Class8 Long haul Truck Evaluation as a Potential Candidate for H_2ICE

Purchase price & TCO parity checks can give a fair comparison of the technology benefits

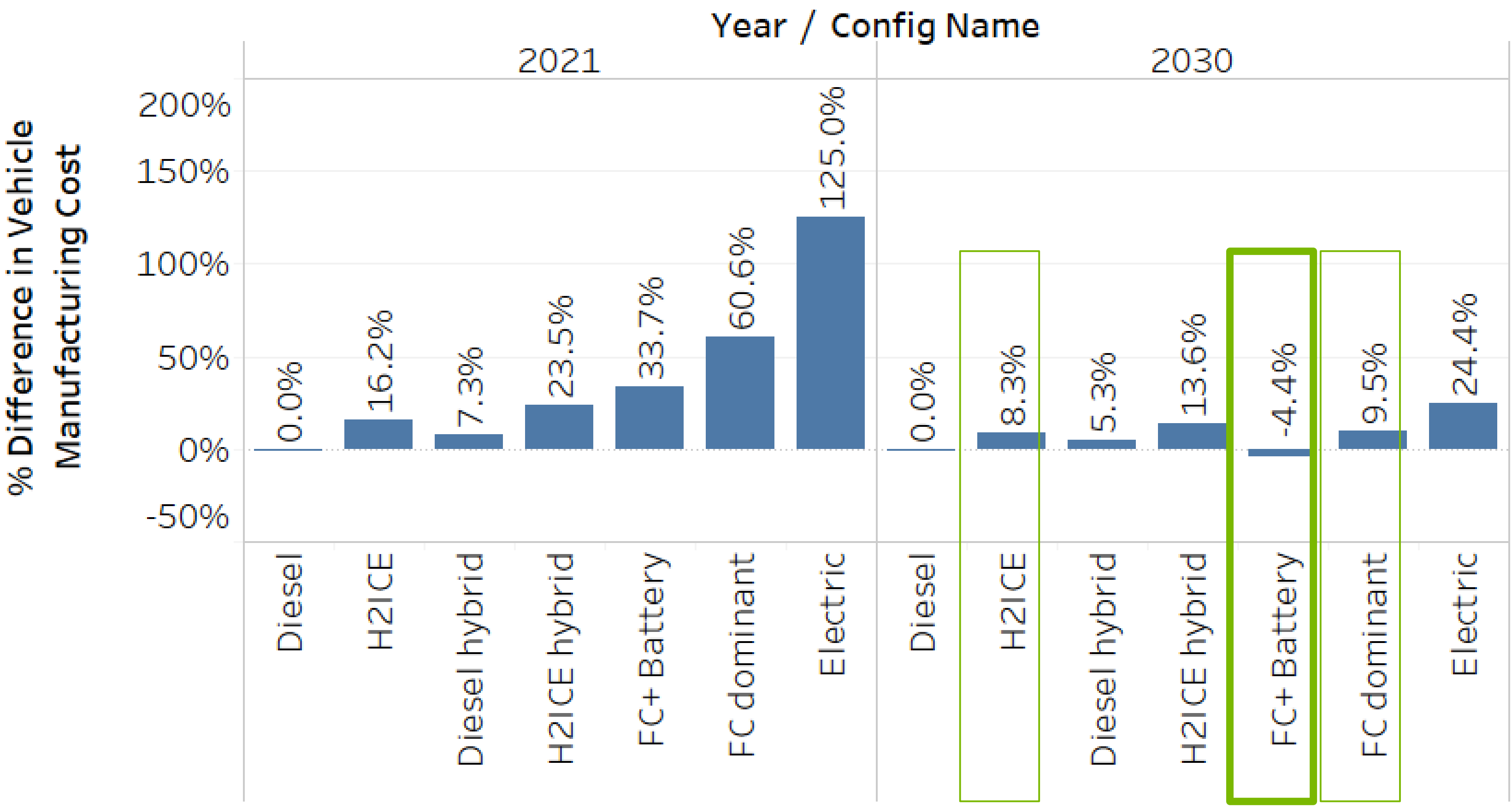
- Expect all technologies to improve over time
  - Improvements in Cd, Cr, light weighting etc will benefit all powertrains
  - Component specific improvements are as shown below

