

NPRE 470: Fuel Cell Powered Consumer Truck

*Junwoo Bae, Simone Bianconi,
Jeffrey Calhoun, Nicole Crosby*



Brief Fuel Cell History



1950s - GE invents PEMFC

1970s - Oil crisis prompts development of alternative energy technology (PAFC)

1980s - US Navy uses FC in submarines

1990s - Large, stationary FC for commercial and industrial applications

2008 - First FC electric car released to public

Automotive Fuel Cell Potential



While several FC cars have been released, no fuel cell trucks have come to the market

PEMFC is the most common type of fuel cell used due to its low temperature operation and its high volumetric and gravimetric power densities despite expensive platinum catalyst

Example in Automotive Industry



Toyota Mirai



Spec	Vehicle
Weight	4078.5 lbs
Max Speed	111 mph
Peak Torque	247 lb-f (335 N-m)
Cruising Range	300 miles

Spec	Fuel Cell
Power Output	153 hp (114 kW)
Output Density	3.1 kW/L, 2.0 kW/kg
Cell thickness	1.34mm
Stack	370 cells, single-line stacking
Weight	123.5 lbs (102 g/cell)
	Fuel Tanks
Tank Volume	122.4 L (60 + 62.4)
Tank Weight	192.9 lbs
Pressure	87.5 psi
Storage Mass	5 kg

Benchmark to Other Trucks



Toyota Tundra

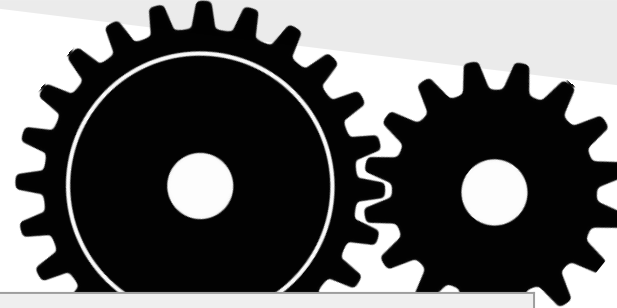
Power	310 hp (231 kW)
Range	501 miles
Weight	5095 lbs
Torque	327 lb-ft



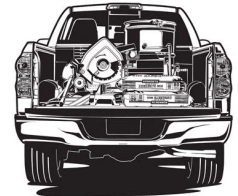
Military FC Chevy Silverado

Spec	Truck	Spec	Fuel Cell
Range	124 miles	Cell	PEM
Weight	7500 lbs	Stacks	2 (94 kW each)
Payload	1600 lbs	Tanks	3 (1000 psi)
Torque	317 ft-lbs	Power Output	188 kW

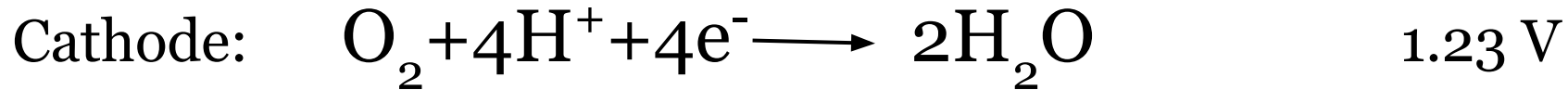
Engineering Requirements



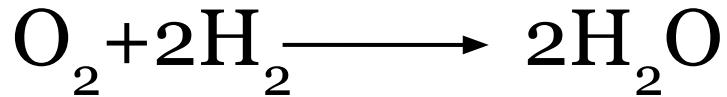
Category	Requirement
FC Type	PEMFC
Justification	Low Temperature, high volumetric and gravimetric power density, and fast response time
Power Output	228 kW (2x Mirai Output) (322 horsepower)
Range	200 miles
Weight	~5000-7000 lbs



