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Overview of fuel cell technology

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Friday 28th 2020

HEJC

Talk overview

- Why are fuel cells interesting?
- A little bit of history
- How do fuel cells work?
- Different types:
    - AFC
    - PEMFC
    - SOFC
    - MOLTEN CARBON FC
- Applications:
    - Stationary power station
    - Electric vehicles
    - Military

Why fuel cells

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http://www.brockpress.com/wp-content/uploads/2014/11/Arctic-melting.jpg

http://images.smh.com.au/2013/02/12/4027241/art-energy-620x349.jpg

Why are fuel cells interesting?

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Benefits:

- Low-to-Zero Emissions
- High Efficiency
- Reliability
- Fuel Flexibility
- Energy Security
- Durability
- Scalability
- Quiet Operation

→

Reasons:

- No exhaust produced
- No intermediate combustion step
- No moving parts
- Fuel reformation fueling options
- No intermittency
- No mechanical fatigue
- Modularity
- No combustion "explosion"

	Reciprocating engine: diesel	Turbine generator	Photo voltaics	Wind turbine	Fuel cells
Capacity Range	500 kW to 5 MW	500 kW to 25 MW	1 kW to 1 MW	10 kW to 1 MW	200 kW to 2 MW
Efficiency	35%	29–42%	6–19%	25%	40–60%
Capital Cost ($/kW)	200–350	450–870	6600	1000	1500–3000
O&M Cost ($/kW)	0.005–0.015	0.005–0.0065	0.001–0.004	0.01	0.0019–0.0153

A. Kirubakaran et al. / Renewable and Sustainable Energy Reviews 13 (2009) 2430–2440

A little bit of history

1801
Humphry Davy demonstrates the principle of what became fuel cells.

1839
William Grove invents the 'gas battery', the first fuel cell.

1889
Charles Langer and Ludwig Mond develop Grove's invention and name the fuel cell.

1950s
General Electric invents the proton exchange membrane fuel cell.

1959
Francis Bacon demonstrates a 5 kW alkaline fuel cell.

1960s
NASA first uses fuel cells in space missions.

1970s
The oil crisis prompts the development of alternative energy technologies including PAFC.

1980s
US Navy uses fuel cells in submarines.

1990s
Large stationary fuel cells are developed for commercial and industrial locations.

2007
Fuel cells begin to be sold commercially as APU and for stationary backup power.

2008
Honda begins leasing the FCX Clarity fuel cell electric vehicle.

2009
Residential fuel cell micro-CHP units become commercially available in Japan. Also thousands of portable fuel cell battery chargers are sold.

Fuel cell today

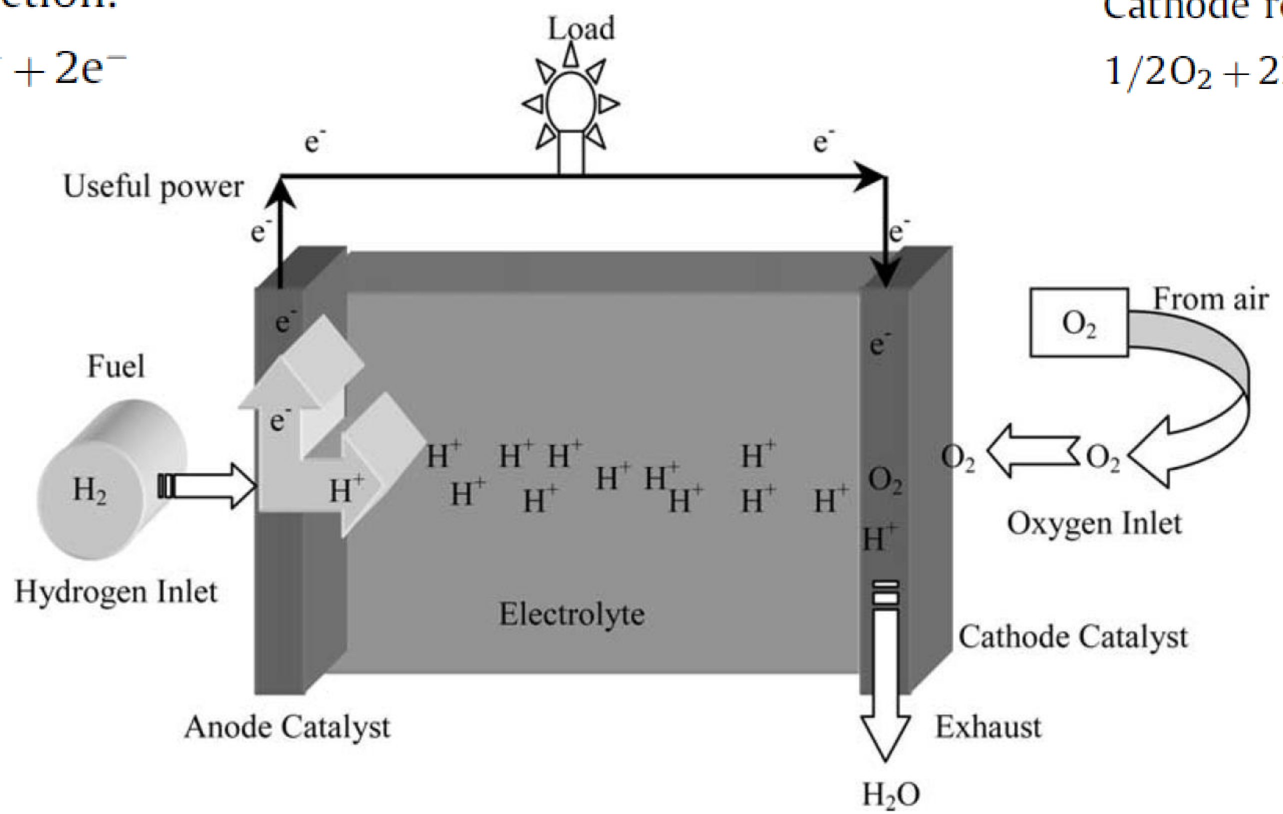
How does a fuel cell work?

Anode reaction:

$$H_2 \Rightarrow 2H^+ + 2e^-$$

Cathode reaction:

$$1/2O_2 + 2H^+ + 2e^- \Rightarrow H_2O$$



Overall reaction:

$$H_2 + 1/2O_2 \Rightarrow H_2O$$

Boudghene Stambouli, E. Traversa / Renewable and Sustainable Energy Reviews 6 (2002) 297–306

Different types of fuel cells

Types	Electrolyte	Operating T (C)	Fuel
Alkaline (AFC)	Potassium hydroxide (KOH)	50–200	Pure hydrogen, or hydrazine
Direct methanol (DMFC)	Polymer	60–200	Liquid methanol
Phosphoric acid (PAFC)	Phosphoric acid	160–210	Hydrogen from hydrocarbons and alcohol
Sulphuric acid (SAFC)	Sulphuric acid	80–90	Alcohol or impure hydrogen
Proton-exchange membrane (PEMFC)	Polymer, proton exchange membrane	50–80	Less pure hydrogen from hydrocarbons or methanol
Molten carbonate (MCFC)	Molten salt such as nitrate, sulphate, carbonates...	630–650	Hydrogen, carbon monoxide, natural gas, propane, marine diesel
Solid oxide (SOFC)	Stabilised zirconia and doped perovskite	600–1000	Natural gas or propane
Solid polymer (SPFC)	Solid sulphonated polystyrene	90	Hydrogen

Low temperature 50-250 °C

High temperature 650-1000 °C

The electrolyte

- determines the operating temperature of the fuel cell
- prevents the two electrodes to come into electronic contact
- allows the flow of charged ions from one electrode to the other

Boudghene Stambouli, E. Traversa / Renewable and Sustainable Energy Reviews 6 (2002) 297–306

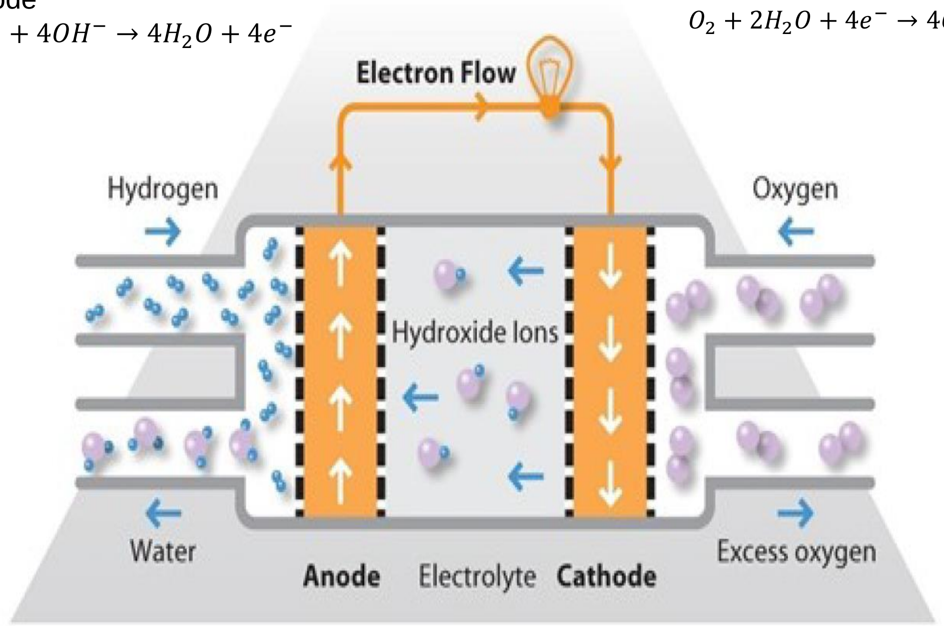
Alkaline Fuel Cell

Alkaline electrolyte KOH in water

Parameters	AFC
Electrolyte	Liquid solution of KOH
Operating temperature (°C)	50–200
Anode reaction	$H_2 + 2(OH^-) \rightarrow 2H_2O + 2e^-$
Cathode reaction	$1/2O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
Charge carrier	OH^-
Fuel	Pure H_2
Oxidant	O_2 in air
Efficiency	~50%
Cogeneration	–
Reformer is required	Yes
Cell Voltage	1.0
Power density (kW/m^3)	~1
Installation Cost (US $/kW)	~1800
Capacity	10–100 kW

Anode
$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$

Cathode:
$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$



Fuel cell Today

First fuel cell developed, used by NASA in Apollo space program to produce electricity and water

Advantages:
- Low operating temperature
- No need for precious metal catalyst (Nickel)

