Workshop on Fuel Cells for Automotive Applications

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IRA A. FULTON SCHOOLS OF engineering

ARIZONA STATE UNIVERSITY

Fuel Cell Commercialization Outlook
FUEL CELL MARKETS

FUEL CELL MARKETS

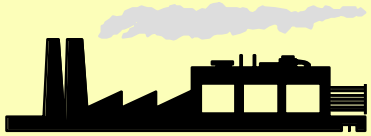
LOCAL

DISTRIBUTED

FIXED

MOBILE

Power Plant



2-1,000 MW
TAM:

Bus / Fleet

50 - 250 kW
TAM: 12 Billion/Year

Residential

N. American:
50-500 kW

3rd. World:
1-10 kW

TAM: 4.8 Billion/Year

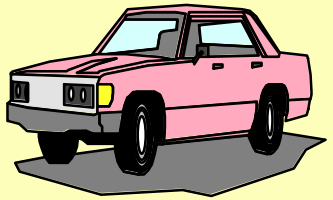
Portable

Generator:
50-150 W

Battery:
1-10 W

TAM: 18.3 Billion/Year

Automotive:



5-50 kW

TAM: 111.8 Billion/Year

MARKET REQUIREMENTS

LOCAL

FIXED

MOBILE

DISTRIBUTED

Power Plant

- Cost:
- Reliability: 40,000 h
- Fuel: NG/oil

Bus / Fleet

- Cost: $ 300/kW
- Reliability: 5000 h
- Size: < 64 ft^3
- Weight: < 200 lb

Residential

	N. American	3 rd. World
• Cost:	$2/W	$3/W
• Size:	< 25 ft^3	< 65 in^3
• Weight:	< 400 lb	< 1 lb
• Fuel	NG/Oil	NG
• Source:	Pipe	Biomass

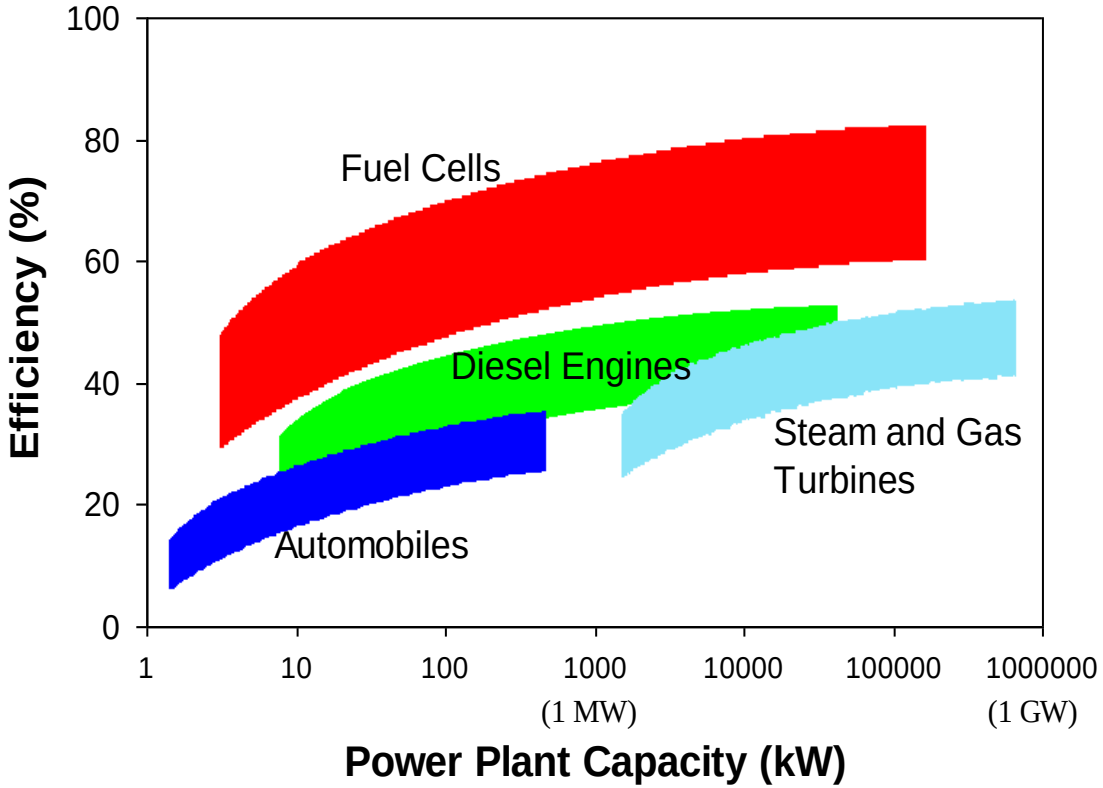
Portable

	Generator	Battery
• Cost:	$0.3/W	$ 2/W
• Temp:	<100ºC	RT
• Size:	< 500 in^3	<25in^2
• Weight:	<20 lb	<0.2lb
• Fuel:	NG/MeOH	H_2

Automotive

- Cost: $ 30/kW
- Reliability: 5000h
- Size: < 16 ft^3
- Weight: < 200 lb
- Fuel: NG/MeOH /H2

CONVERSION EFFICIENCY OF VARIOUS POWER SOURCES

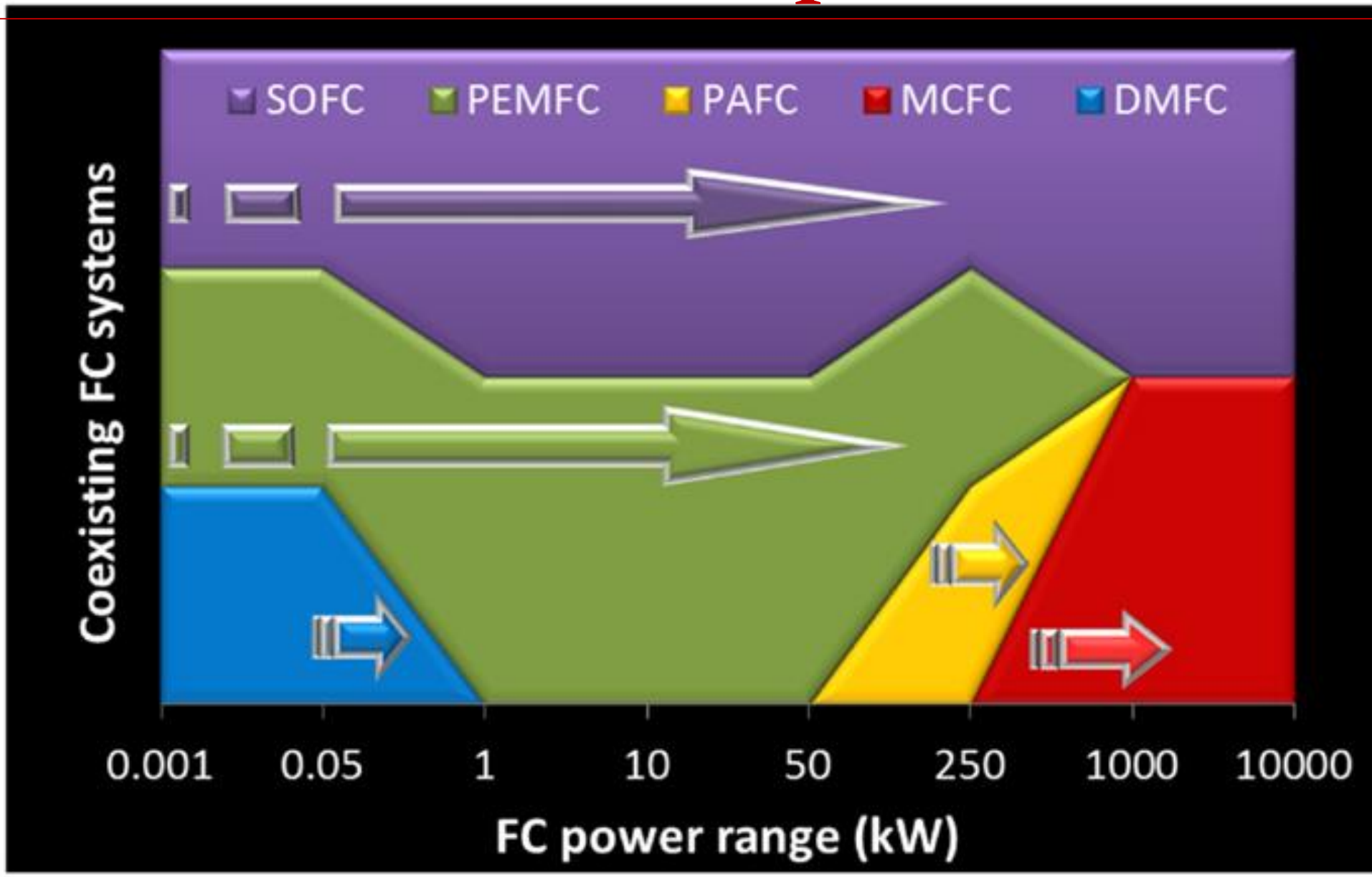


- FCs exhibit maximum efficiency compared to other systems
- Also the efficiency does not depend on load

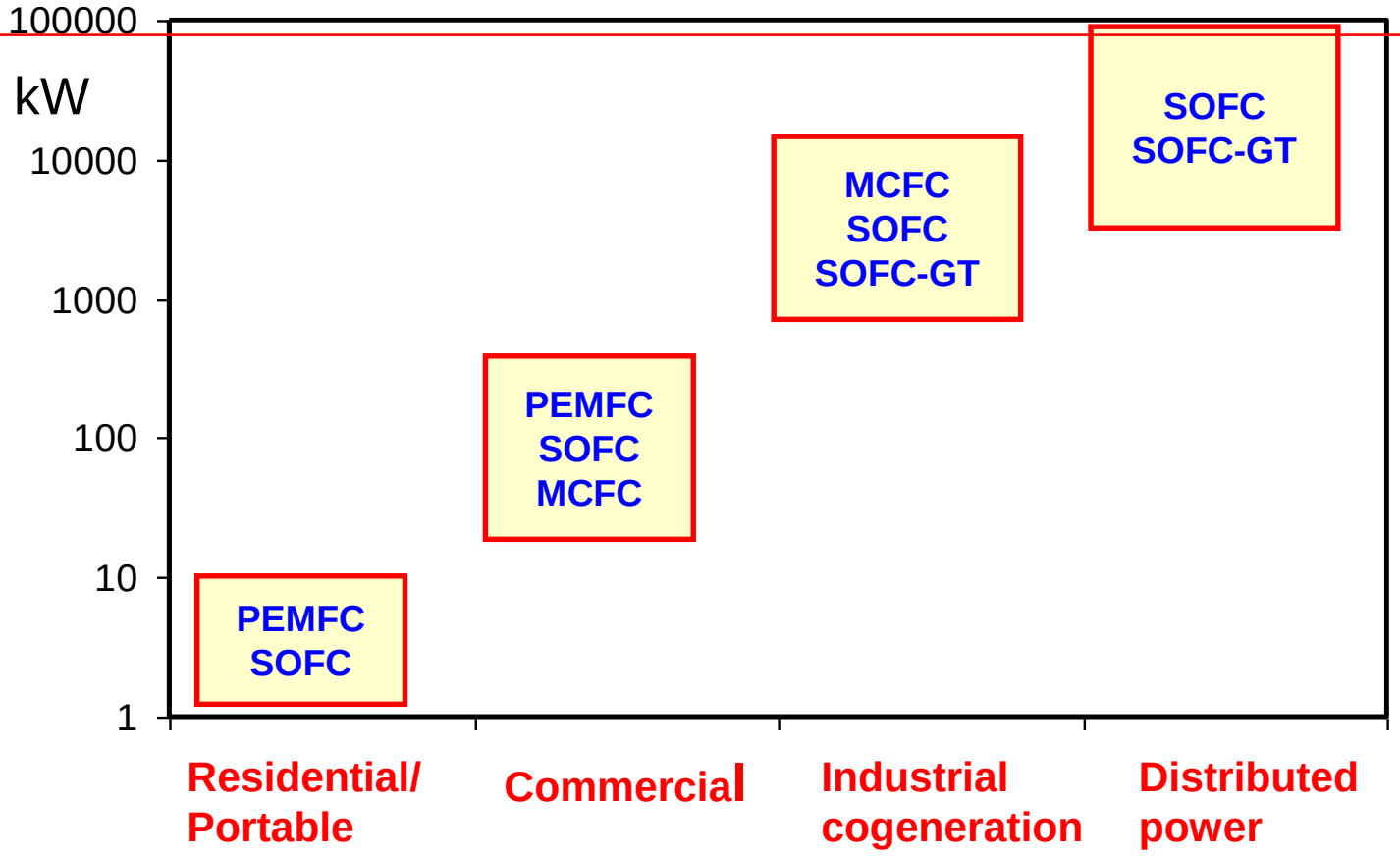
Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Electrical Efficiency	Combined Heat and Power (CHP) Efficiency	Applications	Advantages
Polymer Electrolyte Membrane (PEM)*	Solid organic polymer poly-perfluorosulfonic acid	50 - 100°C 122 - 212°F	<1kW – 250kW	53-58% (transportation) 25-35% (stationary)	70-90% (low-grade waste heat)	▪ Backup power ▪ Portable power ▪ Small distributed generation ▪ Transportation ▪ Specialty vehicles	▪ Solid electrolyte reduces corrosion & electrolyte management problems ▪ Low temperature ▪ Quick start-up
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 - 100°C 194 - 212°F	10kW – 100kW	60%	>80% (low-grade waste heat)	▪ Military ▪ Space	▪ Cathode reaction faster in alkaline electrolyte, leads to higher performance ▪ Can use a variety of catalysts
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 - 200°C 302 - 392°F	50kW – 1MW (250kW module typical)	>40%	>85%	▪ Distributed generation	▪ Higher overall efficiency with CHP ▪ Increased tolerance to impurities in hydrogen
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C 1112 - 1292°F	<1kW – 1MW (250kW module typical)	45-47%	>80%	▪ Electric utility ▪ Large distributed generation	▪ High efficiency ▪ Fuel flexibility ▪ Can use a variety of catalysts ▪ Suitable for CHP
Solid Oxide (SOFC)	Yttria stabilized zirconia	600 - 1000°C 1202 - 1832°F	<1kW – 3MW	35-43%	<90%	▪ Auxiliary power ▪ Electric utility ▪ Large distributed generation	▪ High efficiency ▪ Fuel flexibility ▪ Can use a variety of catalysts ▪ Solid electrolyte reduces electrolyte management problems ▪ Suitable for CHP ▪ Hybrid/GT cycle

Fuel Cell Types and Application Areas

Coexisting fuel cell systems as a function of power



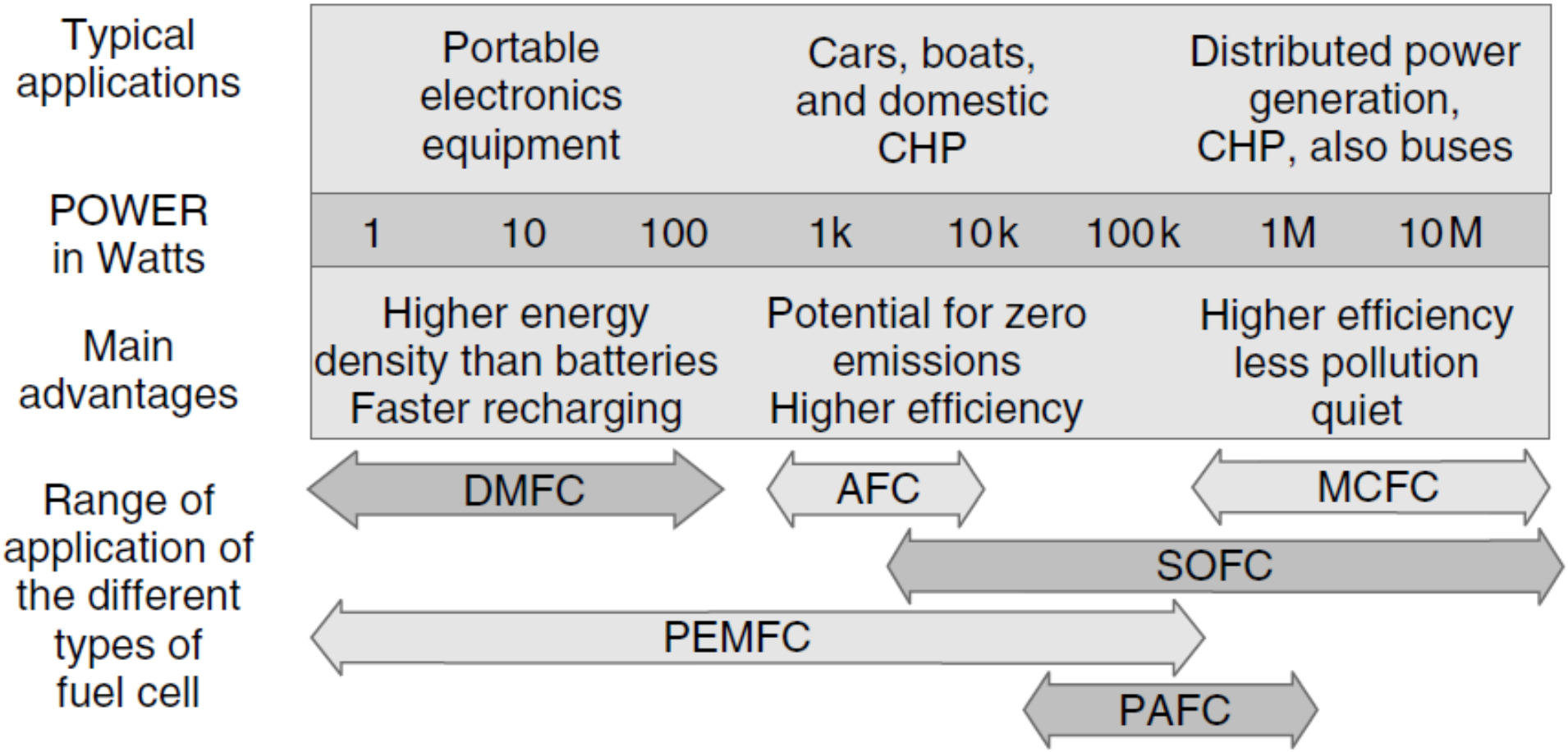
APPLICATIONS OF FUEL CELLS



- Environmentalists have long held that FCs are the world's best hope for replacing the noisy, inefficient and dirty ICs
- The type of fuel cell can be selected depending on application

FC Applications

- **Chart summarizes the applications and main advantages of fuel cells of different types, and in different applications**



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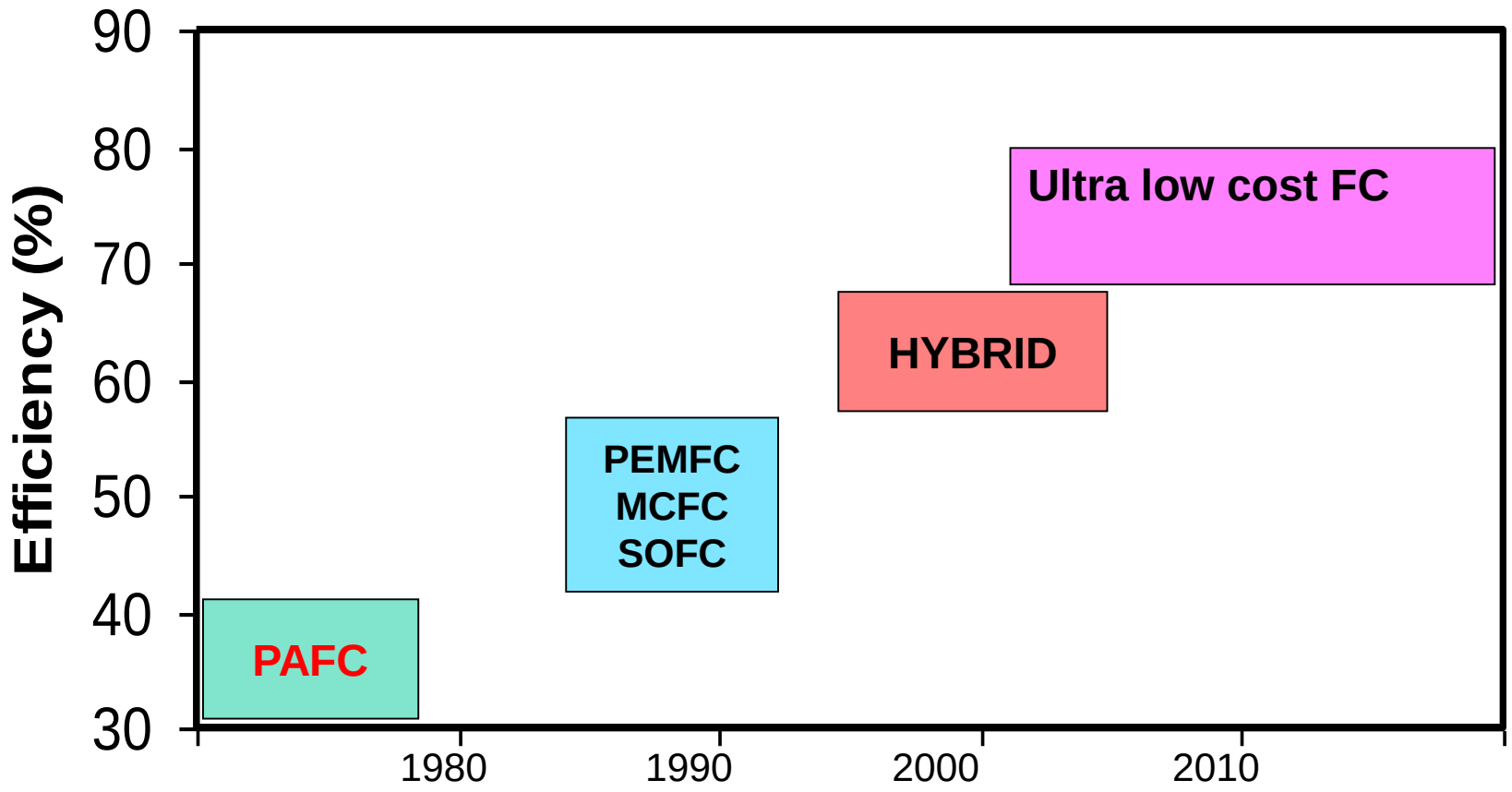
PROGRESS IN FUEL CELL TECHNOLOGY



