Fuel Cell Systems & Applications

- Advantages
- Challenges
- Applications

Historical development

- 1960 alcaline (OH^-) space missions (few kW_e)
- 1970 acid PO_4^{3-} (H^+) 1. generation (200° C, 200 kW_e)
- 1980 molten salt MCFC 2. " (650° C, 1 MW_e)
- 1985 ceramic SOFC 3. " (900° C, 100 kW_e)
- 1990 polymer membrane transport (vehicles, 50 kW_e)

APPLICATIONS

Portable	0.1-100 W	electronics	**DMFC, PEFC**
Small Cogen.	1 kW - 100 kW	"UPS" (low competition from μT or diesel engines)	**PEFC, SOFC**
Transport	20 kW - 200 kW > 1 MW	vehicles, buses ships	**PEFC, DMFC, AFC** **MCFC, SOFC**
Medium Cogen.	0.2 MW - 3 MW	offices, schools, hotels, hospitals, supermarkets; Industry : chem./ steel/ food	**(PAFC)** **MCFC** **SOFC**

Application determines cost target

PEFC:
-membrane : 100$/kW
-Pt : 10$/kW ($H_2$)
(methanol : 300$/kW)

PAFC 200 kW_e:
+30% vs. CHP engine

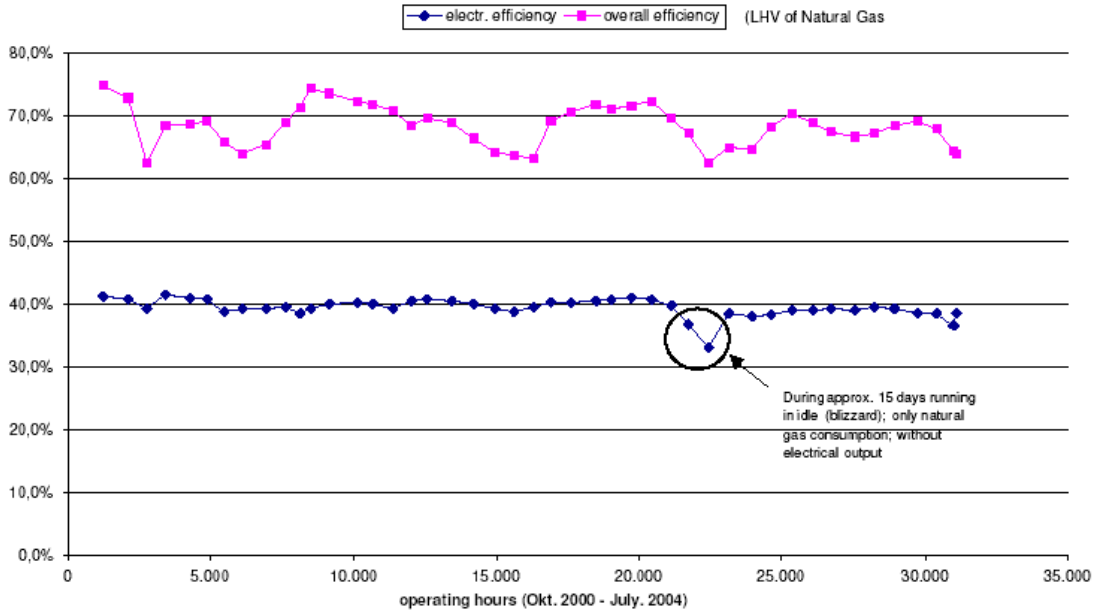
50 300 600 3000 **COST** €/kW

cars buses cogeneration actual

h

5'000 50'000 100'000 **LIFETIME**

✓OK for tubular SOFC



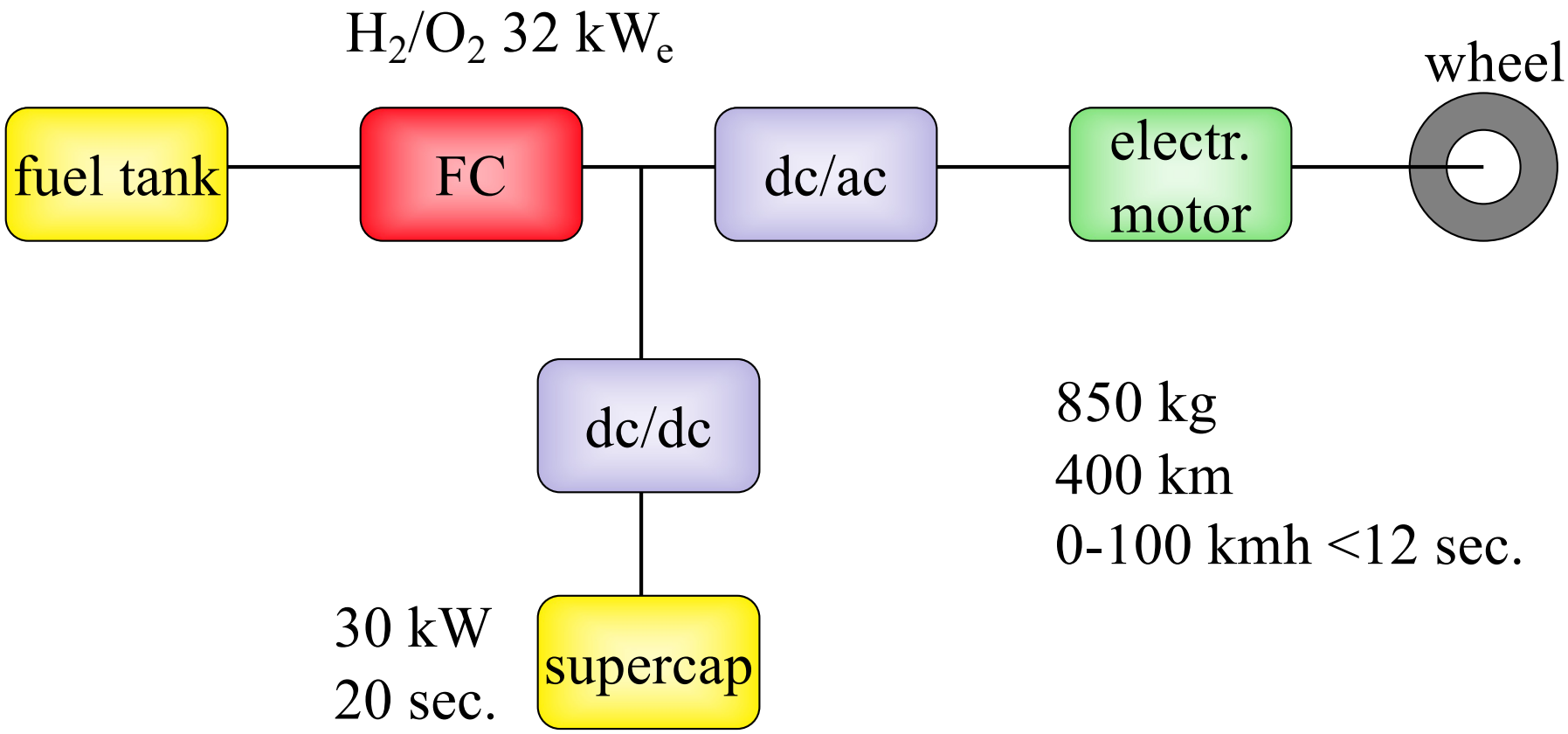
- limitation :
  - power degradation
  - materials problems

Which fuel for which application?

- **Stationary** :
  - natural gas, biogas
  - fuel nature can determine the power size (e.g. biogas production site)

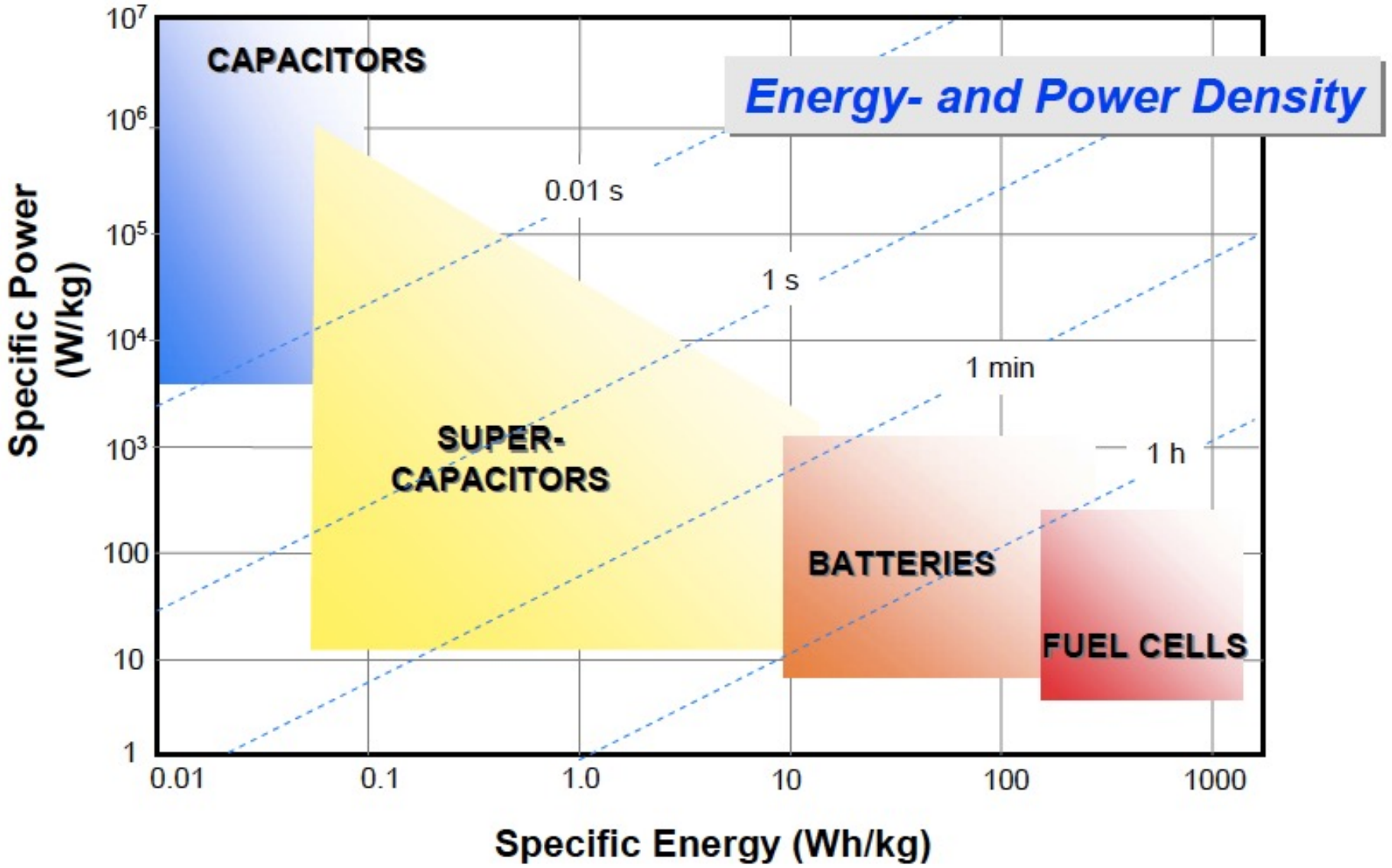
- **Mobile**:
  - small portable:
    - methanol (liquid, easy to store and replace, and to reform)
    - stored H_2 (hydrides,..)
  - APU: liquid hydrocarbon (generates H_2 onboard)
  - transport: H_2 for dynamics