Drawbacks:
- CO_2 poisoning
- Sensitive to fuel impurities

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$

A. Kirubakaran et al. / Renewable and Sustainable Energy Reviews 13 (2009) 2430–2440

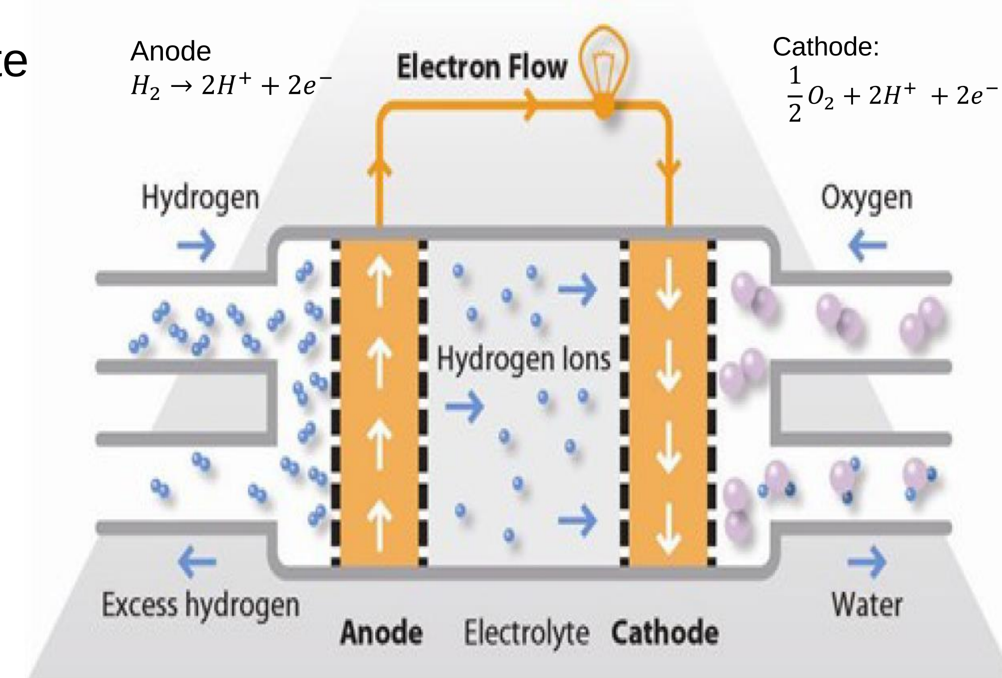
Polymer Electrolyte Fuel Cells

Polymer membranes as electrolyte

Parameters	Fuel cell types
	PEMFC
Electrolyte	Solid polymer membrane (Nafion)
Operating temperature (°C)	50–100
Anode reaction	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode reaction	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Charge carrier	H^+
Fuel	Pure H_2
Oxidant	O_2 in air
Efficiency	40–50%
Cogeneration	–
Reformer is required	Yes
Cell Voltage	1.1
Power density (kW/m^3)	3.8–6.5
Installation Cost (US \$/kW)	<1500
Capacity	30 W, 1 kW, 2 kW, 5 kW, 7 kW, 250 kW

Anode
$H_2 \rightarrow 2H^+ + 2e^-$

Cathode:
$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$



Fuel cell Today

Advantages:

- Low temperature
- High power density
- Quick start up for automotive application
- Meets dynamic power requirements

Drawbacks:

- "Low" efficiency 40-45%
- High cost platinum catalyst
- Need for pure hydrogen

Overall reaction: $2H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

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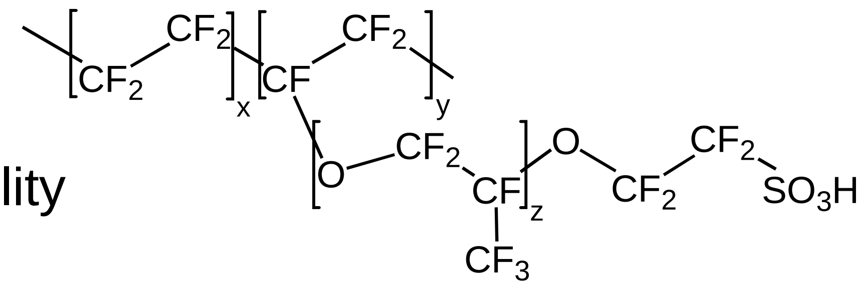
Proton Exchange Membrane Fuel Cell

Membrane requirements:

- Good proton conductivity
- Low permeability to fuel
- Chemical and electrochemical stability
- Adequate mechanical properties
- Sustainable cost projections



Nafion membrane is the state-of-the art of PEM

Light duty vehicles → cars

Used to power handling vehicles, like forklift truck (eliminating the need for battery charging stations)

https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_early_markets_mhe_fact_sheet.pdf

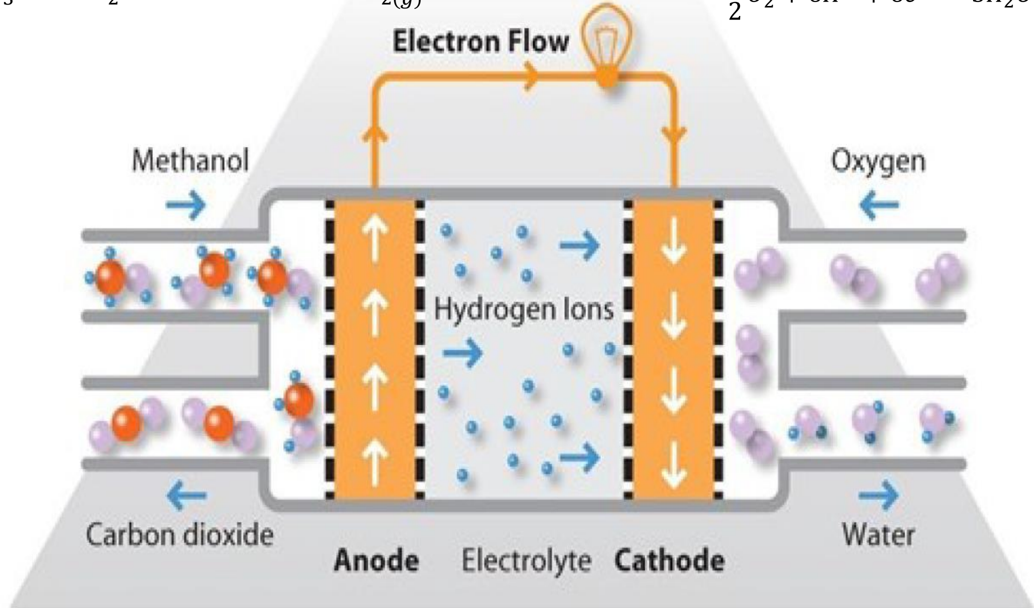
Direct Methanol Fuel Cell

Methanol as fuel

Parameters	DMFC
Electrolyte	Solid polymer membrane
Operating temperature (°C)	60–200
Anode reaction	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6H^-$
Cathode reaction	$3O_2 + 12H^+ + 12H^- \rightarrow 6H_2O$
Charge carrier	H^+
Fuel	CH_3OH
Oxidant	O_2 in air
Efficiency	40%
Cogeneration	No
Reformer is required	–
Cell Voltage	0.2–0.4
Power density (kW/m^3)	~0.6
Installation Cost (US $/kW)	–
Capacity	1 W to 1 kW, 100 kW to 1 MW (Research)

Anode
$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_{2(g)}$

Cathode:
$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$



Fuel cell Today

Advantages:

- Inexpensive fuel
- No need for fuel reformer
- Methanol easy to transport and handle

Drawbacks:

- Expensive catalyst (Pt/Ru at anode)
- Expensive membranes

Overall reaction: $CH_3OH + \frac{3}{2}O_2 \rightarrow 2H_2O + CO_2$

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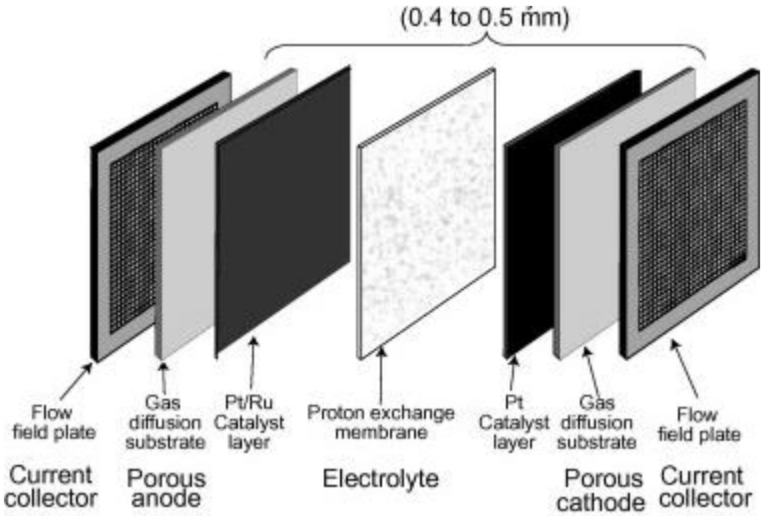
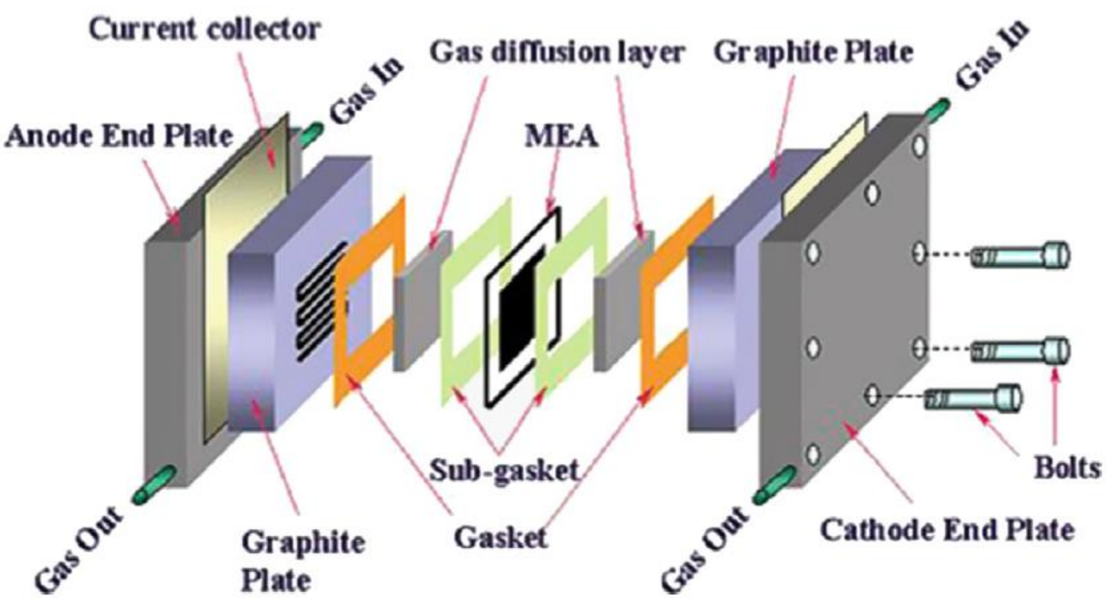
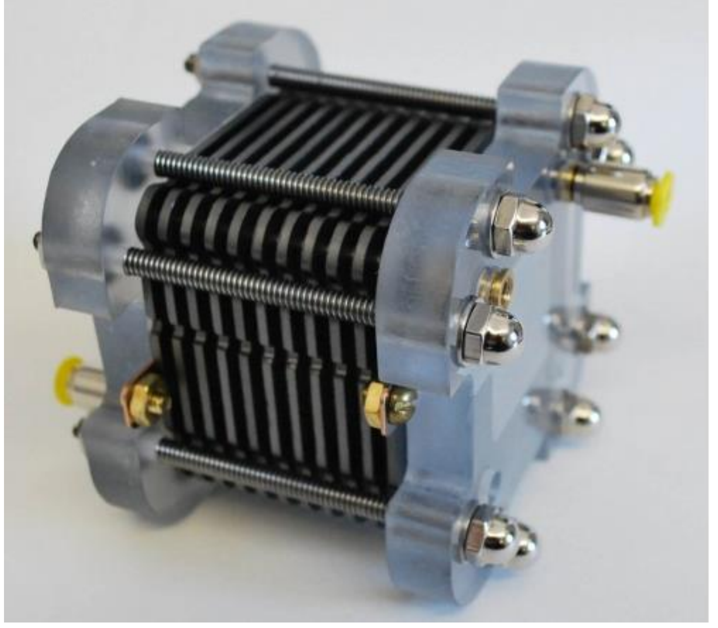
Direct Methanol Fuel Cell