Parameters	Present	Interim (BAU)	Interim (High)
Diesel ICE peak efficiency	47%	50%	54%
H_2ICE peak efficiency	44%	48%	49%
FC peak efficiency	60%	64%	68%
FC Cost ($/kW)	185	110	75
Storage cost ($/kg H_2)	310	275	250
Battery cost ($/kWh)	140	100	75

- H_2ICE does not have a DOE development target.
  - Business as Usual (BAU) & High scenarios are not very different in this case

More details are at : https://vms.taps.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

Considering 2030 HFTO and VTO Targets, FCHEV Manufacturing Costs are Lower than Diesel and H_2ICE Vehicles



- Assumes HFTO/VTO R&D targets are met
  – cheaper, durable fuel cells*
  – no appreciable performance loss over the years**
  – hybridized architecture with larger battery pack

- Uncertainly about FC targets
  – Under BAU scenario, FCHEV will be ~9% costlier than diesel.
  – H_2ICE option has lower uncertainty.

* Assuming high volume production for fuel cell systems.
** No oversizing is assumed.

Class 8 Long Haul

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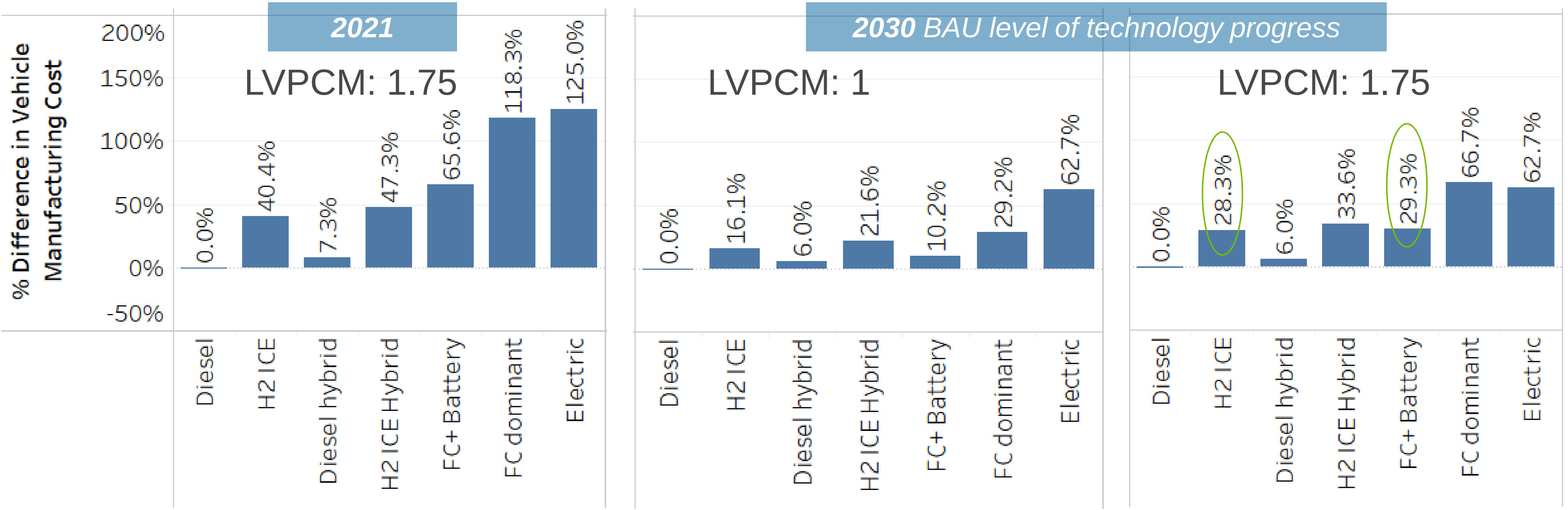
BAU Scenario: H_2ICE Vehicles & FCHEVs have Comparable Vehicle Costs. Both are ~30% Costlier than Diesel Baseline Vehicles.

LVPCM (low volume production cost multiplier) of 1.75 applied for a volume or few thousand units.
At 100k units, this multiplier becomes 1 (HFTO inputs).

