2nd Joint European Summer School on
Fuel Cell and Hydrogen Technology
Crete, 17th – 28th Sept. 2012

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An introduction to Fuel Cells
- Status and applications of fuel cell technology
- Competing technologies & the market place

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University of Birmingham

Overview

- Motivation
- Fuel cell introduction and overview
- Status of Fuel Cell technology today
- Challenges in bringing SOFC to the market

An Introduction to World Energy Issues

The World Needs Energy

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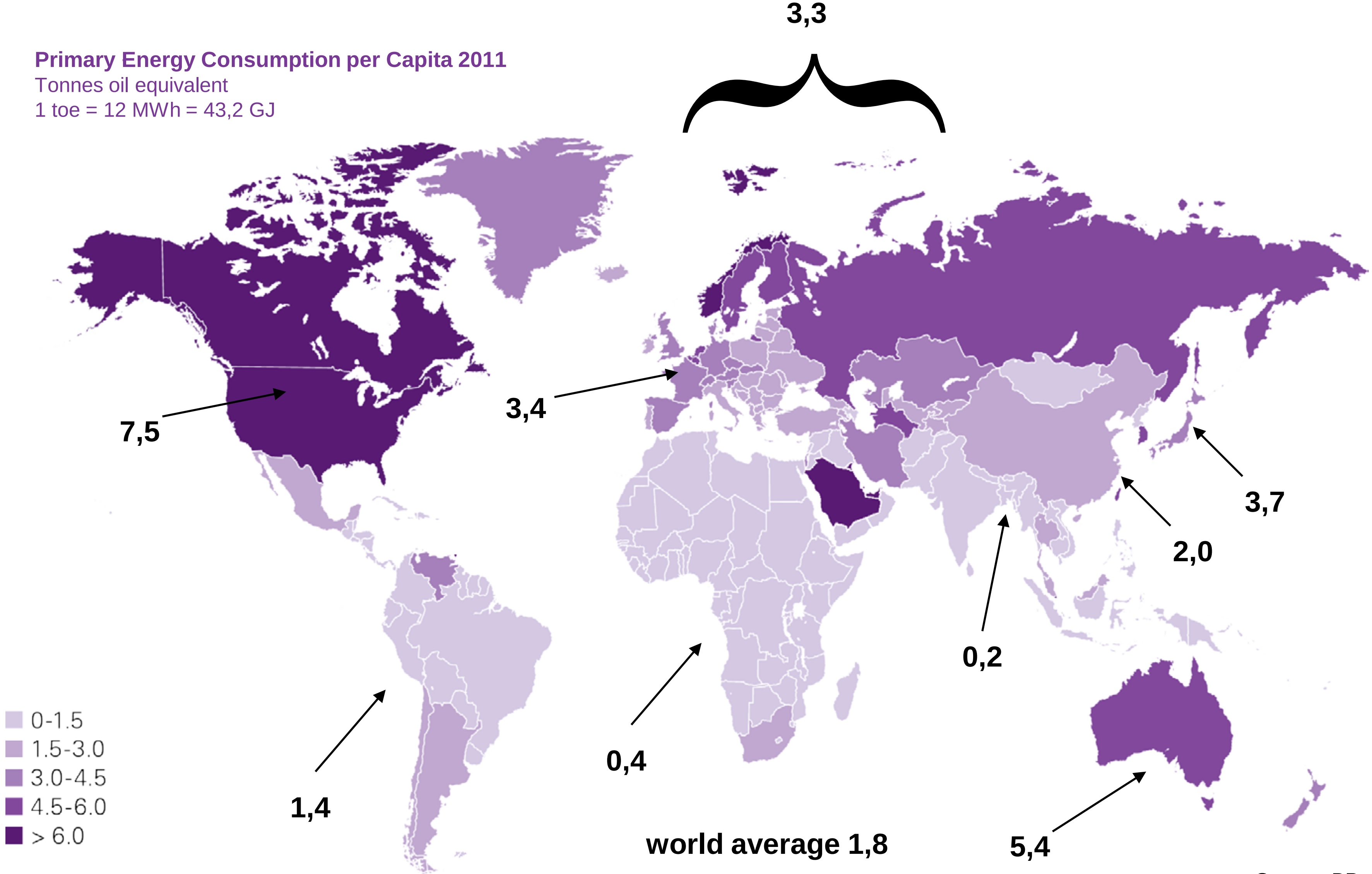
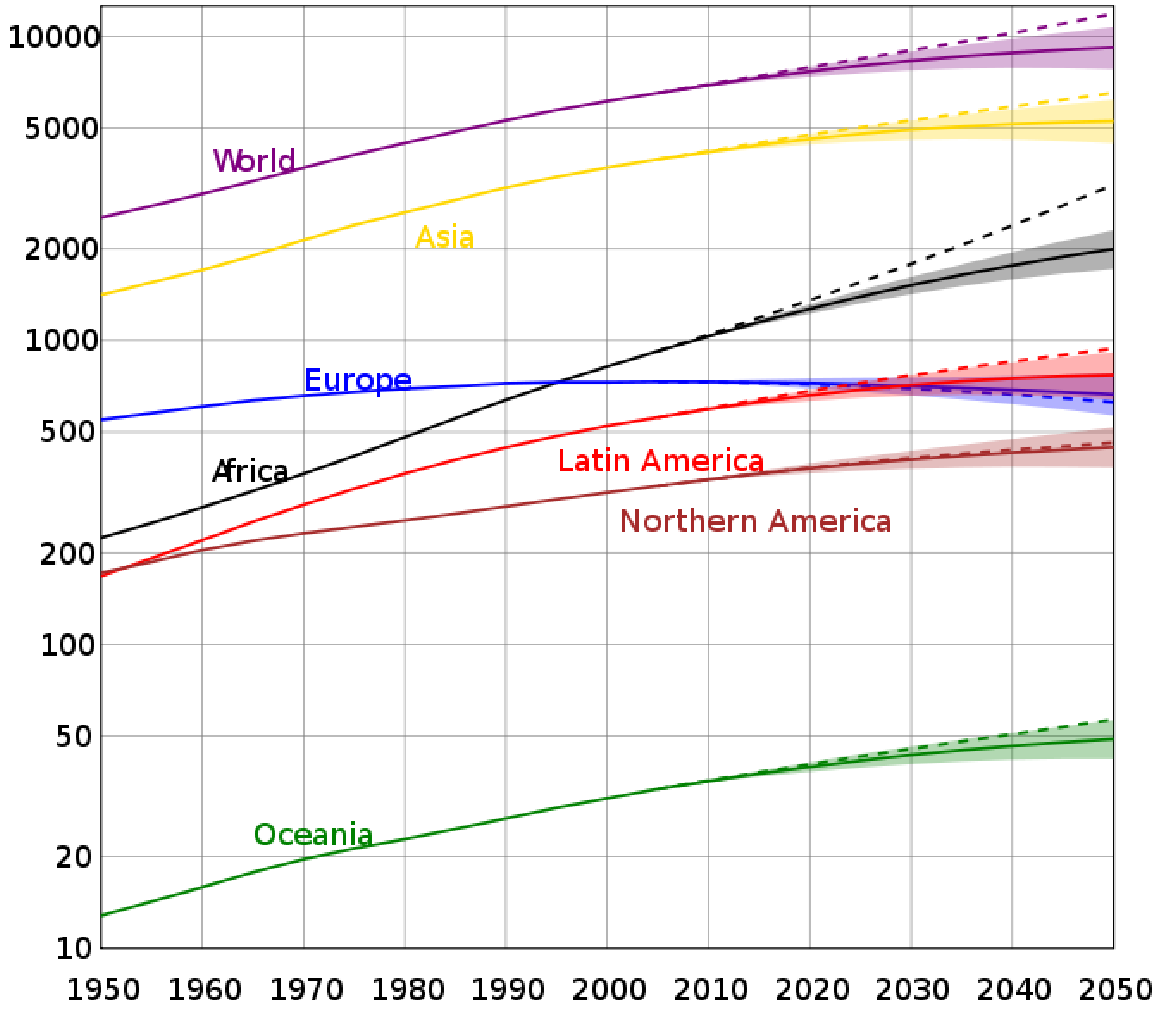


Source: BP

World Population Growth



Source: UN-PP, World Population Prospects 2010

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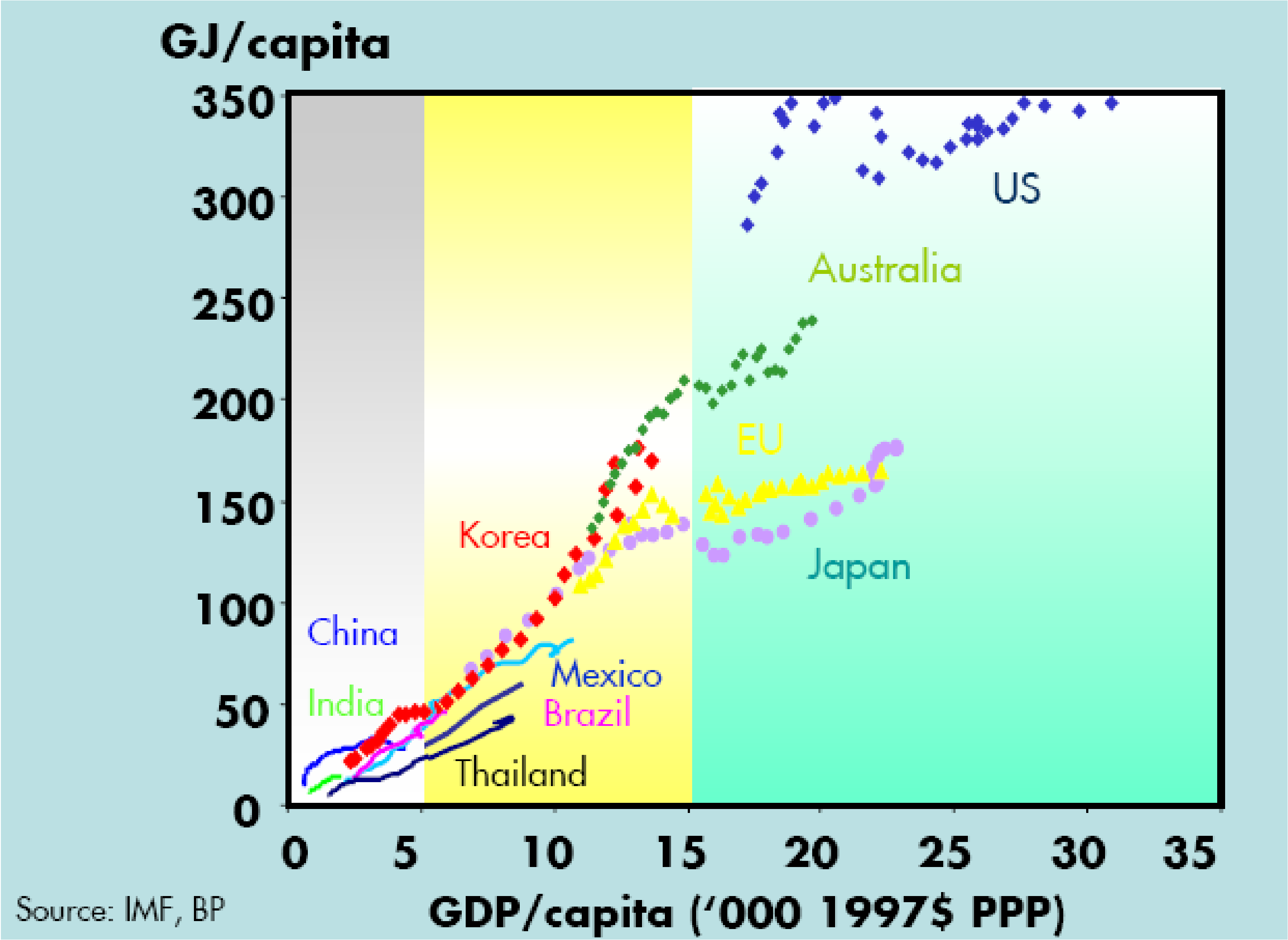
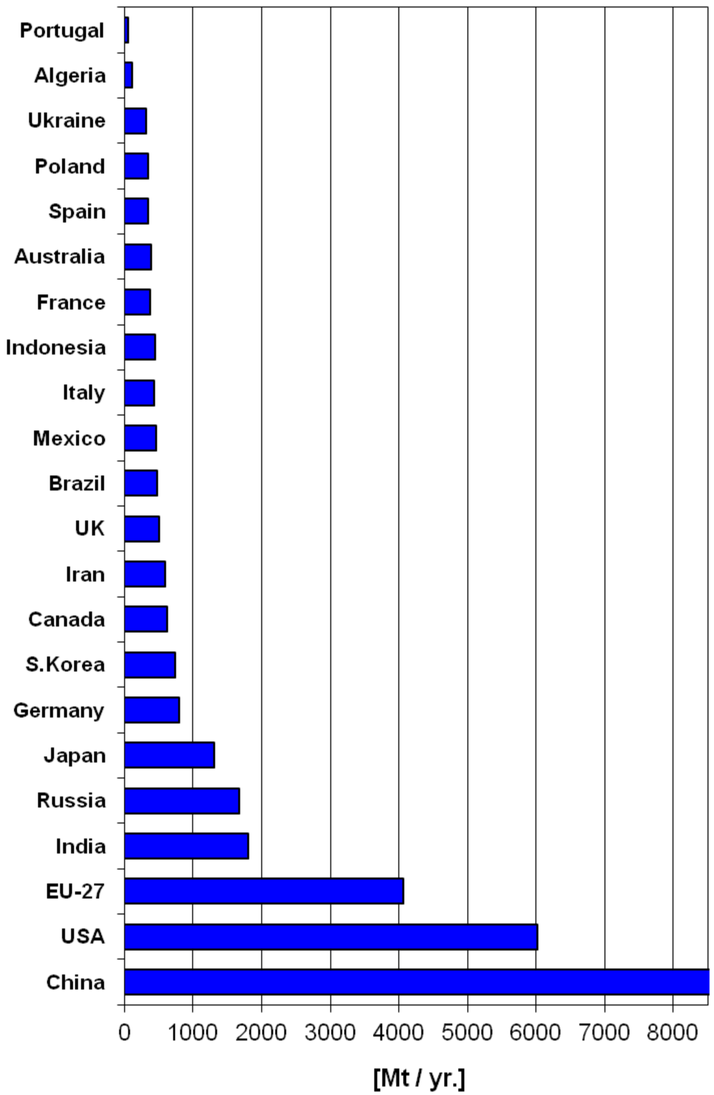
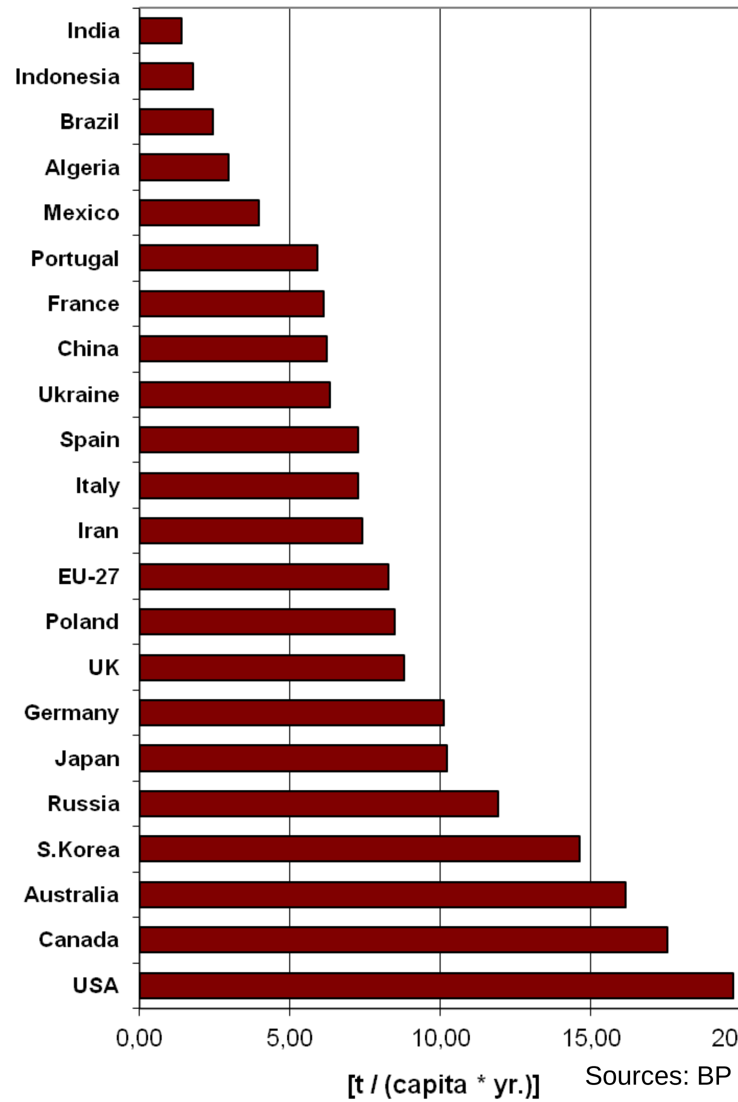
GDP and Energy Consumption