Most recent, invented in the 1990s by NASA and JPL.
Modest power requirements, mobile electronic devices, portable power packs.



Fuel cell store



Fuel cell store

Solid Oxide Fuel Cell

Solid ceramic electrolyte: Zirconia Oxide stabilized by yttrium oxide

Parameters	SOFC
Electrolyte	Stabilized solid oxide electrolyte (Y_2O_3, ZrO_2)
Operating temperature (°C)	800–1000
Anode reaction	$H_2 + O^2 \rightarrow H_2O + 2e^-$
Cathode reaction	$1/2O_2 + 2e^- \rightarrow O^{2-}$
Charge carrier	$O^=$
Fuel	H_2, CO, CH_4, other hydrocarbons
Oxidant	O_2 in air
Efficiency	>50%
Cogeneration	Yes
Reformer is required	–
Cell Voltage	0.8–1.0
Power density (kW/m^3)	0.1–1.5
Installation Cost (US $/kW)	3000
Capacity	1 kW, 25 kW, 5 kW, 100 kW, 250 kW, 1.7 MW

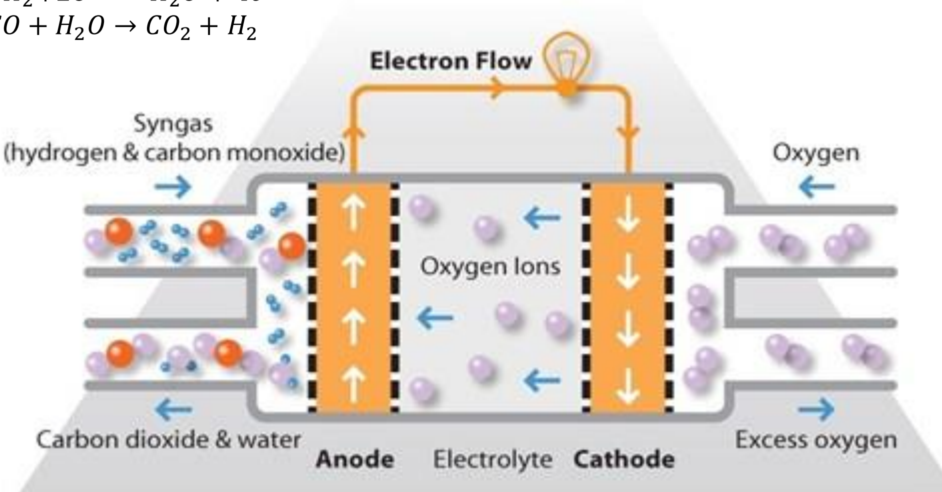
Anode

$H_2 + 2O^{2-} \rightarrow H_2O + 4e^-$

$CO + H_2O \rightarrow CO_2 + H_2$

Cathode:

$O_2 + 4e^- \rightarrow 2O^{2-}$



Fuel cell Today

Advantages:

- Fast kinetics due to high Temp
- No need for metal catalyst
- Resistant to sulfur in the fuel
- Different fuel, no need for former reforming

Drawbacks:

- Slow start due to heating
- Heat resistant materials required

Overall reactions: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ and $CO + \frac{1}{2}O_2 \rightarrow CO_2$

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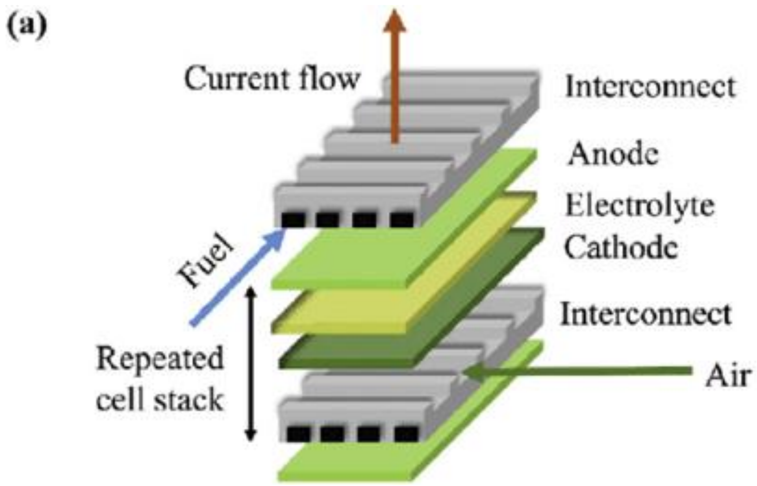
Solid Oxide Fuel Cell

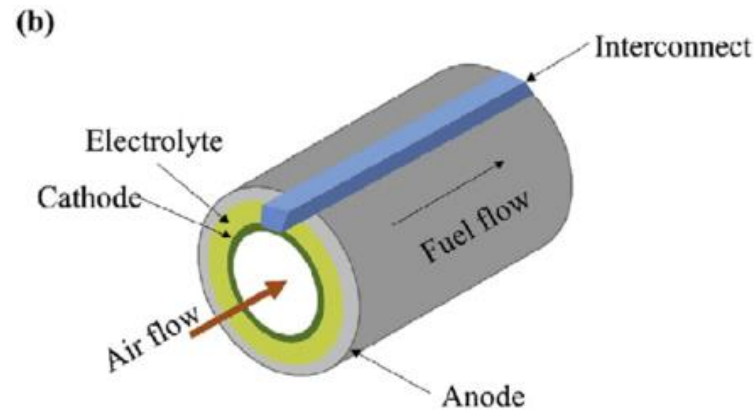
Different geometry

Planar



Electrodes and electrolyte where air and fuel flow through interconnect channels into the cathode and anode

Microtubolar



Long hollow tubes where air and fuel flows through the tube interior and exterior

SOFCs are used in small stationary power generation
200-300 kW Bloomenergy's off-grid power generation
Few Watts for small portable chargers

K.H. Ng International Journal of Hydrogen Energy, 44, 58 (2019) , 30692-30704

Molten Carbonate Fuel Cell

Molten carbonate salt suspended in a porous ceramic matrix as the electrolyte ($LiAlO_2$)

Li_2CO_3, K_2CO_2, Na_2CO_3

Parameters	MCFC
Electrolyte	Lithium and potassium carbonate (LiAlO2)
Operating temperature (°C)	~650
Anode reaction	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
Cathode reaction	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
Charge carrier	$CO_3^{=}$
Fuel	H_2, CO, CH_4, other hydrocarbons
Oxidant	O_2 in air
Efficiency	>50%
Cogeneration	Yes
Reformer is required	–
Cell Voltage	0.7–1.0
Power density (kW/m³)	1.5–2.6
Installation Cost (US $/kW)	~2000–3000
Capacity	155 kW, 200 kW, 250 kW 1 MW, 2 MW

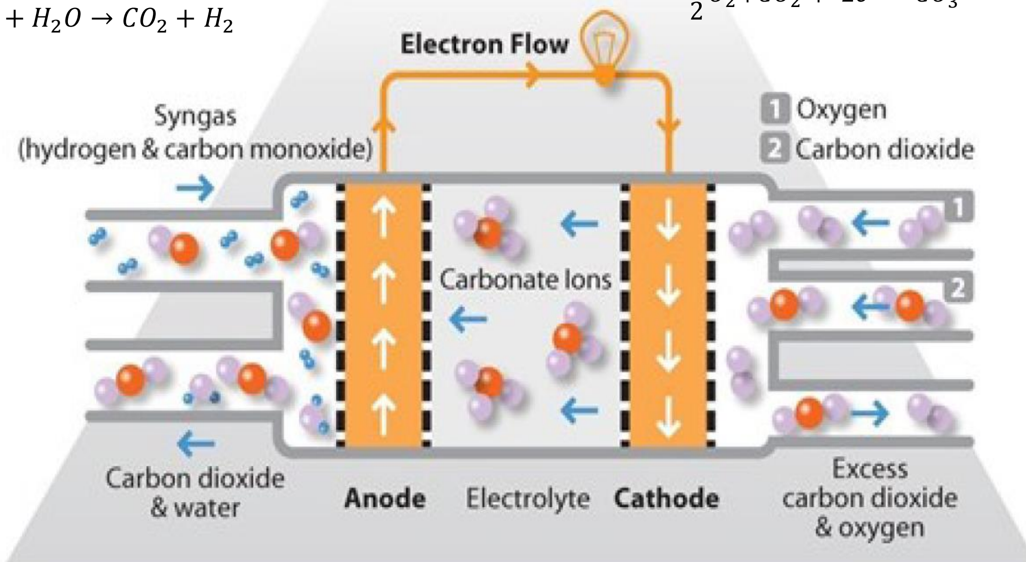
Anode

$H_2 + CO_3^{2-\,-} \rightarrow H_2O + CO_2 + 2e^-$

$CO + H_2O \rightarrow CO_2 + H_2$

Cathode:

$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$



Fuel cell Today

Advantages:

- Fast kinetics due to high Temp
- No need for noble catalyst
- No carbon monoxide poisoning
- Different fuel, no need for former reforming

Drawbacks:

- Liquid electrolyte
- Injection of CO_2 at the cathode as carbonate is consumed at the anode
- High temperature corrosion

Overall reactions: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ and $CO + H_2O \rightarrow CO_2 + H_2$

A. Kirubakaran et al. / Renewable and Sustainable Energy Reviews 13 (2009) 2430–2440

Molten Carbonate Fuel Cell

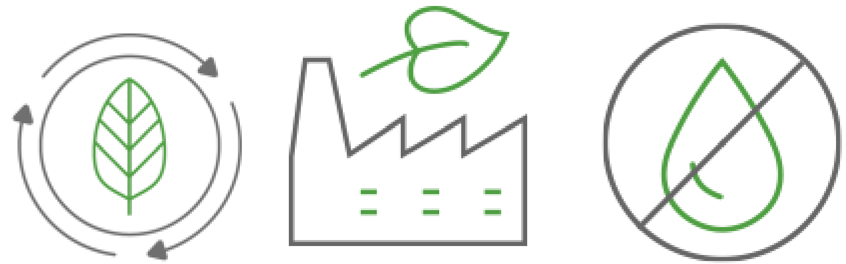
MCFCs are used in large stationary power generation
1 MW in located in Kawagoe, Japan
2 MW plant I located in Santa Clara, CA.