Transport: PSI-Michelin Hy-Light Car



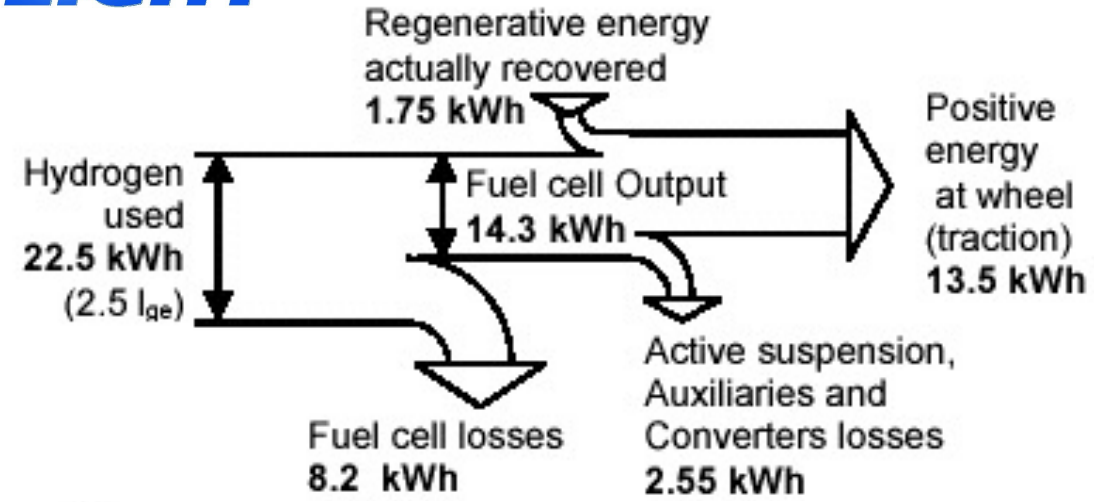
(F. Büchi, PSI)

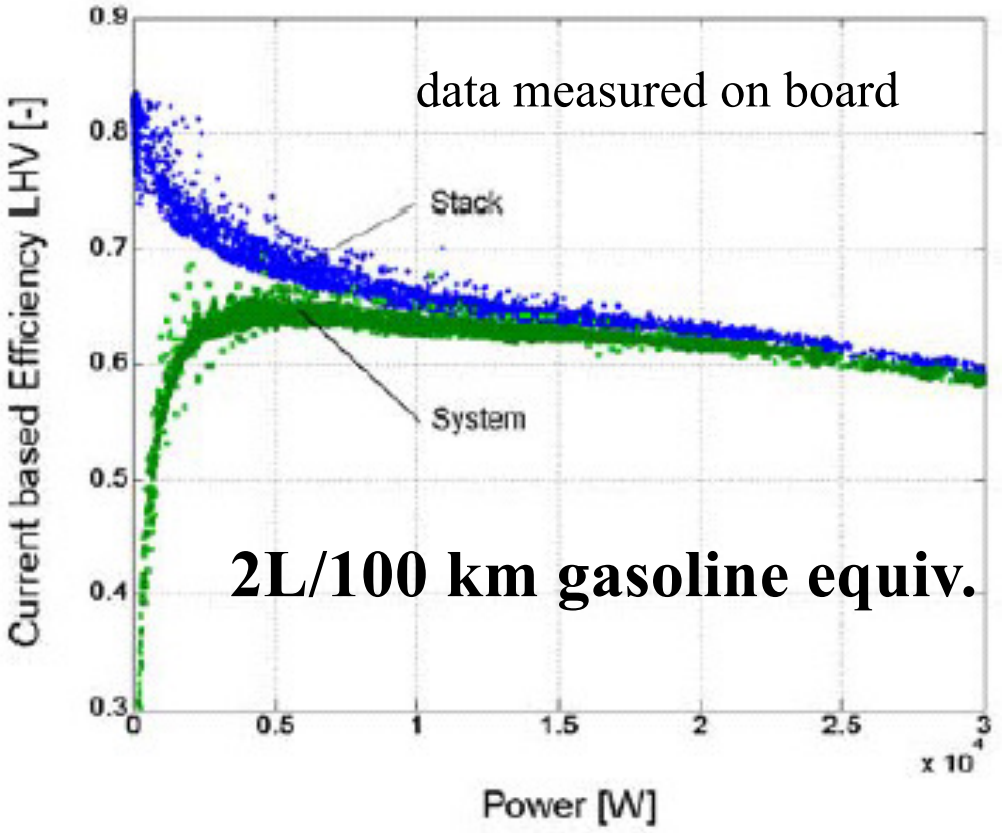
Storage devices – Ragone plot



G.G. Scherer, Lucerne Fuel cell Forum, Fuel Cell Tutorial

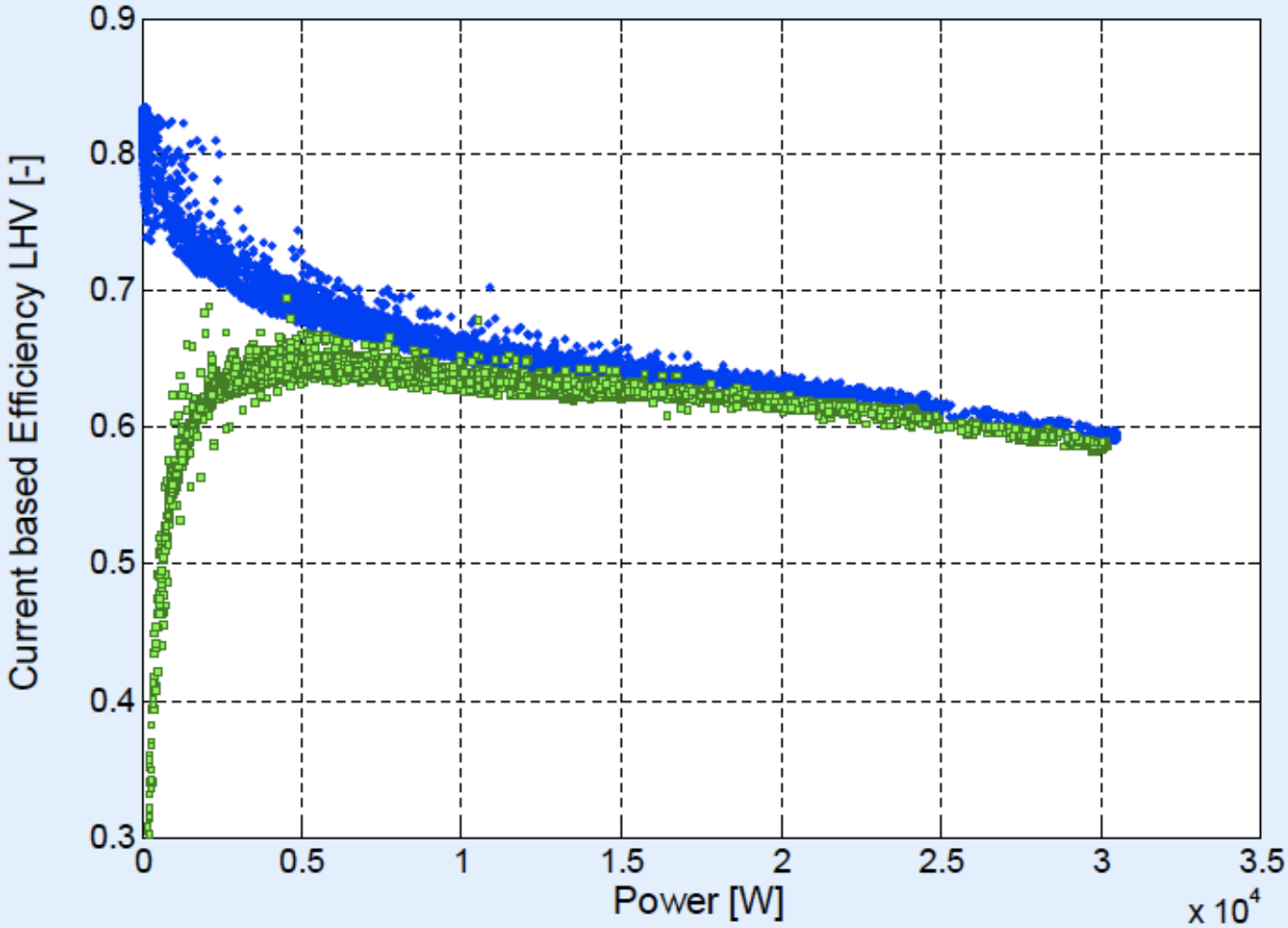
(source : F. Büchi, PSI)