- **Considerable advancement has been achieved in terms of efficiency and cost over the years**

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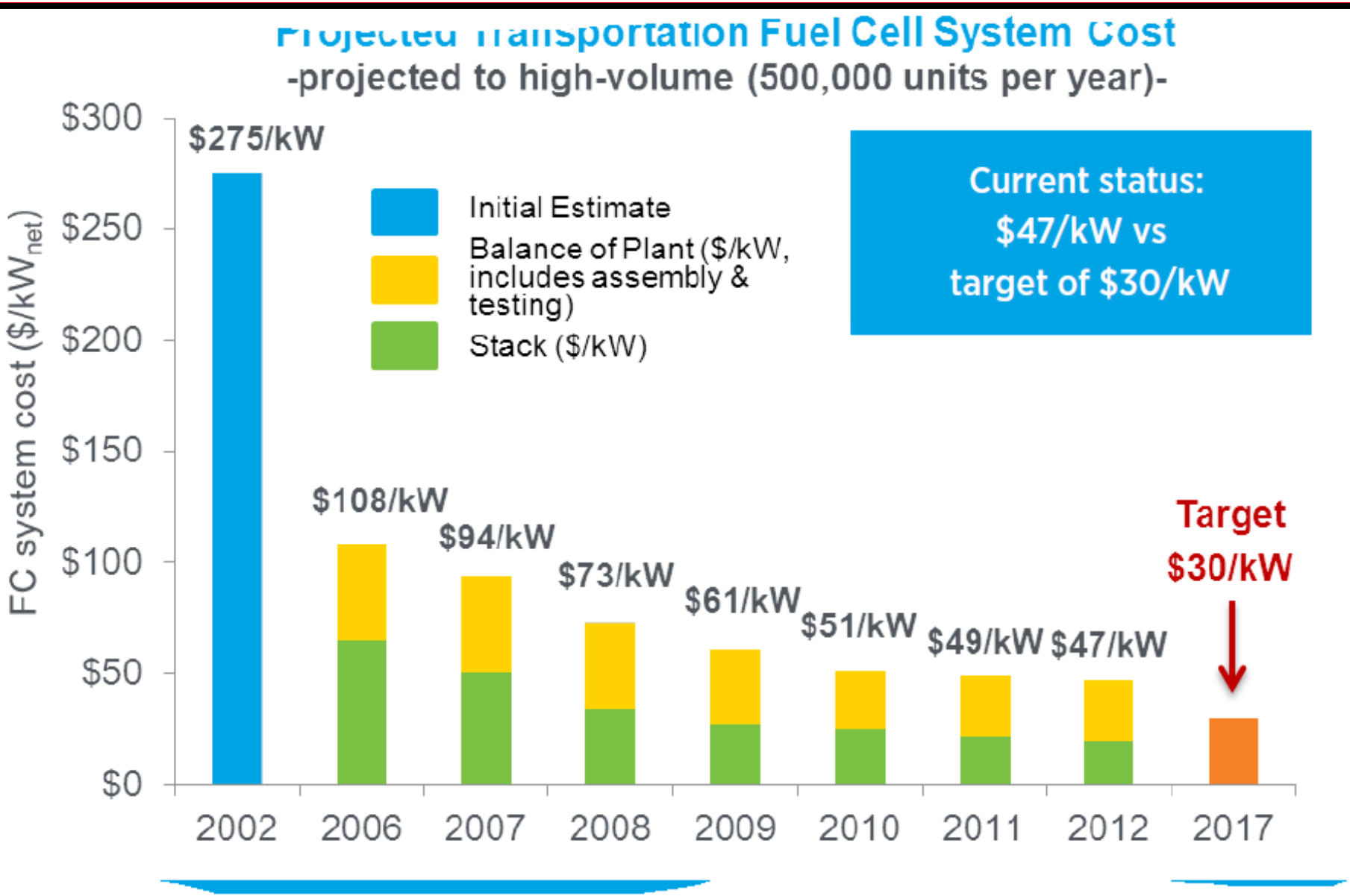
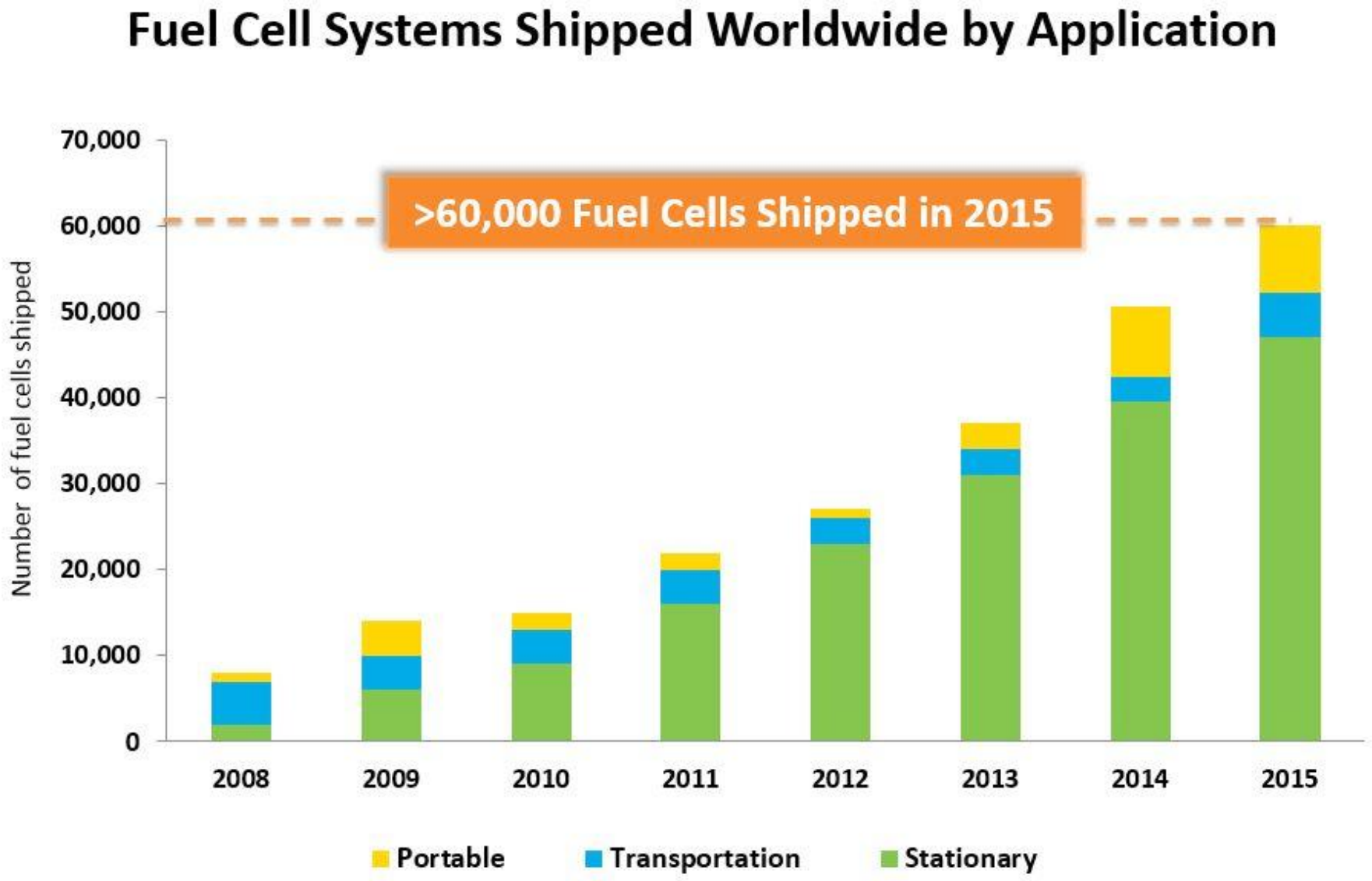
PROGRESS IN FUEL CELL TECHNOLOGY

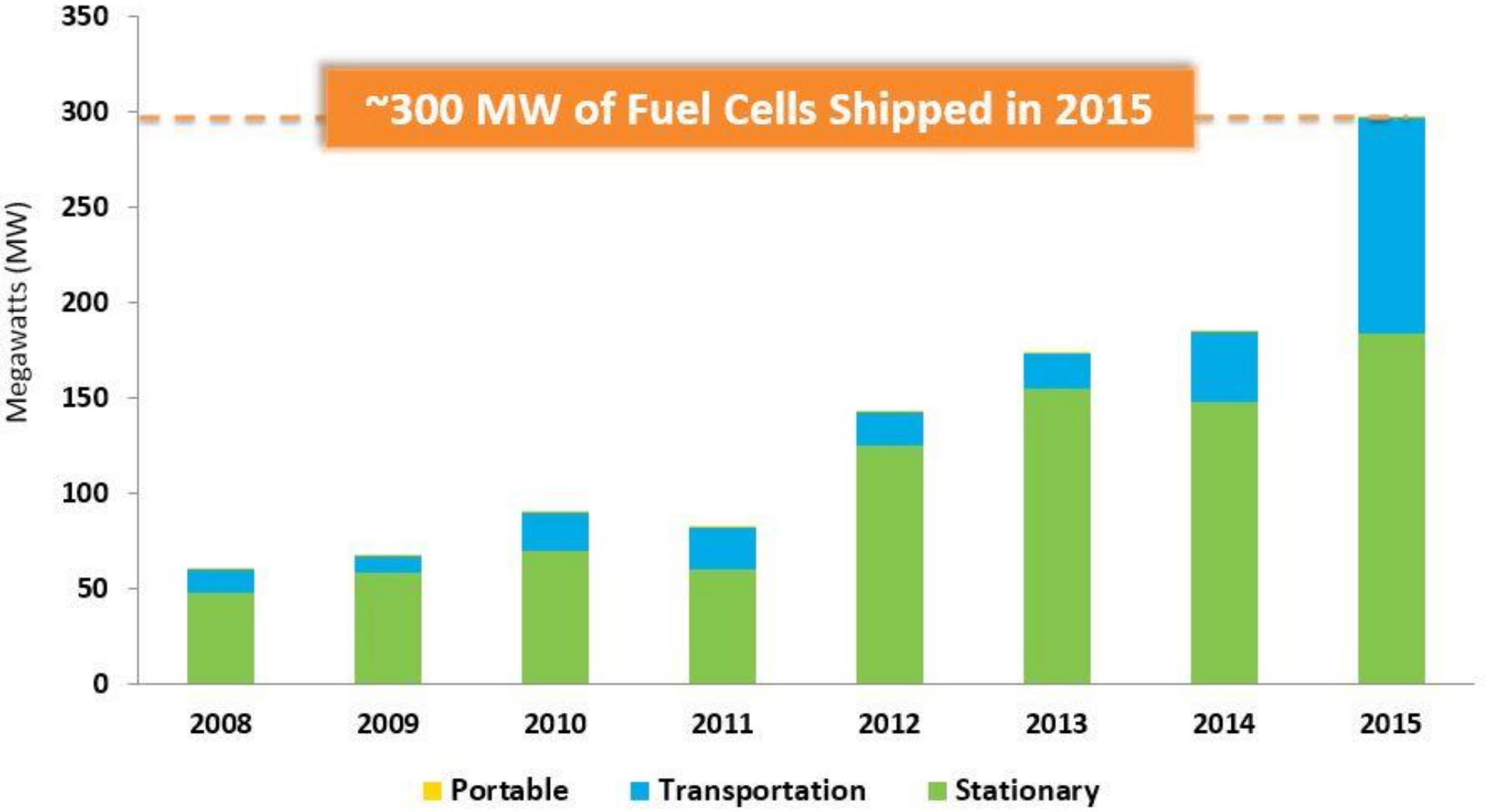


FC Applications

- Automotive, Stationary and Portable electronics



Megawatts of Fuel Cells Shipped Worldwide by Application



Source: Navigant Research (2008-2013) & E4tech (2014-2015)

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Telecommunications

- With the use of computers, the Internet, and communication networks steadily increasing, there comes a need for more reliable power than is available on the current electrical grid, and fuel cells have proven to be up to 99.999% (five nines) reliable.

Reli|On™ Hydrogen Fuel Cells

http://www.plugpower.com/products/relion/product-literature/

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Telecommunications

- Fuel cells can replace batteries to provide power for **1 to 5 kW telecom sites** without noise or emissions, and are durable, providing power in sites that are either hard to access or are subject to inclement weather.
- Such systems would be used to provide **primary or backup power for telecom switch nodes, cell towers, and other electronic systems** that would benefit from on-site, direct DC power supply.

Telecommunications

- Acme.in has contracted with IdaTech (Bend, Oregon) **for up to 30,000 5kW hydrogen fuel cell systems to be delivered by March 2013.**
- Idatech will be using Ballard Power fuel cell stacks.
- Acme is expected to use these systems as back up power for India's telecommunication infrastructure

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Landfills/Wastewater Treatment Plants/Breweries

- Fuel cells currently operate at landfills and wastewater treatment plants across the country, proving themselves as a valid technology for reducing emissions and generating power from the methane gas they produce.
- They are also installed at several breweries - Sierra Nevada, Kirin, Asahi and Sapporo.
- Untreated brewery effluent can undergo anaerobic digestion, which breaks down organic compounds to generate methane, a hydrogen rich fuel.

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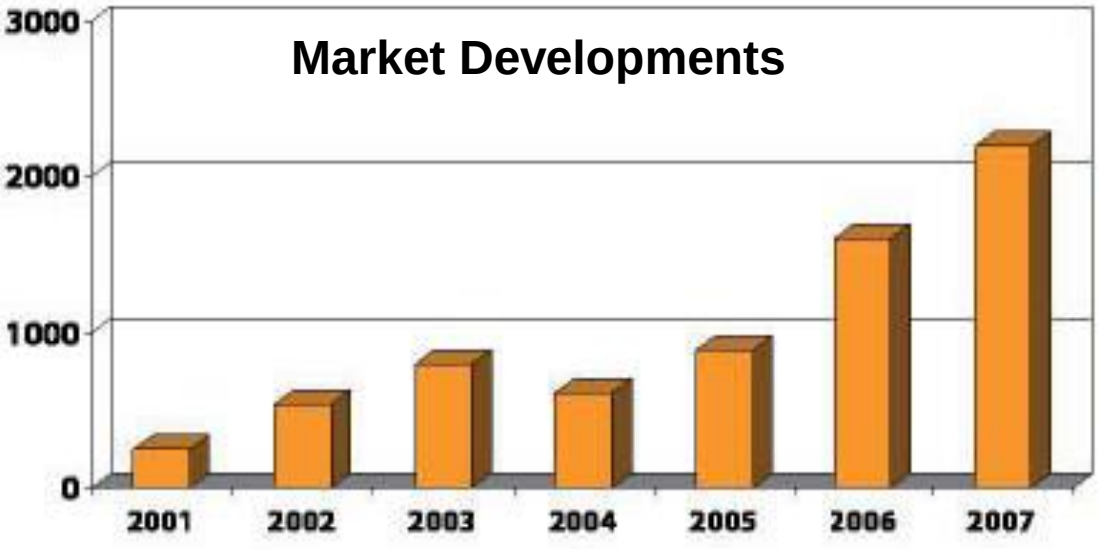
Stationary Fuel Cells

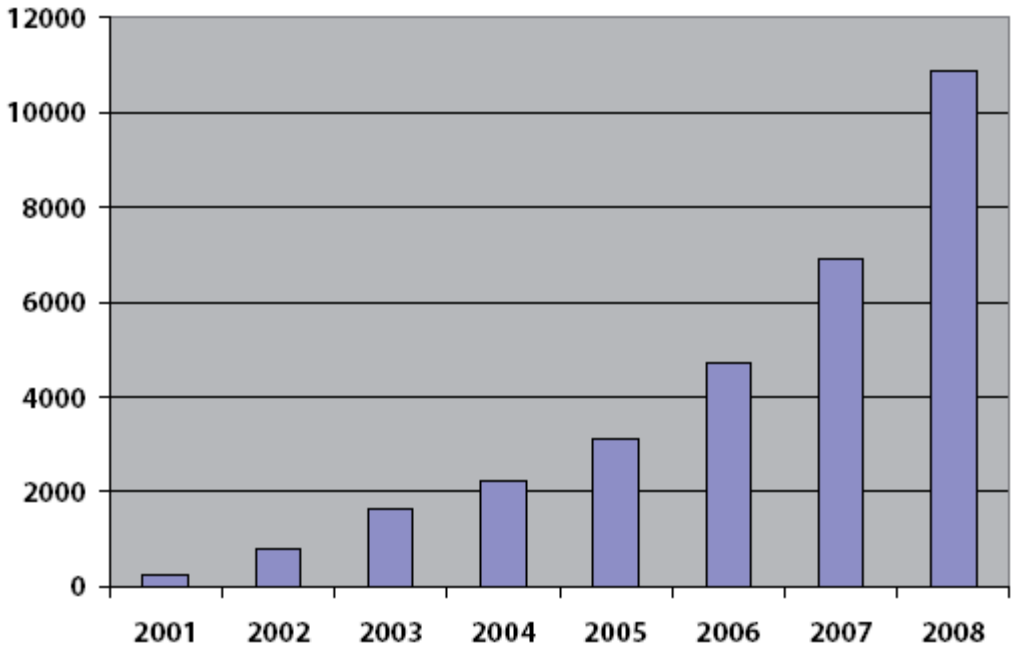
- Small stationary market, units under 10 kW, focus into residential CHP and UPS.
  - The technology split saw an increase in dominance of PEM units with SOFC accounting for less than 10% of units shipped.
  - AFC technology remained on the fringes with only a handful of units produced.
- Large stationary fuel cells are units above 10 kW operating in grid tied or off grid operations.
  - Over the past five years, MCFC, PAFC and SOFC become commercial, settling into three distinct size blocks (10-20, 200-300 kW and above 1MW)

Small Stationary FCs



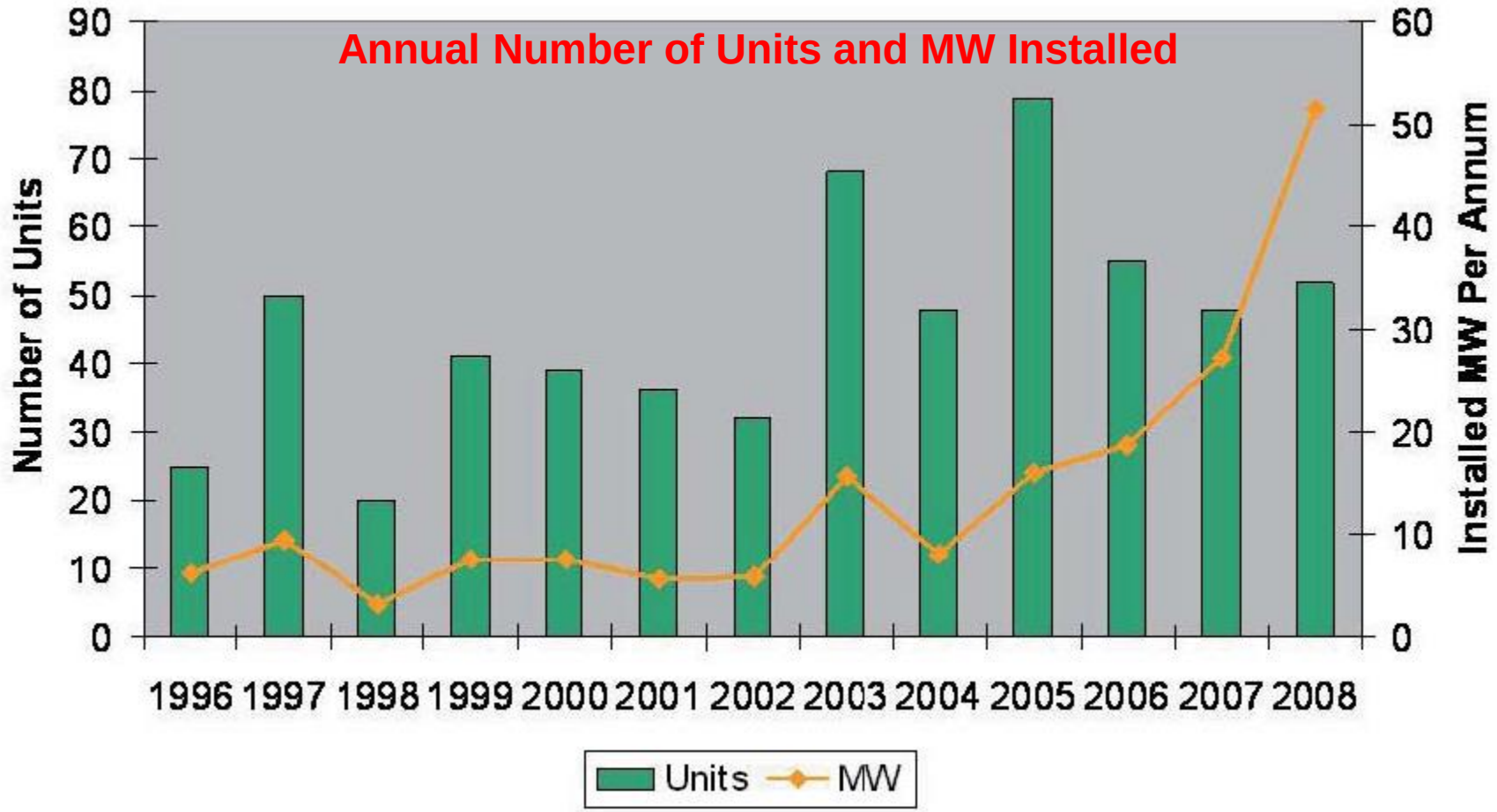
2007 saw an increase of 37% over 2006 with over 2000 new units shipped.