Overall efficiencies can be over 80% in combined heat/cooling and power applications where the process heat is also utilized.

www.grandresearchstore.com/press-release/molten-carbonate-fuel-cells-market

Stationary fuel cells

https://www.bloomenergy.com/



- Low Carbon Emission
- Less Air Pollution and Smog
- No water consumption
- Lock in cost for electric power

10 MW fuel cell installation can be sited in a about an acre of land
1 MW of solar power requires 10 acres
1 MW of wind about requires 50 acres

www.fchea.org/stationary

Fuel Cell Electric Vehicles (FCEV)

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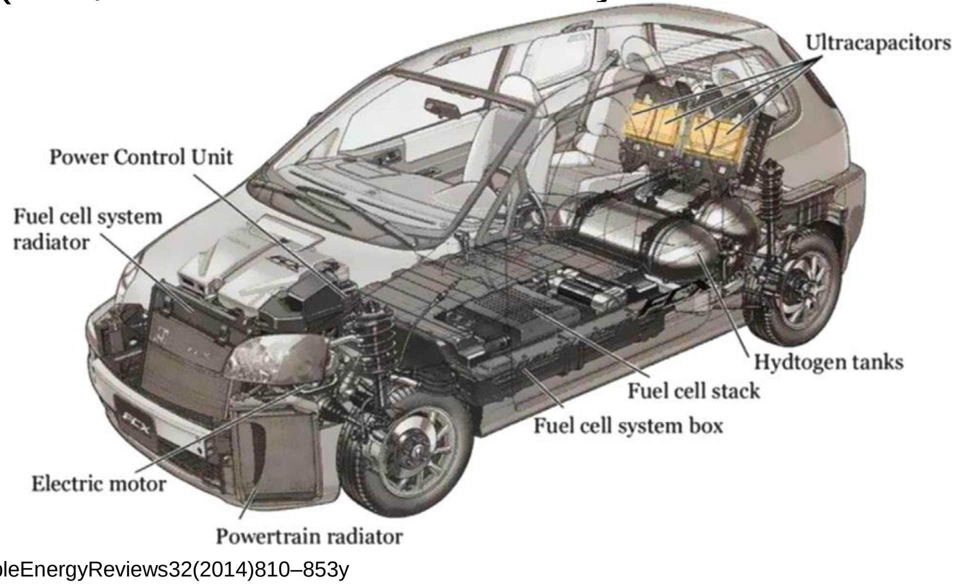
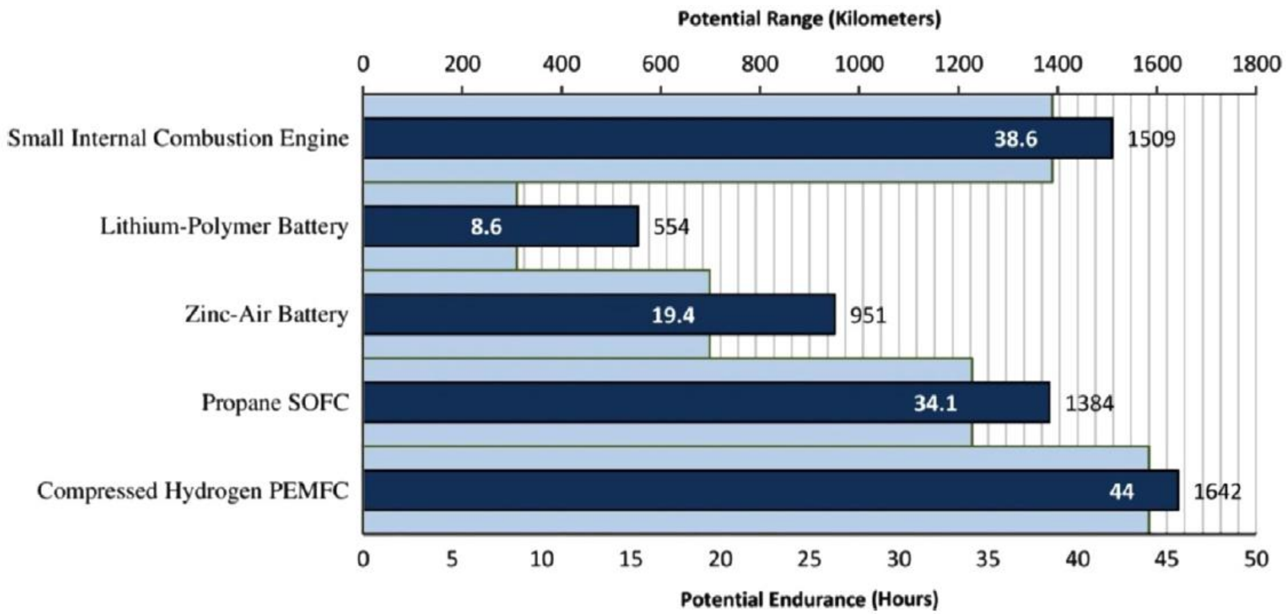
Honda Clarity Fuel Cell

Production size of vehicles very low → few hundreds a year
high price ~$60,000 ($20,000 more than a Battery Electric Vehicles or BEV)



O.Z. Sharaf,M.F.Orhan/RenewableandSustainableEnergyReviews32(2014)810–853y

FCEV vs BEV



Range
Endurance

After 5 minutes of refueling

Electric Vehicle 40 miles

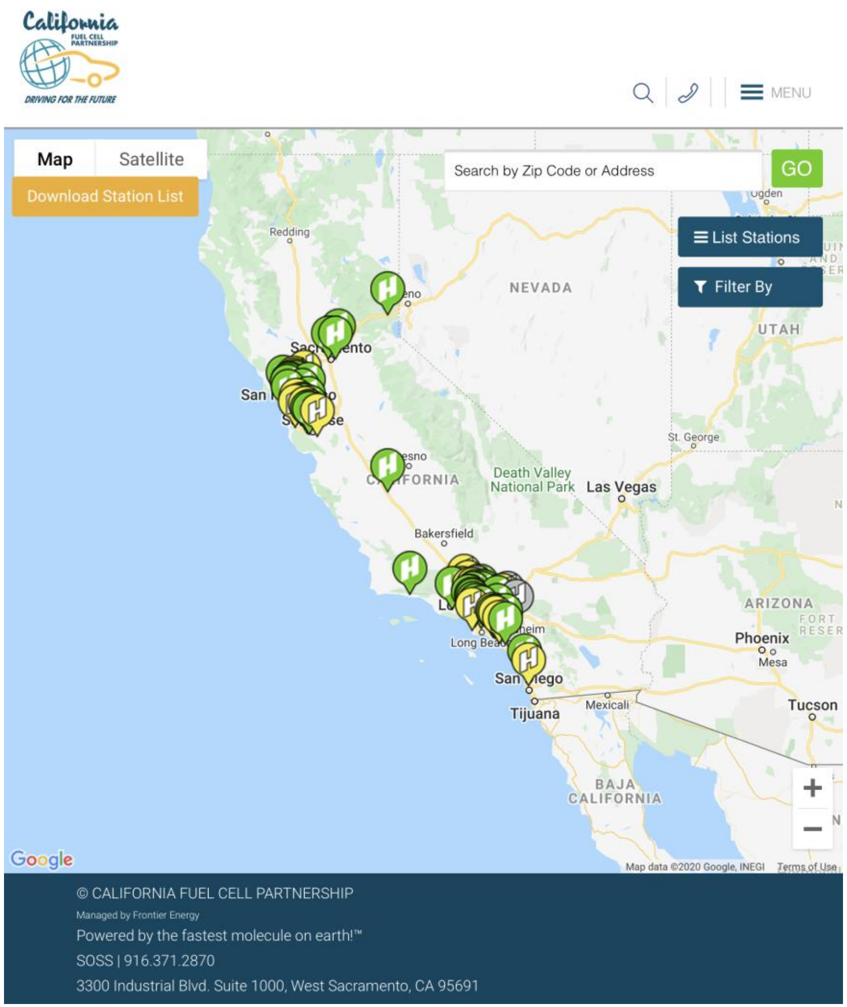
Hyundai NEXO 367 miles

500km-range (310 miles) FCEV with two storage tanks (the Nexo actually has three tanks) would now have cost parity with a 500km BEV, cost-parity milestone depends on making 100,000 of the FCEV per year.

https://tech.hyundaimotorgroup.com/article/the-future-lies-in-ev-or-fcev/

FCEV infrastructure

Refueling stations

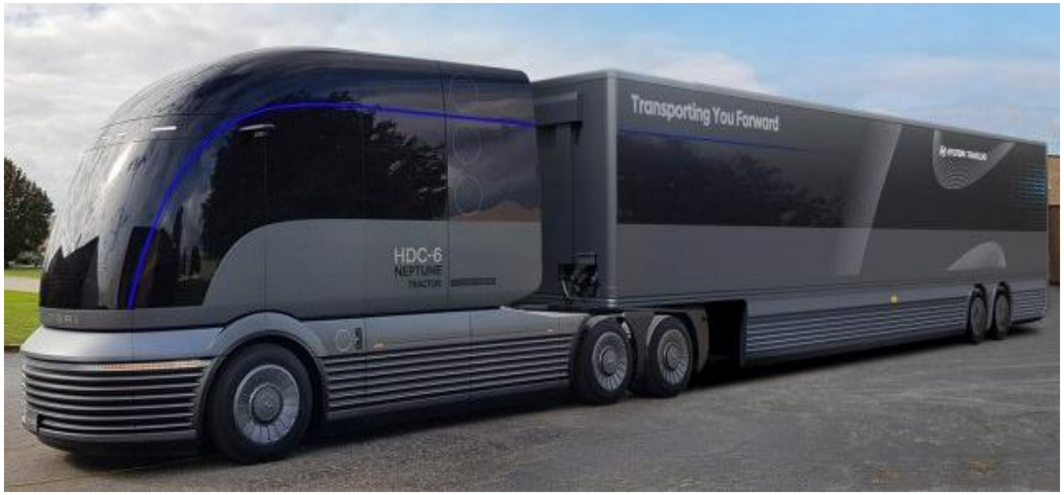


350 bar and 700 bar hydrogen refueling system

https://ww2.energy.ca.gov/transportation/altfueltech/hydrogen.html

Incentives for FCEV:
$4,500 California rebate
$8,000 federal tax credit

Trucks



Hyundai HDC-6 Neptune

Class 8 truck (33,000 lb/15,000kg) is expected to travel 1,000,000 miles (1,600,000 km)

