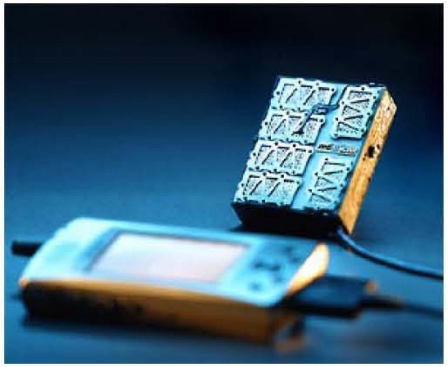
Fuel Cell Types Overview

Fuel Cell Types

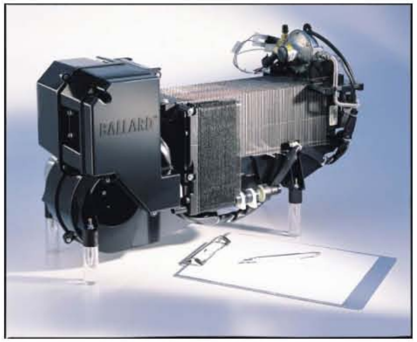
	PEMFC	PAFC	AFC	MCFC	SOFC
Electrolyte	Polymer Membrane	Liquid H_3PO_4 (Immobilized)	Liquid KOH (Immobilized)	Molten Carbonate	Ceramic
Charge Carrier	H^+	H^+	OH^-	$CO3^{2-}$	O^{2-}
Operating Temperature	80 °C	200 °C	60-220 °C	650 °C	600-1000 °C
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites (Ceramic)
Cell Components	Carbon-based	Carbon-based	Carbon-based	Stainless-based	Ceramic-based
Fuel Compatibility	H_2, Methanol	H_2	H_2	H_2, CH_4	H_2, CH_4, CO

- Electrolyte determines the type of fuel cells and operation temperature.
  - Operation temperature significantly affects the use of other components such as catalyst.

Applications vs Power



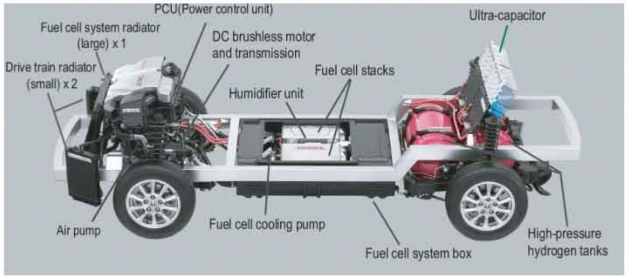
휴대전원



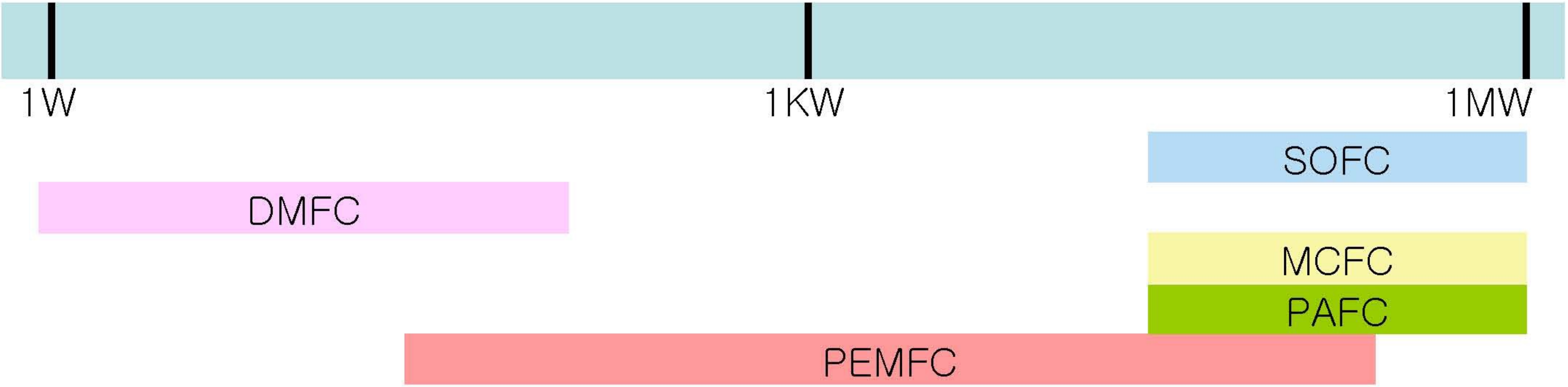
가정용 발전

대형 발전

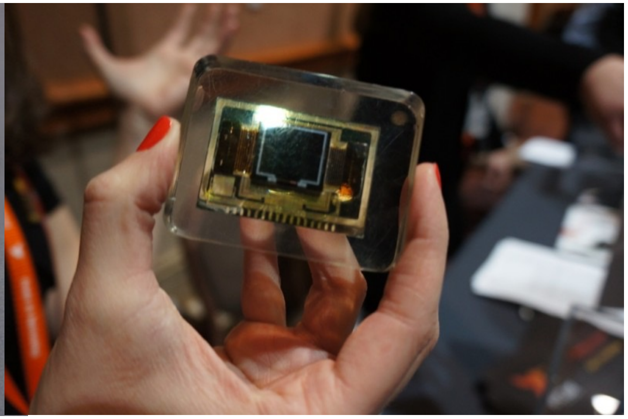
소형 운송수단



중 대형 운송수단

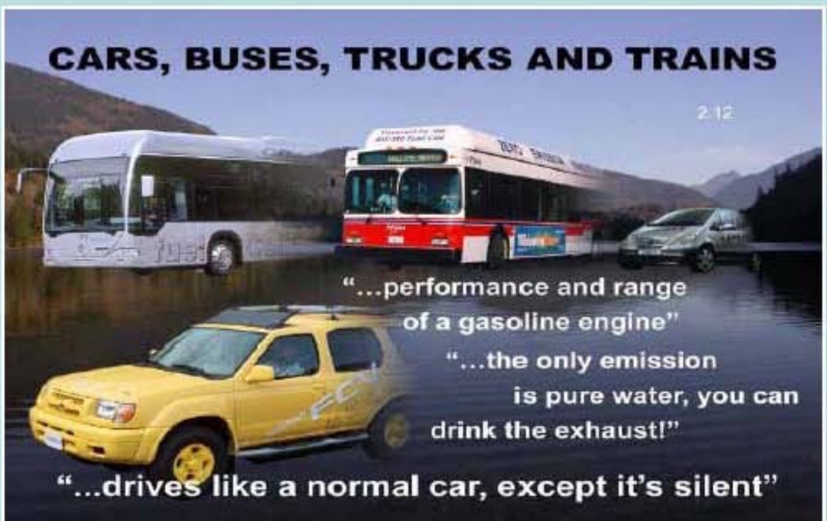


Mobile Application

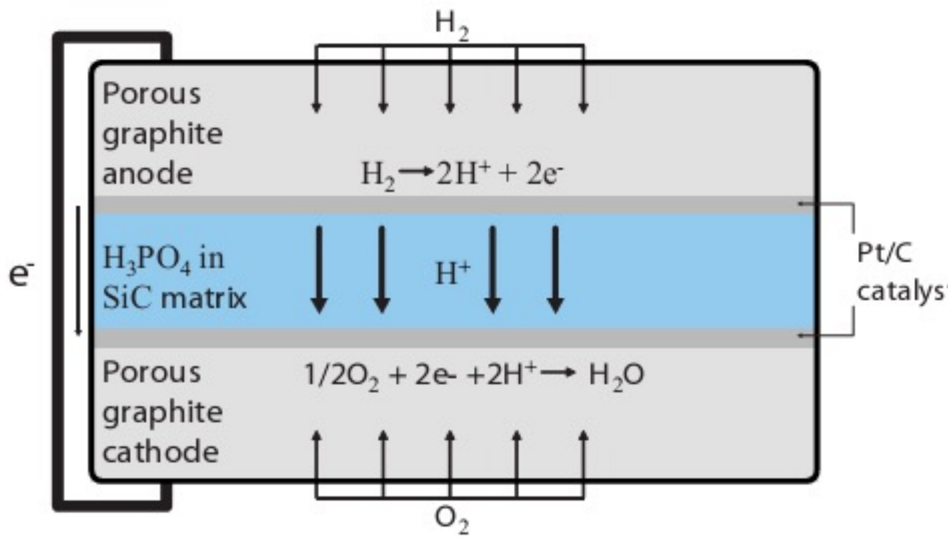


Stationary Application

Transportation Application



PAFC



$$Anode: \ H_2 \rightarrow 2H^+ + 2e^-$$
$$Cathode: \ \tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

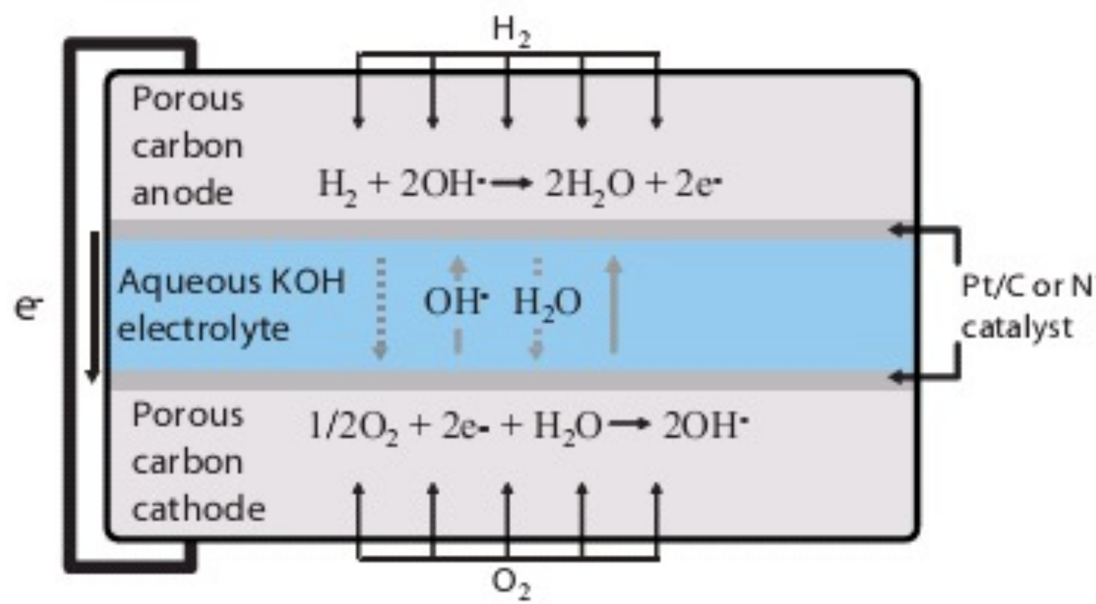
- Low T operation: 200
- Pt/C catalyst
- Solidified liquid electrolyte

PAFC

400 kW PAFC (PureCell) by Doosan Fuel Cell (formerly Clear Edge Power Inc)

- Electrolyte evaporation
- CO, S poisoning
- Moderate success in commercialization (cost barrier, maintenance)
- Emergency power generation

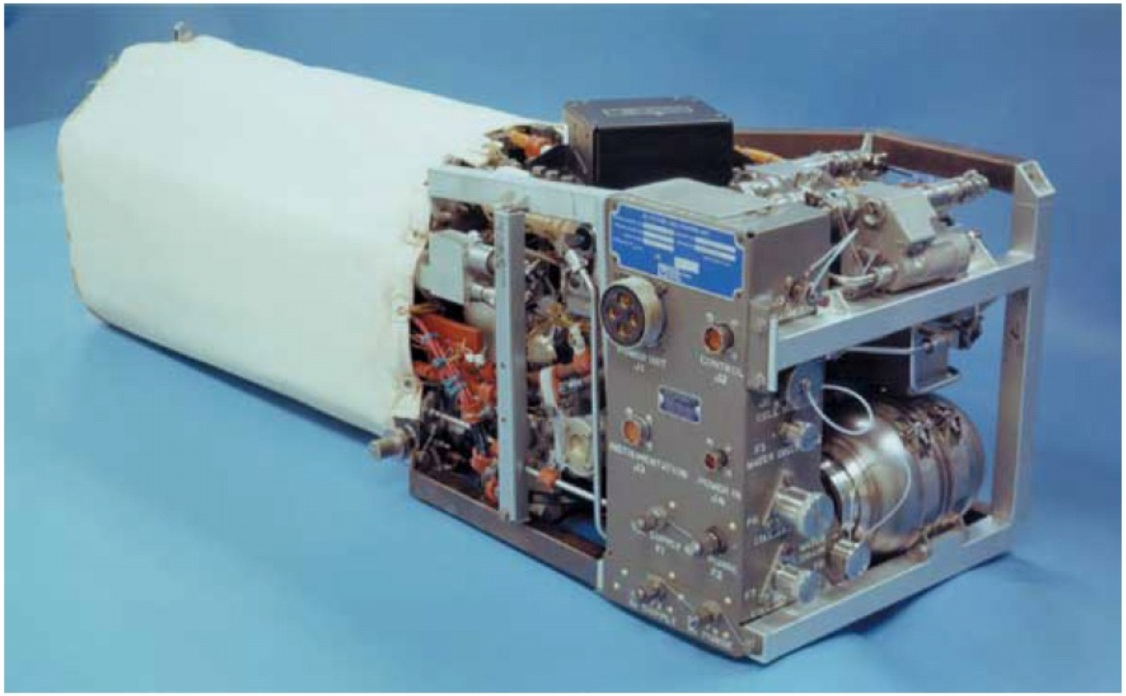
AFC



$$Anode: \; H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$
$$Cathode: \; \tfrac{1}{2}O_2 + 2e^- + H_2O \rightarrow 2OH^-$$

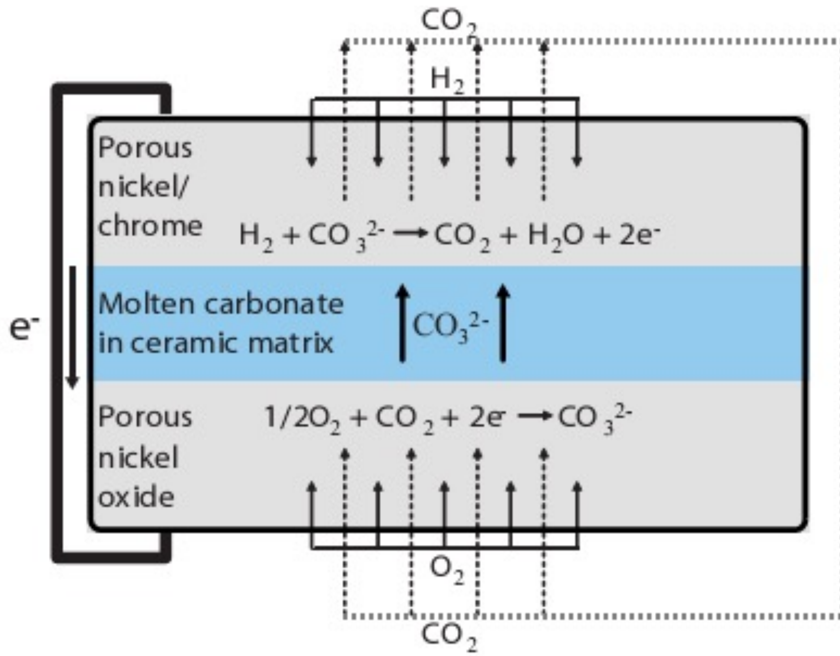
- Low T operation: 60~220
- Pt/C(Ni) catalyst
- Liquid electrolyte

AFC



- Carbon dioxide poisoning
- Pure hydrogen & air (oxygen) only
- Special applications such as space mission (Gemini project)