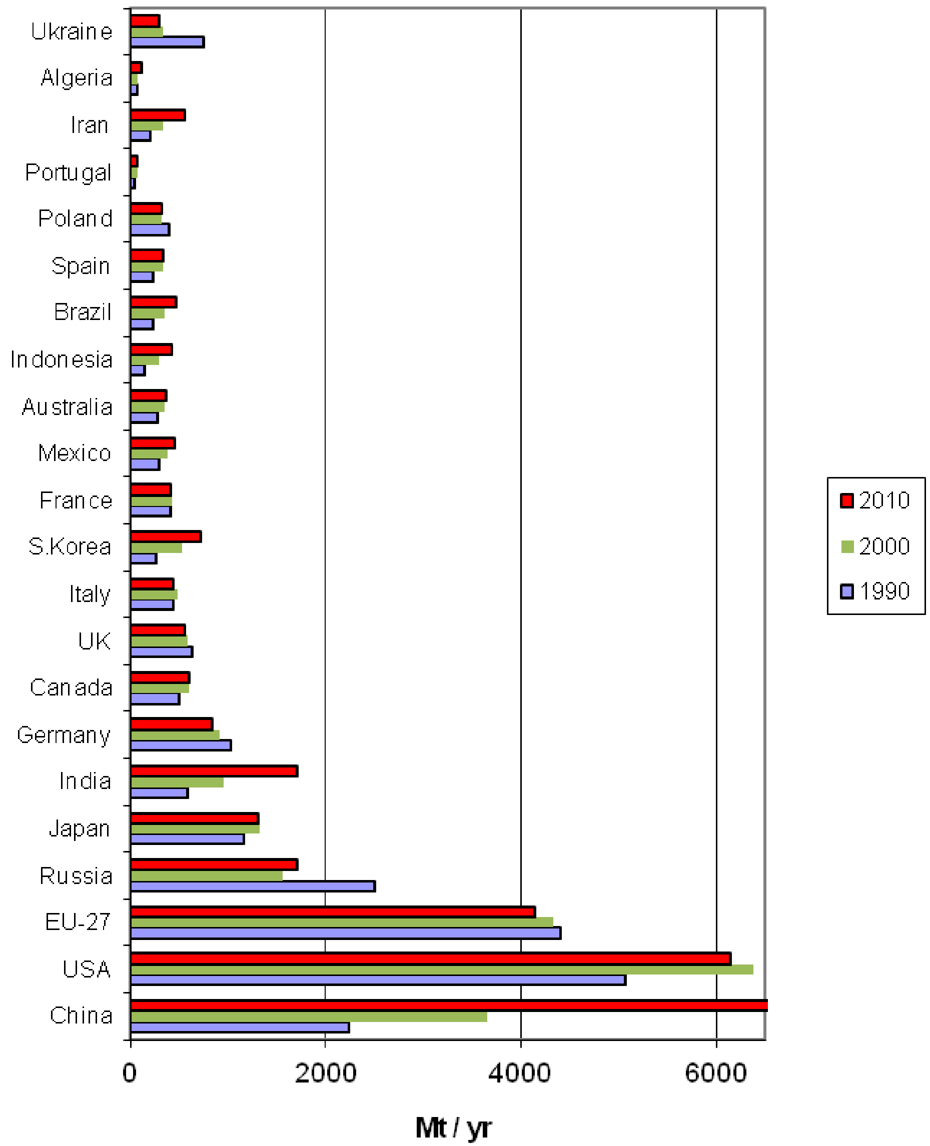
World CO_2 Release (2011, per country)





Sources: BP 2011/wikipedia

World CO_2 Release (1990 to 2010)



Data sources: BP 2011/wikipedia

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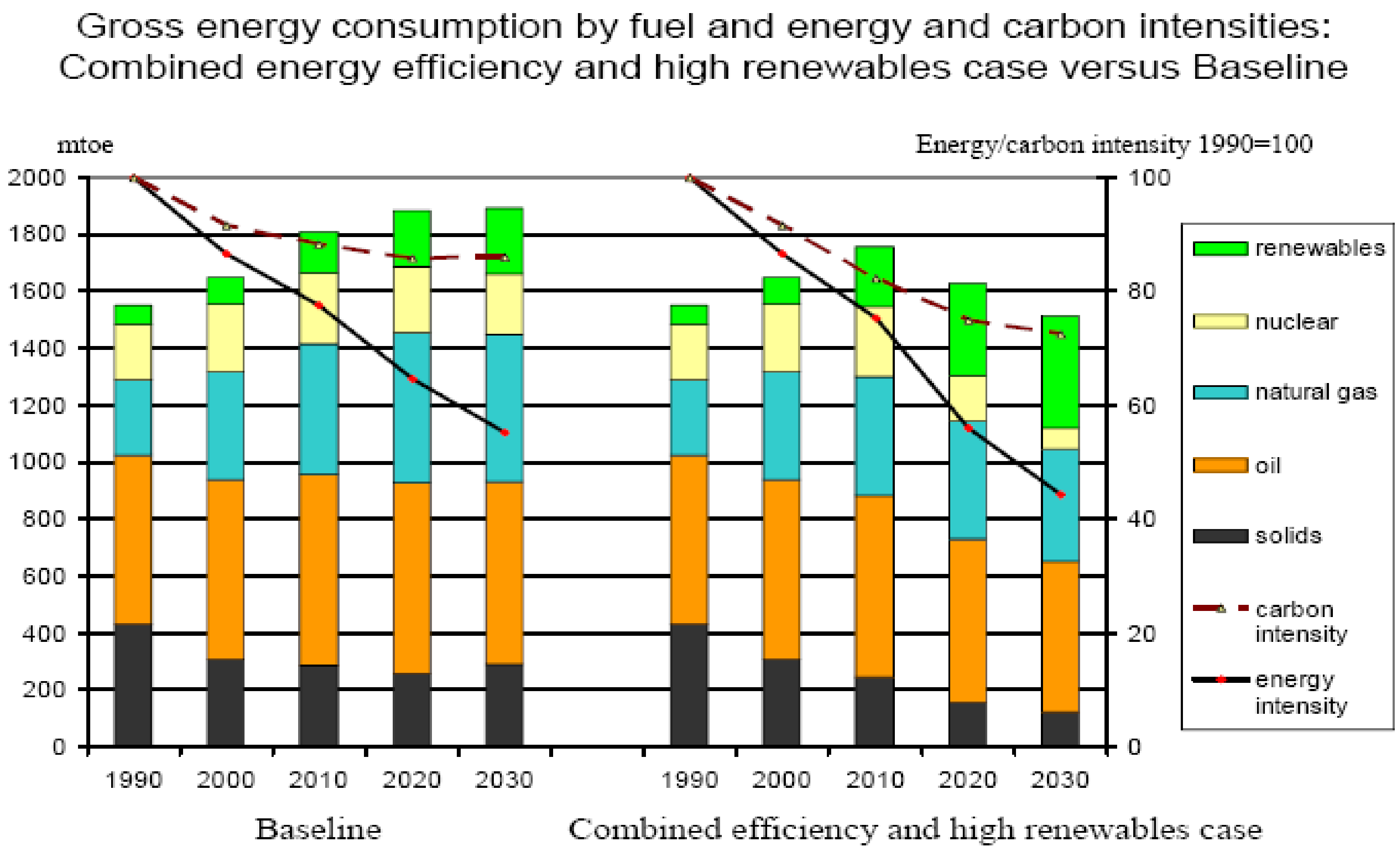
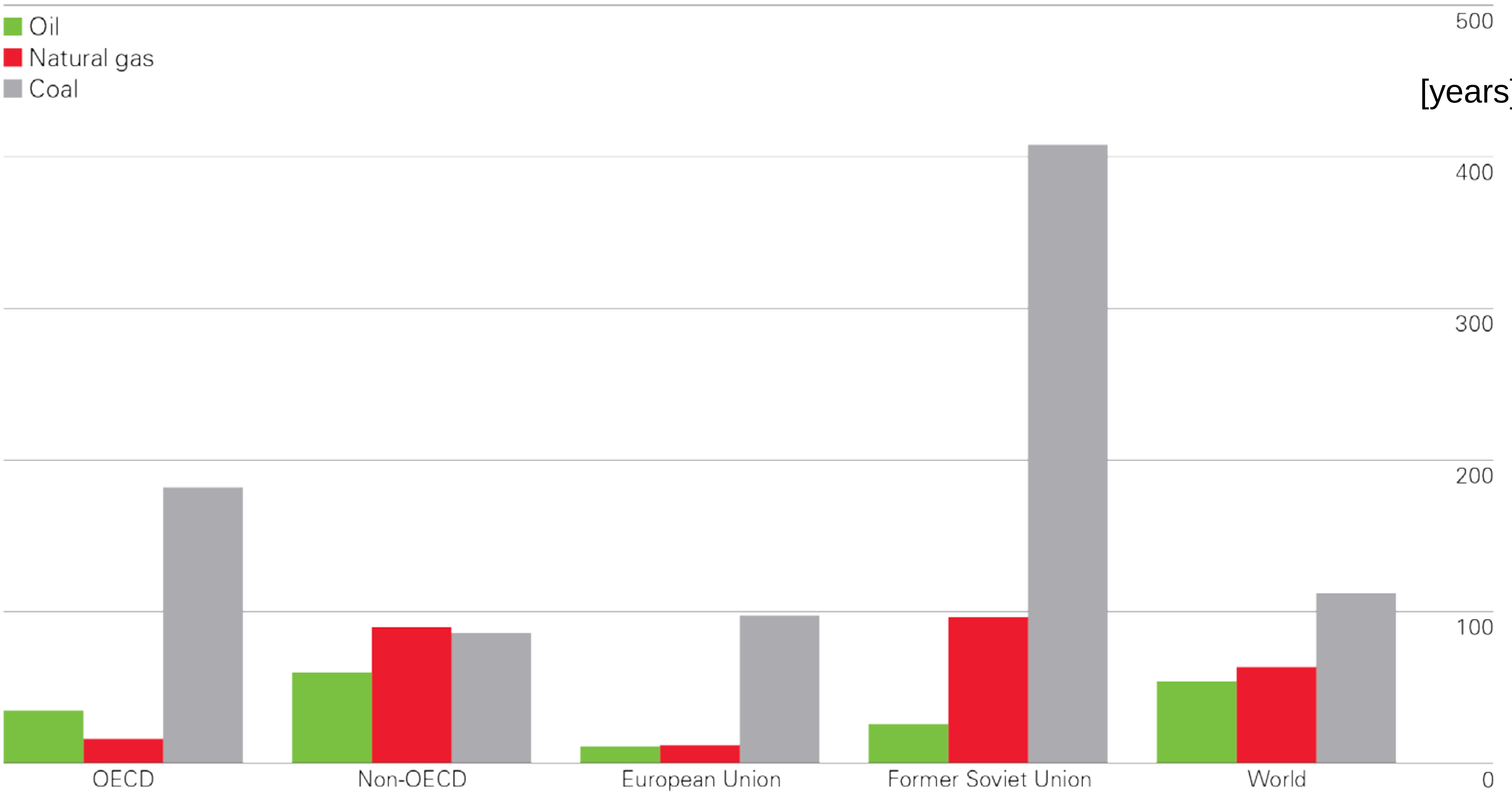
Future Scenarios of World Energy Demand



Source: EU Scenarios, 2006

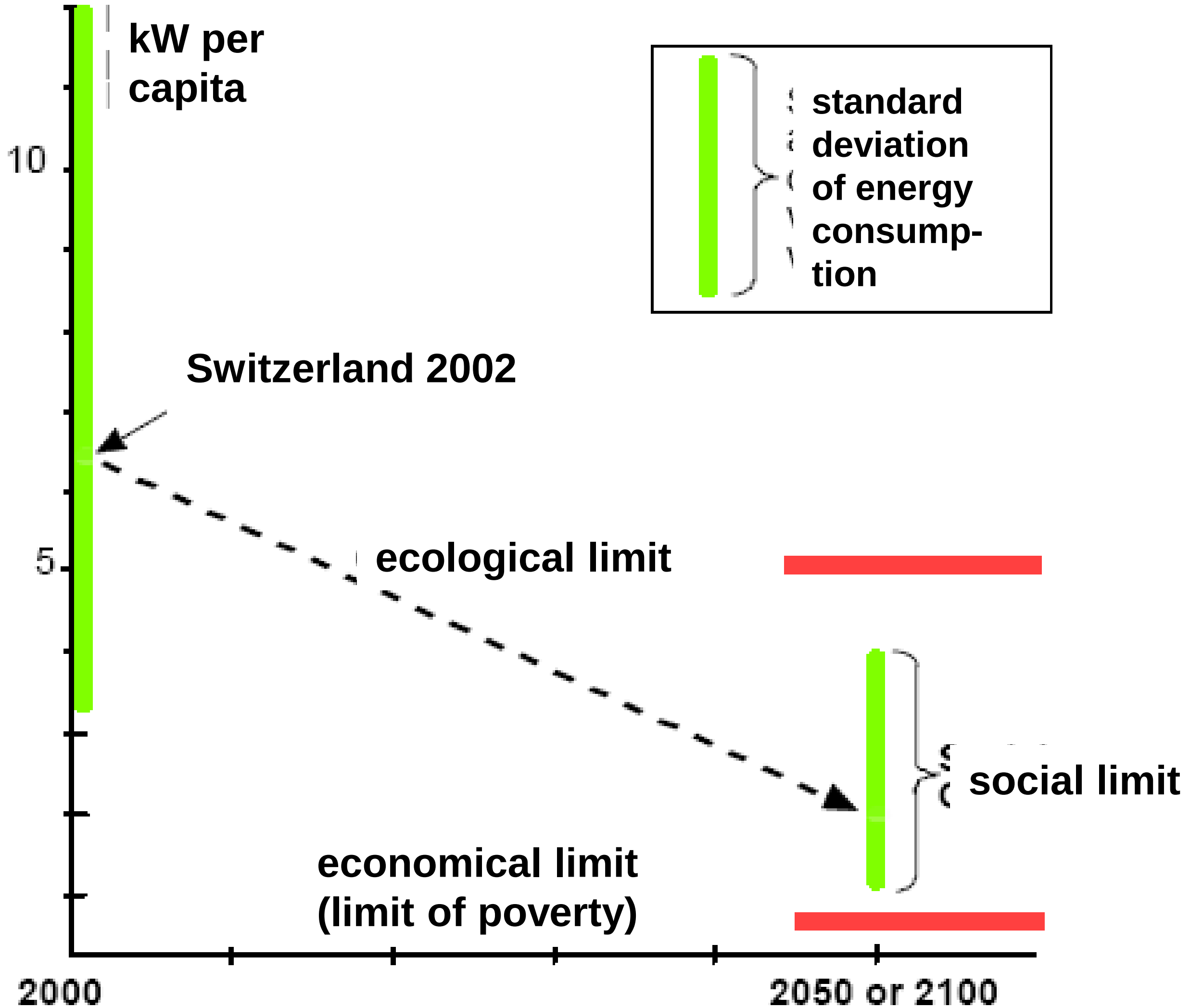
Fossil Fuel Reserves to Production Ratio (2011)

<u>reserves:</u>
known and economically retrievable



Source: BP 2012

The 2-kW-Society



Source: CEPE, 2002

Finding more efficient ways of supplying energy

improves the world situation under the aspects of

- climate change (GHG abatement)
- avoiding (or postponing) depletion of resources
- securing regional growth by avoiding expenses for energy import
- political stability by avoiding import dependencies

EU oil import quota

The possible roles of fuel cells and hydrogen:

- more efficient energy conversion
- lower emissions
- flexibility in fuel choice, including fuels from renewable sources
- increased flexibility in the energy supply system

What is a ‚Fuel Cell'?