Cumulative shipments to date have topped 11000 with the growth curve starting to exhibit a classic S-Curve



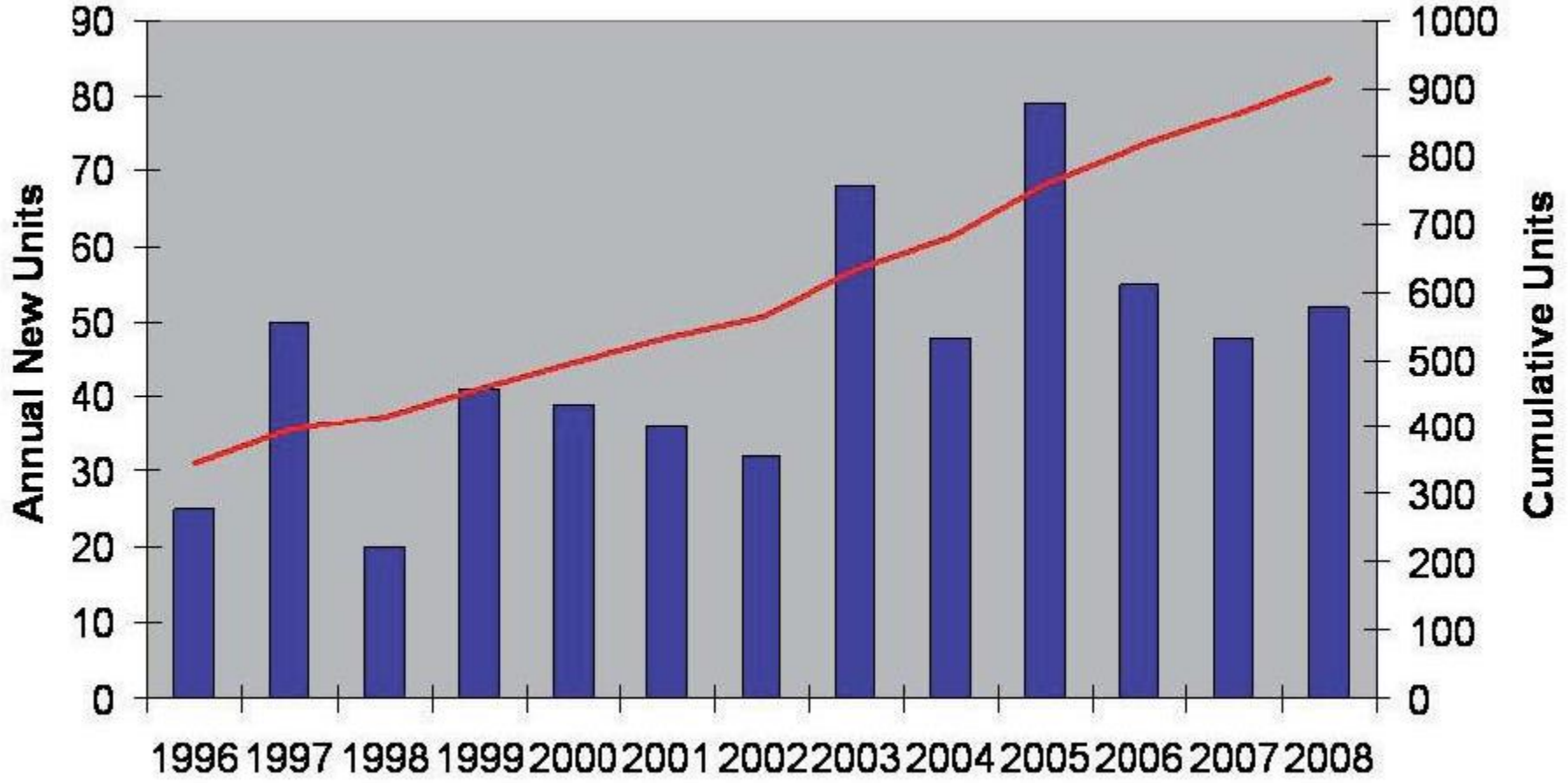
Large Stationary FCs

- Whilst 2007 and 2006 surveys reported substantial market developments, this is now translating into something of a business-as-usual scenario for the sector



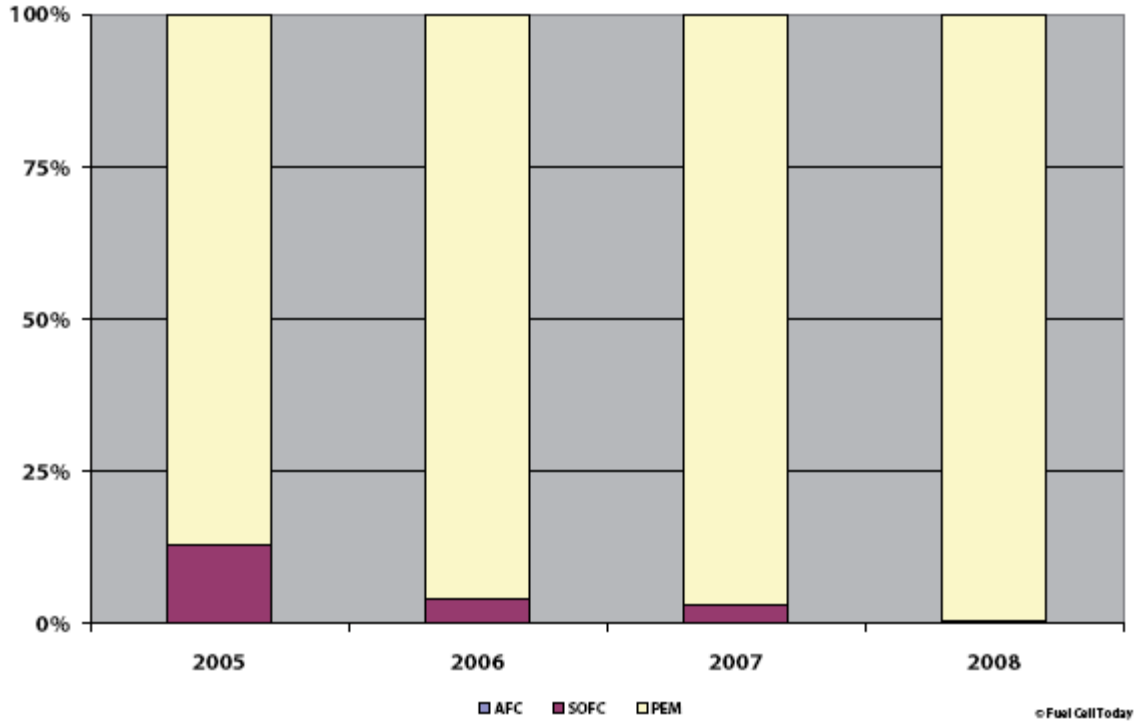
Large Stationary FCs

- As units are getting larger, many stacks are being linked in series to produce them so this 50 systems figure cloaks a much higher stack production figure, more than double that of 2007.



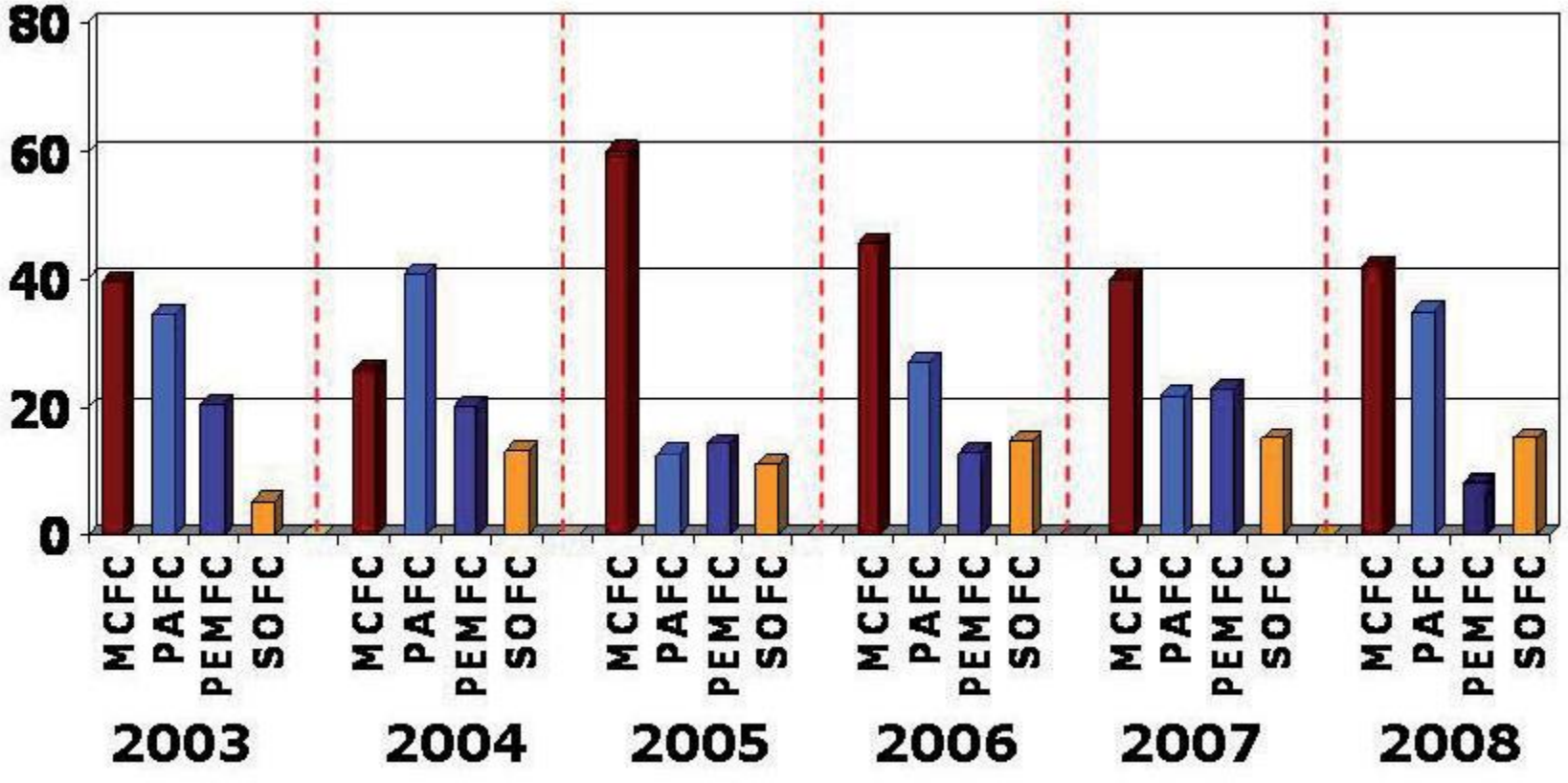
Small Stationary FCs

- Looking at technology development PEM units represented over 90% of units shipped with SOFC taking under 10% of this years shipment.
- AFC technology represents less than 1% of 2007 market shipments, though did increase from 2006.



Large Stationary FCs

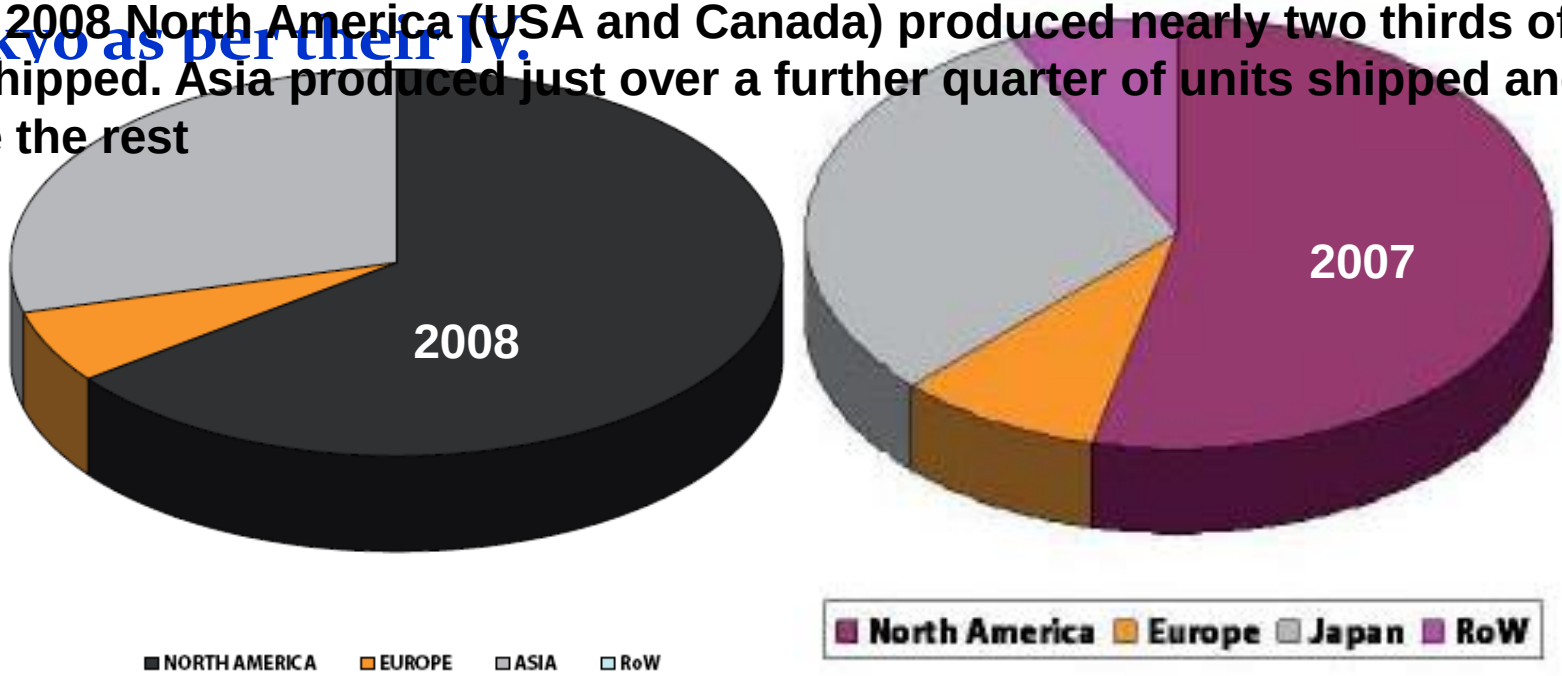
- Turning to electrolyte mix: we see a fairly even balance of systems shipped with MCFC and PAFC taking the lion's shares.
- Note that Graph represents electrolytes of systems shipped



Small FCs: Region of Manufacture

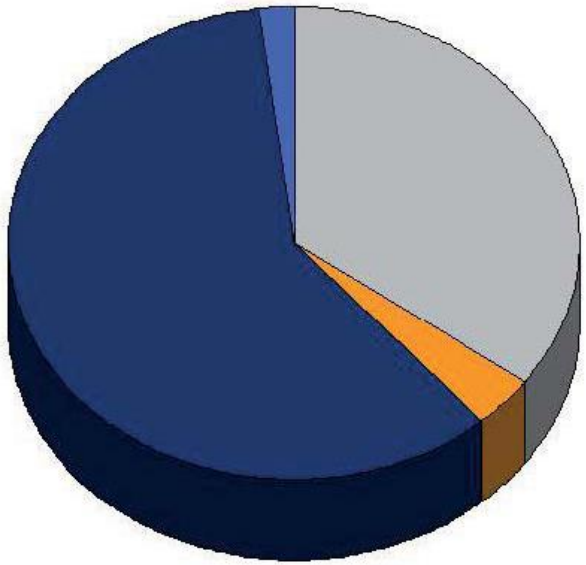
- Looking at region of manufacture the Rest of the World region saw the largest increase in units shipped.
- This trend is expected to continue with companies such as IdaTech completing manufacturing facilities in RoW regions.
- Japan saw an increase in units manufactured, part of this is from Ballard transferring manufacturing to Ebara Ballard in Tokyo as per their JV.

During 2008 North America (USA and Canada) produced nearly two thirds of all units shipped. Asia produced just over a further quarter of units shipped and Europe the rest



Large FCs: Region of Stack Manufacture

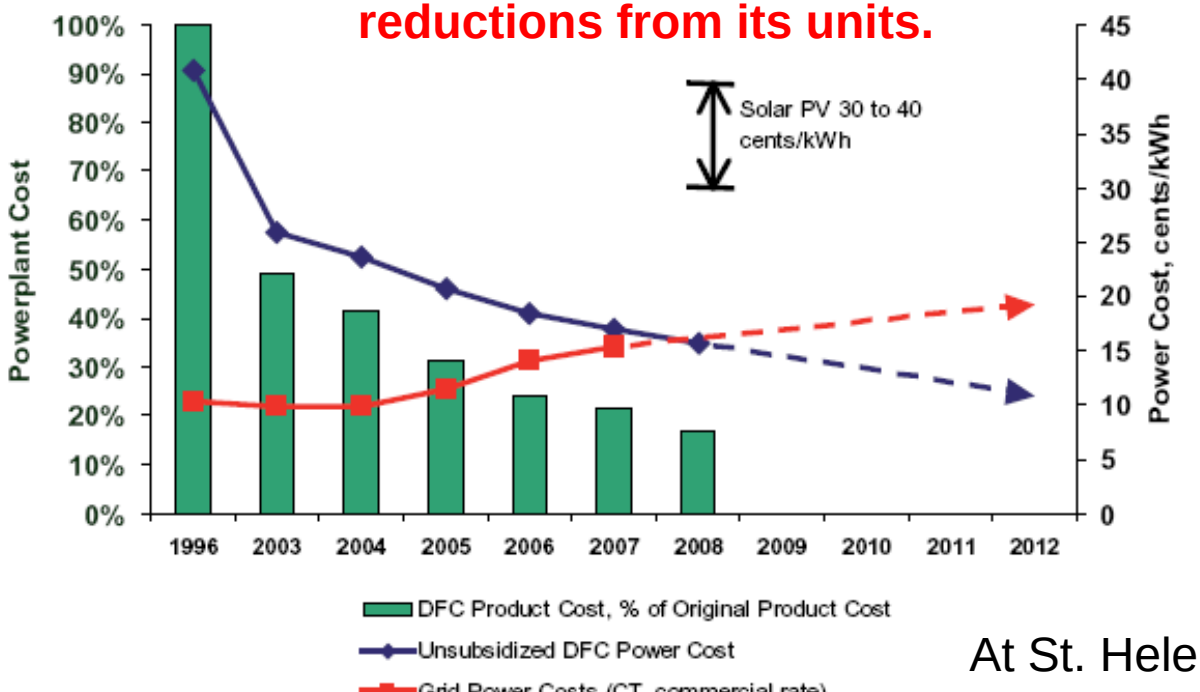
- It is clear that North America is very strong with around two thirds of the current, 2008, market.
- This market split has been fairly consistent over the past few years and is anticipated to remain so unless companies such as Rolls Royce and Nuvera, both European companies, decide to manufacture their stacks in Europe and not at their North American plants.
- At present the Rest of the World category has really only one serious player, ElectroCell (Brazil), which is developing PEM technology for both small and large scale applications.
- BHEL (India), which is also developing PEM technology, is currently at development scale testing.



Economics

- Last year saw the launch of the 400kW PureCell from UTC Power.
- The company has provided a clear market signal regarding the unit by forward pricing it at US$1 million installed cost, or US$2500 per kW.
- According to the company's own calculations this brings the unsubsidized electricity price in at US$12 cents per kWh.

FuelCell Energy investor presentation showing the historic and projected cost reductions from its units.