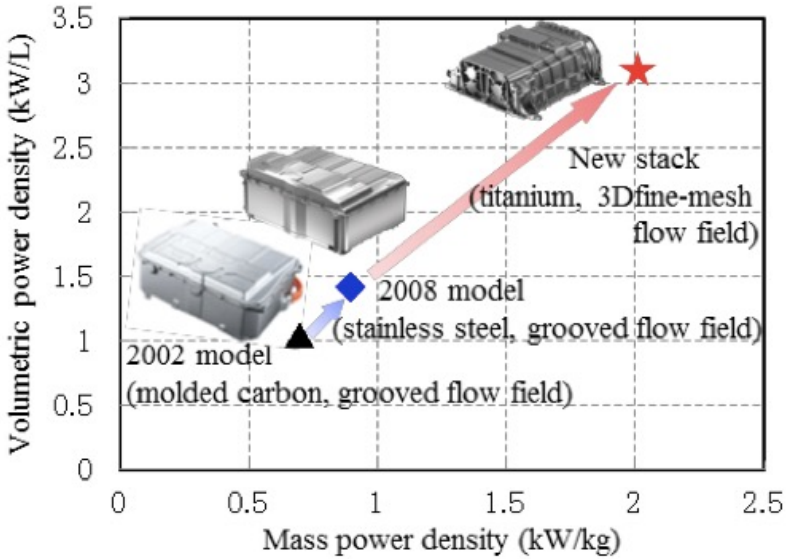
PSI 30 kW_e H_2 / O_2 stack (on-board)

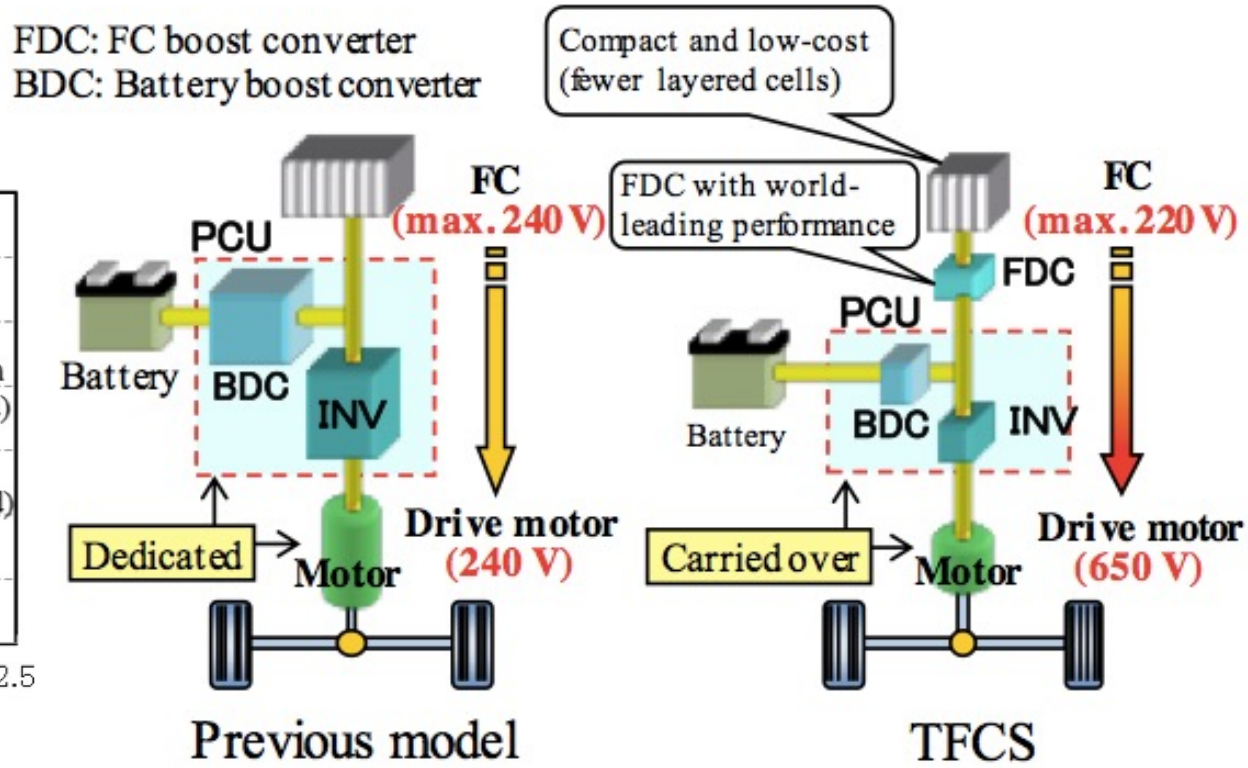
Efficiency FC stack, FC-system



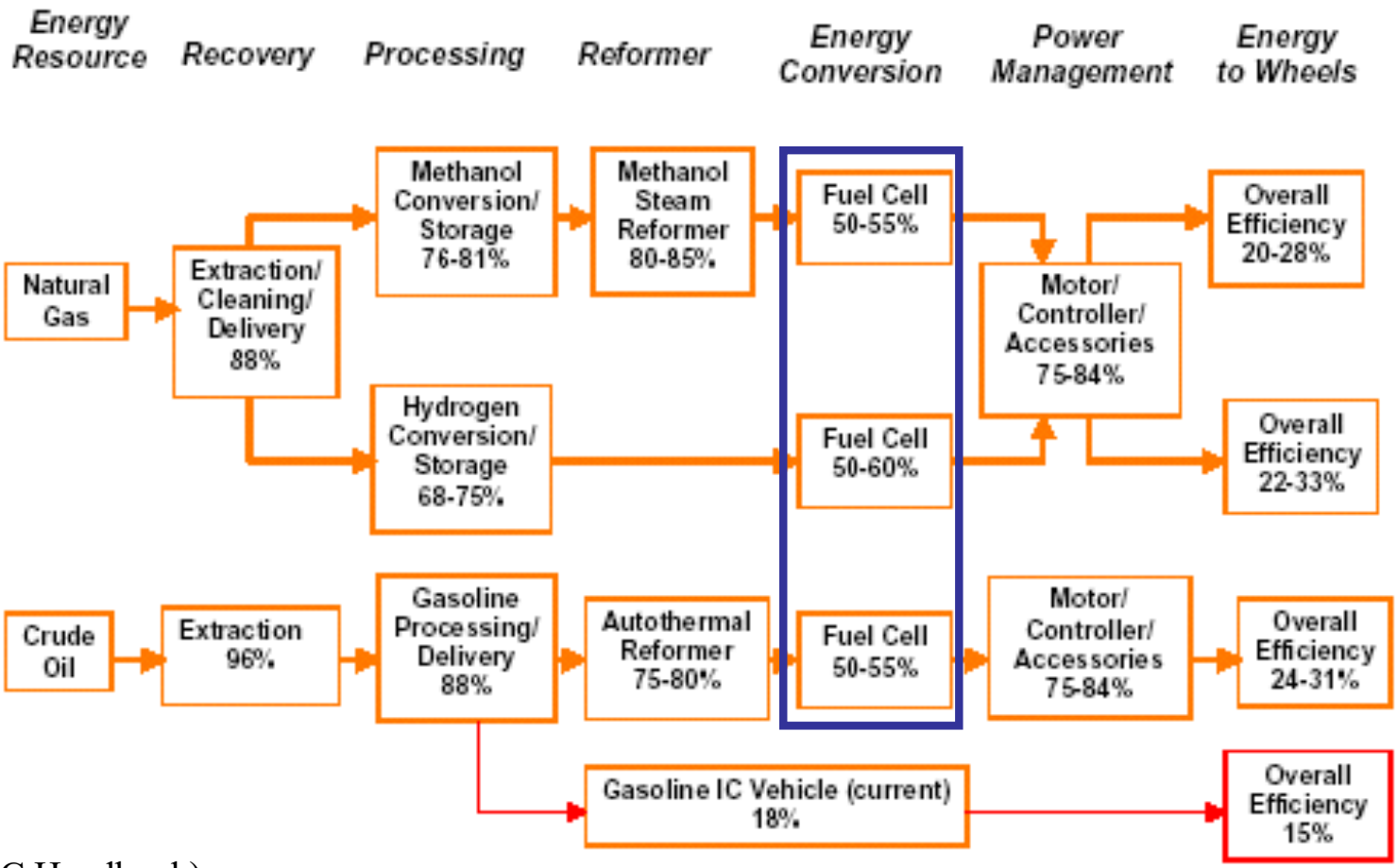
Toyoto Mirai

https://fr.toyota.ch/world-of-toyota/articles-news-events/2014/the-toyota-mirai.json#/youtube/8Lpt_9UqzOI