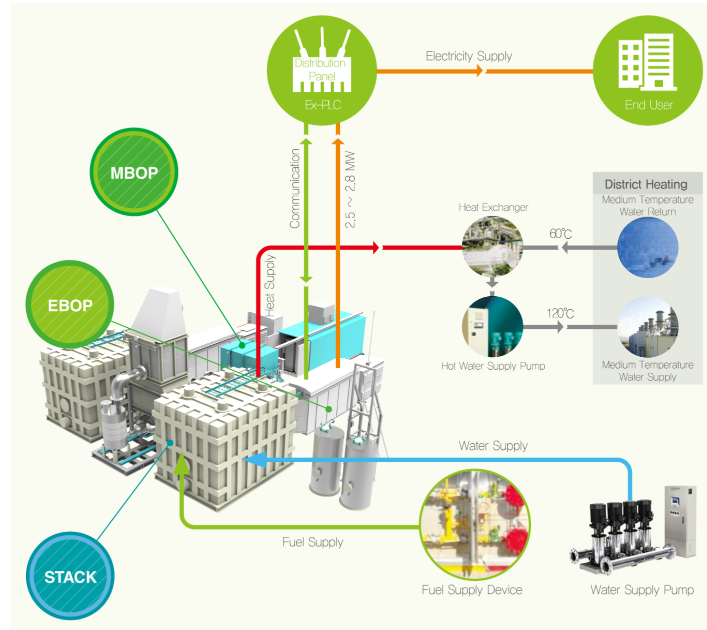
MCFC



$$Anode: \ H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^-$$
$$Cathode: \ \tfrac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$$

- High T operation: 650C
- Ni catalyst
- Immobilized Li2CO3 electrolyte in LiOAlO2
- CO2 recycling

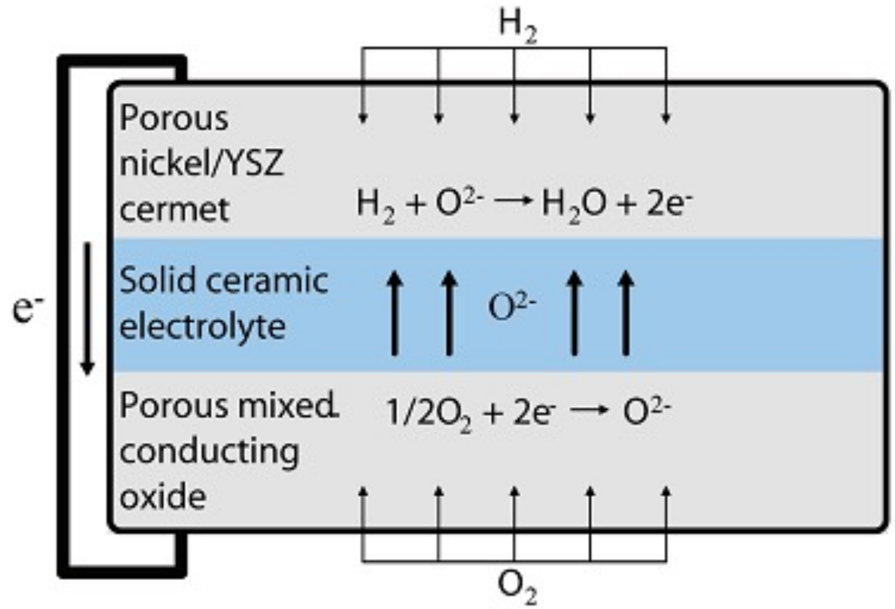
MCFC



2.5 MW MCFC power plant by POSCO Energy (in partnership with FuelCell Energy Inc.)

- Stationary power generator
- Demonstration upto MW
- Well demonstrated technology
- High efficiency (50%> for CHP system)
- No CO issues (CO as fuel)
- Difficult to increase power density

SOFC's



$$Anode: \ H_2 + O^{2-} \rightarrow H_2O + 2e^-$$
$$Cathode: \ \tfrac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$$

- High T operation: 600~1000C
- Ceramic electrolyte: YSZ, SDZ, SDC, GDC, LSGM…
- Anode: Ni/YSZ
- Cathode: LSM, LSC, LSF, LSCF

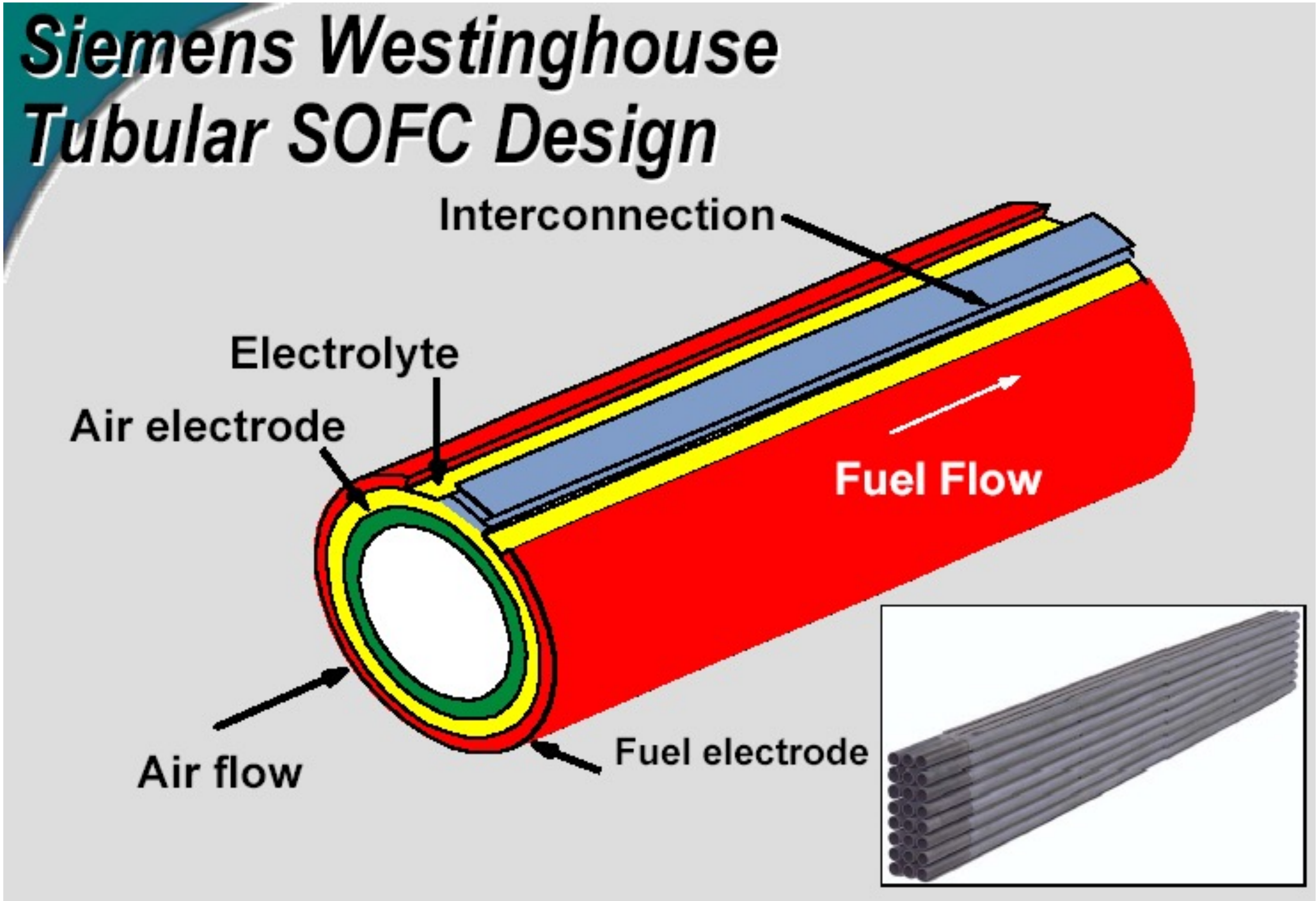
SOFC's

200kW Bloombox by Bloom Energy

1 kW Ceres Power SOFC

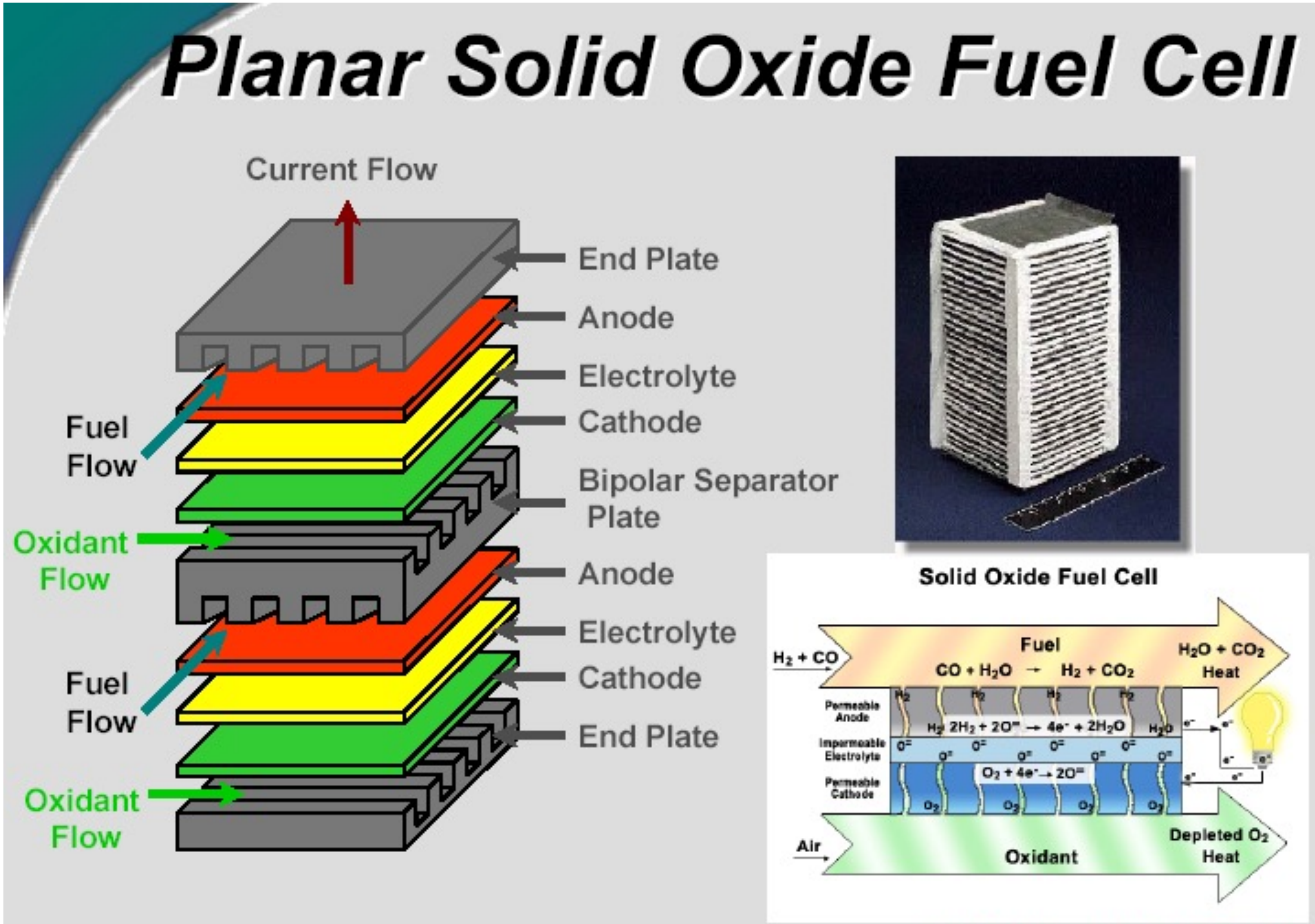
- Stationary power generator
- Demonstration upto MW
- Fuel flexibility
- High efficiency (50%> for CHP system)
- Relatively high power density
- Relatively expensive components/fabrication

SOFC's



Siemens Westinghouse
Tubular SOFC Design
Interconnection
Electrolyte
Air electrode
Fuel Flow
Air flow
Fuel electrode

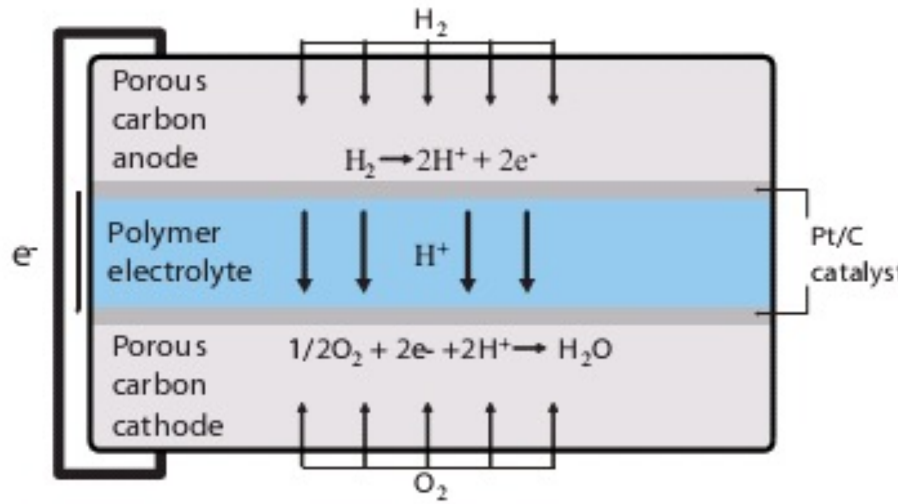
SOFC's


Planar Solid Oxide Fuel Cell
Current Flow
End Plate
Anode
Electrolyte
Cathode
Bipolar Separator Plate
Anode
Electrolyte
Cathode
End Plate
Fuel Flow
Oxidant Flow
Fuel Flow
Oxidant Flow
Solid Oxide Fuel Cell
Fuel
$H_2 + CO$
$CO + H_2O \rightarrow H_2 + CO_2$
$H_2O + CO_2$
Heat
Permeable Anode
Impermeable Electrolyte
Permeable Cathode
$2H_2 + 2O^= \rightarrow 4e^- + 2H_2O$
$O_2 + 4e^- \rightarrow 2O^=$
Air
Oxidant
Depleted O_2
Heat

Design Comparison

	Tubular Cells	Planar Cells
Specific Power (W/cm^2)	Low (0.2-0.3)	High (0.6-2.0)
Volumetric Power (W/cm^3)	Low	High
Manufacturing Cost($/kW)	High	Low
High Temperature Seals	Not necessary	Required

PEMFC's

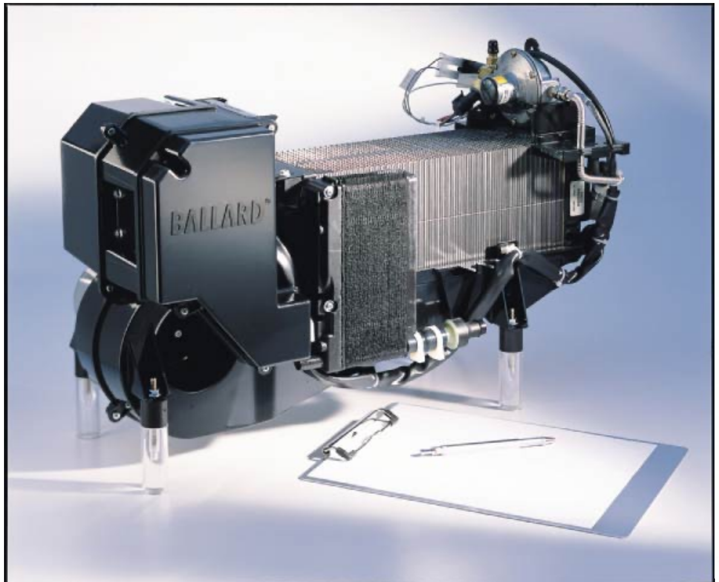


$$Anode:\ H_2 \rightarrow 2H^+ + 2e^-$$

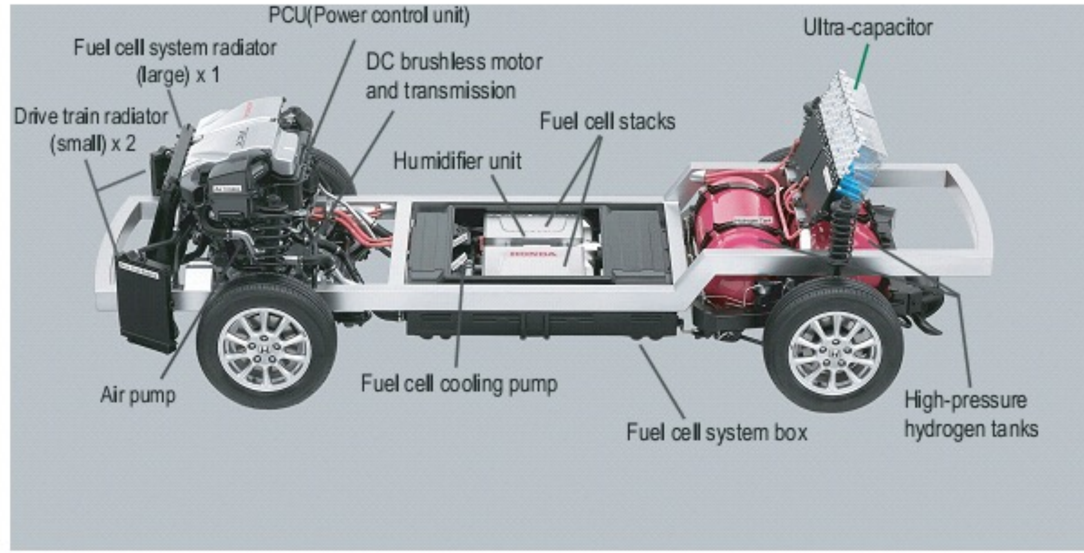
$$Cathode:\ \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