Estimated FC cost in 2030
$75/kW : high production volume
$130/kW : low production volume



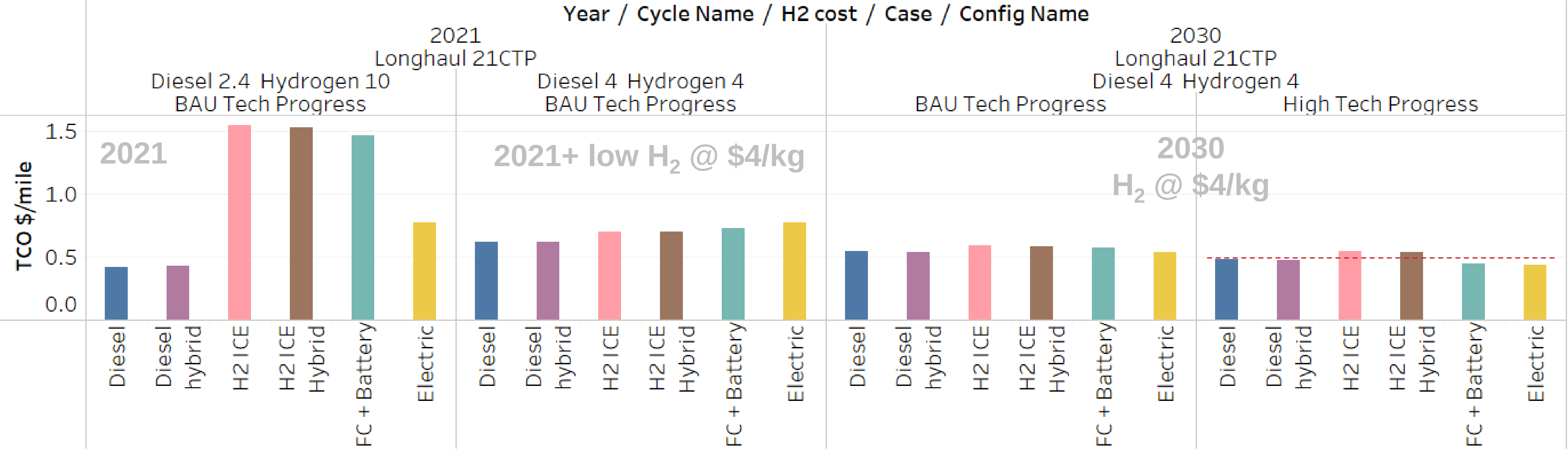
Class 8 Long Haul

Same LVPCM is used for FC & storage.

Fuel Cost is Critical to Vehicle Technology Assessment

Long term H_2 cost target from HFTO is $4/kg.

H_2ICE approaches operating cost parity with diesel vehicles at this cost level.



Class 8 Long Haul

Note: H2ICE improvements assumed in this work are not as aggressive that in case of diesel ICE or FC systems. DOE funded research could potentially improve H_2ICE even further.

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Class 8 Long Haul Overview Summary:
Present day scenario (assuming high volume production for FC)

Negative values denote cases that are better than the baseline vehicle considered

	Vs. Conventional Diesel			Vs. FC HEV	
	H2ICE Conv	H2ICE Hybrid	FC HEV	H2 ICE Conv	H2 ICE Hybrid
Fuel Consumption (diesel equiv)	14%	8%	-4%	18%	12%
Manufacturing Cost	16%	24%	34%	-14%	-8%
TCO Diesel $4/gallon H_2 $4/kg	25%	22%	14%	10%	7%

Class 8 Long Haul Overview Summary:
2030 high technology progress scenario

Negative values denote cases that are better than the baseline vehicle considered

	Vs. Conventional Diesel			Vs. FC HEV	
	H2ICE Conv	H2ICE Hybrid	FC HEV	H2 ICE Conv	H2 ICE Hybrid
Fuel Consumption (diesel equiv)	20%	5%	-14%	40%	22%
Manufacturing Cost	8%	14%	-4%	13%	19%
TCO Diesel $4/gallon H_2 $4/kg	26%	16%	-4%	31%	21%

Overall GHG Impact

Results from GREET: Assuming NG-SMR for H_2 pathways, both current and future

WTW CO2e g/mile	Diesel	H_2ICE	H_2ICE Hybrid	FCHEV
2021	1,724	2,009	1,903	**1,691**
2030 High technology progress	1,365	1,644	1,438	**1,177**

Green H_2 production is necessary to further reduce the overall CO_2 emission for FCHEVs and H_2ICE.