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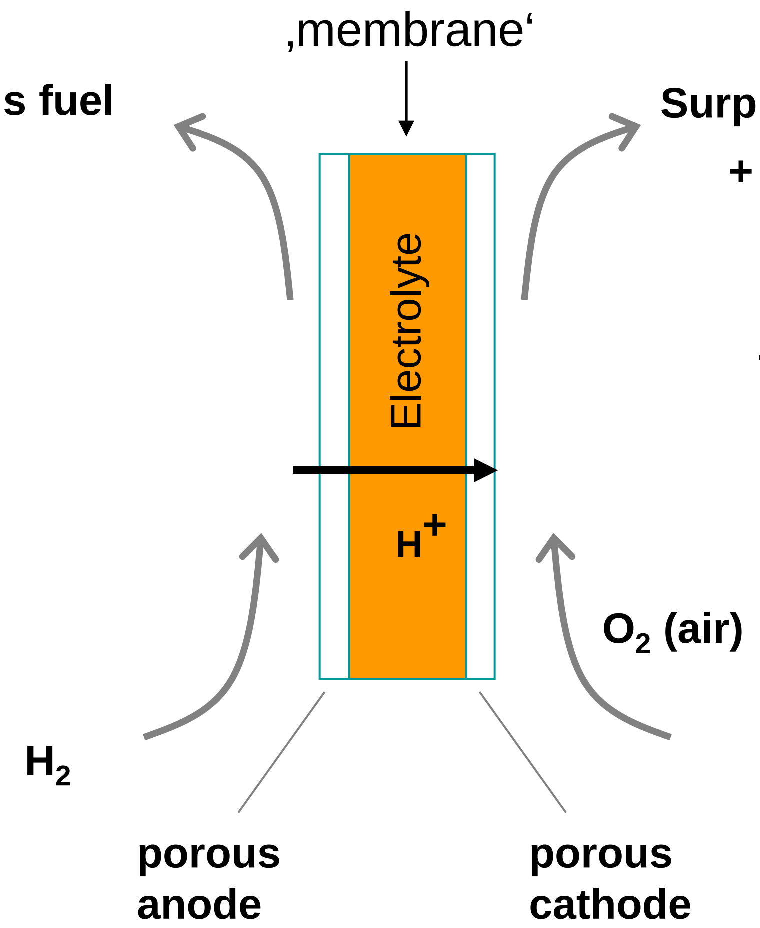
Fuel Cell Principle



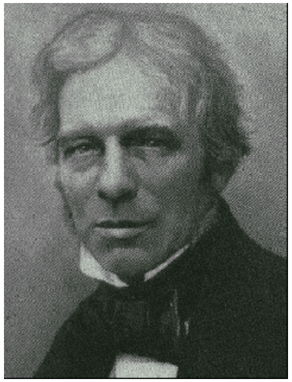
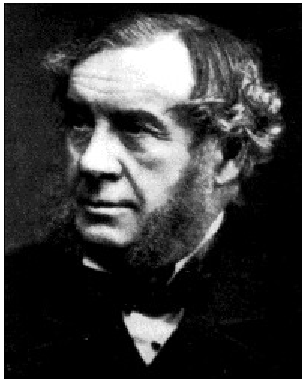
PEFC: typical ‚hydrogen fuel cell'

membrane properties:

- gas tight
- high ionic conductivity
- low electronic conductivity

FC History

- Definition of terms 'electrolyte', 'electrode' etc. and various electrochemical processes by Michael Faraday (1791-1867)
- Reverse electrolysis first realised by Sir William Grove 1839 (1811-1896) on basis of his own and Friedrich Schönbein's (1799-1868) research
- Major contributions to electrochemistry theory by Wilhelm Ostwald (1853-1932)
- First technical developments and patents ca. 1902-1913 (VARTA)
- Slow progress due to insufficient understanding of reaction kinetics and materials' issues

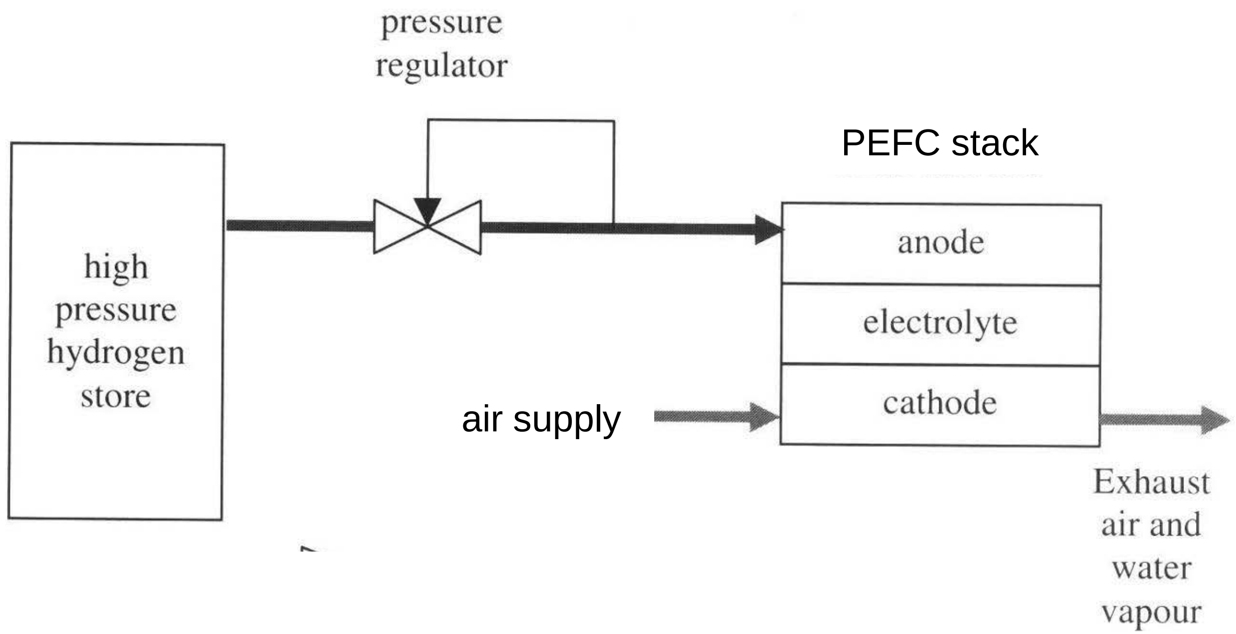
Some Fuel Cell Principal Properties

1. not limited by Carnot efficiency (~ $(T_1-T_2)/T_1$),
   only by electrochemical, kinetic and ohmic losses
2. modular
3. low (no) noise
4. exhaust emission predominantely water (and maybe CO_2)
5. no moving parts

ergo:

- efficient and low-emission energy conversion technology

The Beauty of Simplicity



Source: adapted from Larminie/Dicks

Fuel Cells could replace

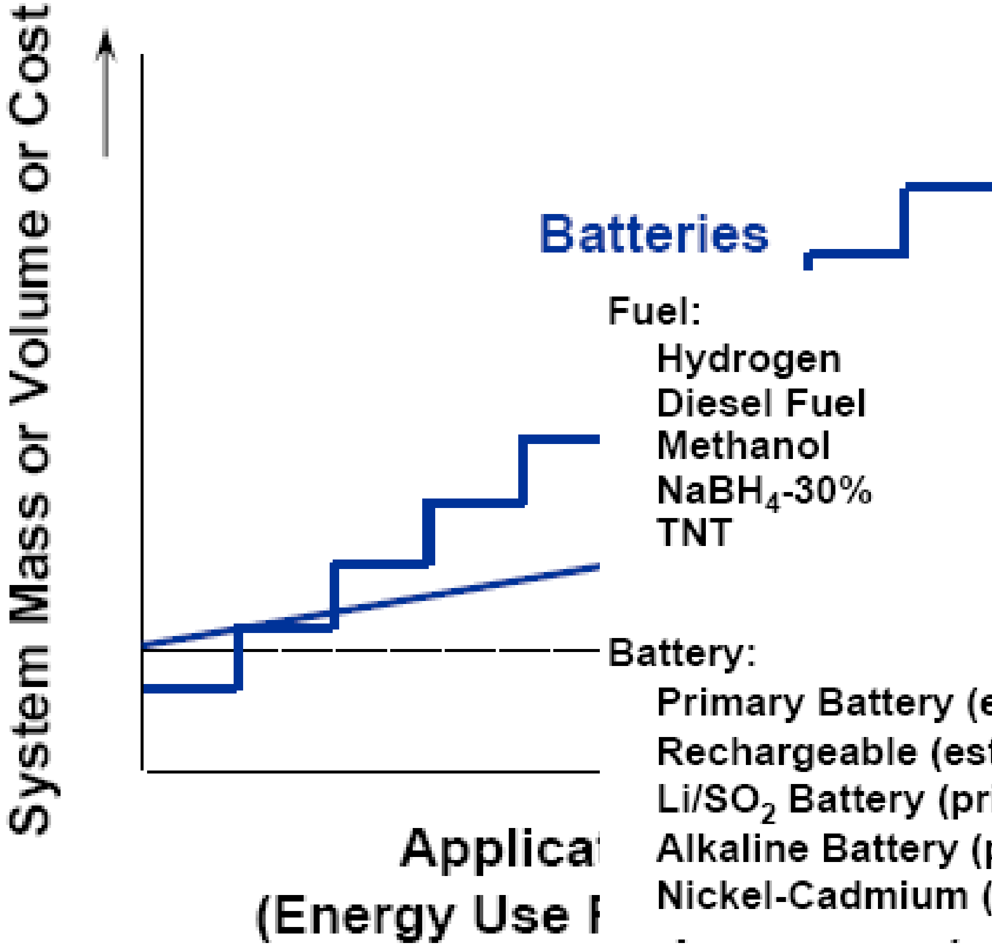
- Internal combustion engines (ICE)
  - in vehicles
  - in Combined Heat and Power (CHP) units
- GenSets (mobile power)
- Batteries
- Combined Cycle Power Stations
- On-board Electricity Generation (Auxiliary Power Units, APU)

and supply decentralised or grid-independent power anywhere at any scale

Fuel Cells in Comparison to Their Competitors

	battery	CHP	ignition engine	fuel cell
el. Efficiency	n.a.	~ 30-40%	n.a.	25 to 55%
Noise	++	-	--	+
Modularity	++	--	-	++
Weight	--	n.a.	o	+
Range	--	n.a.	+	o
Costs	--	o	+	--
Emissions	n.a.	o	-	++
Overall Efficiency	n.a.	~ 95%	12 to 18%	~ 90%

Competing with Batteries

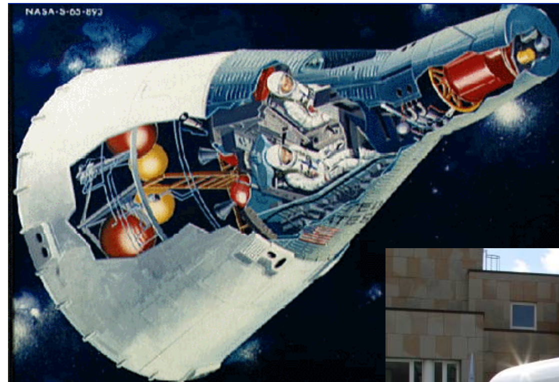


Fuel:	Specific Energy (Wh/kg)
Hydrogen	33,000
Diesel Fuel	13,200
Methanol	6,200
$NaBH_4$-30%	2,500
TNT	1,400
Battery:	
Primary Battery (est. max.)	500
Rechargeable (est. max.)	200
Li/SO_2 Battery (primary)	176
Alkaline Battery (primary)	80
Nickel-Cadmium (secondary)	40

Source: AZ State Univ

Applications of Fuel Cells: Mobile

- FC vehicles
- special craft
- off-road
- APU



On-Board E-Power Generation

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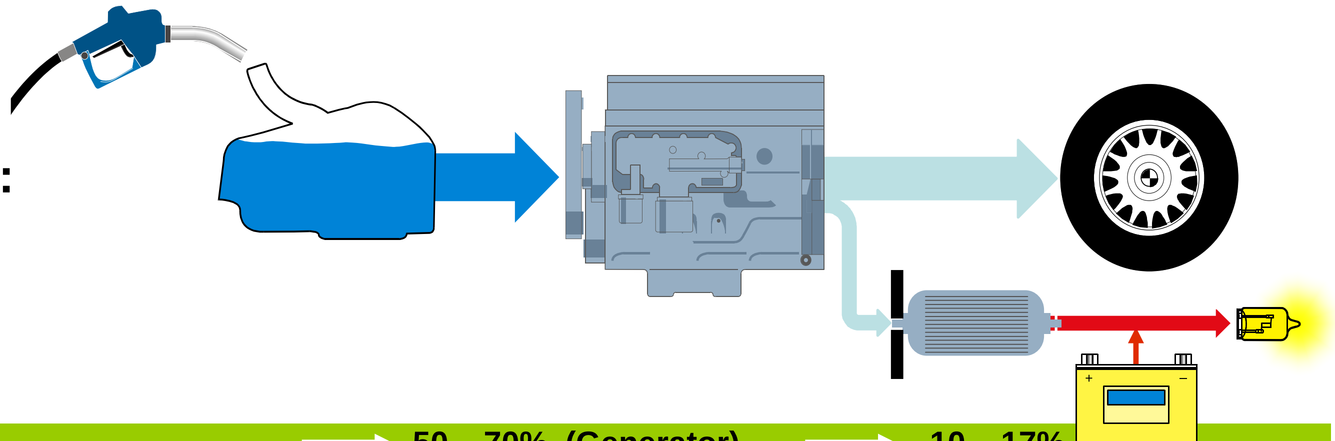
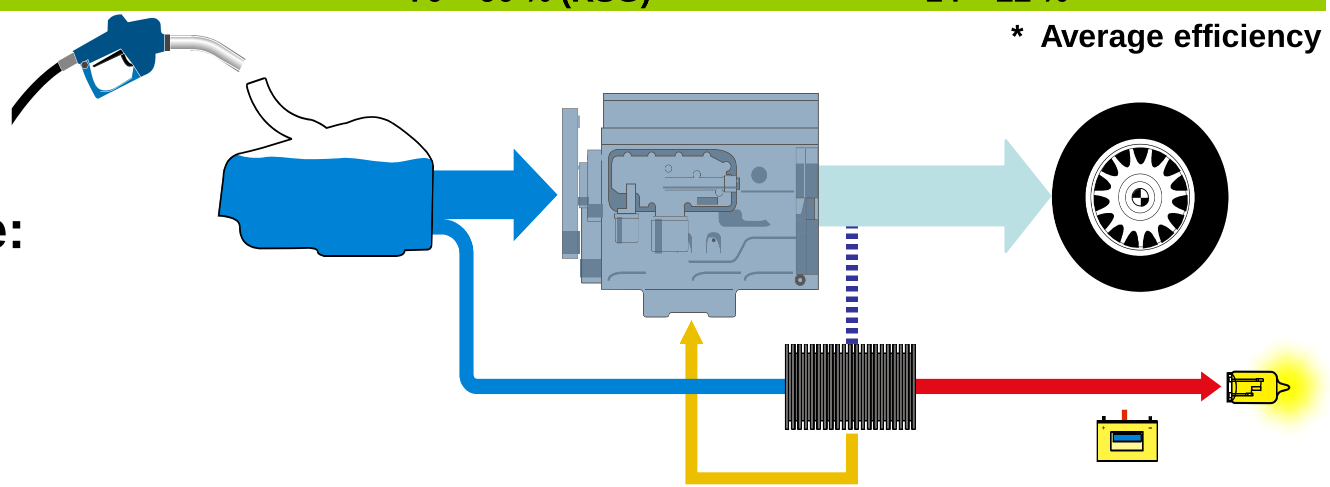
Today:



100% → 20 – 25%* → 50 – 70% (Generator) → 10 – 17%
→ 70 – 90 % (KSG) → 14 – 22 %

* Average efficiency

Future:



100% → 35 – 50% (FC-APU) → 35 – 50%

Graph: BMW

APU in Ships and Aircraft

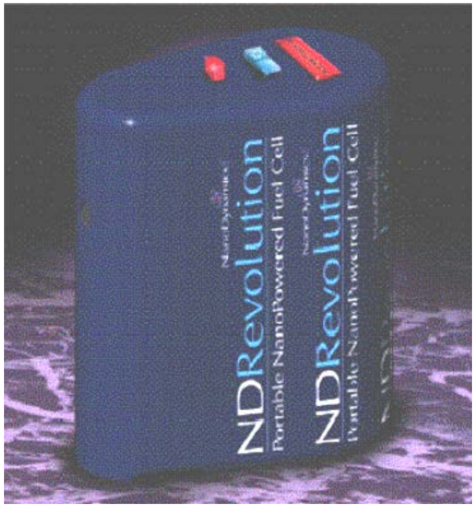
- emission control
- efficiency
- safety