- Low T operation: 30~130C
- Pt/C catalyst
- Polymer membrane: Sulfonated PTFE(Nafion, Dow, Membrane-S, Gore..), PBI(Celanese), PEEK, Polymide…
- Carbon cloth (paper) electrode

PEMFC's



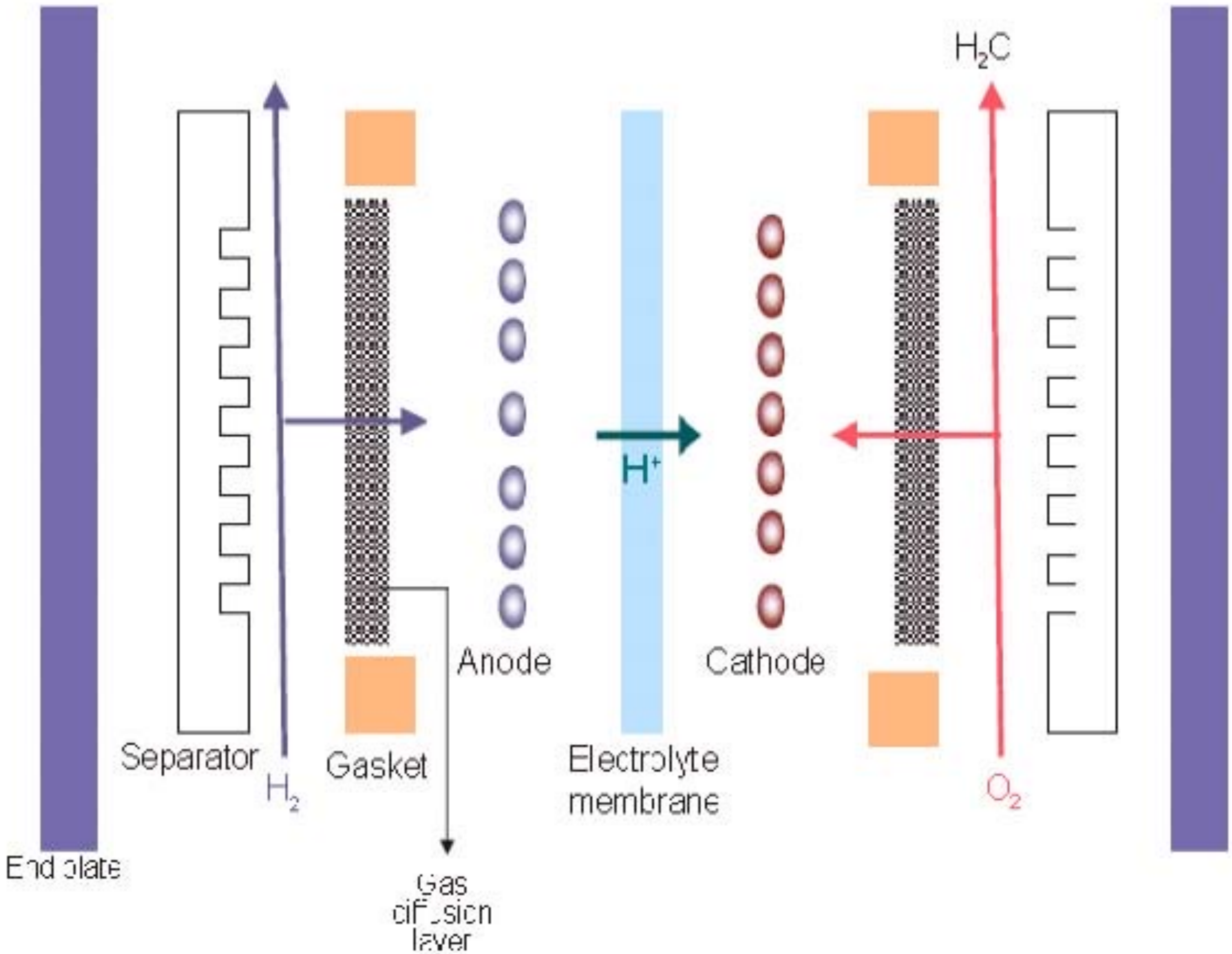
1.5kW portable PEMFC system by Ballard



Honda fuel cell car platform

- Highest power density
- Fast start-up
- Low operating temperature makes it suitable for portable market.
- Poor CO & S tolerence
- Water management issue

연료전지 구성: 단위 전지



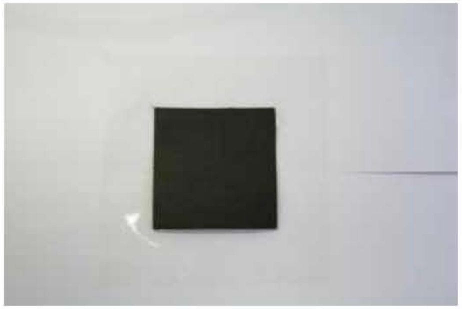
H_2O
H^+
Anode
Cathode
Separator
H_2
Gasket
Electrolyte
membrane
O_2
End plate
Gas
diffusion
layer

-Pressure Plate & Current Collector

- Pressure Plate
- Insulator
- Current Collector

-Gasket

- Spacer

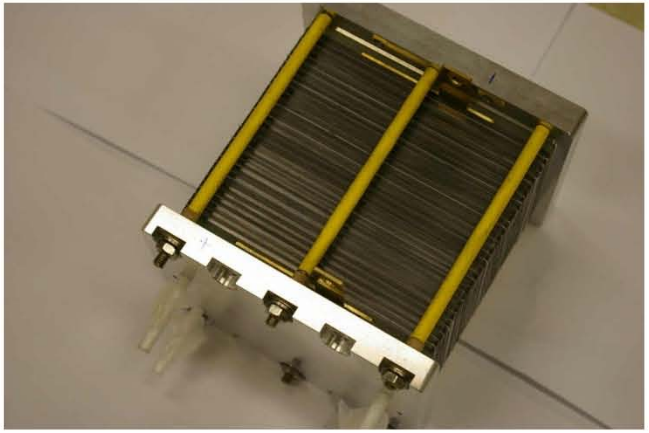


– MEA

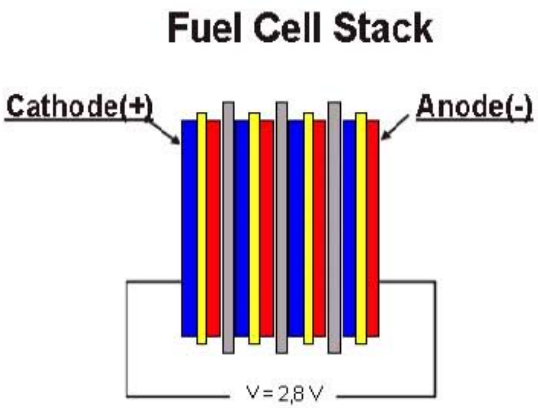
- Gas Diffusion Layers
- Catalyst Layers
- Membrane

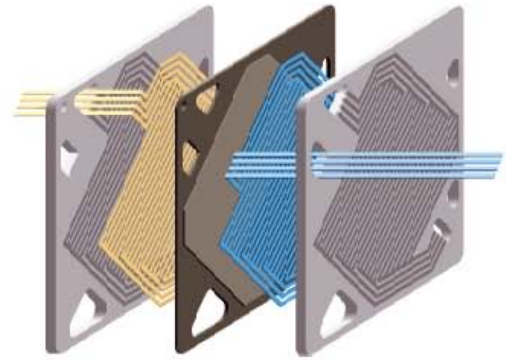
– Separator

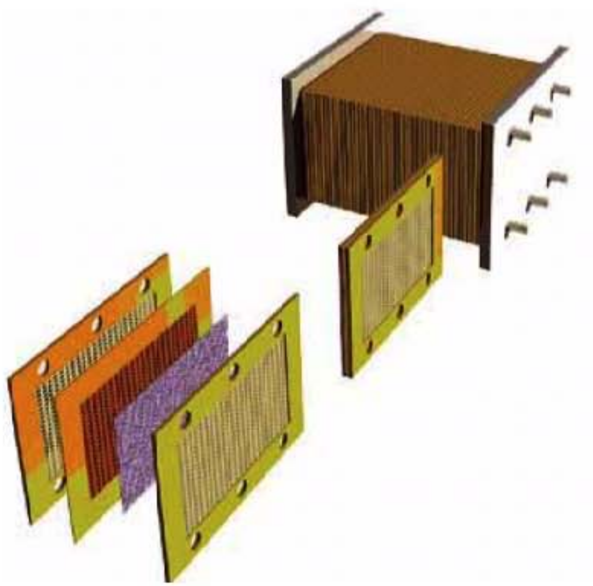
- Carbon Plate or etc.

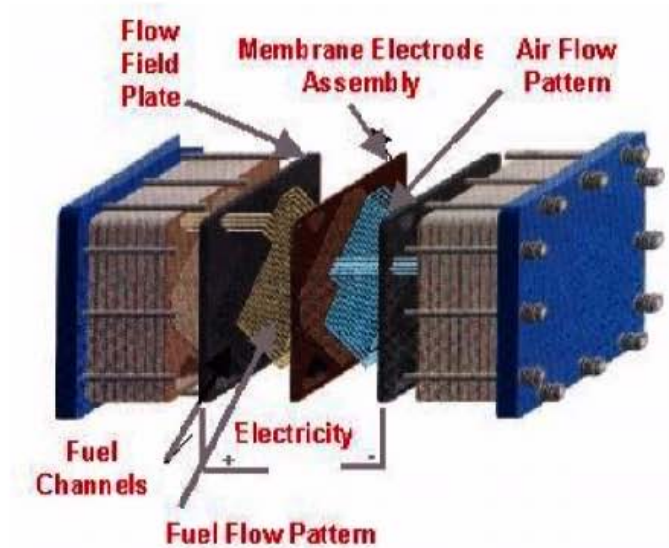


PEMFC Stack

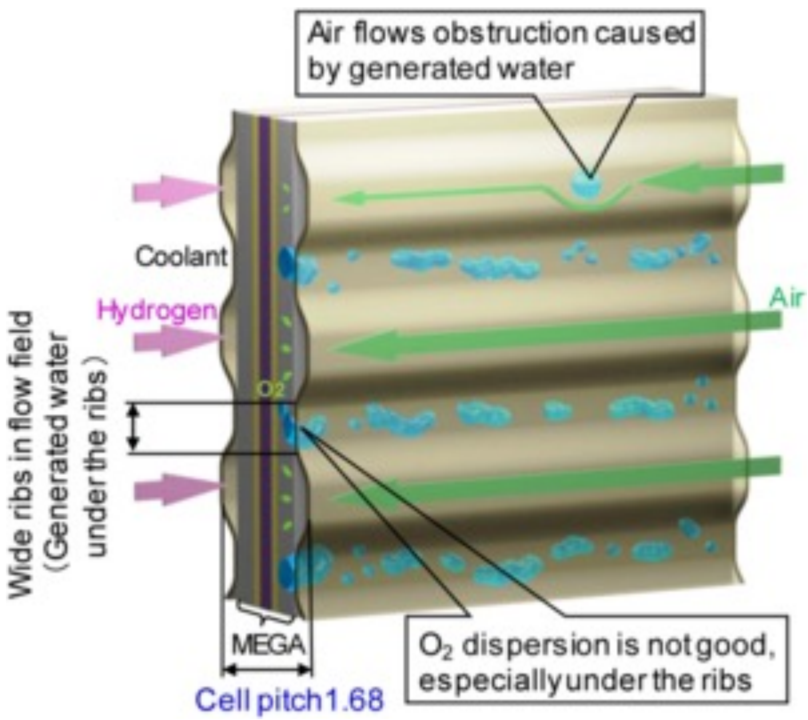

Fuel Cell Stack
Cathode(+)
Anode(-)
V=2,8 V

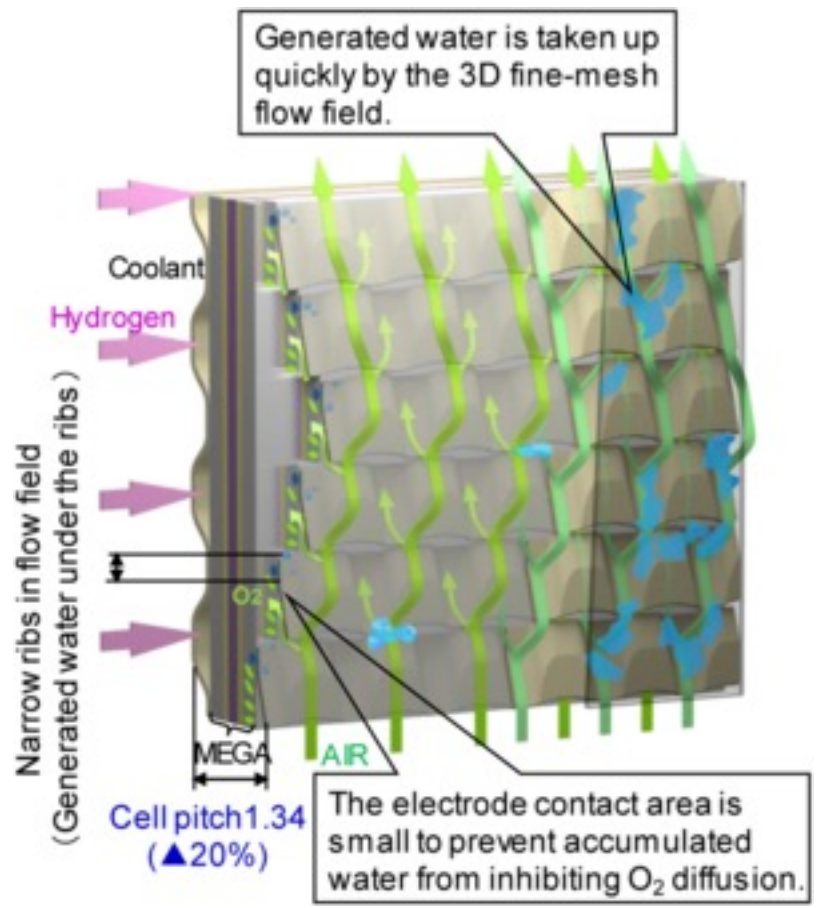




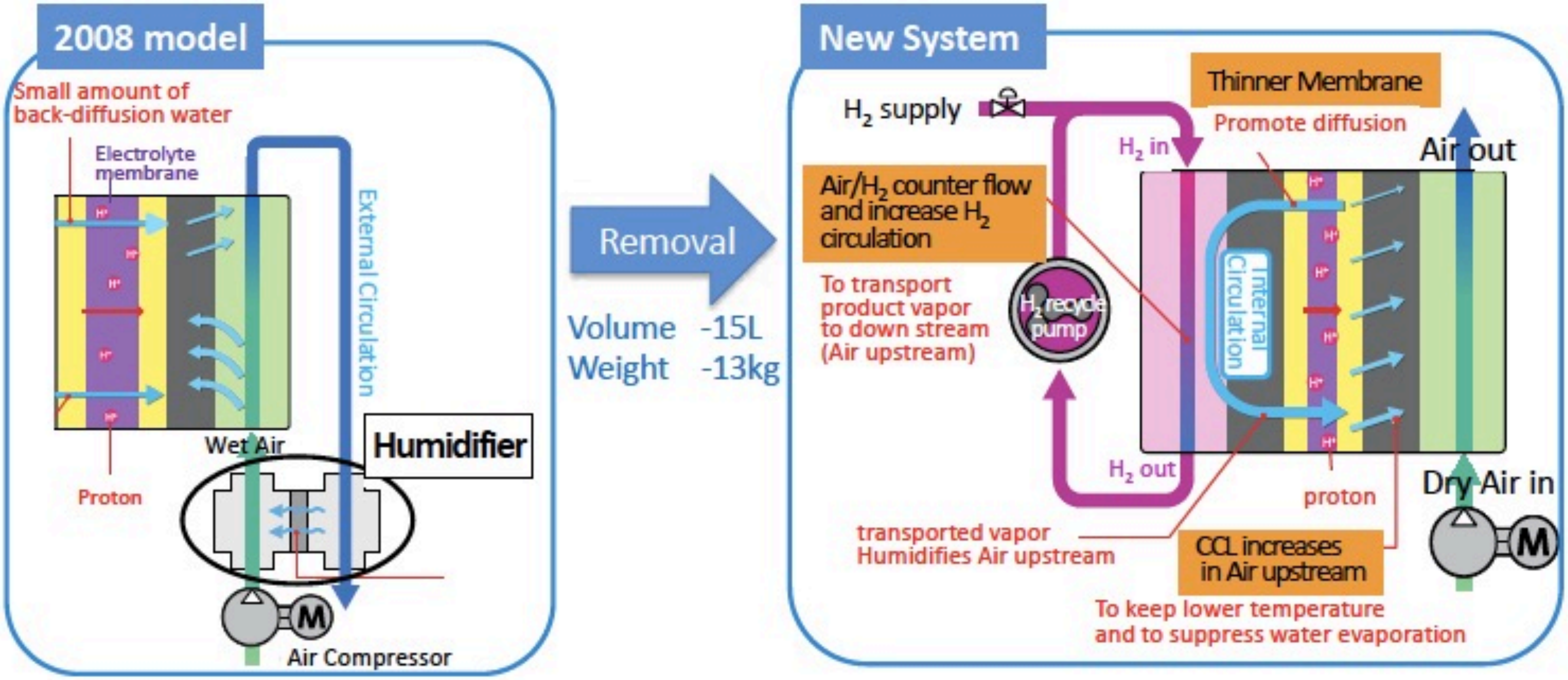

Flow Field Plate
Membrane Electrode Assembly
Air Flow Pattern
Electricity
+
-
Fuel Channels
Fuel Flow Pattern