34 tons gross weight truck :

- Makes 400 km between refills
- Refuel in 7 minutes

South Korea government announced:

- 310 hydrogen stations by 2022
- Hyundai Motor Group will produce 0.5 million FCEV by 2030

Hyundai has signed an agreement with H_2 Energy of Switzerland to supply 1000 of a new FCEV truck.

www.extremetech.com/extreme/301095-hyundai-makes-the-case-for-fuel-cell-trucks-with-gorgeous-hdc-6-neptune

Military applications

Wearable backpacks:

- decrease battery weight by 50% replacing lithium-ion
- power military radios and laptop computers over the course of 6 days

Fuel cell powered Unmanned Aerial Vehicles :

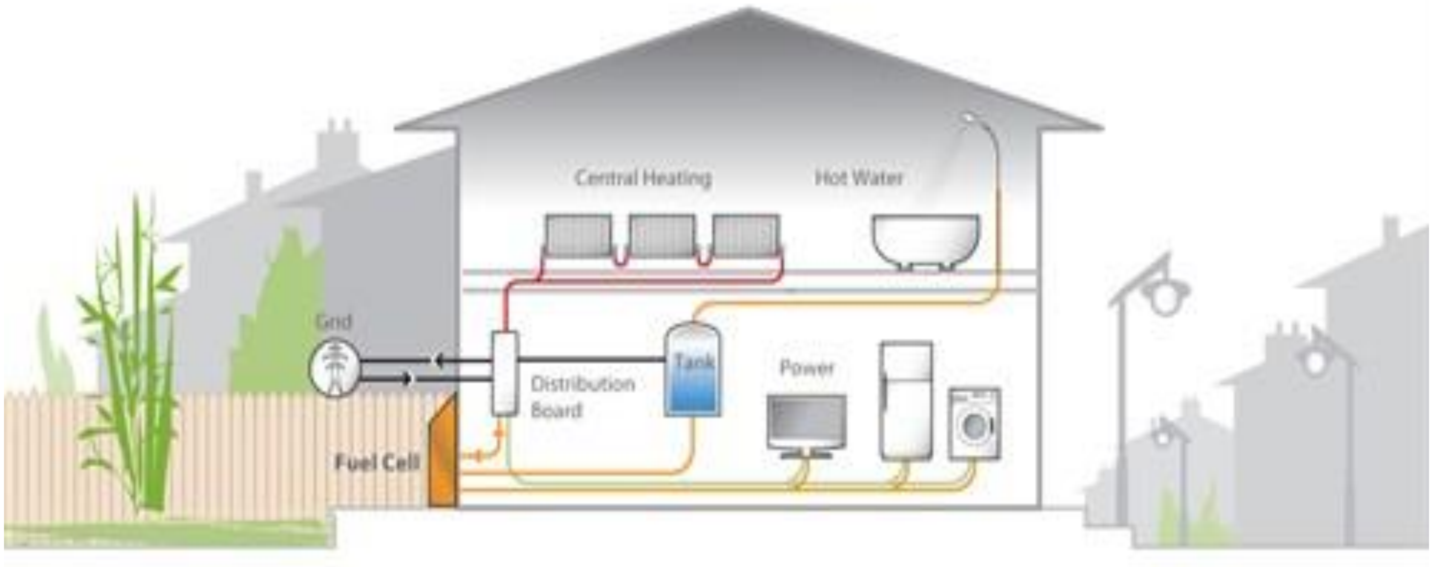
- Airtime 8 hours and
- refueled in less than 15 minutes
- no moving parts →less maintenance

Fuel cell powered light duty truck:

- Reduce sound
- Reduce thermal signature
- Keep the soldiers hydrated (H_2O byproduct)

https://www.energy.gov/eere/articles/4-ways-fuel-cells-power-us-military

Stationary applications



Possible uses:

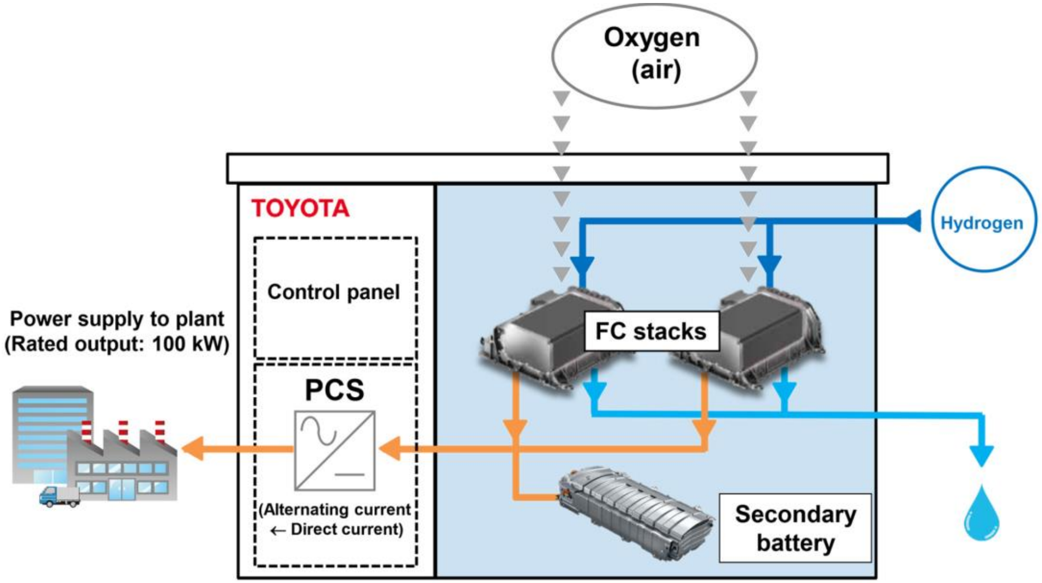
- replace the grid
- areas where there is little or no grid infrastructure
- provide grid expansion node

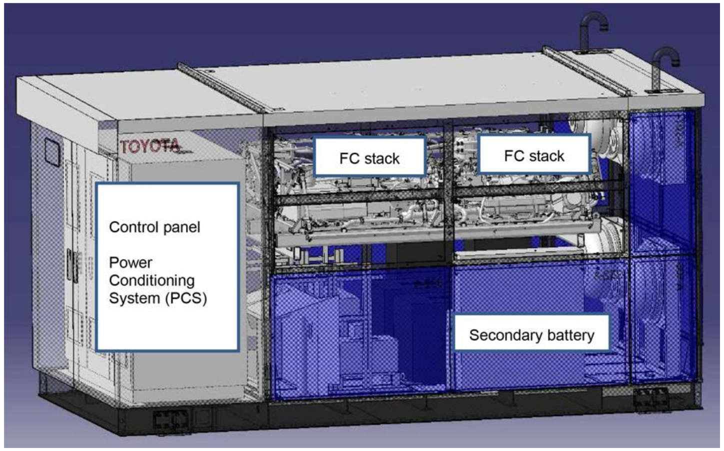
Fuel cells are also more efficient at generating electricity which gives combined heat and power units overall efficiencies of 80-95%

Fuel cell today

Stationary applications

Honsha Plant grounds in Toyota City, Aichi Prefecture, Japan





Operates continuously for 24 hours per day
Rated output of 100 kilowatts
Fueled by hydrogen (99.97% pure)
Rated voltage: AC 210 V
Number of phases: three-phase three-wire
Frequency: 50/60 Hz
Start up time (time to reach output): 40 seconds

https://global.toyota/en/newsroom/corporate/29246629.html

Summary

- Fuel cell vehicles might be better for commercial and filter vehicles
- Manufacturing FCEV is less carbon intense than BEV
- It is easier to recycle the fuel cell stack into its component metals, than a battery
- Combine cooling/heating and power for stationary application

BREAK THE LOOP:

Increase the request for fueling stations to increase the request of FCEV and vice versa

https://ww2.energy.ca.gov/transportation/altfueltech/hydrogen.html

Thanks!!!

Some extra info

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Different type of Fuel cells

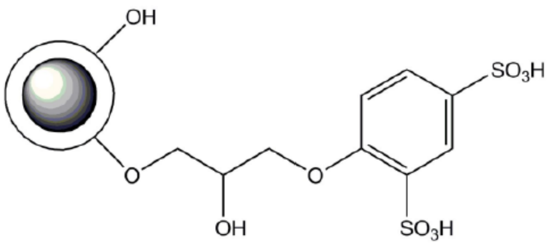
Parameters	Fuel cell types					
	PEMFC	AFC	PAFC	MCFC	SOFC	DMFC
Electrolyte	Solid polymer membrane (Nafion)	Liquid solution of KOH	Phosphoric acid (H_3PO_4)	Lithium and potassium carbonate (LiAlO2)	Stabilized solid oxide electrolyte (Y_2O_3, ZrO_2)	Solid polymer membrane
Operating temperature (°C)	50–100	50–200	~200	~650	800–1000	60–200
Anode reaction	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + 2(OH^-) \rightarrow 2H_2O + 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$H_2 + O^2 \rightarrow H_2O + 2e^-$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6H^-$
Cathode reaction	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$1/2O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$1/2O_2 + 2e^- \rightarrow O^{2-}$	$3O_2 + 12H^+ + 12H^- \rightarrow 6H_2O$
Charge carrier	H^+	OH^-	H^+	$CO_3^=$	$O^=$	H^+
Fuel	Pure H_2	Pure H_2	Pure H_2	H_2, CO, CH_4, other hydrocarbons	H_2, CO, CH_4, other hydrocarbons	CH_3OH
Oxidant	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air
Efficiency	40–50%	~50%	40%	>50%	>50%	40%
Cogeneration	–	–	Yes	Yes	Yes	No
Reformer is required	Yes	Yes	Yes	–	–	–
Cell Voltage	1.1	1.0	1.1	0.7–1.0	0.8–1.0	0.2–0.4
Power density (kW/m^3)	3.8–6.5	~1	0.8–1.9	1.5–2.6	0.1–1.5	~0.6
Installation Cost (US $/kW)	<1500	~1800	2100	~2000–3000	3000	–
Capacity	30 W, 1 kW, 2 kW, 5 kW, 7 kW, 250 kW	10–100 kW	100 kW, 200 kW, 1.3 MW	155 kW, 200 kW, 250 kW 1 MW, 2 MW	1 kW, 25 kW, 5 kW, 100 kW, 250 kW, 1.7 MW	1 W to 1 kW, 100 kW to 1 MW (Research)
Applications	Residential; UPS; emergency services such as hospitals and banking; industry; transportation; commercial	Transportation; space shuttles; portable power	Transportation; commercial cogeneration; portable power	Transportations (e.g. marine-ships; naval vessels; rail); industries; utility power plants	Residential; utility power plants; commercial cogeneration; portable power.	It is used to replace batteries in mobiles; computers and other portable devices
Advantages	High power density; quick start up; solid non-corrosive electrolyte	High power density; quick start up	Produce high grade waste heat; stable electrolyte characteristics	High efficiency; no metal catalysts needed	Solid electrolyte; high efficiency; generate high grade waste heat	Reduced cost due to absence of fuel reformer
Drawbacks	Expensive platinum catalyst; sensitive to fuel impurities (CO, H_2S)	Expensive platinum catalyst; sensitive to fuel impurities (CO, CO_2, CH_4, H_2S)	Corrosive liquid electrolyte; sensitive to fuel impurities (CO, H_2S)	High cost; corrosive liquid electrolyte; slow start up; intolerance to sulfur	High cost; slow start up; intolerance to sulfur	Lower efficiency and power density