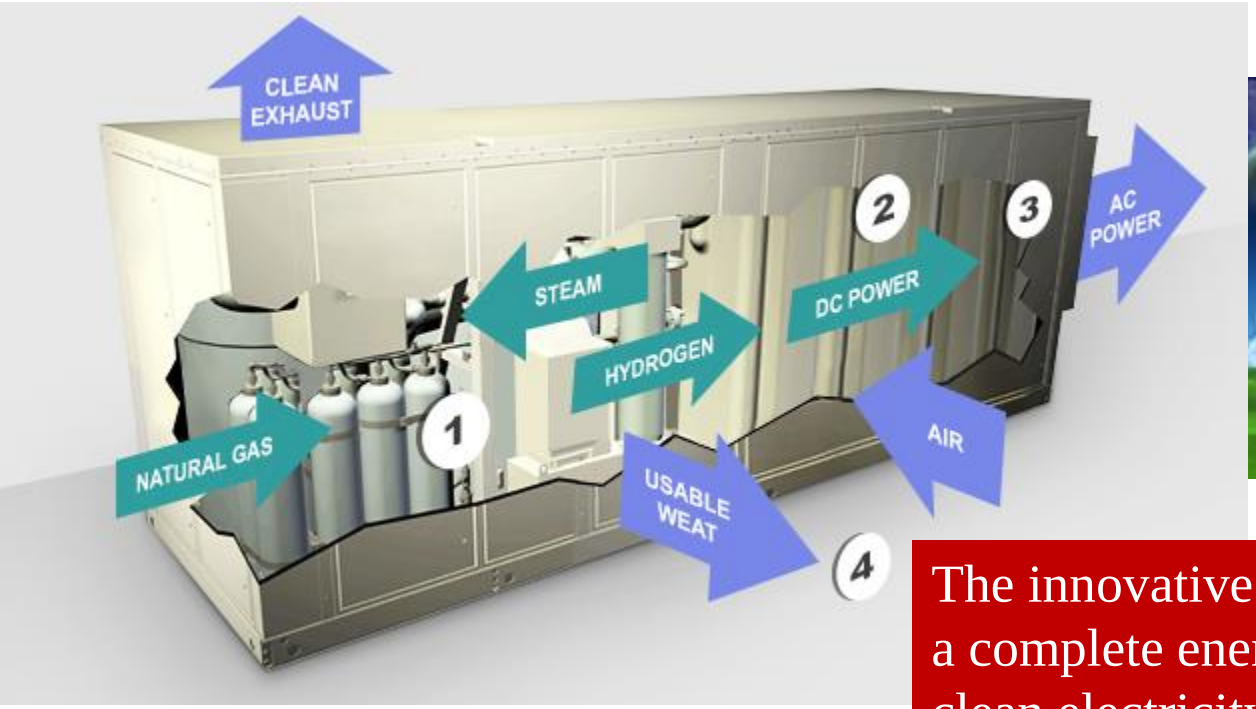


At St. Helena Hospital, CA

Possible CHP

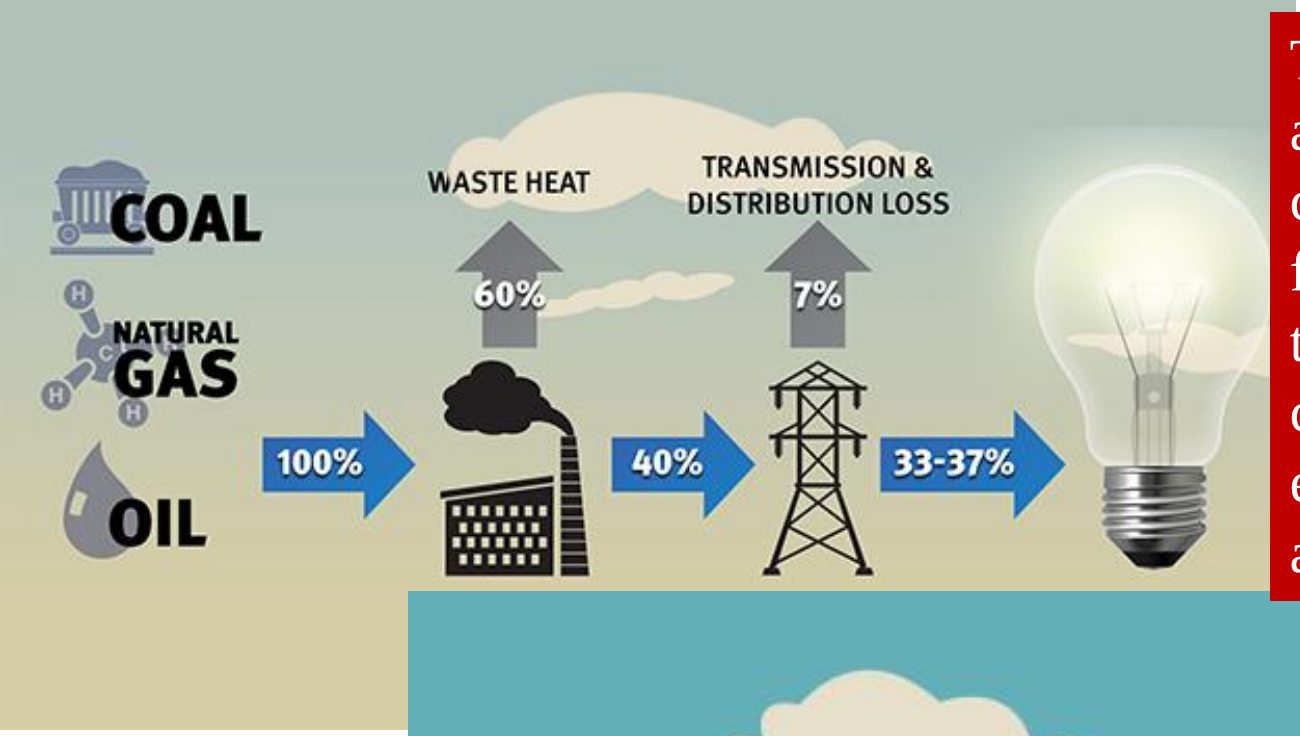
- /http://www.doosanfuelcell.com/en/main.do

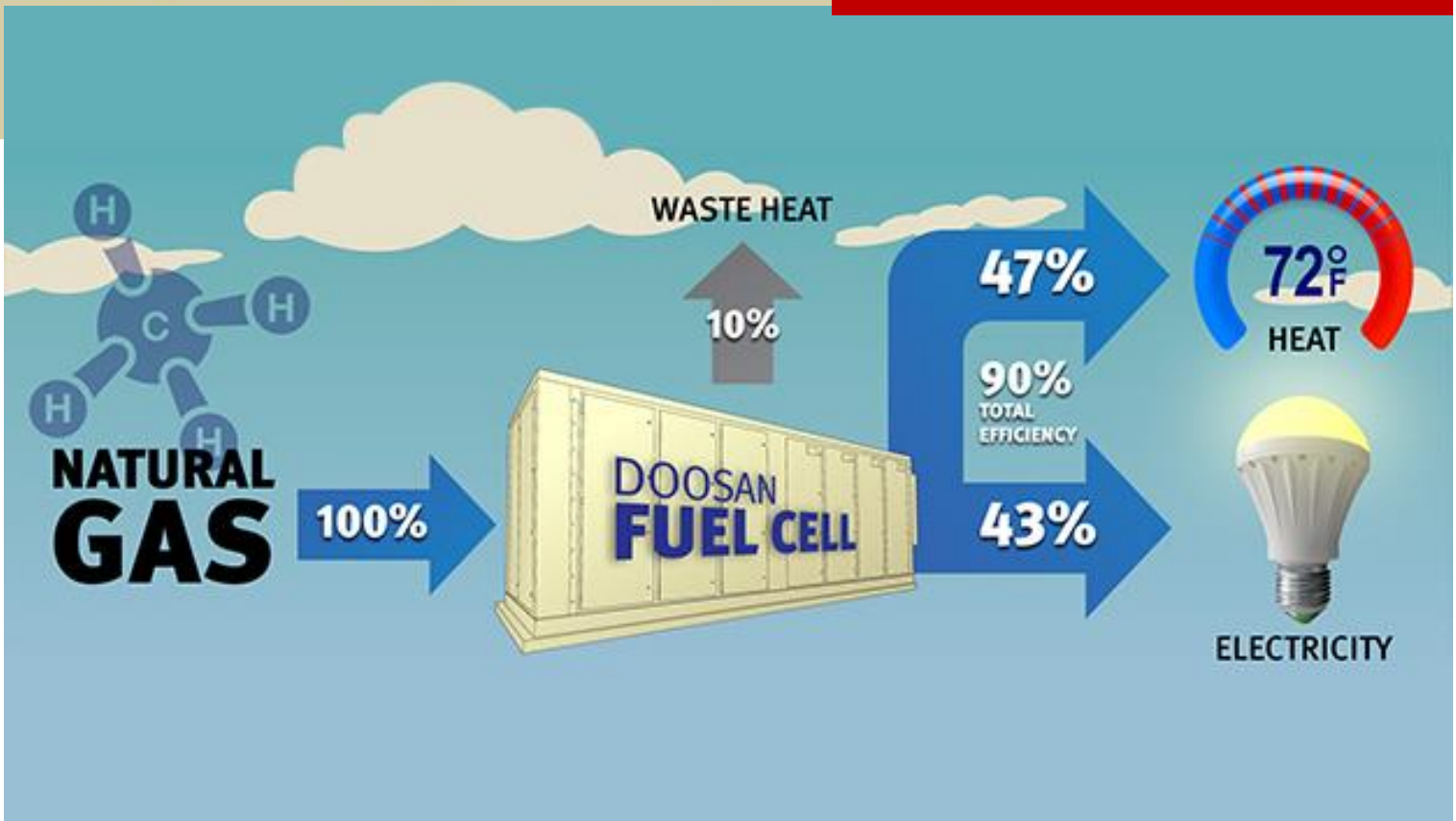
http://www.doosanfuelcell.com/attach_files/link/PureCell%20Model%20400%20Datasheet.pdf



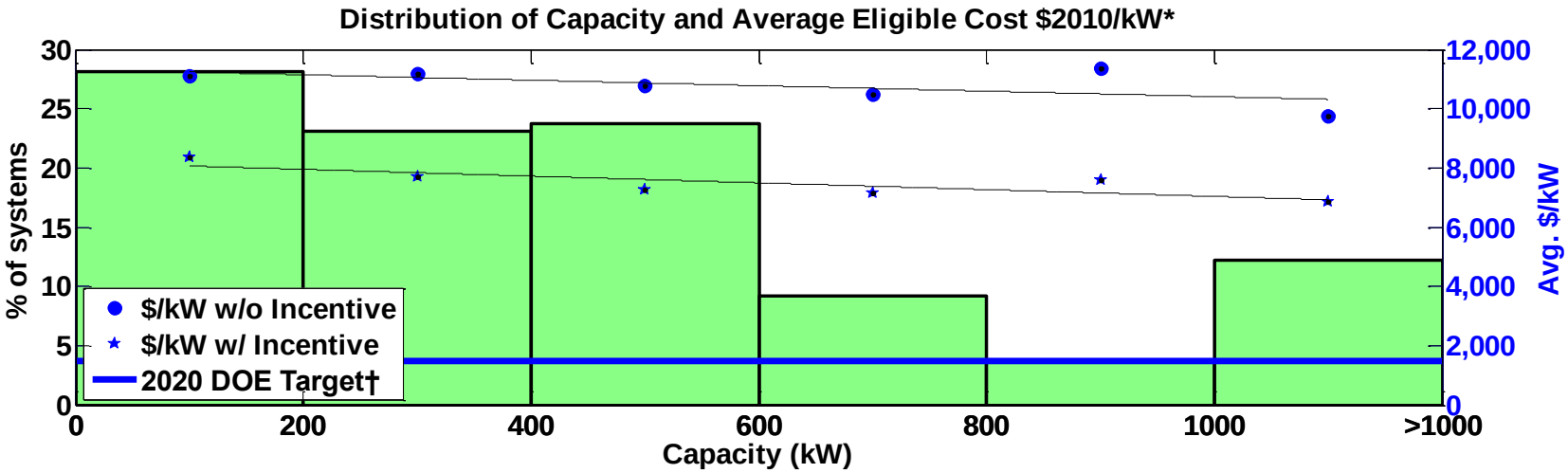
The innovative Doosan PureCell® System is a complete energy solution for generating clean electricity and heat from natural gas with a market-leading energy efficiency and reliability.

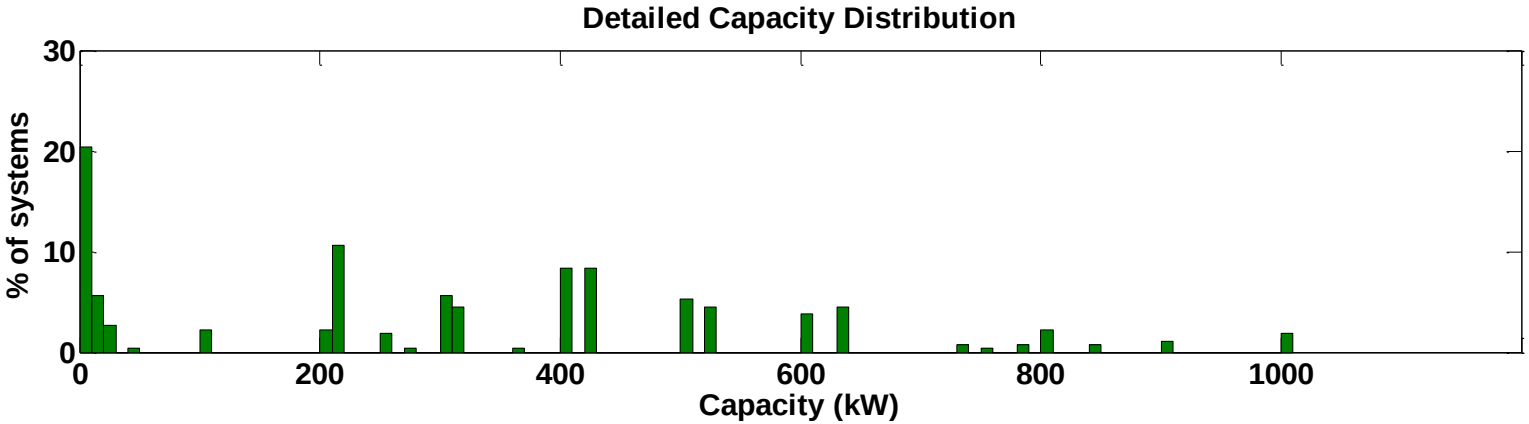
The PureCell® System is a clean-tech marvel, a complete energy solution for commercial buildings that generates not only clean continuous electricity, but also heat and cooling.





Fuel Cell Stationary Capacity and Average Prices





Eligible Costs May Include: Planning & Feasibility Study, Engineering & Design, Permitting, Self-Generation Equipment Waste Heat Recovery Costs, Construction & Installation Costs, Gas & Electric Interconnection, Warranty, Maintenance Contract Metering, Monitoring & Data Acquisition System, Emission Control Equipment Capital Gasline Installation, Fuel Gas Clean-up Equipment, Electricity Storage Devices, Bond to Certify Renewable Fuel Sales Tax, Fuel Supply (digesters, gas gathering, etc.), Thermal Load, & Other Eligible Costs

†for the year 2020, operating on natural gas.
*Data from the California SGIP.

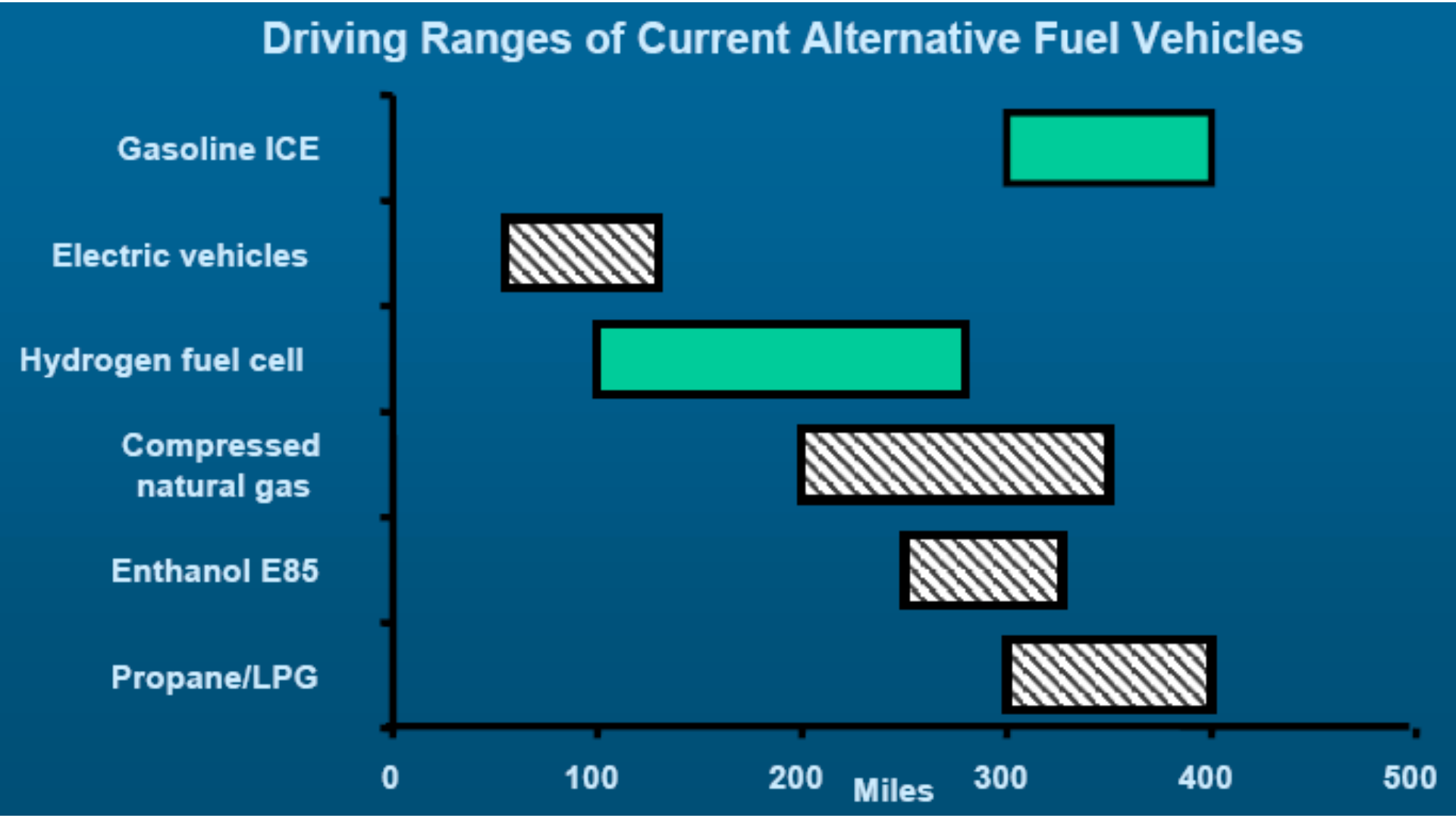
NREL cdp_stat_06
Created: Sep-27-13 11:23 AM | Data Range: 2001Q2-2013Q2

Bloom Energy FC Systems

- On March 3, 2016 Hotels Magazine published an article, written by the Fuel Cell and Hydrogen Energy Association, highlighting Bloom Energy's solid oxide fuel cell (SOFC) installation at the Hyatt Regency in Greenwich, Connecticut.
- In December of 2015, Hyatt installed a 500 kilowatt (kW) SOFC fed by natural gas, which supplies 75% of the facility's electric load. The SOFC is expected to result in costs savings, as well as CO2 emission reductions of 40% when compared to utility-purchased electricity.
- The article breaks down the numerous other benefits of stationary fuel cells, including scalability, silent operation, and reliability.

http://ac.els-cdn.com/S1464285915303436/1-s2.0-S1464285915303436-main.pdf?_tid=e4c5e84c-f76e-11e5-aafc-00000aacb35f&acdnat=1459449316_cf098dace960763a183a8840ac0d8ec8

Can FC Vehicles Perform as Customers Expect Them To?



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Transportation

- Cars - All the major automotive manufacturers have a fuel cell vehicle either in development or in testing right now, and several have begun leasing and testing in larger quantities.
- Commercialization is a little further down the line (**some automakers already have, others later**), but every demonstration helps bring that date closer.

Commercially Available FCEVs—2015 Activities and 2016 Plans

Commercially Available FCEVs – 2015 Activities and 2016 Plans				
Automaker	**Model**	**Image**	**2015 News**	**Specs**
Hyundai	Tucson Fuel Cell (North America) ix35 Fuel Cell (South Korea, Europe)		The first Tucson Fuel Cell vehicles were delivered to customers in Vancouver, Canada. 70 vehicles delivered in the U.S.through May 2015.	50 miles/gallon gas equivalent (gge) 265 mile range 100 kW stack
Toyota	Mirai		Mirai sales were started in California, The U.K., Belgium, Denmark and Germany. 200 vehicles delivered in the U.S. in 2015.	67 miles/gge 312 mile range 114 kW fuel cell stack
Honda	Clarity Fuel Cell		Honda unveiled its new FCEV, the Clarity Fuel Cell, at the Tokyo Motor Show.	300) mile range (preliminary range estimate determined by Honda) 100 kW stack

Hyundai

- Series production of the Hyundai ix35 fuel cell electric vehicle (FCEV) is to begin later this month the automaker has confirmed as the car wins the prestigious FuturAuto accolade at the 2013 Brussels Motor Show
- 1,000 units of the car built in 2015 and 2016

https://www.hyundaiusa.com/tucsonfuelcell/

Transportation

- Buses - Over the last 4 years, **more than 50 fuel cell buses** have been demonstrated in North and South America, Europe, Asia and Australia.
- Fuel cells are highly efficient, so even if the hydrogen is produced from fossil fuels, fuel cell buses can reduce transit agencies' CO_2 emissions.

The Starbus has a H2 FC with gross peak power of 114 HP, coupled with an electric motor with peak output of 250 HP; top speed: 70 km/h.

Ballard to Supply 21 Fuel Cell Bus Modules to Van Hool

- Ballard Power Systems has signed an equipment supply agreement with Van Hool NV, Europe's fourth largest bus manufacturer, for 21 of Ballard's latest-generation FCvelocity™-HD6 fuel cell power modules.
- John Sheridan, Ballard's CEO, called the agreement “an important step toward fuel cell bus commercialization”.

Ballard and Van Hool Launch Service Centre to Support European Clean Energy Fuel Cell Buses

Transportation

- And **emissions are truly zero if the hydrogen is produced from renewable electricity**, which greatly improves local air quality.
- Because the fuel cell system is so much quieter than a diesel engine, **fuel cell buses significantly reduce noise pollution** as well.

FCHV-BUS Operation Plan

Dec. 7, 2010: Toyota Motor Corporation (TMC) and Hino Motors, Ltd. (Hino) announce that they will provide a fuel-cell hybrid bus for a commercial bus route between central Tokyo and Tokyo International Airport (Haneda Airport)

TMC and Hino plan to analyze data from the operations of the bus and, with a mind toward practical application of fuel-cell hybrid buses, to proceed with further research and development.

Start	December 16, 2010
Routes	Haneda Airport Route (Airport Transport Service Co., Ltd.) Morning: Shinjuku Station West Exit ↔ Haneda Airport Afternoon: Tokyo City Air Terminal ↔ Haneda Airport
Schedule	1 round trip daily on each route
Vehicles used	1 unit (and 1 reserve unit)

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AC Transit Hydrogen Fuel Cell

- UTC Power has announced on January 13, 2010, one of its latest generation PureMotion Model 120 FC powerplants for hybrid-electric transit buses has surpassed 5,000 operating hours in real-world service with its original cell stacks and no cell replacements.
- This powerplant is aboard an Alameda-Contra Costa Transit District (AC Transit) bus operating in the Greater Oakland, California area.
- According to UTC Power Vice President-Transportation Ken Stewart, "Stack durability matters".