Toyota Metal Mesh Flow Field





Toyota Metal Mesh Flow Field

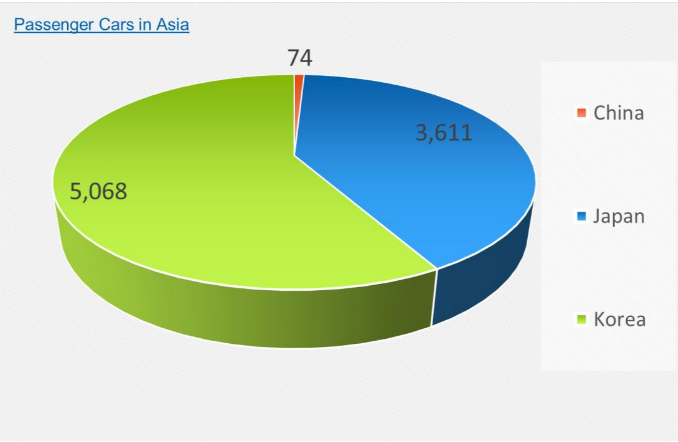


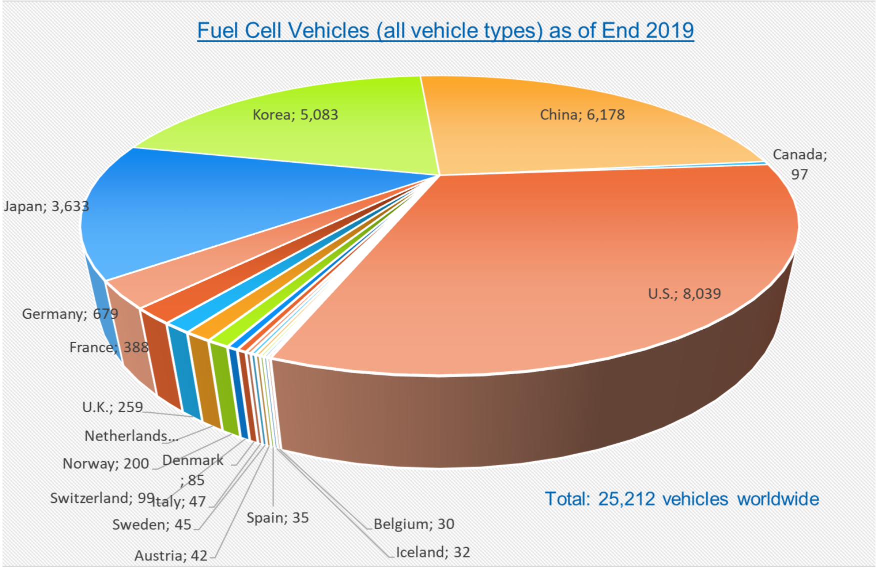
- 박막전해질로 역확산을 통한 물공급
- Counter flow에 의한 물 교환 (수소과급율 증가)
- 양극층 두께 증가

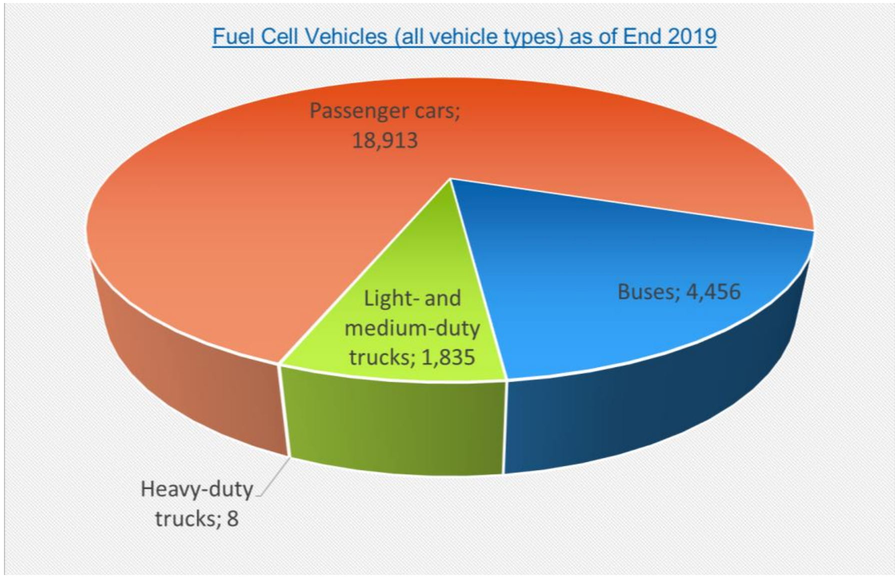
Where Are We Now

Fuel Cell Vehicle stock exceeded 25,212 as of end of 2019 vs. 12,900 in 2018)

- 95% increase in 2019 (80% in 2018)
- Asia(59%), US(32%), Eu(9%)
- Passenger cars(75%), Buses(17.7%), MDV(7.3%)
- Passenger cars dominate South Korean market







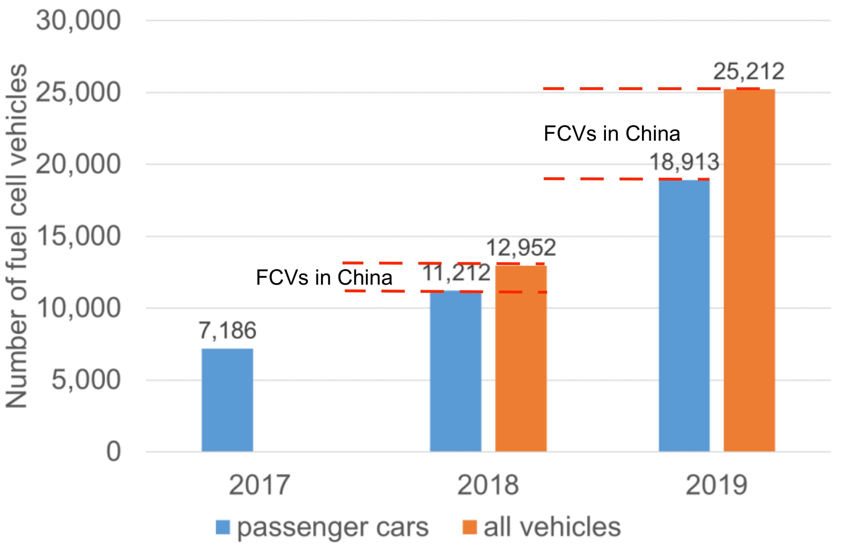
'20 IEA

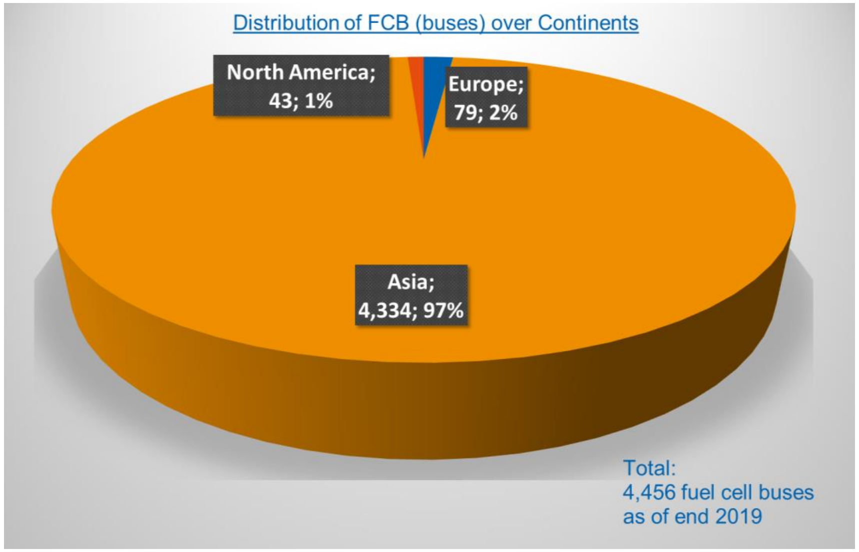
Where Are We Now

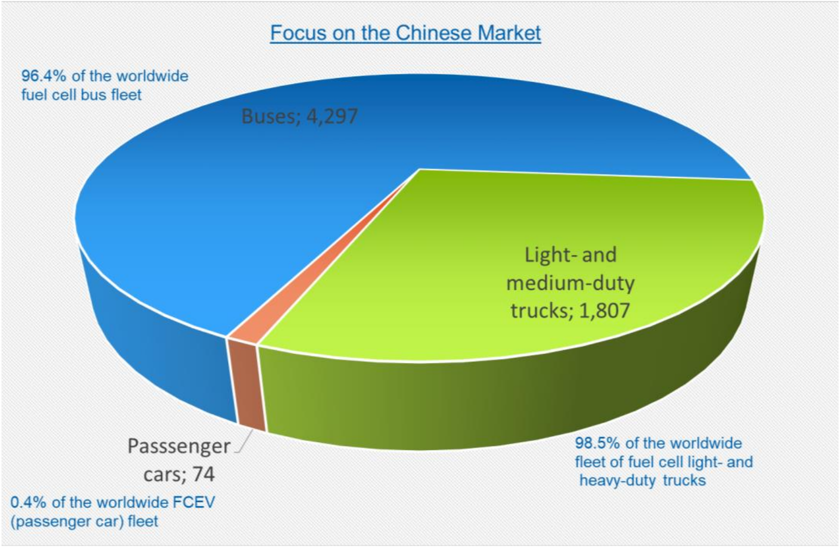
Most of the buses and LDV operate in Asia

– Buses and LDV dominates Chinese market

– Rapid increase of number of buses in China







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Where Are We Now

Typical FCV specifications

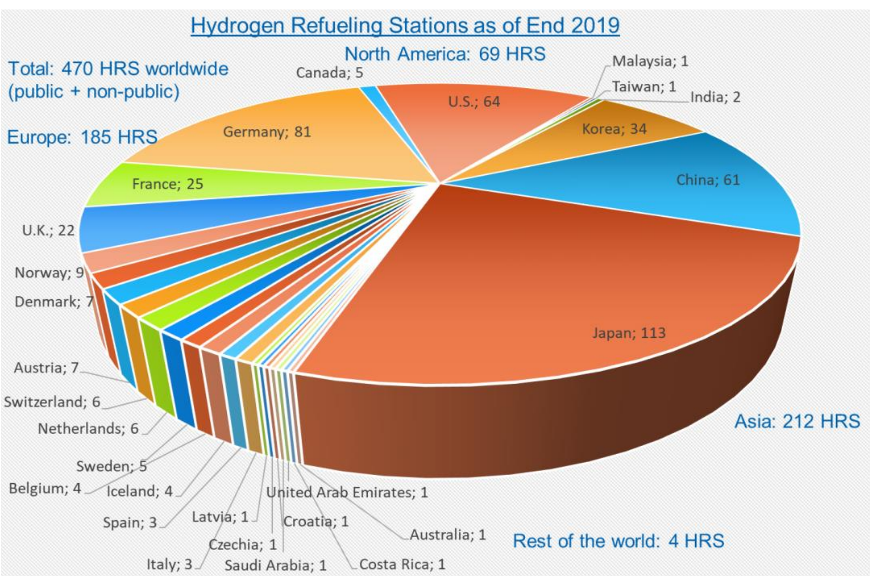
- Toyota MIRAI vs Hyundai NEXO vs Honda CLARITY vs Mercedes Benz GLC F-CELL

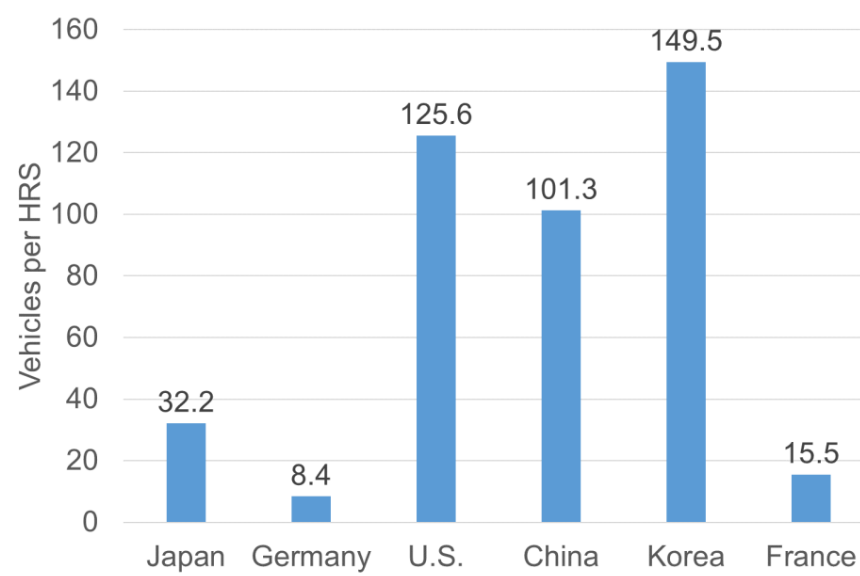
Fuel con-sumption / Driving range	0.76 kg/100 km com-bined 0.80 kg/100 km extra urban 0.69 kg/100 km urban	666 km WLTP 756 km NEDC	650 km NEDC	1 kg / 100 km hydrogen 478 km NEDC hybrid mode (50 km battery only)
Tank system	700 bar nominal work-ing pressure 5.7 wt.% tank storage density approx. 5 kg fuel tank capacity Two tanks: 60 l front tank, 62.4 l rear tank	6.33 kg hydrogen 156.6 l overall capacity, 3 tanks, each 52.2 l	700 bar 5.46 kg hydrogen 141 l overall capacity, 2 tanks, 24 l and 117 l	700 bar 4.4 kg hydrogen
Weight	1,850 kg curb weight 2,180 kg gross vehicle weight	2,340 kg gross vehicle weight 1,814 – 1,873 kg curb weight	1,875 kg curb weight	
Exterior	4,890 mm overall length 1,815 mm overall width 1,535 mm overall height 0.29 drag coefficient	4,670 mm overall length 1,860 mm overall width 1,630 mm overall height 2,790 mm wheelbase 0.329 drag coefficient	4,915 mm overall length 1,875 mm overall width 1,480 mm overall height 2,750 mm wheelbase	4,671 mm overall length 2,096 mm overall width 1,653 mm overall height 2,873 mm wheelbase

Where Are We Now

470 HRS in the world as of end 2019 (23% increase vs 15% in 2018)

- Asia(212), Europe()185, North America(69)
- Japan(113), Germany(81), US(64), China(61 with mobile HRS), South Korea(34), France(25) (South Korea is worst in FCV/station)
- 350 bar (for buses) or 700 bar (for passenger cars) for 10 year operation





