Stationary and Mobile Applications with Fuel Cell Technology

K. Andreas Friedrich
Institut für Technische Thermodynamik
Pfaffenwaldring 38-40, Stuttgart

INTERNATIONAL SUMMER SCHOOL ON PEM FUEL CELLS
16 – 20 July 2012
Nevsehir, Turkey

DLR
German Aerospace Center

- Research Institution
- Space Agency
- Project Management Agency

Research Areas

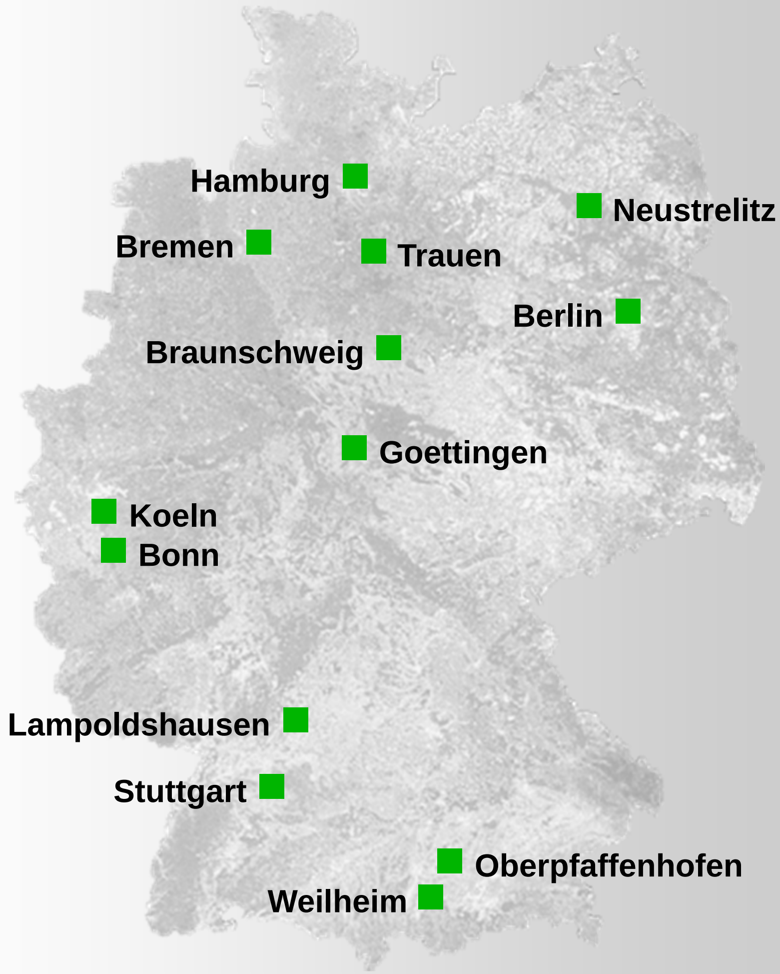
- Aeronautics
- Space
- Transport
- Energy
- Space Agency
- Project Management Agency

Locations and employees

7000 employees across
33 research institutes and
facilities at

- 15 sites.

Offices in Brussels,
Paris and Washington.

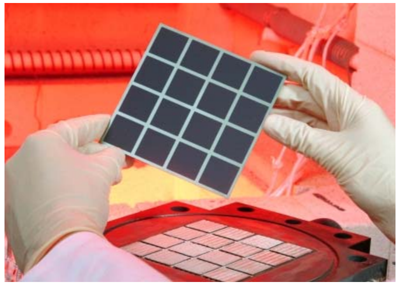


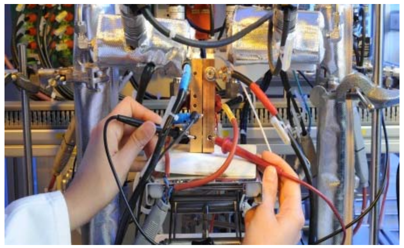
DLR

Section Electrochemical Energy Technology

Fundamentals

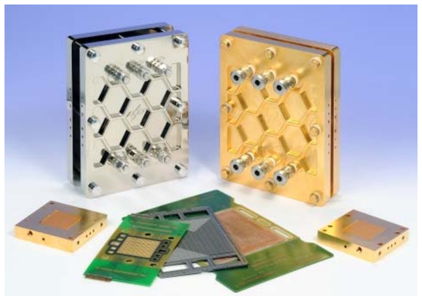
Systems

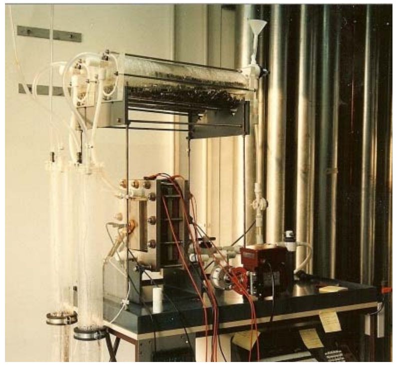


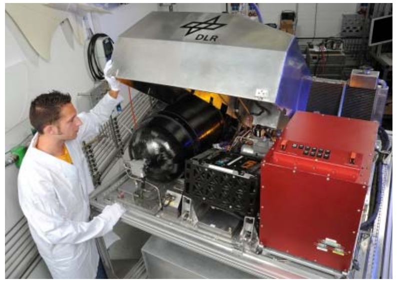


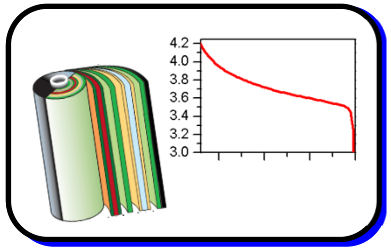
Electrochemical Energy Technology:

- Electrolysis (intermittent Alkaline, Polymer and Solid Oxide Electrolysis)
- Fuel Cells (PEFC, SOFC, DMFC)
- Battery technology (Lithium) since 2009









Content

- Introduction to mobile and stationary applications
- Electromobility with hydrogen PEM fuel cells and batteries
- Hybridization of power trains
- Fuel cell technology for transport
- Main system components
- Stationary applications of PEM fuel cells
- Residental application / demonstration programs
- State of art in Japan, Gemany, USA
- Backup power application

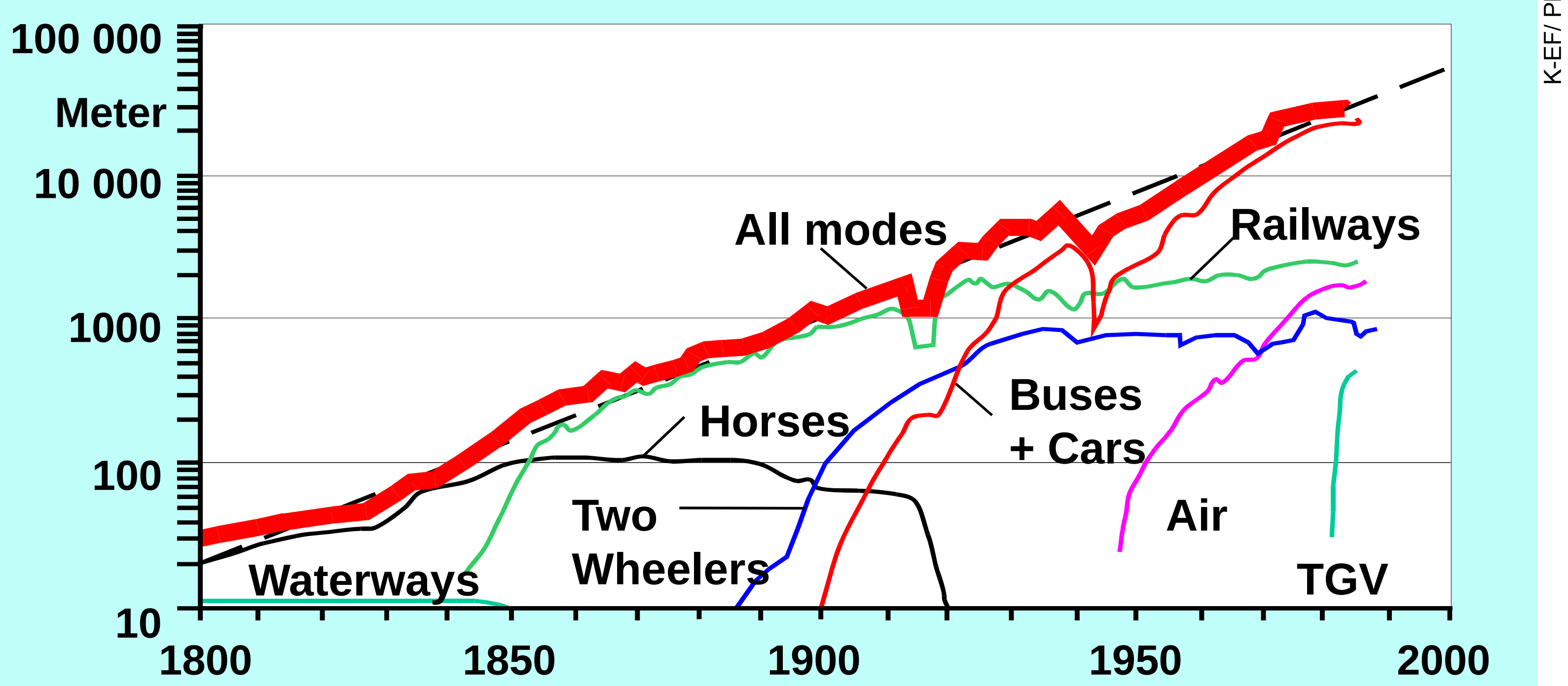
Challenges for the 21st Century

- Environmental pollution and climate change
- Alarming increase of energy consumption due to world population growth
- Increase of competition for usage of available arable land
- Geopolitical dependencies will increase
- Efficient utilization of fossil and renewable energies
- Competitiveness of national industries
- Securement of jobs and creation of new jobs with innovative products

→ **Global driver for electromobility and high efficiencies**

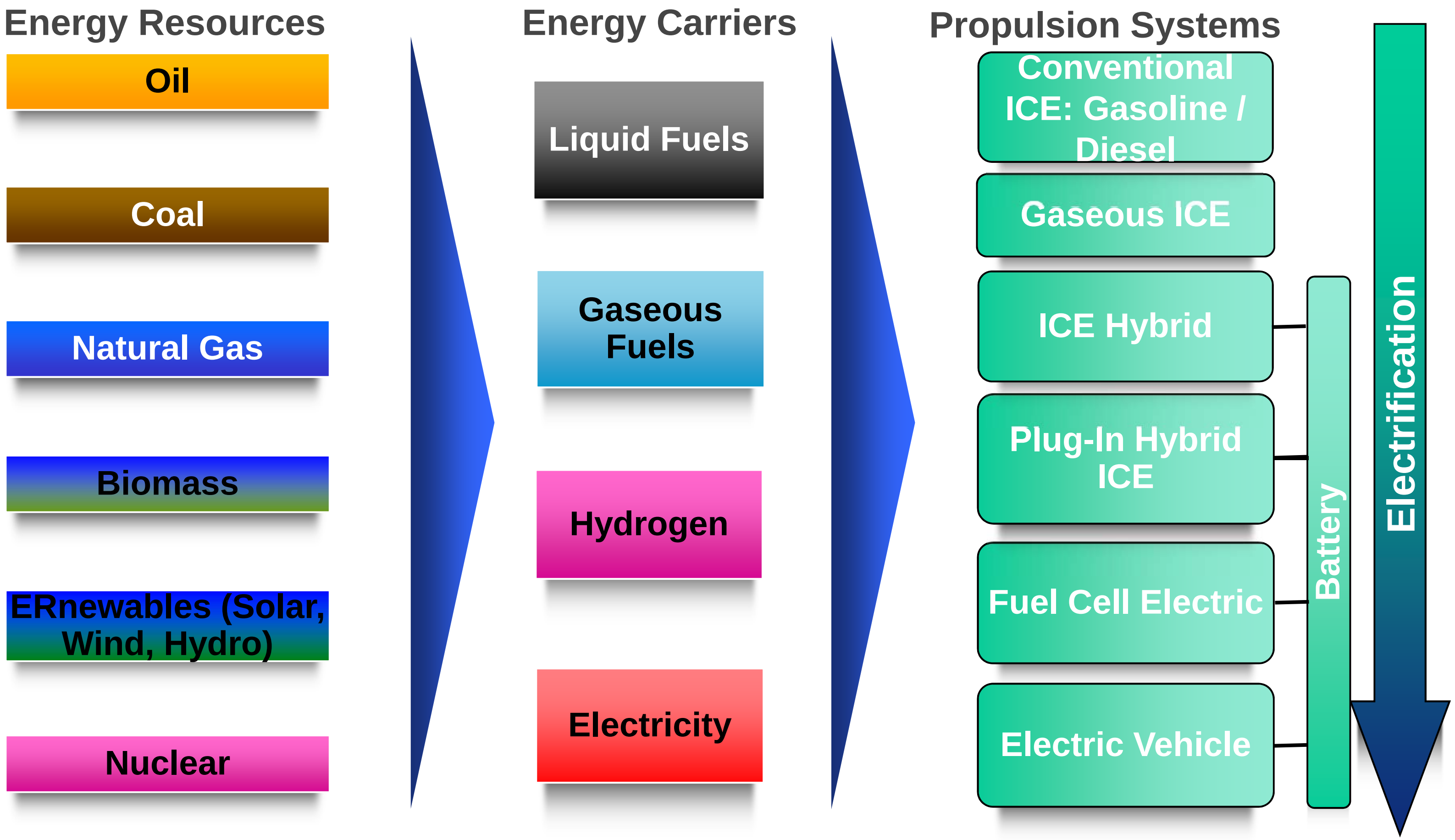
Growth of Mobility

as Distance Traveled per Day per Capita



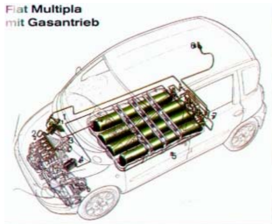
Source: Nakicenovic, 1992, IIASA *Laxenburg*, Austria

Energy and Powertrain Alternatives



Automobile Vehicle Concepts

- **Internal Combustion Engine Gasoline/Diesel**
  + High range, high power, expertise, infrastructure
  - Nitrous oxides, carbon dioxide, efficiency improvements potentials
- **Internal Combustion Engine Natural Gas**
  + Low emissions
  - Large tanks, inadequate infrastructure
- **Hybrid power train**
  + low emissions, large range
  - Komplex system, high mass
- **Electric power train with batteries**
  + Locally emission-free
  - geringe Rechweite, hohes Gewicht, Ladezeit
- **Electric power train with fuel cells**
  + High efficiency, better range, low emissions
  - Complex technology, infrastructure

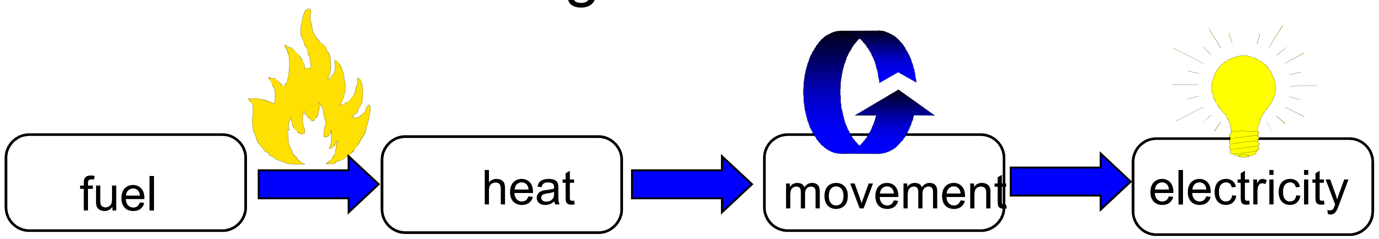




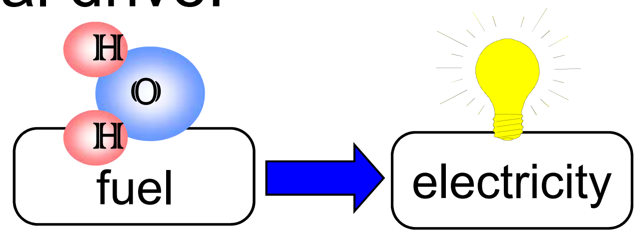
Efficiencies

Typical car efficiency (Tank to Wheel):

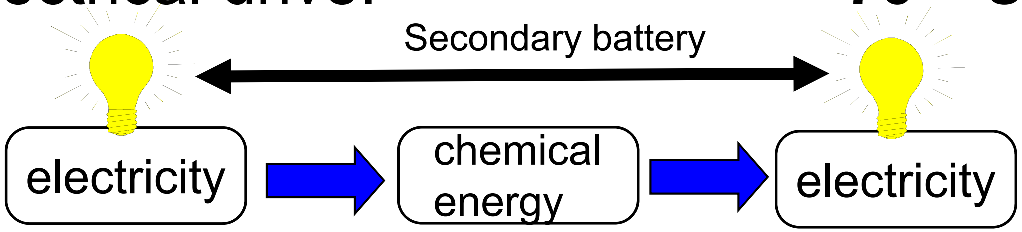
- Internal combustion engine: **20 – 25 %**



- Fuel cell electrical drive: **40 – 50 %**



- Battery electrical drive: **70 – 80 %**



Historical development of electric cars

Early Years of Electric Cars: 1890 - 1930

- First electric vehicle invented in 1828
- Many innovations followed
- The interest in electric cars increased greatly in the late 1890s and early 1900s
- First real and practical electric car (with capacity for passengers) designed by William Morrison
- 1902 Phaeton built by the Woods Motor Vehicle Company of Chicago

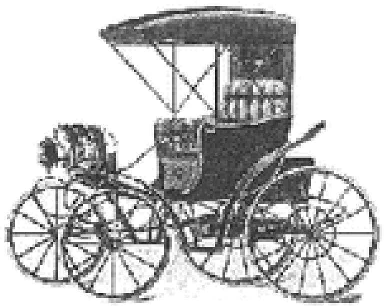


Figure: 1902 Wood's Electric Phaeton
(Inventors, http://inventors.about.com/od/estartinventions/a/History-Of-Electric-Vehicles.htm, 7.5. 2011).

Historical development of electric cars

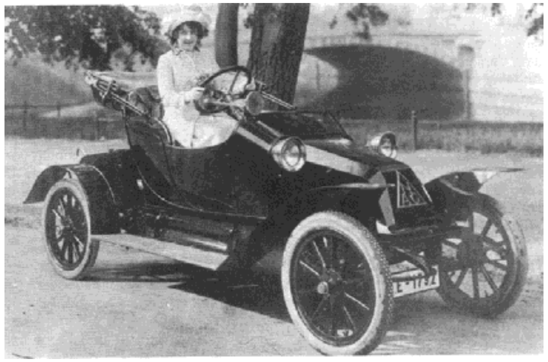
Decline of Electric Cars: 1930 – 1990

- The electric car declined in popularity because of the following reasons:
    - Better system of roads → need for longer-range vehicles
    - Reduction in price of gasoline → gasoline was affordable to the average consumer
    - Invention of the electric starter disposed of the need for the hand crank.
    - Initiation of mass production of internal combustion engine vehicles by Henry Ford.