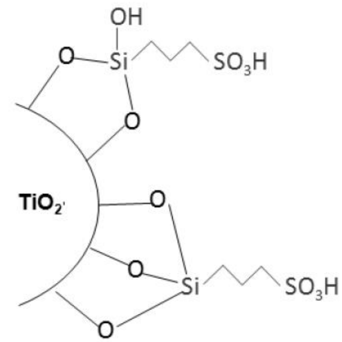
A. Kirubakaran et al. Renewable and Sustainable Energy reviews 13 (2009) 2430-2440

Polymer electrolyte

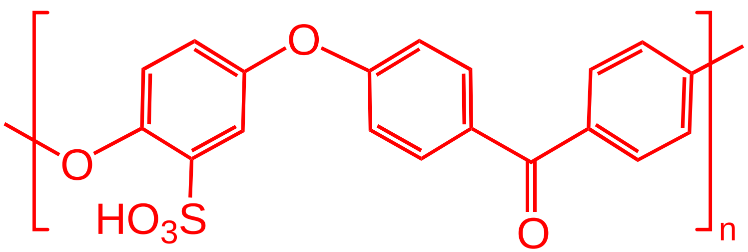
Approaches to Nafion replacements

- Nanometric fillers dispersed in matrix

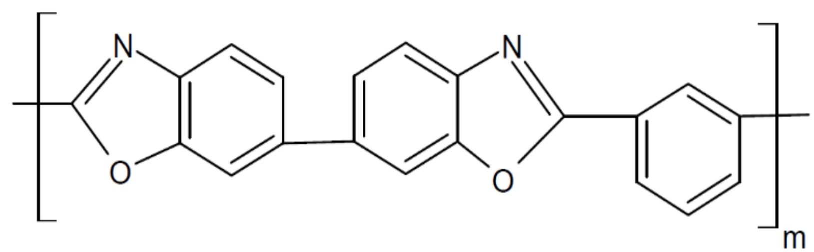




- Non fluorinated hydrocarbon based membranes



sPEEK



PBI

reduce costs
maintain high electrochemical performance

Technoeconomic comparison

Table 2
Technoeconomic comparison between fuel cells and their competitors in the portable power sector (adapted from [5]).

Portable power technology	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Power density (W/kg)	Capital cost ($/kWh)
Direct methanol fuel cell	> 1000	700–1000	100–200	200[a]
Lead-acid battery	20–50	50–100	150–300	70
Nickel–cadmium battery	40–60	75–150	150–200	300
Nickel–metal hydride battery	60–100	100–250	200–300	300–500
Lithium-ion battery	100–160	200–300	200–400	200–700
Flywheel	50–400	200	200–400	400–800
Ultracapacitor	10	10	500–10,000	20,000

[a] In $/kW.

Table 3
Technoeconomic comparison between fuel cells and their competitors in the stationary power/CHP sector (adapted from [5]).

Stationary power/CHP technology	Power level (MW)	Efficiency[a] (%)	Lifetime (years)	Capital cost ($/kW)	Capacity factor (%)
Phosphoric acid fuel cell	0.2–10	30–45	5–20	1500	Up to 95
MCFC/gas turbine hybrid	0.1–100	55–65	5–20	1000	Up to 95
SOFC/gas turbine hybrid	0.1–100	55–65	5–20	1000	Up to 95
Steam cycle (coal)	10–1000	33–40	> 20	1300–2000	60–90
Integrated gasification combined cycle	10–1000	43–47	> 20	1500–2000	75–90
Gas turbine cycle (natural gas)	0.03–1000	30–40	> 20	500–800	Up to 95
Combined gas turbine cycle (natural gas)	50–1000	45–60	> 20	500–1000	Up to 95
Microturbine	0.01–0.5	15–30	5–10	800–1500	80–95
Nuclear	500–1400	32	> 20	1500–2500	70–90
Hydroelectric	0.1–2000	65–90	> 40	1500–3500	40–50
Wind turbine	0.1–10	20–50	20	1000–3000	20–40
Geothermal	1–200	5–20	> 20	700–1500	Up to 95
Solar photovoltaic	0.001–1	10–15	15–25	2000–4000	< 25

[a] From energy input to electrical output.

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Technoeconomic comparison

Table 4
Technoeconomic comparison between fuel cells and their competitors in the transportation propulsion sector (adapted from [5]).

Transportation propulsion technology	Power level (kW)	Efficiency[a] (%)	Specific power (kW/kg)	Power density (kW/L)	Vehicle range (km)	Capital cost ($/kW)
Proton exchange membrane fuel cell (on-board fuel processing)	10–300	40–45	400–1000	600–2000	350–500	100
Proton exchange membrane fuel cell (off-board hydrogen)	10–300	50–55	400–1000	600–2000	200–300	100
Gasoline engine	10–300	15–25	> 1000	> 1000	600	20–50
Diesel engine	10–200	30–35	> 1000	> 1000	800	20–50
Diesel engine/battery hybrid	50–100	45	> 1000	> 1000	> 800	50–80
Gasoline engine/battery hybrid	10–100	40–50	> 1000	> 1000	> 800	50–80
Lead-acid or nickel-metal hydride battery	10–100	65	100–400	250–750	100–300	> 100

[a] From energy input to electrical output.

Table 5
Summary of the similarities and differences between fuel cells, batteries, and heat engines.

Comparison	Fuel cell	Battery	Heat engine
Function	Energy conversion	Energy storage & conversion	Energy conversion
Technology	Electrochemical reactions	Electrochemical reactions	Combustion
Typical fuel	Usually pure hydrogen	Stored chemicals	Gasoline, diesel
Useful output	DC electricity	DC electricity	Mechanical power
Main advantages	High efficiency	High efficiency	High maturity
	Reduced harmful emissions	High maturity	Low cost
Main disadvantages	High cost	Low operational cycles	Significant harmful emissions
	Low durability	Low durability	Low efficiency

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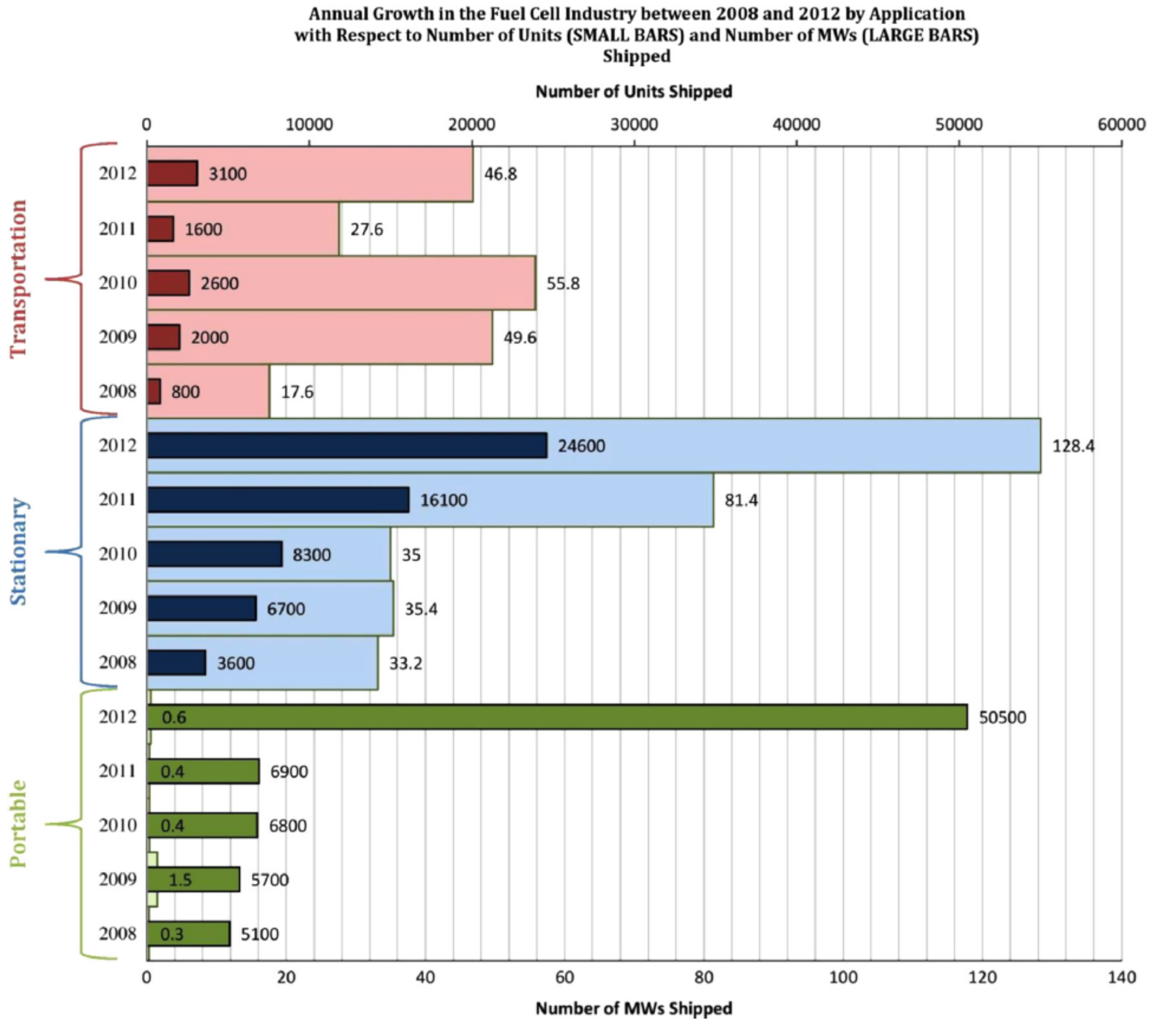
Technoeconomic comparison



