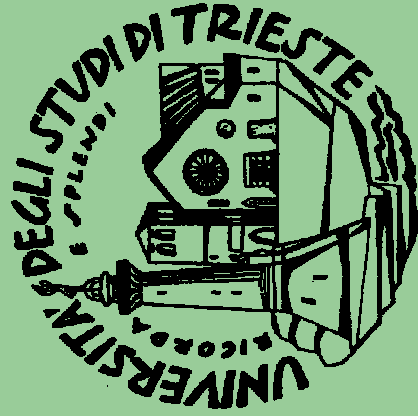


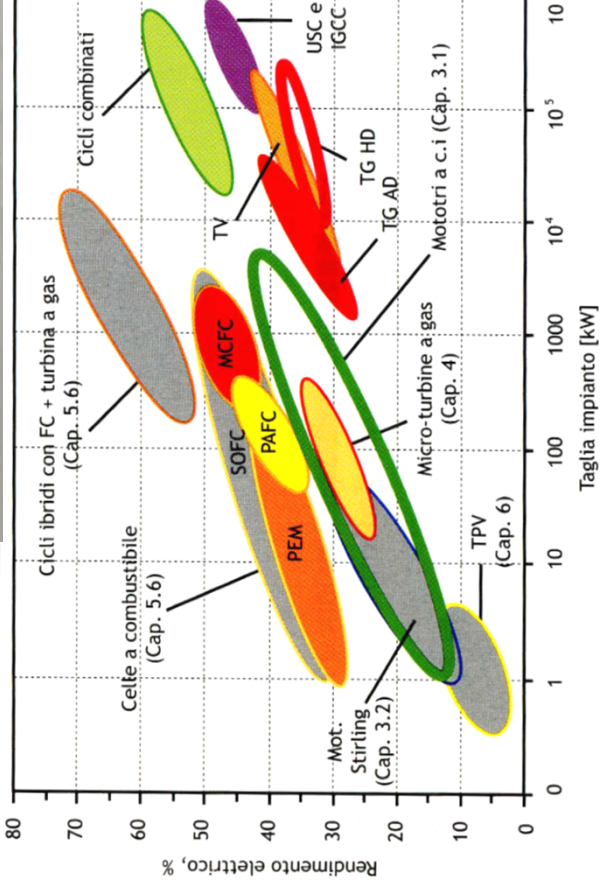
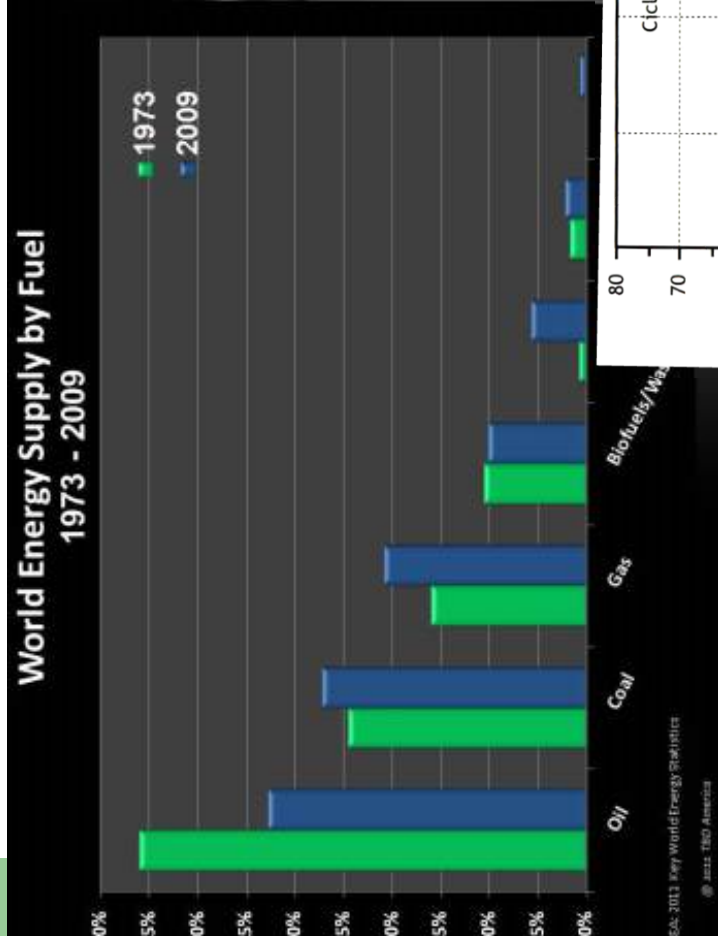
Fuel cells: Choice, Design and Application