Electric Automobile Vehicles around 1900

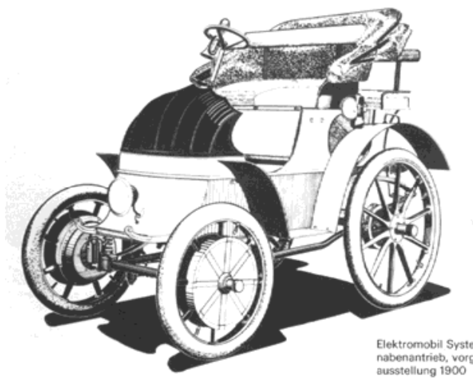
Columbia, 1901, Electric Vehicle Company

Electric Hotel Bus



Electric Car NAG
(Neue Automobilgesellschaft mbH)
1903
Quelle: Ledjeff, Energie für Elektroautos

Baker Electric Vehicle, 1912

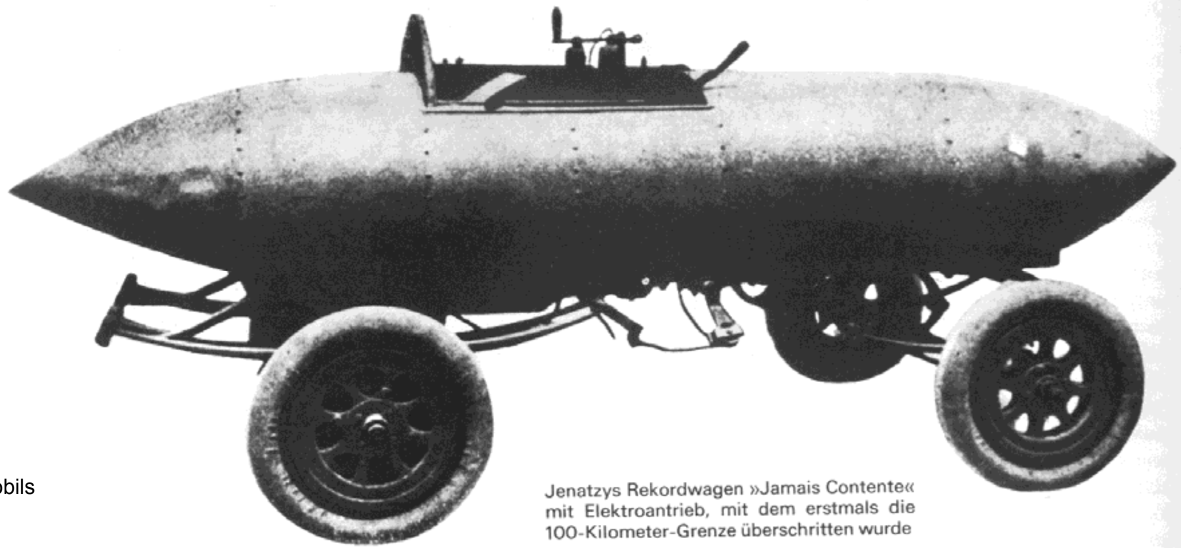


Elektromobil System Lohner-Porsche mit Radnabenantrieb, vorgestellt auf der Pariser Weltausstellung 1900

Lohner-Porsche Electric Vehicle
With in-wheel drive, 1900

Source: Frankenberg, Geschichte des Automobils

Speed record around 1900



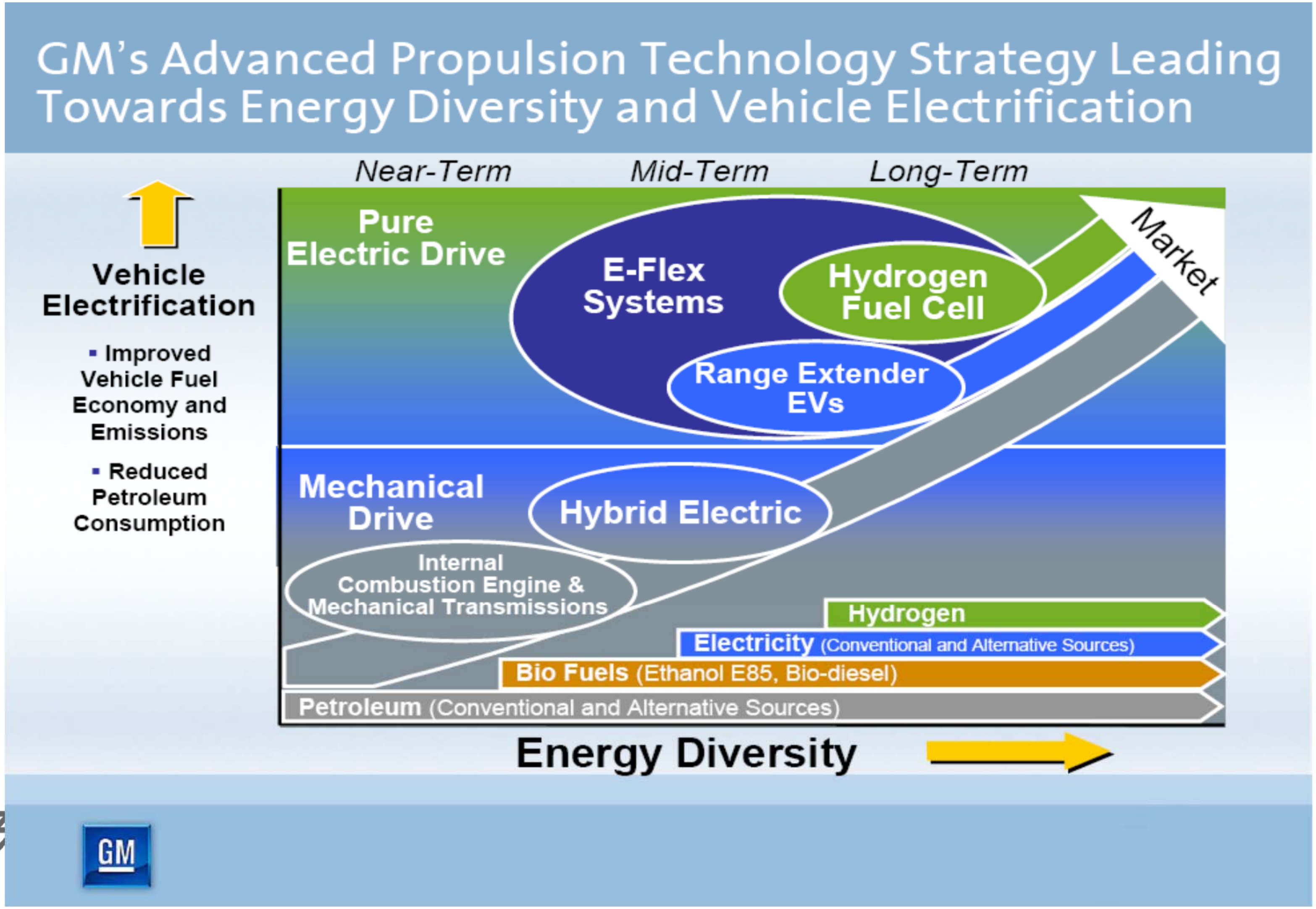
Jenatzys Rekordwagen »Jamais Contente« mit Elektroantrieb, mit dem erstmals die 100-Kilometer-Grenze überschritten wurde

Source: Frankenberg, Geschichte des Automobils

Date	Driver	Car	Place	Record km/h
Elektrische Antriebe 1898/99				
18. 12. 1898	G. de Chasseloup-Laubat	Jeantaud	Achères	63,149
17. 1. 1899	C. Jenatzy	Jenatzy	Achères	66,657
17. 1. 1899	G. de Chasseloup-Laubat	Jeantaud	Achères	70,310
27. 1. 1899	C. Jenatzy	Jenatzy	Achères	80,336
4. 3. 1899	G. de Chasseloup-Laubat	Jeantaud	Achères	92,696
29. 4. 1899	C. Jenatzy	Jenatzy	Achères	105,876

DLR

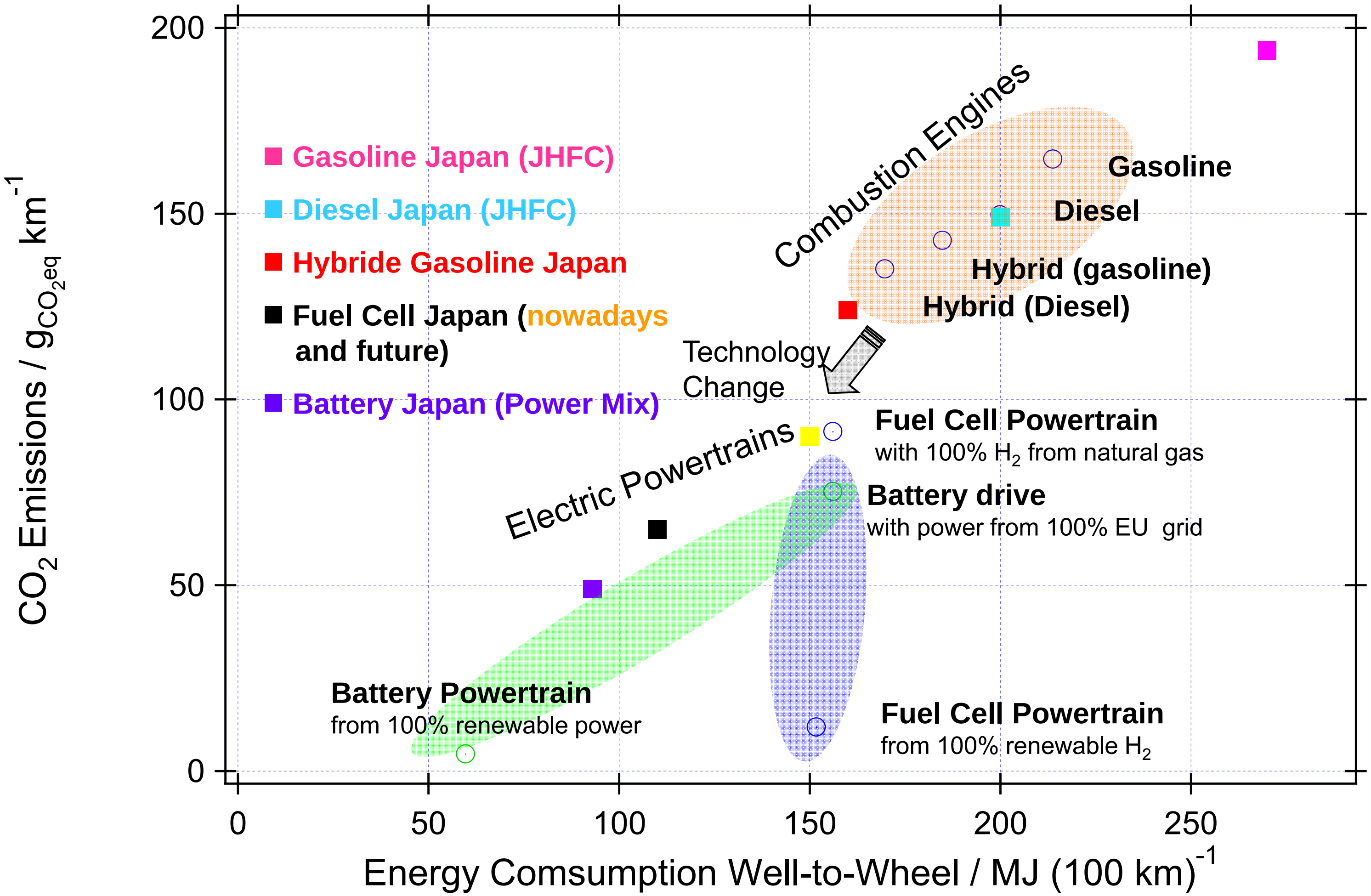
Automotive Roadmaps (GM as example)



Discovery to first practical use …

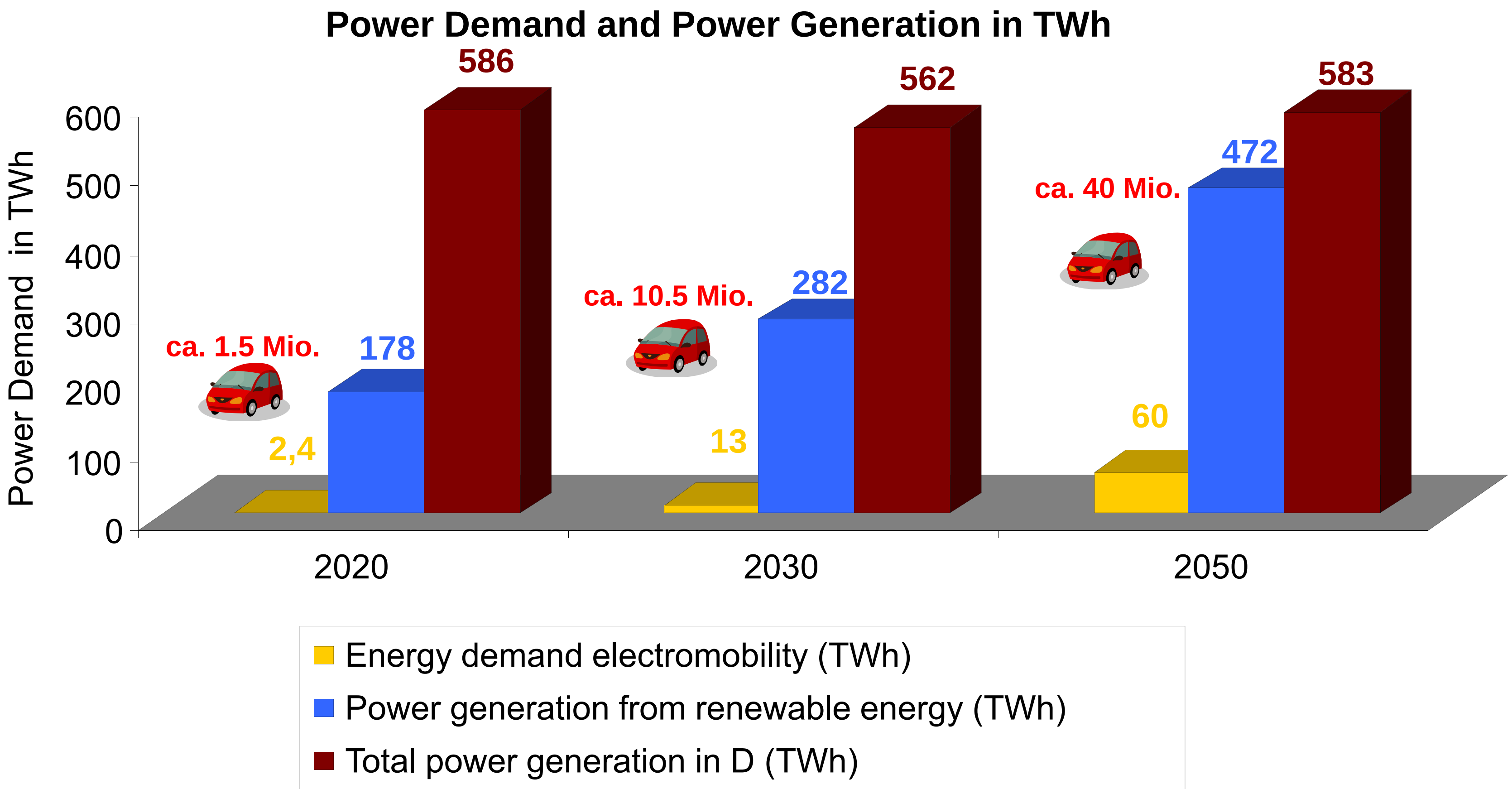
- ICE:	1680 – 1889 (209 yrs)
- Steam Engine:	1690 – 1769 (79 yrs)
- Gas Turbine:	1791 – 1942 (150 yrs)
- Fuel Cells:	1838 – 1965 (127 yrs)
- Photovoltaics:	1839 – 1958 (119 yrs)

Efficiency Comparison of Automotive Power Trains



Based on Well-to-Wheel studies of European and Japanese Sources: Concawe, EUCAR, JRC und JHFC

Potentials of Power Generation from Renewables and Demand for Electromobility in Germany



Source: “Leitstudien” for BMU regarding the potential of renewable energies

Electromobility and Renewable Energy

Areal demand for renewable fuel for the use of a passenger car with 12 000 km driving performance per year

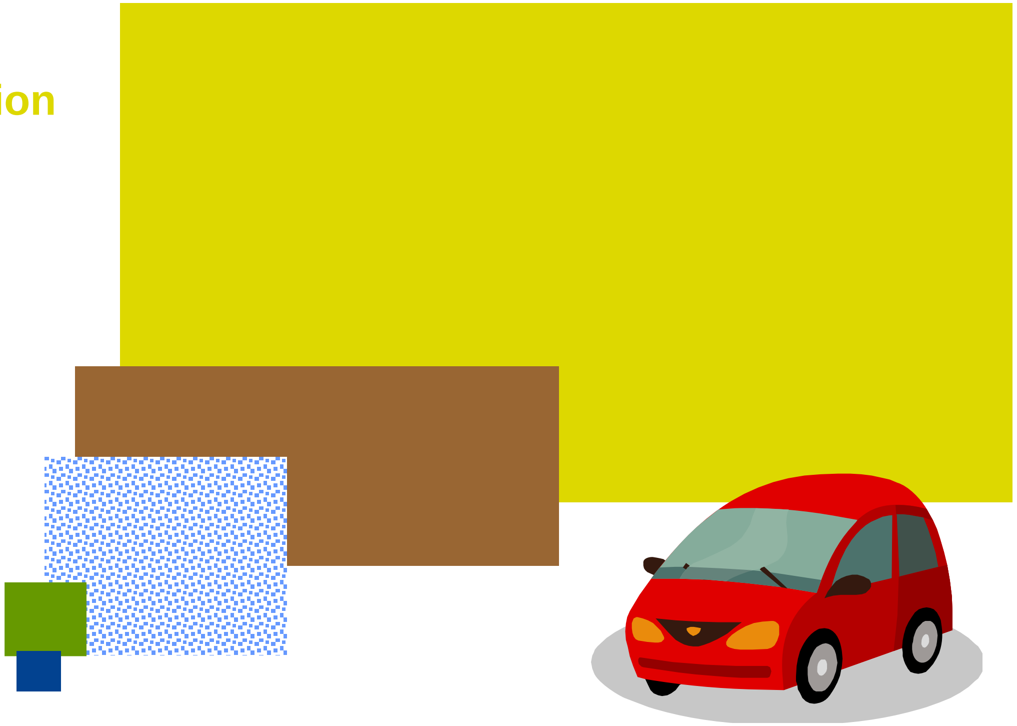
5000 m^2 for Biodiesel and combustion engine

1000 m^2 for hydrogen from biomass + fuel cell powertrain

500 m^2 for hydrogen from wind energy + fuel cell powertrain (area can be used for agriculture)

65 m^2 for PV power + fuel cell power train

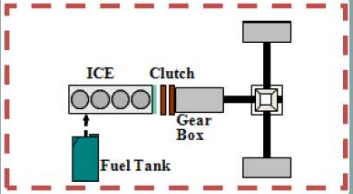
20 m^2 for PV power + battery power train



Source: ZSW

Configuration of Electrical Cars

Conventional Vehicles



Hybrid Electric Vehicles

Micro Hybrid | **Mild Hybrid** | **Full Hybrid (Parallel / Power-Split / Serial)** | **Plug-In Hybrid Range Extender**

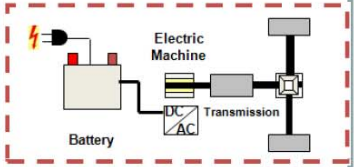
+ Pure Electric Drive
+ Electric Take-off
+ Engine Assistance
+ Kinetic Energy Recovery

Start - Stop

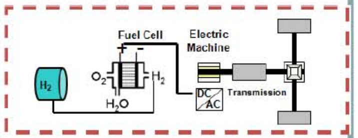
Hybridisation aiming at assisting the combustion engine