~ 25 kW

~ 3 kW

Applications of Fuel Cells: Portable

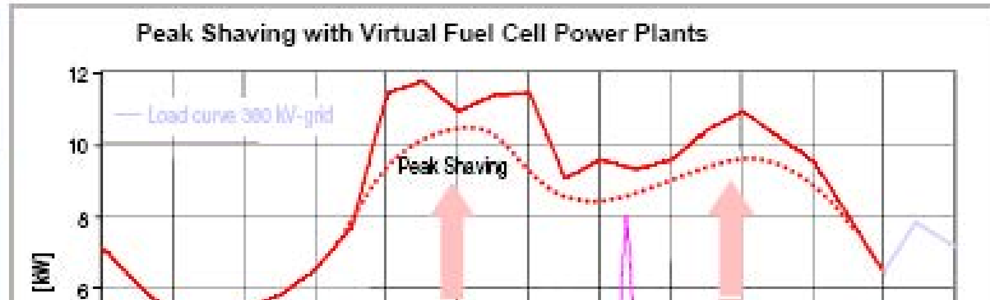
- battery replacement
- battery charger
- gen-set

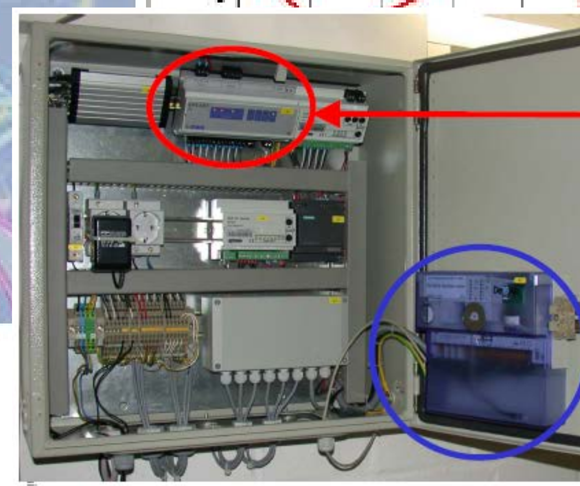


Applications of Fuel Cells: Stationary

- residential
- industrial and commercial scale CHP
- power generation
- uninterruptible power supply

Vaillant Virtual Power Plant Project





- Multifunctional Data Logger (MfD)
- Impulse Logger
- Temperatur Logger
- **Radio Ripple Control Receiver**
- Modem

Two motivations:

- elimination of grid losses
- build-up of generation capacity for electricity deistributors

Source: Vaillant

Overview Fuel Cell Types

	Low temperature			High temperature	
	AFC	**PEFC**	**PAFC**	**SOFC**	**MCFC**
Electrolyte	Alkaline	Polymer	Phosph.acid	Ceramic	Molten carbonate
Temperature	80-200°C	80-100°C	200°C	700-1000°C	650°C
Fuel	H_2	H_2	H_2	$H_2/CO/CH_4$	$(H_2)/CO/CO_2$ $/CH_4$
Oxidant	O_2/(air)	O_2/air	O_2/air	O_2/air	O_2/air
Efficiency (*)	50-60%	40-45%	40-45%	50-55%	50-55%

	PEFC → DMFC	PEFC → HT-PEFC	SOFC → LT-SOFC
	DMFC	**HT-PEFC**	**LT-SOFC**
	80-100°C	120-180°C	500-650°C
	MeOH	H_2 (CO)	$H_2/(CO)/CH_4$
	25-30%	40-50%	50-55%

(*) LHV

Fuel Purity Requirements

Requirements for fuel purity with various FC types

Type	CO	CO_2	N_2	H_2S	Cl	Particles
PEFC	<10 ppm	tol.	tol.	0	<0,05 ppm	0
PAFC	<2%	tol.	<2%	<50 ppm	<1 ppm	<1 mg/m³
MCFC	tol.	tol.	tol.	<0,1 ppm	<1 ppm	<1 µm
SOFC	tol.	tol.	tol.	<1 ppm	<1 ppm	<1 mg/m³

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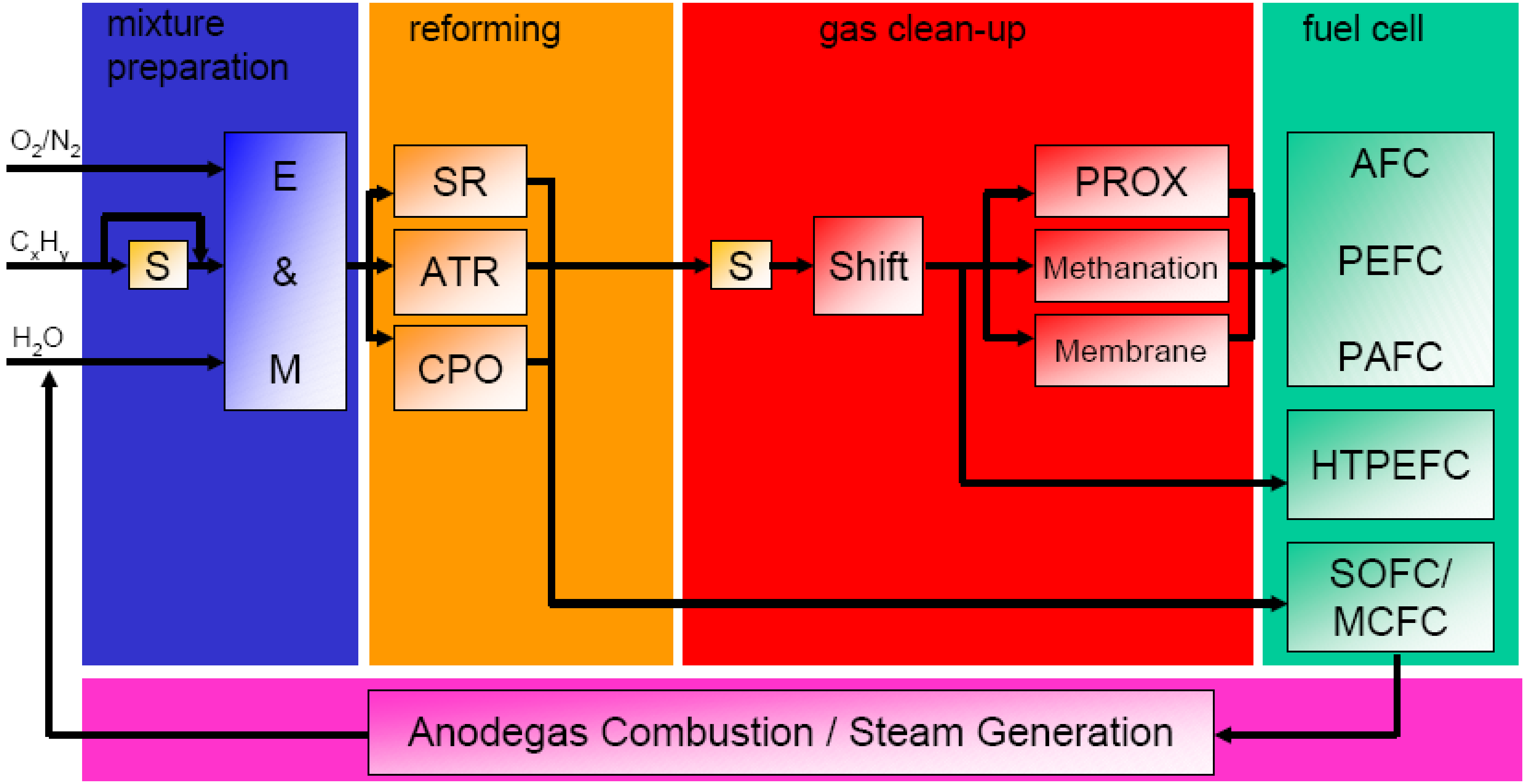
Fuel Processing Effort



Fuel Cells compared

Low Temperature Fuel Cells (PEFC, AFC, PAFC):

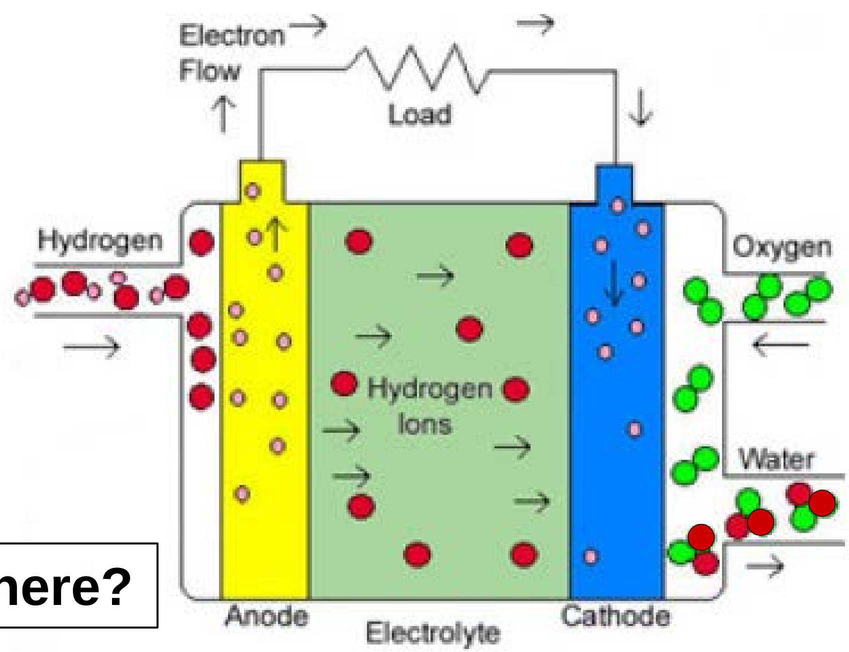
- hydrogen fuel
- typically mobile and portable applications
- stationary with reformer unit (on-site hydrogen production)
- predominantly lightweight materials (plastics, graphite etc.)

High Temperature Fuel Cells (MCFC, SOFC):

- hydrogen fuels, natural gas, hydrocarbons
- typically stationary applications
- mobile as APU
- predominantly heavyweight materials (steels, ceramics etc.)

The Hydrogen Fuel Cells: PEFC & PAFC

Cathode side	$O_2 + 4\,H^+ + 4\,e^-$	$\longrightarrow$	$2\,H_2O$
Anode side	$2\,H_2$	$\longrightarrow$	$4\,H^+ + 4\,e^-$
Overall reaction	$2\,H_2 + O_2$	$\longrightarrow$	$2\,H_2O$

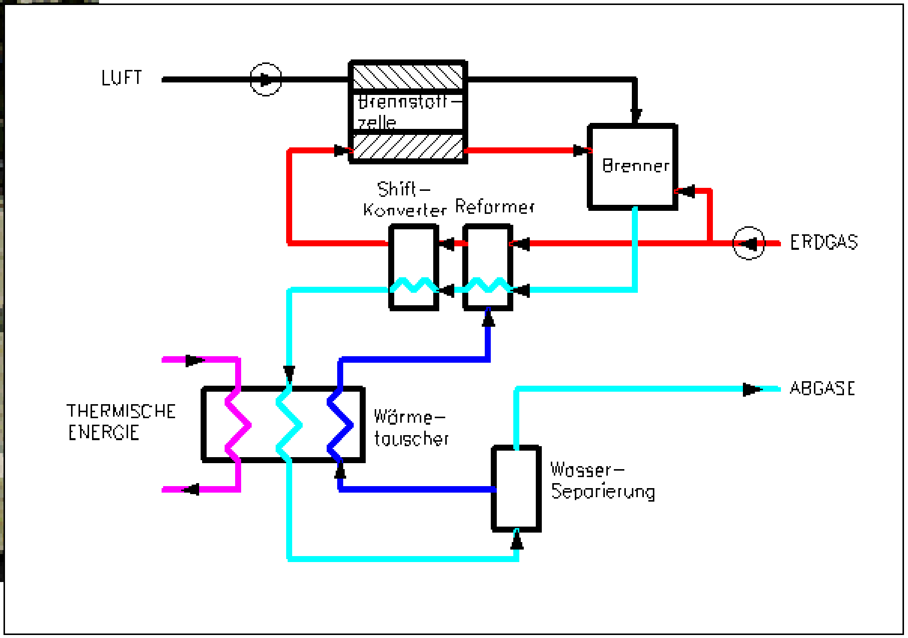


what's wrong here?

ONSI/UTC stationary power 1990 - 2000

Dimensions:
PC25A: Width (3 m), Length (7,3 m), Hight (3,5 m)
PC25C: Width (3 m), Length (5,5 m), Hight (3,0 m)

Electrical Power Rating:	**200 kW**
Useful Thermal Power:	**110 kW**
Electrical Efficiency:	**ca. 40%**



Light Passenger Vehicles

DaimlerChrysler
f-cell A & B class

Opel Zafira

VW Touran HyMotion

Ford
FC Hybrid

Honda Clarity

Musashi 1990

Ford / Th!nk

Toyota RAV4L V

Sources: various

Alkaline Fuel Cell (AFC): Reaction

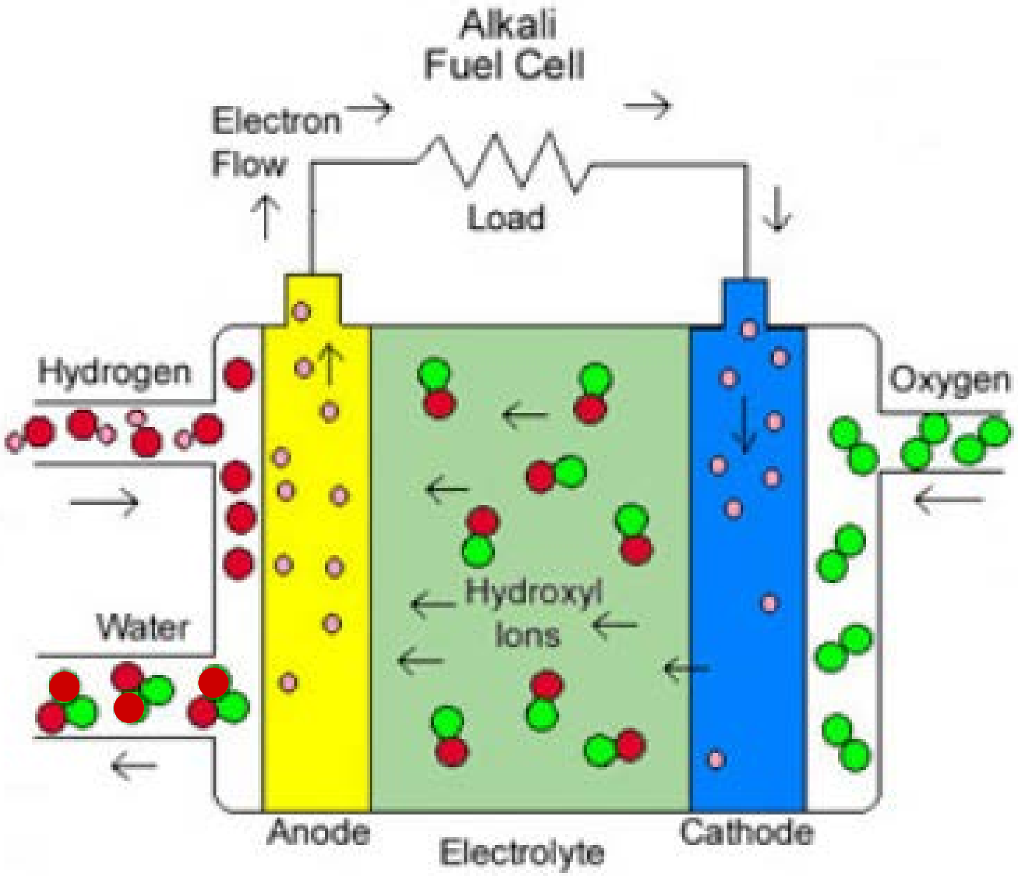
Cathode side	$O_2 + 2\ H_2O + 4\ e^-$	$\longrightarrow$	$4\ OH^-$
Anode side	$2\ H_2 + 4\ OH^-$	$\longrightarrow$	$4\ H_2O + 4\ e^-$
Overall reaction	$2\ H_2 + O_2$	$\longrightarrow$	$2\ H_2O$

Reverse of typical electrolysis process.