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AC Transit Hydrogen Fuel Cell

- Three of AC Transit's buses are equipped with UTC Power fuel cell systems and have now traveled more than 213,000 miles, with an average fuel economy that is 65 percent better than the control fleet of diesel buses running the same routes and duty cycles.

http://www.actransit.org/environment/fuelcell_photogallery.html

World Tour (Jan 2011)

- Mercedes, in a media presentation at the North American International Auto Show, said it will have **70 fuel-cell powered B-class vehicles on the road soon in California to help prove the concept**.
- The company promoted an **around-the-world tour by fuel-cell B Class**, starting in Vancouver, Canada, to promote the concept and prove its viability.
- 4 continents & 125 fueling stops

https://www.youtube.com/watch?v=HfLN7aM_Zjk

The Invisible Car

- In a promotion for its first production fuel-cell vehicle in Germany, Mercedes-Benz turned a B-Class hatchback invisible -- at least, from a distance, using the same idea behind the invisible car in the James Bond film "Die Another Day."

http://autos.yahoo.com/blogs/motoramic/invisible-mercedes-brings-james-bond-technology-life-171557818.html

Transportation

- **Scooters - In spite of their small size, many scooters are pollution powerhouses.**
- Gas-powered scooters, **especially those with 2 stroke engines, produce tailpipe emissions at a rate disproportionate to their small size.**
- These two-stroke scooters produce almost as much particulate matter and significantly more hydrocarbons and carbon monoxide as a heavy diesel truck. FC scooters running on H2 will eliminate emissions - **in India and Asia** where many of the population use them - this is a great application for FCs

FC Scooter

fuel	hydrogen
climb	10 km/hr@ 10 degree
fuel storage	metal hydride
fuel consumption@30km/hr	1.2 g H_2/km@30km/hr
refuel	canister exchange
range (1)	80 km@ 30 km/hr


FCU Bio-H2 Car
FC Micro-Car

Audi

http://www.theverge.com/2016/1/11/10748442/audi-h-tron-quattro-naias-2016

https://www.youtube.com/watch?v=qj7ve6im7po

Toyota FCV Concept

- http://www.youtube.com/watch?feature=player_embedded&v=rN3aqDpl_Vw

https://www.youtube.com/watch?v=xFyY7_hc-14

http://www.youtube.com/watch?feature=player_detailpage&v=niM7VMjRU9Q

https://www.youtube.com/watch?v=GUjYIaUGmqU

TATE
Y

Toyota Patents are Free To Use

- Toyota will be making more than 5,600 of its hydrogen fuel-cell technologies patents free to use for a large number of companies in the industry/sector — absolutely no charges, including no royalty payments

Mirai

- The Mirai's futuristic interior design is thoughtful and appealing, and puts everything in easy reach.

Refueling a FC Car

- Fueling the Mirai is as simple as filling a traditional car with gasoline, and about as quick

Affordability

- Toyota Mirai: MSRP of $58,335
- Tax incentives : up to $8,000
- Lease: $499 a month, 3 years, $4,000 down
- Fuel: First three years, up to $15,000 worth of H2 Free.
- **Powertrain:** 113 kW, H2 fuel cell
- **Horsepower:** 151
- **Torque:** 247 pound feet

EPA fuel economy rating: 67 miles per gallon equivalent city / 67 MPGe highway / 67 MPGe combined

A Comprehensive System

Energy diversification

- Hydrogen can be made using a wide variety of primary energy sources.

Fun to drive

- Smooth and quiet, with excellent low- and mid-range acceleration characteristic of motor-driven cars

Zero emissions

- Zero emissions of harmful substances when driven

Performance

- Cruising range on par with a conventional gasoline-fueled vehicle; can be refueled in about three minutes.

Can be used as a power supply

- Can double as a high capacity power supply during emergencies

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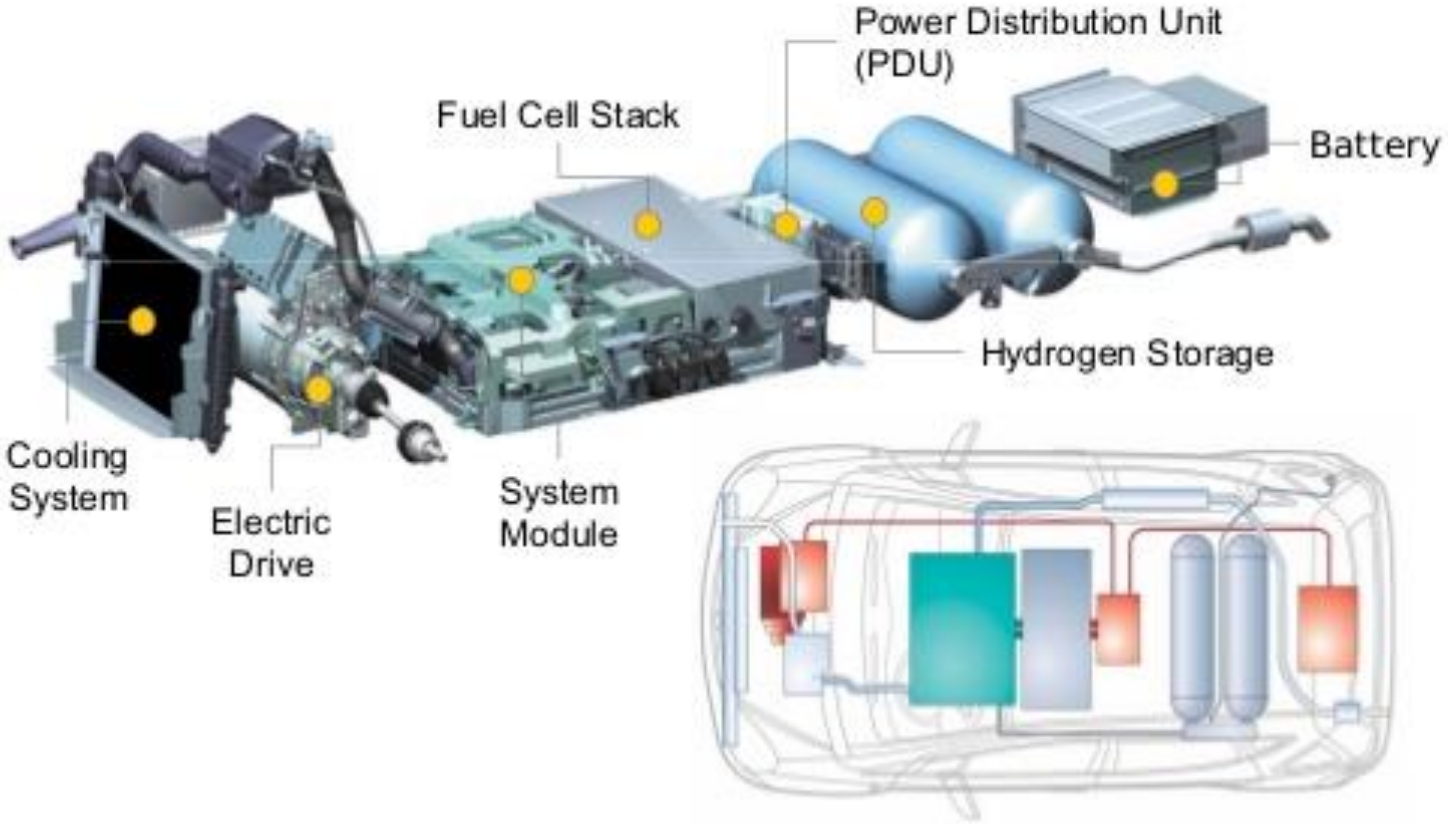
Daimler, FCell Packaging



Honda's New 'Clarity' Fuel-Cell Car Arrives in March

OCTOBER 28, 2015

- The vehicle is notable because it's the first time that a fuel cell powertrain is as compact as a V6 engine. Most other fuel-cell batteries are much larger, requiring more space, and thus, a larger car. The Clarity fuel cell stack, though, is 33 percent smaller than its predecessor.

Honda says it will begin selling the Clarity in March in Japan for approximately $63,600.

FC Cars: in Cold or Hot....

- http://www.youtube.com/watch?v=Gh11nb8KDpU
- http://www.youtube.com/watch?v=ajo-eAAmvxk&feature=youtu.be

The Clarity's hydrogen tanks fit beneath and behind the rear seats.

Honda to launch hydrogen fuel-cell car in California this year

- Honda Motor Co Ltd said on Thursday (1/21/16) its hydrogen fuel cell car, dubbed Clarity Fuel Cell, will be launched in California before the end of 2016.
- The new 5-passenger sedan is expected to be priced at around $60,000 with a monthly lease of under $500, Honda said in a statement released at the D.C. Auto show.

Honda Clarity 2017

- Range: 366 Miles
- Lease: $369/mo., 36 Months with $2,868 down

Video Address:

https://automobiles.honda.com/-/media/Honda-Automobiles/Vehicles/2017/Clarity/All-Videos/MP4/Honda-Fuel-Cell-Clarity-Video.mp4

Can you buy one?

- https://www.hyundaiusa.com/tucsonfuelcell

  - The amazing Tucson Fuel Cell
  - $499/month
  - • Free Fuel
  - • Free Concierge Maintenance
  - • HOV Lane Access
  - 36-month lease, $2,999 due at lease signing.

Nikola One is probably bigger than an apartment

18 Wheeler Truck

- Nikola One, America's first hydrogen-powered semi, is straight outta the future
- With a claimed range of 1,200 miles and massive amounts of emissions-free power, could the Nikola One revolutionize trucking?
- https://www.cnet.com/roadshow/news/nikola-one-ev-semi-fuel-cell-hydrogen/

Comparison

- **Volvo Trucks:** 375 to 500 hp & 1,450 to 1,850 pound-feet of torque.
- The Nikola One gets the job done with zero emissions.
- The One's hydrogen fuel cell feeds a set of high-density 320-kWh lithium batteries that power the fully electric drivetrain

- http://www.huffingtonpost.com/entry/toyota-mirai-hydrogen-fuel-cell_us_56a10492e4b076aadcc56fd6?

Hydrogen Fuels Cells Could Be In Your Next Car. Watch How They Work

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Audi Buys Patents For Fuel-Cell Technology From Ballard Systems

- Audi announced today that it will acquire a package of patents from fuel-cell company Ballard Power Systems, which it says will be applied across all VW Group brands.

Sustainable Transportation

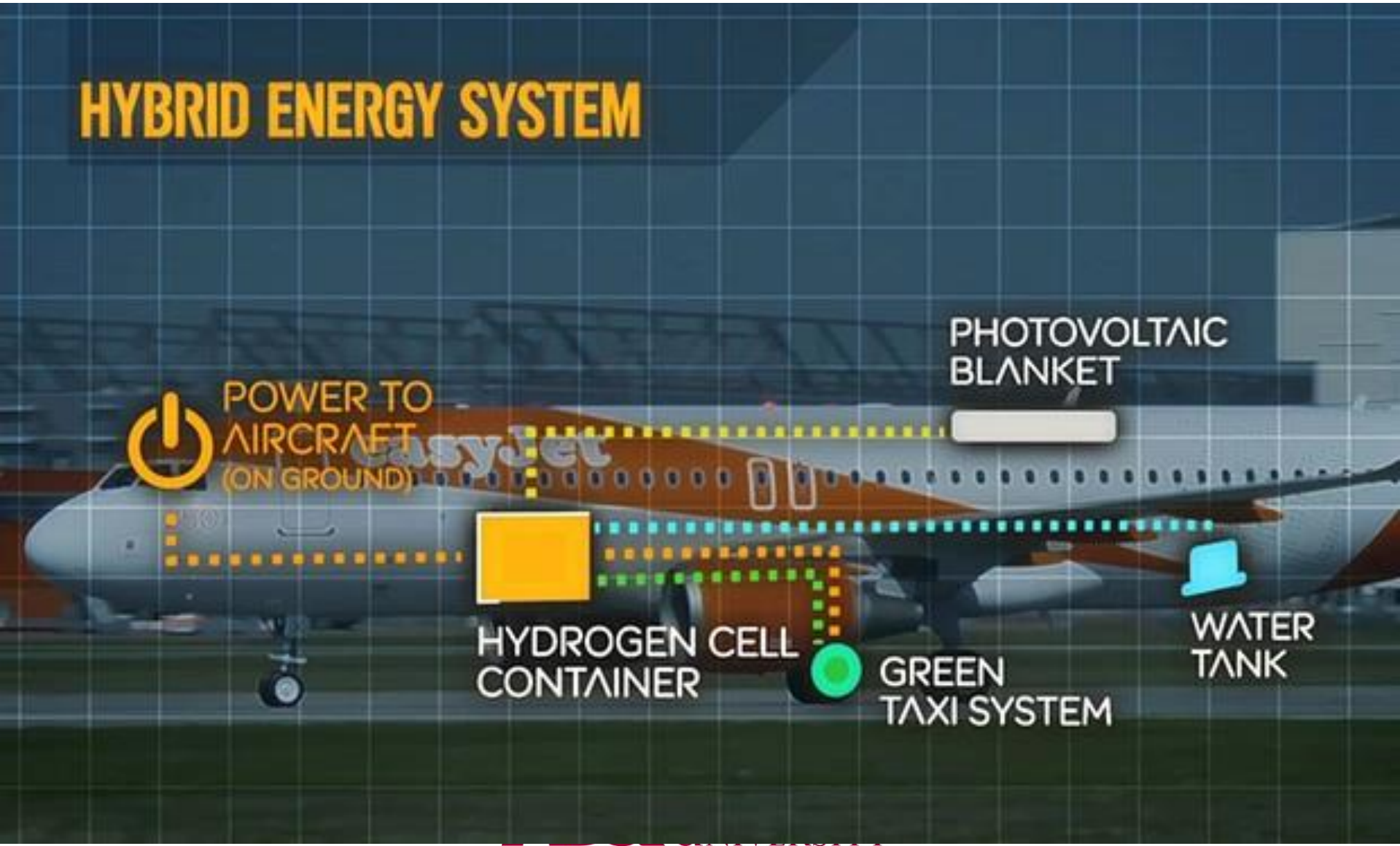
With the global urban population set to reach 6.4 billion by 2050, radical new transportation solutions are needed to avoid ever greater fossil fuel consumption, congestion and pollution.

Transportation

- Planes - **Fuel cells are an attractive option for aviation since they produce zero or low emissions and make barely any noise**.
- The military is especially interested in this application because of the **low noise, low thermal signature and ability to attain high altitude**.
- Companies like Boeing are heavily involved in developing a fuel cell plane.

http://www.theguardian.com/travel/2016/feb/02/easyjet-plans-cut-carbon-emissions-hydrogen-fuel-cell-trial

- EasyJet plans to cut carbon emissions with hydrogen fuel-cell trial



Transportation: Locomotives

- East Japan Railway Company recently conducted fuel cell tests on this single carriage unit
- The NE Train appears no different from any other train

Transportation

- **Forklifts/Materials Handling** - Besides reducing emissions, fuel cell forklifts have potential to effectively lower total logistics cost since they require minimal refilling and significantly less maintenance than electric forklifts, whose batteries must be periodically charged, refilled with water, and replaced.

Transportation

- Due to the frequent starting and stopping during use, electric forklifts also experience numerous interruptions in current input and output - fuel cells ensure constant power delivery and performance, eliminating the reduction in voltage output that occurs as batteries discharge.

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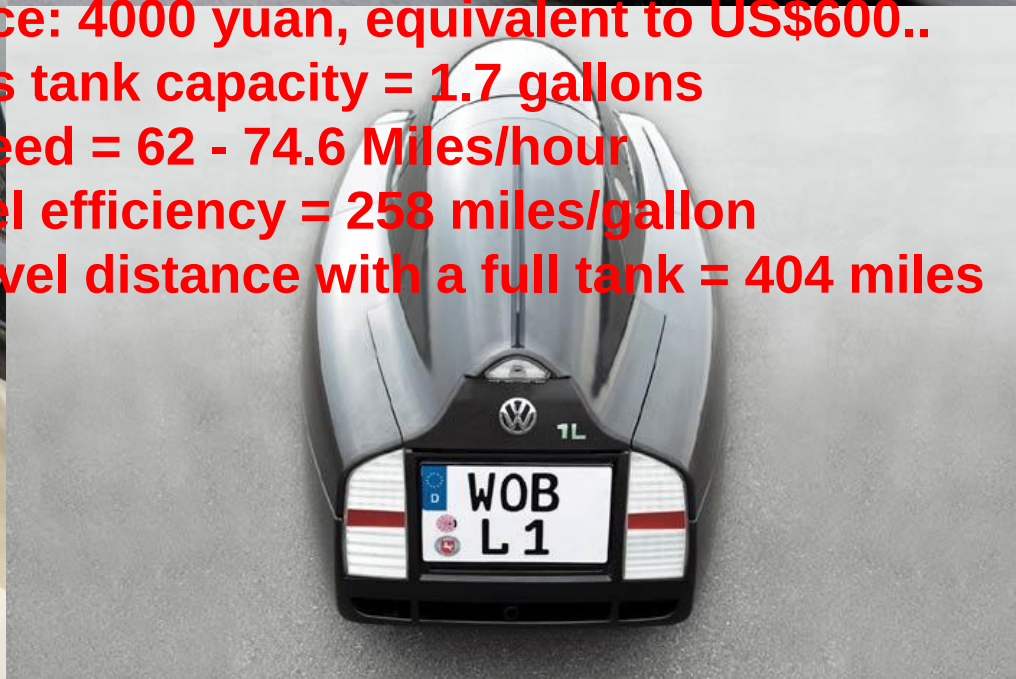
Single Seat Car from VW

Better than Electric Car - 258 miles/gallon:

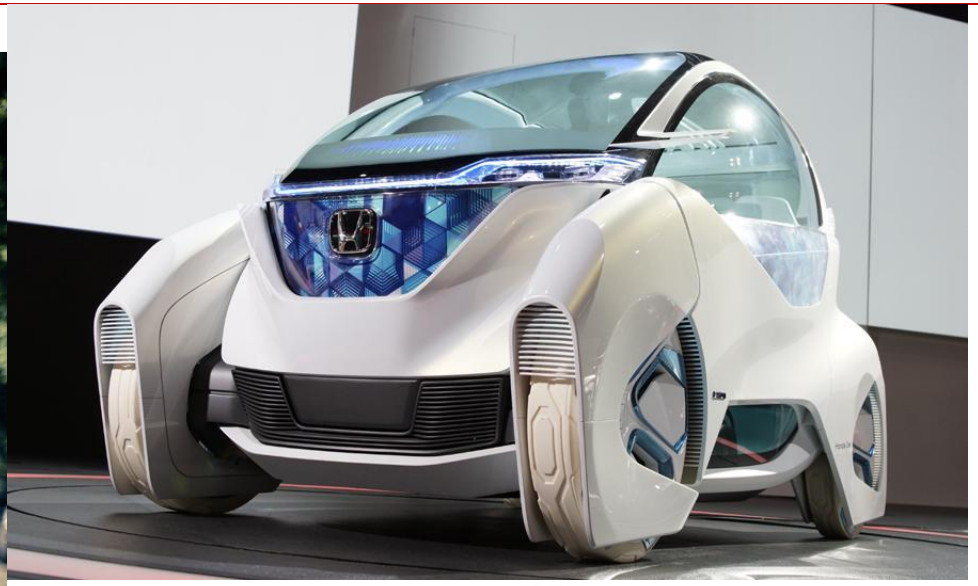
Price: 4000 yuan, equivalent to US$600..
Gas tank capacity = 1.7 gallons
Speed = 62 - 74.6 Miles/hour
Fuel efficiency = 258 miles/gallon
Travel distance with a full tank = 404 miles



P-NUT from Honda

- Personal-Neo Urban Transport (P-NUT)

Other Bugs



The World's Smallest Hydrogen Fuel Cell Car

- An external fueling station
- H2 gas in a small balloon inside the car
- Runs for three minutes and can travel up to 325' on a full tank.

The fueling station is powered by a solar panel or two AA batteries.
6 1/3" L x 2 3/4" W. (7 oz.)