Hybridisation aiming at running the vehicle by electric propulsion

Battery Electric Vehicles



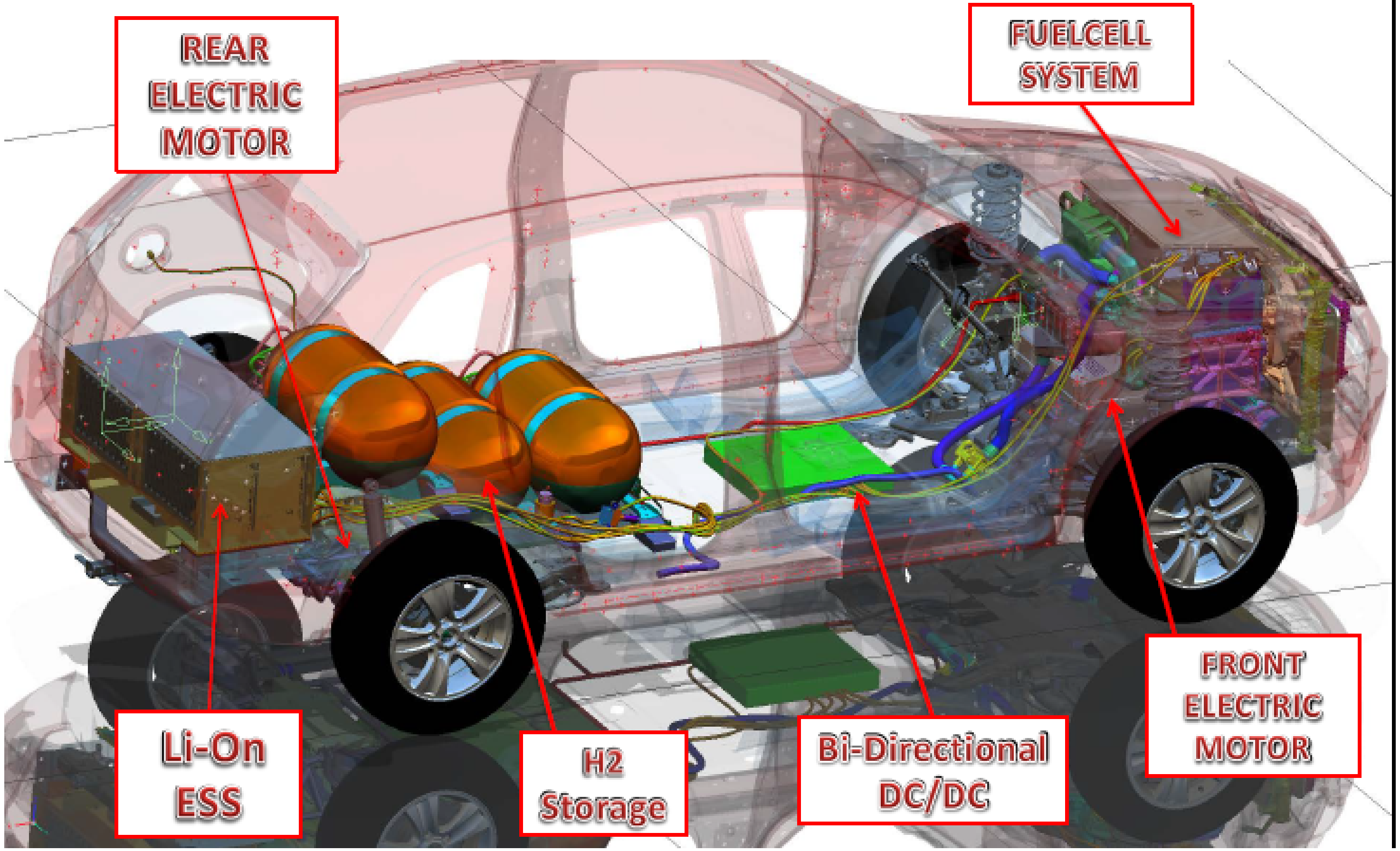
Fuel-Cell Electric Vehicles



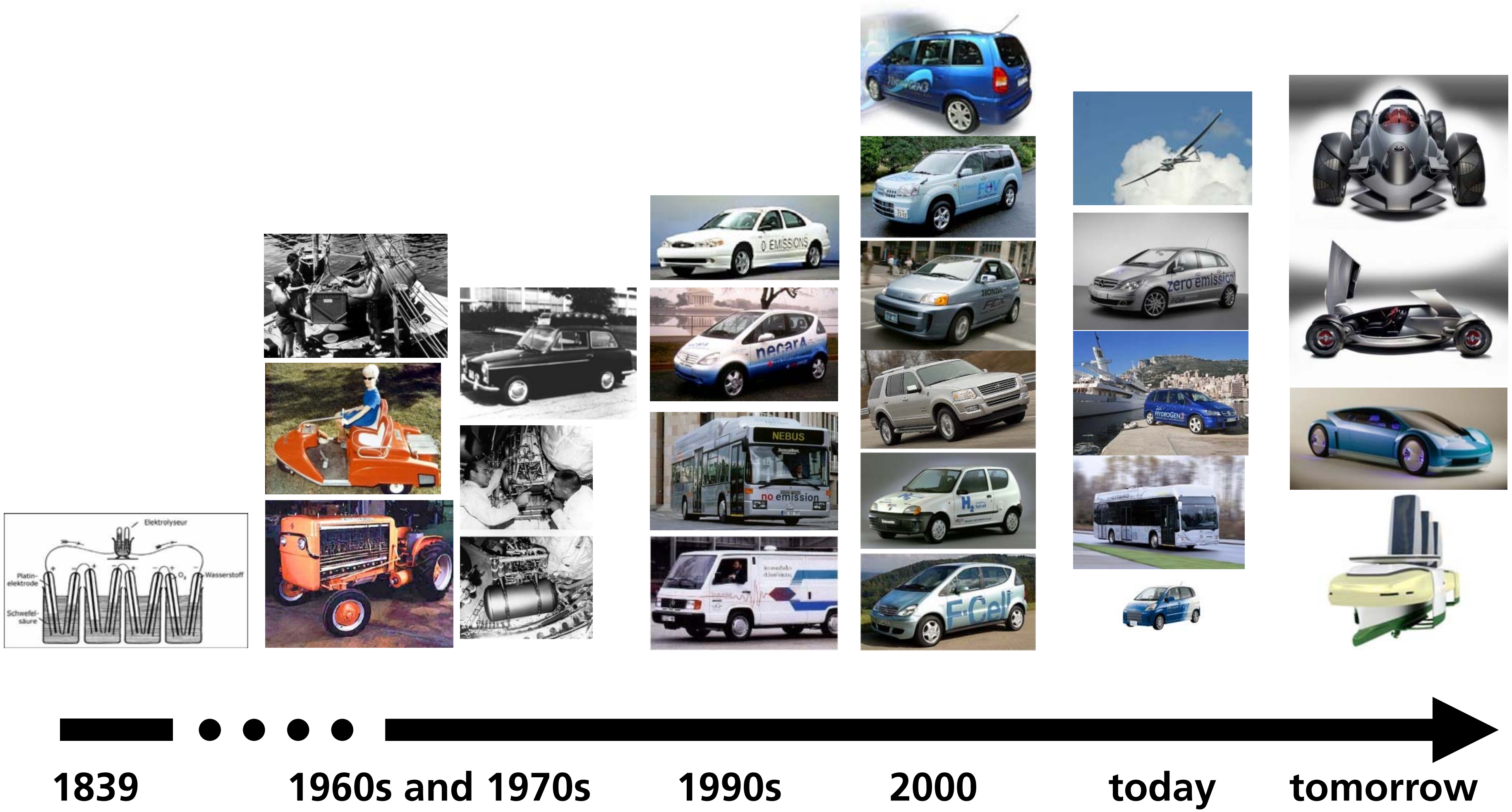
Hybridisation Possibilities

	Micro Hybrid	Mild Hybrid	Full Hybrid	Plug-In Hybrid	Battery E Vehicle
Motor assistance		+	+	+	+
Recuperation of breaking energy	+	+	+	+	+
Start-Stop	+	+	+	+	+
Electrical range			few km	Up to 60 km	100 – 200 km
Fuel savings	8%	12– 20 %	25 – 40%	60 – 100%	100%
Examples	BMW 1.3 Mini	GM Saturn Vue, Honda Civic, Mercedes S-Klasse BMW 7 Serie	Ford Escape, Toyota Prius	DAI Sprinter, VW Twin Drive GM Chevrolet Volt	Mitsubishi i-EV, BMW Mini-El, Peugeot i-On

Automobile with Fuel Cells / System example from GM



Electromobility with Fuel Cells

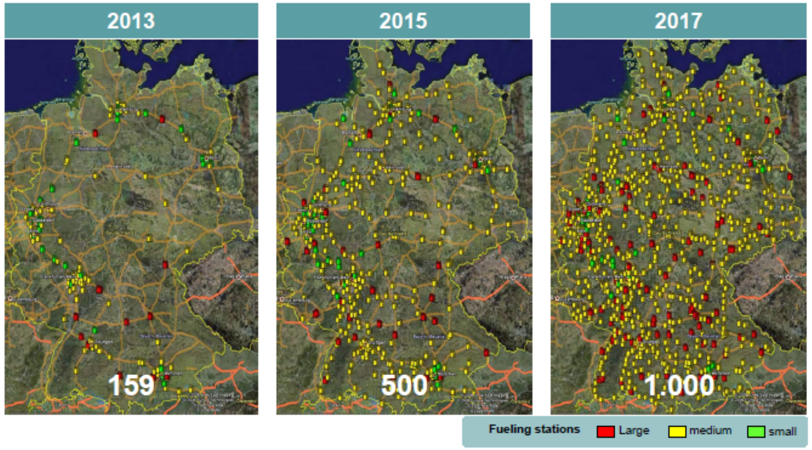


DLR

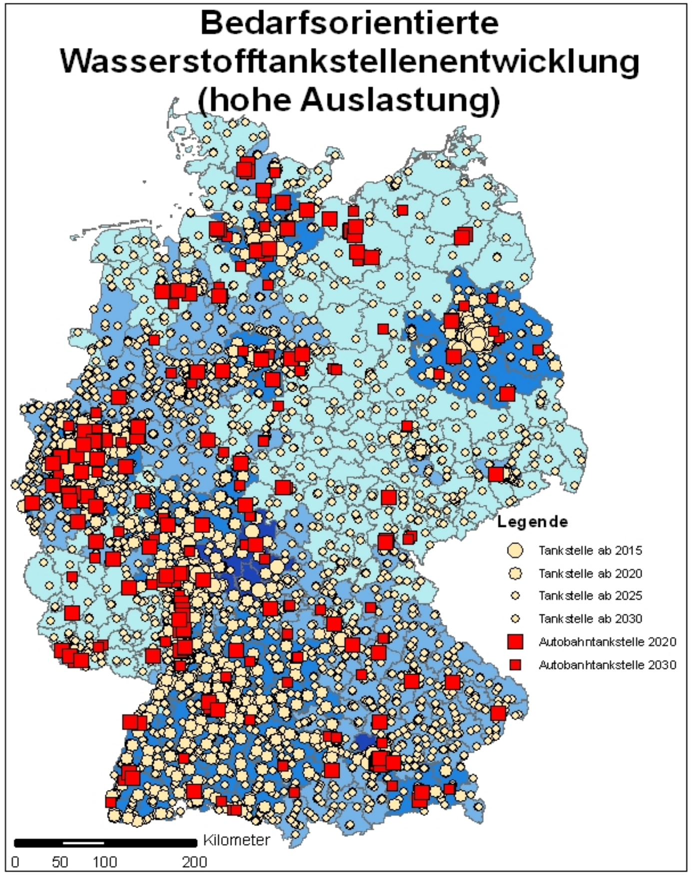
Maturity of Technology – Daimler World Drive

B-Class F-CELL
30,000 kilometers around the world
14 countries on four continents

H_2 Infrastructure for Refueling is requirement



DAIMLER EnBW THE LINDE GROUP AIR LIQUIDE NOW OMV AIR PRODUCTS TOTAL VATTENFALL

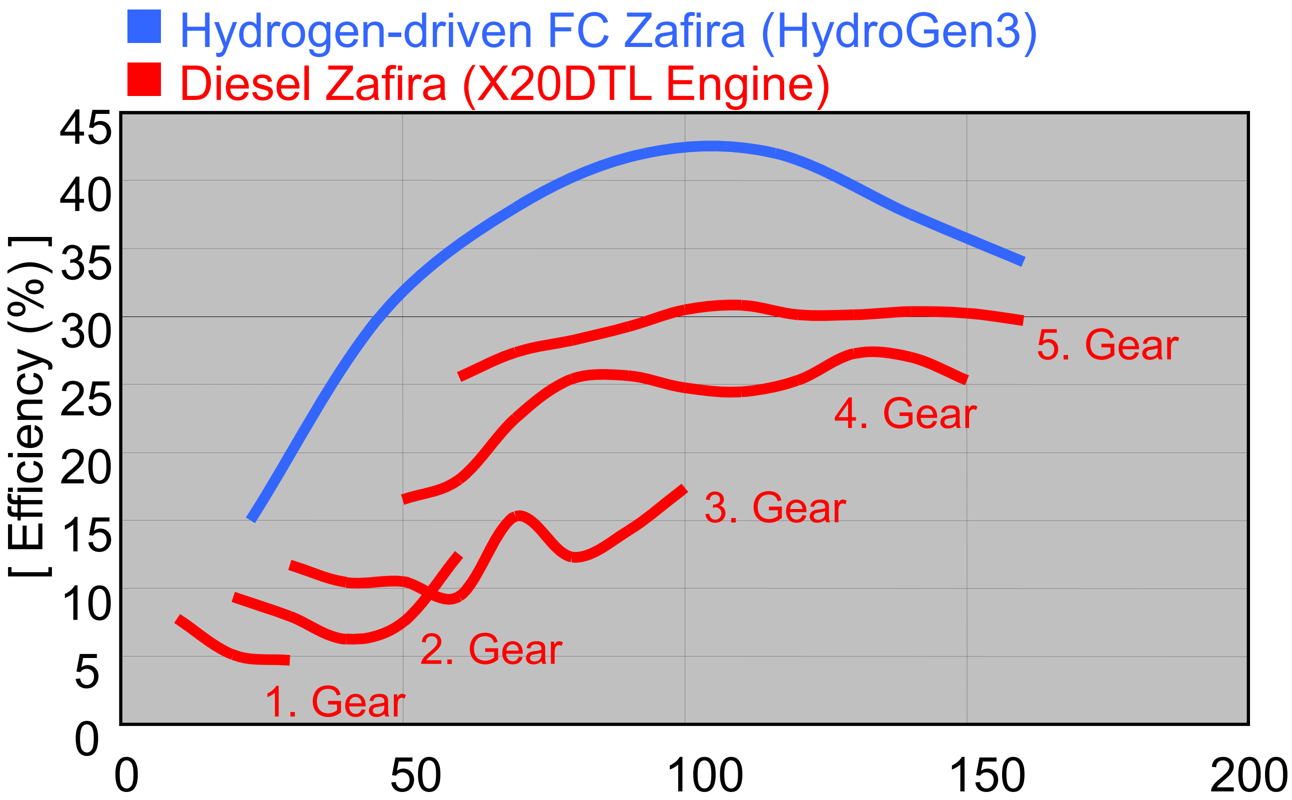


DLR

Chevrolet Equinox Fuel Cell from GM

- Electric traction:
  - 73 kw 3-Phase asynchronous motor. 94 kw max.
  - Nominal Torque 320 Nm.
- Fuel Cell System:
  - Stack: 440 cells, 93 kW.
  - NiMH battery 35 kW.
  - Operation life: 2.5 years, 80.000km.
  - Operation temperature: -25 to +45° C.
- Fuel storage:
  - 3 CGH2 vessels.
  - 70 MPa.
  - 4.2. kg Hydrogen.
- Performance:
  - Acceleration: 0-100 km/h in 12s.
  - Top speed 160 km/h.
  - Operation range 320 km.
- Curb weight: 2010 kg.

Comparison of Efficiency and CO_2-Emission



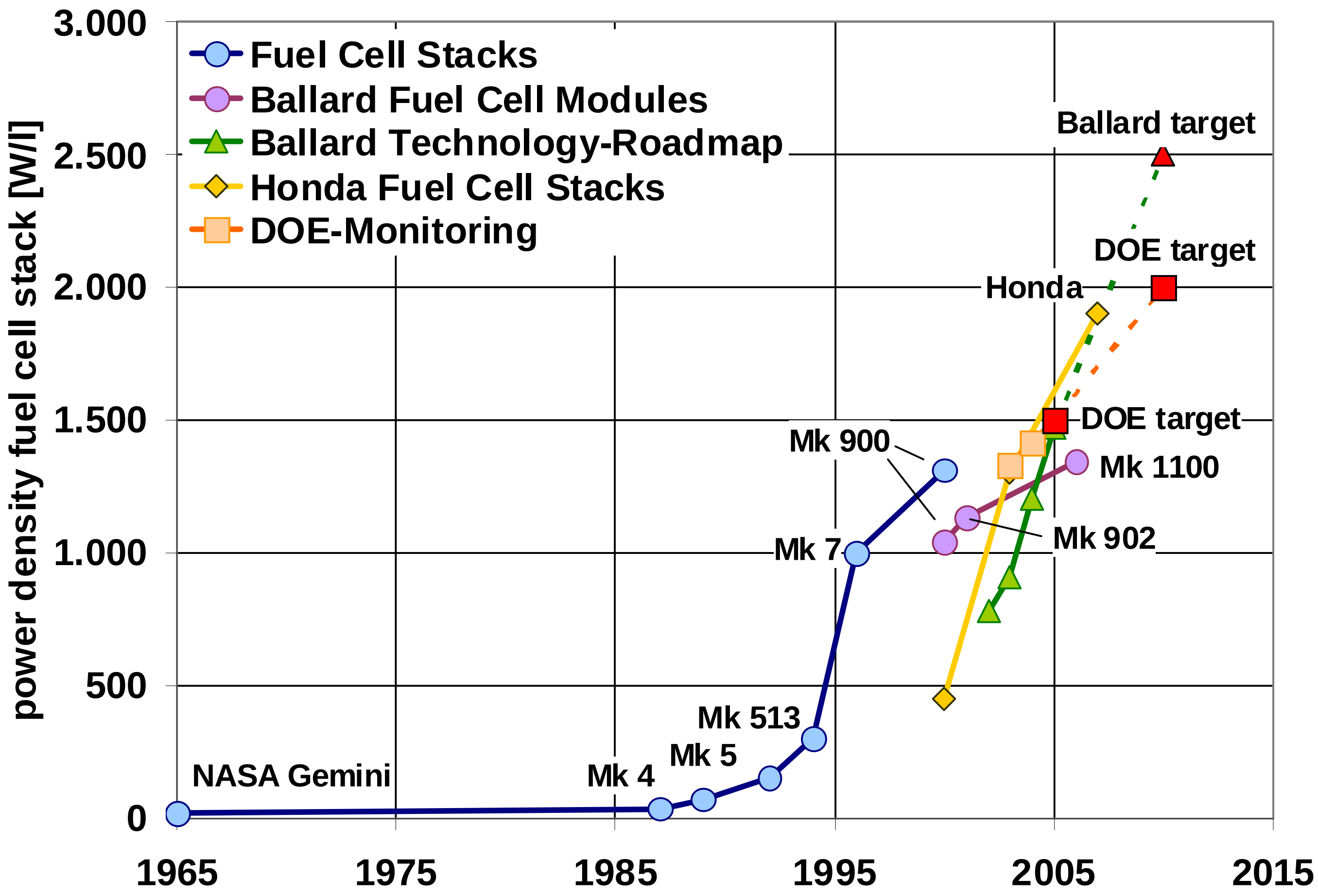
→ Average efficiency (European Drive Cycle):

Efficiencies: 36 % / 22 %

CO_2-Emissions (direct): 0 g/km / 177 g/km

Source: Hermann/Winter 2003

Stack Improvements over the last Decades

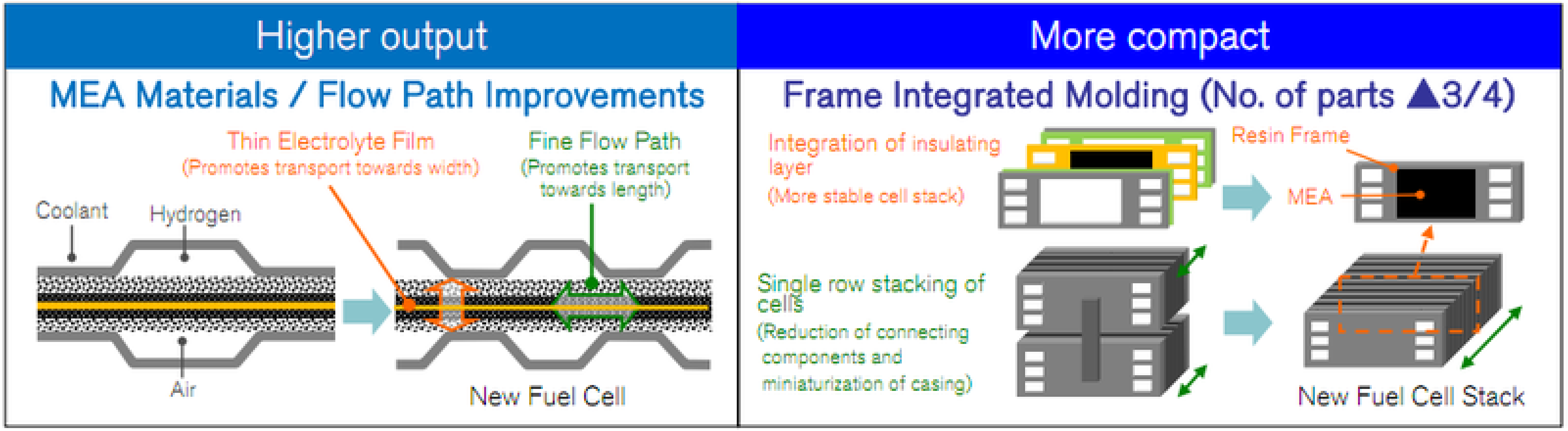


DLR

Recent Announcement by Nissan Motors

Stack improvement to 85 kilowatts into a 34-liter package; 40.8 kg

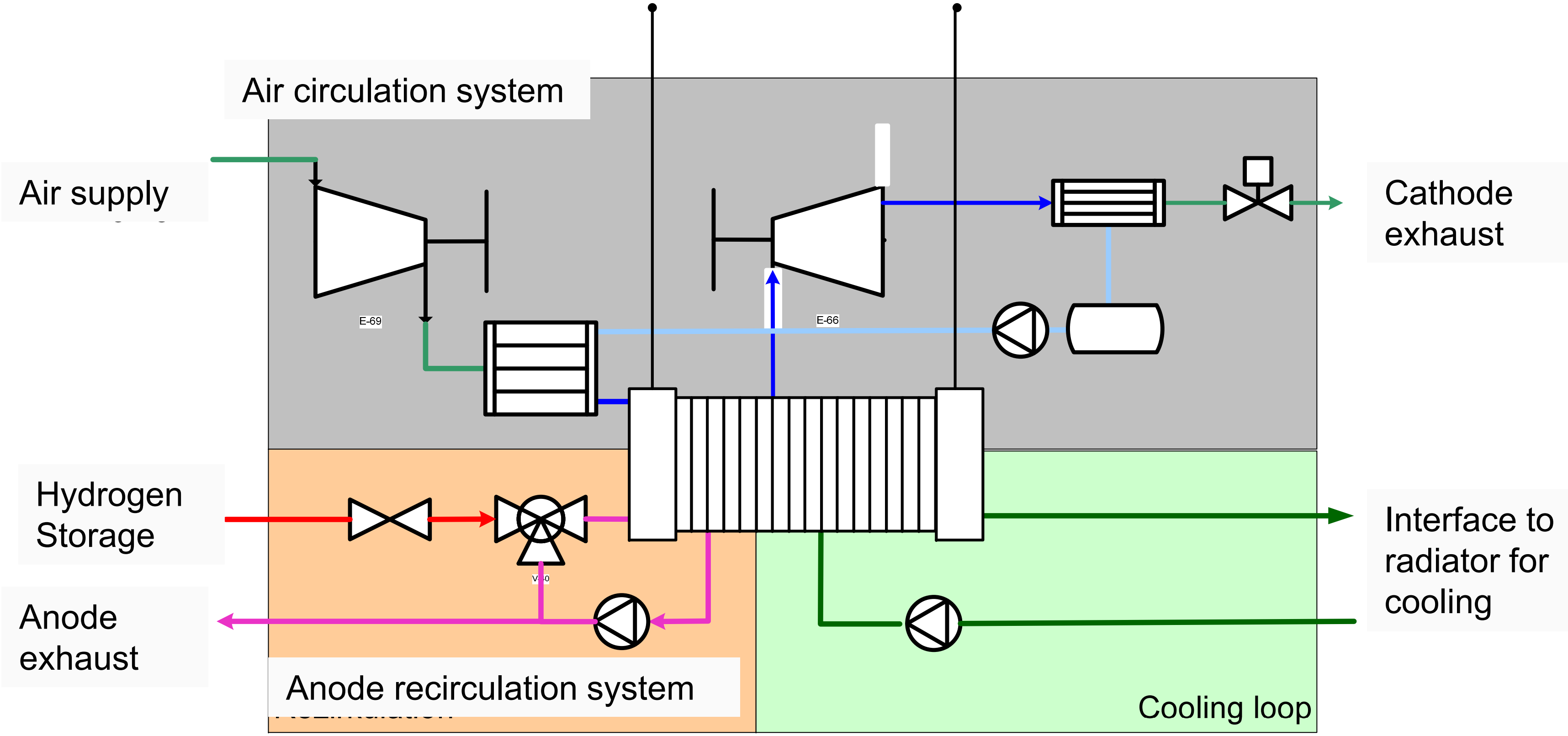
(2.5 kW per liter and 2.08 KW/kg)