Electro-chemical Reaction

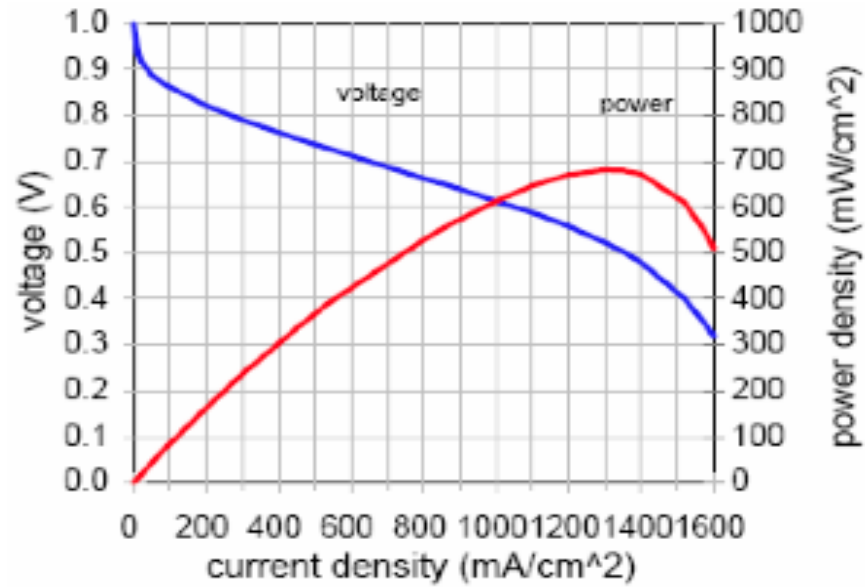


Overall reaction:

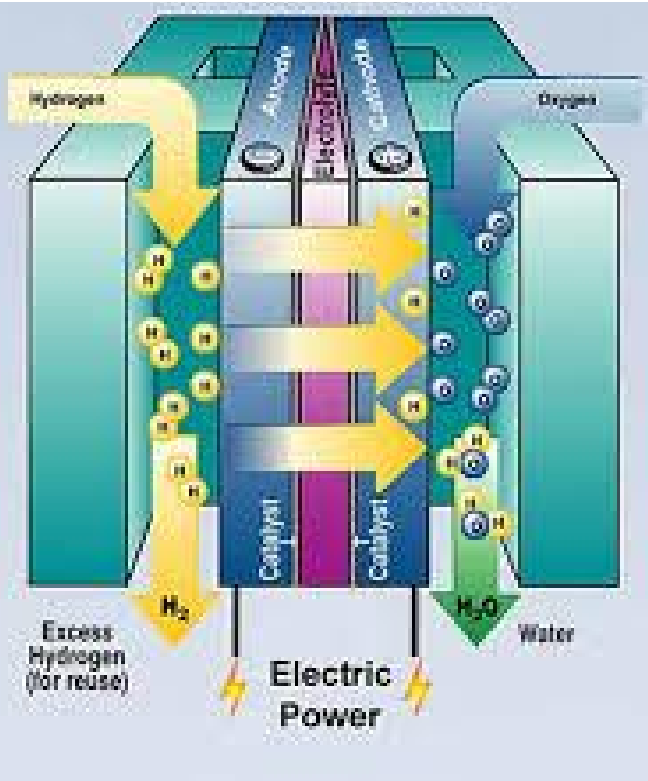


Reversible voltage:

$$E_0 = 1.23 \text{ V}$$



PEM Fuel Cell



Maximum power density: 0.7 W/cm^2 (at STP)

Polymer membrane electrolyte: Nafion™

Fuel utilization factor: 100 % ($\lambda_{\text{H}}=1$)

Air utilization factor: 50 % ($\lambda_{\text{A}}=2$)