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Everybody's Ambitious

Announced Targets, Visions and Projections

today
- 25,212 Vehicles, 470 HRS (end of 2019)

2020
- China: 5,000 FCV, 100 HRS
- Germany: 100 HRS
- Hydrogen Mobility Europe project: 1,400 FCEV, >45 HRS
- Japan: 40,000 FCEV, 100 FCB, 160 HRS
- Spain: 500 FCEV, 20 HRS
- Switzerland: 50 heavy duty trucks

2022
- Korea: 81,000 FCEV, 310 HRS
- California: 26,900 FCEV

2023
- Europe: 291 buses (JIVE projects)
- France: 5,000 FCEV, 100 HRS, 200 heavy duty vehicles
- Germany: minimum 41 passenger trains

2025
- California: 48,000 FCEV, 200 HRS
- China: 50,000 FCV, 300 HRS
- Europe: minimum 747 HRS
- Germany: 400 HRS
- Japan: 200,000 FCEV, 320 HRS
- Switzerland: 1,600 heavy duty trucks

2028
- France: 20,000 – 50,000 FCEV, 400 - 1000 HRS, 800 – 2,000 heavy duty vehicles

2030
- CAFP vision / California: 1,000,000 FCEV, 1,000 HRS
- China: 1,000,000 FCV, 1,000 HRS
- Hydrogen Council vision: Globally 10-15 million cars and 500,000 trucks
- Japan: 800,000 FCEV, 1,200 FCB, 900 HRS
- Hydrogen Europe vision / Europe: 5 million cars, 15,000 buses, 95,000 trucks, 4,500 HRS

2040
- Korea: 6,200,000 FCEV (5,900,000 passenger cars, 120,000 taxis, 60,000 buses, 120,000 trucks), 1200 HRS

2050
- Hydrogen Council vision: 400 million cars, 15-20 million trucks, 5 million buses
- Europe / FCH 2 JU vision: 45 million cars, 6.5 million LCVs, 1,7 million trucks, 250,000 buses

FCEV: Fuel cell electric vehicle (passenger cars)
FCV: Fuel cell vehicle (all categories)
FCB: Fuel cell bus
LCV: Light commercial vehicles
HRS: Hydrogen refueling station

Hydrogen ≈ Policy

'20 IEA

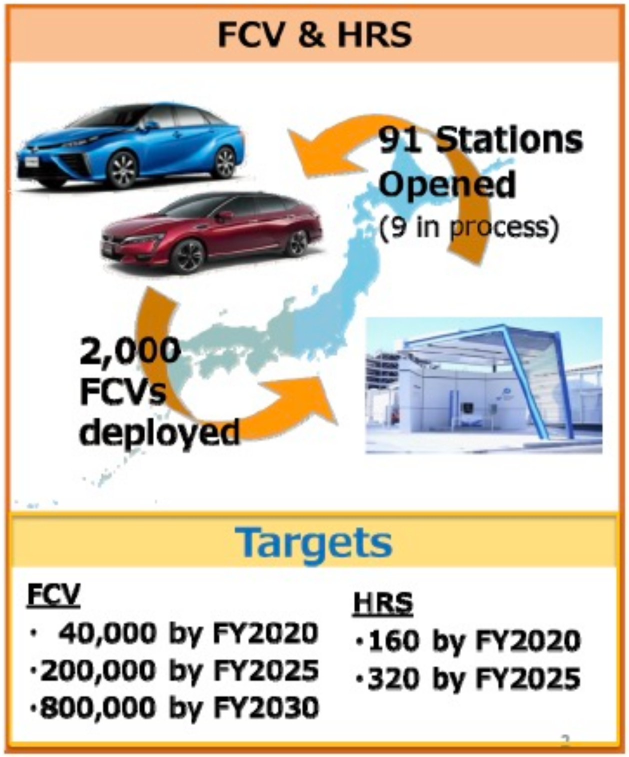
China Deployment Examples

BALLARD®

China MIIT Certified Vehicles Powered by Ballard

Japanese Deployment Plan

Japan has a reasonable plan of infrastructure-first approach.



	2016 (Result)	2030(Target)
Gasoline Vehicle	65.15%	30～50%
Next Generation Vehicle	**34.85%**	50～70%
Hybrid Vehicle	30.76%	30～40%
Electric Vehicle Plug-in Hybrid Vehicle	0.37% 0.22%	20～30%
Fuel Cell Vehicle	0.02%	～3%
Clean Diesel Vehicle	3.46%	5～10%

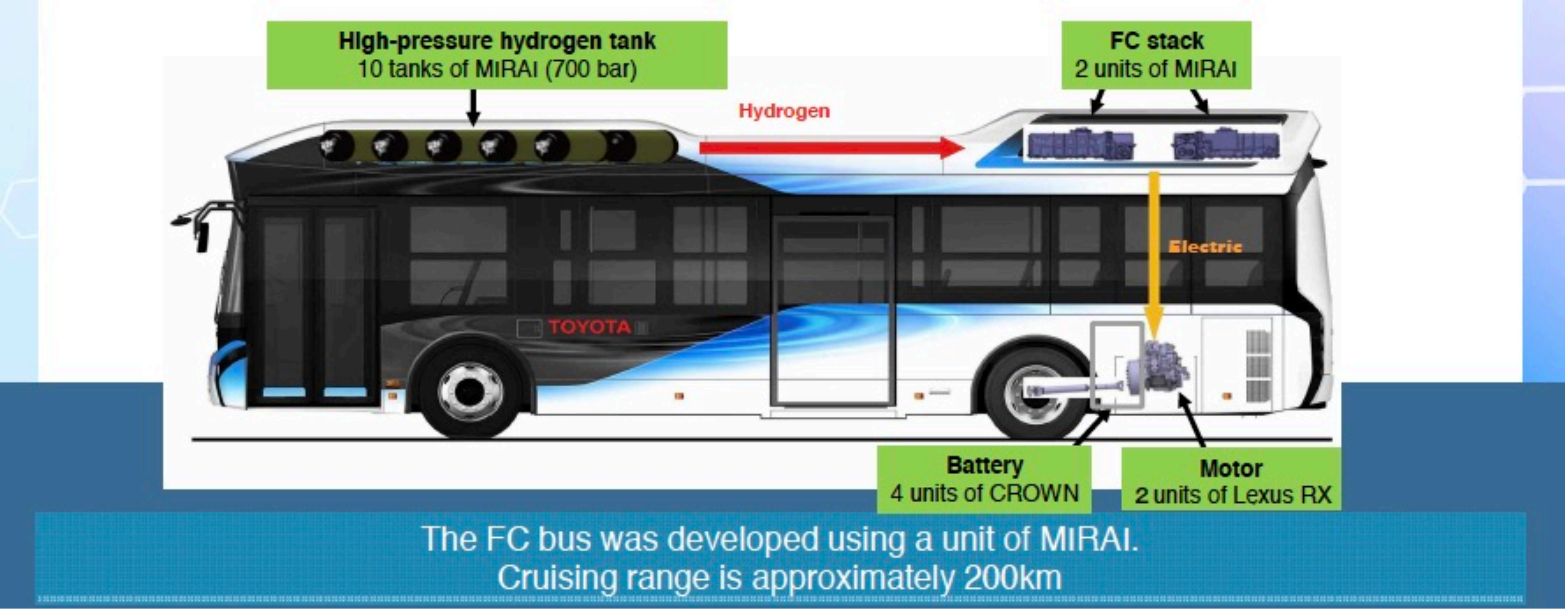
Two 700 atm-H2 FC buses in Tokyo, 2017 (100 by 2020)

38 FC Forklifts in 2017 '17 NEDO

Toyota Bus Example

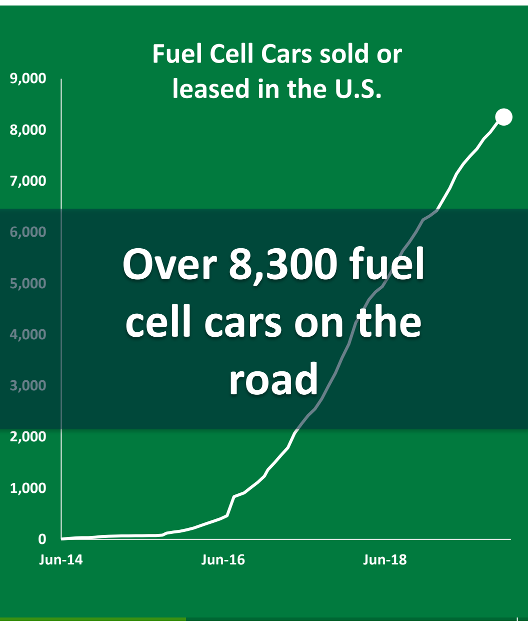
Two Toyoda FC bus under operation since 2017 in Tokyo.

Technology and supply chain sharing is the key advantage.



‘18 Toyota

US Deployment

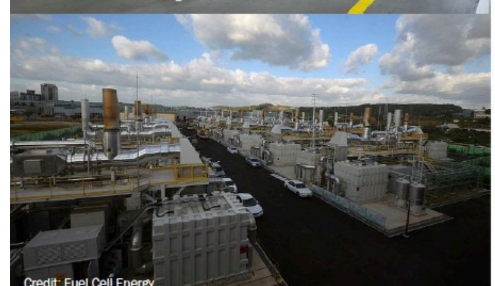


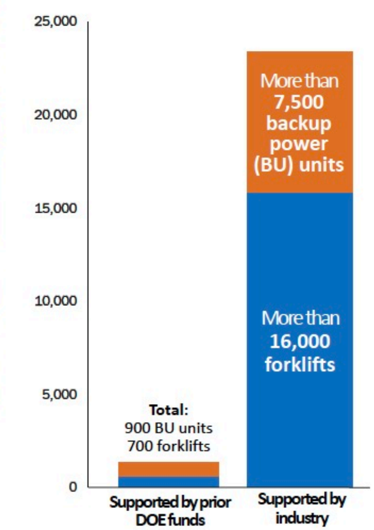
UPS unveils first extended range fuel cell electric delivery vehicle

The Nikola Badger, a fuel cell truck with a 966 km range

ProGen-powered Fedex operates more than 10,000 miles on-road

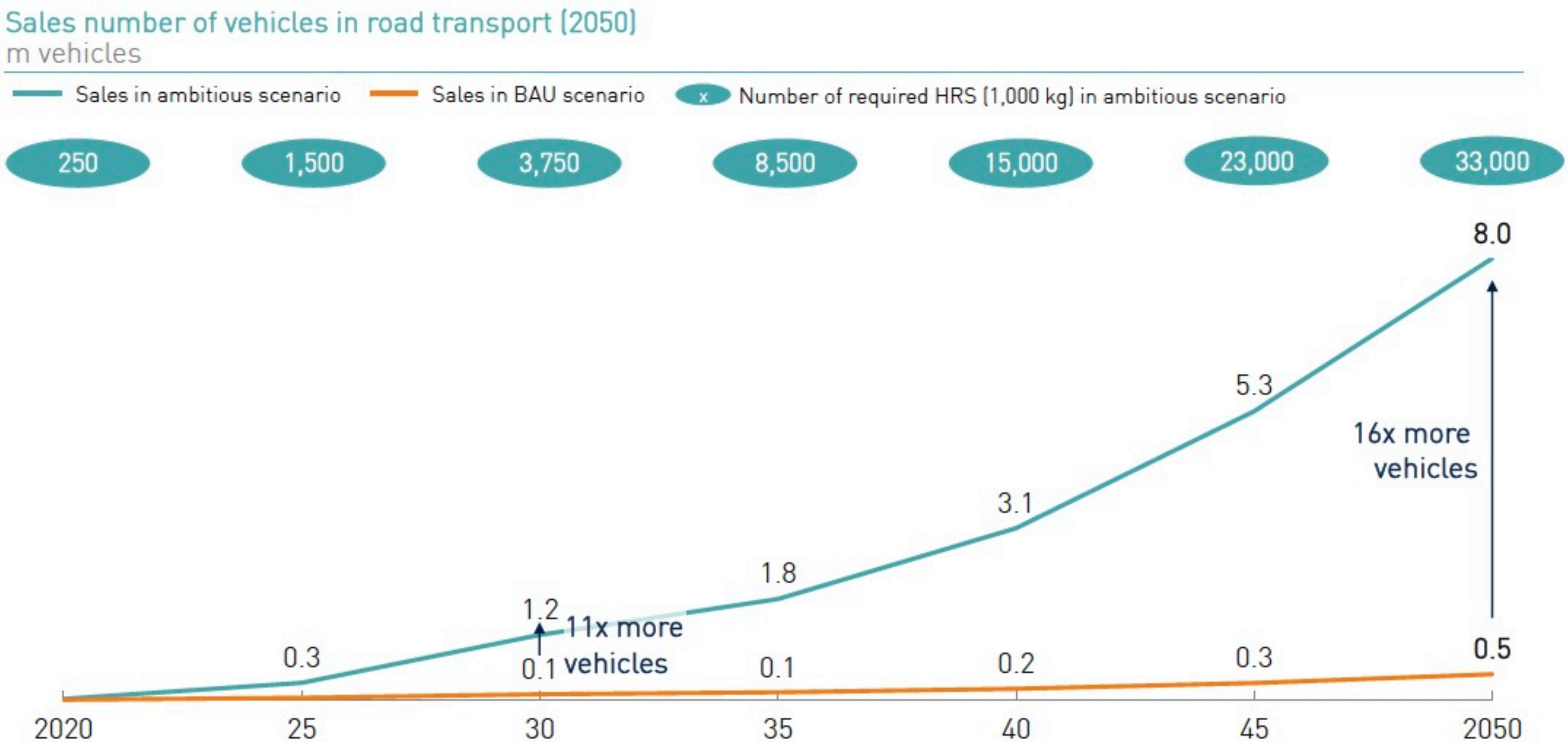
1st Hydrogen ferry under construction in U.S.





'20 DOE

EU Deployment Plan



Alstom iLint FCH train

Concept for a 27t rigid FC truck by VDL

'19 FCH

FC global deployment expectation

Low, medium and high volume scenarios

Application	Comments	Units	2024			2030		
			L	M	H	L	M	H
FCEV	Passenger cars and light commercial vehicles (LCV)	millions	0.33	0.90	1.8	1.6	5.5	10
FC Buses		thousands	16	24	35	61	120	190
HGV		thousands	3.0	3.8	10	20	37	80
FC Forklifts		thousands	48	67	93	85	140	230
Trains and light rail		units	87	190	490	420	1,200	2,400
Maritime and inland boats		units	16	38	110	75	240	520
HRS		thousands	0.76	1.9	3.9	3.5	11	20
Micro CHP	1-5 kW_e	millions	0.75	1.4	1.7	2.3	4.8	7.0
Commercial CHP	5-100 kW_e	thousands	4.7	7.3	26	31	72	200
Large CHP	> 100 kW_e	thousands	7.3	14	27	17	45	97
Back-up power and gensets		thousands	42	60	75	85	150	230
Electrolysers	Not applicable as stack sizes vary significantly							

’19 E4tech, FCH

EU Deployment Plan

The path towards a European hydrogen eco-system step by step :

Today - 2024 → **2025 - 2030** → **2030 -**

From now to 2024, we will support the **installation of at least 6GW of renewable hydrogen electrolysers in the EU**, and the production of **up to 1 million tonnes** of renewable hydrogen.

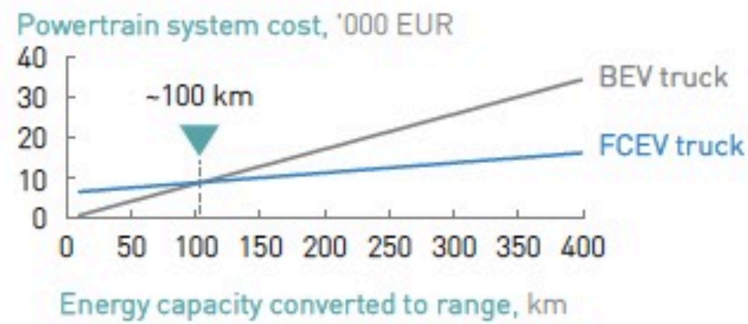
From 2025 to 2030, hydrogen needs to **become an intrinsic part of our integrated energy system**, with at least 40GW of renewable hydrogen electrolysers and the production of **up to 10 million tonnes** of renewable hydrogen in the EU.

From 2030 onwards, **renewable hydrogen will be deployed at a large scale** across all hard-to-decarbonise sectors.

Why So Ambitious?