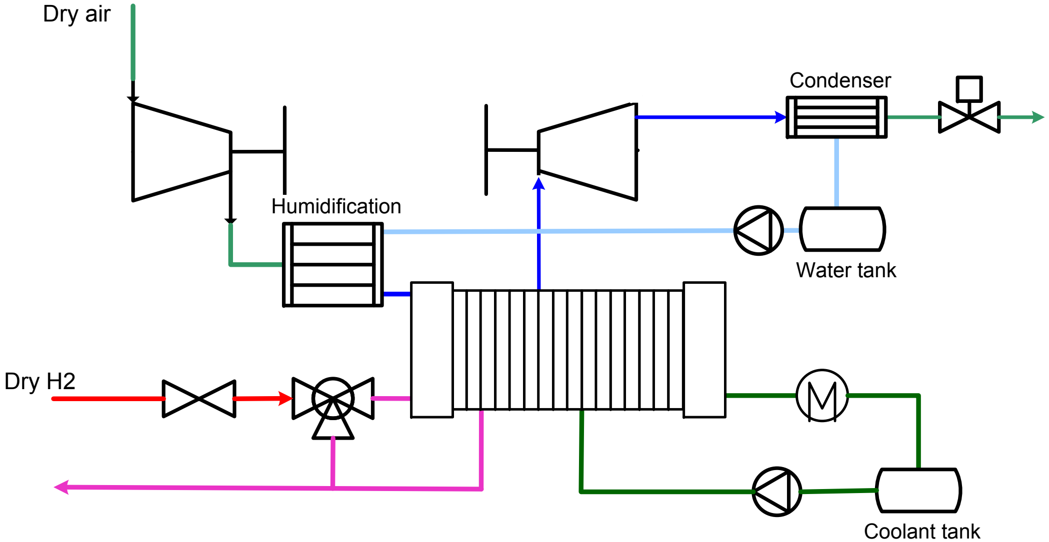
GM Next Generation Fuel Cell system

	Equinox Fuel Cell	Gen 2
		
Net Power	93 kW	85-92kW
Max Excursion Temp	86C	95C
Durability	1500-hrs	5500-hrs
Cold Operation	Start from -25C	Start from -40C
Mass	240 Kg	<130 Kg
Sensors/Actuators	30	≤15
Stack Subsystem: **Plates** **UEA**	Composite 80g Platinum / FCS	Stamped Stainless Steel <30g Platinum / FCS
Air Subsystem & Humidification	Tube-style Humidifier sensor based RH control	GM designed Humidifier model based RH control
Design Integration	Semi-Integrated	Highly Integrated for Thermal Performance

System Components



DC A-Class Fuel Cell System (~2002)

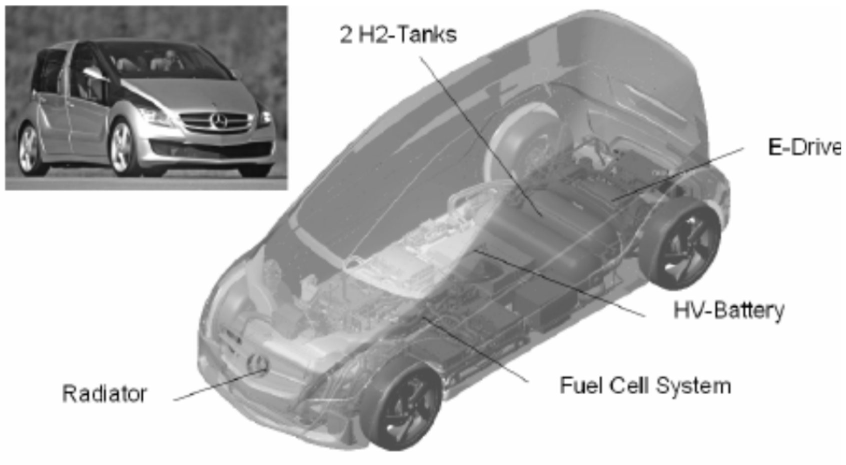


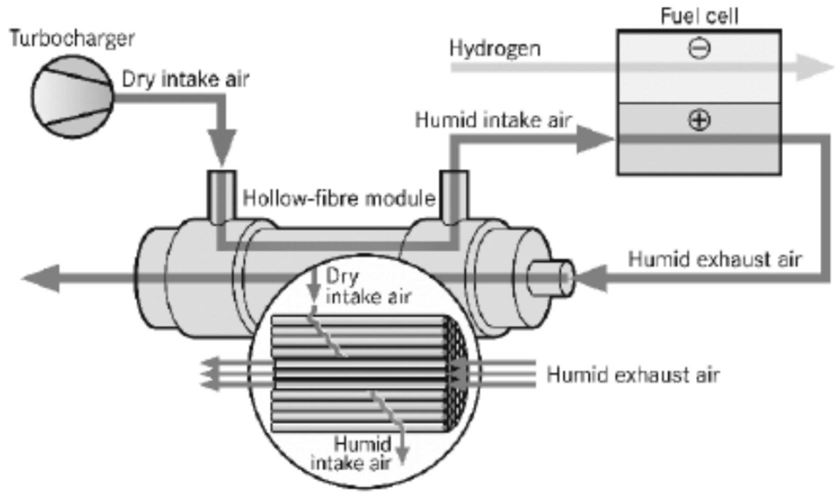
- Ballard Hy80 System
  220 kg, 220 l, 68 kW
- Stack Mark 902
- Rotary Screw Compressor + Expander
- Active humidification

Power (Stack):	85 kW
Power Density (Stack):	1.1 kW/l – 0.9 kW/kg
Active Area:	
Number of Cells:	
Compressor (Lambda):	Screw, λ=2 from about 10% P_{max}
Humidifaction:	yes - evaporator
H_2 Recirculation (Lambda):	yes
Cooling:	Ethylene / Glycol
System pressure:	2 bar (overpressure)
Operation Temperature:	80° C
Bipolar Plate:	Graphite
H_2 Storage:	350 bar C-H_2

Bru2006-Testing-Expo-Fiat-NUVERA.pdf
Moh2006-VDI-Berichte-1975-Technical-Status-DaimlerChrysler.pdf
Bal2007-Datenblatt-Ballard-Mark902.pdf
Stra2005-F-Cell-Ballard-Hy-80.pdf

DC F600 – Research Car (~2005/2006)





Power:	78kW (personal communication)
Power Density:	1.9kW/l – 1.0kW/kg (personal comm.)
Active Area:	ca. 312 cm²
Number Cells:	440 (personal comm.)
Compressor:	Elect. Turbo Charger (personal comm.)
Humidification:	„Hollow-fibre“ gas to gas humidification
Motor drive:	Direct current motor
Hybrid Battery:	Lithium Ionen Battery
Air System:	Electrical Turbo charger
Bipolar plate:	metallic 0.15mm (gold coating)
H_2 Storage:	700 bar C-H_2 (4 kg H_2)

- New Stack
- Turbo compressor
- Lower cathode pressure
- Gas-to-gas-Humidification

Moh2006-VDI-Berichte-1975-Technical-Status-DaimlerChrysler.pdf

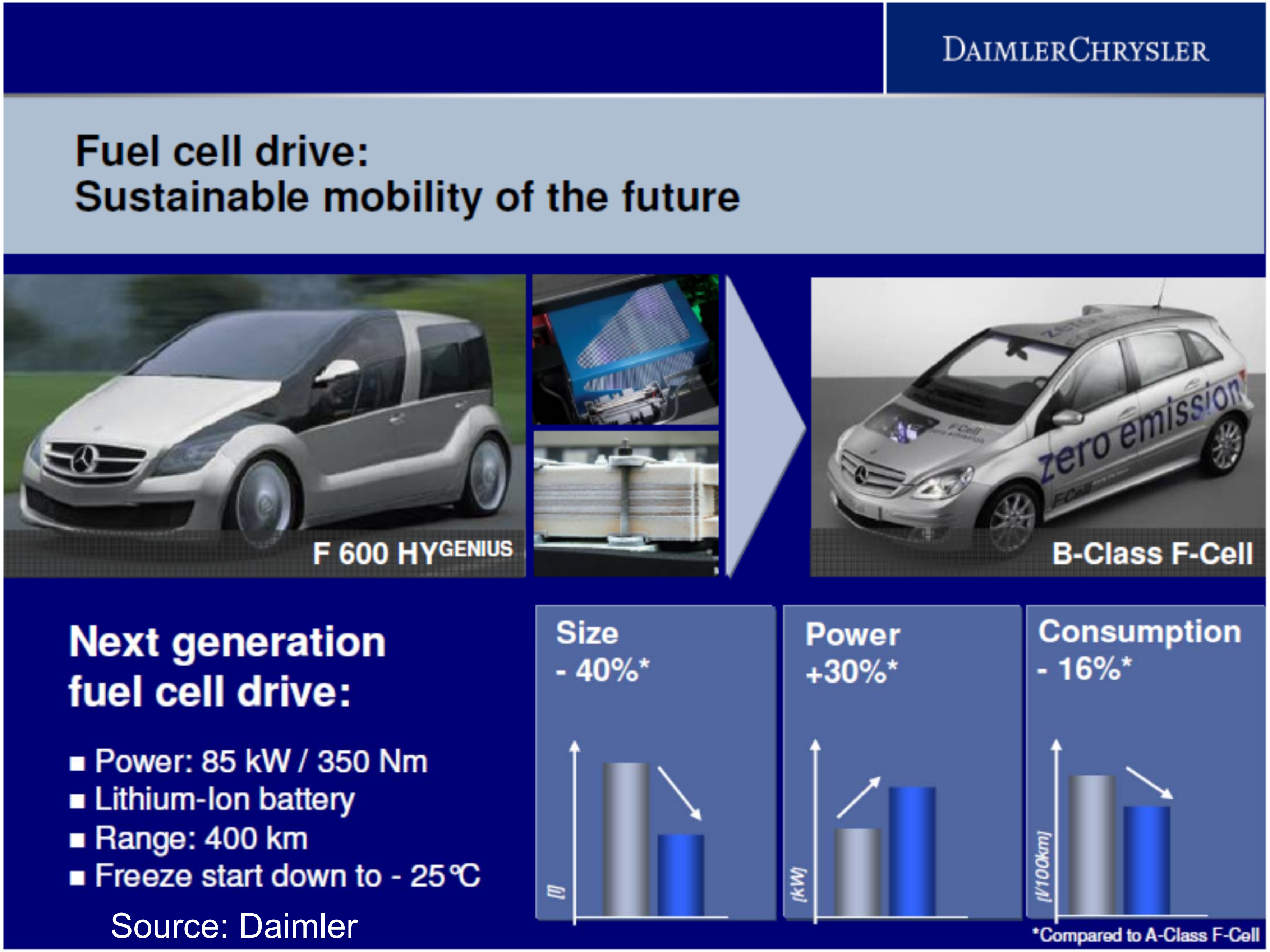
DLR

B Class F-Cell Vehicle (Daimler)

- H_2 Tank with 700 bar
- Variable-speed asynchronous motor ~ 350 Nm
- Hybrid configuration with Li ion battery
- Electrical turbocharger
- New humidifier with membranes
- 400 km range
- 170 km/h max. velocityt
- NEDC: 2.9 l – Diesel-Equiv. / 100 km; ~ 105 MJ/100 km

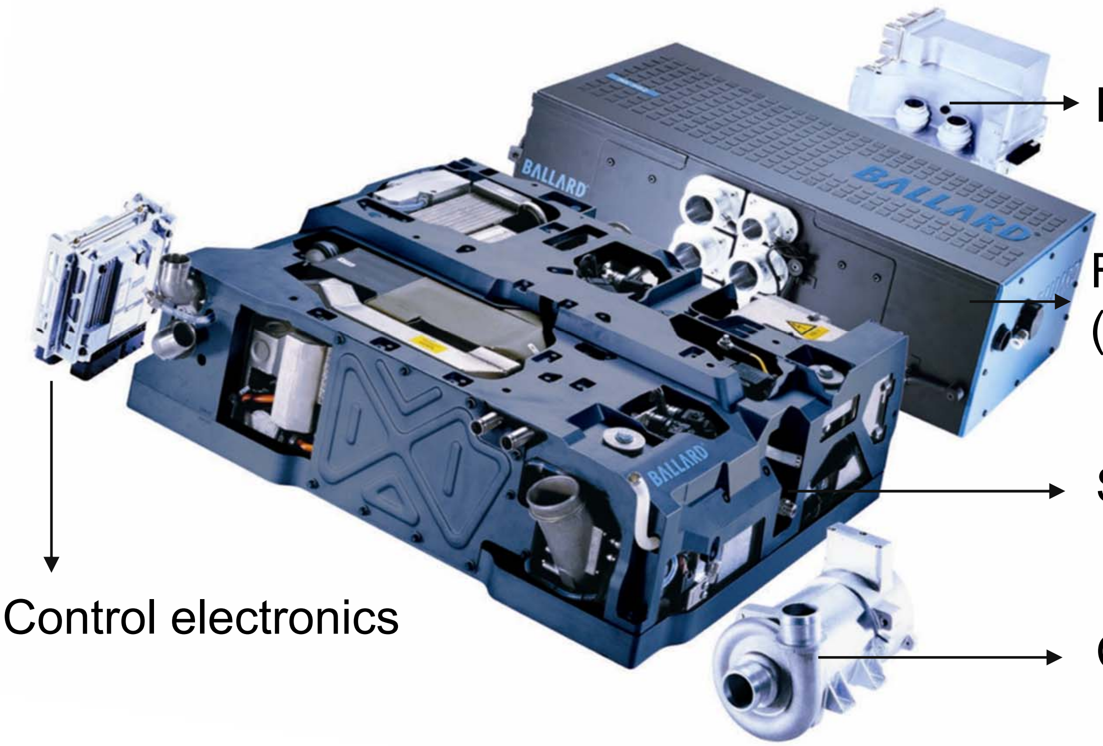
B-Class F-Cell

Specifications	
Vehicle type	Mercedes-Benz B-Class
FC-System	PEM, 80 kW
Drive	IPT Output (Continuous / Peak) 70kW / 100kW (136hp) Max. torque: 320 Nm
Fuel	Hydrogen (70 MPa / 10,000 psi)
Range	400 km (250 miles)
Max. Speed.	170 km/h (106 mph)
Battery	Li-Ion (Mn), Power (Continuous / Peak): 24 kW / 30 kW (40hp); Capacity 6.8 Ah, 1.4 kWh

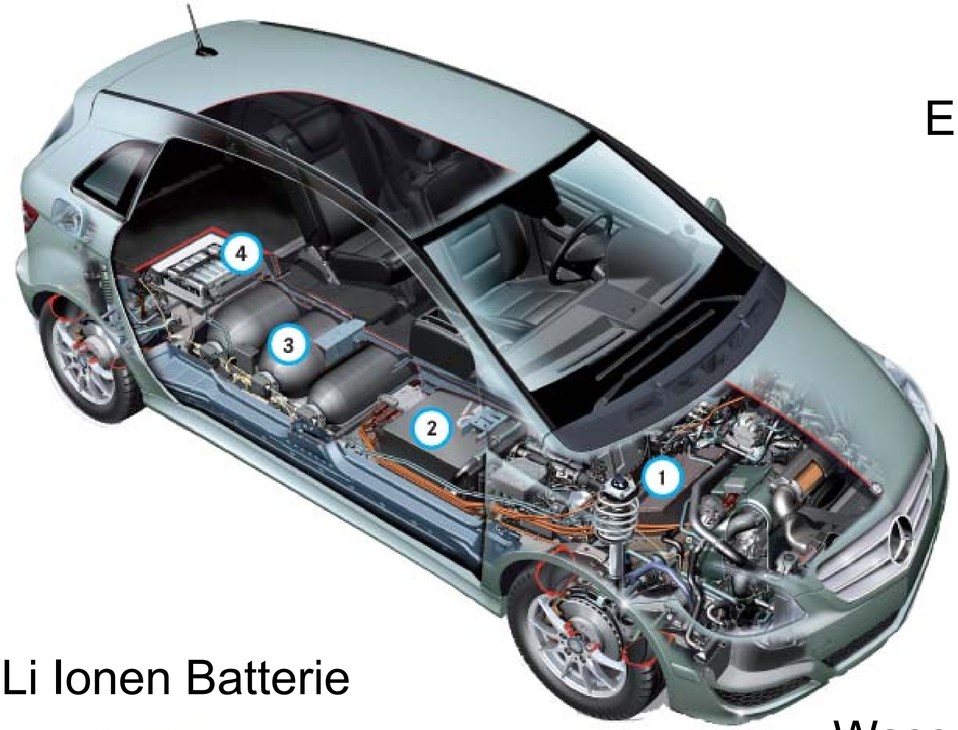


Source: Daimler

Fuel Cell System Xcellsis^{TM}HY-80



F-cell Hauptkomponenten



Elektromotor

BZ-Stack

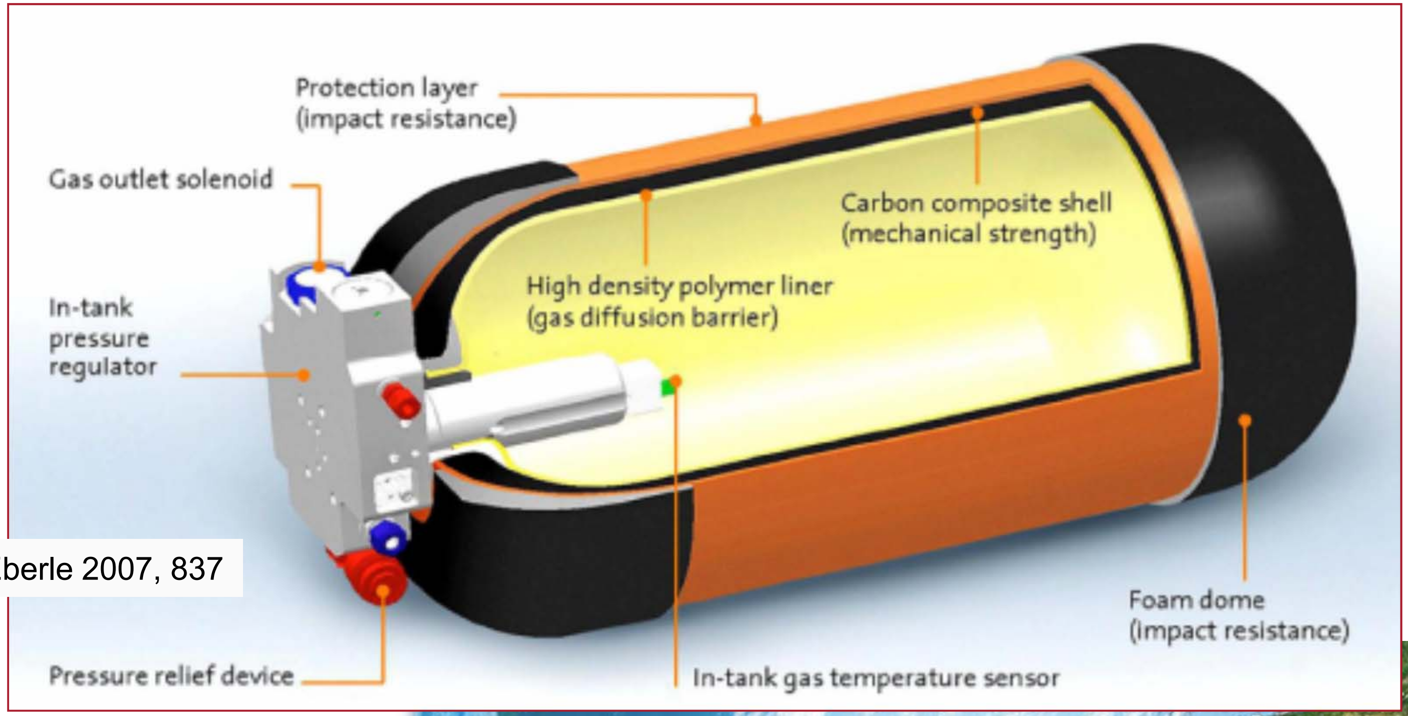
Li Ionen Batterie

Wasserstofftank

DLR

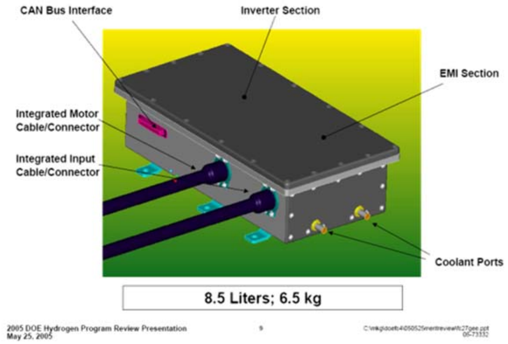
Tank-System for compressed Hydrogen gas

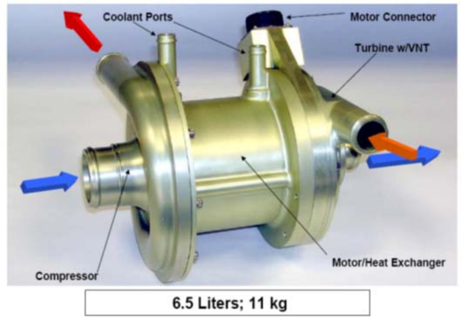
- CGH2: compressed gaseous hydrogen,
- Pressure 35–70 MPa and room temperature.
- Usually 2 or 3 vessels can be placed in a car. In busses up to 8 vessels can be placed.
- Cruising range is between 200km (350 bar) up to 500 km (700 bar).