Catalyst: Pt/C

Flow channel: 3D fine-mesh flow field

Humidification system: Internal recirculation

Capability for fast Start-Stop due to low T of operation

Fuel selection and storage

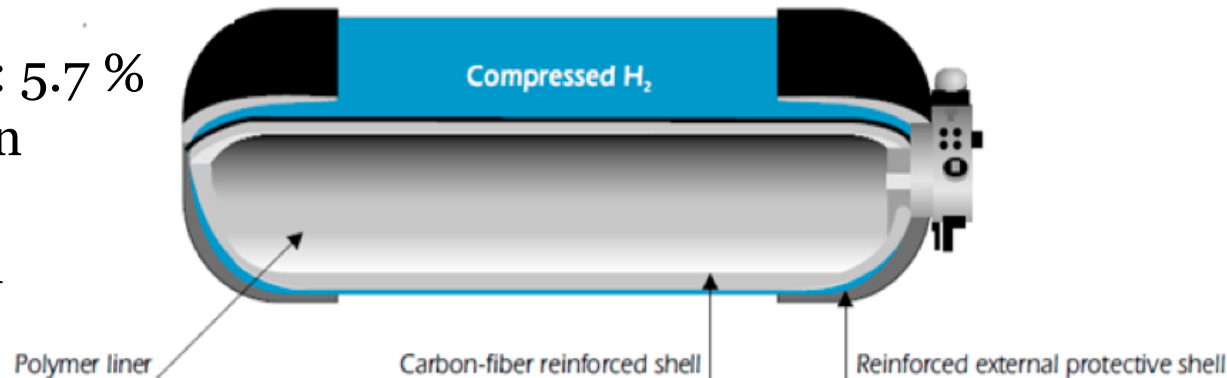


The fuel selected is pure Hydrogen:

- Highest power density
- No catalyst poisoning (from CO)
- No CO₂ emissions

Compressed H₂ at 70 MPa is stored in tanks:

- Carbon fiber high-pressure tanks (with three layer structure to prevent Hydrogen leakage)
- Storage density (weight): 5.7 %
- Capacity: 10 kg Hydrogen
- Volume. 60 L per tank
- Refueling time: 5-10 min



Turbocharged air intake



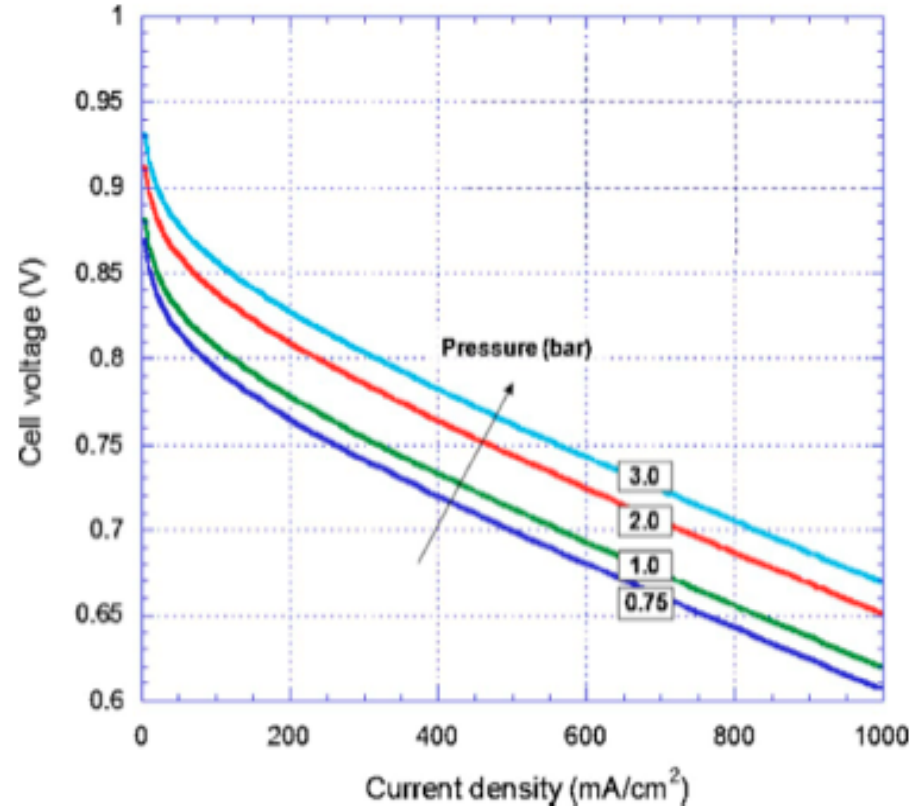
Reversible voltage at STP: $E_o = 1.23 \text{ V}$