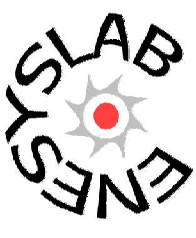
Rodolfo Taccani
Energy System Laboratory
Mechanical Engineering
Department
University of Trieste
- Italy -

Aprile 2019 – IEE

Aim of the presentation



Topics



- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusions

Objectives (today and tomorrow)

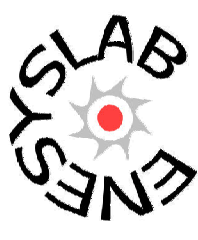
Overview on power generation (with some figures on energy demand and power conversion efficiency)

Overview on microcogeneration and in particular on fuel cells

Possible integration with renewable energy resources

EneSys Lab

Energy System Lab

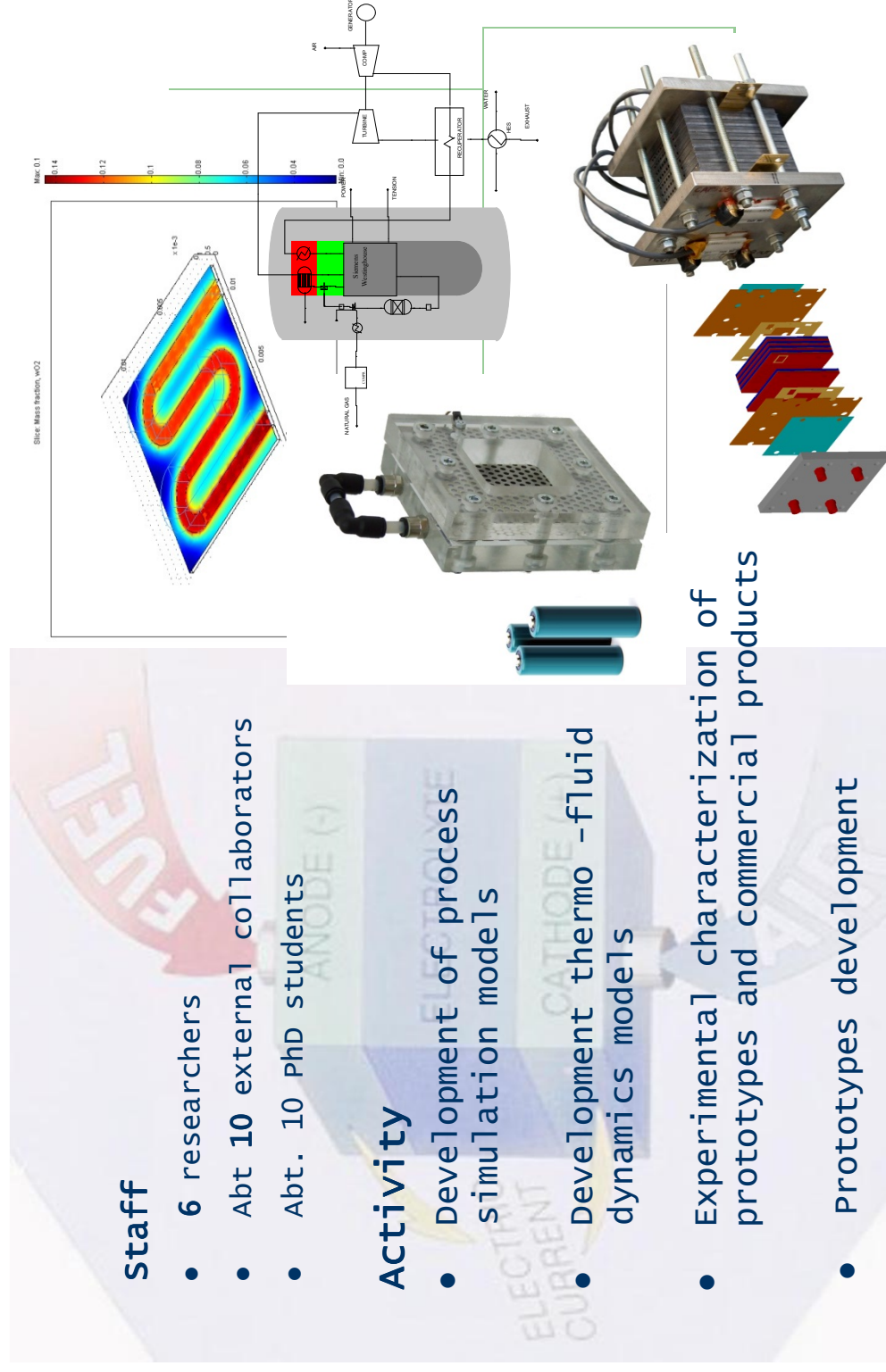


Staff

- 6 researchers
- Abt 10 external collaborators
- Abt. 10 PhD students

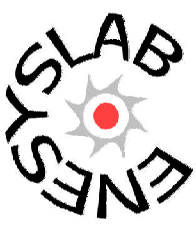
Activity

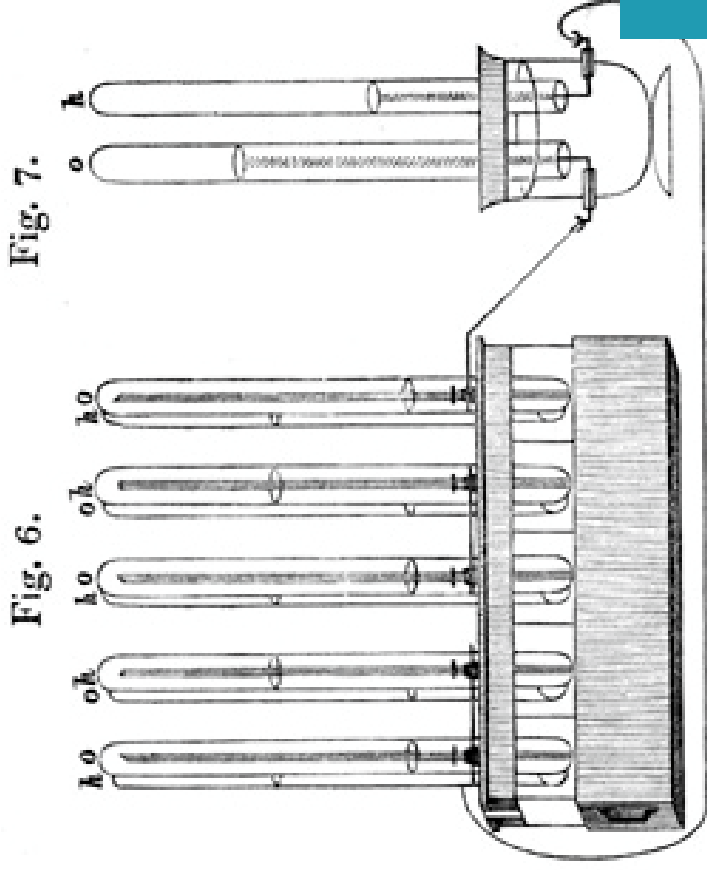
- Development of process simulation models
- Development thermo -fluid dynamics models
- Experimental characterization of prototypes and commercial products
- Prototypes development