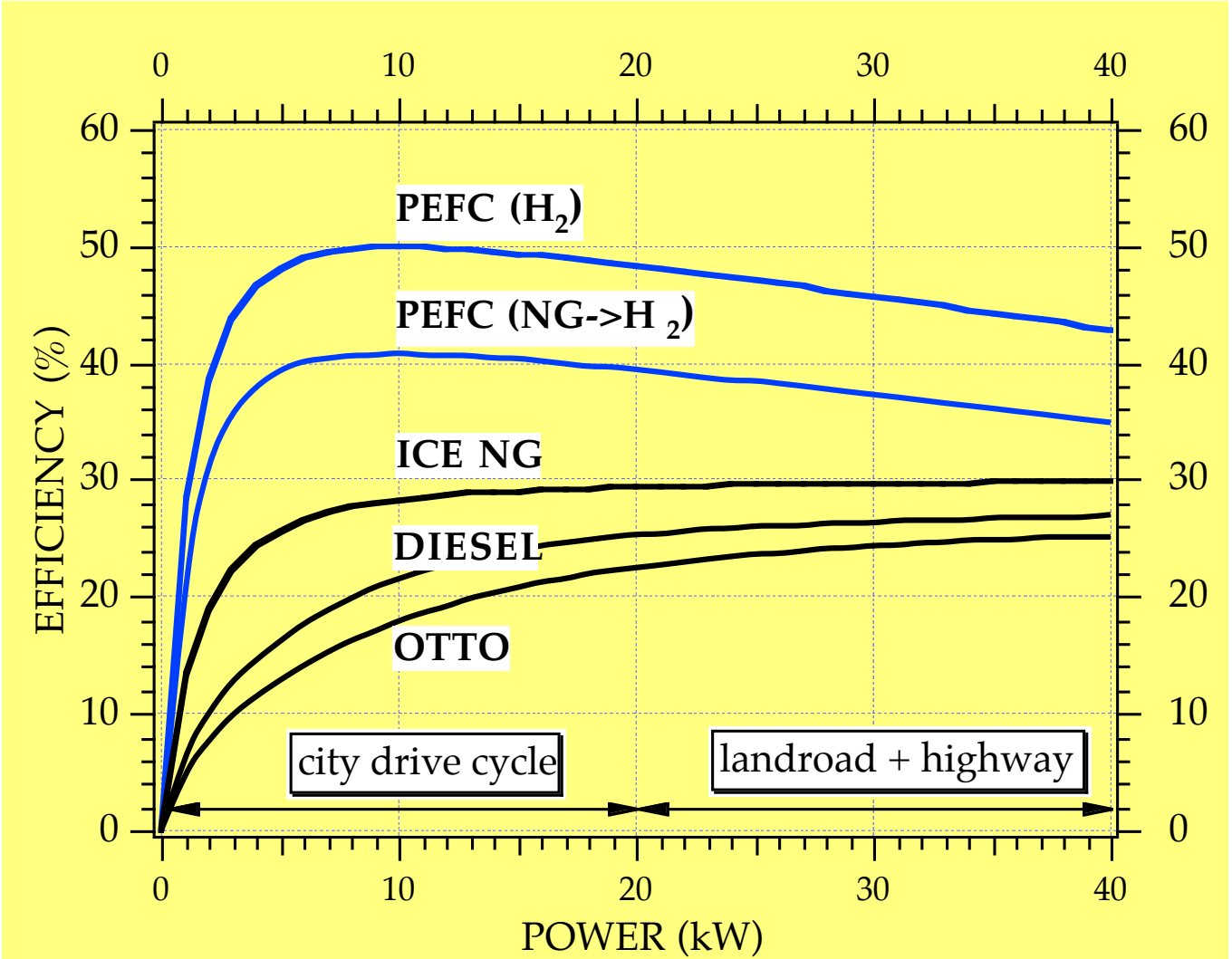
Full cycle efficiency



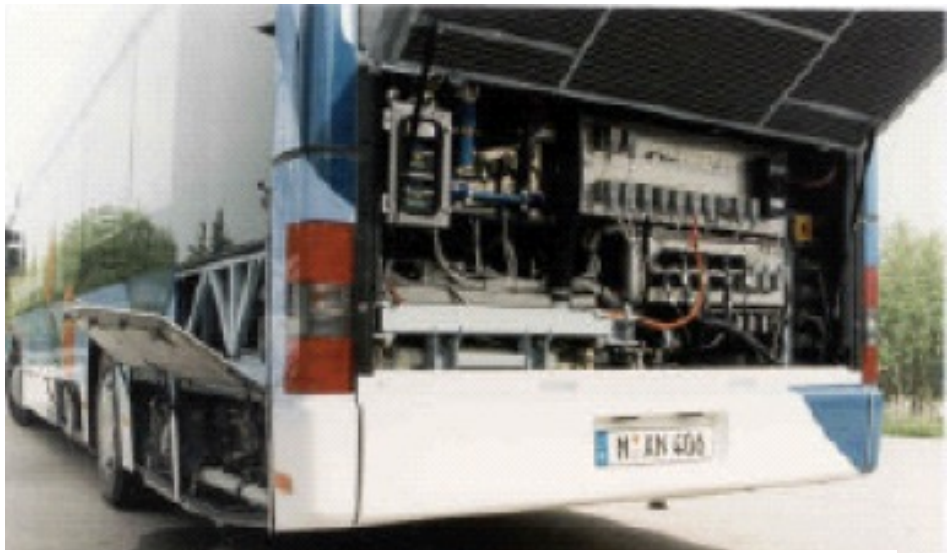
(source : FC Handbook)