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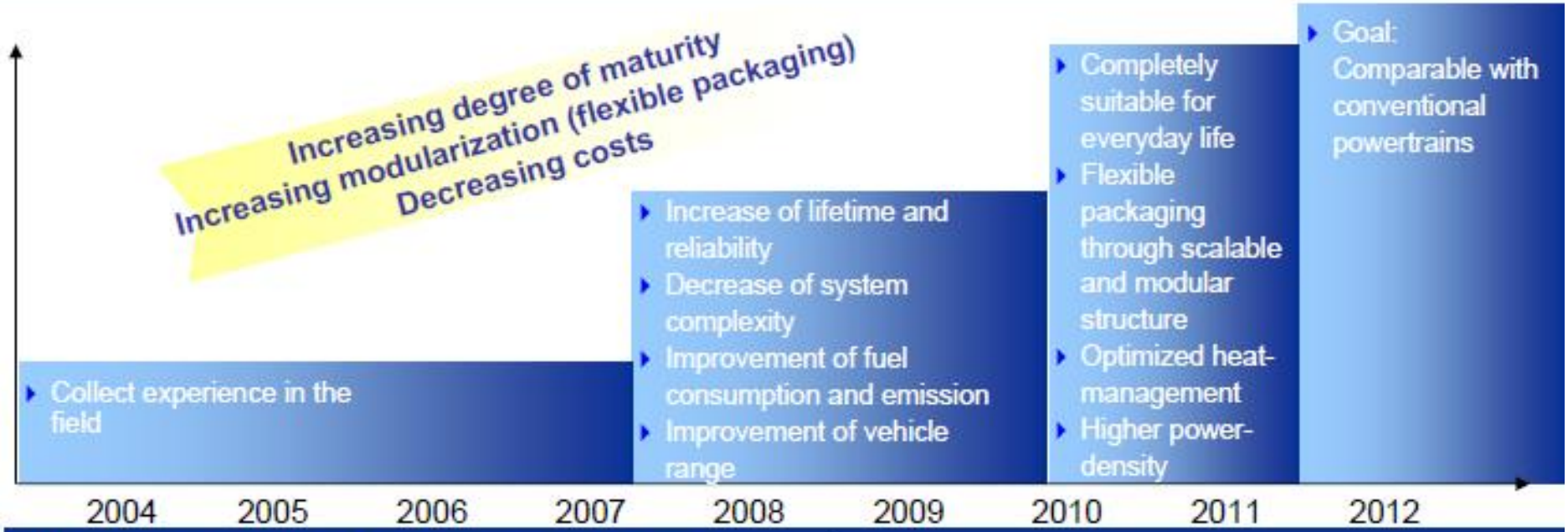
R&D Roadmap for FC Vehicles



Necessary work fields for fuel cell research

- Materials (e.g. HT-Membrane)
- Components (e.g. new MEAs)
- Concepts (System, Stack)
- H2-Storage
- Operation strategies
- Test procedures / analytical tools
- Modeling

- **Focus research activities on major challenges**
- **Align research activities of academia and industry**

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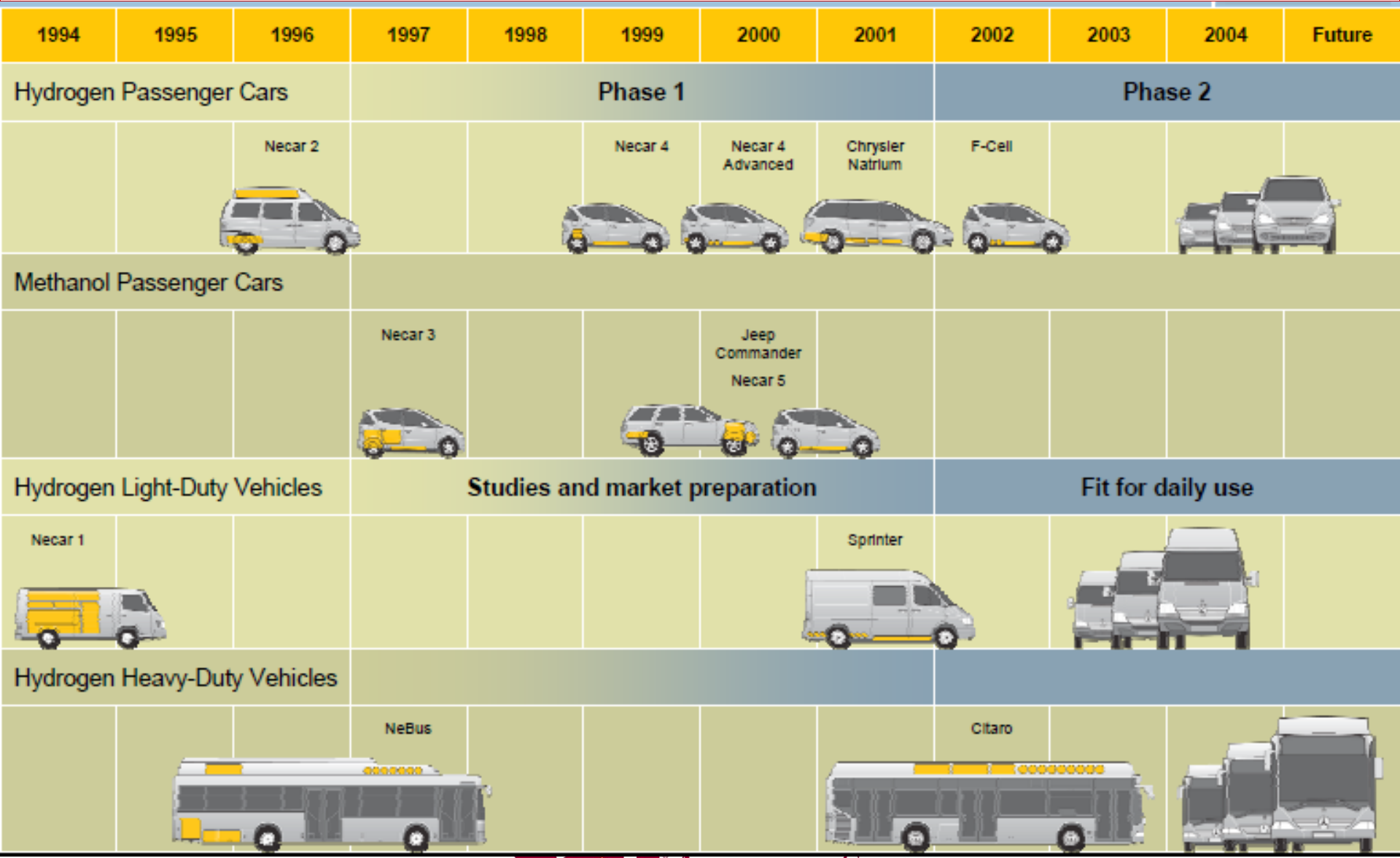
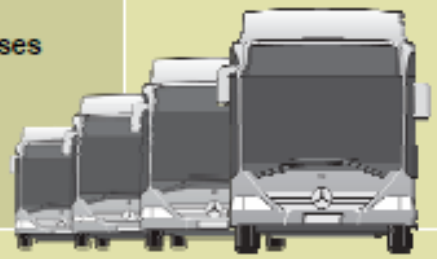
At the Daimler-Chrysler



4 Phases to Commercialization

2003	2007	2010	Future
Market preperation	Fit For Daily Use	Ramp-Up	Commercialisation
Passenger Cars	60 F-Cell vehicles		
Light-Duty Vehicles	2 FuelCell Sprinter		
Heavy-Duty Vehicles	36 Citaro Fuel Cell Buses		



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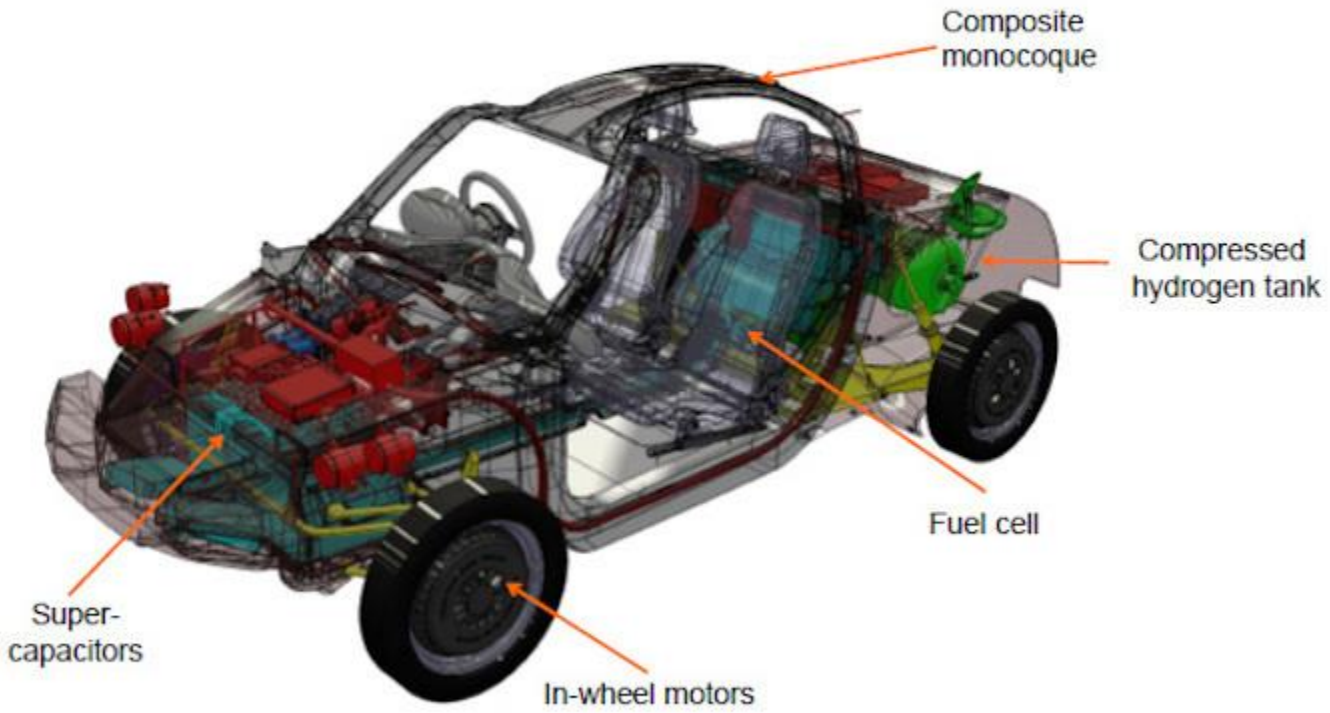
http://www.computerworld.com/article/3034318/emerging-technology/this-car-travels-300-miles-on-just-85oz-of-hydrogen-gas.html

Feb 17, 2016

The Rasa hydrogen fuel cell car from Riversimple Movement has a chassis made from carbon fiber composite skin weighing less than 90lbs. Range of up to 300 miles on 85 ounces (1.5 kilograms) of hydrogen; that's an estimated fuel economy equivalent to 250mpg using 8.5 kilowatt (kW) fuel cell .


Composite
monocoque
Compressed
hydrogen tank
Fuel cell
Super-
capacitors
In-wheel motors

Tata Iris Magic Ziva Unveiled in India

http://www.hydrogencarsnow.com/index.php/hydrogen-cars/tata-iris-magic-ziva-unveiled-in-india/

http://www.alternative-energy-news.info/headlines/hydrogen/

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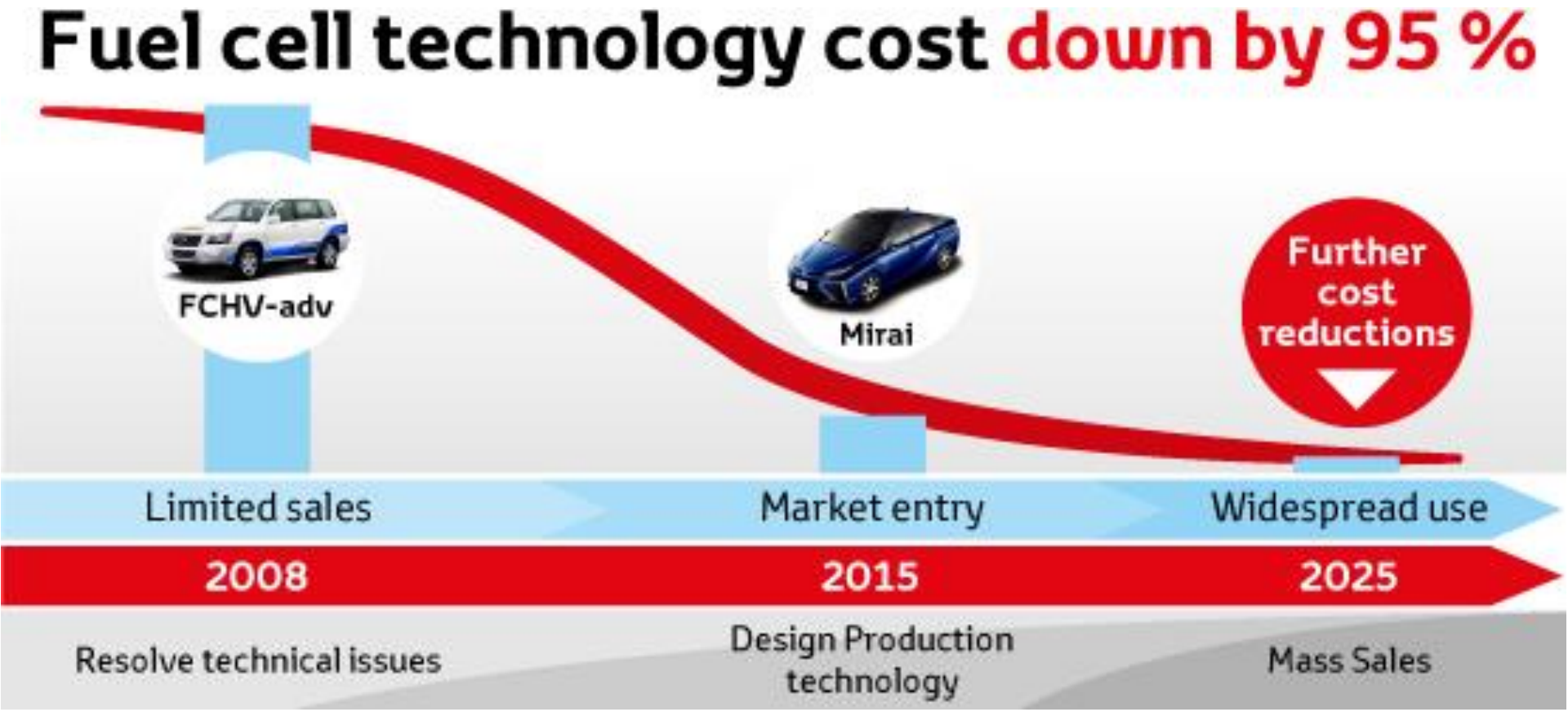
Nissan To Launch Fuel Cell Vehicle By 2021

- Nissan is planning to add a fuel cell vehicle to its zero-emission lineup, though the company noted that it won't be rushing to get the vehicle to market

A portion of the FCV will be developed in collaboration with Daimler AG.
"The only question about fuel cells is, we just think it is too early," Ghosn said. "We're facing already a problem with the charging infrastructure in electric cars. You can imagine the problem we're going to have with fuel cells

"An analysis by the National Renewable Energy Laboratory put the cost of upgrading one service station to dispense hydrogen at $2.5 million," he said. "By comparison, EVs can be charged at home or work; a typical home EV charger costs less than $2,000 installed. In the United States, there are more than 8,800 public charging stations, compared with 13 hydrogen stations."

FC vehicles are too expensive?



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California Fuel Cell Partnership, USA

Project profile

California is the home to a unique collaborative of auto manufacturers, energy companies, fuel cell technology companies, and government agencies.

The partnership aims to achieve four main goals:

- Demonstrate vehicle technology by operating and testing the vehicles under real-world conditions in California
- Demonstrate the viability of alternative fuel infrastructure technology, including hydrogen and methanol stations
- Explore the path to commercialization, from identifying potential problems to developing solutions
- Increase public awareness and enhance opinion about fuel cell electric vehicles, preparing the market for commercialization

Mobility partners	Infrastructure partners
DaimlerChrysler	BP
General Motors	Exxon Mobil
Ford	Shell
Hyundai	Methanex
Honda	Chevron Texaco
VW	Praxair
Nissan	Air Products
Toyota	
Technology partners	**Flanking partners**
Ballard	AQMD
UTC Fuel Cells	California Energy Commission

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Auxiliary Power Units (APUs)

- Today's heavy-duty trucks are equipped with a large number of electrical appliances–from heaters and air conditioners to computers, televisions, stereos, even refrigerators and microwaves.
- To power these devices while the truck is parked, drivers often must idle the engine.
- DOE has estimated the annual fuel and maintenance costs of idling a heavy-duty truck at over $1,800 and that using FC APUs in Class 8 trucks would save 670 million gallons of diesel fuel/ yr and 4.64 million tons of CO_2 per year.

Boats

- Fuel cell engines have higher energy efficiencies than combustion engines, and therefore offer better range and significantly reduced emissions.
- Iceland has committed to converting its vast fishing fleet to use fuel cells to provide auxiliary power by 2015 and, eventually, to provide primary power in its boats.

Portable Power

- Fuel cells can provide power where no electric grid is available, plus they are quiet, so using one instead of a loud, polluting generator at a campsite would not only save emissions, but it won't disturb nature, or your camping neighbors.
- Portable fuel cells are also being used in emergency backup power situations and military applications.
- They are much lighter than batteries and last a lot longer, especially important to soldiers carrying heavy equipment in the field.

Consumer Electronics

- Fuel cells will change the telecommuting world, powering cellular phones, laptops and palm pilots hours longer than batteries.
- Companies have already demonstrated fuel cells that can power cell phones for 30 days without recharging and laptops for 20 hours.
- Other applications for micro fuel cells include pagers, video recorders, portable power tools, and low power remote devices such as hearing aids, smoke detectors, burglar alarms, hotel locks and meter readers.

News (January 16,09)

- On 14 January 2009, the US Department of Transportation's (US DOT) Pipeline and Hazardous Material Safety Administration (PHMSA) published its final rule allowing transport of fuel cells and a wide range of fuels on board US passenger aircraft as carry-on baggage, the US Fuel Cell Council (USFCC) has reported.
- This new rule also provides for routine cargo shipment of fuel cells and fuel cell cartridges by road and rail, as well as international ocean shipment in bulk.

Swedish company MyFC showed off JAQ, a compact fuel cell designed to provide an 1800ma charge to smartphones. Itself the size of a smartphone, the JAQ uses thin, light plastic cartridges that you insert when you need a charge.

http://www.zdnet.com/article/fuel-cell-come-of-age-at-ces-2016/#ftag=YHFb1d24ec?ref=yfp

A second practical fuel-cell comes from Japanese company **Aqua Power Systems.** They have sold 8 million fuel-cell water-activated AA batteries and fuel-cell lanterns in Japan. Now they're bringing their newest products - a USB charger lantern and a charger-only cell - to the US.

FC Tech Could Power Smartphones for a Week

http://fortune.com/2016/02/09/smartphone-fuel-cell-battery/

On Monday (2/9/16), the British company announced a new, mysterious partnership with what it describes as an “emerging” smartphone manufacturer (as in, likely not Apple or Samsung) to bring hydrogen fuel cell technology to mobile devices. That could mean consumers would get an entire week’s worth of phone usage on a single charge.

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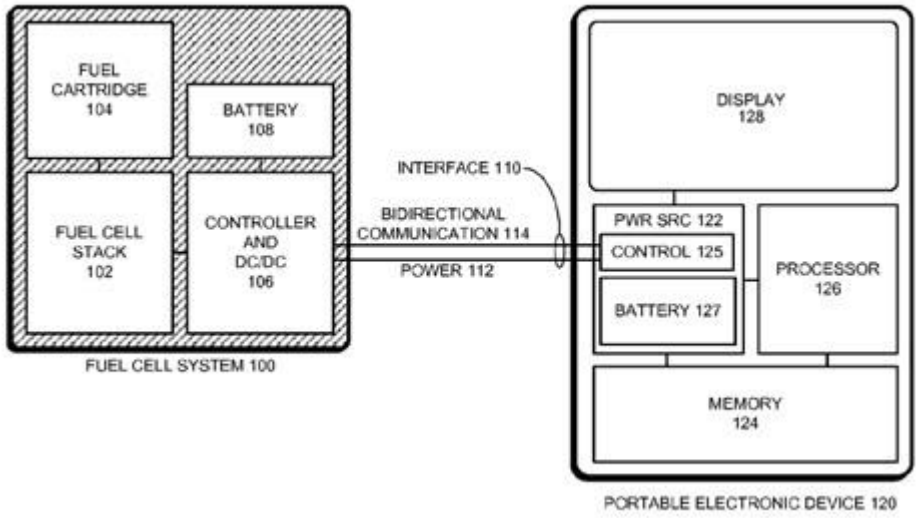
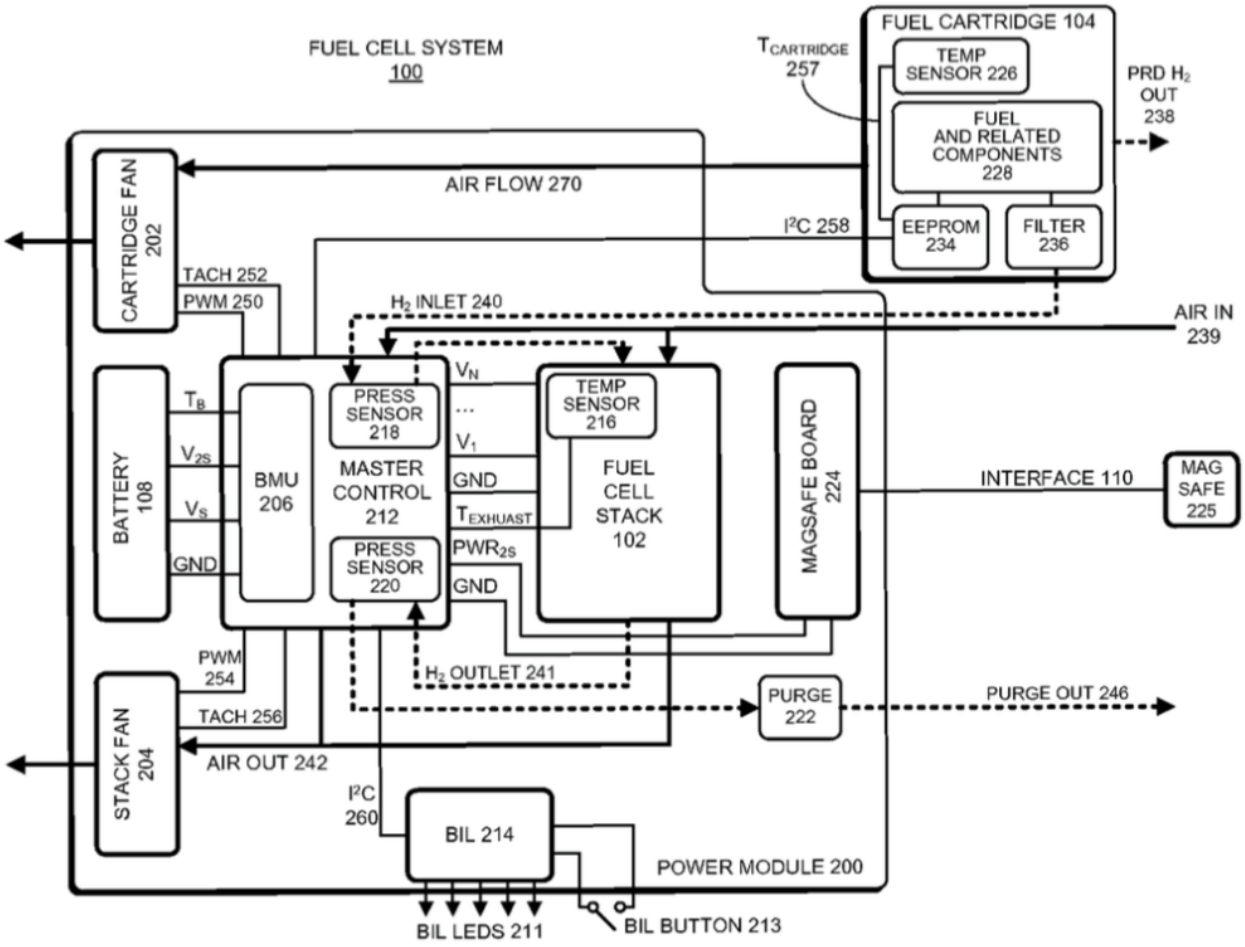
Apple to use FCs

- **Apple Patents** (US 2011/0311895 and 2011/0313589) **Show How Fuel Cells Could Integrate into Future MacBooks, Charge iDevices**

- A duo of patents uncovered in October 2011 signalled that Apple was actively interested in the use of fuel cells for powering some of its consumer devices. Apple is notorious in its obsession with thinness and lightness and October's patents showed how the company could develop lightweight monopolar fuel cells.