Topics

- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusion





Fuel cells

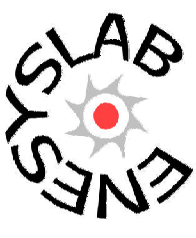
...yesterday

Sir Grove 1842

...today

Ballard Power System



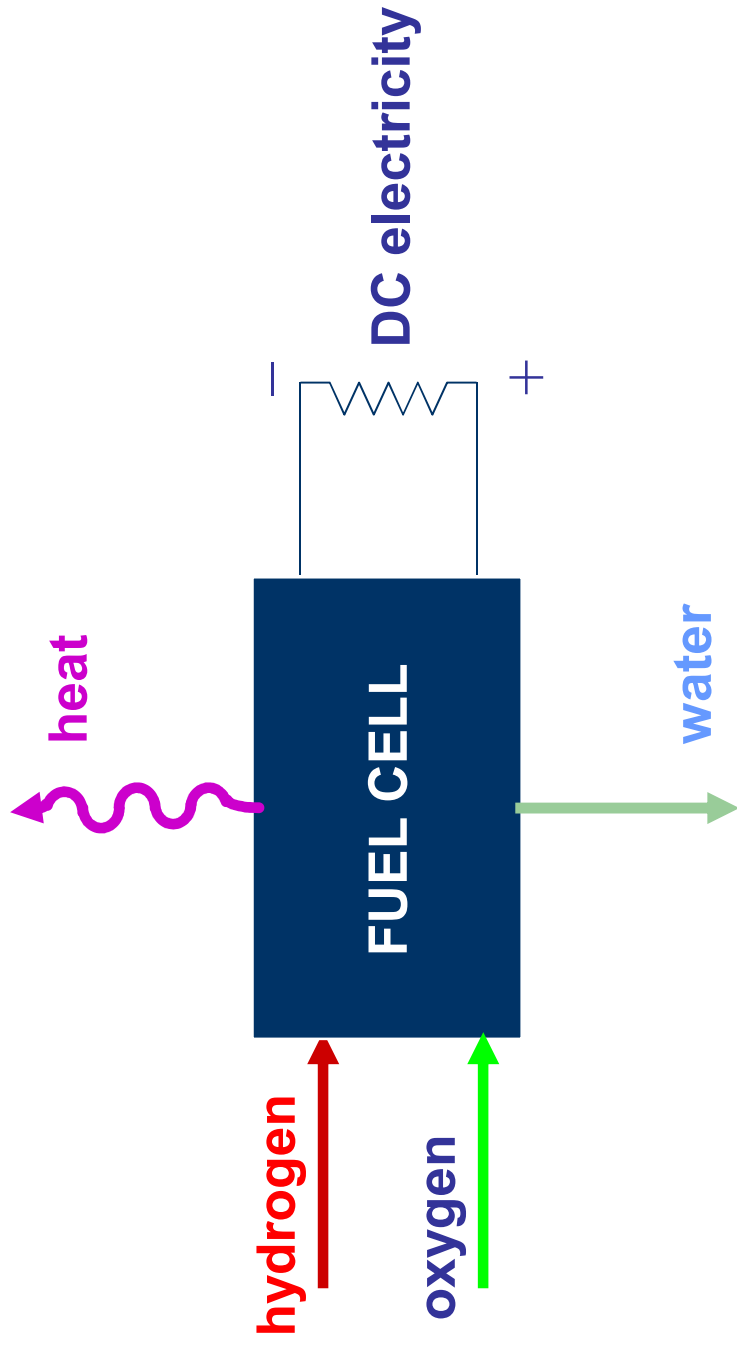


What is fuel cell?

Fuel cell is an electrochemical energy converter.