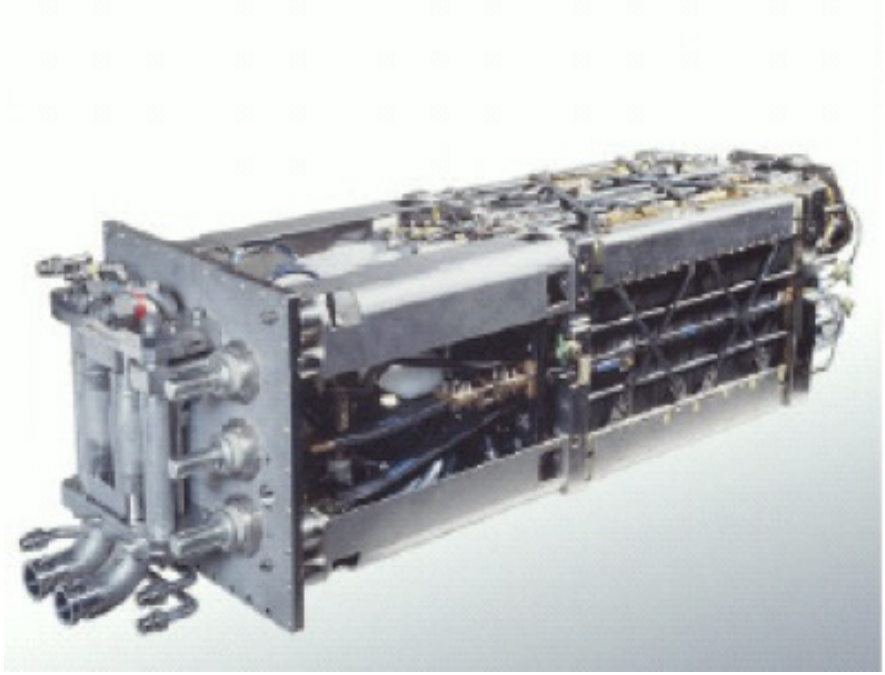
"well-to-wheel" efficiency

Partial load efficiency / Power modulation



Siemens: MAN City Bus

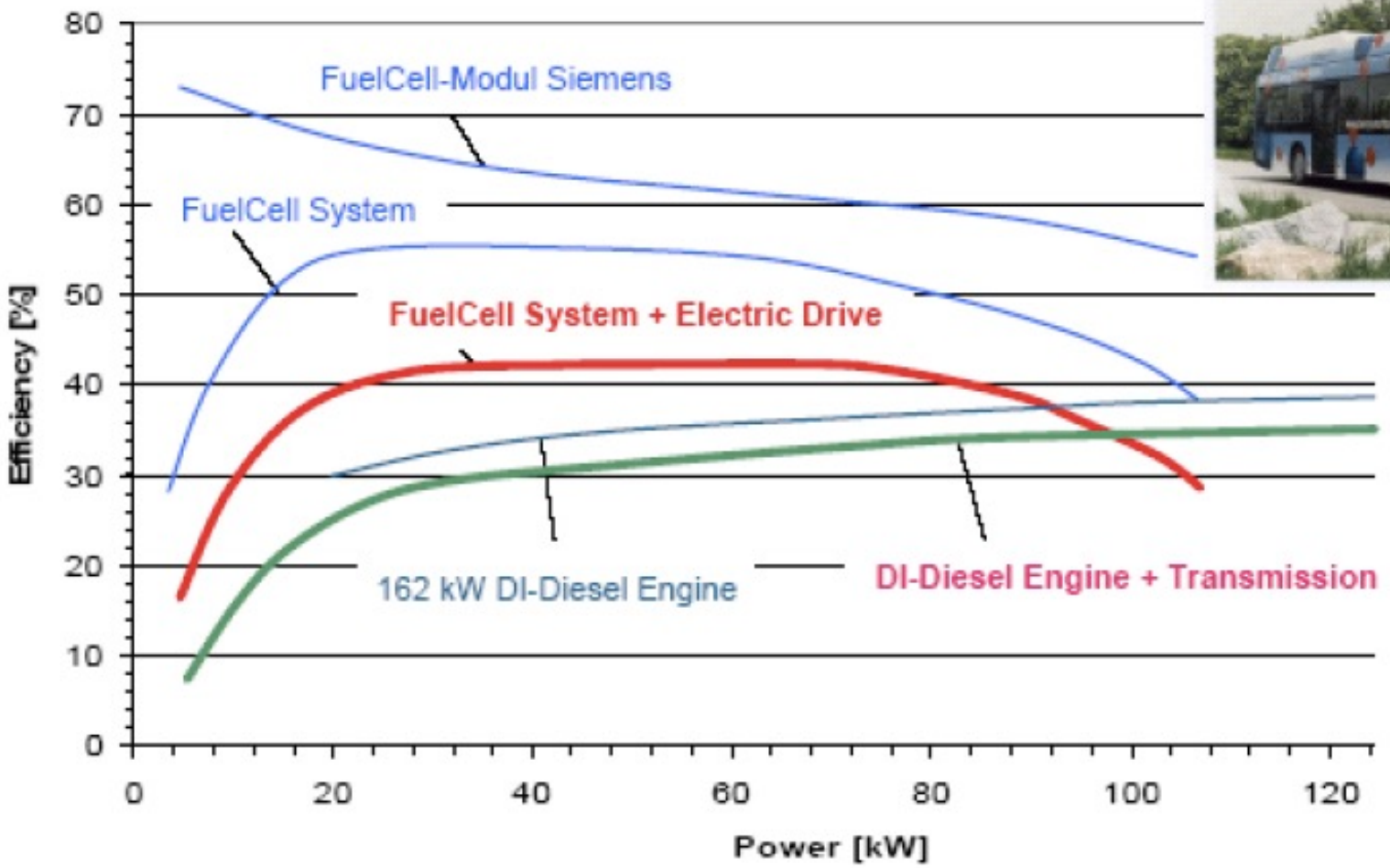




number of cells		320
rated power	≈	120 kW
rated current		560 A
rated voltage	≈	215 V
operating temperature		80° C
dimension	≈	176x53x50 cm^3
weight	≈	900 kg
Rated efficiency (at 20% load)	≈	68 %
(at rated load)	≈	56 %

G.G. Scherer, Lucerne Fuel cell Forum , Fuel Cell Tutorial

Measured efficiency (MA City Bus)



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Portable power: FC vs. batteries

How Do Fuel Cells Compare?

MOTOROLA LABS

Energy Source	Volumetric Energy Density (Watt*Hours per Liter)	Specific Energy Density (Watt*Hours per Kg)
Rechargeable Batteries		
Ni/Cd (cell only)	130	40
Ni/MH (cell only)	200	60
Li-Ion Polymer (cell only)	300	160
Li-Ion (cell only)	310	125
Li-Ion Polymer (pack)	170	Now: 105
Li-Ion (pack)	190	300Wh/kg 100
Fuel Cells		
Methanol (theoretical)	4,780	5,960
Methanol (35% eff)	1,673	2,086
Methanol (35% + FC)	<< 1,673	<< 2,086

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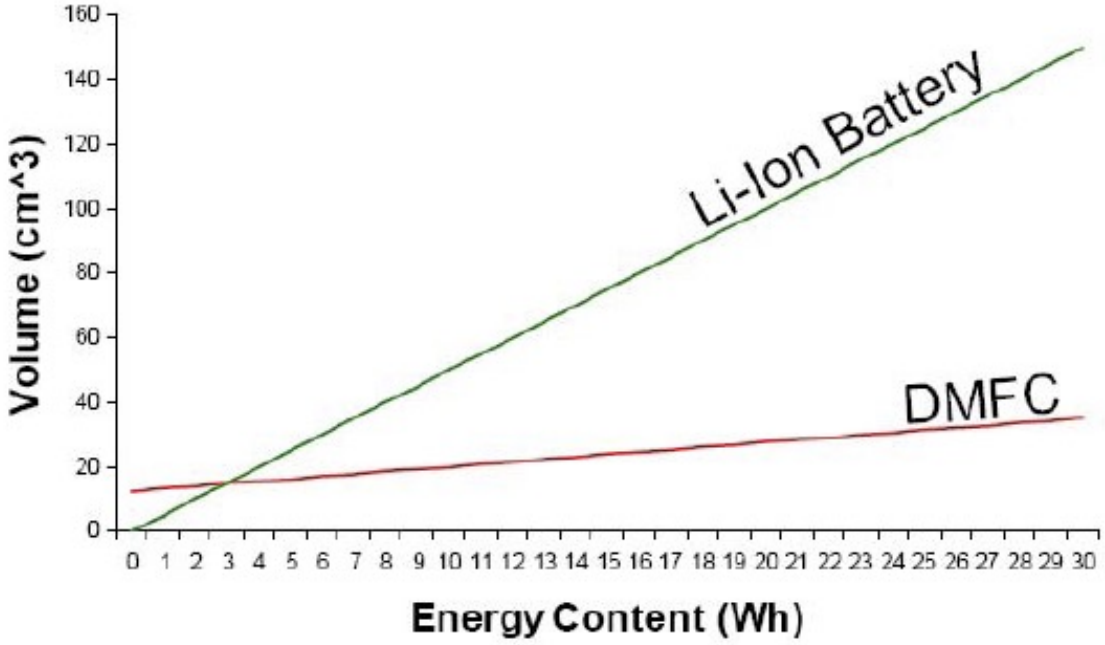
Portable power: density

mechanical technology

Energy Density Comparison For a 1 Watt System



the power behind new energy™

G.G. Scherer, Lucerne Fuel cell Forum , Fuel Cell Tutorial

Stationary residential products (μCHP – few kWe)

- SOFC

HEXIS (SOFC)

Vaillant (SOFC)

Kyocera

CERES Power

CFCL BlueGen

ELCO Acumetrics

- PEMFC

Toshiba Enefarm

Panasonic Enefarm

Baxi Gamma

Sony Enefarm

Hytheon

Bluegen SOFC efficiency, 60% ac @ 1.5 kW_{el}

13000 kWh_{el} / yr
200 L hot water / day

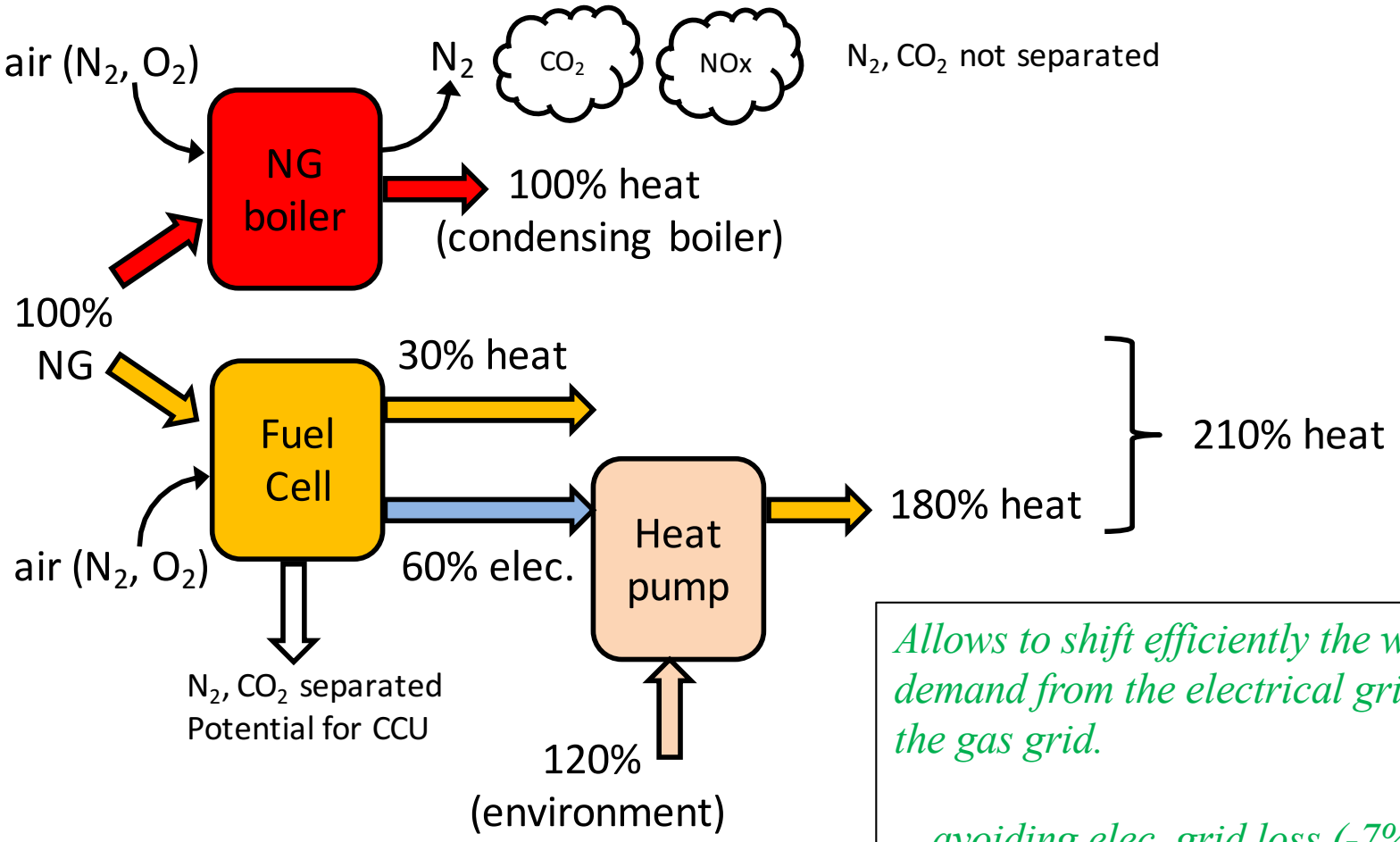
Heat (W) (@30° C return T)

η_{el} (%) (LHV)

(CFCL presentation, SOFC Satellite Seminar, Okinawa (J)

For residential case : fuel cell + heat pump

(heat/electricity need ≈ 3/1)



Allows to shift efficiently the winter demand from the electrical grid to the gas grid.