Example of a fuel cell heavy truck

1 FCEV powertrains for trucks are cost competitive with BEV from 100 km range



2 Hydrogen refueling is 15 times faster than fast charging

After 10 minutes refueling/recharging time

90% FCEV truck vs. 10% BEV truck of ~1000 km range

3 Recharging infrastructure ...

requires 10-15x less space and creates flexible instead of peak load

‘19 FCH Hydrogen Roadmap Europe

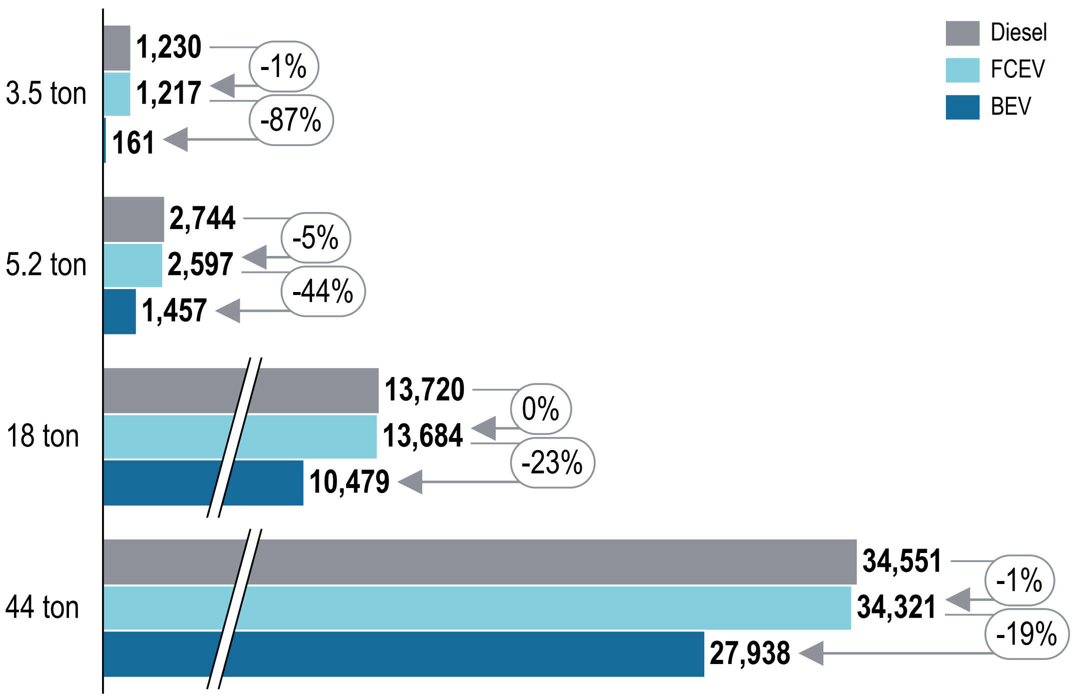
Why So Ambitious?

A viable option for 0–emission heavy–duty/long–haul trucking from a payload perspective

Trade-off between alternative powertrains and payload acc. to US DOE

Payload benchmark of alternative powertrains

Available payload for different truck categories and powertrains [kg]



Trade-off considerations

> Assumption: payload considered at **800 km driving range**

> Fuel cell trucks only compromise up to 5% of the payload of the incumbent diesel technology

> BEV trucks offer between 19 and 87% less available cargo payload

> Please note:

- 800 km driving range is at the upper limit of feasible mileage per day
- Currently available batteries are economically not fit to match a 800 km driving range. Size and weight of necessary units are show stoppers

Key take-away

FCEV trucks are an attractive option to replace regional and long distance diesel trucks – from an payload point of view

Why So Ambitious?

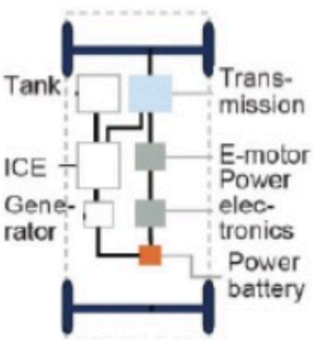
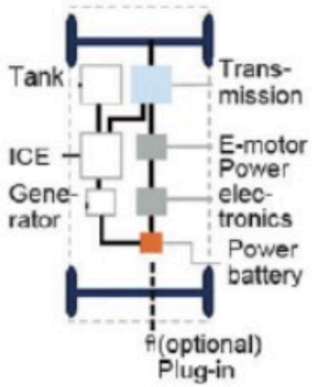
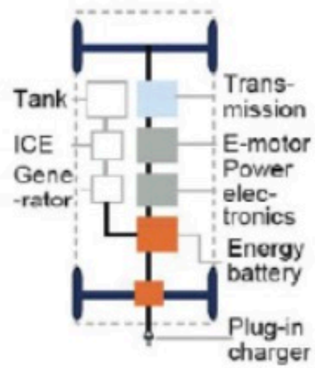
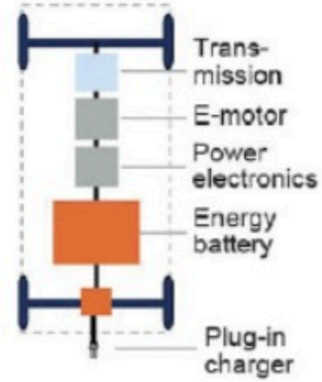
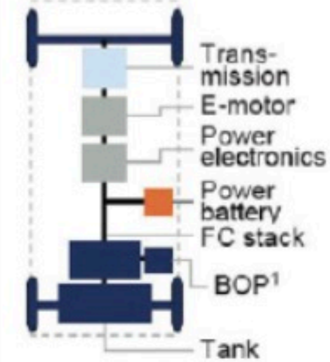
FCEVs : Lower cost for large size classes and longer driving range

Year 2040: FCEV minus BEV-X Total Cost of Ownership
Green shows where FCEVs are more cost effective

	50 mi.	100 mi.	150 mi.	200 mi.	250 mi.	300 mi.	350 mi.
Two-seaters	$0.05	$0.01	-$0.03	-$0.07	-$0.11	-$0.15	-$0.19
Minicompacts	$0.05	$0.02	-$0.01	-$0.04	-$0.07	-$0.10	-$0.13
Subcompacts	$0.05	$0.02	-$0.01	-$0.04	-$0.07	-$0.11	-$0.14
Compacts	$0.04	$0.01	-$0.02	-$0.05	-$0.09	-$0.12	-$0.15
Midsize Cars	$0.05	$0.01	-$0.03	-$0.06	-$0.10	-$0.13	-$0.17
Large Cars	$0.04	$0.01	-$0.02	-$0.06	-$0.09	-$0.12	-$0.16
Small Station Wagons	$0.05	$0.01	-$0.03	-$0.07	-$0.11	-$0.15	-$0.19
Pass Van	$0.03	-$0.01	-$0.06	-$0.11	-$0.15	-$0.20	-$0.24
SUV	$0.03	-$0.02	-$0.08	-$0.14	-$0.19	-$0.25	-$0.30
Std Pickup	$0.14	$0.11	$0.07	$0.04	$0.01	-$0.03	-$0.06
Small Pickup	$0.06	$0.02	-$0.02	-$0.07	-$0.11	-$0.15	-$0.19

’18 DOE

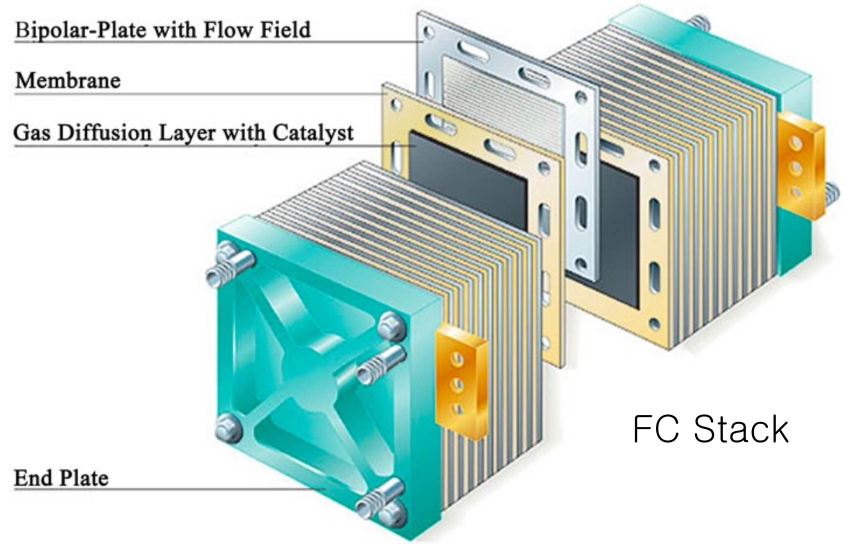
Electric Vehicles

Hybrid Electric Vehicle	Plug-in Hybrid Electric Vehicle	extended-Range Electric Vehicle	Battery Electric Vehicle	Fuel Cell Electric Vehicle
				
IC engine and battery power. No external charging	Same as hybrid. But external charging possible	Small engine charges the battery. Battery powers motor (e.g. GM Volt)	No IC engine. Battery and motor only	Fuel cell and battery power. No external charging

FCEC shares >60% system with BEV

But, FCEV $\neq$ BEV FCEV = ???

Fuel Cell Vehicle System



Fuel Cell Electric Vehicle

FC Stack

Stacked unit cells composed of membrane, catalyst, GDL and bipolar plate

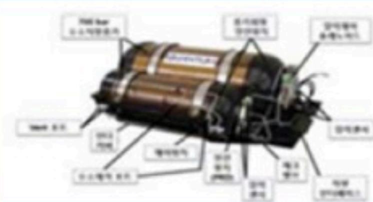
M-BOP

Hydrogen and air supply, thermal management and water management

E-BOP

Inverter, power electronics and motor (sharable with BEV)

Hydrogen Tank



Compressed hydrogen storage and safety controller

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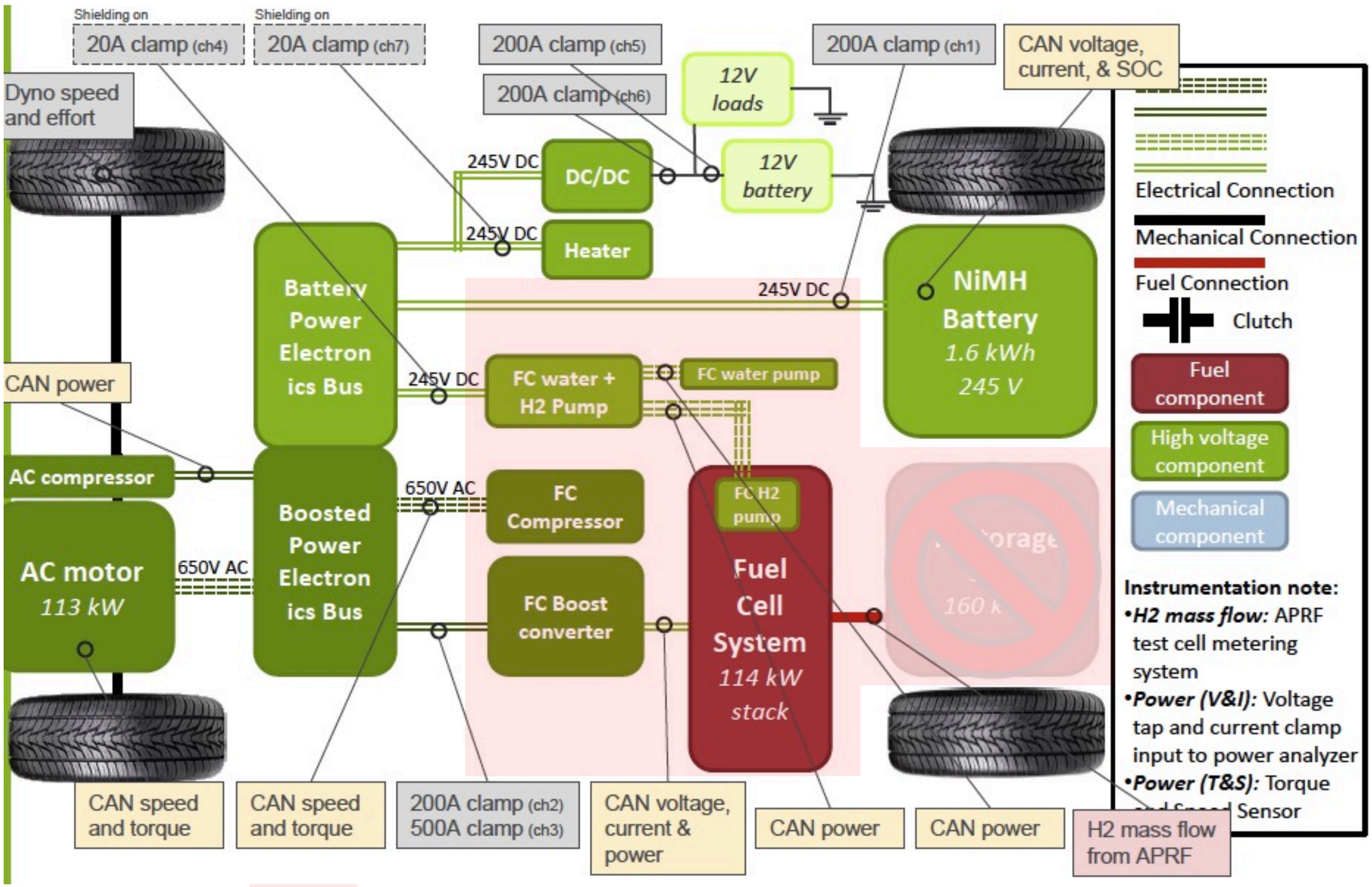
Toyota MIRAI Architecture

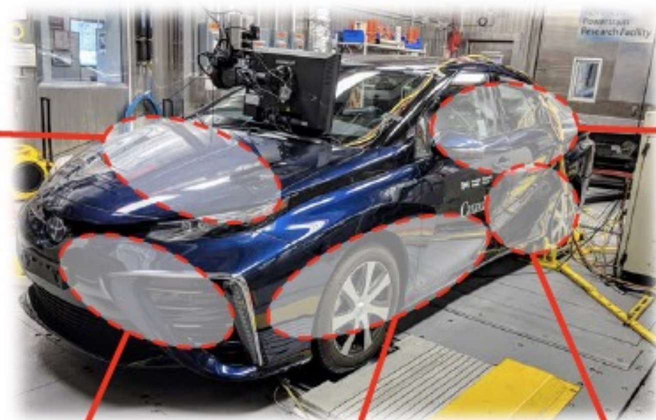
Over 60% of FCEV system is shareable with BEV.

This does NOT mean the rest are simple.



: Fuel cell system, M-BOP and hydrogen tank

Toyota MIRAI component layout



Power Electronics

The high voltage power distribution system is under the hood along with the inverters for the motors.

Battery Pack

The air cooled NiMH battery pack is packaged in the trunk similar to most Toyota Hybrid vehicles.

Electric motors

The electric drive motor and the air compressor are packaged in-line between the front wheels.

Fuel Cell System

The fuel cell stack along with the boost converter is under the center of the vehicle.