Nernst equation:

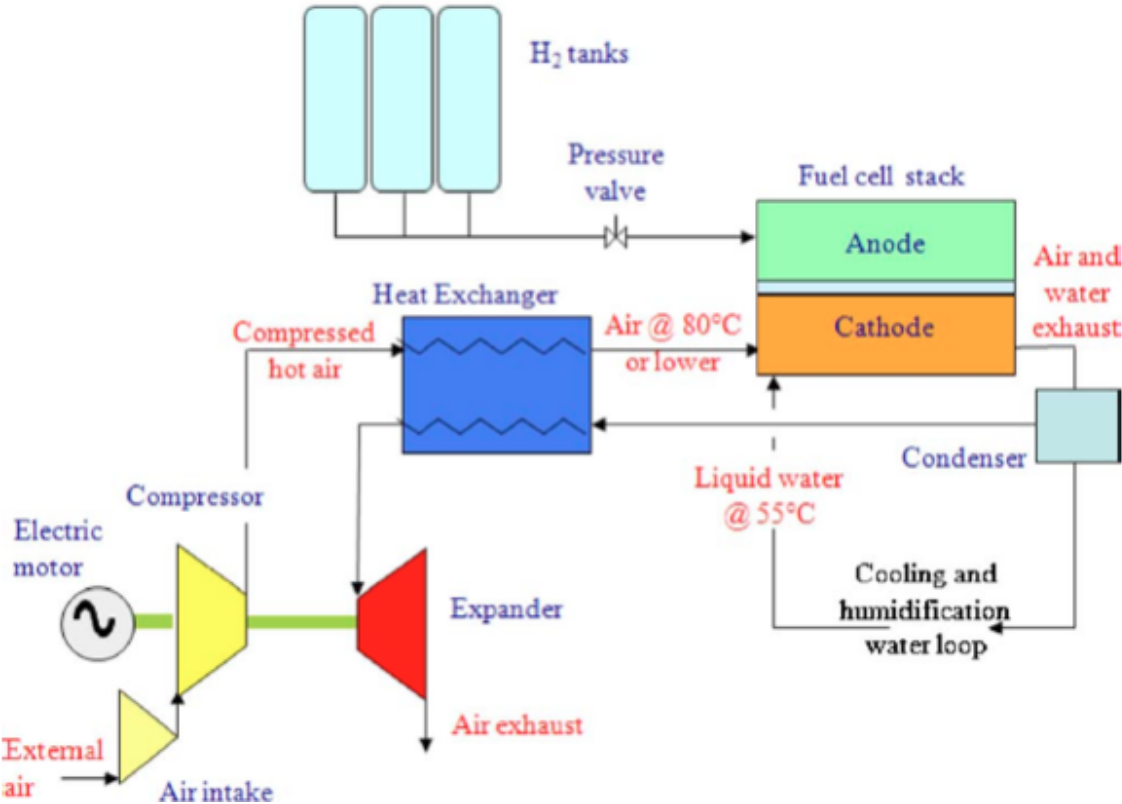
$$E = E_o - \frac{R \cdot T}{n \cdot F} \cdot \ln \frac{a_M^m \cdot a_N^n}{a_A^a \cdot a_B^b}$$

using: $a_{\text{H}_2} = 100 \text{ atm}$, $(a_{\text{O}_2})^{1/2} = (3 \text{ atm})^{1/2}$