…avoiding elec. grid loss (-7%), and recovering the heat.

EU Building sector

Figure 1C3 – Historical final energy use in the residential sector in EU27, Norway and Switzerland

Source: Eurostat database

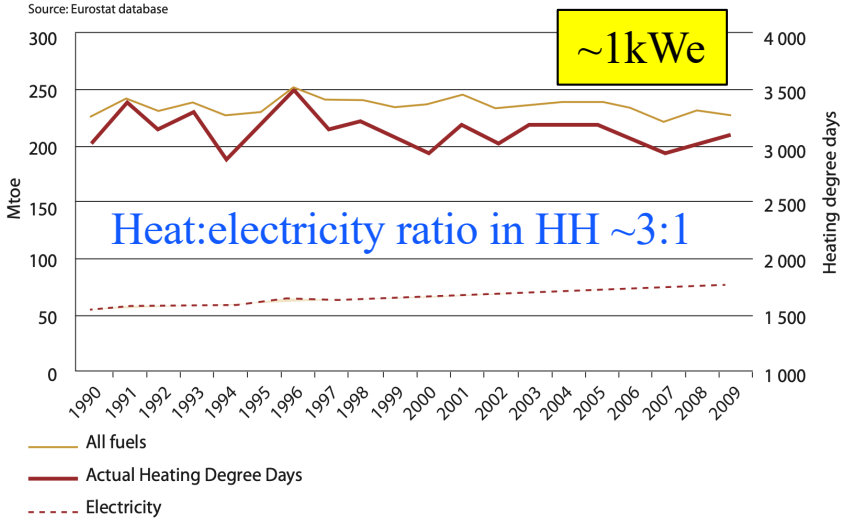
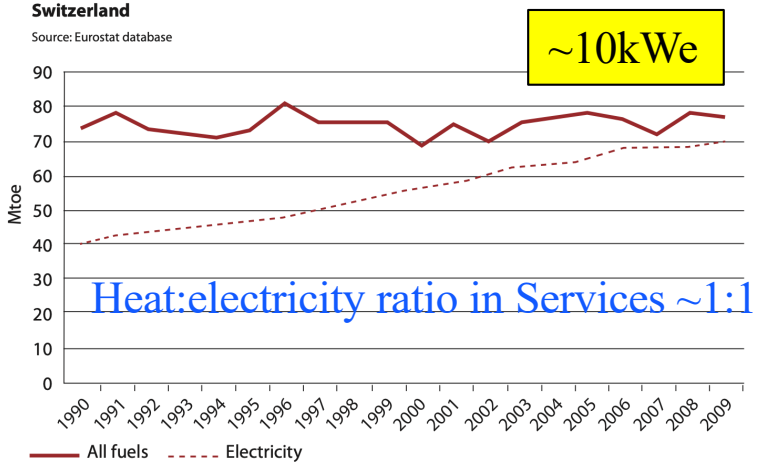


Figure 1C9 – Historical final energy use in the non-residential sector in the EU27, Norway and Switzerland

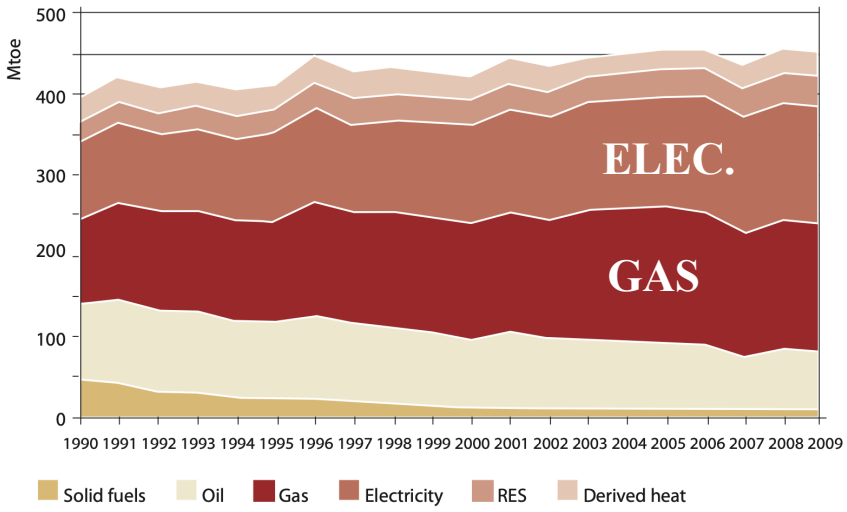
Source: Eurostat database



Source: EUROPE'S BUILDINGS UNDER THE MICROSCOPE
A country-by-country review of the energy performance of buildings
2011, Buildings Performance Institute Europe (BPIE)

Figure 1C1– Historical final energy consumption in the building sector since 1990s for the EU27 Switzerland and Norway

Source: Eurostat database



A clean gas-based decentralised CHP (combined heat & power) technology with high electrical efficiency for use in buildings could be interesting

=> **Fuel cells**

Electricity ↗ 50% in Industry/Services (Switz.)

Demand is often 'only' 10 – 100 kWe per site

				Heating fuel %						Elec.%		
		GAS cons	Share	GAS	Oil	Coal	IW	DH	Wood		kWe/site	Sites
	INDUSTRY SECTOR	36,3	100	30	8	4	9	4	4	43	27	62102
1	**Chemie/Pharma**	11,7	32	44			16			33	337	839
2	**Food**	7,5	21	44	10					46	61	4086
3	**Ferrous metal**	3,3	9	42		5				52	1189	112
4	**Metal devices**	2,9	8	20	14					65	37	8201
5	**Paper/Impression**	2,2	6	21			3	22	7	48	94	1754
6	**Cement/concrete**	1,8	5	13		27	41		7	12	1268	41
7	**Other minerals**	1,7	5	43	8	7				42	53	963
8	**Other industries**	1,4	4	12	11				19	57	26	8726
9	**Non-ferrous metal**	1,4	4	49						48	395	109
10	**Machines**	1,0	3	19	20			2		60	51	1864
11	**Building construction**	0,7	2	18	43					39	1,4	34148
12	**Textiles**	0,6	2	43	20					37	14	1259
		PJ	%	36	9,7	4,5	11,0	5,0	4,4	%	kWe	

				Heating fuel %						Elec.%		
		GAS cons	Share	GAS	Oil	Coal	IW	DH	Wood		kWe/site	Sites
	SERVICE SECTOR	25,1	100	22	20	0	0	4	1	53	6,4	298861
1	**All other services**	7,6	30	23	16			4	1	57	5	126337
2	**Hospitals/EMS/Health**	5,1	20	31	17			8	2	43	6	36262
3	**Schools**	4,1	16	33	23			5	1	40	9	17718
4	**Trade**	3,3	13	13	23					63	7	69932
5	**Hotels/restaurants**	2,2	9	15	27					57	10	26030
6	**Administration**	2,1	8	31	17			7	2	42	10	8699
7	**Banks/insurances**	0,9	4	20	15			5		60	7	13883
		PJ	%	25	22			4	1	%	kWe	

(adapted from: Energieverbrauch in der Industrie und im Dienstsektor, July 2018)