Source: Helmolt/Eberle 2007, 837

Compression of Air





Carlson – NREL: „Cost analysis for PEMFC“:
- Turbo compressor expander (Honeywell)
  - maximum rotation speed: 110.000 rpm
  - Idle speed: 36.000 rpm
  - Mass: 17.5 kg (with controller)
  - Volume: 15 l (with controller, gee2005-Honeywell-TurboCompExp.pdf

Mohrdieck:
- A-Klasse F-Cell: Screw compressor (Opcon)
  - Rotation speed: 20.000 rpm
  - Mass:
- F600 HyGenius: Elektrischer Turbolader
  - Rotation speed : 120.000 rpm
  - Lower weight: to 1/3 in comparison to screw compressorr

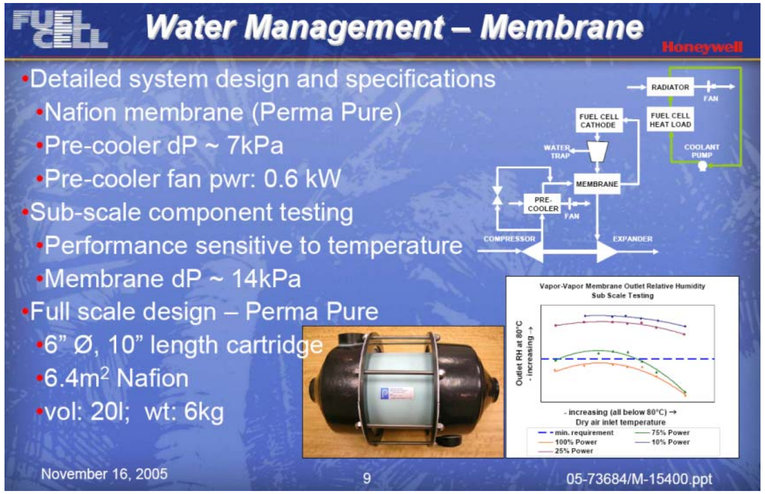
Problems with turbo chargers:
- Stall line → complex control syste,
- High pressure ration → complex dimensioning of blade and rotation speed
- Demand of oil free operation

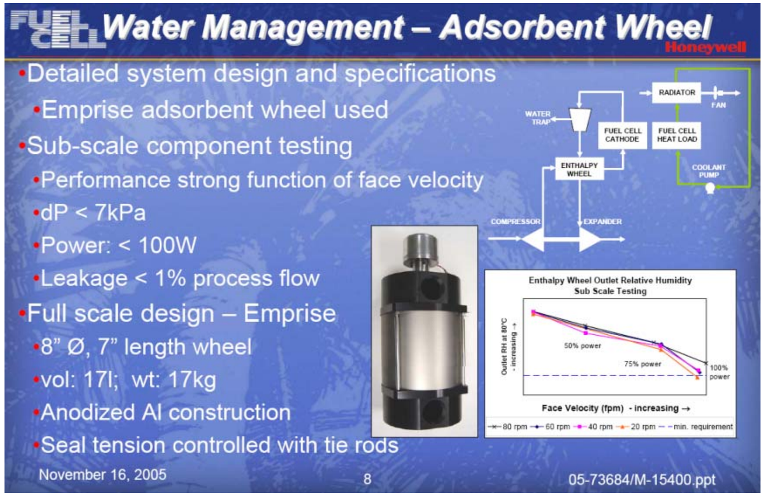
Car2005-NREL-Cost Analysis of PEM Fuel Cell.pdf
Moh2006-VDI-Berichte-1975-Technical-Status-DaimlerChrysler.pdf
http://www.hytran.org
gee2005-Honeywell-TurboCompExp.pdf

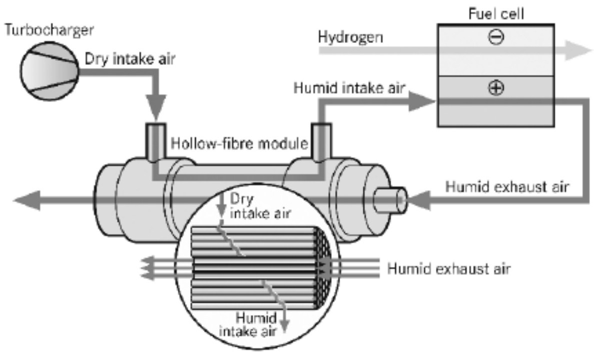
Humidifier

- PermaPure
- „Hollow Fibre Module“ (Daimler)

„Enthalpy wheel“





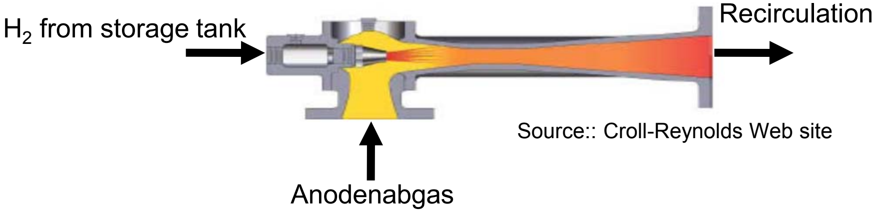


Hon2005-Honeywell-Air-thermal-water-management.pdf
Car2005-NREL-Cost Analysis of PEM Fuel Cell.pdf
Moh2006-VDI-Berichte-1975-Technical-Status-DaimlerChrysler.pdf
http://www.hysys.de/objectives.htm

H_2 Recirculation

Carlson – NREL: „Cost analysis for PEMFC“:

- Ejectore (Croll-Reynolds):



- Recirculation pumps:

H2 Systems Inc.

From Nuvera

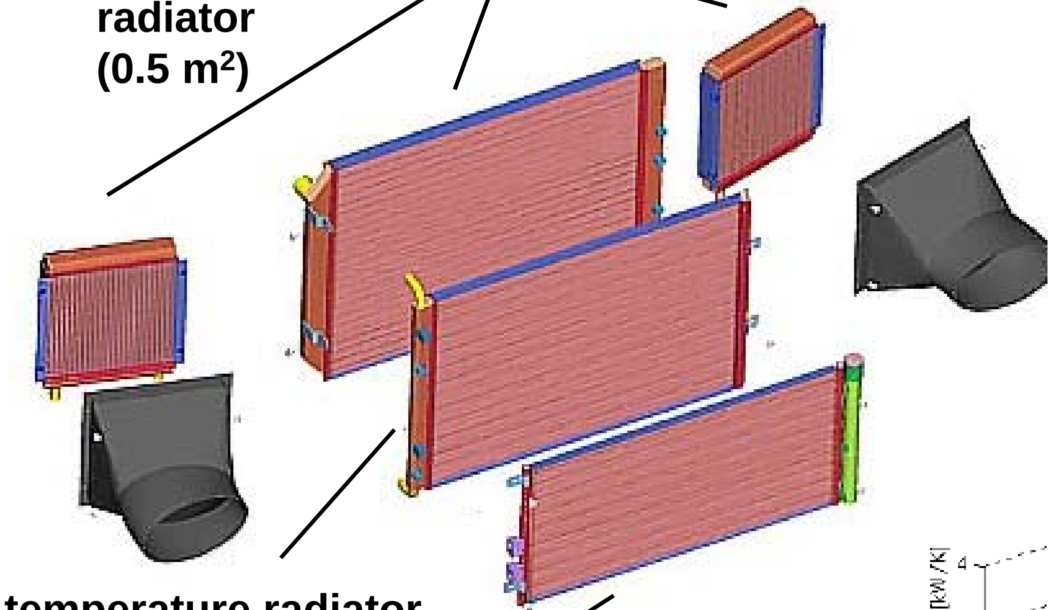
Reciculation need:

- Dynamics
- Hydrogen utilization

Car2005-NREL-Cost Analysis of PEM Fuel Cell.pdf
Moh2006-VDI-Berichte-1975-Technical-Status-DaimlerChrysler.pdf
Bru2006-Testing-Expo-Fiat-NUVERA.pdf

Cooling System – F- Cell - Daimler

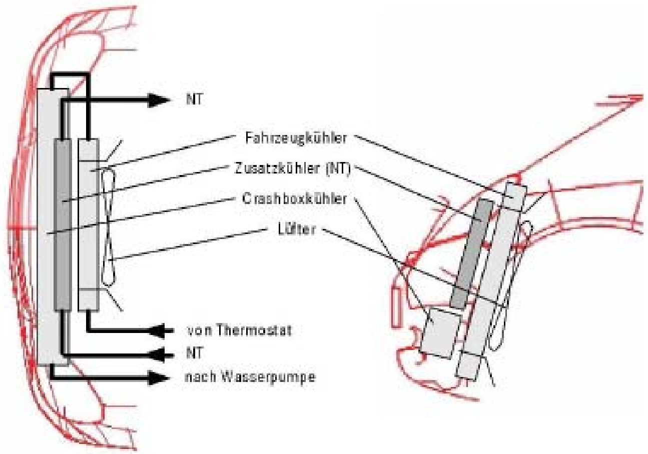
High temperature radiator (0.5 m²)



Low temperature radiator

Cooling liquid condenser

- $T_{coolant}$: ~80 ° C
- ~80 kW @ 25 ° C
- ~50 kW @ 40 ° C
- P_{blower}: ~2.5 kW



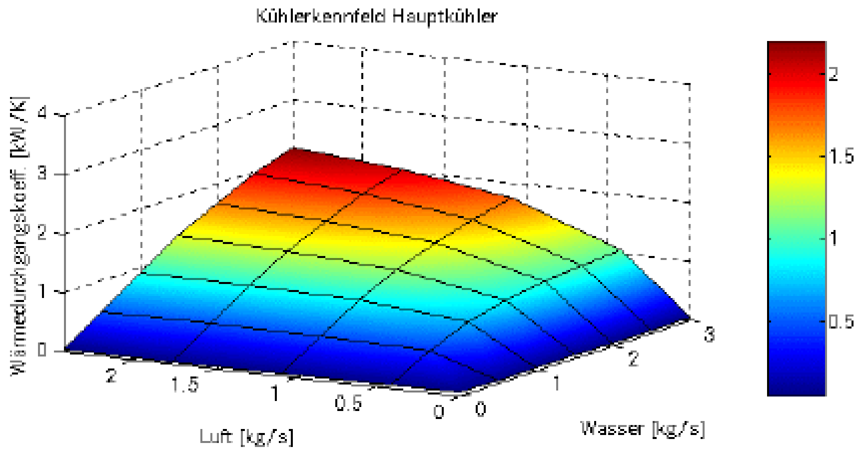


Abbildung C.6: Wärmedurchgangskoeffizientenkennfeld des Hauptkühlers

Span2003-Dissertation-Energiesparmaßnahmen-Methanol-BZ-Fahrzeug.pdf
Car2005-NREL-Cost Analysis of PEM Fuel Cell.pdf

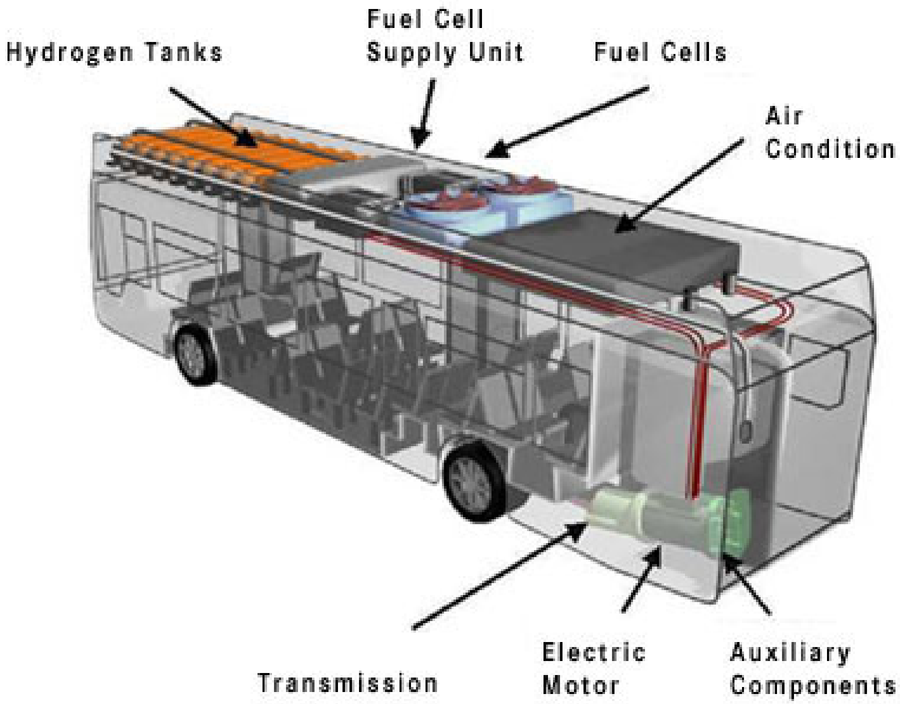
Cooling System– DaimlerCrysler – F- Cell

Vehicle at F-Cell Meeting Stuttgart, 2005

Fuel Cell Busses

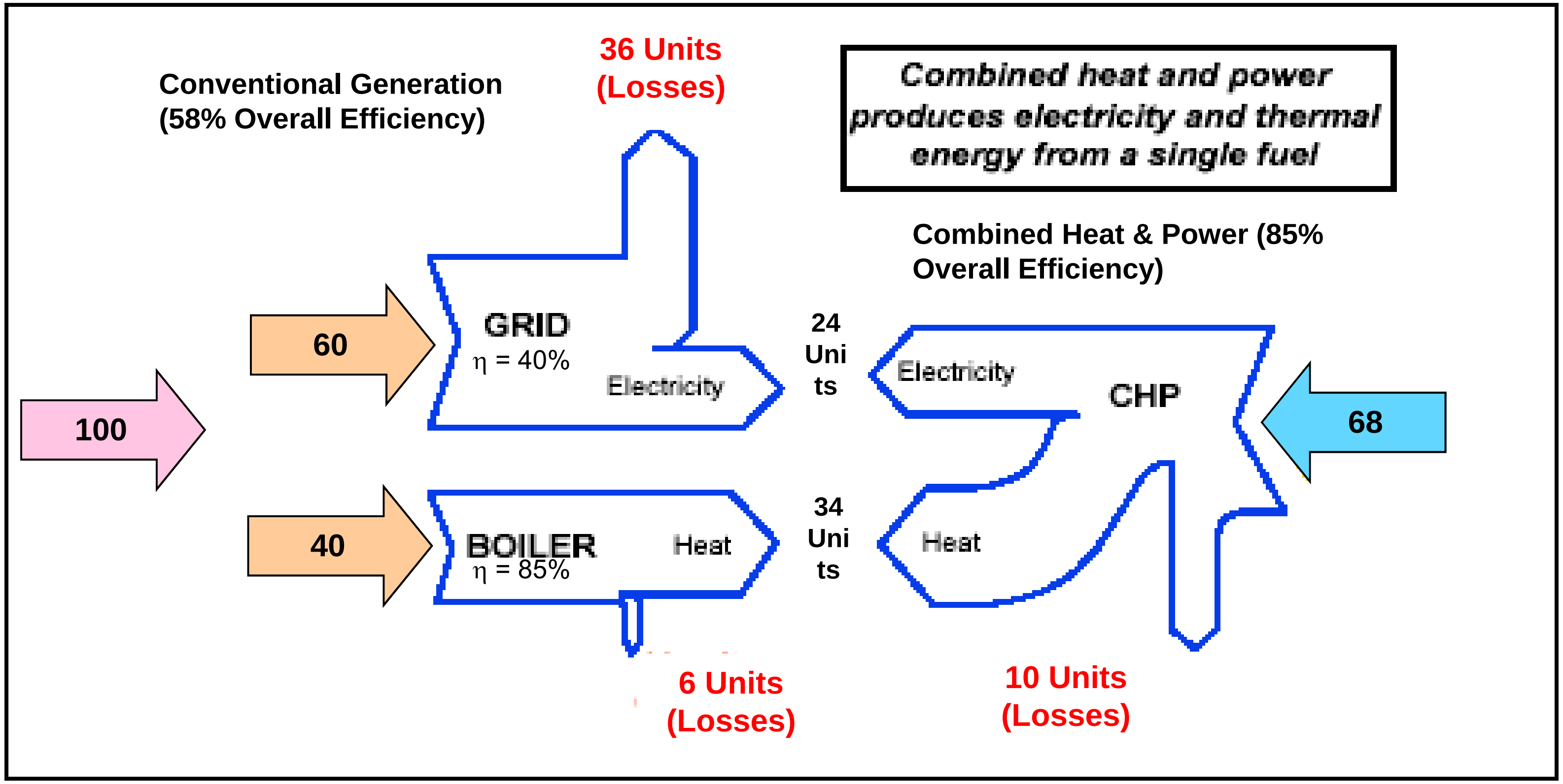
- DaimlerChryslers “Citaro-Bus” based on fuel cell technology.
- 27 Citaro buses were tested during 2003 to 2005 in 9 European cities.
- Stack-Technology from Ballard:
  - Two modules “MK902 Heavy Duty“ with 300 kW.
- Tank-System
  - 9 CGH2-vessels with 350 bar can store 1845 litre.
- operating range
  - 200 to 250 kilometres.
- maximum speed
  - approx. 80 kilometres.

Fuel Cell Bus “Citaro”