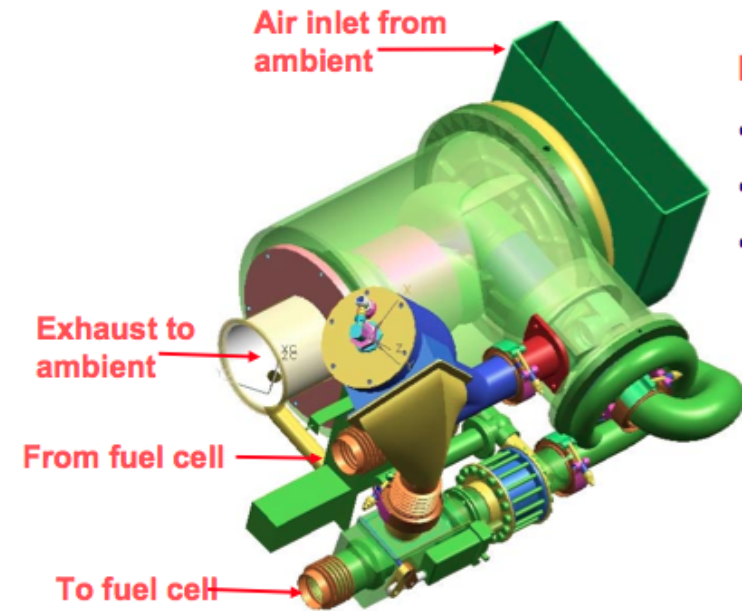
$$E = 1.28 \text{ V}$$



Turbocharged air intake



Rolls Royce Fuel Cell Hypercharger



Turbocharged air intake



PEM pressure (bar)	1.2	0.8	2.5
Pressure ratio β	4.5	4.4	2.6
Cell voltage V_c (V)	0.719	0.695	0.757
Cell current density (A/cm ²)	0.400	0.421	0.381
m_{air} (kg/s)	0.068	0.072	0.065
PEM fuel heat input ($m_{\text{fuel,PEM}} \times \text{LHV}$) (kW)	118.7	125.1	113.1
$P_{\text{el,PEM}}$ (kW)	64.00	65.20	64.21
$P_{\text{el,motor}}$ (kW)	4.00	5.20	4.21
$P_{\text{compressor}}$ (kW)	12.11	13.26	7.89
P_{turbine} (kW)	9.13	9.39	4.76
Losses (mech., el.) (kW)	1.02	1.33	1.08
Electric efficiency η_{el}	50.53	47.98	53.04

5% Efficiency gain

Hydrogen Storage



- Carbon-fiber 3-layer structure
 - Common in fuel cell vehicle transportation applications
 - Durable
 - Lightweight comparatively
 - High resistance to puncturing/damage (safety)
- Monitoring H₂ output



Fuel Cell Stack



- Want to meet design requirement of 228 kw (322 hp with 5% efficiency increase) output.
- Mirai FC stack: 370 cells with 153 hp output.
- With turbocharged intake, total output power from the stack is 161 hp.
- A truck with twice the desired power output should have a fuel cell stack of 740 cells or two stacks of 370 cells.

Power Assist (Battery)



- Li-Ion
 - enables assist to be provided to the output of the fuel cell stack to allow maximum power for an extended period
 - Safety
 - Battery management to avoid thermal runaway
 - Life-span
 - 8-10 years
 - Performance
 - Conversion efficiency: ~30% for ICE ~90% for electric
 - Cost
 - \$250-\$400 per kWh usually
- NiMH?