Gas = main heating fuel in the service and esp. industry sector

Elec. demand = often 50% and even 60%

Power size = ~10 kWe in service sector and mostly <100 kWe in industry sector

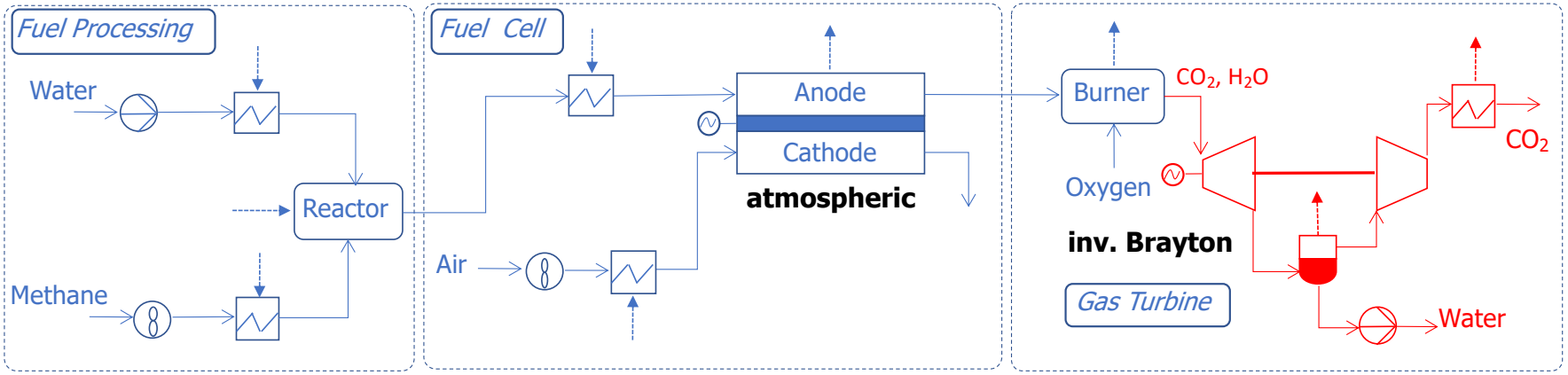
⇩

Efficient gas-based CHP is interesting

SOFC + microgasturbine

LABORATORY FOR APPLIED MECHANICAL DESIGN

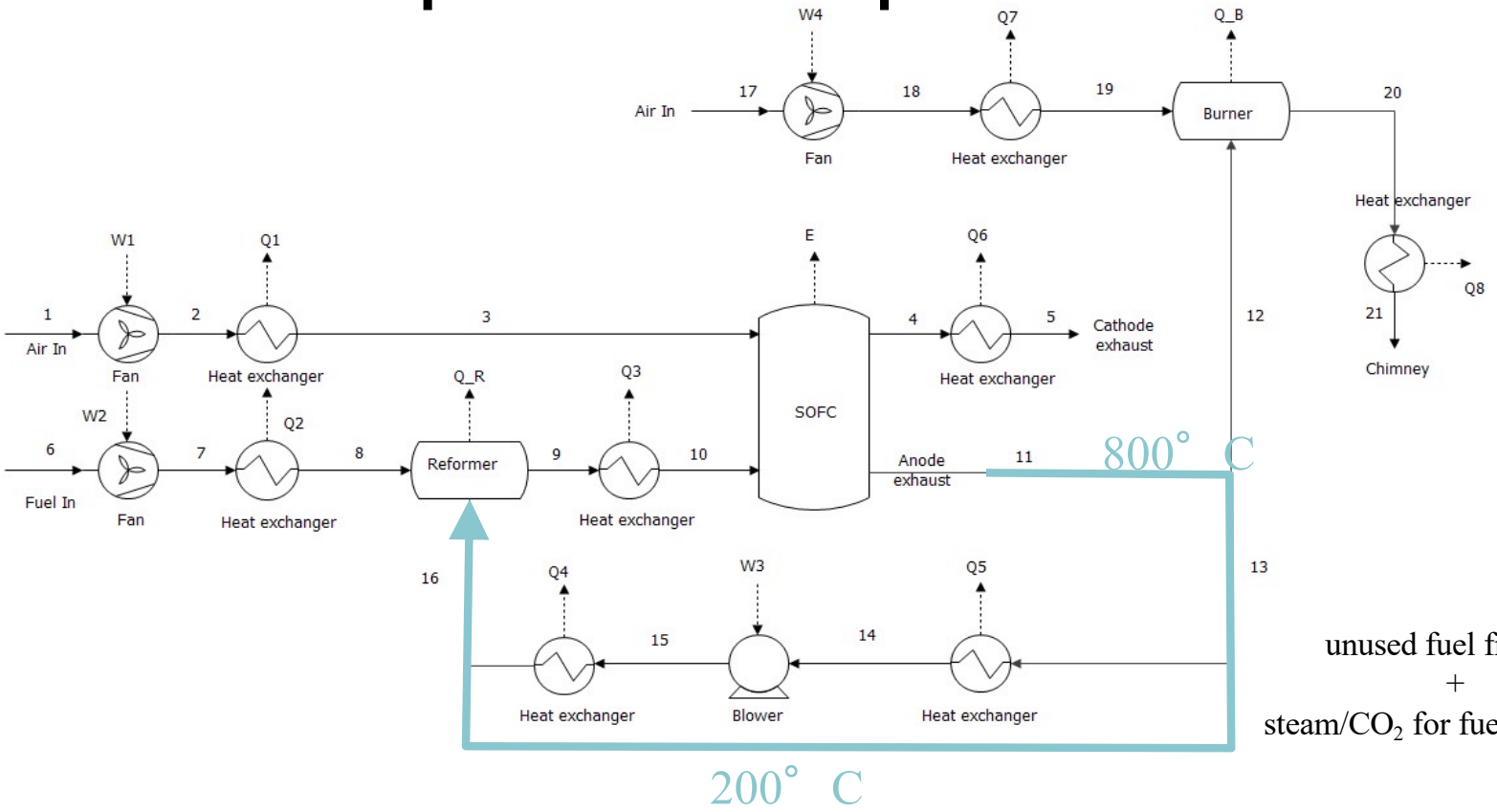
Prof Jürg Schiffmann



CO_2 separation at exhaust

gaz nat

Anode outlet gas recirculation with high speed microcompressor

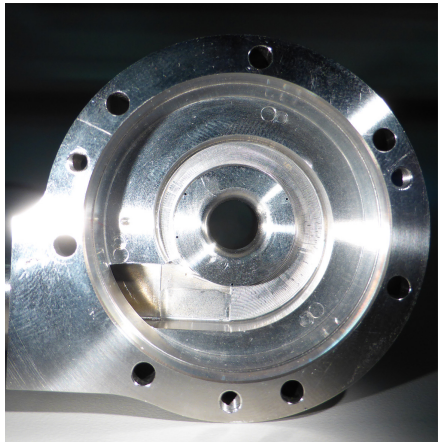


unused fuel fraction
+
steam/CO_2 for fuel reforming

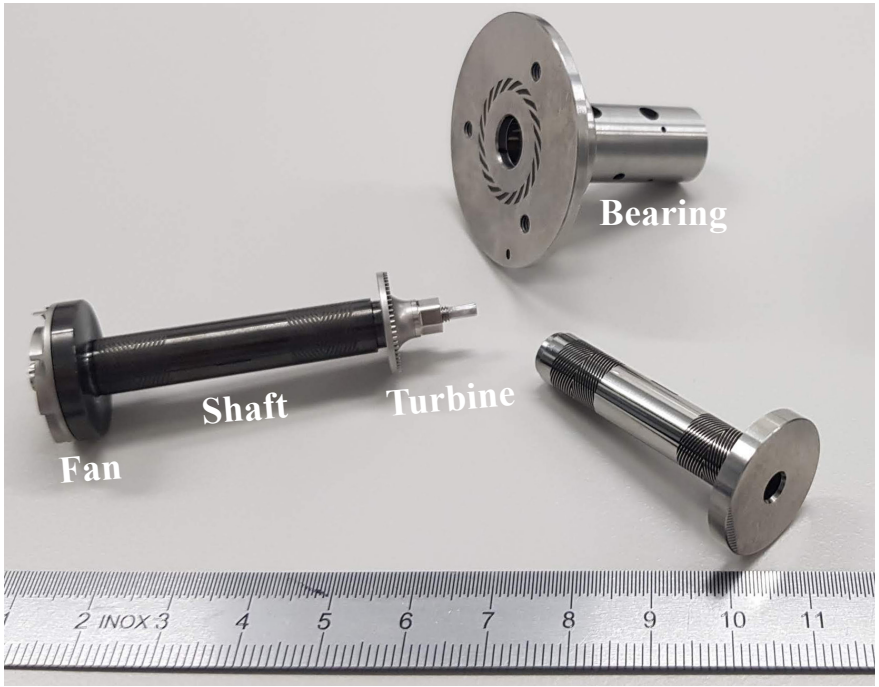
2022Feb10

Components design

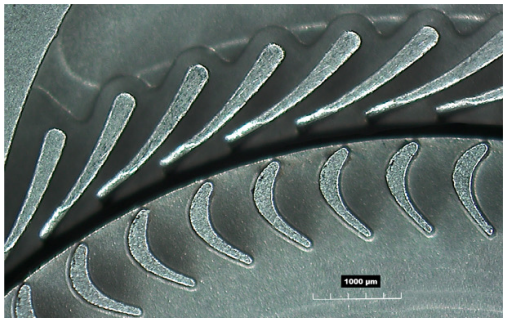
FAN



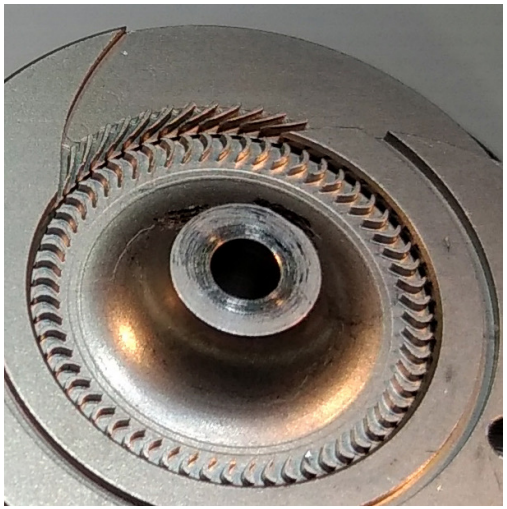
BEARING, SHAFT



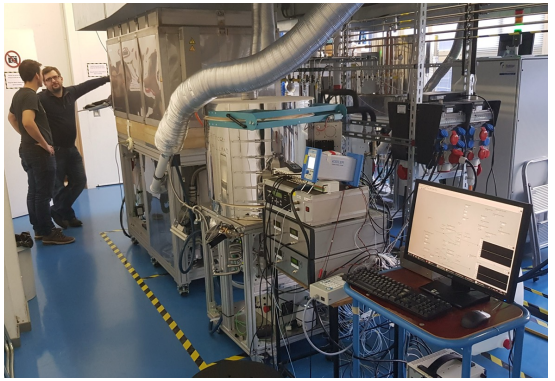
TURBINE



Digitally mirrored!