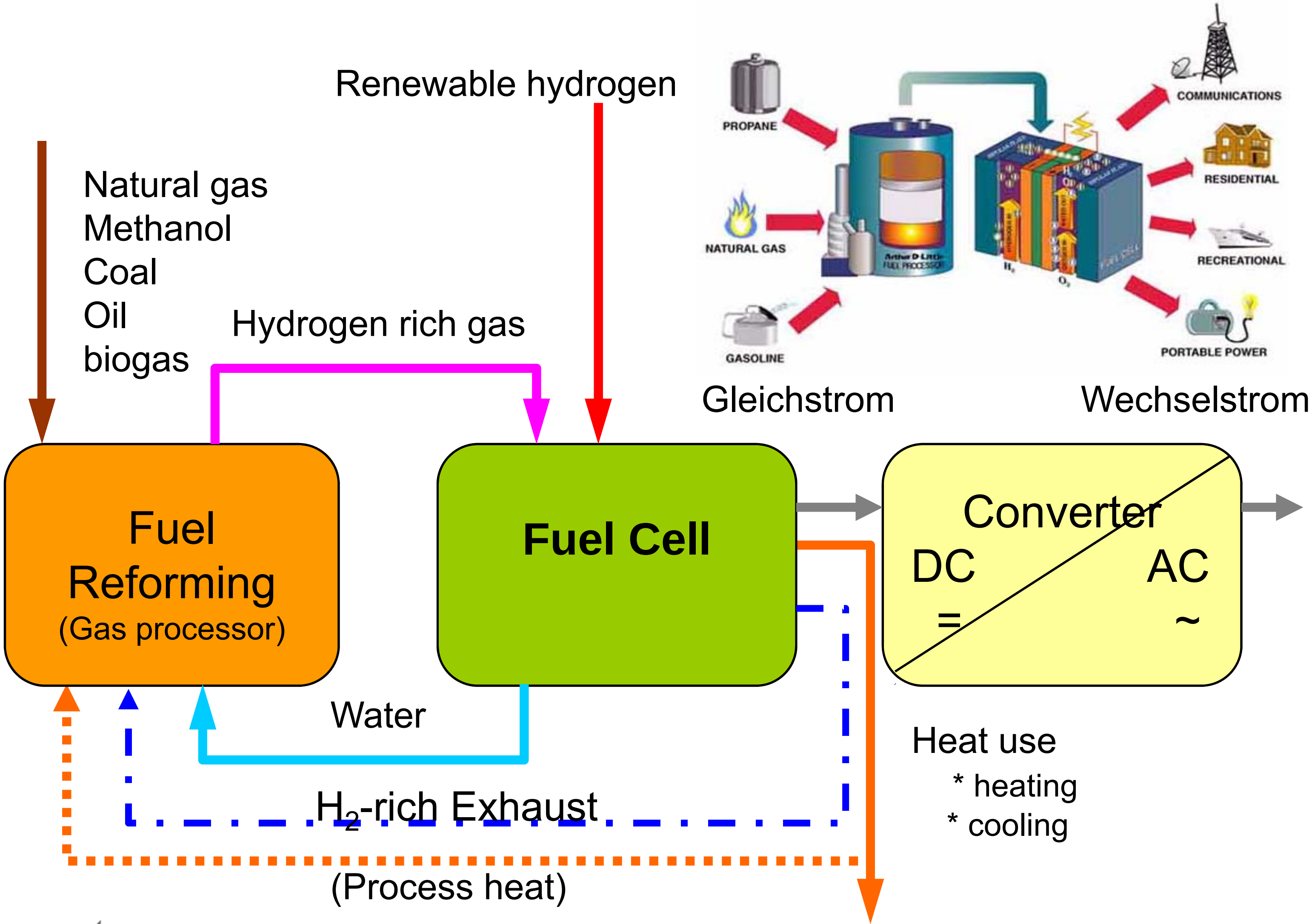


Source: Fuel Cell Bus Club 2004

Efficiency Advantage of CHP

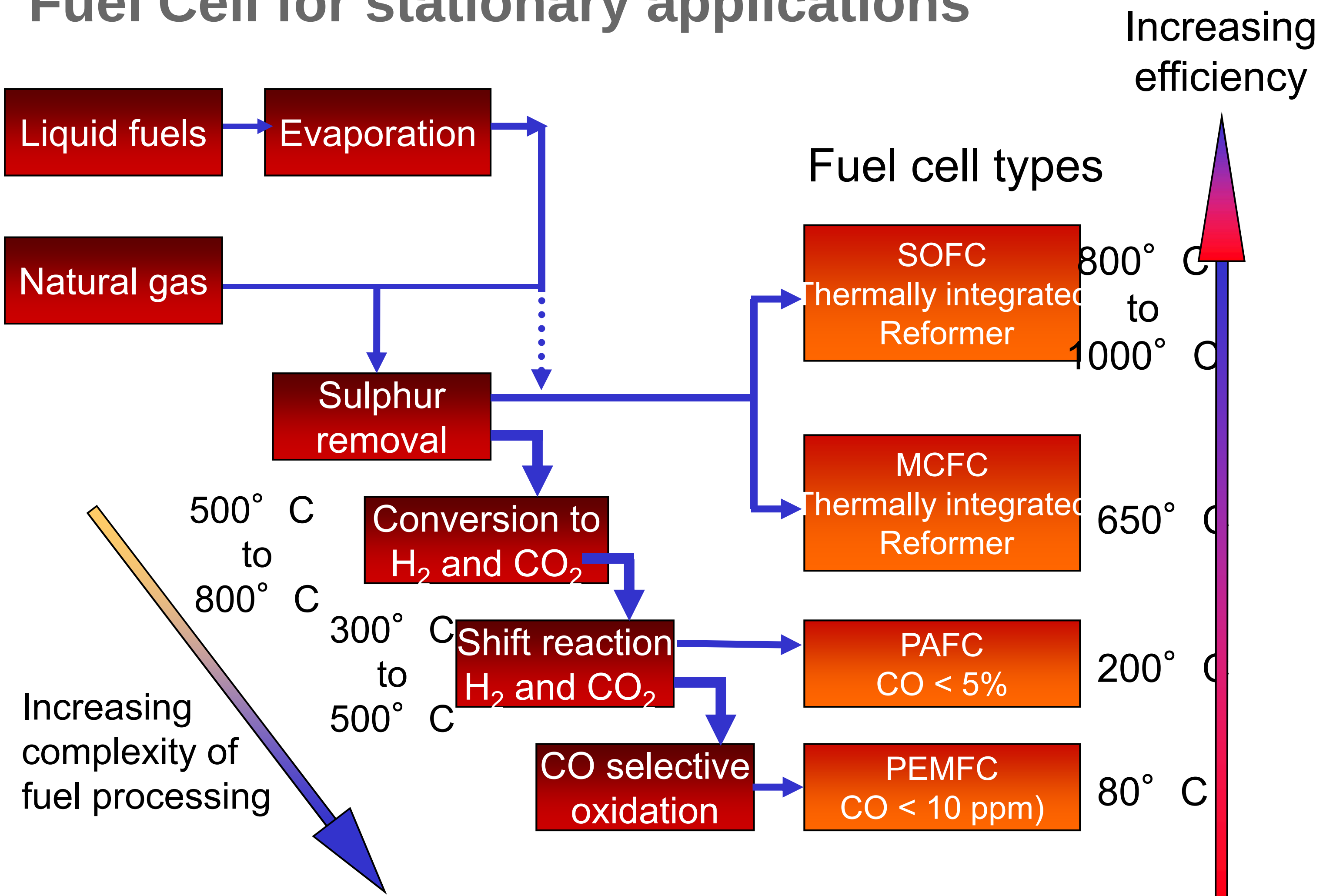


Fuel Cell Power Plant



DLR

Fuel Cell for stationary applications



Source: B.C.H. Steele, Nature '99

Reformierung STR / CPOx

STR = Steam Reforming

$$CH_4 + 2H_2O \longrightarrow 4H_2 + CO_2 \qquad \Delta G>0$$

CPOx = Catalytic Partial Oxidation

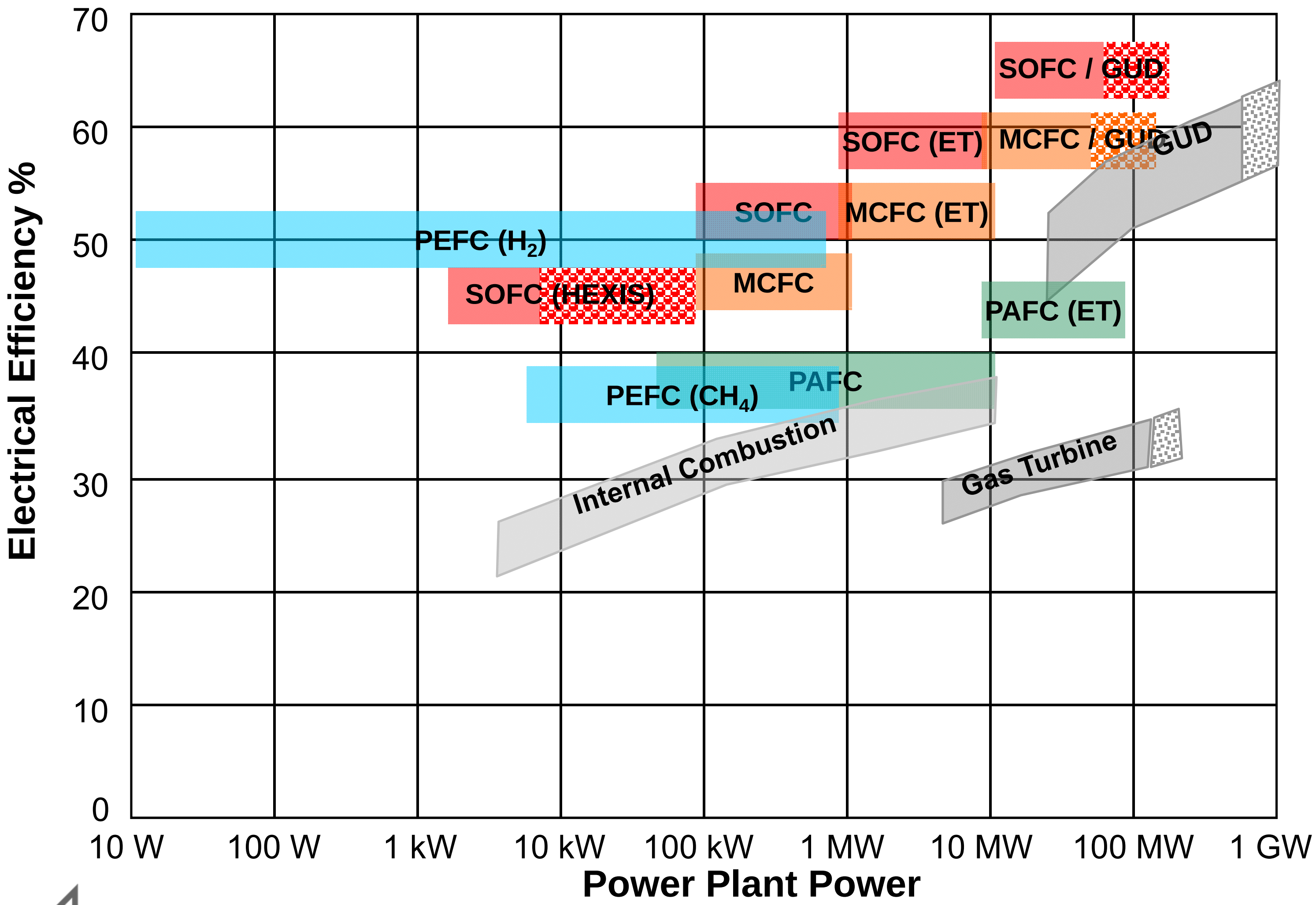
Combination of

$$CH_4 + 0.5O_2 \longrightarrow 2H_2 + CO \qquad \Delta G<0$$

$$CH_4 + 2O_2 \longrightarrow 2H_2O + CO_2 \qquad \Delta G<0$$

DLR

Efficiencies in Comparison



Fuel Cell Technology for Residental Application

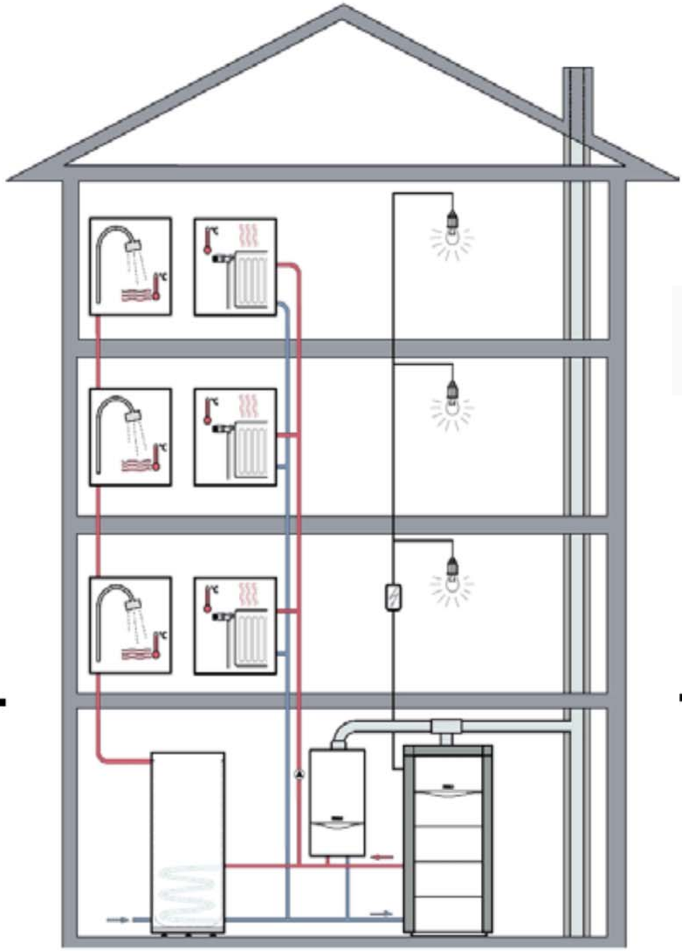
- Extension of Cogeneration possibilities below 10 KW_{el}
- „Heating device“ with power generation
- New technology with positive associations (low emissions, high efficiecies)
- Modular system with development potential for futher applications and products

Advantage of fuel cell systems for residental application:

- Low emissions
- High power to heat ration
- High efficiency at part load
- Low noise level

Residental System

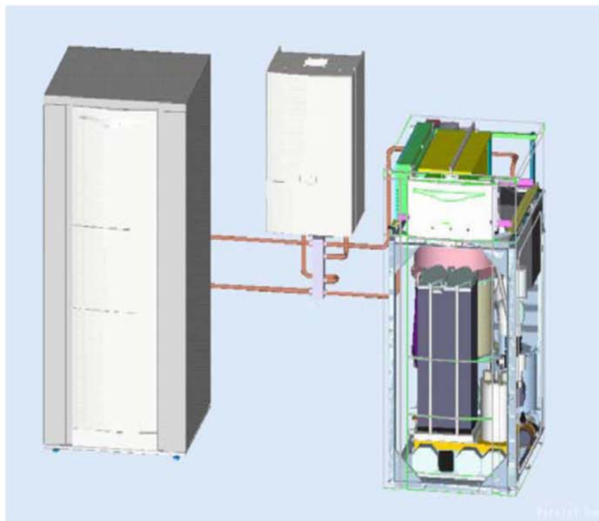
KWK-System für die Hausenergieversorgung



Hot water storage tank

Boiler

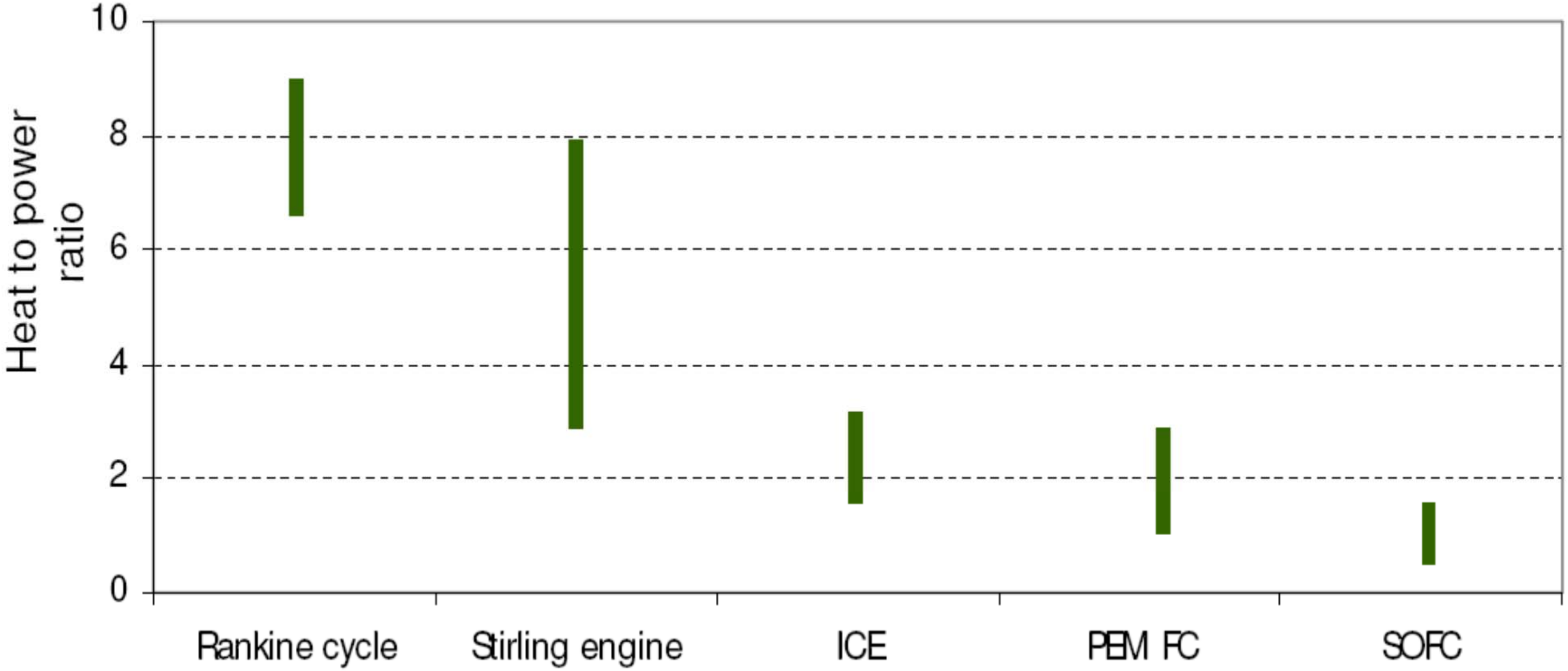
Fuel cell system



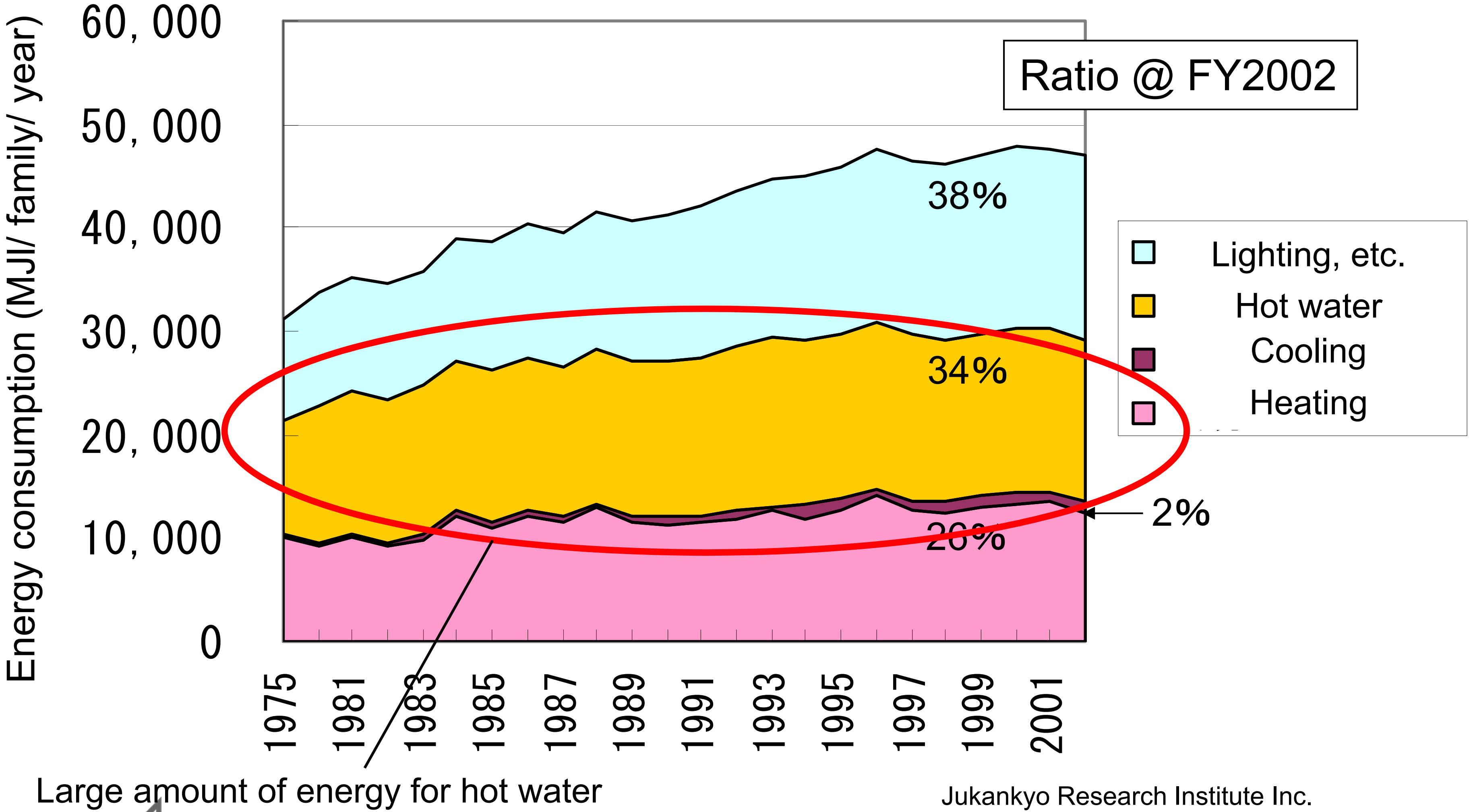
Requirements for Fuel Cell Systems in the stationary application

- Residential: small power units (1-10 kW)
- Dynamic response (advantage PEFC fast cold start)
- Higher power to heat ration
- Temperature level for heat utilization
- Low parasitic energy comsumption (system simplification)
- durability > 40.000 h
- Low cost < 1000 €/kW
- Low level of maintainance
- High availability
- High total efficiency
- Low emissions

Heat to Power Ratio for different Technologies



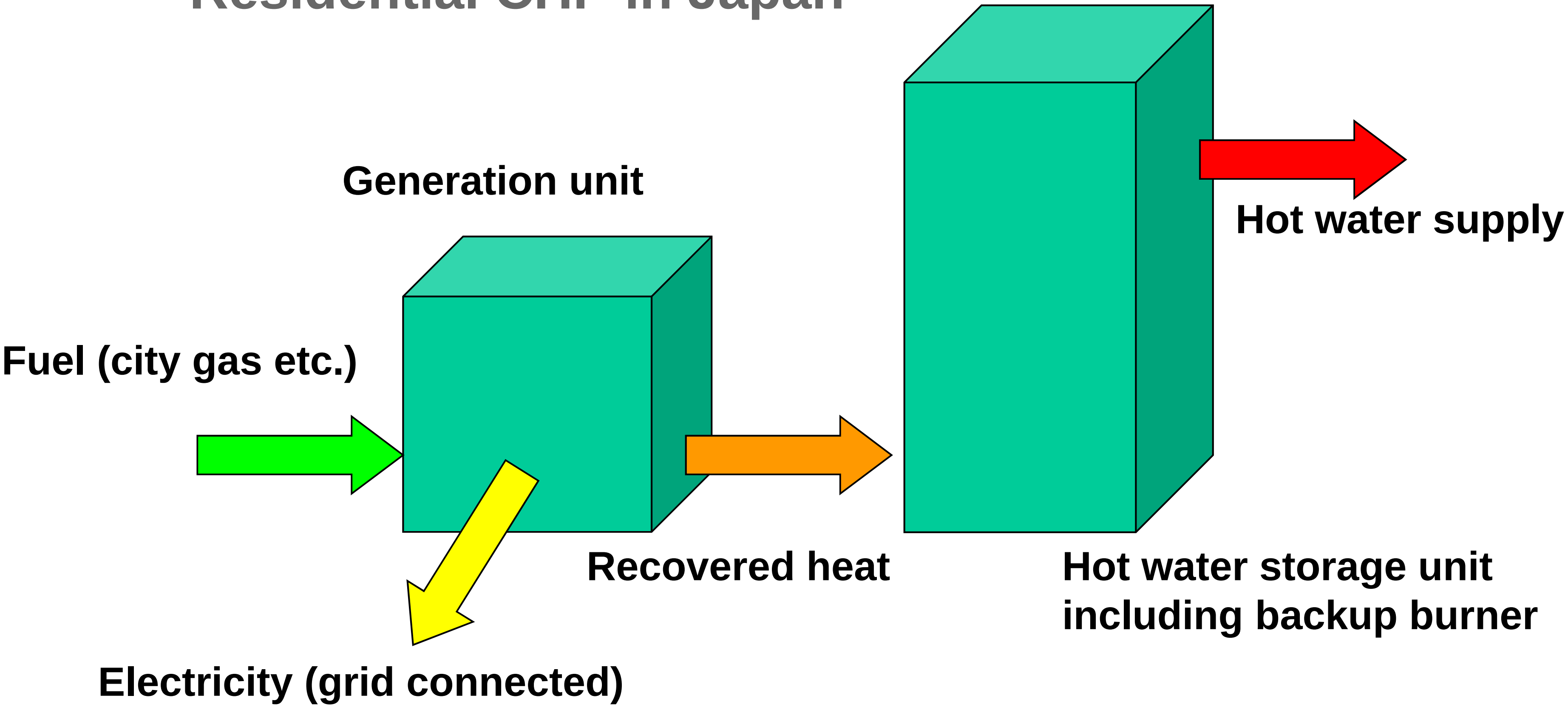
Japanese Application and experience



Jukankyo Research Institute Inc.