Apple's Patent



September 3, 2015

The U.S. Patent and Trademark Office has today published a patent application from Apple for a fuel cell system designed to allow a MacBook to operate without external power "for days or even weeks." The patent was published shortly after a British company rumored to be working with Apple managed to fit a fuel cell battery into an iPhone 6, powering it for a week at a time.

The fuel source comprises at least one of: sodium borohydride and water; compressed hydrogen gas; and liquid hydrogen.

TE

News updates

Fuel cell and Hydrogen Energy Association for monthly updates

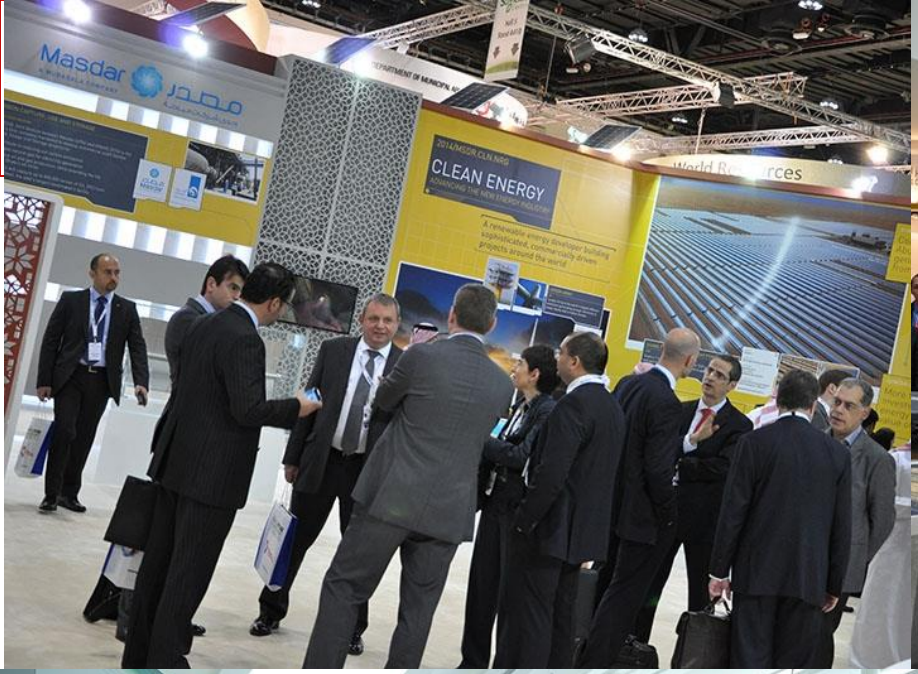
- http://fchea.org/

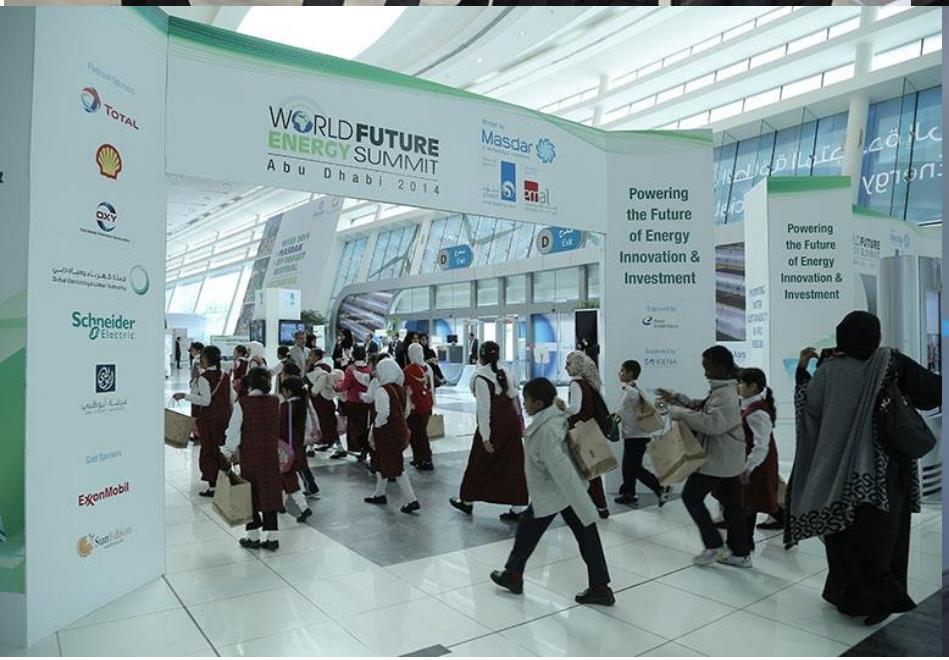
World Future Energy

http://www.worldfutureenergysummit.com/Portal/media-centre/wfes-videos.aspx

World Future Energy Summit

The UAE hosted the World Future Energy Summit, in partnership with Masdar, the $22 billion project that is set to be the first zero-carbon footprint, zero-waste, totally renewably powered settlement


Masdar
CLEAN ENERGY


TOTAL
WORLD FUTURE ENERGY SUMMIT
Abu Dhabi 2014
Masdar
Powering the Future of Energy Innovation & Investment
Powering the Future of Energy Innovation & Investment
Schneider Electric
ExxonMobil


WORLD FUTURE ENERGY SUMMIT
TOTAL

What is Masdar Initiative?

- In April 2006, Abu Dhabi took a bold and historic decision to embrace renewable and sustainable energy technologies.
- As the first major hydrocarbon-producing nation to take such a step, it has established its leadership position by launching the **Masdar Initiative**, a global cooperative platform for open engagement in the search for solutions to some of mankind's most pressing issues: **energy security, climate change and truly sustainable human development**.

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On the corporate side, the Masdar Initiative has attracted some of the global leaders in sustainable energy and clean-tech development, including GE, BP, Shell, Mitsubishi, Rolls Royce, Total, Mitsui and others, as core strategic partners.

Masdar Initiative

- Masdar, a zero-carbon, zero-waste city is being built on the outskirts of Abu Dhabi, near the international airport.
- It will be home to around 40,000 people, with a further 50,000 commuting in each day.
- The Masdar Institute, a university built in conjunction with MIT, opened in Sept. 09 and powered by a 10 MW solar power plant, also opened in September.



Masdar Initiative

- There is a great deal of discussion going on with the Masdar authorities on integrating fuel cells and hydrogen, not only to allow storage of solar-generated energy, but for fuel cell and hydrogen power plants for electricity, cooling and hydrogen fuel.

http://www.masdar.ae/en/masdar/our-story

Masdar Initiative

- In terms of transport, in keeping with the aim of zero emissions, the Masdar authorities procured H2 powered cement mixers, hydrogen buses and **are looking into building fuel cell powered Passenger Rapid Transit (PRT) booths and Freight Rapid Transit (FRT) vehicles**.
- As conventional ground-based vehicles will not be allowed in Masdar, these underground 'pods' will deliver passengers and goods alike throughout the city and will have to be zero emissions.

https://www.youtube.com/watch?v=z-RpVO6QuDY

Masdar's Personal Rapid Transit Pod

Masdar Initiative

- The streets of Masdar themselves will be akin to a traditional Arabian city, with close-set buildings and narrow streets designed to maximize natural cooling.
- The procurement opportunities in Masdar are huge, as set out in in the World Future Energy Summit-10.
- When the city is completed, everything from power plants to toilet rolls (to quote the Masdar representative) will be required - **the fuel cell industry needs to speak to Masdar to get the dialogue started!**

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Public acceptance of the FC technology

SOCIAL IMPLICATIONS

SOCIAL IMPLICATIONS

- Cost expectations
- Life-cycle analysis of environmental and social impacts
- Uncertainties
- Opportunities
- Obstacles
- The way forward

H_2 production cost

- The cost of H_2 production from natural gas by steam reforming methods is well established; it is about 1.0 US$ kg^{-1} based on inexpensive natural gas available.
- The delivered H_2 cost from biomass waste is only about 2.5 US$ kg^{-1} and
- From electricity (at 2001 US electricity costs) by electrolysis about 5 US$ kg^{-1}.
- Based on coal gasification, the H_2 cost is estimated as over 12 US$ kg^{-1}.

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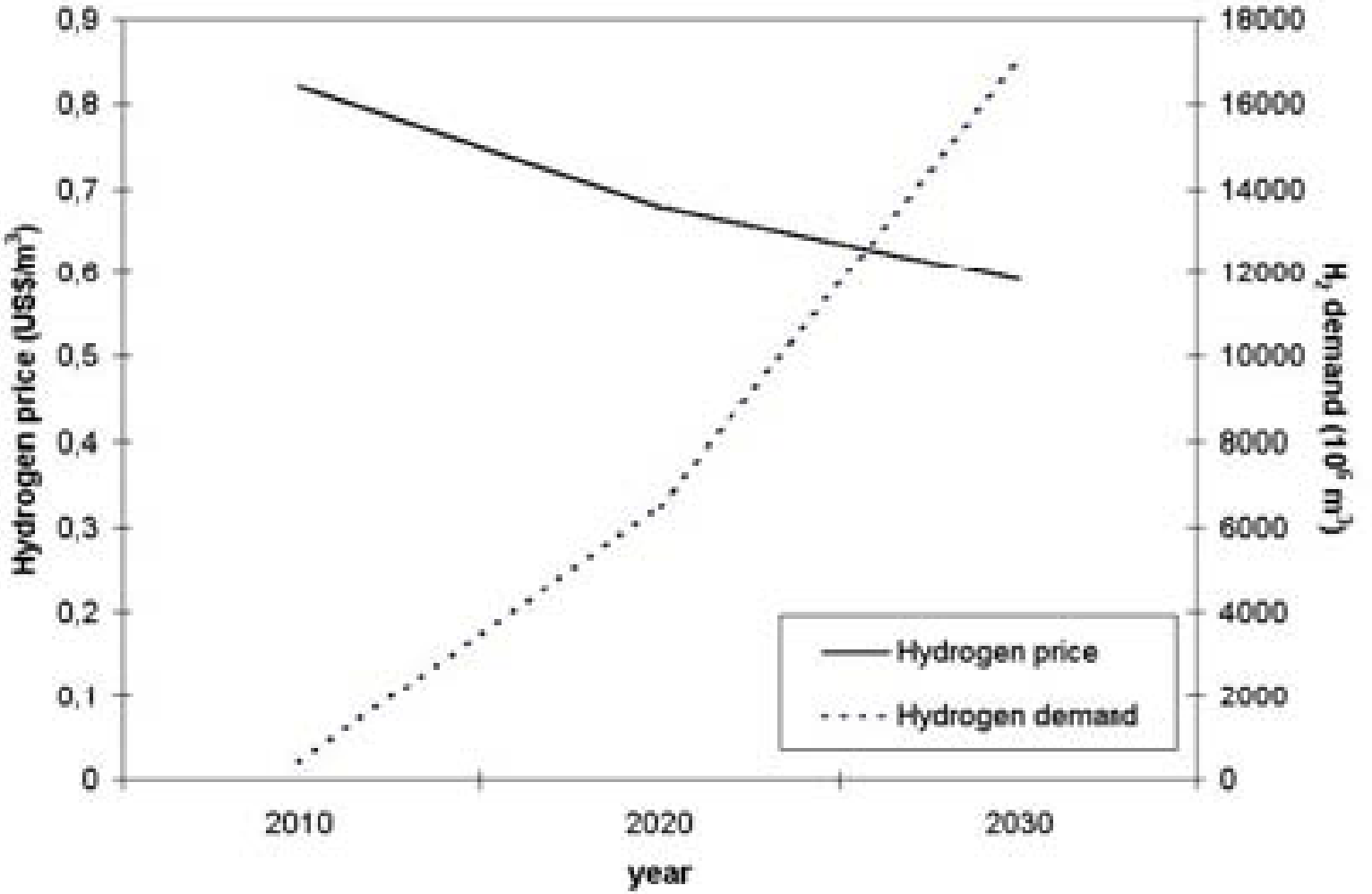
Hydrogen storage costs

- H_2 storage costs comprise capital costs for the equipment used and operational costs, such as power for compression or liquefaction.
- The large-scale underground hydrogen storage in caverns, abandoned natural gas wells, aquifers or salt domes has much lower costs of one order of magnitude below that of liquefied H_2 storage and two orders of magnitude below that of compressed storage) and constitutes a natural choice for centralized storage of hydrogen.

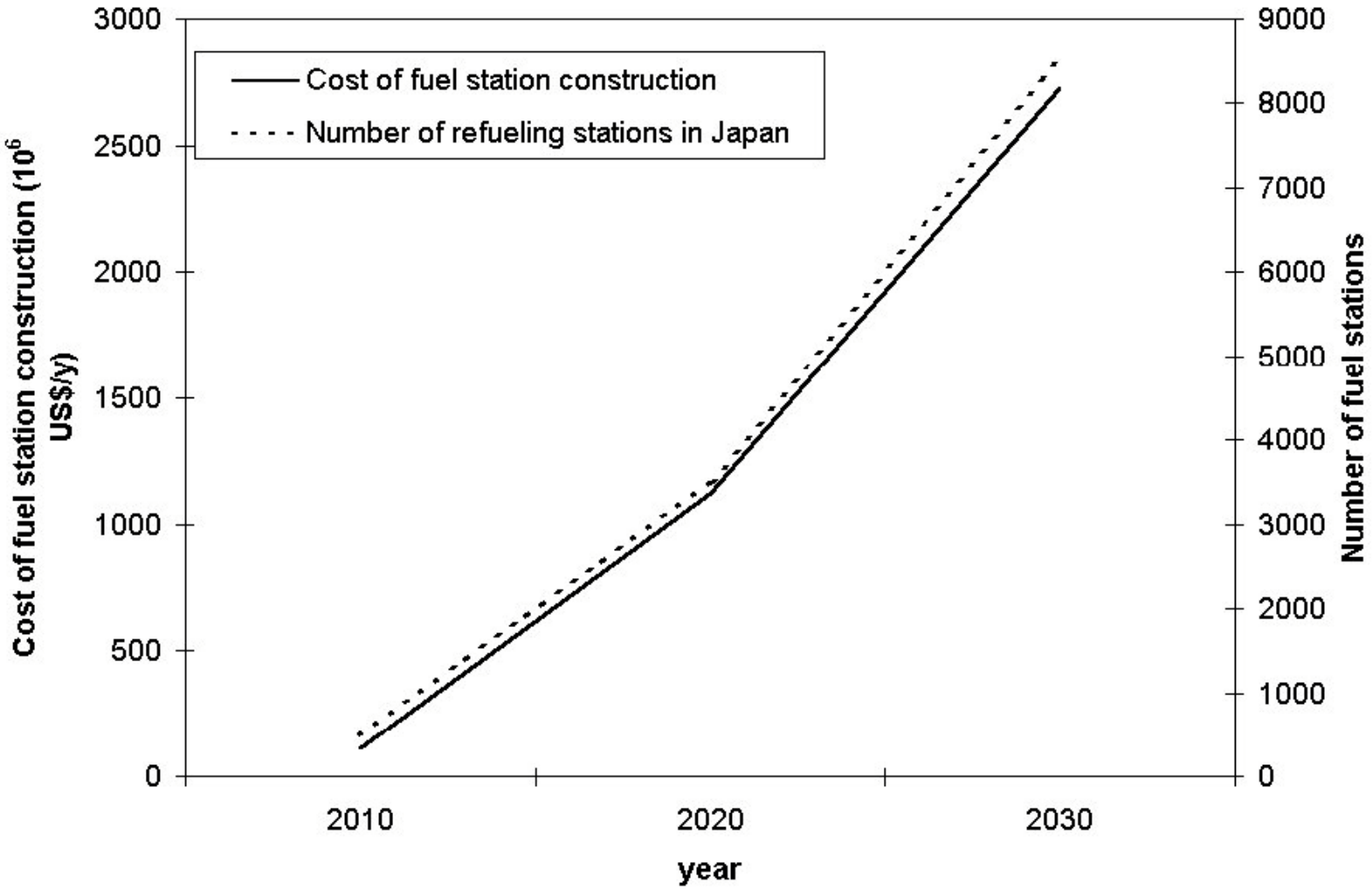
H_2 Price

- Japanese hydrogen demand and price delivered to the customer



H_2 Filling Stations

- Japanese requirement for hydrogen filling stations and their cost



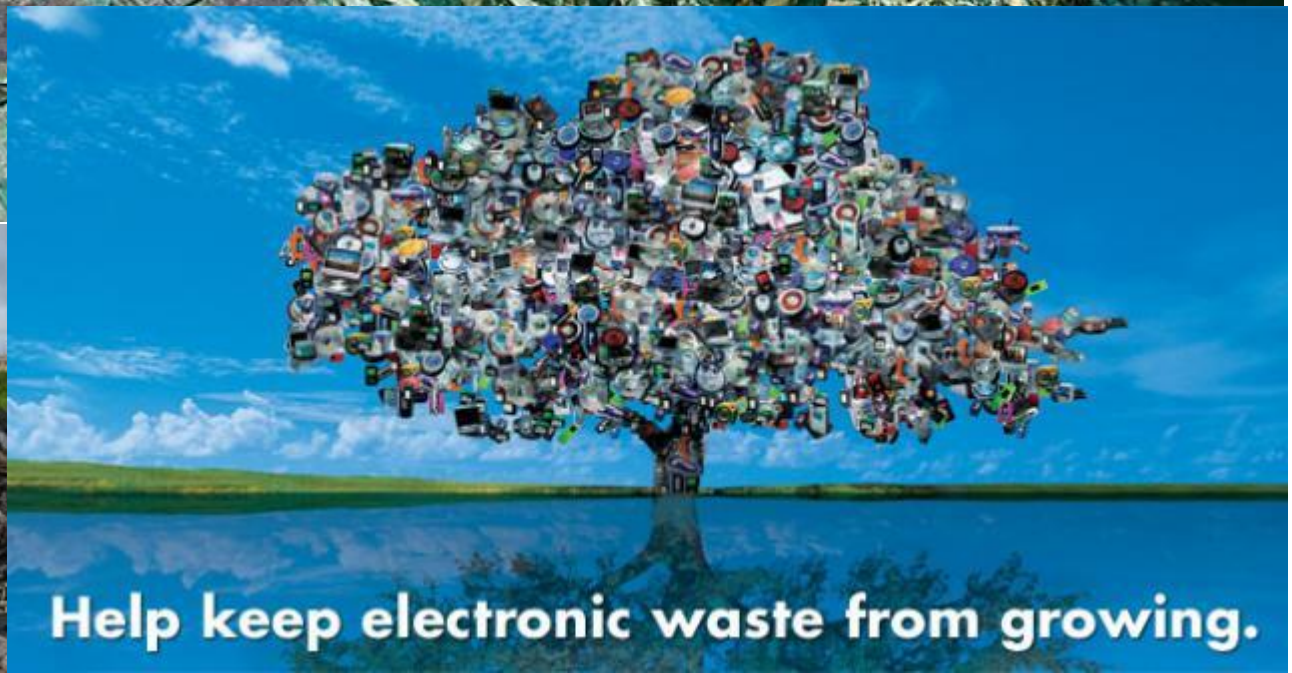
Life-cycle analysis of environmental and social impacts

- The life-cycle assessment of hydrogen production is, in the cases where conventional fuels are converted into hydrogen, similar to many existing studies, in that **major impacts are found to derive from air pollution and global warming issues.**
- For fuel cell conversion of hydrogen, the industrial progress is such that meaningful life-cycle studies can start to be made on a fairly detailed basis.

LCA of FCVs

- Life cycle analysis involves both the analysis of the car manufacture, including the specific additions to traditional cars necessary for fuel cell operation, and also the infrastructure impacts and contributions from the fuel provision and from the final disposal of the product.
- Various definitions ranging from restricted net energy analyses over environmental impact studies to the full consideration of both environmental and social impacts.