Power Drive Unit (PDU)



- AC Synchronous Motor
 - Ideally 190kW peak to allow torque of 325Nm
- Power electronics integration - control logic, system cooling, motor control
- Gear set connected in between drive shaft and motor
- Controller used to maximize motor efficiency

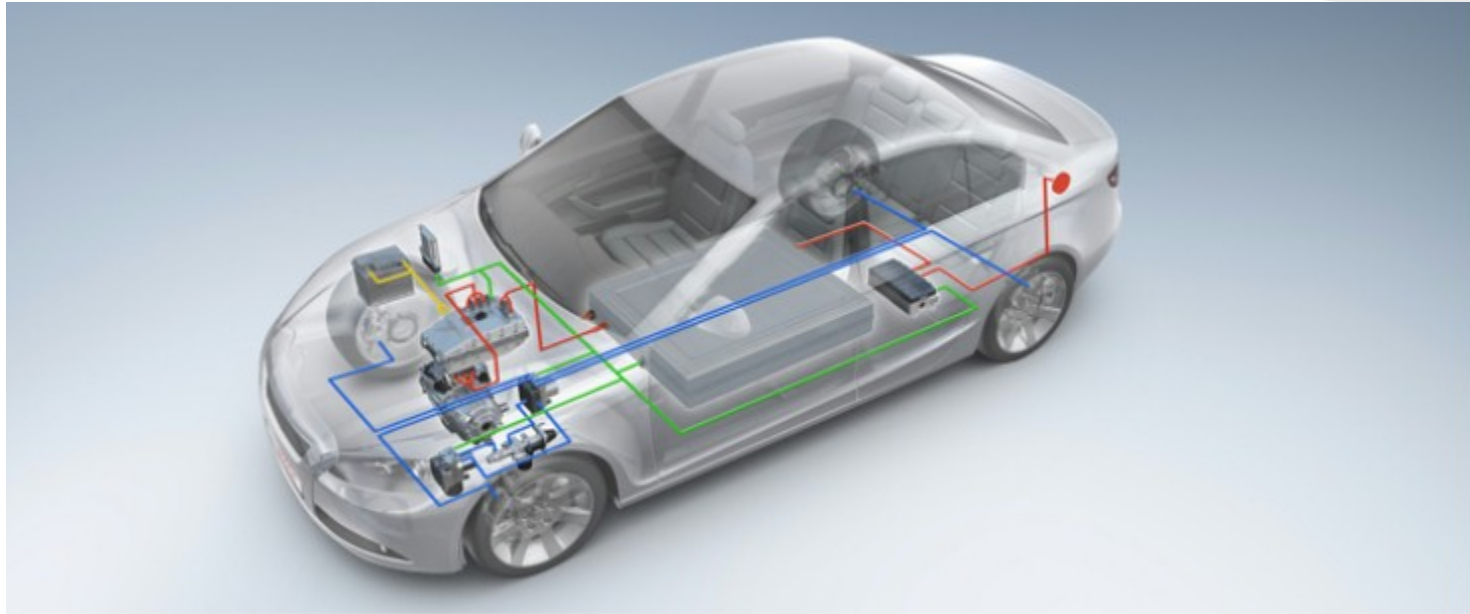
Motor Drive



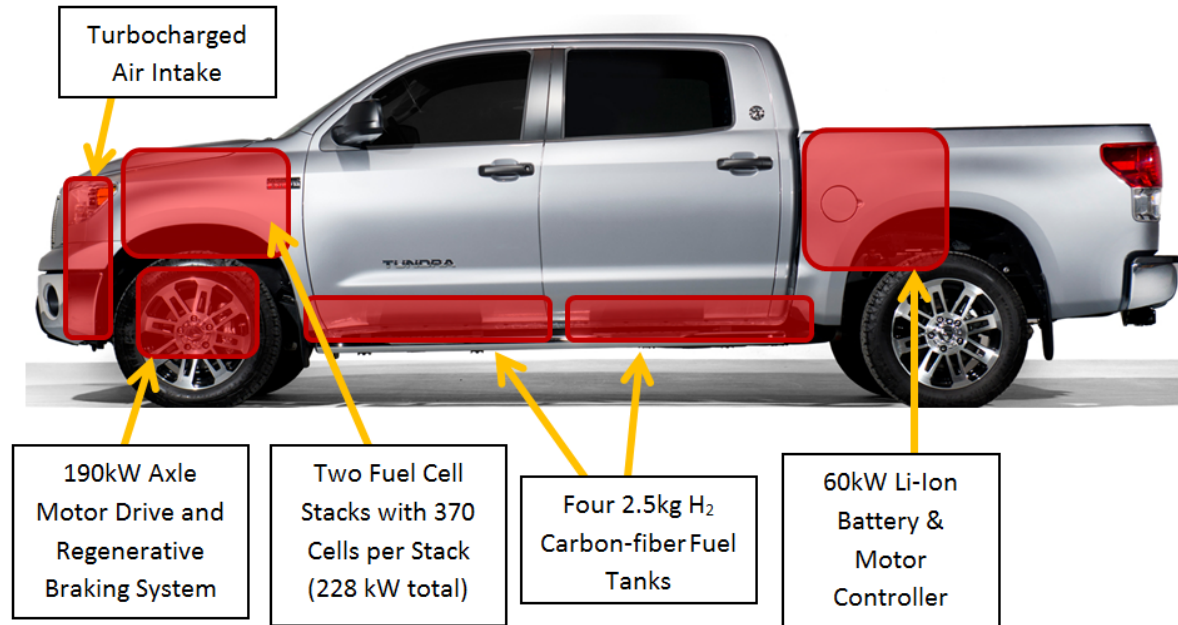
- Power Assist
- Inverter
- Electric Axle Drive
- Cooperative Regenerative Braking



An Overview



Design & Structure



Characteristic Features



Fuel cell
(our design)



Toyota Tundra
(gasoline)



VIA eREV
(electricity&gasoline)

Power and Parts comparison



	Our design	Toyota Tundra	Via E-Rev
Power	322hp	310hp	255hp