On-board hydrogen Storage

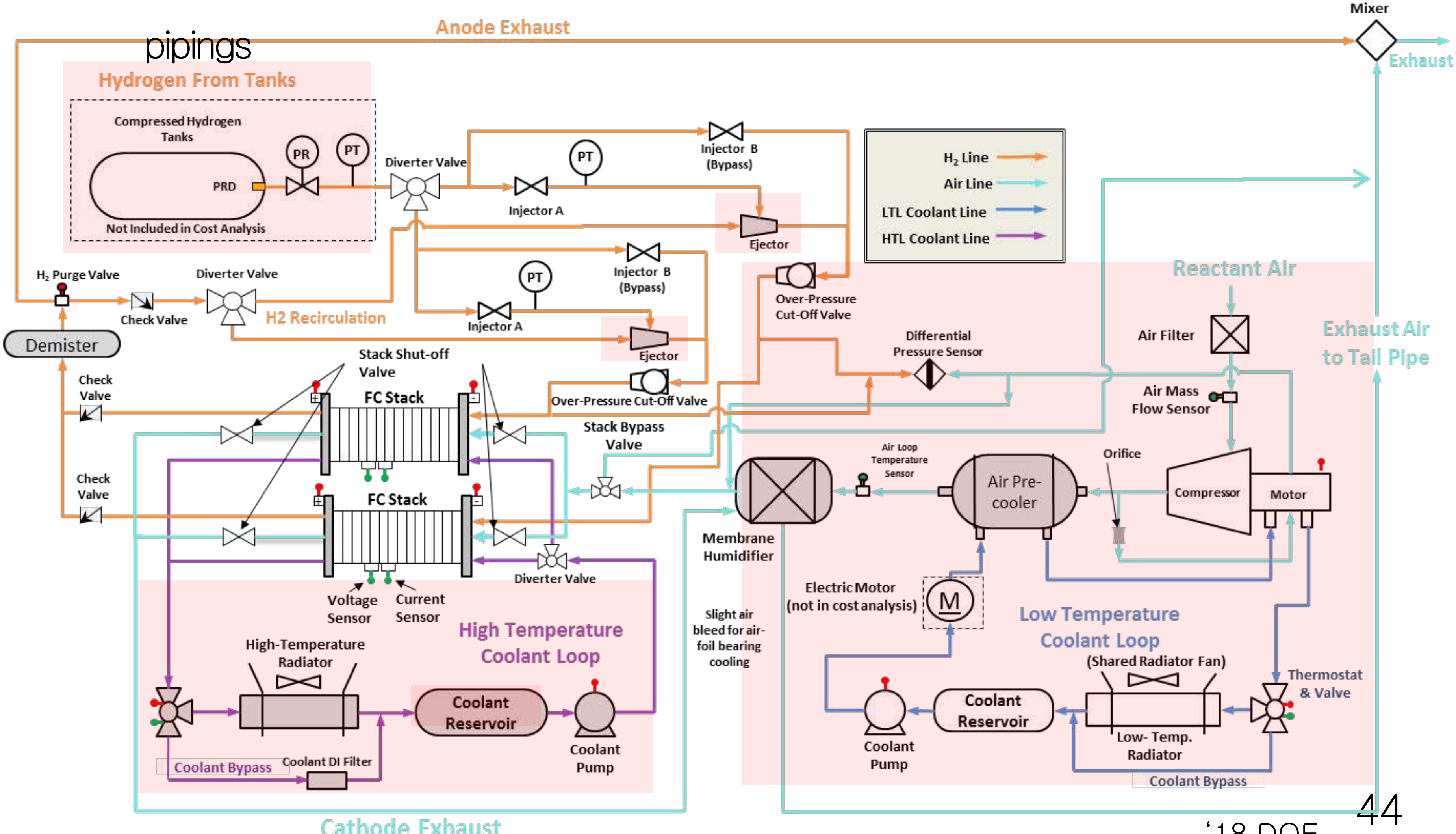
The two hydrogen tanks are under the trunk and the rear passenger seats. These tanks are disabled for the testing.

‘18 ANL Report

Heavy Duty Vehicle FC System

Fuel cell vehicles use new and conventional components.

- Hydrogen tank, humidifier, radiators, pumps, compressor, injectors, ejectors, valves, pipings



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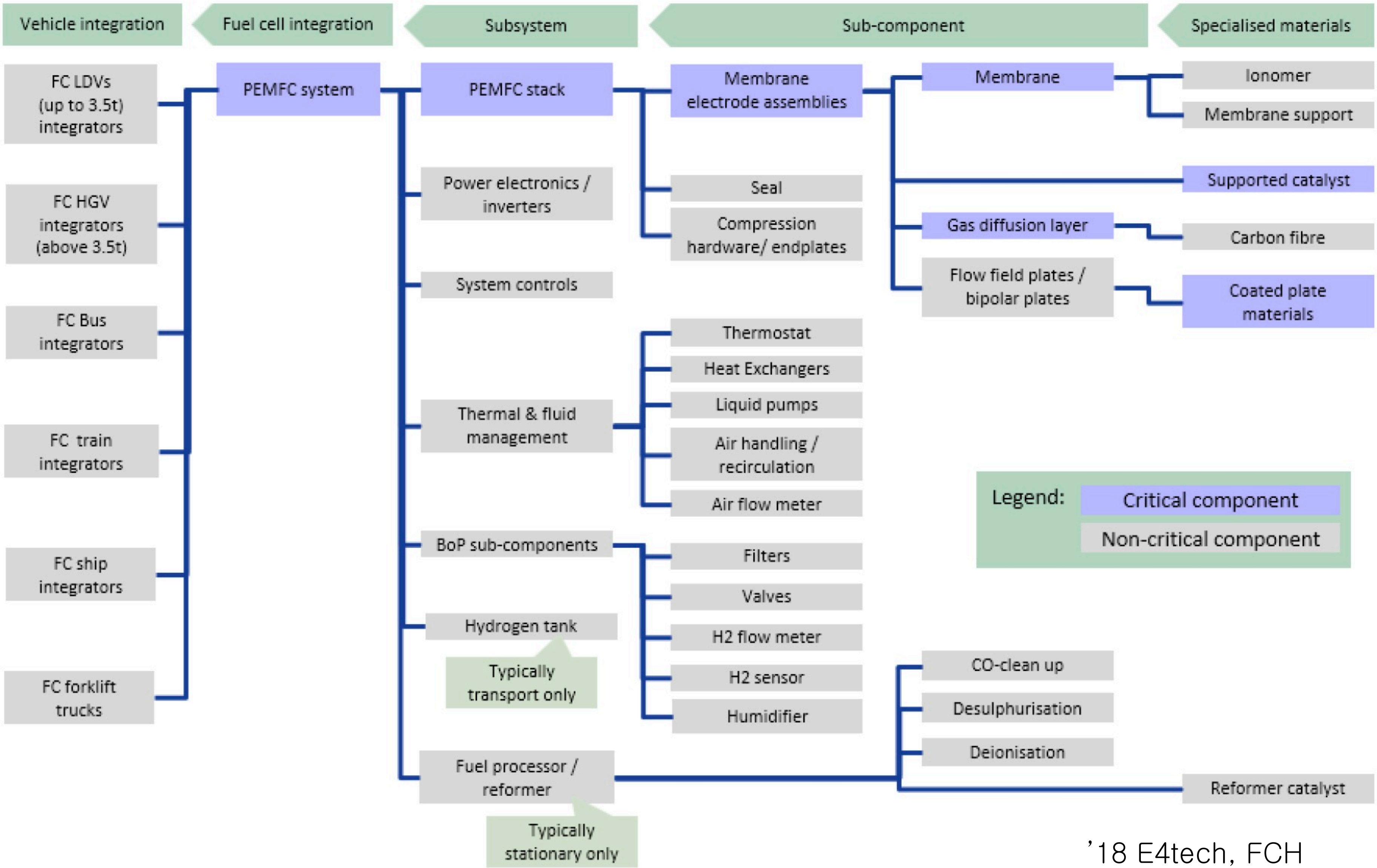
Well to Wheel Efficiency

Vehicle Type	Well to Tank		Tank to Well	Overall Efficiency
	Production	Delivery	Use	
FCEV	23~69% H2 production method dependent	54~80% Loss during H2 compression & transportation	36~45% FCEV system Loss	4~25%
BEV	35~60% Electricity production method	81~84.6% Transmission loss	65~82% EV system loss	18~42%
ICEV	82~87% Fuel production loss	~99% Transportation loss	17~21% ICEV loss	14~18%

FC Vehicle Supply Chain



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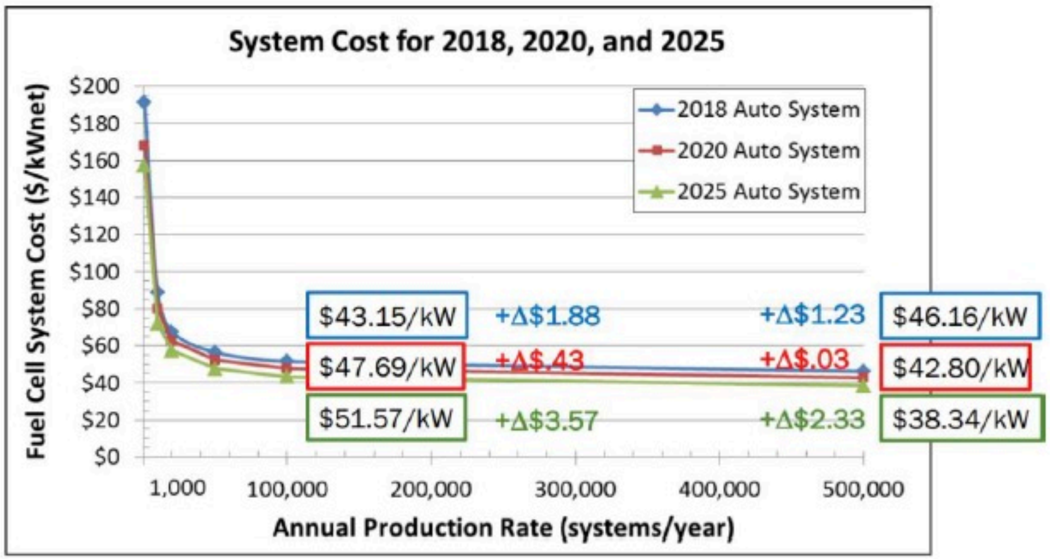
FC System Cost Analysis

FC technology is mature enough.

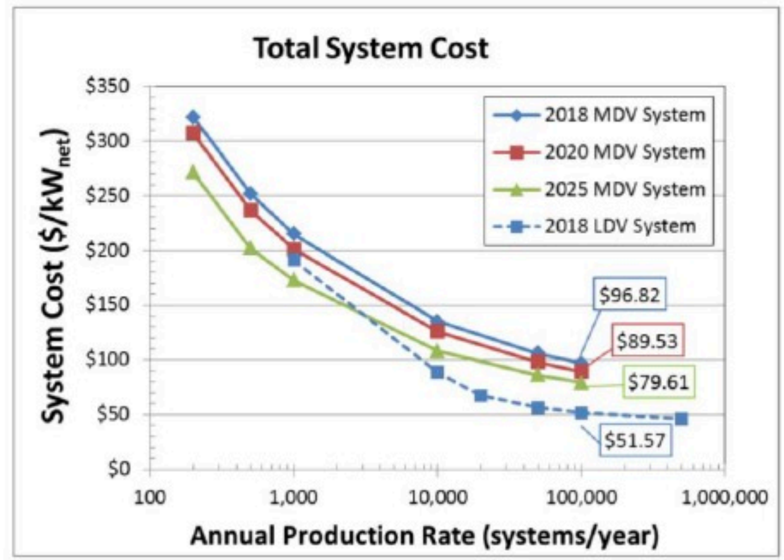
Mass production is the key factor.

Passenger car fuel cell systems



*Cost results shown for both 100,000 & 500,000 systems/year

Heavy duty fuel cell systems (for trucks and buses)



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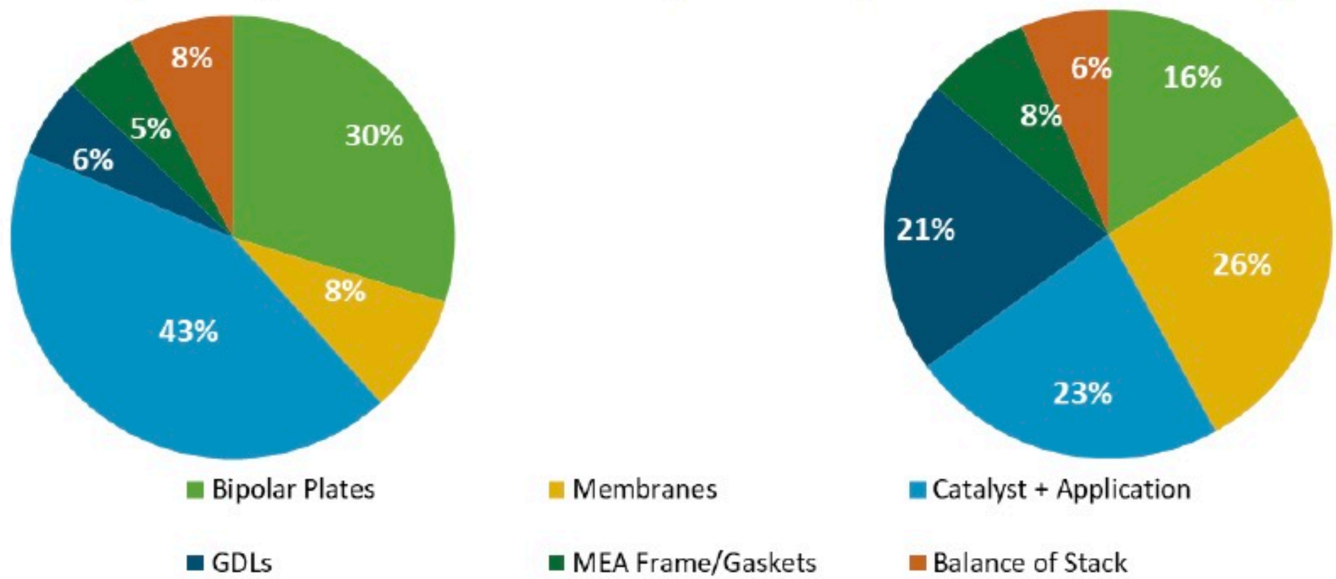
FCEV Challenges

Major cost components – examples

- Manufacturing volume and scale is important

Cost by Component – DOE Independent peer-reviewed analysis



High- Volume (500,000/yr)

Challenges: Catalyst and Bipolar Plates

Low- Volume (1,000/yr)