Undesired reaction:

$$2\ KOH + CO_2 \longrightarrow K_2CO_3 + H_2O$$

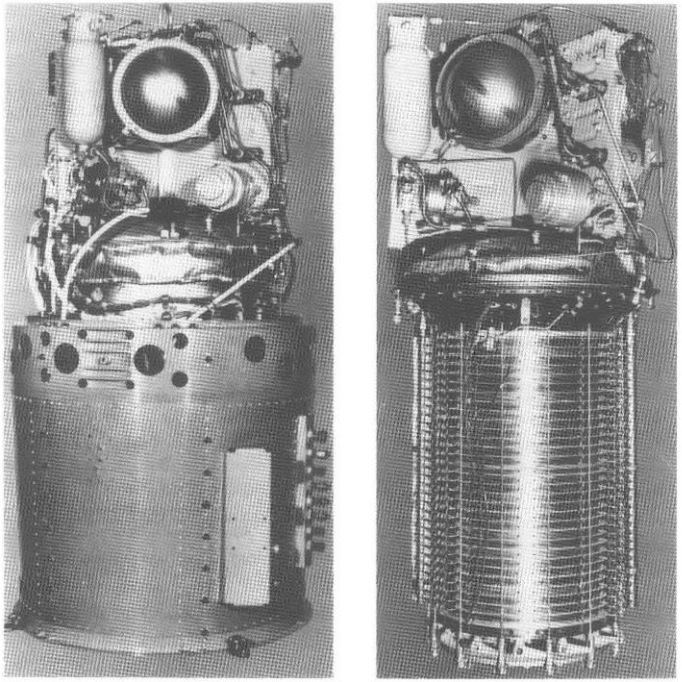
AFC cell principle



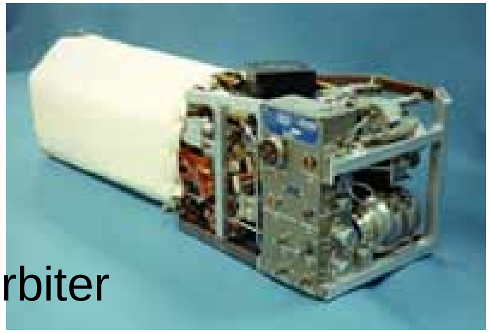
AFC History

Kordesch Austin 1970

ZevCo Taxi Mk.2, 1998/99



Apollo mission 1964



Lunar Orbiter

Reaction DMFC

Cathode side	$3/2\ O_2 + 6\ H^+ + 6\ e^-$	$\rightarrow$	$3\ H_2O$
Anode side	$CH_3OH + H_2O$	$\rightarrow$	$6\ H^+ + 6\ e^- + CO_2$
Overall reaction	$CH_3OH + 3/2\ O_2$	$\rightarrow$	$2\ H_2O + CO_2$

Reaction temperature	70 to 80°C
Issues	catalyst loading and methanol drag

DMFC for portable und small mobile Applications

battery replacers

SAMSUNG

Vectrix

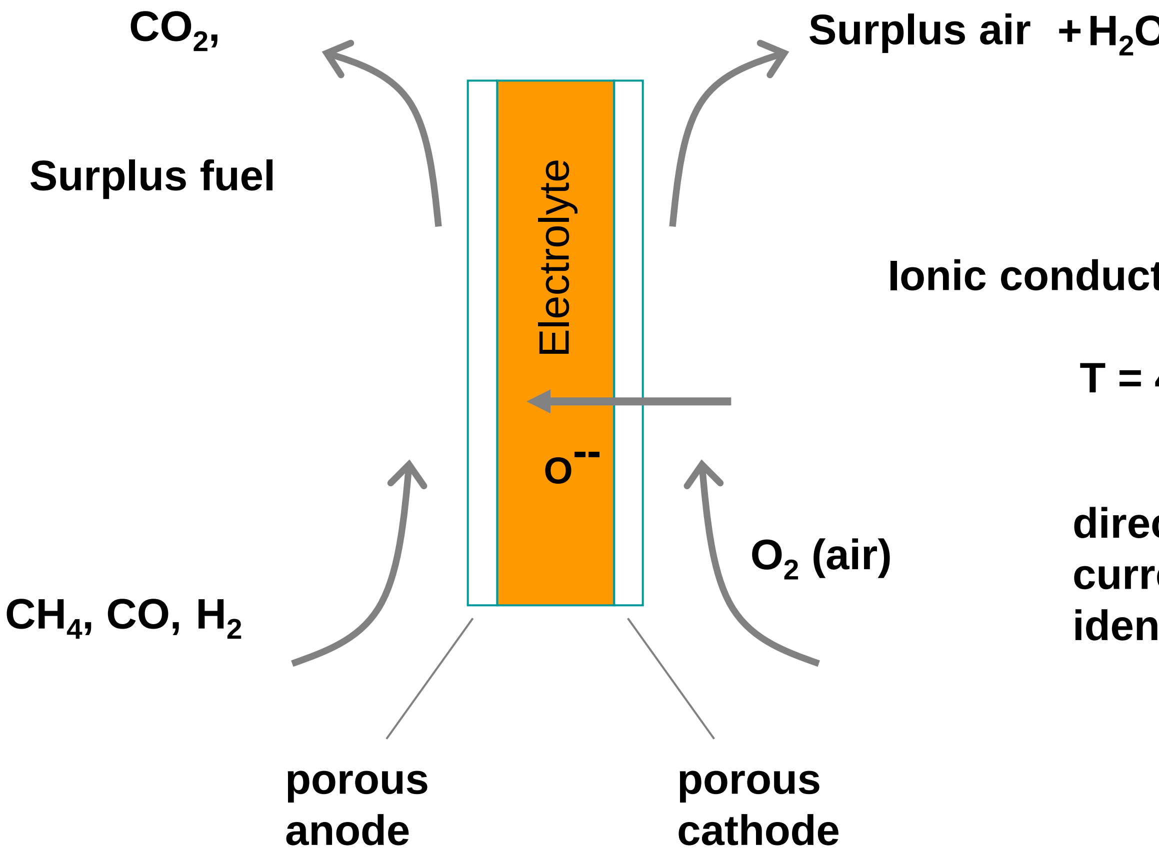
small vehicles

JuMove ‚scooter'

SOFC Development History

- 1890s - description of ion conductivity in ZrO_2 by W.Nernst
- 1937 - E.Baur/H.Preis build first Solid Oxide Fuel Cell
- from mid 1960s development of high temperature FC‘s in U.S. (Westinghouse) and Japan (Tokyo Gas, MHI etc.)
- Siemens acquires Westinghouse (-> SWPC) and shuts down own SOFC development in Germany in 1996
- 1998: SWPC starts first tests with 100 kW-size system
- 1999: SulzerHexis starts field tests with 1 kW residential system

Solid Oxide Fuel Cell



Ionic conductivity = f(T)

T = 400 ... 1000°C

direction of current flow is identical to PEFC!

Reaction PEFC

Cathode side	$O_2 + 4\,H^+ + 4\,e^-$	$\longrightarrow$	$2\,H_2O$
Anode side	$2\,H_2$	$\longrightarrow$	$4\,H^+ + 4\,e^-$
Overall reaction	$2\,H_2 + O_2$	$\longrightarrow$	$2\,H_2O$

Reaction SOFC

Cathode side	$O_2 + 4\,e^-$	$\longrightarrow$	$2\,O^{2-}$
Anode side	$2\,H_2 + 2\,O^{2-}$	$\longrightarrow$	$2\,H_2O + 4\,e^-$
Overall reaction	$2\,H_2 + O_2$	$\longrightarrow$	$2\,H_2O$

SOFC Design Concepts

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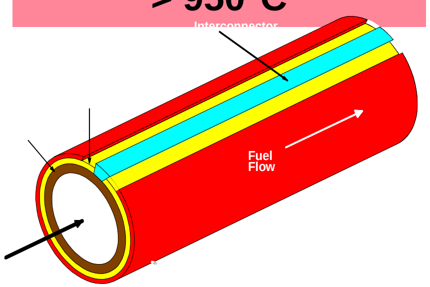
planar

tubular

advantage
- no sealing at high temperature
- mechanical robustness
- long term stability

disadvantage
- low power density
- expensive manufacturing
- high temperature

> 950°C



Integrated Planar

advantage
- no sealing at high temperature

disadvantage
- low power density
- high temperature

> 900°C

Electrolyte substrate

advantage
- high power density
- low manufacturing costs

disadvantage
- HT-sealing
- rel. high temperature

> 850°C

Anode substrate

advantage
- high power density
- low manufacturing costs
- big cells
- low temperature

disadvantage
- HT-sealing

> 600°C

Applications of SOFC

Portable, Mini and Micro: < 500 W
- military
- gen-set (disaster control, roadworks etc.)
- battery recharger

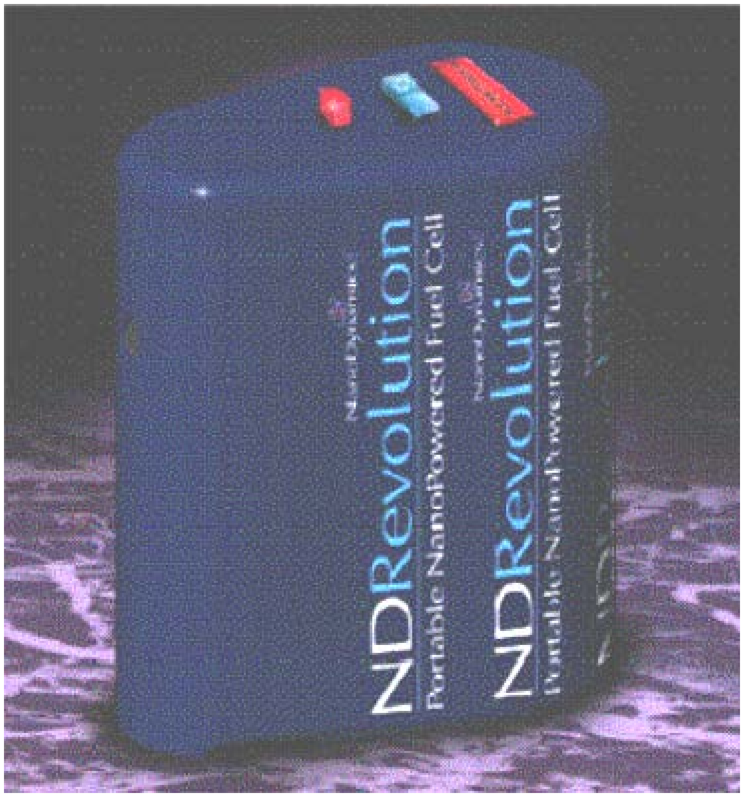
APU: 5 to 25 kW and > 100 kW
- passenger vehicles
- lorries, building machines, earth movers
- ships, aircraft

Small Scale CHP: 1 to 100 kW
- residential
- industrial (hospitals, polygeneration etc.)

Power Generation: > 1 MW
- including gas turbine hybrid plants

Vehicle Propulsion: 5 to 25 kW
- hybrid vehicles?

Miniaturised SOFC Developments

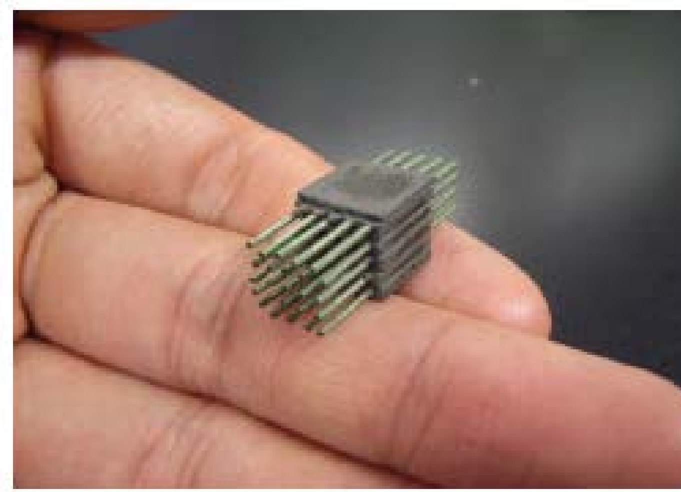


Military: Nanodynamics

- mini-tubes
- limited lifetime required
- cost and efficiency less important
- operation on military fuels

50 W miniature SOFC

AIST ‚sugar cube‘ stack

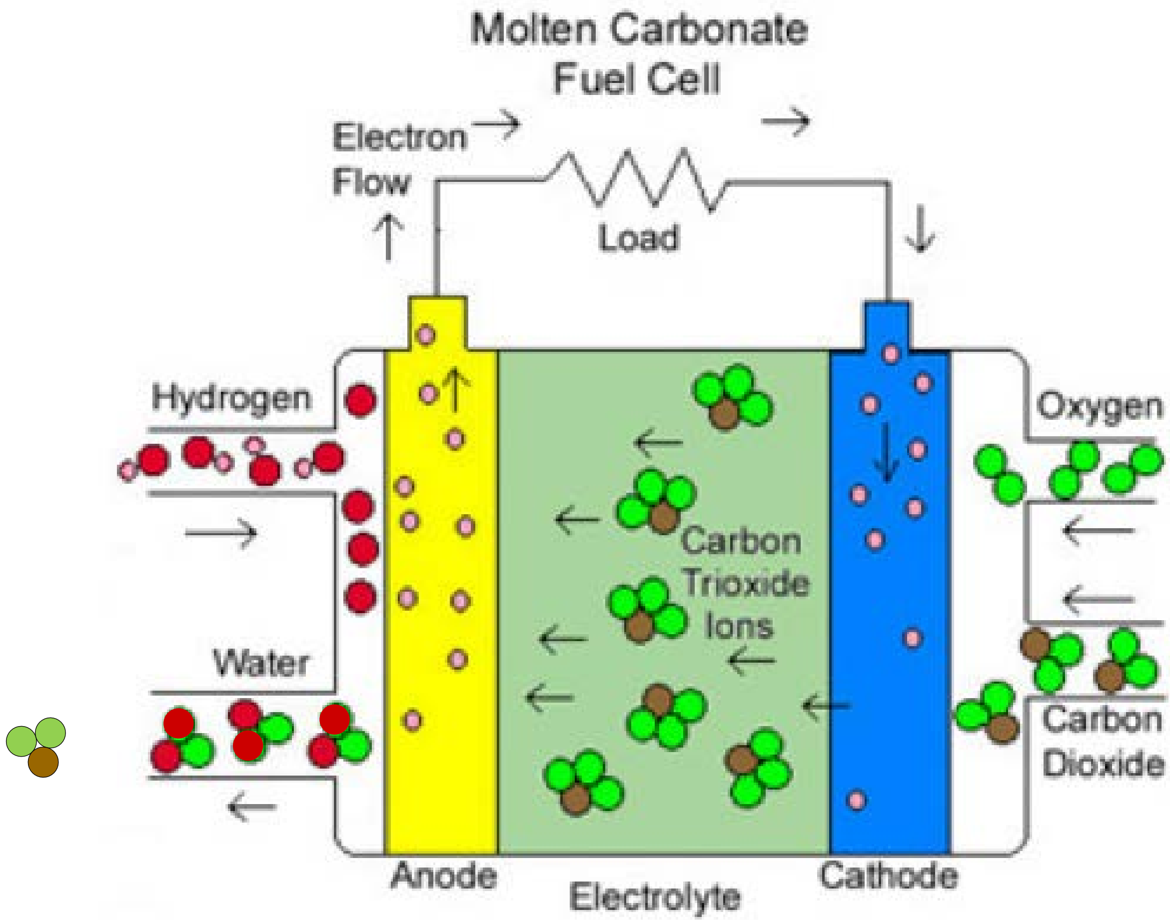


Reaction MCFC - hydrogen case

Cathode side	$O_2 + 2\ CO_2 + 4\ e^-$	$\longrightarrow$	$2\ CO_3^{2-}$
Anode side	$2\ H_2 + 2\ CO_3^{2-}$	$\longrightarrow$	$2\ H_2O + 2\ CO_2 + 4\ e^-$
Overall reaction	$2\ H_2 + O_2$	$\longrightarrow$	$2\ H_2O$

note: CO_2 supply necessary on cathode side

Reaction MCFC

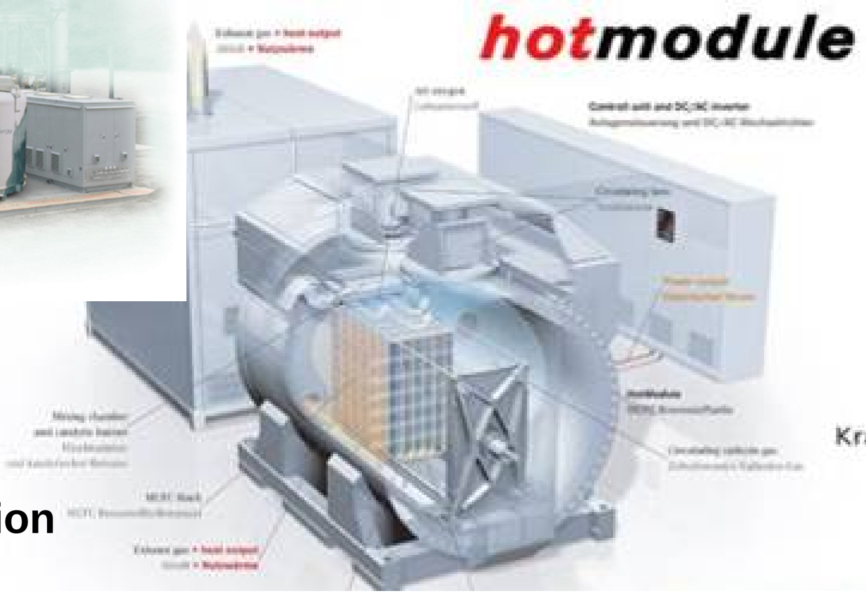


here’s another mistake ...