It converts chemical energy of fuel (H_2) directly into electricity.

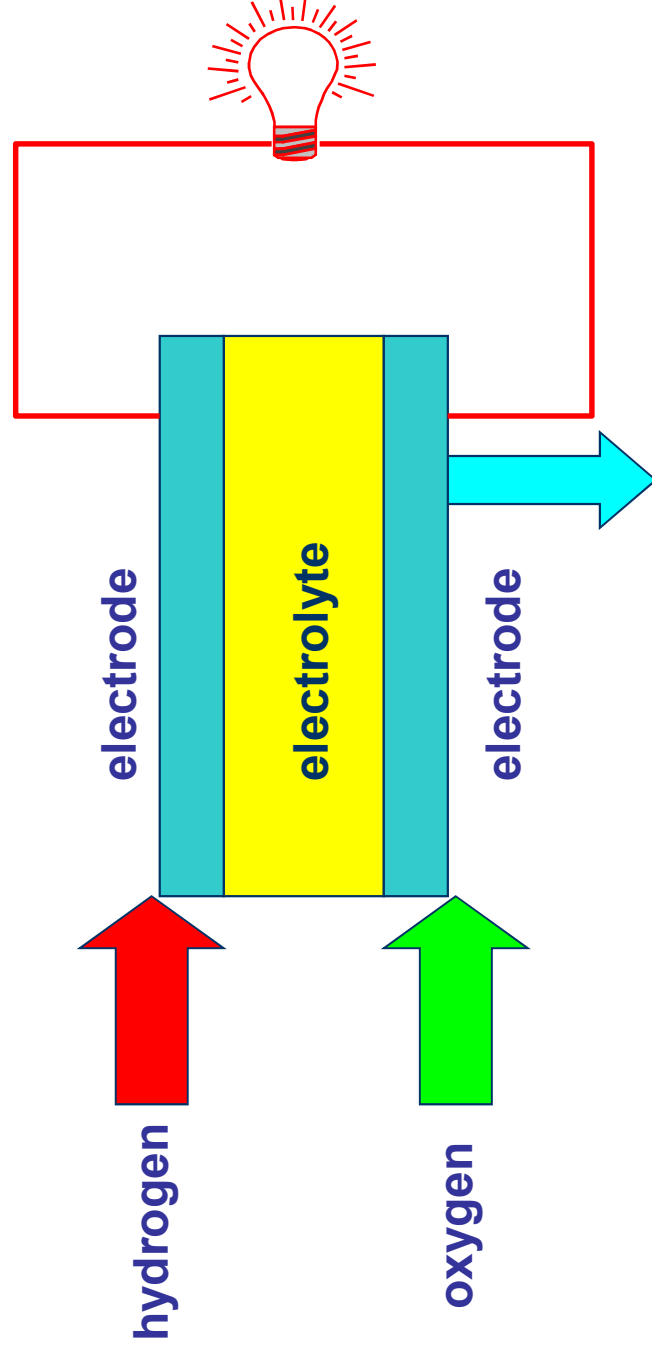
Fuel cell is like a battery but with constant fuel and oxidant supply.