Challenges: Membrane, GDL, Catalyst

'16 DOE

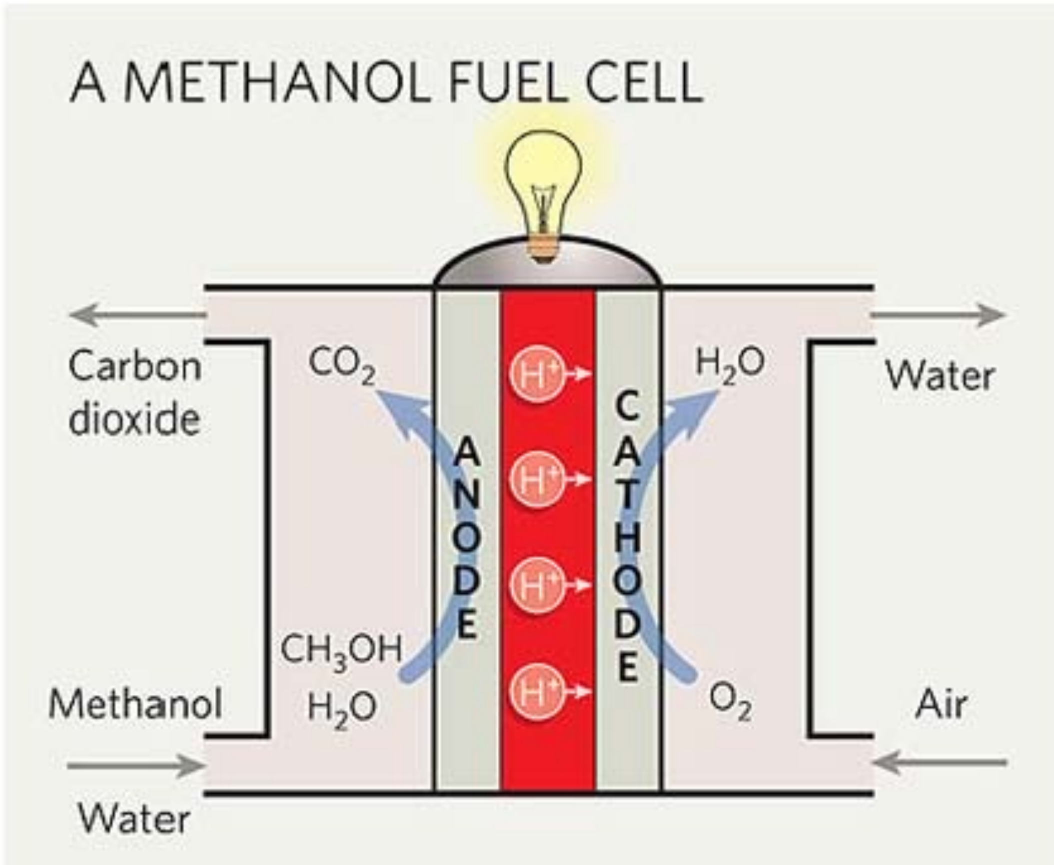
FCEV Challenges

22,000 euro in high volume scenario for 80kWe and >500,000 production

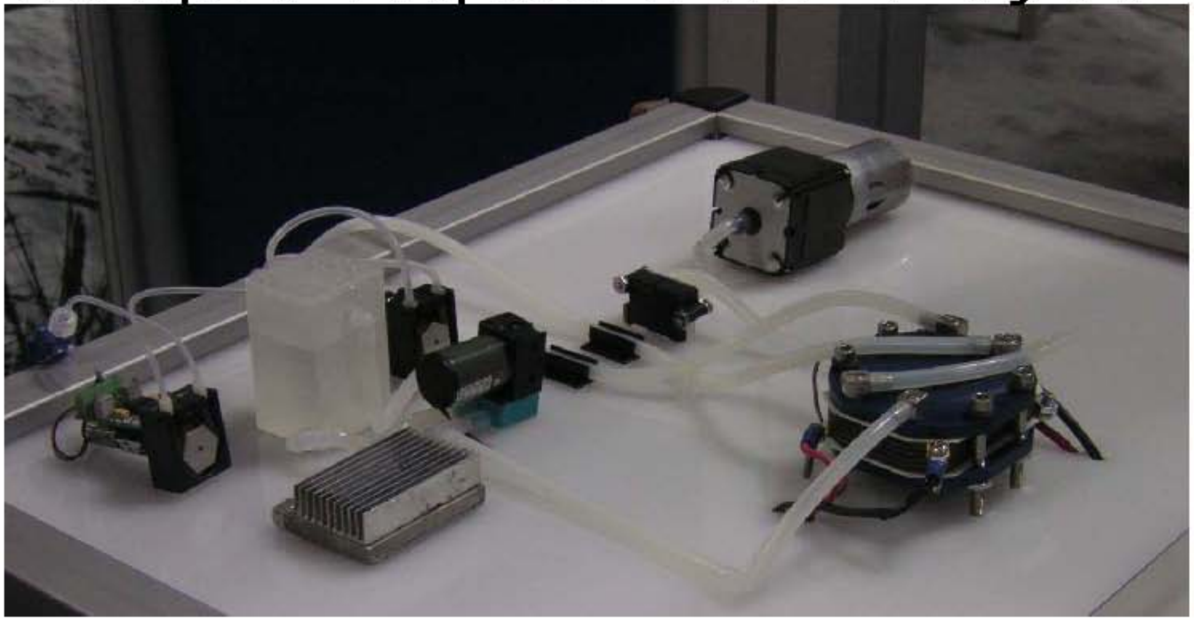
	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 11,000	€ 8.600	€ 7,700	€ 8,800	€ 7,000	€ 6,400
System integration	€ 290	€ 260	€ 250	€ 270	€ 240	€ 230
Storage system (Type IV)	€ 3,800	€ 3,100	€ 2,800	€ 3,100	€ 2,600	€ 2,400
BOP	€ 2,600	€ 1,900	€ 1,700	€ 2,000	€ 1,500	€ 1,300
Projected stack cost	€ 4,300	€ 3,300	€ 3,000	€ 3,400	€ 2,700	€ 2,400
Balance of stack	€ 100	€ 93	€ 89	€ 94	€ 85	€ 82
Bipolar plates (BPP)	€ 440	€ 400	€ 380	€ 400	€ 360	€ 350
Membrane electrode assemblies (MEA)	€ 2,800	€ 2,100	€ 1,800	€ 2,200	€ 1,700	€ 1,500
Membrane	€ 560	€ 410	€ 360	€ 430	€ 320	€ 280
Catalyst	€ 1,300	€ 1,000	€ 950	€ 1,100	€ 880	€ 810
Gas diffusion layer (GDL)	€ 370	€ 190	€ 140	€ 210	€ 110	€ 83

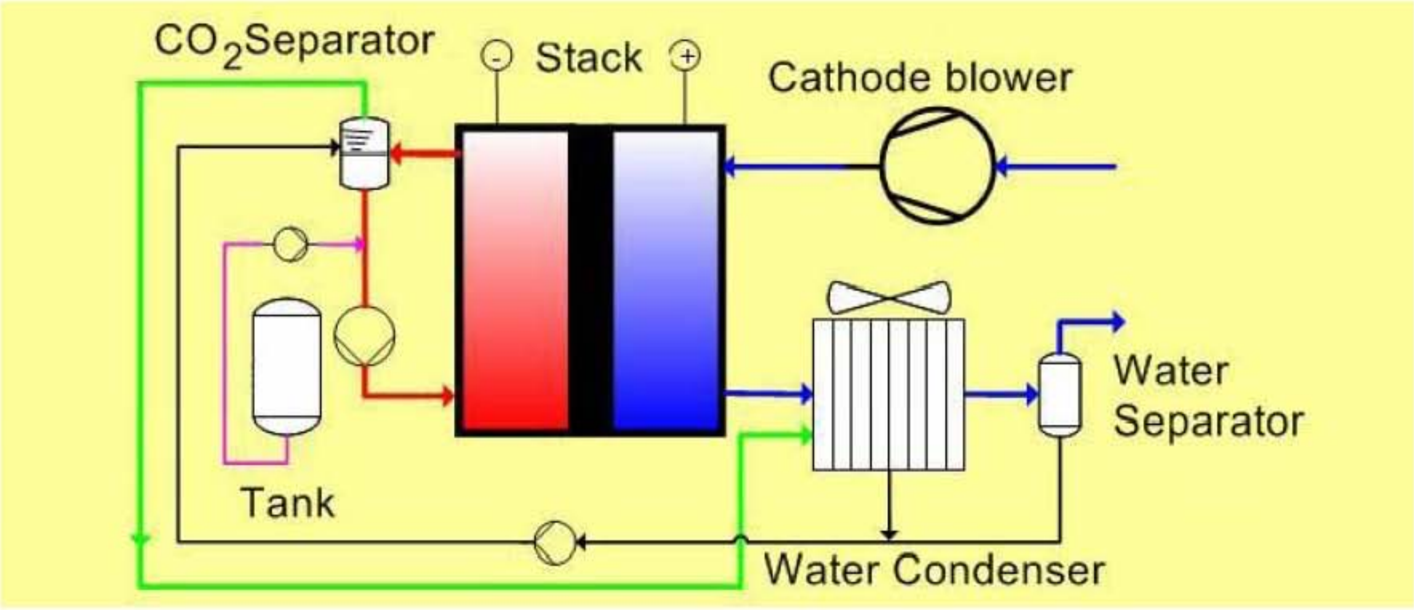
‘20 FCH

DMFC's


A METHANOL FUEL CELL
Carbon dioxide
CO_2
H^+
H_2O
Water
ANODE
CATHODE
CH_3OH
H_2O
Methanol
O_2
Air
Water

Simple Liquid DMFC System

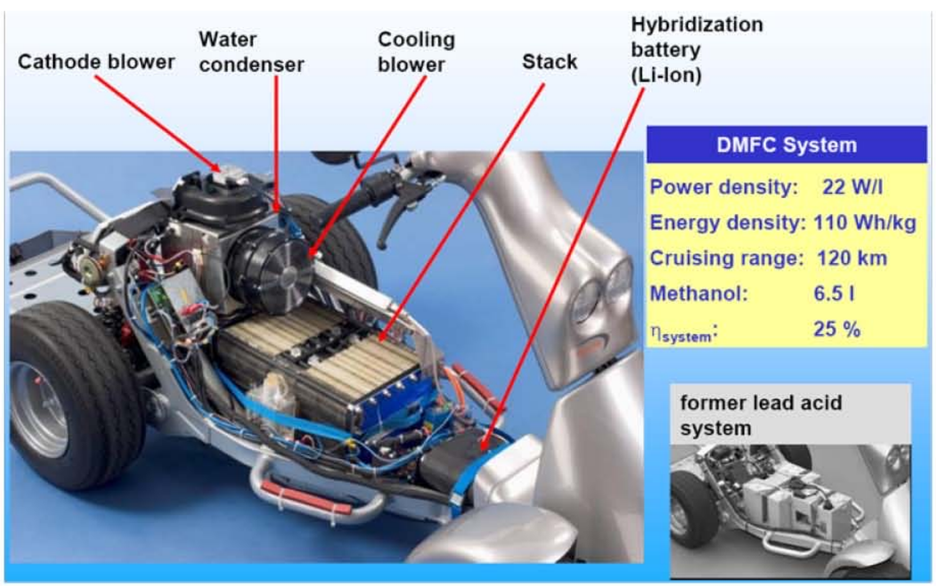




DMFC's


mobion


EFOY
COMFORT
210
EFOY
M10


Cathode blower
Water condenser
Cooling blower
Stack
Hybridization battery (Li-Ion)
DMFC System
Power density: 22 W/l
Energy density: 110 Wh/kg
Cruising range: 120 km
Methanol: 6.5 l
η_{system}: 25 %
former lead acid system


VIEWIMAGES

DMFC Electrode Reaction Steps

Anode Reaction

$CH_3OH + s_1^* \rightarrow CH_3OH_{(ad)1}$

$CH_3OH_{(ad)1} \rightarrow CO_{(ad)1} + 4\ H^+ + 4\ e^-$

$H_2O + s_2^* \rightarrow OH_{(ad)2} + H^+ + e^-$

$CO_{(ad)1} + OH_{(ad)2} \xrightarrow[rds]{} CO_2 + H^+ + e^- + s_1^* + s_2^*$

$CH_3OH + H_2O \rightarrow CO_2 + 6\ H^+ + 6\ e^-$

Cathode Reaction

$3/2\ O_2 + 6\ H^+ + 6\ e^- \rightarrow 3\ H_2O$

Problems with Nafion DMFC

- **Methanol crossover from anode to cathode**

  - Dilution (5-15% in water)
  - Electro-osmotic drag of water
  - Reduces fuel utilization
  - Competing reactions at the cathode
  - Polarizes the cathode (poisons catalytic sites for O_2)
  - Reduces overall cell potential

- **Poor oxidation kinetics**

  - Anode polarization dominates cell performance
  - Need for good anode catalyst

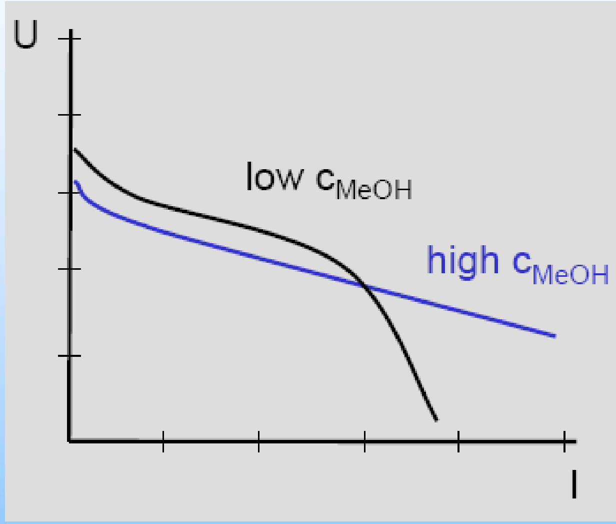
- **Reduce or eliminate precious metal catalysts**

Best performance : 0.4 Ω/cm^2 at 130 ^oC using 3 atm. O_2 at cathode

Methanol Concentration Control

High methanol concentration
• low anode overpotential
• high methanol permeation
• high cathode overpotential (mixed potential)

Low methanol concentration
• high anode overpotential
• low methanol permeation
• lower cathode overpotential



The **methanol concentration** is always a **compromise** between **cathode and anode** impact. It mainly depends on:
• current density
• temperature
• air flow rate

Direct Formic Acid Fuel Cells

$$HCOOH \rightarrow CO_2 + 2H^+ + 2e^- \quad (1)$$

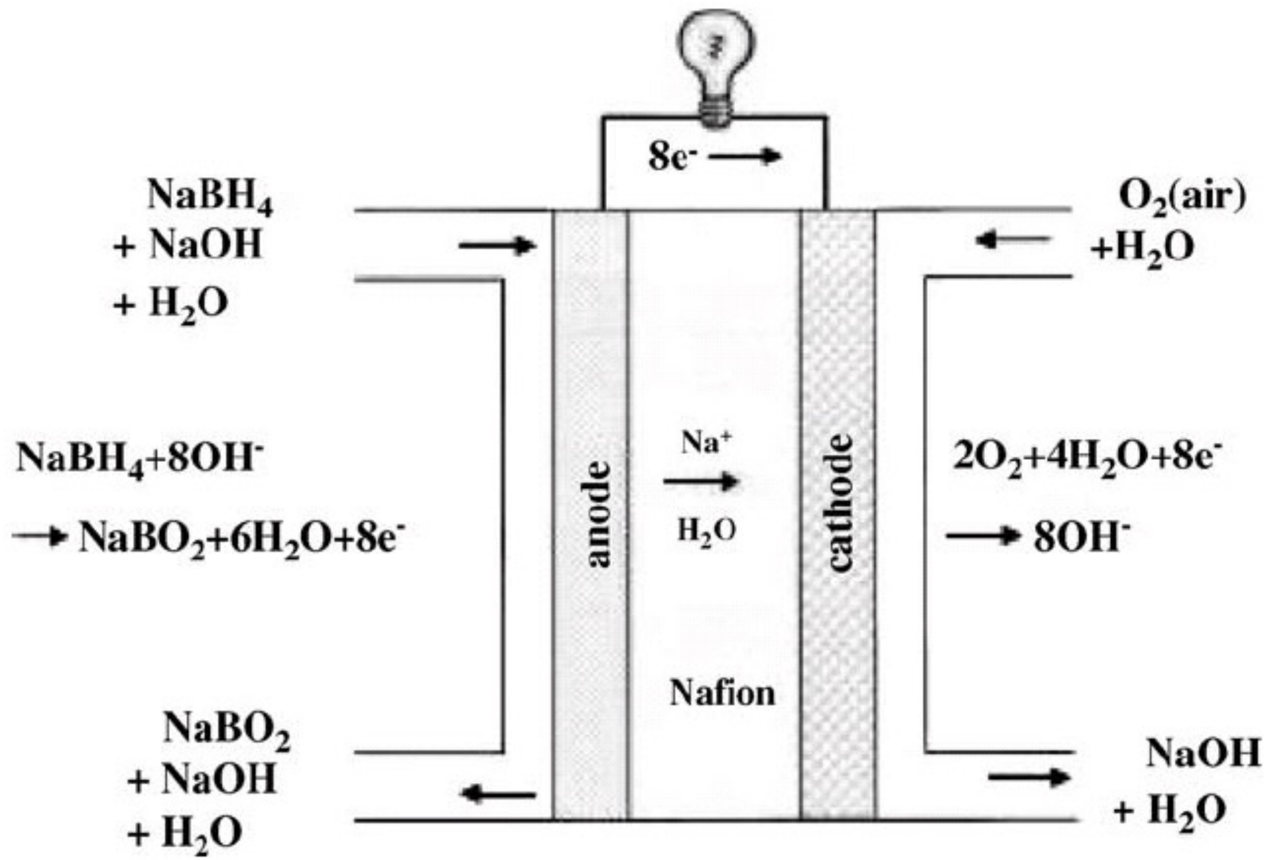
$$HCOOH + Pt^0 \rightarrow Pt{-}CO + H_2O \quad (2)$$

$$Pt^0 + H_2O \rightarrow Pt{-}OH + H^+ + e^- \quad (3)$$

$$Pt{-}CO + Pt{-}OH \rightarrow 2Pt^0 + CO_2 + H^+e^- \quad (4)$$

$$\text{Overall :} \quad HCOOH \Rightarrow CO_2 + 2H^+ + 2e^- \quad (5)$$

Borohydride Fuel Cells



Borohydride Fuel Cells

Anode (negative electrode):

$$NaBH_4 + 8OH^- \rightarrow NaBO_2 + 6H_2O + 8e^-, \quad E^{o} = 1.24\,V \tag{4}$$

Cathode (positive electrode):

$$2O_2 + 4H_2O + 8e^- \rightarrow 8OH^-, \quad E^{o} = 0.40\,V \tag{5}$$

Overall:

$$NaBH_4 + 2O_2 \rightarrow NaBO_2 + 2H_2O, \quad E^{o} = 1.64\,V \tag{6}$$

Borohydride Fuel Cells

$$NaBH_4 + 6OH^- \rightarrow NaBO_2 + 4H_2O + H_2 + 6e^-,$$

$$E^o = -1.38\,V$$

Cathode (positive electrode):

$$\frac{3}{2}O_2 + 3H_2O + 6e^- \rightarrow 6OH^-, \quad E^o = 0.40\,V$$

Overall:

$$NaBH_4 + \frac{3}{2}O_2 \rightarrow NaBO_2 + H_2O + H_2, \quad E^o = 1.78\,V$$

Membraneless Fuel Cells