Fuel Cell Energy, MTU & Ansaldo

FCE:
off-the-shelf
300 to
3000 kW units

50 units worldwide

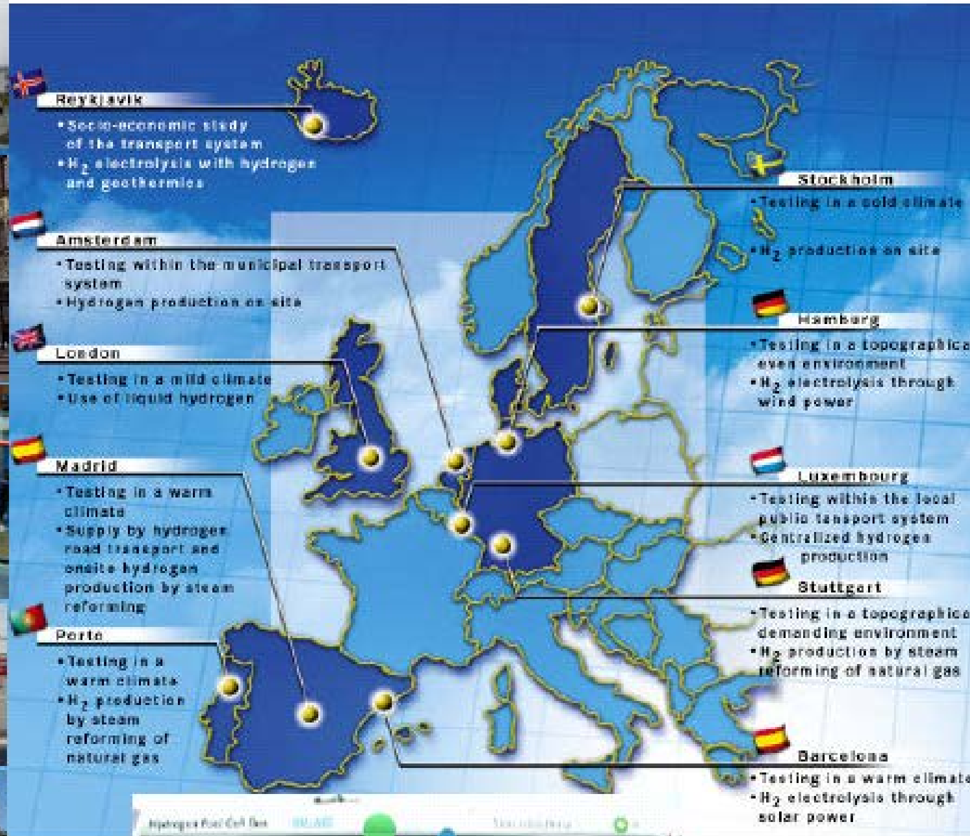


Ansaldo:
biomass syn-gas
operation

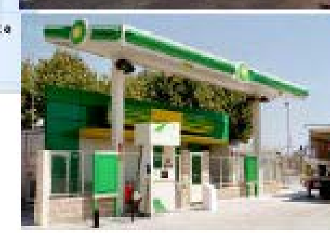
MTU:
17 in total
7 still in operation
250 kW / unit

Technology Status of Fuel Cells & Hydrogen applications

Clean Urban Transport for Europe - CUTE

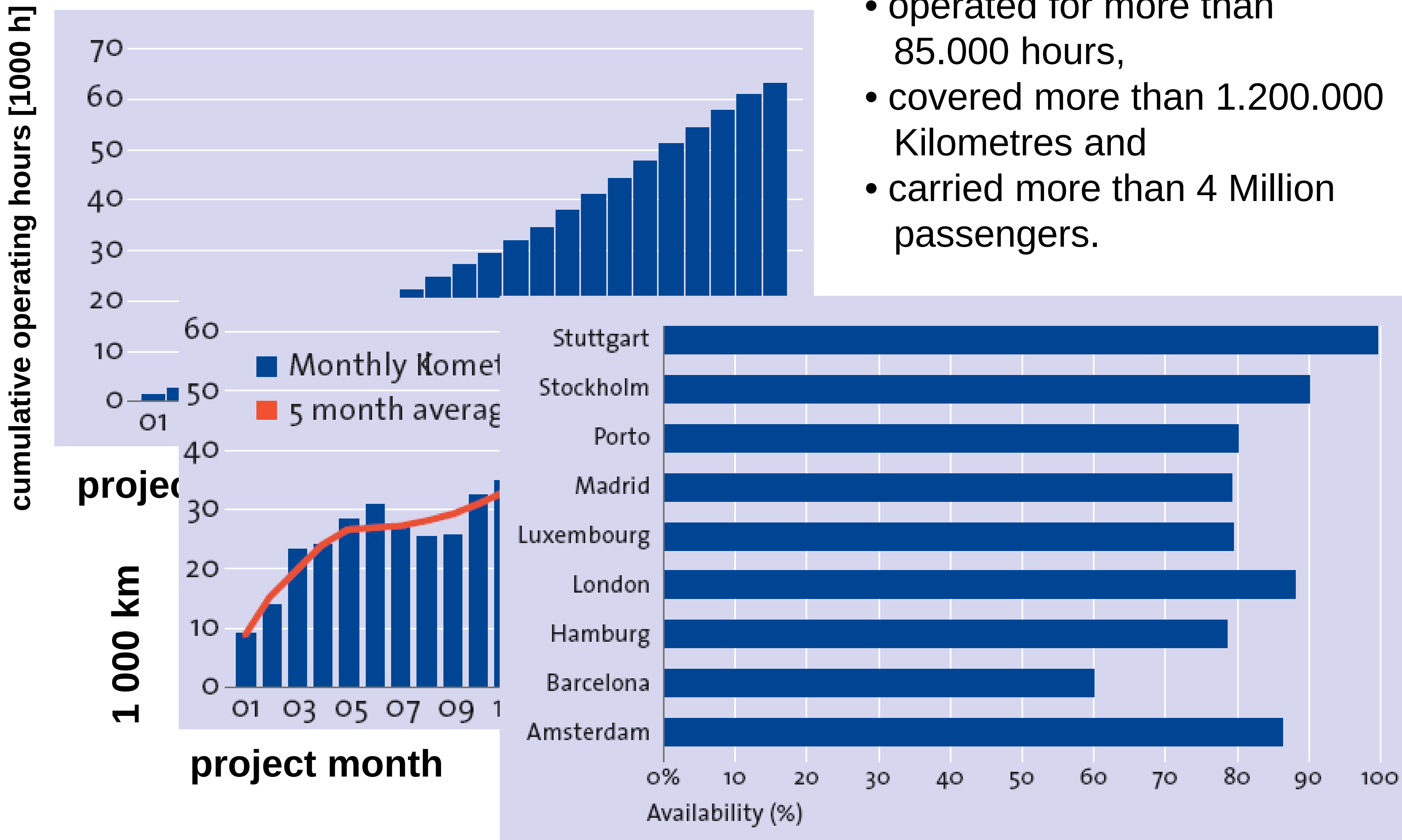


Perth, Australia



source: CUTE

CUTE Results



- operated for more than 85.000 hours,
- covered more than 1.200.000 Kilometres and
- carried more than 4 Million passengers.

CUTE: Hamburg Filling Station

Hydrogen Applications and Markets

- Ammonia production
- Petroleum refining
- Methanol production and Industrial chemicals
- Hydrogenation of fats and oils (food industry)
- Metallurgy
- Electrical power generation
- Electronics industry

H_2 world market size is comparable in volume with European natural gas market (~500 x 10^9 Nm^3 per year)

Existing Hydrogen Distribution Pipelines

Courtesy Air Liquide

Daimler f-cell Concept

60 built and operated in worldwide clusters (DE, SP, JP, US, etc.)
3.650.000 km (Nov. 2007)
100.000 km with one car (within ~3 years)

Generation 2 F-Cell Car:

- 40% more power
- 100% additional driving range (400 km)
- Improved lifetime of the FC stack (2000 h)
- Higher reliability
- Freeze start ability
- Li-Ion battery

F600 Hy^{Genius} Research Car:

- Technology carrier for advanced components (intended for serious production)
- Air supply: turbo charger with turbine
- Compact fuel cell stacks with metallic bipolar plates and improved MEA-technology
- Freeze-start ability as low as -25°C

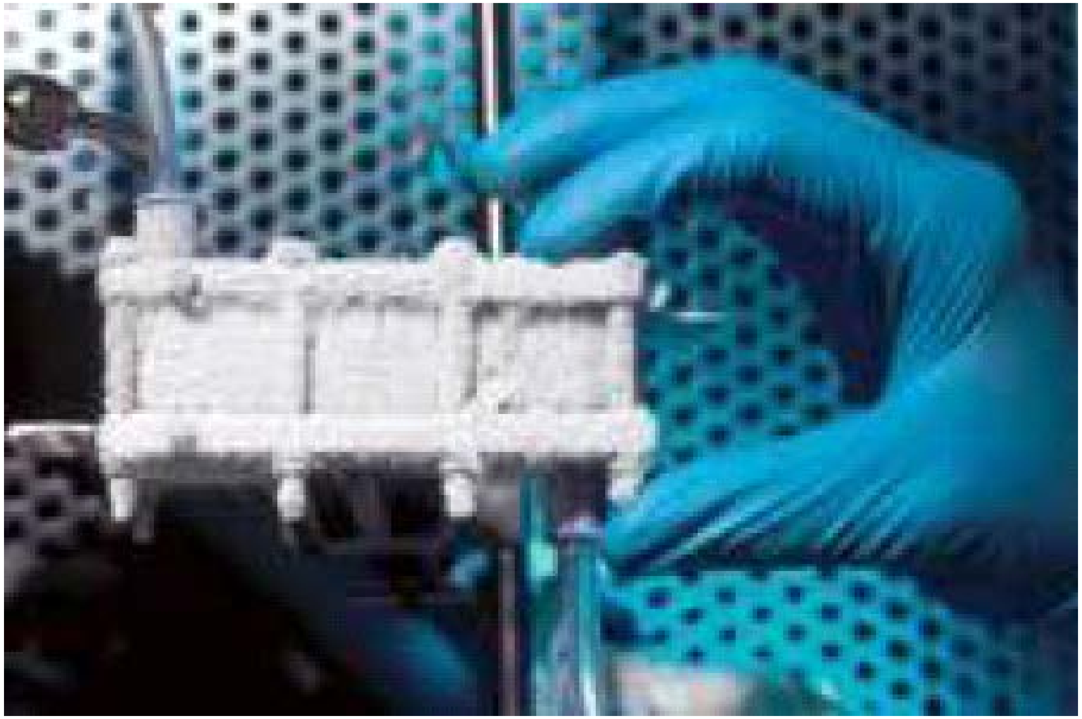
Source: Daimler FCSem 07

PEFC ‚Freeze‘ start

15 W
freeze-proof to -20°C
operational up to 40°C

Masterflex

developed in cooperation with FhG-ISE



PEFC Products and Near-market Developments

Proton Motor

Intelligent Energy

Nedstack

Heliocentris

Voller Energy

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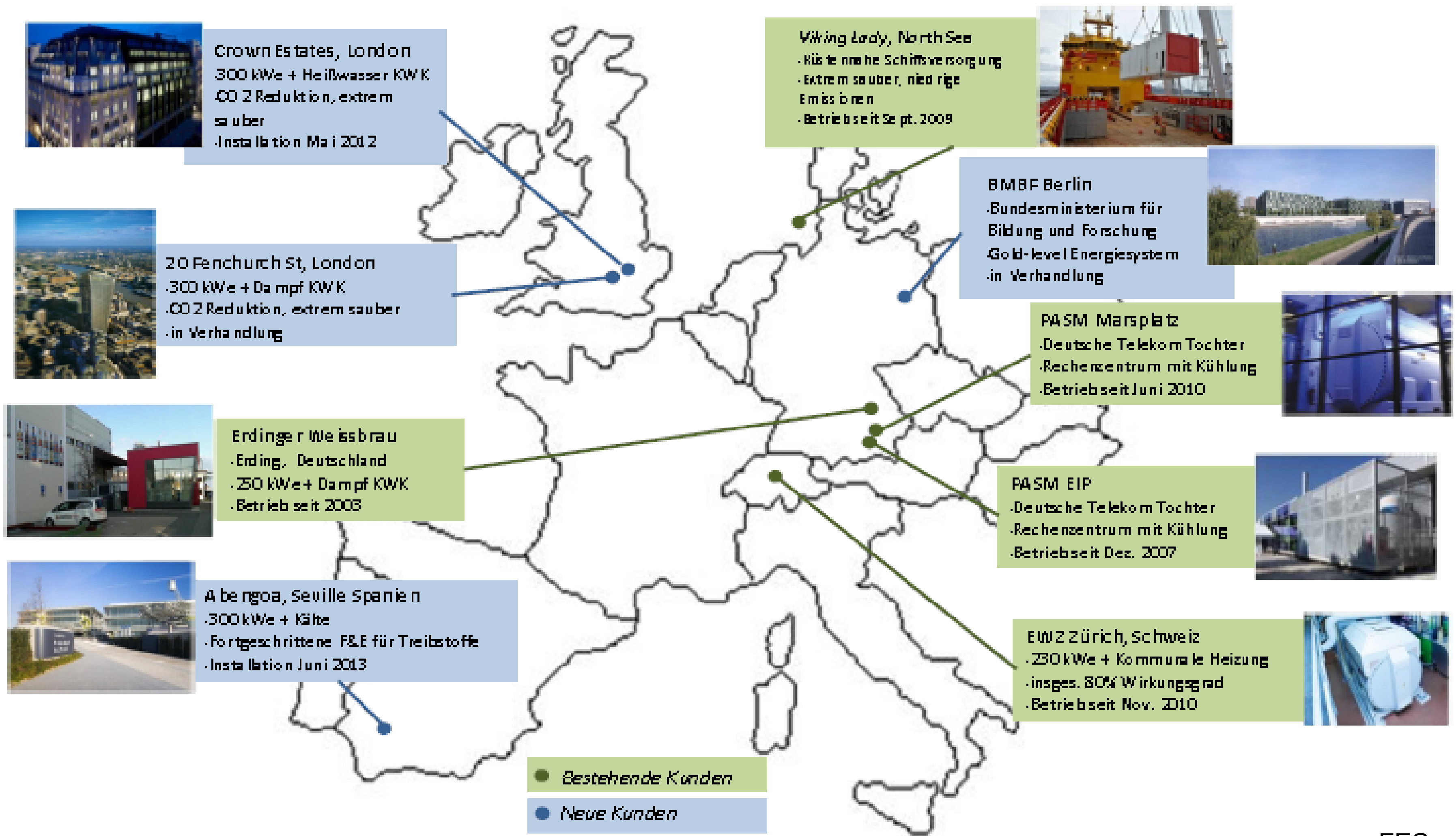
MCFC HotModule European Sites