Compared to Diesel Engines, H_2ICE Offer Significant NOx Emission Benefits

H_2ICEs have comparable NOx output as diesel for higher loads and are significantly cleaner at low loads.

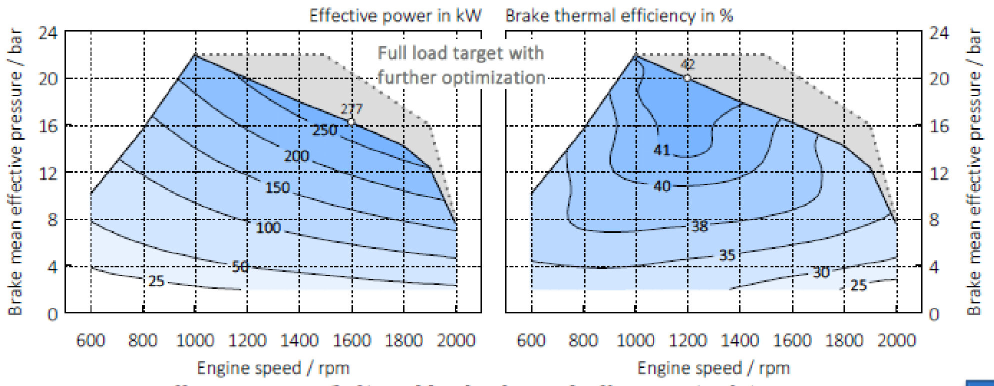


Figure 6: Effective power (left) and brake thermal efficiency (right) in MPI operation

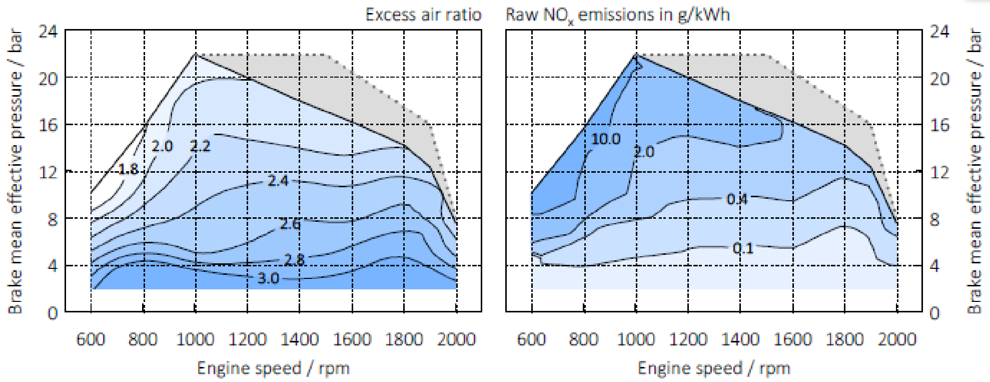
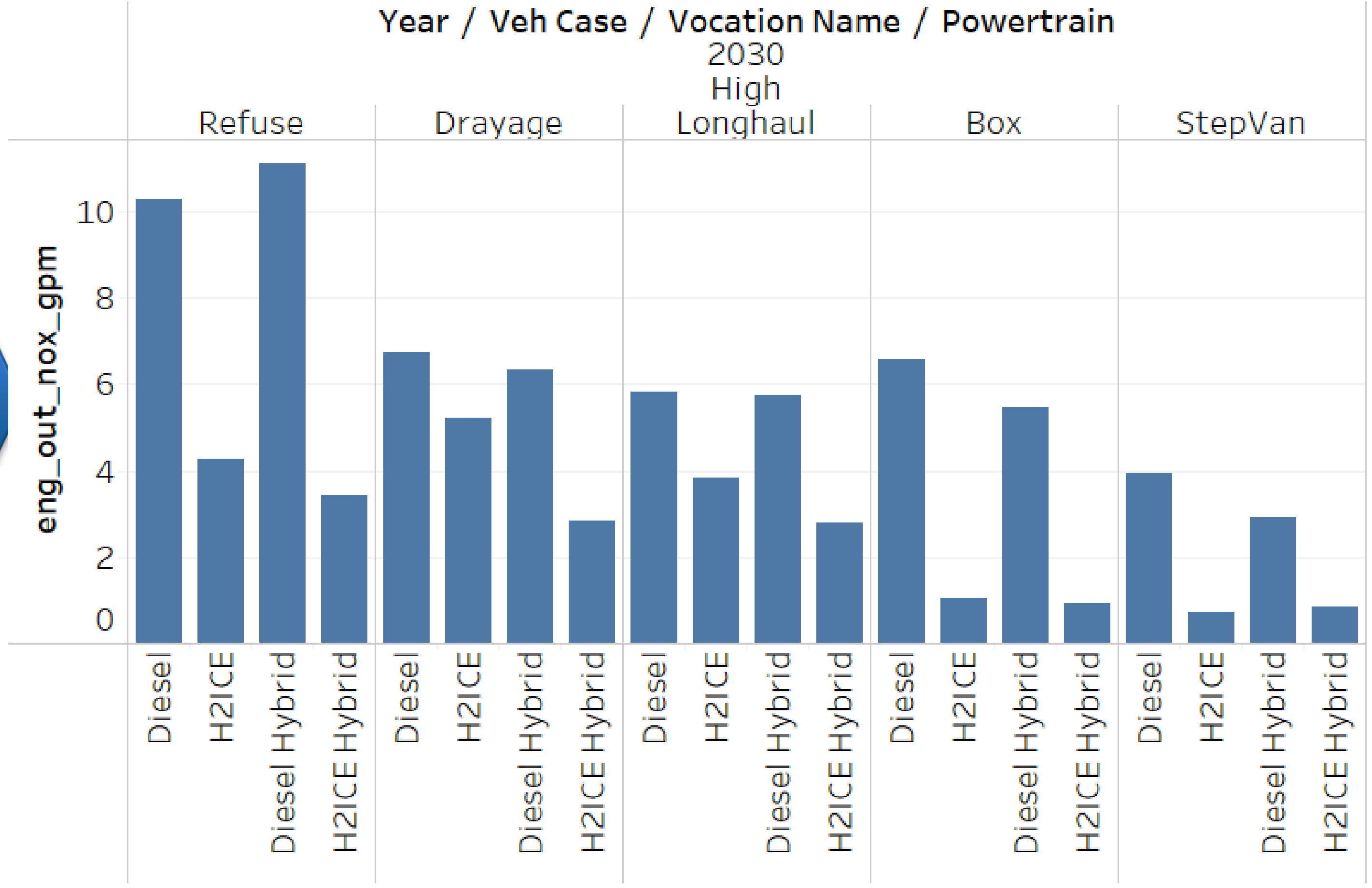