DLR

Residential CHP in Japan



>Rated power: 1kW class

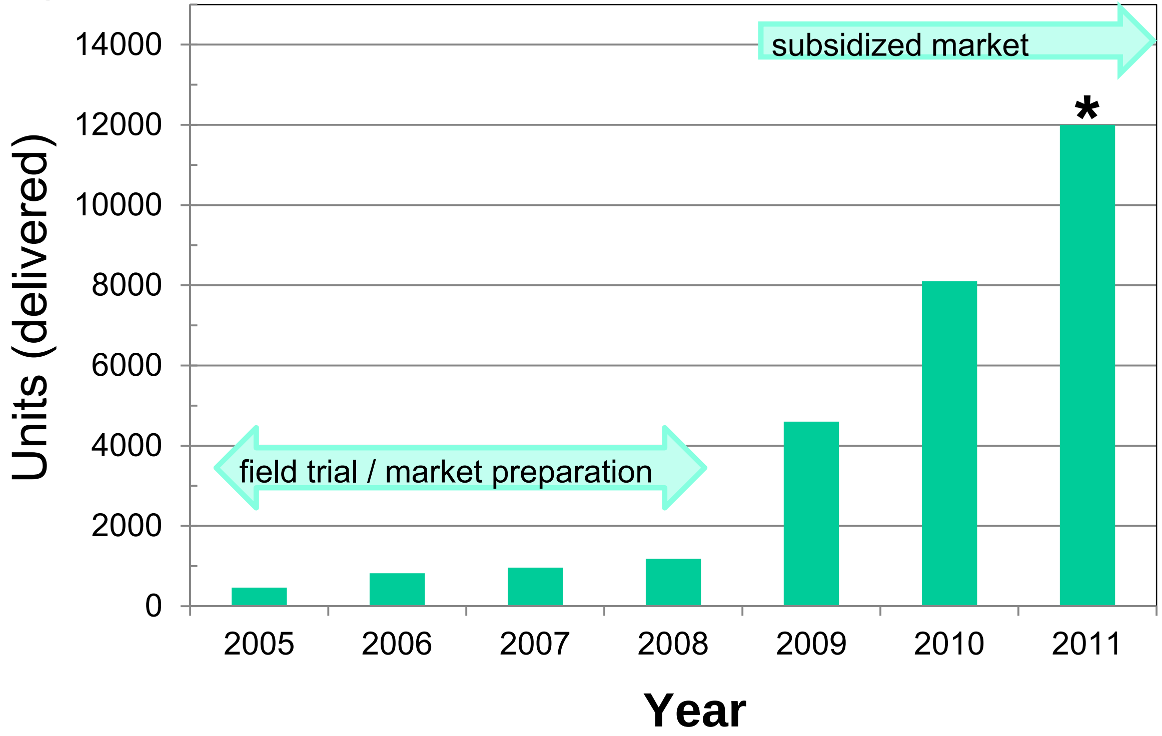
>Recovered heat used as hot water

Residential CHPs in Japan

	Gas Engine	PEFC	SOFC
Efficiency E / H (%LHV)	22.5 / 63	37 / 50	45 / 30
Operation	Start & stop	Start & stop	Continuous
Stage	Commercial	Limited market entry	Field trial Market entry 2012
			

PEFC: Polymer Electrolyte Fuel Cell, SOFC: Solid Oxide Fuel Cell

Market Development in Japan for Residential Fuel Cell Systems



* Cummulated from Panasonic and Toshiba numbers

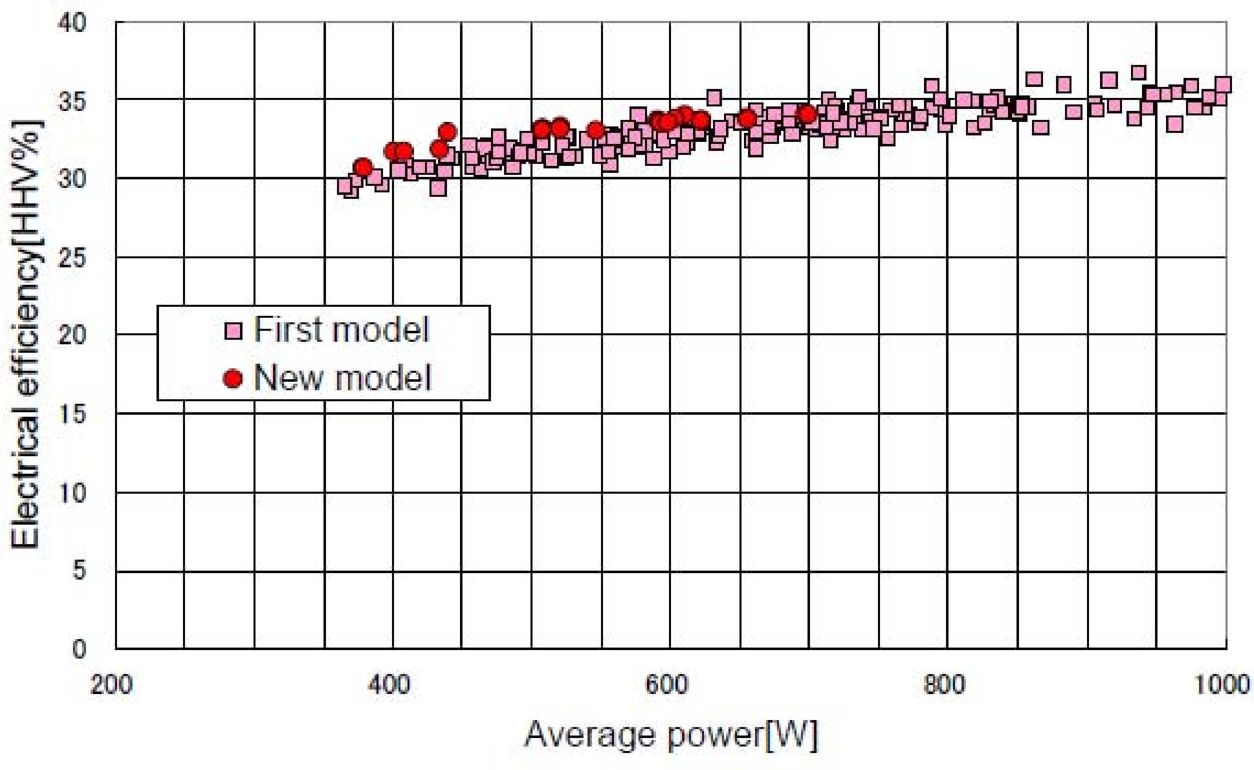
Residential PEFC Cogeneration System from Tokyo Gas

- Fuel Cell Systems from Panasonic and Toshiba

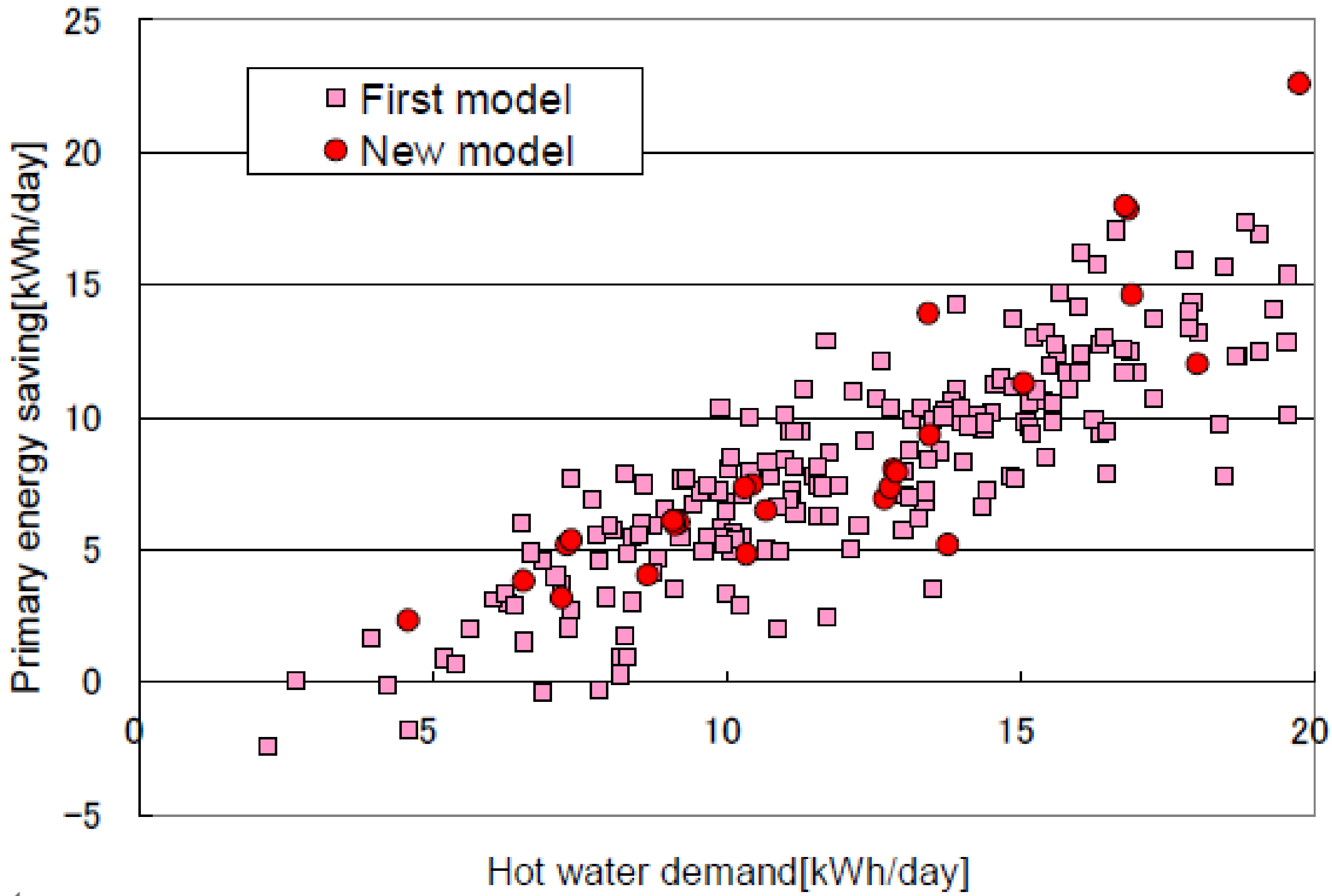
Table 1: Specifications of the first model and the new model

		First model	New model
Fuel type		LNG based natural gas (category 13A)	
Fuel cell unit	Max. output	1kW	0.75kW
	Min. output	0.3kW	0.25kW
	Electrical efficiency	37 % LHV/33 % HHV	40 % LHV/36% HHV
	Heat recovery efficiency	52 % LHV/47 % HHV	50 % LHV/45 % HHV
	Heat recovery temperature	60 °C	
	Dimensions	W780 D 400 H 860 mm	W315 D480 H 1883 mm
	Dry weight	125 kg	100kg
	Fuel consumption rate	3.0kW HHV	2.1kW HHV
Hot water storage unit	Dimensions	W 750 D 480 H 1883 mm	
	Dry weight	125 kg	
	Tank capacity	200 L	
	Backup burner input	64.7kW HHV	
Appearance			 connected all-in-one design installation

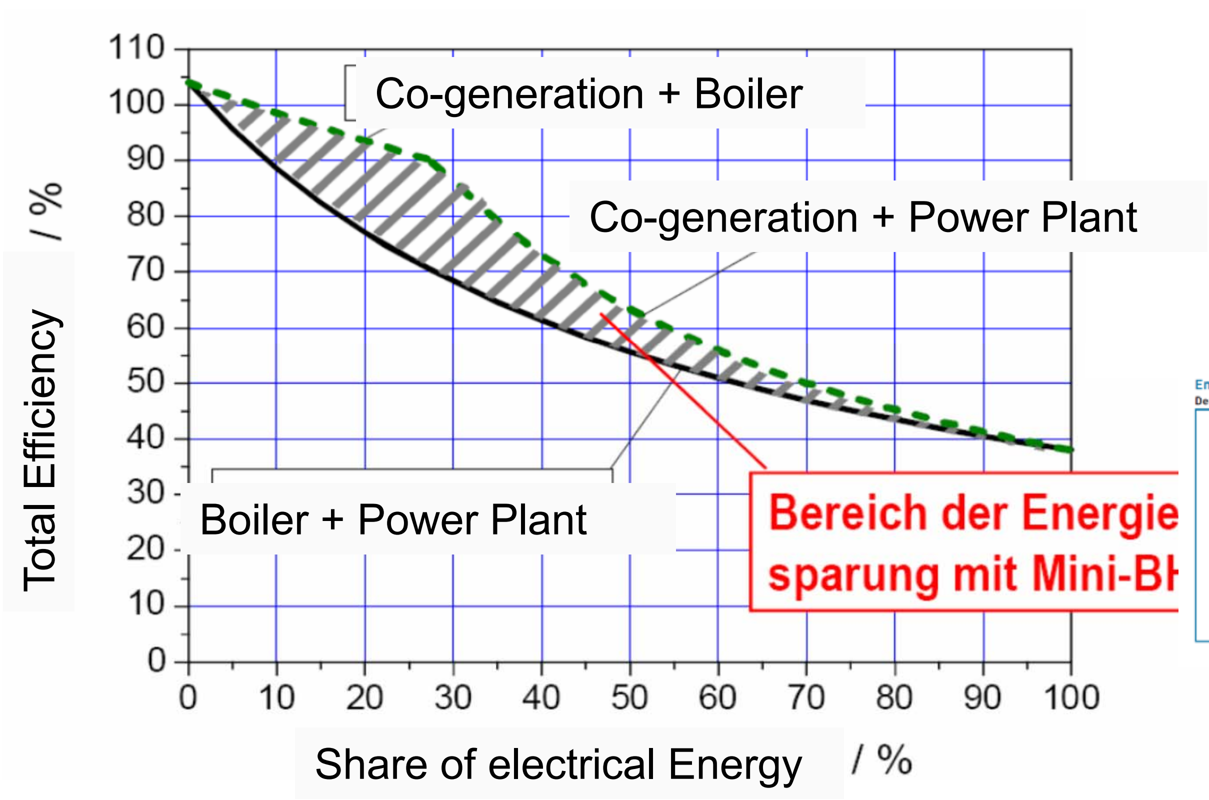
Data from Tokyo Gas (Panasonic Fuel Cell Systems)



Data from Tokyo Gas (Panasonic Fuel Cell Systems)



CHP in Residential Application in Germany



Co-generation ratio

η_{el} = 25 %

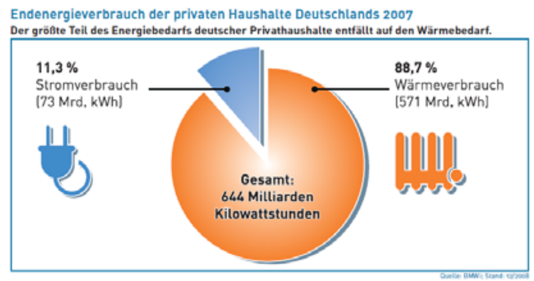
η_{th} = 65 %

Boiler

η_{th} = 104 %

Power Plant

η_{el} = 38 %



7

Field Testing in Germany within the Callux Project

callux
Praxistest Brennstoffzelle fürs Eigenheim

EnBW
BAXI INNOTECH
e-on Ruhrgas
HEXIS
EWE
Vaillant
MVV Energie
ZSW
Verbundnetz Gas AG

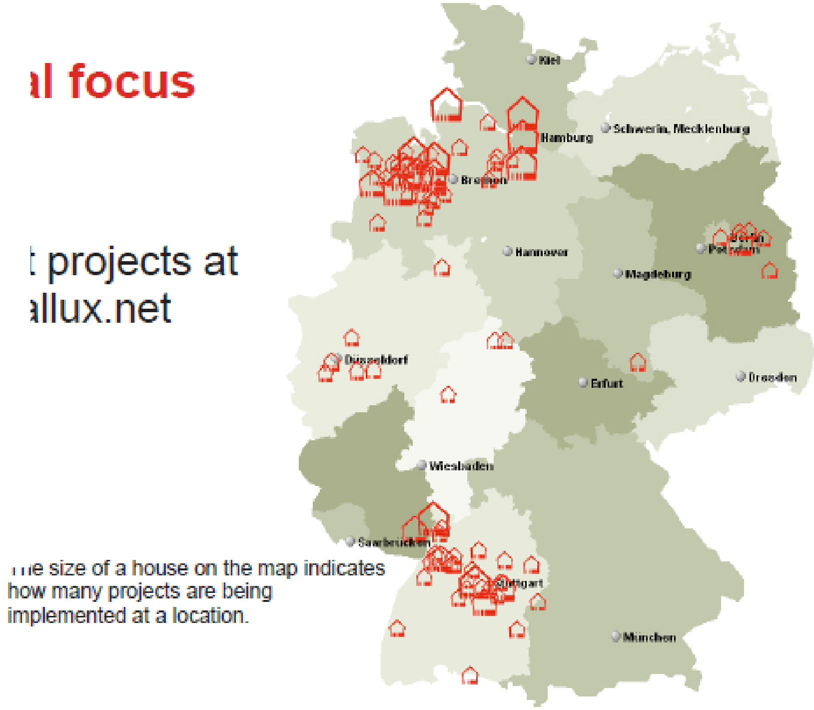
Gefördert durch:

Bundesministerium
für Verkehr, Bau
und Stadtentwicklung

aufgrund eines Beschlusses
des Deutschen Bundestages

nip

NOW
Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie



Source: Callux

DLR

Systems installed in the Field Test

Baxi Innotech fuel cell heating appliance: GAMMA 1.0

CHP section	
Type	low-temperature PEM fuel cell (70 °C)
Output (e/th)	max. 1.0 kWe/1.8 kWth
Modulation range	approx. 100 – 30% PeN
Fuel	natural gas, biomethane
Electrical efficiency (NCV)	32%
Total CHP efficiency	> 91%
Integrated auxiliary heater	
Type	condensing appliance
Output	3.5-15 kW or 3.5-20 kW
Efficiency	109% (ηN at 40/30 °C)
Complete system	
Total efficiency	> 97% (to EN 50465 with 60/40 °C flow/return)
Dimensions (mm)	600 long x 600 wide x 1,600 high
Weight	approx. 200 kg
Housing	coated, fully enclosed
Natural gas pressure	20/25 mbar (EN 437)
Electrical connection	230 V/50 Hz
Operating mode	power-controlled, heat-controlled, energy manager-controlled; central control (virtual power plant)

Hexis fuel cell heating appliance: Galileo 1000 N

CHP section	
Type	solid oxide fuel cell (SOFC)
Output (e/th)	1.0 kWe/2.0 kWth
Modulation range	100-50%
Fuel	natural gas, biomethane
Electrical efficiency (NCV)	> 30-35%
Total CHP efficiency	> 92%
Integrated auxiliary heater	
Type	condensing appliance
Output	4-20 kW
Efficiency	109% (ηN at 40/30 °C)
Complete system	
Total efficiency	> 95% (to EN 50465 at 60/40 °C flow/return)
Dimensions (mm)	550 long x 550 wide x 1,600 high
Weight	approx. 170 kg
Housing	coated, fully enclosed
Natural gas pressure	20-25 mbar (EN 437)
Electrical connection	230 V/50 Hz
Operating mode	heat-controlled, energy manager-controlled; remote control option

Vaillant fuel cell heating appliance

(Technical target values)

Type	solid oxide fuel cell (SOFC)
Output (e/th)	max. 1.0 kWe/2.0 kWth
Application	single-family home
Fuel	natural gas, biomethane
Electrical efficiency (NCV)	30%
Total CHP efficiency	80 – 85%
Appliance data	
Dimensions (mm)	600 long x 625 wide x 986 high
Weight	approx. 150 kg
Housing	coated, fully enclosed
Natural gas pressure	20-25 mbar (EN 437)
Electrical connection	230 V/ 50 Hz
Operating mode	heat-controlled, energy manager-controlled; remote control option
External peak heater	
Type	condensing appliance
Output	configuration as required by user
Efficiency	109% (ηN at 40/30 °C)

SOFC Systems

Source: Callux

PEM Fuel Cell System

Baxi Innotech fuel cell heating appliance: GAMMA 1.0

CHP section

Type	low-temperature PEM fuel cell (70 °C)
Output (e/th)	max. 1.0 kWe/1.8 kWth
Modulation range	approx. 100 – 30% PeN
Fuel	natural gas, biomethane
Electrical efficiency (NCV)	32%
Total CHP efficiency	> 91%

Integrated auxiliary heater

Type	condensing appliance
Output	3.5-15 kW or 3.5-20 kW
Efficiency	109% (ηN at 40/30 °C)

Complete system

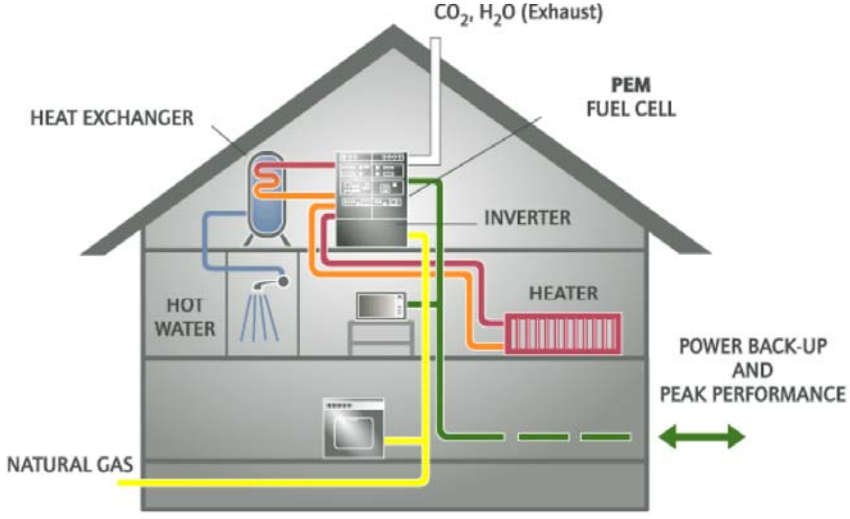
Total efficiency	> 97% (to EN 50465 with 60/40 °C flow/return)
Dimensions (mm)	600 long x 600 wide x 1,600 high
Weight	approx. 200 kg
Housing	coated, fully enclosed
Natural gas pressure	20/25 mbar (EN 437)
Electrical connection	230 V/50 Hz
Operating mode	power-controlled, heat-controlled, energy manager-controlled; central control (virtual power plant)

DLR

Source: Callux

Business Case for Germany / Baxi Innotech

Fuel cell heating CHP for single family homes with natural gas supply



The Micro CHP Fuel Cell Heating Unit supplies ...