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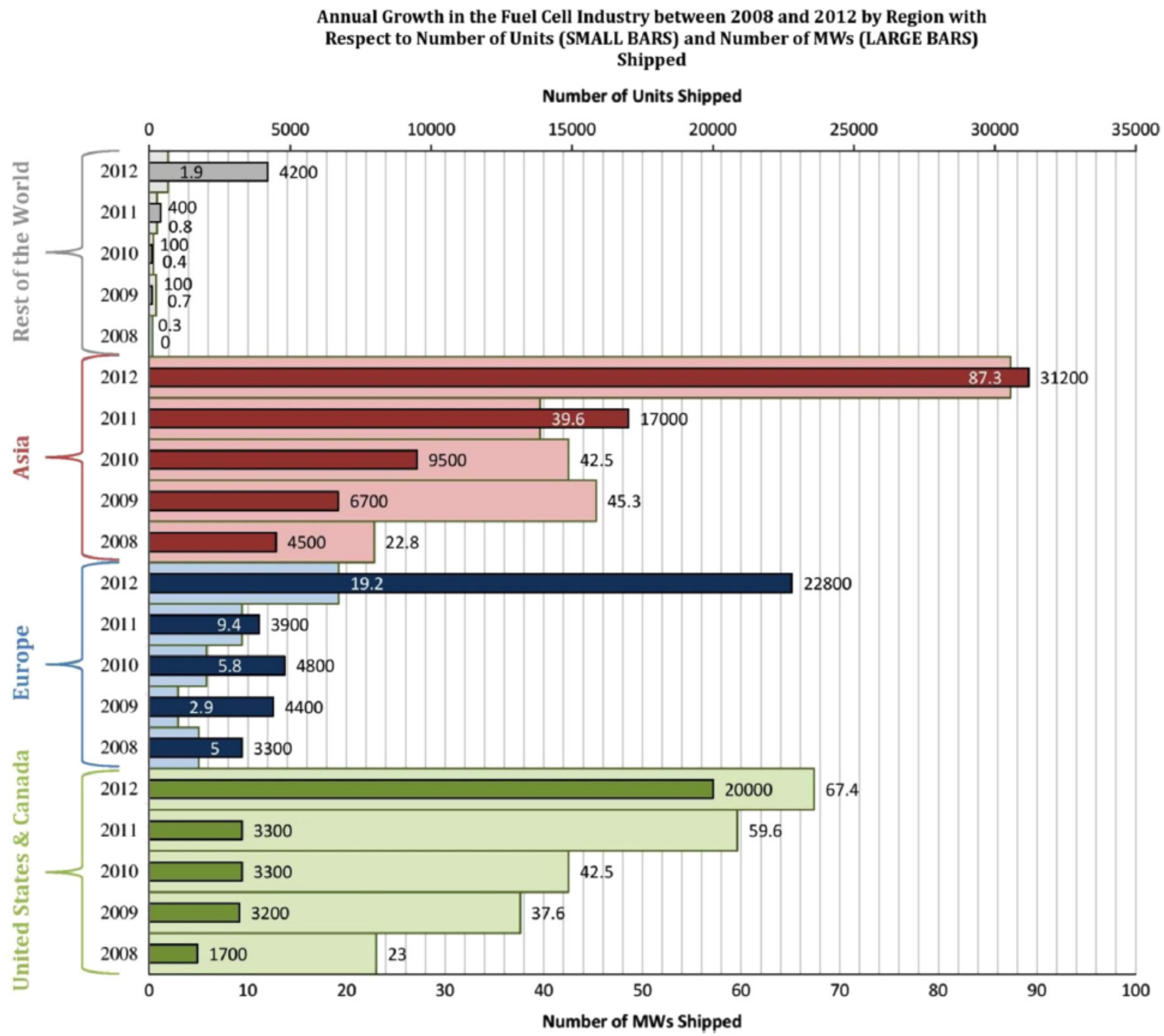
Technoeconomic comparison



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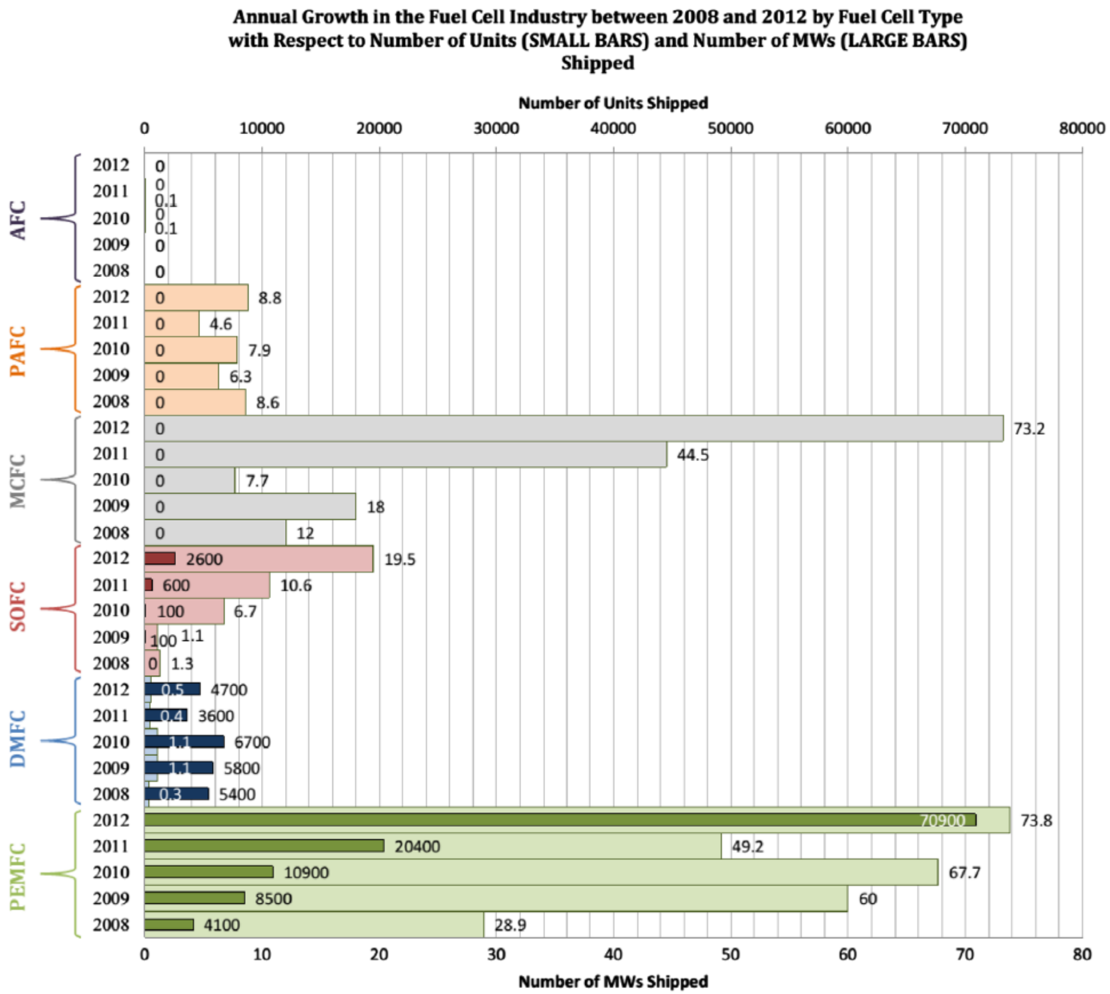
Technoeconomic comparison



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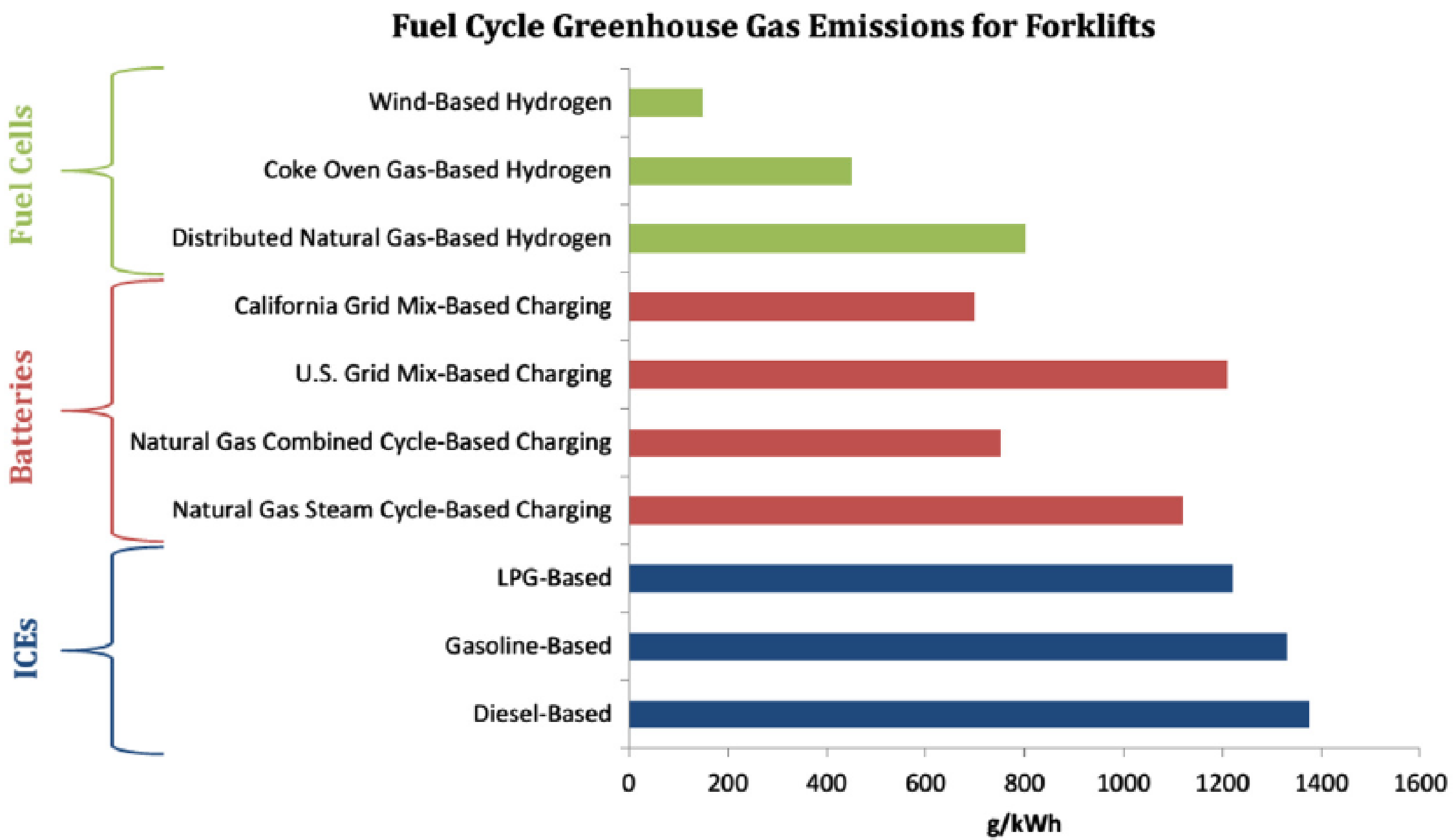
Technoeconomic comparison