Figure 7: Excess air ratio (left) and raw NO_x emissions (right) in MPI operation

Based on AVL's work on a 12.8L engine



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Summary

H_2ICEs have the potential to be a bridge technology until HFTO interim targets are met

- **H_2ICE** de-risk H_2 infrastructure investments while offering a viable option for freight decarbonization.
  - H_2ICEs can provide an immediate switch to H_2 as fuel.
  - Help improve the demand and user base for hydrogen infrastructure.
  - DOE funded research can further improve H_2ICE.

- If **HFTO targets & VTO battery targets** are met, FCHEVs will be economically competitive by 2030.

- Hydrogen earth shot is critical for any H_2 fueled vehicle competitiveness

Potential Next Steps

- Include H_2ICE as part of a larger analysis to quantify the potential benefits across more types of trucks

Thank you!

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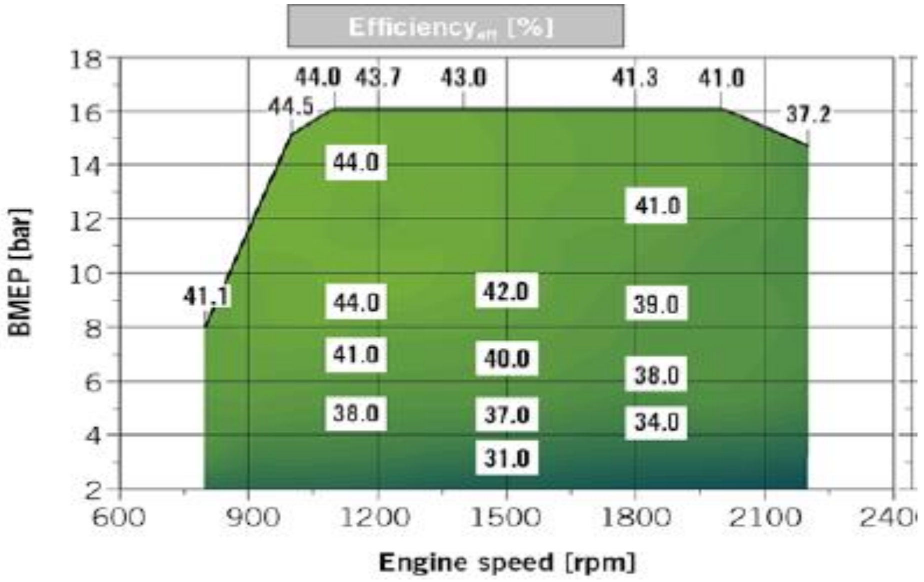
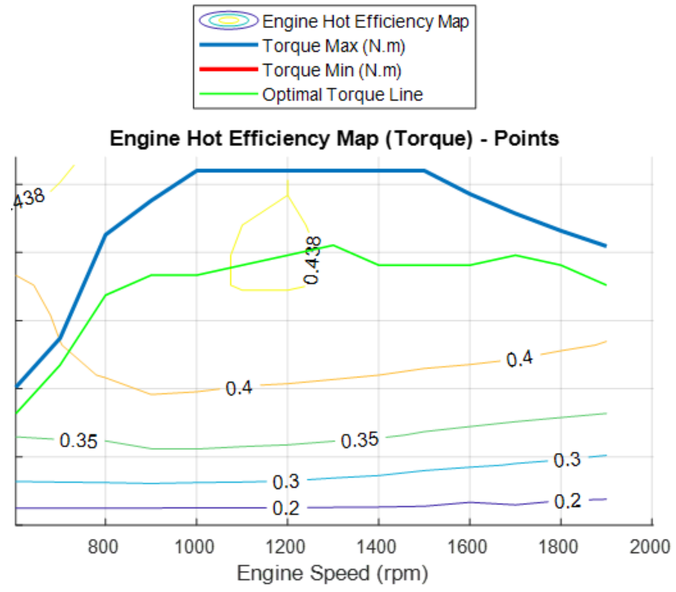
Heavy Duty Truck H_2ICE Fuel Map

- Peak thermal efficiency:
  - 44% (current); 48-49% (2030)
  - Studies have shown that efficiency can be improved further https://doi.org/10.1016/j.fuel.2021.121909
  - MECA believes low NOx targets can be achieved with H_2ICE.

- Engine map modified for Class 8 longhaul and vocational applications based on inputs from industry partners.





* H_2 ICE map developed based on work by Koch et. al

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Factors considered for Simplified TCO calculation

- Ownership cost comparison covers cost related to vehicle and fuel use.
- Wages, insurance etc. are constant across powertrains.

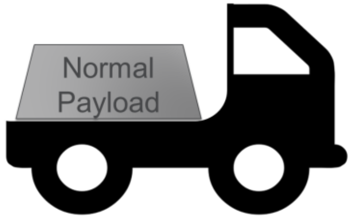
	Parameters	Simplified TCO
Capital expenses	Vehicle purchase price	yes
	Resale value	yes
	Financing costs	no
	Insurance	no
	Registration	no
	Taxes & Incentives	no
Operating expenses	Fuel cost	yes
	Driver Wage	no
	Maintenance	no
	Tolls	no
	Charging time penalty	no
	Cargo limit penalty	no

Performance Based Sizing is Critical for Fair Comparison

Sizing criteria and tests are updated periodically with inputs from 21CTP & USDRIVE partners

- **Sizing Updates**
  - Launch at grade
  - Highway gradeability
  - Performance at max GVWR for each class
  - Energy consumption tests with vocation specific cargo loads
  - Test durations added for electric powertrains
- Vehicle specifications & sizing logic details are published as supporting documents of VTO Benefit Analysis report