Experimental results



EPFL

SOFC (5.4 kW_{el} load) without AOR	
Gross efficiency (LHV, DC)	52 %
Global fuel utilization (FU)	75 %
Local fuel utilization (FU)	75 %
Recirculation rate	0

SOFC (5.9 kW_{el} load) with AOR	
Gross efficiency (LHV, DC)	57 %
Global fuel utilization (FU)	75 %
Local fuel utilization (FU)	61 %
Recirculation rate	48 %

Stack: 6.4 kW_{el} (full load) with AOR	
Gross efficiency (LHV, DC)	62 %
Global fuel utilization (FU)	85 %
Recirculation rate	48 %

Stack: 4.5 kW_{el} (partial load) with AOR	
Gross efficiency (LHV, DC)	66 %
Global fuel utilization (FU)	85 %
Recirculation rate	46 %

Fan Turbine Unit	
Shaft rotational speed	166 krpm
Fan pressure rise fan	65 mbar
Fan mass flow rate fan	2.5 kgh^{-1}
Turbine expansion ratio	1.8
Turbine inlet mass flow rate	2.0 kgh^{-1}

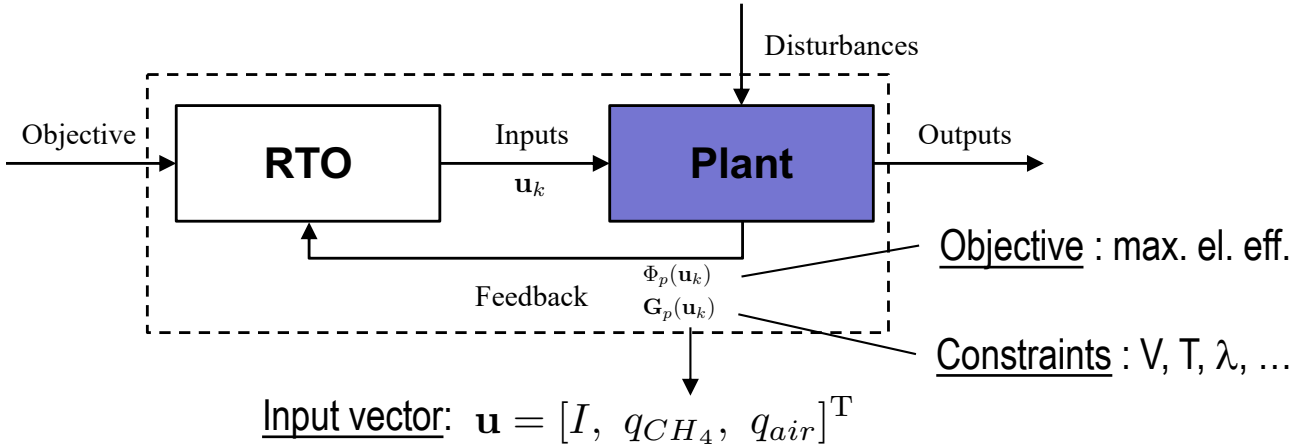
Fan Turbine Unit	
Shaft rotational speed	128 krpm
Fan pressure rise	39 mbar
Fan mass flow rate	1.7 kgh^{-1}
Turbine expansion ratio	1.6
Turbine inlet mass flow rate	1.5 kgh^{-1}

GEM

Real-Time Optimization (RTO) of a FC system

Use process measurements to improve 'plant' performance in the presence of

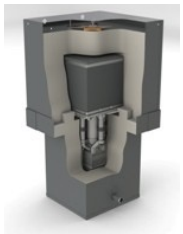
- Constraints
- Disturbances
- Plant-model mismatch



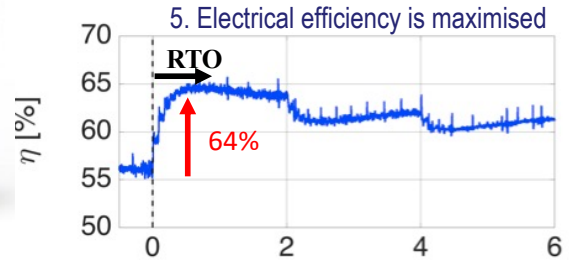
Real-time optimisation (RTO) with constraint adaptation – experimental results on a commercial SOFC system

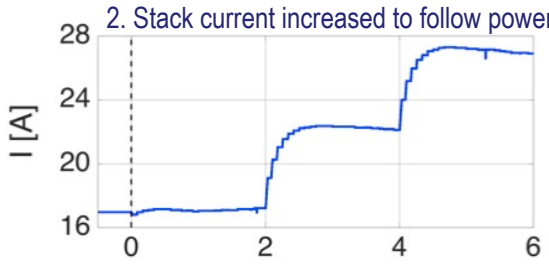
RTO Control of a 1.5 kWe BlueGen μCHP

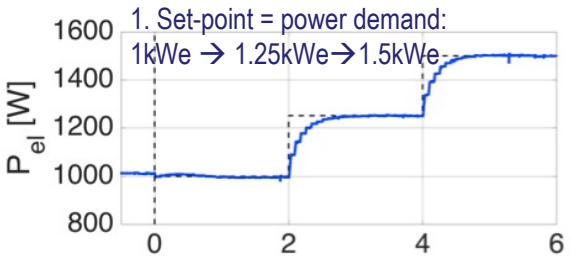
A 'crude' model is good enough !

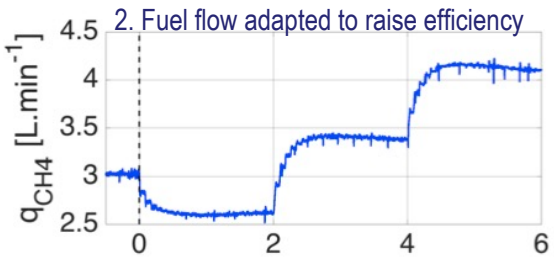


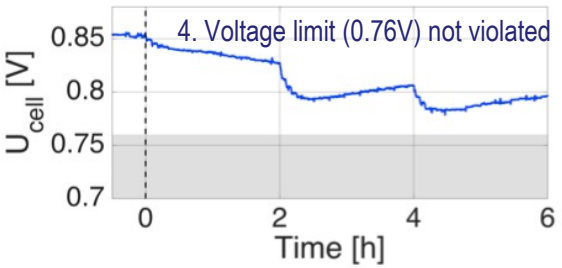
SOLID POWER

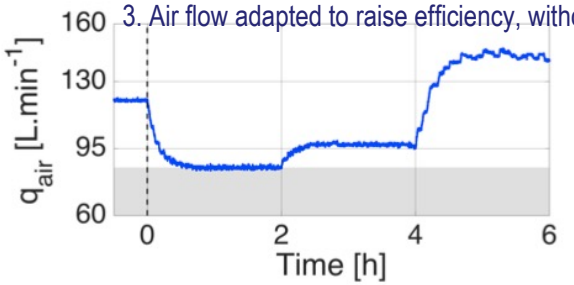












Biogas => SOFC

Waste2Watts

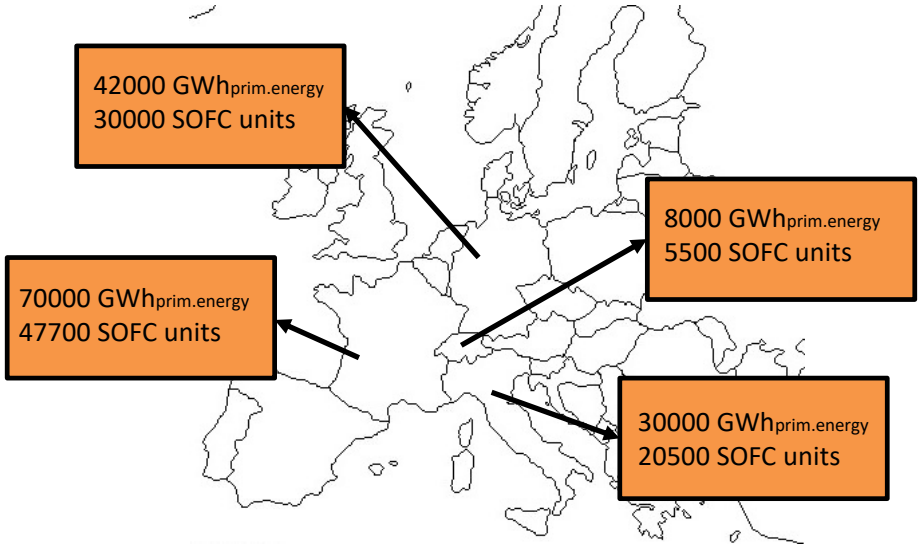
EPFL

Biogas potential

For 🇩🇪 + 🇫🇷 + 🇮🇹 + 🇨🇭 :

>100’000 sites of 50 kWe

from agrowaste presently not used, and assuming only ½ of total potential is exploited



- For CH (5500 units of 50 kWe):
- 275 MWe * 8000 h => 2.2 TWhe
- = **4% of electricity**
- = same as waste incineration plants (2.2 TWhe from 13 TWh solid wastes, elec. efficiency <20%)

NAUTILUS

https://www.nautilus-project.eu/news

60 kWe SOFC
>60% elec. eff. on CH_4
Emissions measured on site:
99% réduction in NOx, particles (vs. ICE), 'no-slip' CH_4

http://www.demosofc.eu/

DEMOSOFC
FCH2-JU PROJECT

convion

Biogas WWTP Torino (IT)
2 x **50 kWe** SOFC (17'300 h test)
Simple cleaning (25 ppm H_2S, 3 ppm Si)
49% elec. eff. on biogas
No NOx, CH_4, PM, 10x less CO
Potential (EU) : 4000 WWTP of <80 kWe

Annex:

Hybrid SOFC - μturbine

a combined system efficiency study