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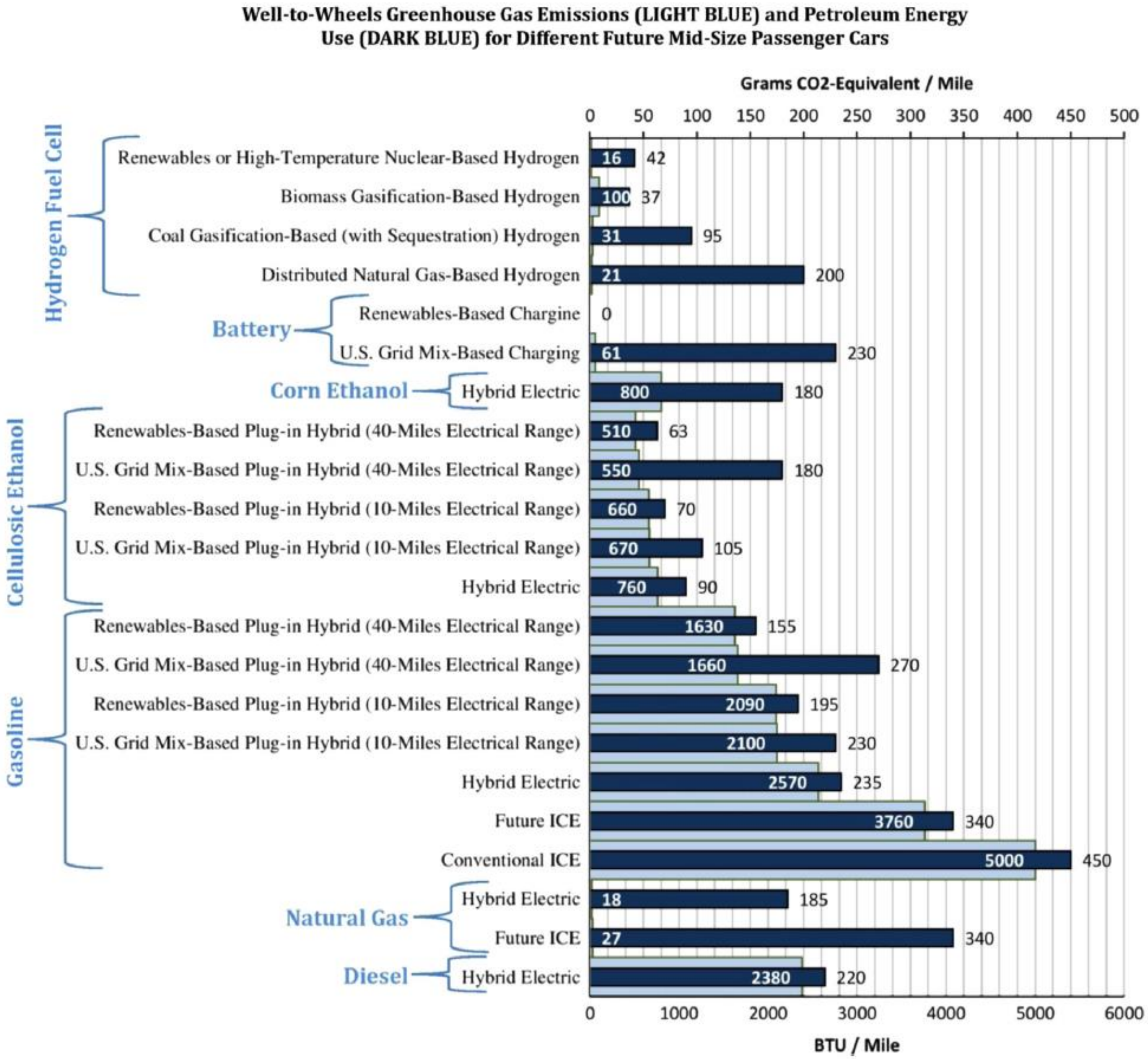
Technoeconomic comparison



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Technoeconomic comparison

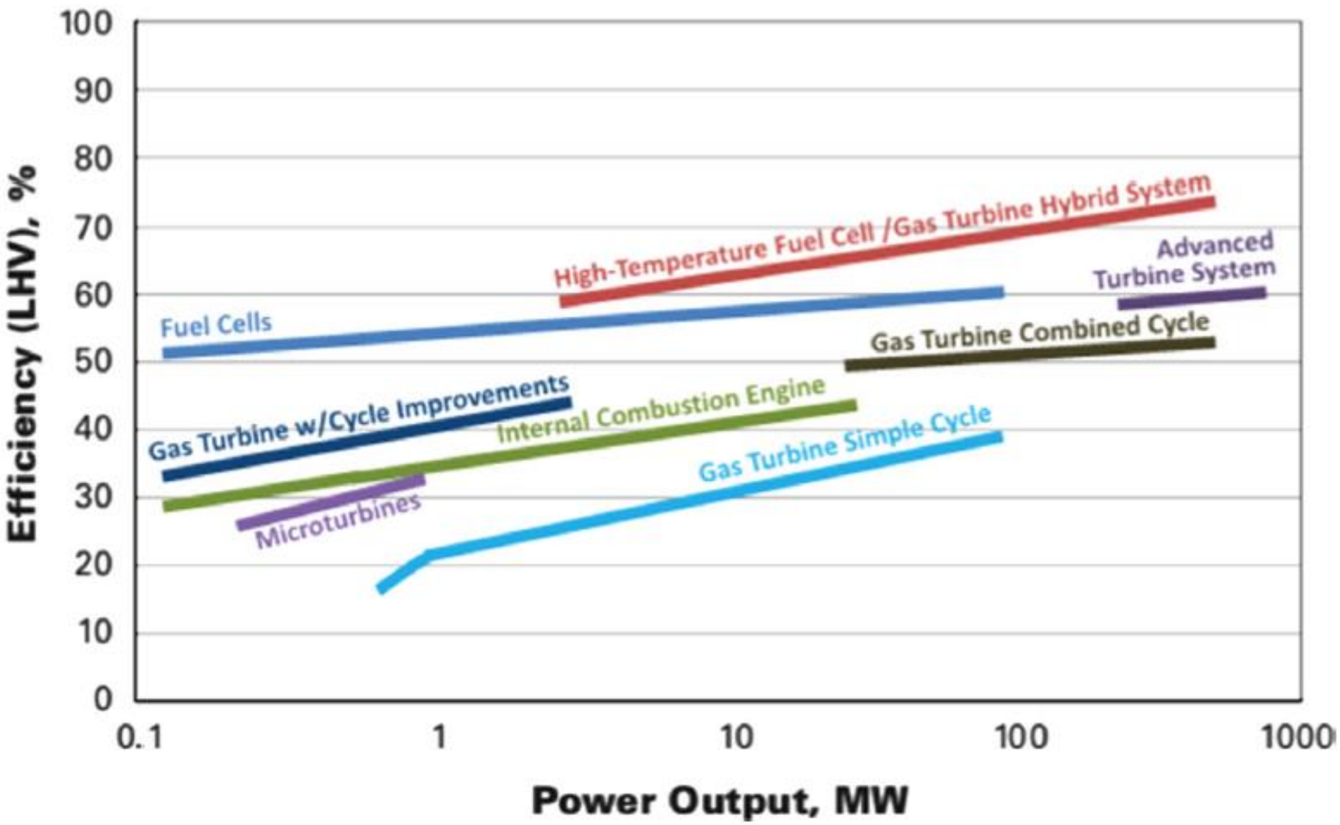

Fig. 5. Efficiency comparison between fuel cells and other energy conversion devices with respect to system size [9].

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Efficiency

HARVARD School of Engineering and Applied Sciences

The amount of heat that could be converted to useful work in a heat engine is limited by the ideal reversible Carnot efficiency, given by the following equation:

$$\eta_{Carnot} = \frac{T_i - T_e}{T_i} \quad (4)$$

where T_i is the absolute temperature at the engine inlet and T_e is the absolute temperature at the engine exit. However, a fuel cell is not limited by the Carnot efficiency since a fuel cell is an electrochemical device that undergoes isothermal oxidation instead of combustion oxidation. The maximum conversion efficiency of a fuel cell is bounded by the chemical energy content of the fuel and is found by (will be further discussed in Section 7.1):

$$\eta_{rev} = \frac{\Delta G_f}{\Delta H_f} \quad (5)$$

where ΔG_f is the change in Gibbs free energy of formation during the reactions and ΔH_f is the change in the enthalpy of formation (using lower heating value (LHV) or higher heating value (HHV)). Fig. 5

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Fuel smarts

HARVARD
School of Engineering and Applied Sciences

There are currently three hydrogen power systems in development:

- Nikola (Bosch fuel cells),
- Kenworth/Toyota (Mirai fuel cell),
- a Canadian consortium collaborating on the AZETEC project (Alberta Zero-Emissions Truck Electrification Collaboration).

Contributors to the Canadian project include Ballard Power Systems (hydrogen fuel cells), Daimler Trucks (tractors), Dana Corp. (electric motors), and others. The goal is to put two fuel-cell-electric tractors pulling **140,000-pound** combination vehicles over a **430-mile round trip** between Calgary and Edmonton, Alberta, between refueling. Each truck will have three **70kW** FCmove-HD Ballard fuel cells. The trial is set to get under way next year and run through 2022.

Hydrogen has two clear advantages over battery-electric today: longer range without sacrificing payload. **Nikola** has said its purpose-built truck will have a **500-800 mile range on 80 kg of hydrogen** in a chassis that it says weighs no more than a typical diesel sleeper tractor. Kenworth and **Toyota** say their prototype trucks, unveiled at the CES electronics show in January, will have a range of **350 miles** based on the hydrogen storage capacity. Since the tractors will be minus the diesel engine, transmission, fuel tanks and aftertreatment system, it will offset the weight of the six carbon fiber hydrogen tanks, **the fuel cell stack and a 12-kW drive battery**, making it close to weight-neutral compared to a diesel truck

https://www.truckinginfo.com/339798/will-future-trucks-be-powered-by-batteries-of-fuel-cells