type of motor	AC synchronous electric generator	4.6-L DOHC v8	Electric Drive motor
cost of motor	\$15,000	\$3,600	~6,000
Fuel cell/generator	\$100,000	x	\$10,000
fuel tanks(\$)	1200 *4	400	400
batteries	lithium ion hydride	lithium ion hydride	lithium ion hydride

Fuel cell vs gasoline truck vs hybrid



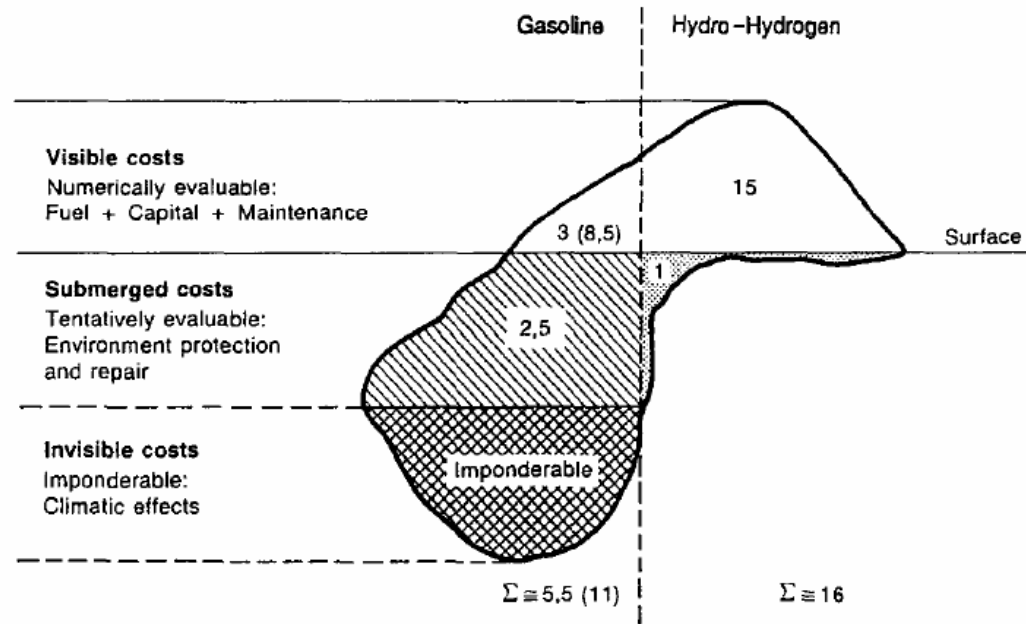
	Fuel Cell	Gasoline	Hybrid (electric & gasoline)
miles/price(\$)	~10(assuming halved since doubled power of Mirai)	6.66	9 (20miles/\$ for first 40miles)
distance(miles)/per station	unknown(very few, about 3 per city) -Number of Planned stations	~70(over US)	~70(over US)
emission	water	Nitrogen,CO, CO2	Nitrogen,CO, CO2 (nothing for first 40miles)