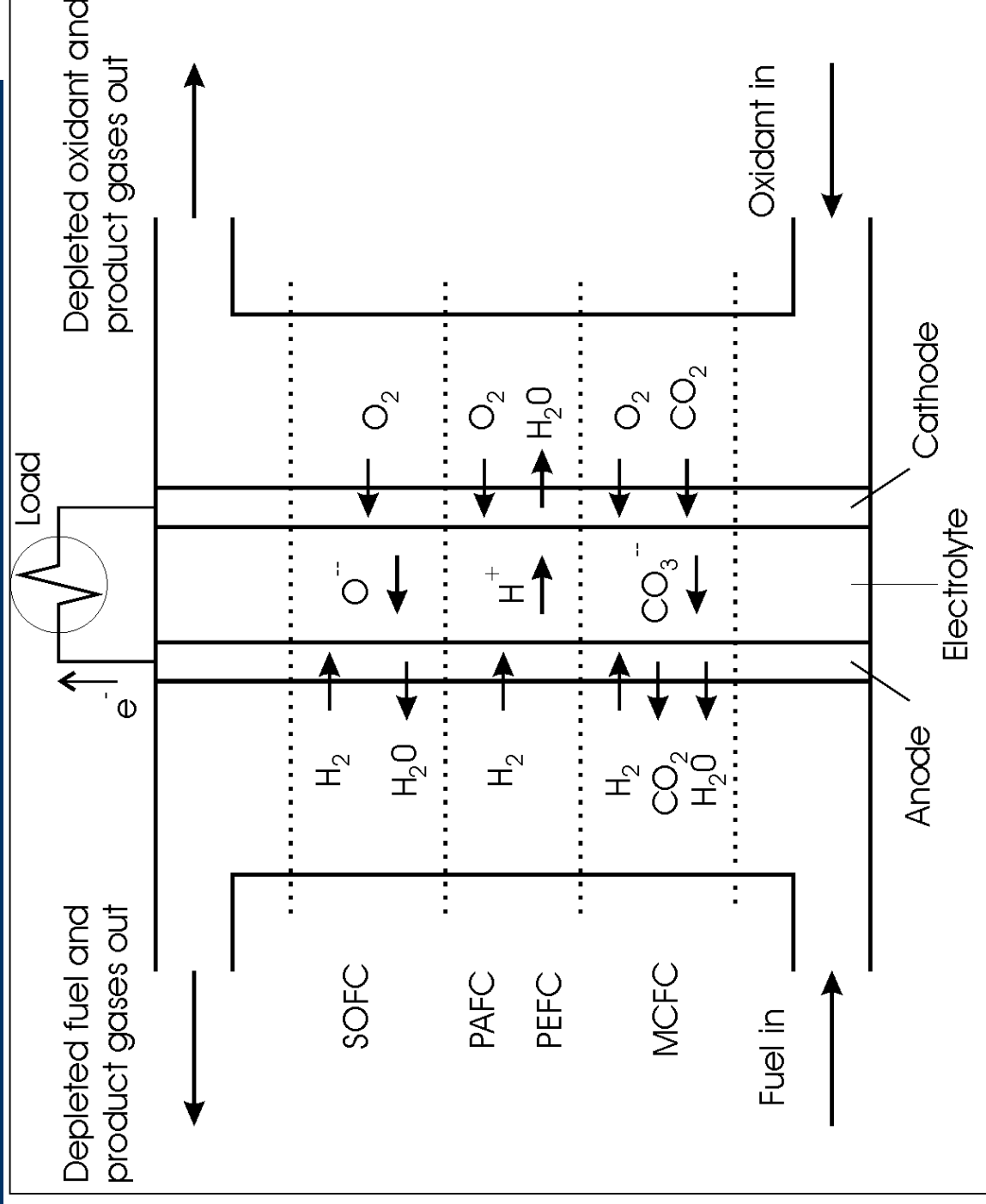
What is fuel cell?

Fuel cell is an electrochemical energy converter.