- total number 17
- 7 still operating
- electrical efficiency 47%
- accumulated operating time > 170.000 h
- incl. bio-fuels and trigeneration

Cartagena/Spain

24.211 h

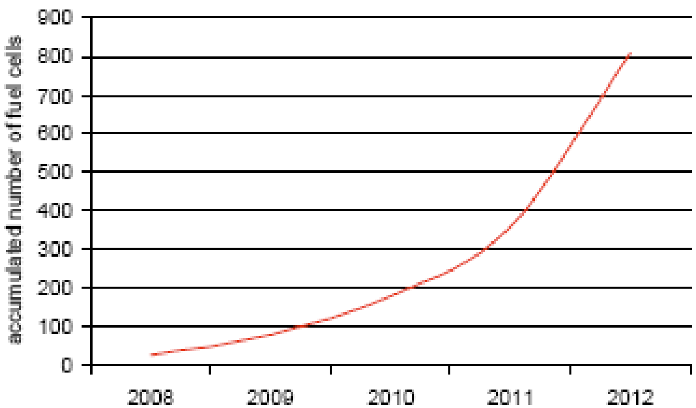
MTU – FCE – IKTS Cooperation



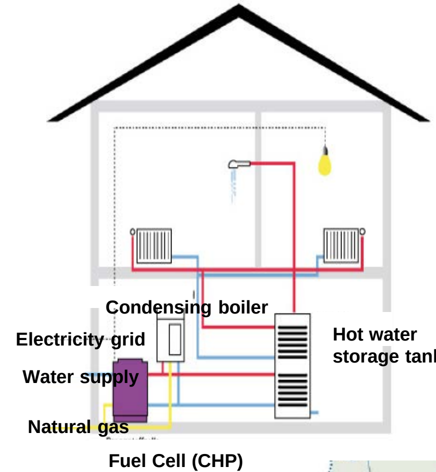
source: FES

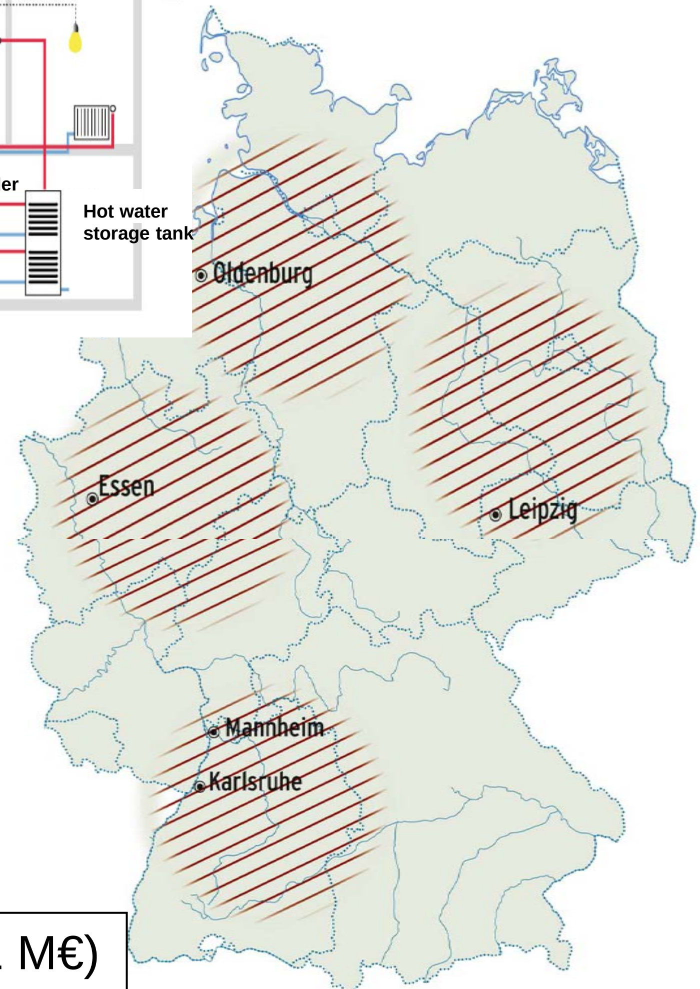
CALLUX Project: Field Testing Germany 2008-2012

Scheduled number of fuel cells



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





Total budget 86 M€ (funding 41 M€)
Total installations: >600

CALLUX Project Installations

BAXI PEFC
1 kW_e/1.7 kW_{th}
η_{el} = 32%
Integrated boiler

HEXIS SOFC
1 kW_e/2 kW_{th}
η_{el} = >30%
Integrated boiler

Vaillant SOFC
1 kW_e/1.7 kW_{th}
η_{el} = 30%
external boiler

Japan: ENE FARM FC Demonstration

- susidised residential systems, 700W
- original cost ~28 000 EUR (2.6 MYen)
  (~20% cost reduction to 2009), subsidy ~9 000 EUR
- 20 000 units to be sold in 2012, prevalently PEFC
- 10 year warranty, 80 000 hours lifetime (PEFC)
- 6 companies / development groups
- sales goal for 2030:
  2.5 Mio. units p.a.


Kyocera

Nippon Oil

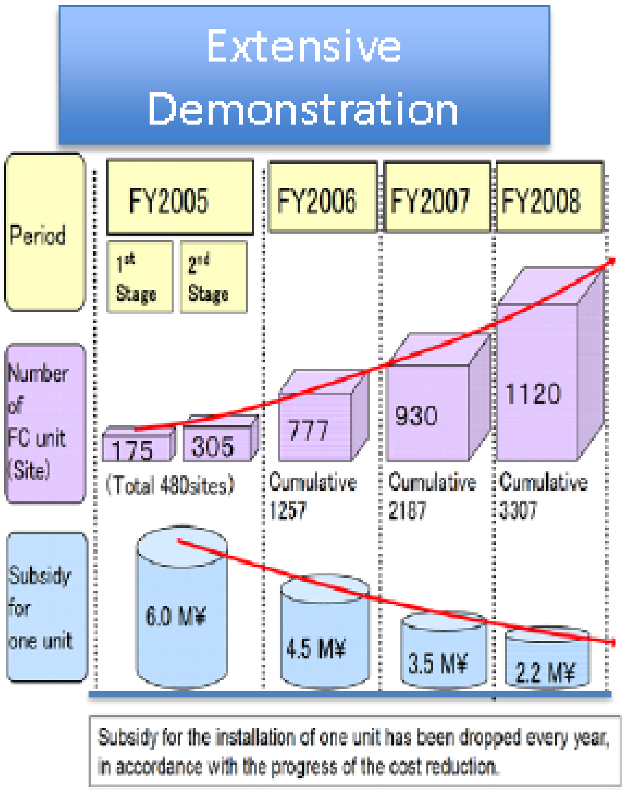

TOTO

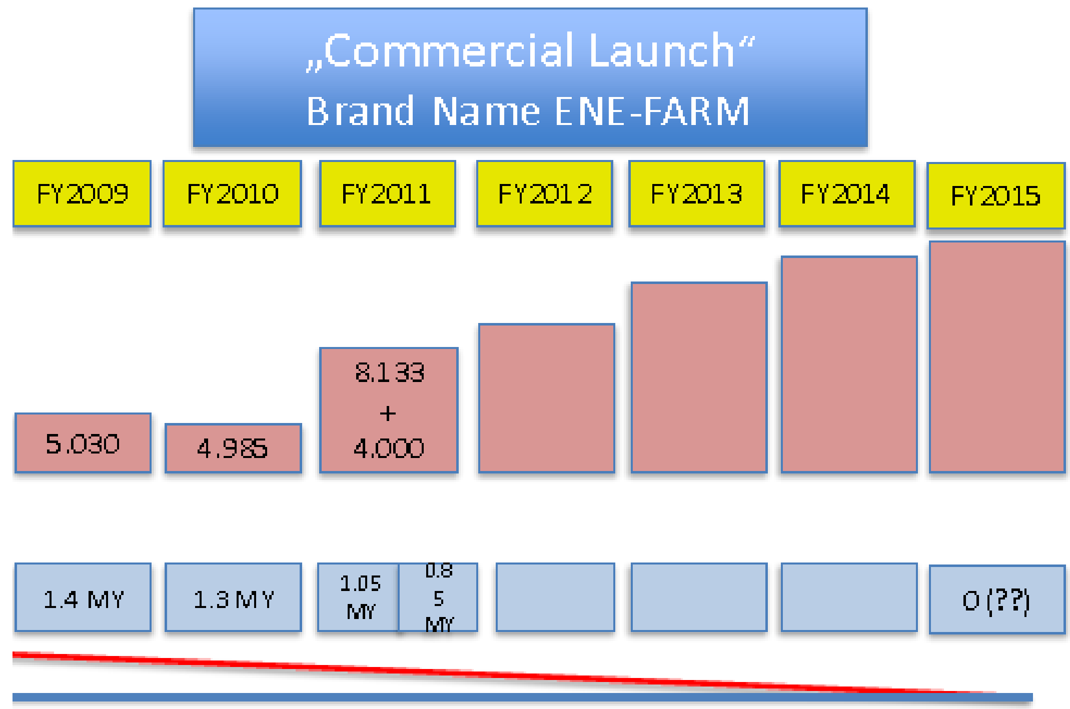
SOFC unit 0.7kW


Hot Water Tank unit

Toyota/Aisin

Japan: Installations & Subsidies Scheme





source: NEDO

Japan: Demo Requirements

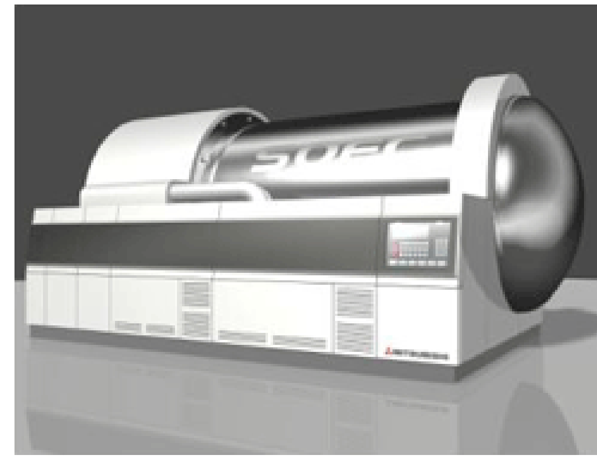
PEFC

	2010	2015	2020	2030
Electric Efficiency (HHV/LHV)	33% / 37%	33% / 37%	33% / 37%	36% / 40%
Durability	40,000 hour	60,000 hour	90,000 hour	90,000 hour
System Cost / unit	2.0–2.5 Mil. Yen (19,000 Euro)	0.5–0.7 Mil. Yen (5,000 Euro)	0.4–0.5 Mil. Yen (3,750 Euro)	under 0.4 Mil. Yen (3,000 Euro)

SOFC

	2010	2015–2020	2020–2030
Electric Efficiency (HHV/LHV)	40% / 45%	40% / 45%	50% / 55%
Durability	20,000–40,000 hour	40,000 hour	90,000 hour
System Cost / kW	9 Mil. Yen (75,000 Euro)	0.5–1.0 Mil. Yen (6,000 Euro)	under 0.4 Mil. Yen (3,000 Euro)

Japan: Test Lab & 100 kW class CHP



Mitsubishi Heavy Industries system mock-up of prototype run in 2006,

UNIVERSITY OF BIRMINGHAM

Direct Methanol Fuel Cells

SMART FUEL CELL

Product SFC A50

Product SFC A25

HYMER

Bloom Energy: Adobe, e-bay & Wal-Mart

- 100 kW units
- 70 installed (partly in ‚clusters')
- decentralised electricity generation, grid stabilisation & backup
- partly running on bio-fuels

Bringing Fuel Cells & Hydrogen to the Market(s)

Fuel Cell Steps to Market Entry

Problem:

How to establish a new technology in an existing and well developed market?

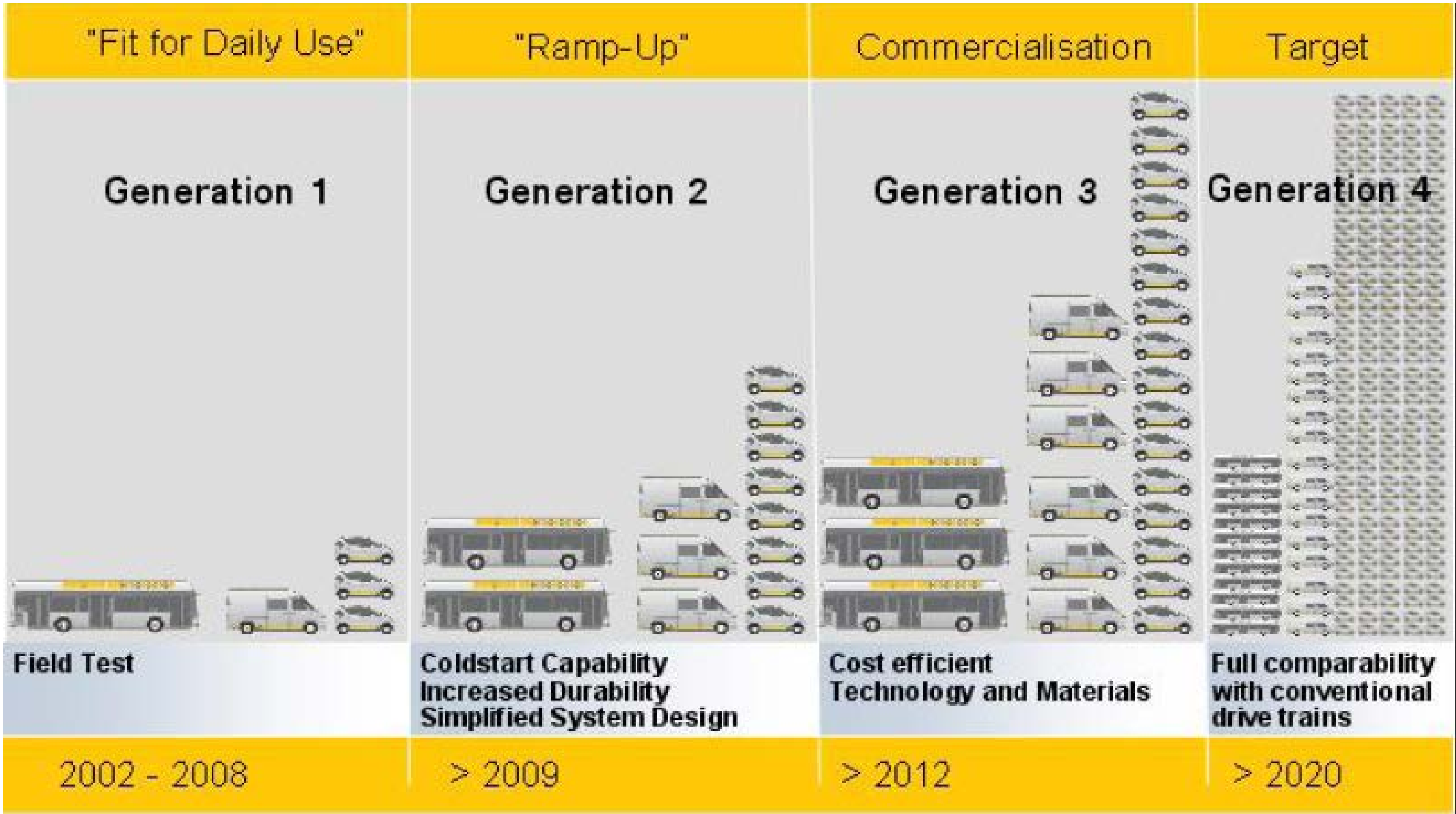
‚Disruptive' technology versus continuous improvement of existing technology

Market entry costs

Customer attractivity (desireability)