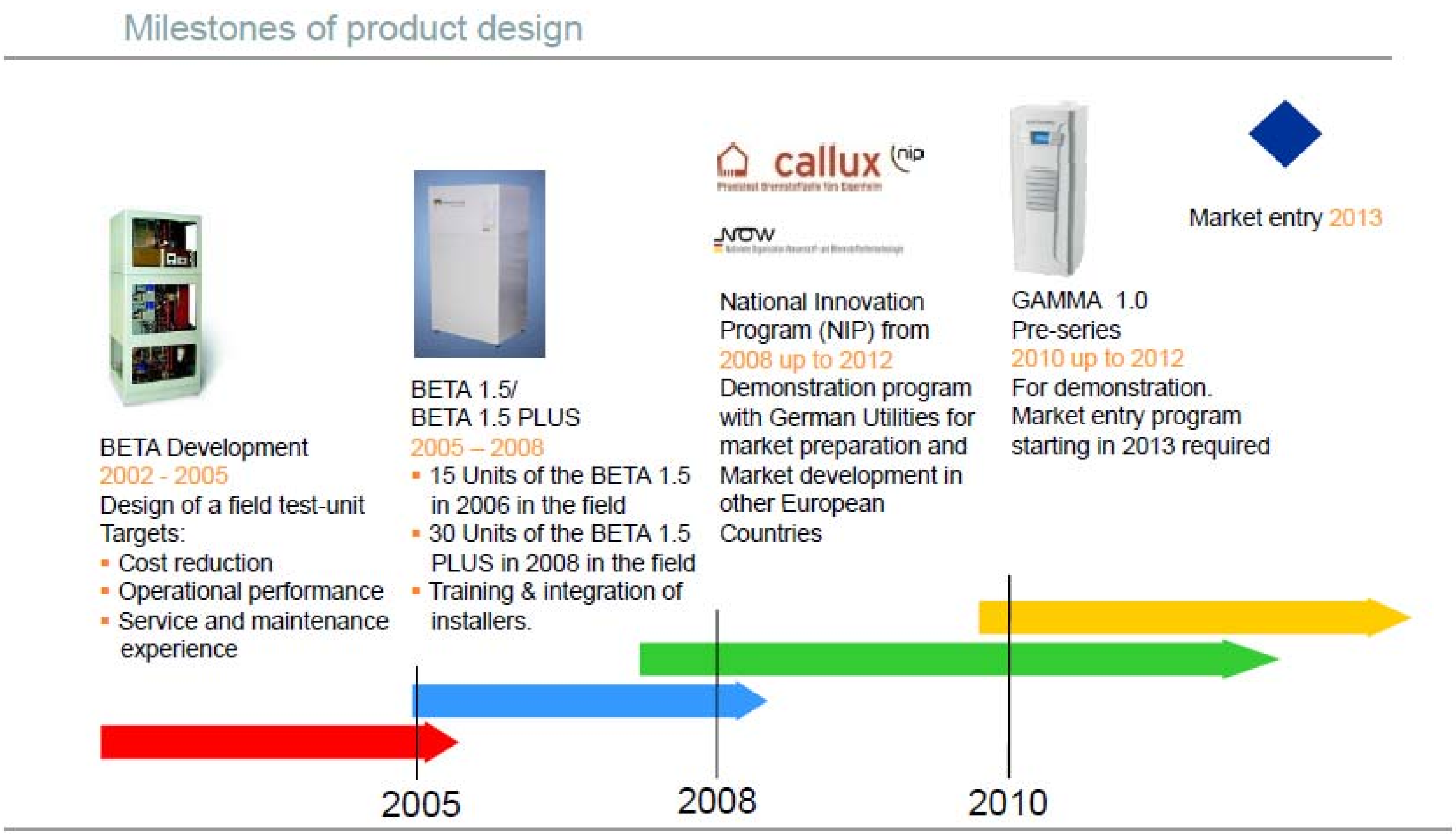
... 100% of the heat demand of a single-family house

... and produces 5000-6000 kWh of electricity

... proportional coverage of up to 73% of the electrical consumption of the house.

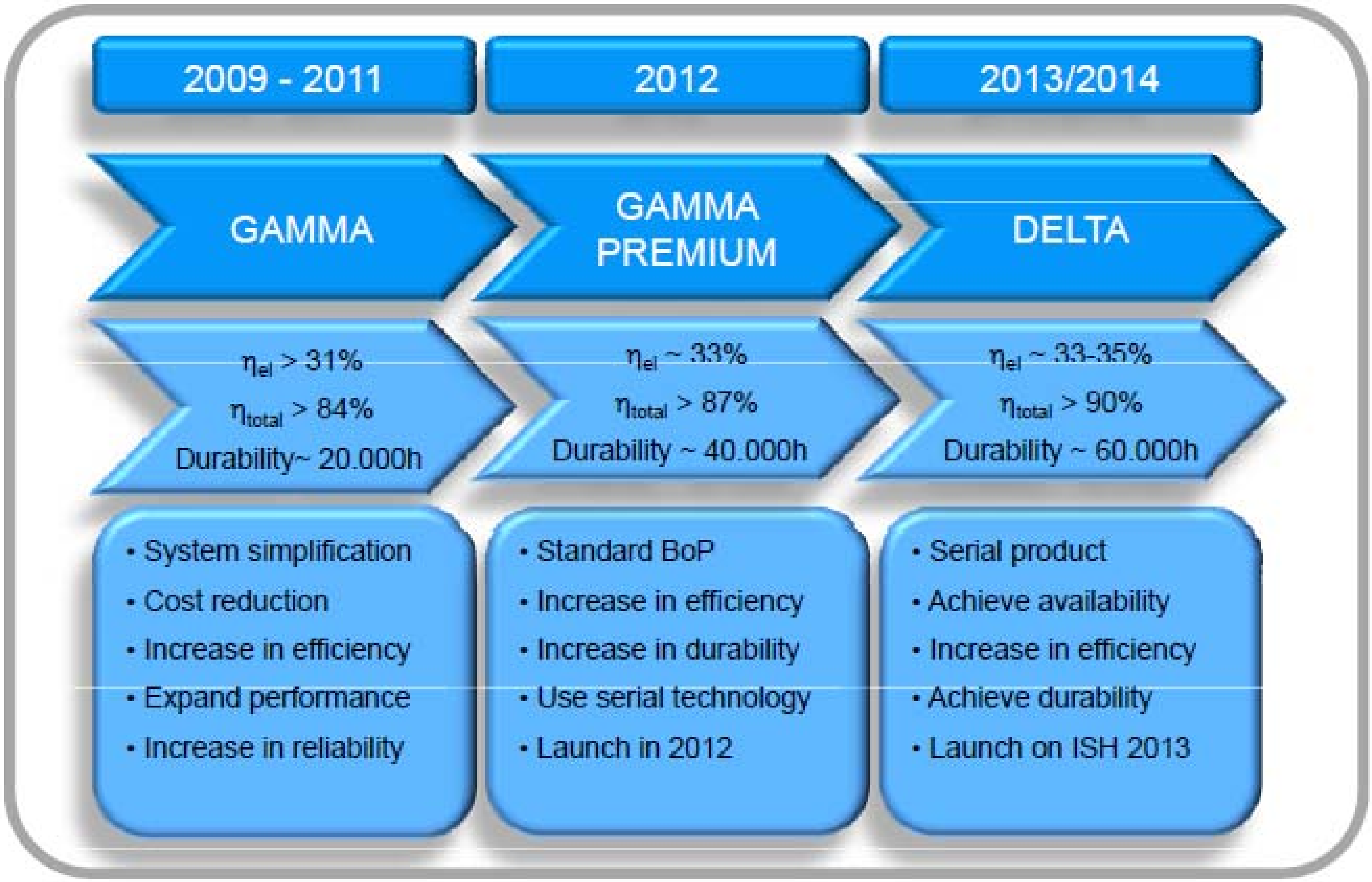
Source: Baxi Innotech

BAXI Innotech Roadmap



Source: Baxi Innotech

BAXI Innotech Roadmap



Source: Baxi Innotech

Fuel Cell Technologies – Short Comparison

Low Temperature PEFC

- Excellent chemical and mechanical stability
- High proton conductivity :
  - 10^{-2} - 10^{-1} S/cm
- Depending on temperature, degree of membrane hydration...
- Lifetime in FC operation > 60,000 h
- High cost
- Instability at high temperature - current membrane technology appropriate for functioning at ≤80° C

High Temperature PEFC

- PBI is a basic polymer and forms complexes with acids. Phosphoric acid "doped" membranes. Generally around 6 mol H_3PO_4/PBI unit (RT doping); *ca.* 16 (HT doping)
- Acid is the electrolyte, polymer a "support"
- High conductivity at low relative humidity 150 – 200° C
- Low electroosmotic drag.
- acid elution possible when liquid water is formed
- No cold start capability

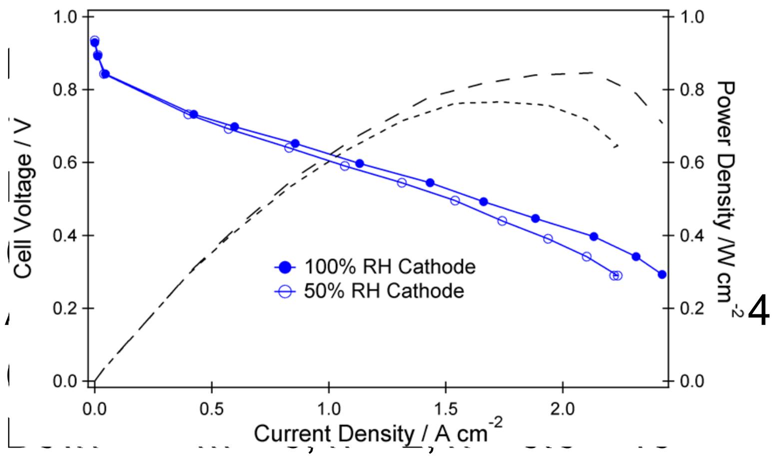
Fuel Cell Technologies – Membrane Comparison

Nafion® - DuPont - perfluorinated polymer with perfluorosulfonic acid side groups

$(CF_2CF_2)_x(CF_2CF)_y$

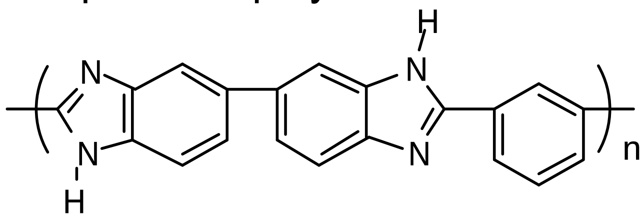
|

$(O\text{-}CF_2CF)_m(CF_3)O(CF_2)_nSO_3H$



CCM: Gore PRIMEA
Anode: 0.1 mg Pt /cm² Cathode: 0.4 mg Pt /cm²
p H_2: 1.5 bar_a; p Air: 1.5 bar_a

Polybenzimidazol – high temperature polymer



"Celazole" PBI

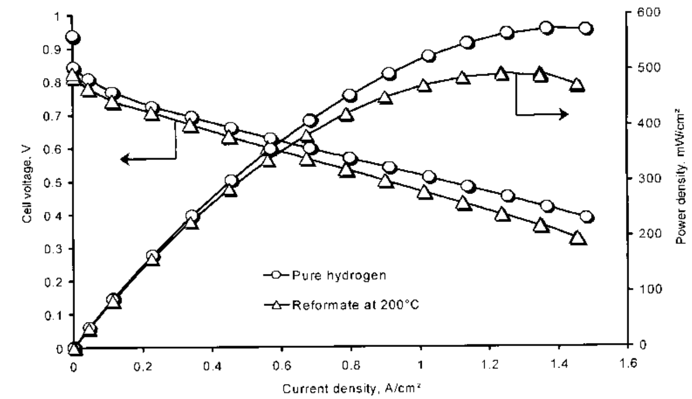


Figure 9. Cell voltage and power density versus current density of a PBI cell at 200 °C under ambient pressure. The membrane was a PBI–SPSF blend doped with H_3PO_4. The fuel was pure hydrogen and reformed hydrogen-rich gas directly from a methanol

atmospheric pressure; 0.45 mg Pt/cm²
peak power density 500 mW/cm²

High Temperature PEFC for micro CHP in the US

ClearEdge5: A New Energy Solution

- **Lower cost than grid:** LCOE as low as $0.09 per commercial kWh and $0.12 per residential kWh[1]
- **Cleaner than grid:** 37% less CO_2 with untraceable levels of NOx and SOx
- **Continuous base-load power:** Provides clean, uninterrupted power 24x7 including during grid disturbances
- **High efficiency:** Up to 90% CHP energy efficiency and designed for 40% electrical efficiency
- **Scalable with multi-fuel capacity:** Easily installed in multi-unit configuration. Currently utilizing natural gas, future versions expected to operate on biogas or propane
- **Aesthetic design:** Compact and quiet system operates indoors or outdoors

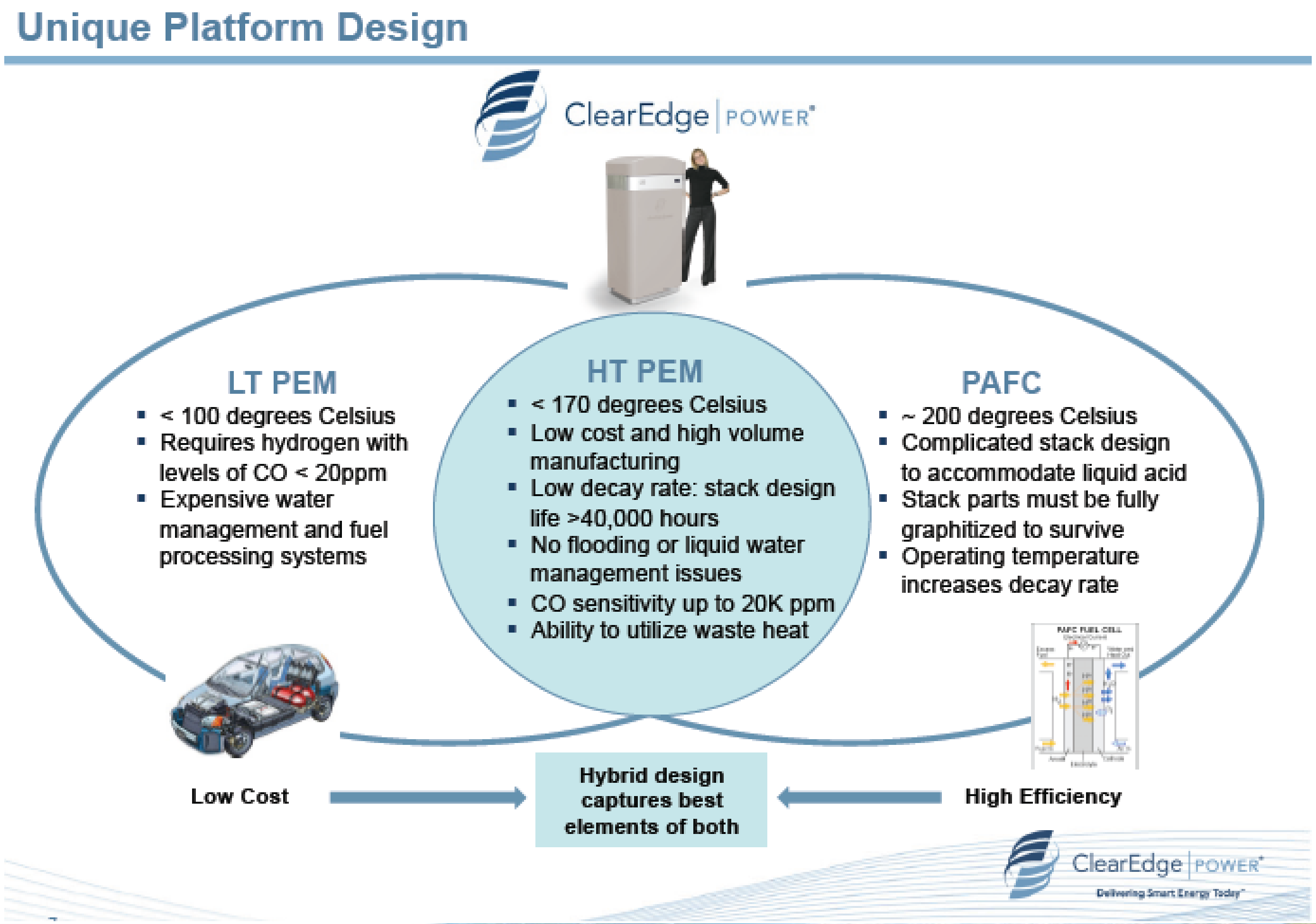
[1] Levelized cost of energy applies to initial launch market of California.

ClearEdge | POWER
Delivering Smart Energy Today

4

Source: ClearEdge Power

High Temperature PEFC for micro CHP in the US

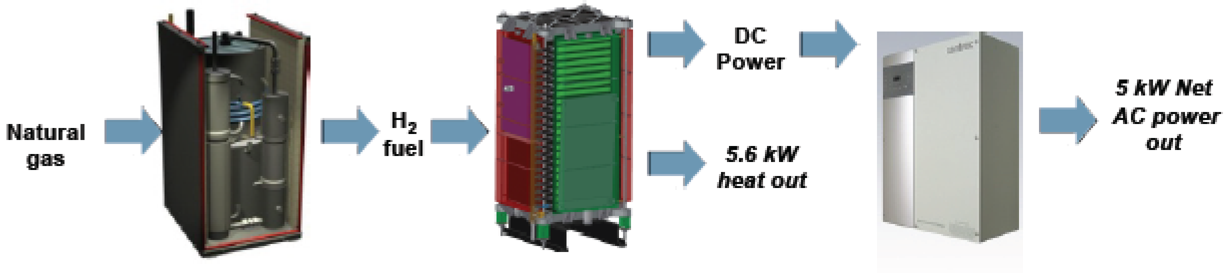


Backup Power Application for Fuel Cell Systems

Main Requirement	Specification
Number of start / stop cycles per year	Few cycles (some for maintenance and auto tests)
Operating hours per year	1 to 100 h
Probability of non start up	About 10^{-3}/starts
MTBF *Mean Time Between Failure*	About 10^{-4}/h
MTTR *Mean Time To Repair*	Some hours per action
MDT *Mean Down Time*	Some tens of hours per action
Life time	15 years

System Design

The ClearEdge5 System Architecture



Fuel Processor

- Sulfur removal, CSR and WGS with commercially available catalyst
- No PROX or other H2 cleanup system necessary
- Proven proprietary design, high durability

Cell Stack

- HT PEM stack
- No water management or humidification
- High CO sensitivity
- High H2 utilization efficiency
- High-grade waste heat helps boost electrical efficiency

Inverter & Controls

- Commercially available inverter
- Certified for all applicable codes and standards
- Allows GC/GI operation and multiunit load sharing capability

ClearEdge POWER
Delivering Smart Energy Today

DLR

PEM Fuel Cells: Backup Power Systems

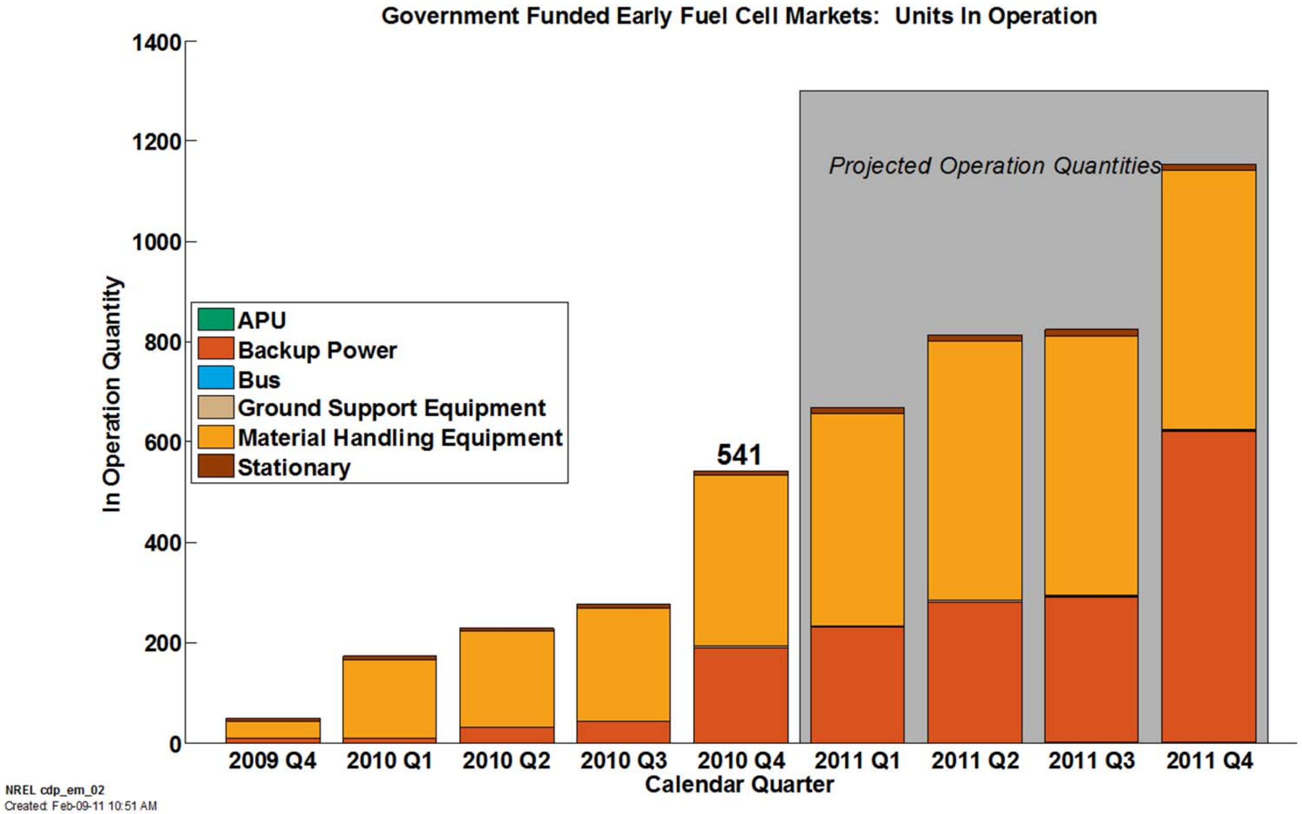
20 minutes

12 kW

Hydrogenics delivers numerous Fuel Cell Power Modules for Backup Power Applications

For e-commerce systems in urban centres this is a promising power backup option

ARRA Demonstration Program (USA) managed by NREL



System Comparison: H_2/O_2 vs H_2/Air PEMFC

- **High reliability and availability**
- **External conditions independent**
- **Quick startup at ambient temperature**
- **Clean, quiet and pollution-free**

- **Electrical performances and power density of H_2/O_2 systems higher than H_2/Air ones :**
- **Pure O_2 minimizes concentration polarization**
- **H_2/O_2 allows higher current densities than operation in air**
- **H_2/O_2 system efficiency higher than H_2/Air system**
- **No compressor : O_2 and H_2 pressures depend on H_2/O_2 storage pressures**
- **No gas humidifier**