Sizing → **Analysis**



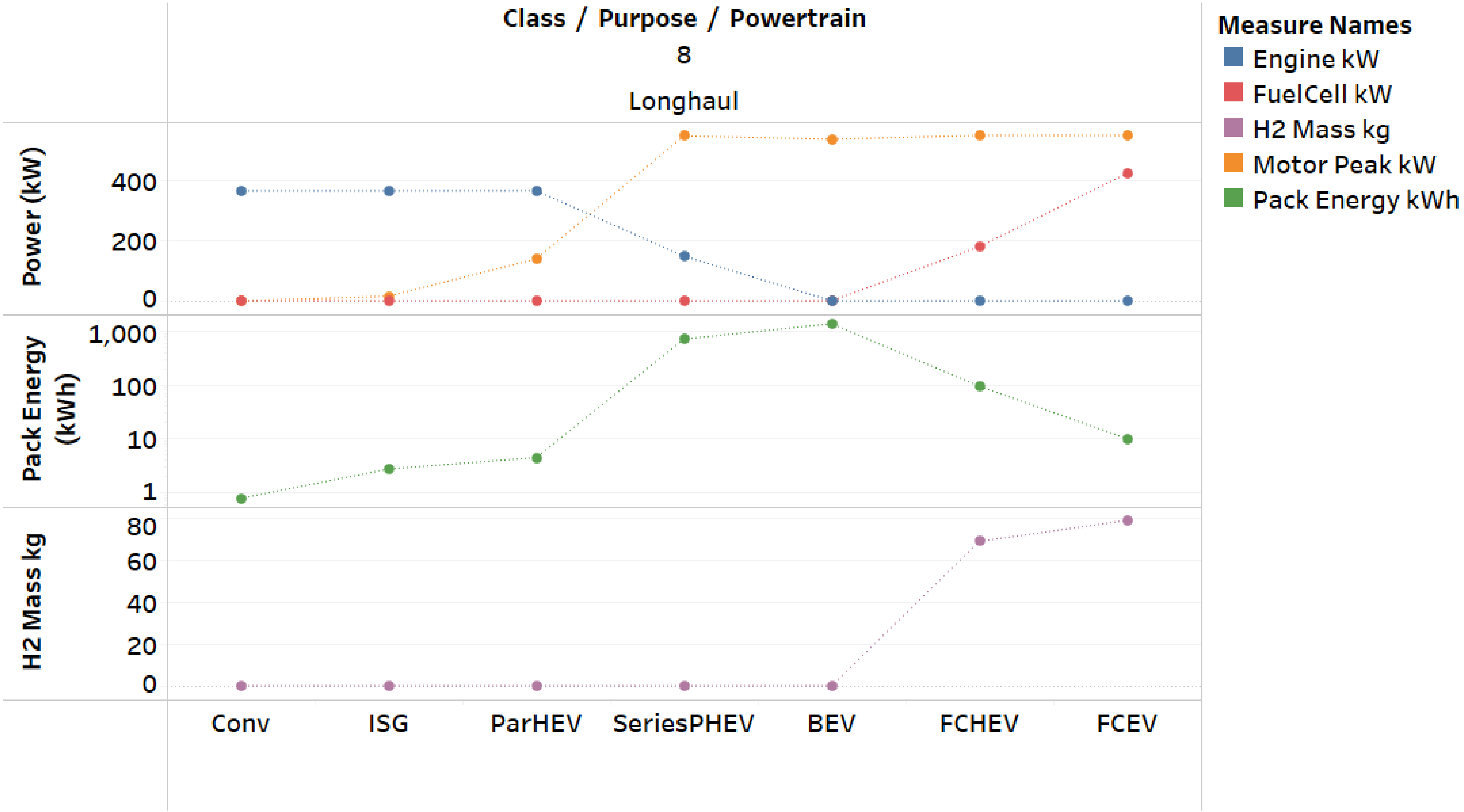
- Performance tests @ max GVWR
  - Cruising speed
  - 1% Grade @ 65mph
  - 6% Grade climb for 11 miles at 30mph
  - Launch @ 15% grade
  - Acceleration & Passing
    - 0-30mph & 0-60mph
  - All Electric/Driving Range

- Fuel economy tests @ regular load
  - Real World Cycles (Livewire, FleetDNA, CERC)
- TCO (Total cost of Ownership)
  - DOE cost targets & industry feedback
- Fuel Costs
  - AEO report

More details are at : https://vms.taps.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

Long haul truck:
Component sizes from performance based sizing

500 mile driving range is expected between charging or refueling



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