Expected Benefit



- *Fuel Cell's only emission is water
- *There is no production of NO_x, SO_x, PM and CO₂
- *Better miles per dollar
- *Safer to use hydrogen than gasoline due to its high self-ignition temperature and higher diffusion rate

Hidden Value comparison



Expected Benefit



*Electric powered(erev) cannot go for long distance (40miles max for erev without usage of gasoline). They require gasoline to run, resulting in requirement of large batteries as well as gasoline tank, generator, and electric motor.

*Hydrogen fuel cell on the other hand, can have range similar to gas with lower miles per dollar.

Conclusion



Possible to make a competitive FC pickup truck

- Can achieve horsepower above Toyota Tundra
- Have sufficient driving range

2 fuel cell stacks (322 hp) (370 cells per stack)

4 tanks (10 kg Hydrogen)

Limitations

- ~200 mile range
- Not cost competitive due to expensive components
 - Pt catalyst for PEM
 - Overall FC materials
- Limited hydrogen refueling stations

References



“2016 Mirai Product Information,” Toyota

“2015 Tundra Product Information,” Toyota

Kocha, S., “Polymer Electrolyte Membrane (PEM) Fuel Cells, Automotive Applications,” Encyclopedia of Sustainability Science and Technology. pp. 8231-8264. 2012.

S. Berenyi, High Pressure Turbocharging for SOFC/ Hybrid Fuel Cell Systems. 3rd Annual DOD/U.N. Hybrid Power System Conference and Workshop, May 13-15, 2003

BorgWarner Knowledge Library 2014, Charging System for Fuel Cell Applications

S. Campanari et al. Performance Assessment of Turbocharged Pem Fuel Cell Systems for Civil Aircraft Onboard Power Production. Journal of Engineering for Gas Turbines and Power, Mar 2008 vol. 130/ 021701-1

Aeristech Ltd, Electric Compressor for Fuel Cell Systems for Automotive Application. Aeristech 2014

C. He et al. PEM Fuel Cell Catalyst: Cost Performance, and Durability. The Electrochemical Society Interface Fall 2005

M. Kotisaari, VTT. Maximizing the Efficiency and Lifetime of Fuel Cell with Optimum Humidification. Vaisala Application Note 2014

References



<https://transportevolved.com/2014/11/25/toyota-admits-cutting-costs-hydrogen-fuel-cell-technology-will-tough/>

<http://www.viamotors.com/vehicles/electric-truck/>

<http://www.triplepundit.com/special/energy-options-pros-and-cons/fuel-cell-energy-pros-cons/>

http://batteryuniversity.com/learn/article/is_li_ion_the_solution_for_the_electric_vehicle

http://www.autonomie.net/docs/6%20-%20Papers/Hydrogen_fueled/energy_storage_requirements.pdf

<https://www.daimler.com/dccom/0-5-1228971-1-1231030-1-0-0-1401206-0-0-135-0-0-0-0-0-0-0.html>

<http://www.epa.gov/fuelcell/basicinfo.htm>

<https://fastlane.gm.com/2014/07/10/gm-military-concept-vehicles-didnt-make-cut/>