E-Wastes (Elephant in the living room)



Life Cycle analysis

- The actual work required for making a life-cycle analysis and assessment of a fuel cells technology may be summarized in the following way:
- Make an inventory of substances or processes with potential harm, from production through the use phase to final decommissioning,
- Perform an impact analysis including environmental effects, health effects and other less tangible social effects,
- Conduct a damage assessment in terms of actual physical damage, or

Life Cycle analysis

- Make an assessment in comparative terms, weighing the different damage contributions on a common scale as far as possible, and eventually
- Suggest alternative procedures for production, materials choice, conditions of use and decommissioning that will reduce those identified impacts deemed critical, and possibly formulate norms and regulation, if it is not preferred to impose taxation or otherwise create economic incentives.

Life Cycle analysis

- A fairly comprehensive list of items to include in a life-cycle analysis:
- ***Economic impacts,*** *as seen from the point of view of the owner (private* economy) or from society (public economy, including considerations of employment and balance of foreign payments).
- ***Environmental impacts,*** *e.g., land use, noise, visual impact, pollution of air,* water, soil and biota, on a local, regional or global scale, including climate change induced by emissions of greenhouse gases or ozone depleting substances.

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Life Cycle analysis

- **Social impacts**, including health impacts, accident risks, effect on work environment and satisfaction of human needs.
- **Security impacts**, including terror actions, misuse, as well as supply security issues.
- **Resilience**, i.e., sensitivity to system failures, planning uncertainty and future changes in value and impact assessments.
- **Impact on development**, i.e., furthering or countering the development goals of society
- **Political impacts**, including requirements for control, regulation and centralisation of decision-making.

Life Cycle analysis

- In order to analyze some (or all) of these impacts, including upstream and downstream components relative to the system or device of primary interest, it is as mentioned a good idea to establish an inventory of substances and processes of relevance and to assess their individual impacts, first in physical terms (emissions, etc.) and then in damage terms (injuries, disease, death, etc.).
- This list can in some cases be reused for assessing other technological items, provided that the inventory is not site- or time-specific.

Life Cycle analysis

- The outcome will be in different units, or in some cases non-quantifiable, and must be submitted to an assessment by decision-makers or by public debate.
- This involves many difficult issues, as damage often occurs at other places or times than the benefits of using the technology.

H_2 Production

- Life-cycle impacts from H2 production by steam reforming of natural gas.

Impact category	*Physical amount g/kWh of H_2*	*Monetised value euro-c/kWh of H_2*	*Uncertainty (range)*
Environment:	Emissions:		
Plant operation: CO_2	320	12.1	(8–30)
SO_x	0.29	0.17	high
NO_x	0.38	0.23	high
CH_4	4.4	2.0	(1–4)
C_6H_6	0.042	NQ	
CO	0.18	NQ	
N_2O	0.0012	–	
non-C_6H_6 hydrocarbons	0.79	NQ	
particulates	0.06	0.04	high
Ni catalyst material	NA		
Plant construction/decommissioning	NA		
Occupational:	Number:		
Industrial disease and accident	0.5 major injury/TWh	0.0004	low
Economic:			
Direct economy (production costs)		3–6	
Resource usage	serious in long run	NQ	
Labour needs for manufacture	5 person-years/MW	NQ	
Import fraction	NA		
Benefits (value of product)		6–12	
Other:			
Supply security	low to fair	NQ	
Robustness	medium	NQ	
Geopolitical	competition	NQ	

H_2 Production

- Life-cycle impacts from photo-induced H2 production using cyanobacteria.

Impact category	*Physical impacts*	*Monetised value euro-c/kWh of H_2*	*Uncertainty, assumptions*
Environment:			
Plant construction/decommissioning	NA		
Land or ocean use	large	NQ	
Use of genetic engineering	problematic	NQ	
Hydrogen cleaning	NA		
Occupational:			
Industrial disease and accident	NA		
Economic:			
Direct economy (production costs)		> 40	efficiency 0.1%
Resource usage	area covered	NQ	
Labour needs for manufacture	5 person-years/MW	NQ	
Import fraction	NA		
Benefits (value of product)		6–12	
Other:			
Supply security	good	NQ	
Robustness	medium	NQ	
Geopolitical	positive	NQ	

LCA of SOFCs

- For SOFCs, a number of environmentally critical items have been identified .
- The electrolyte may be produced from YSZ with added electrodes made of, e.g., LaSrMn-perovskite and NiO-cermet.
- Nitrates of these substances are used in manufacturing, and metal contamination of wastewater is a concern.
- The high temperature of operation makes the assembly very difficult to disassemble for decommissioning, and no process for recovering yttrium from the YSZ electrolyte material is currently known.

LCA of MCFCs

- For MCFCs, a full life-cycle analysis has been Attempted.
- Both electrodes and the electrolyte matrix are manufactured by mixing powdered constituents with binders and solvents to form a sheet after casting and drying.
- The results of the analysis comprise resource usage and emissions to air, wastewater and soil.
- A critical resource may be Ni, for which the largest supplier is Cuba.

Nickel sources

COUNTRIES	PRODUCTION (in metric tonnes)	COUNTRIES	PRODUCTION (in metric tonnes)
Russia	280,000	Cuba	74,000
Philippines	230,000	Colombia	72,000
Indonesia	230,000	South Africa	42,000
Canada	200,000	Botswana	32,000
Australia	180,000	Madagascar	25,000
New Caledonia	140,000	Dominican Republic	14,000
Brazil	83,000	Other Countries	100,000
China	80,000		

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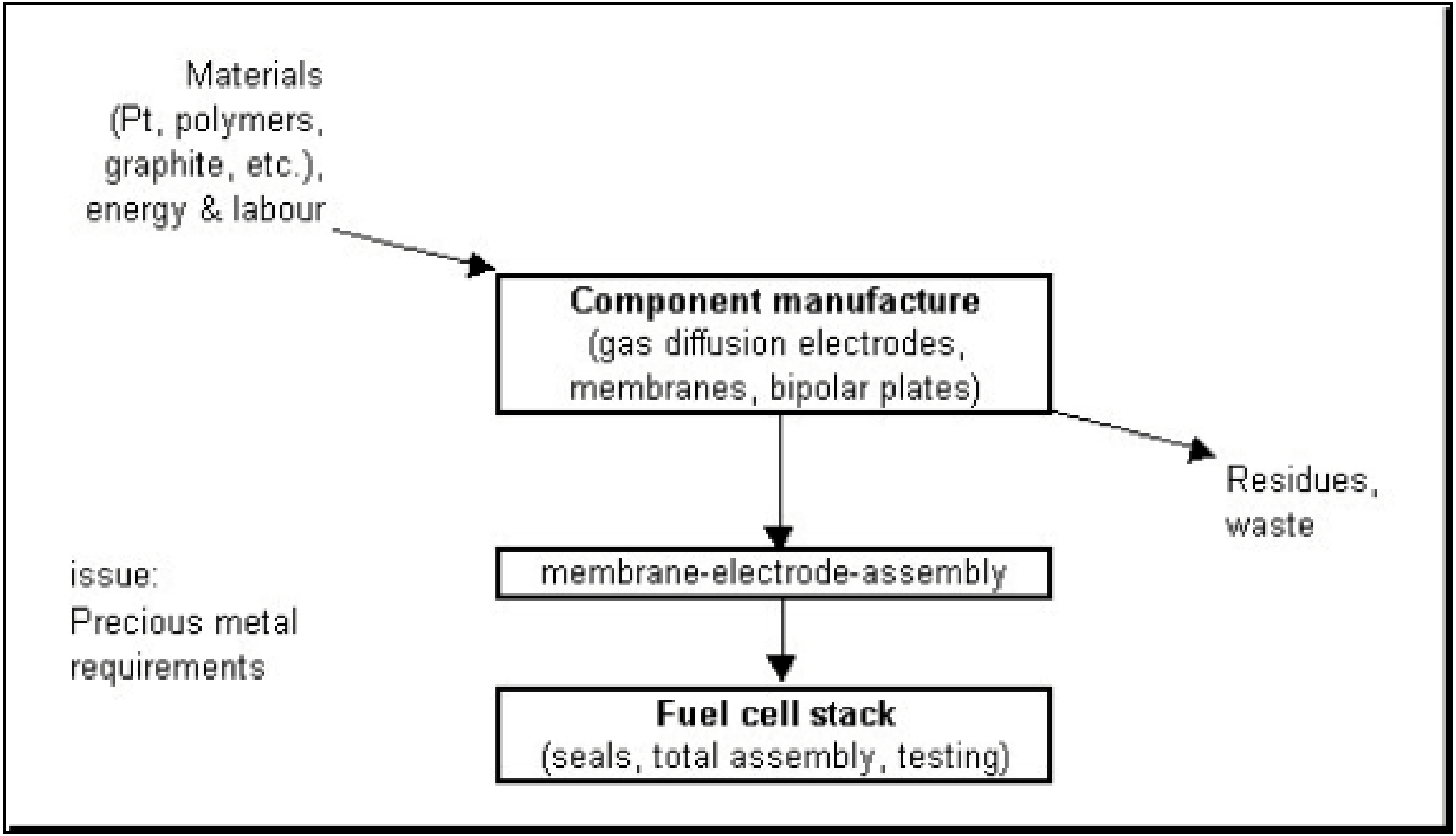
Life Cycle analysis of MCFC

- Contributions to life-cycle impacts from different components of a 1 m^2 unit single MCFC

Life-cycle impact	*Negative electrode*	*Positive electrode*	*Electrolyte matrix*	*Bipolar plate*	*Total*	*Unit*
Electric energy input	153.2	82.6	73.03	5.47	314	kWh
CO_2	508	214	127	8.03	857	kg
CH_4	423	131	36.2	0.502	591	g
N_2O	12.2	3.8	3.5	0.0014	19.4	g
SO_2	10.9	6.67	1.5	0.26	19.4	kg
SO_x (as SO_2)	2.01	0.61	0.08	–	2.7	kg
CO	121	45.4	25.2	37.6	229	g
NO_2	366	224	–	14.3	604	g
NO_x (as NO_2)	697	214	27.8	–	939	g
Non methane VOC	420	129	16.8	0.03	566	g
VOC	–	–	–	15.5	15.5	mg
Benzene	0.895	0.31	0.031	0.01	1.3	g

LCA of PEMFCs

- Life-cycle flow path for the industrial manufacture of PEM fuel cell stacks



Technical Targets for Catalysts

	Units	2020 Target
Platinum group metal (PGM) total content (both electrodes)	g/kW	<0.125
PGM total loading (both electrodes)	mg/cm^2	<0.125
Loss in catalytic (mass) activity[a,b]	% loss	<40
Loss in performance at 0.8 A/cm^2 [a]	mV	30
Loss in performance at 1.5 A/cm^2 [b]	mV	30
Mass activity @ 900 $mV_{iR\text{-}free}$ [c]	A/mg_{PGM}	0.44

Technical Targets for Automotive-Scale (80 kWe net) FC System with H2

Characteristic	Units	Status	2020 Target
Energy efficiency[b] @ 25% of rated power	%	60[c]	60
Power density	W/L	640[d]	650
Specific power	W/kg	659[e]	650
Cost[f]	$/kW$_e$	51[f]	40
Cold start-up time to 50% of rated power			
@ -20°C ambient temp	sec	20[g]	30
@ +20°C ambient temp	sec	<10[g]	5
Durability in automotive load cycle	hours	2,500[h]	5,000
Unassisted start from[i]	°C	-30[j]	-30

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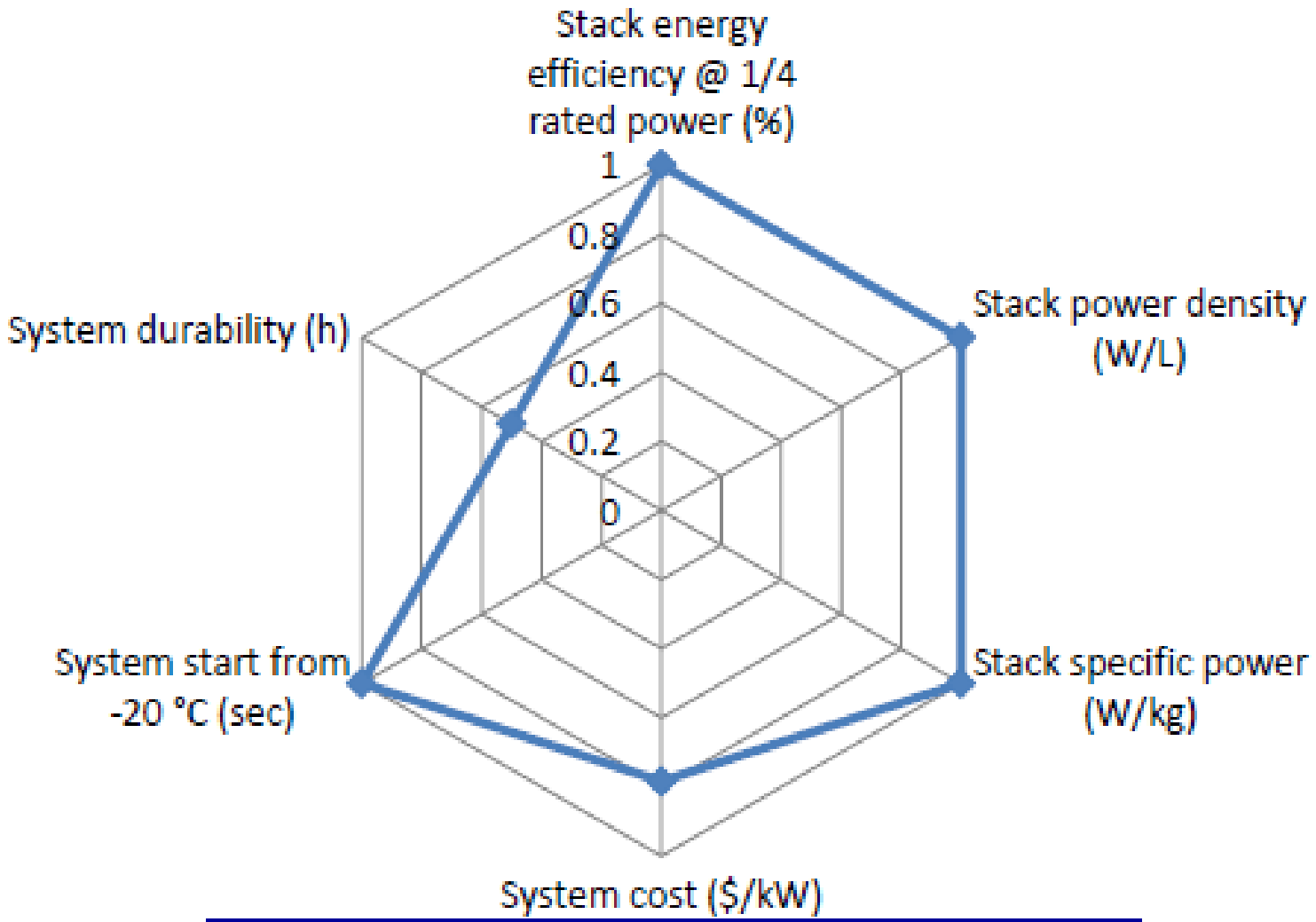
Key Issues and Challenges



Targets vs status

DOE Efforts Addressing Automotive FC Durability and Cost

Research Area	Cost	Durability
Catalyst/electrode development	X	X
Degradation studies		X
Transport studies	X	X
Membrane development	X	X
Impurity studies	X	X
BOP	X	X
Analysis/characterization studies	X	X
Bipolar plate and seal studies	X	X

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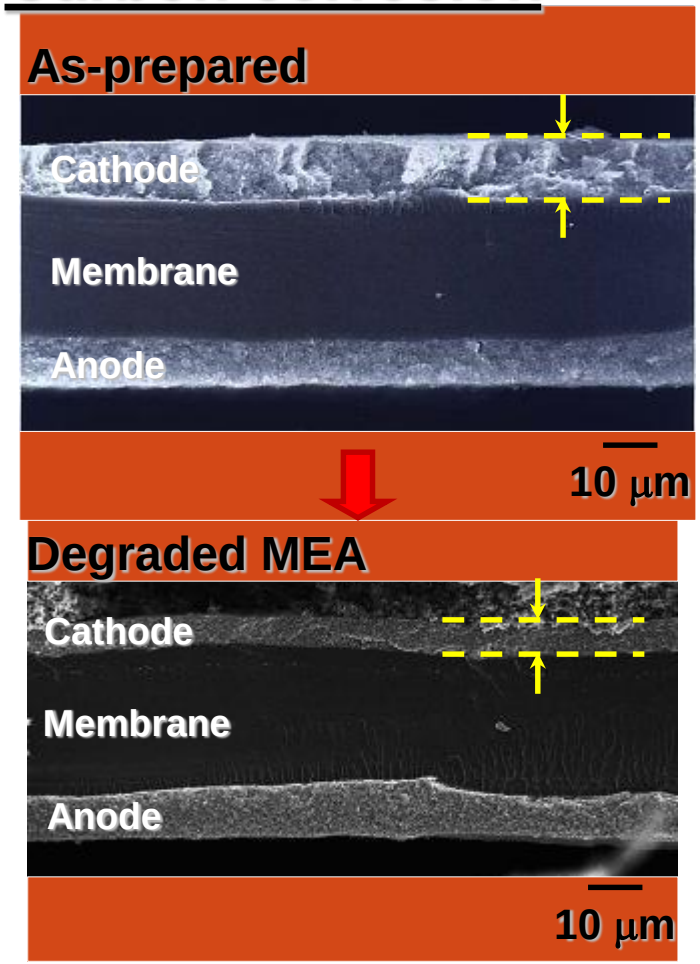
FC system durability

Fuel cell durability demonstrated in vehicles

- **1,700 hours actual (51K miles)**
- **1,900 hours projected (57K miles)**
- **Target durability 5,000 h (~150,000 miles)**

Degradation of catalyst

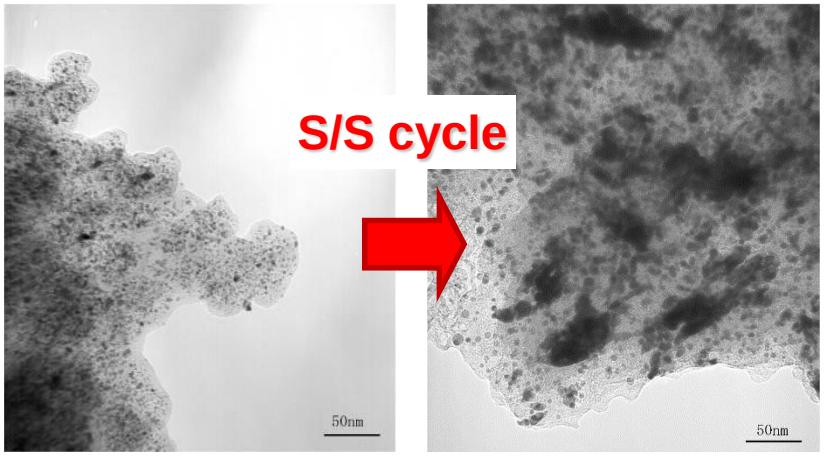
Carbon corrosion



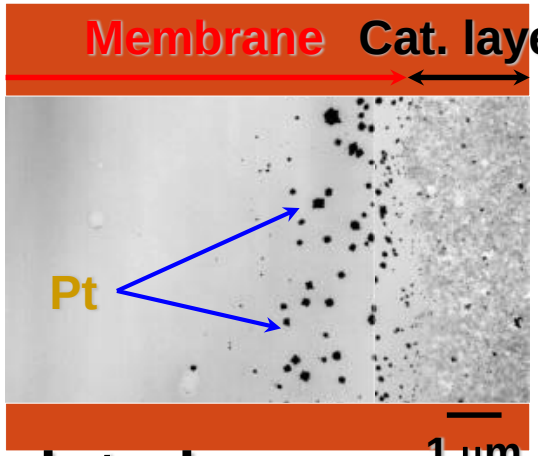
Thinning and destruction of catalyst layer

Pt dissolution

1.



2.



1. Pt sintering
2. Deposited Pt in membrane

Strategies for addressing challenges focus on components

Addressing Cost, Durability, and Performance

Catalysts/Supports

- Carry out Pt and non-PGM studies in parallel
- Identify degradation mechanisms and mitigate effects
- Increase OCV and performance of non-PGM catalysts
- Test catalysts in fuel cells

Impurity effects

- Characterize effects of impurities on membranes and catalysts

Water Management

- Improve tolerance to freeze / thaw conditions
- Prevent membrane flooding or dehydration

MEAs

- Develop characterization tools, understanding of material behavior

Membranes

- Operate at higher temperature, lower RH to reduce BOP size and cost
- Lower cost by eliminating fluorine
- Identify degradation mechanisms and mitigate effects

Platinum Production, 2011

Australia	130	
Botswana	600	
Canada	7,000	
Colombia	1,231	
Finland	400	
Japan	1,765	
Poland	25	
Russia	25,000	
South Africa	145,000	
United States	3,700	
Zimbabwe	10,600	
Total	195,000	

In KG

All the platinum ever mined throughout history would fill a basement of less than 25 cubic feet.

The way forward

- The assessments made above suggests five key areas of hydrogen introduction, which could happen individually or in combination. They are
- **Hydrogen as energy store for variable renewable energy systems.**
- **Applications of hydrogen and fuel cells in the transportation sector.**
- **Stationary applications of fuel cells in building environments.**
- **Stationary application of fuel cells in large power plants.**

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How much time do we have?

The time-frame for the necessary changes in the energy system and thus the urgency of the development efforts related to H_2, is illustrated by the prospects for continued reliance on oil and expectations of oil price developments.

The end, and a beginning

- **It is time to end this Session, but not without the concluding remark signaling the need to create the conditions for a new beginning, based on a partnership between research, industry and policy makers to make the conditions for a H_2 society realistic.**

The motivation is the fact that there are so few alternatives that we better have to make the H_2 route work out if we want to preserve the progression in wealth for all of us.