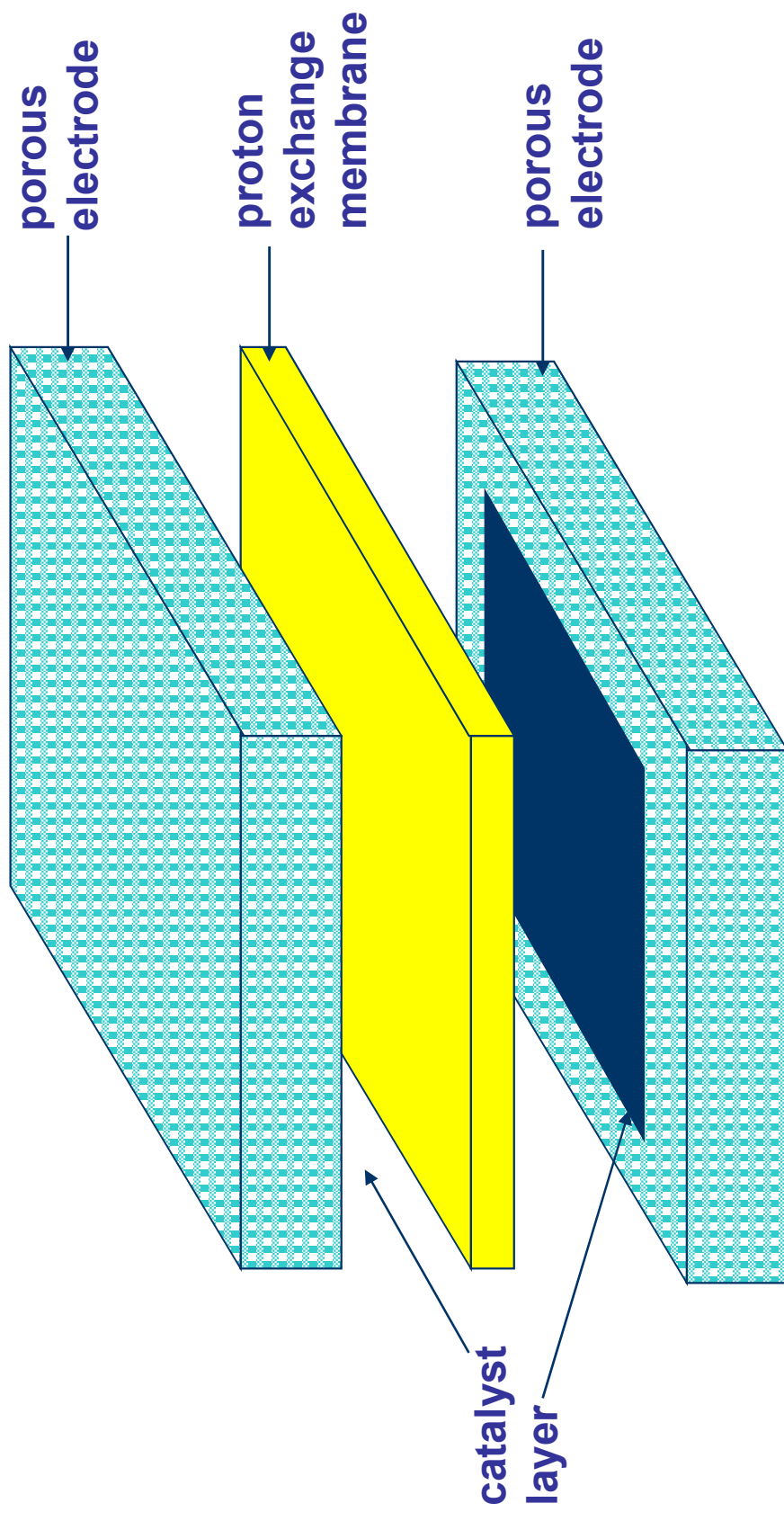
It converts chemical energy of fuel (H_2) directly into electricity.