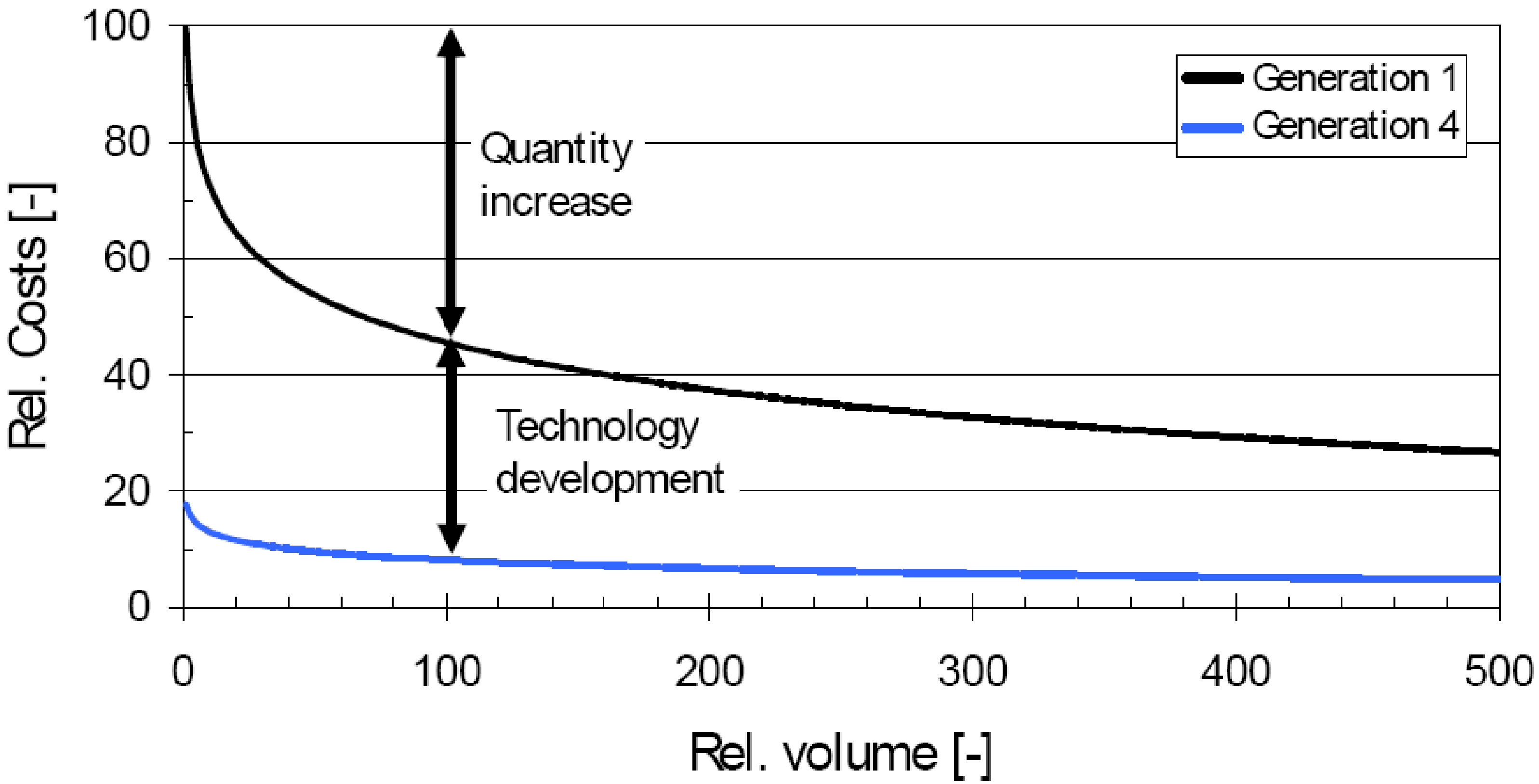
Technological supremacy

Daimler Development Time Table



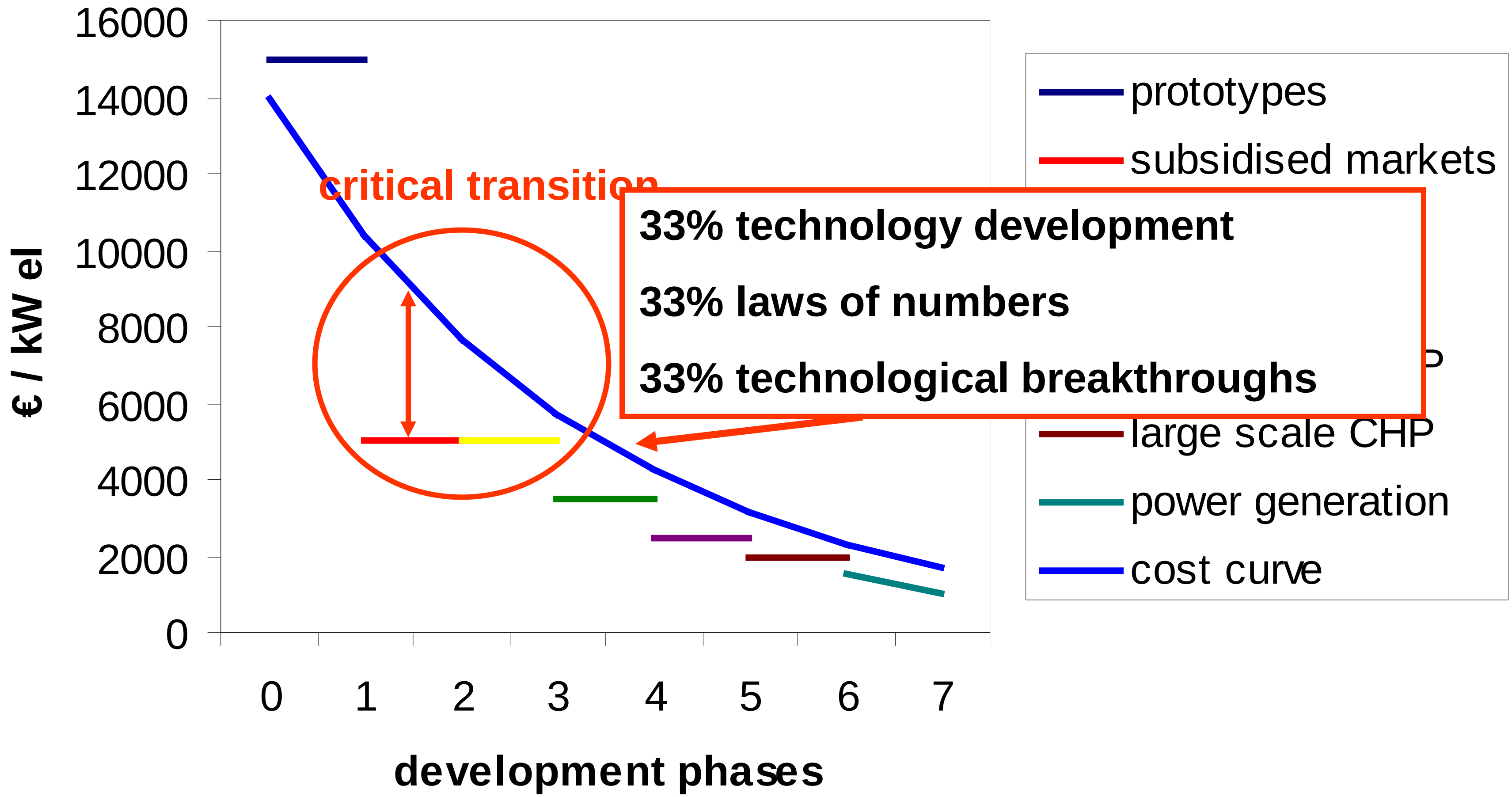
Source: Daimler, FCSem 2007

Daimler Cost Learning Curve

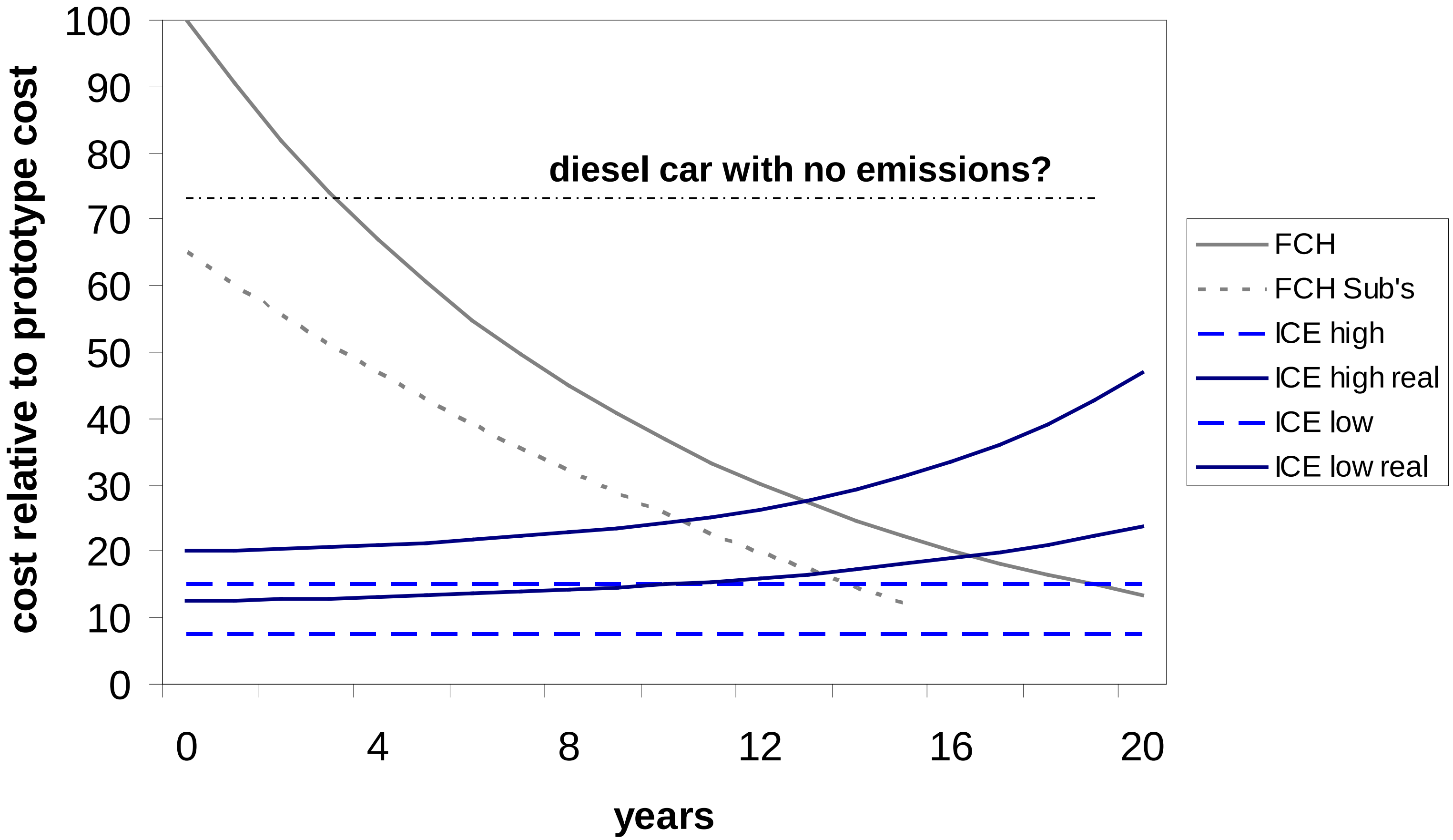


Source: Daimler, FCSem 2007

Cost Development Curve vs. First Markets



Cost Projections – Moving Targets



free market vs. regulatory vs. subsidy approach

What Can We Learn From History?

New technologies have been permanently introduced to the markets with varying success. All the problems of costs and market introduction have existed before.

Examples:

mobile phones

mineral oil

photovoltaics

green electricity

unleaded fuel

The Concept of ‚Added Value‘

Consumers will pay a price above the market price for a service or consumable, if they gain some additional performance compared to ‘conventional’ equipment.

This could be:

improved performance (power, size, other technical data)

improved handling

improved utilisability

prestige

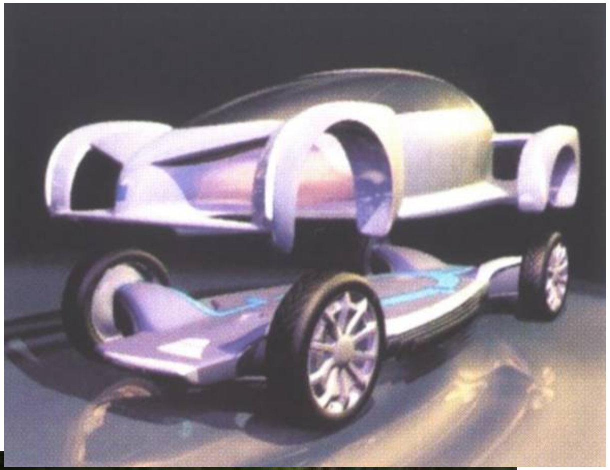
fun & recreation

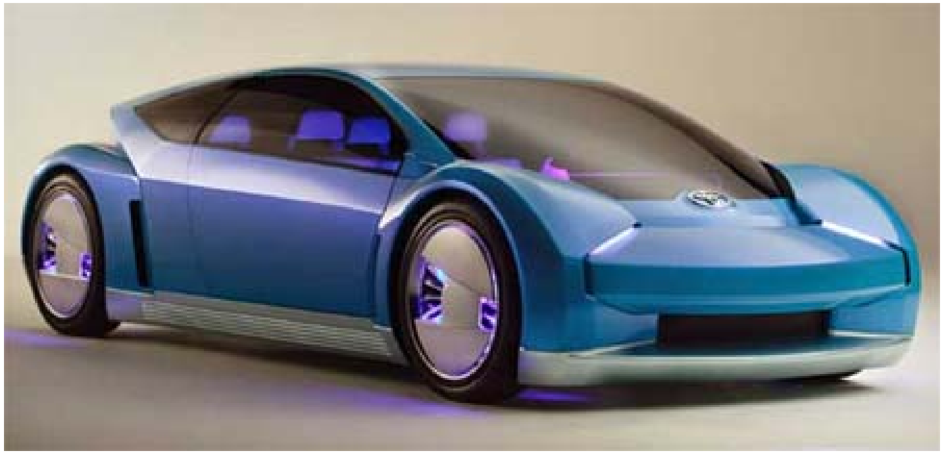
Marketing Products: APU's for RV's

Proc

Electric / Fuel Cell Vehicle Concepts

GM Autonomy concept





Toyota study

GM HyWire

Sources: various

Engineer‘s Frustration Ahead .....

Increasing personal valuing

Lifestyle
Prestige
Social position
‚Feel‘/emotions

Usefulness
Efficiency
Freedom from pollutant emissions
Low noise emission
Low weight

Environment
Environmental performance
Sustainability

Economics
Cost effectiveness
Low O&M requirements

Increasing technical effort

Design
‚soft‘ engineering

consumer design
customer design

performance
engineering

cost engineering

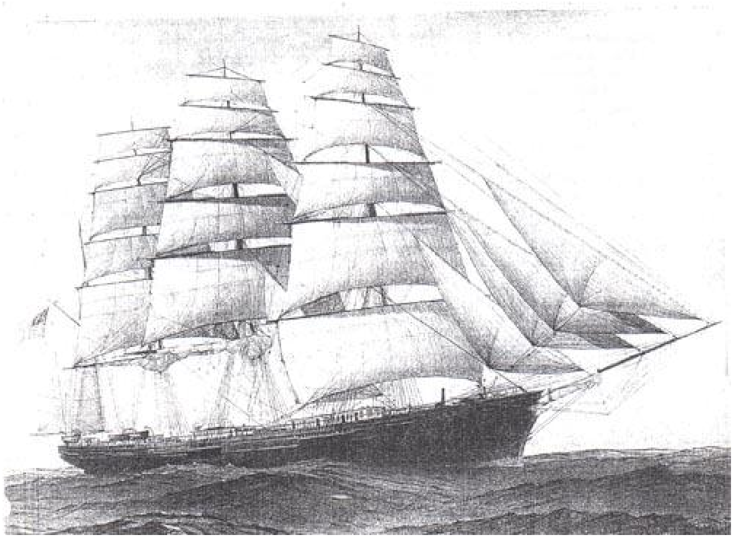
Fuel Cells Will be Immediately Competitive When ....

- carbon dioxide emissions are taxed
- fossil energy ressources are depleted
- energy inefficiency is taxed (or constrained)
- hydrogen becomes abundant

or

- harmful emissions are considered vile by society
- noiseless and exhaust-free operation becomes desireable
- they supply power for otherwise unserviced locations
- they are ‚in'

The Sailing Ship Effect



The advent of the steam ship in the early 19th century spurred new developments in sailing ship technology

Safety surprises …

Photo 8 - Time: 2 min, 40 sec - Driver's side rear tire rupture sends debris out the passenger side of the vehicle.

Photographs courtesy of Swain, U Miami

Thanks for your Attention!

Any Questions?