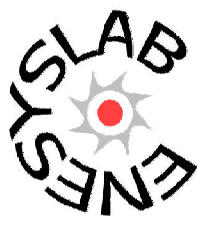
Fuel Cell Basic Principles



PEM Fuel Cell Basic Components

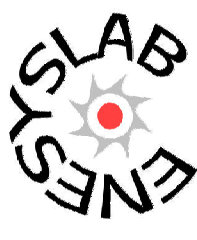


FUEL CELL TECHNOLOGIES

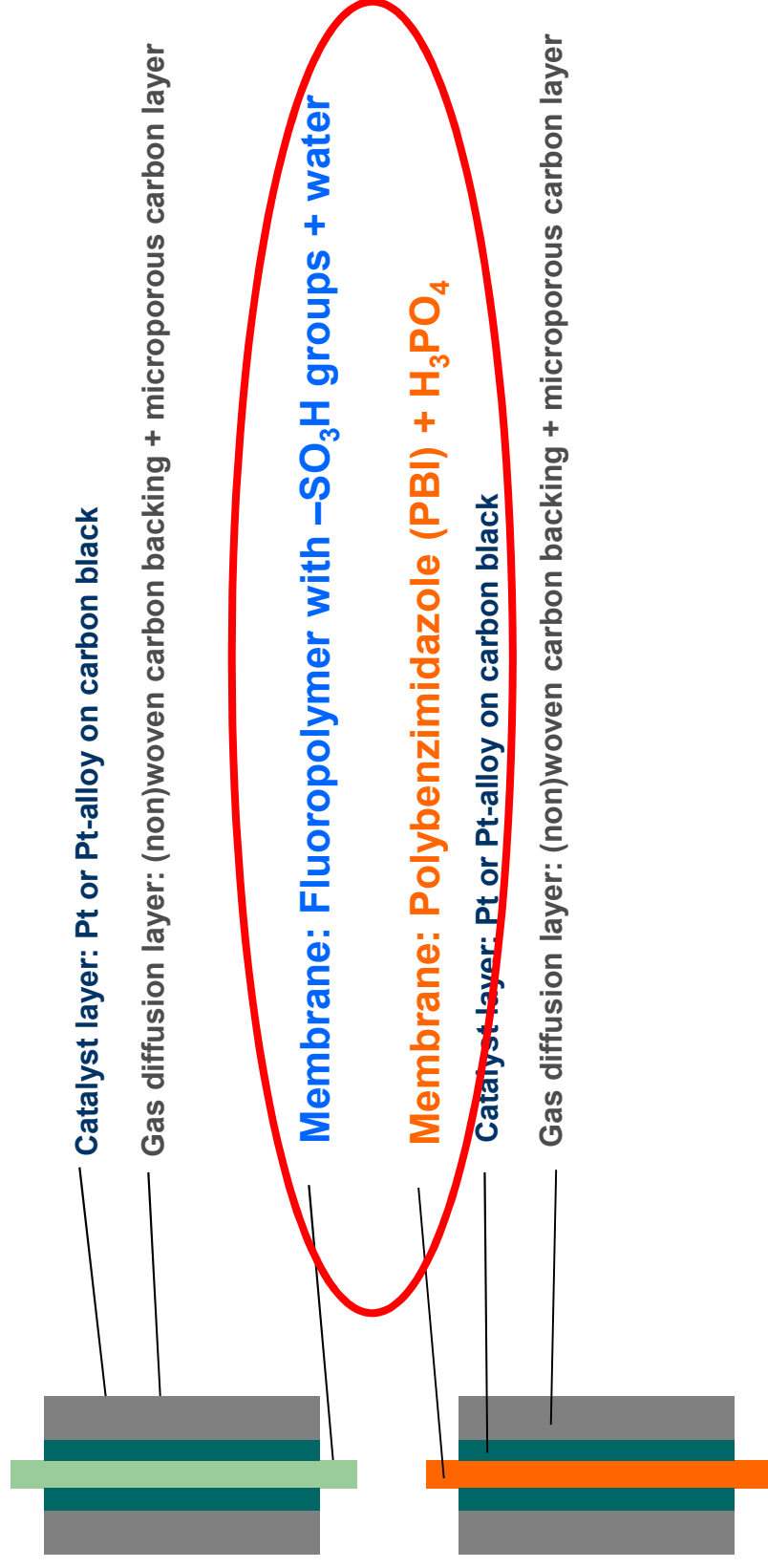


	PEMFC	AFC	PAFC	MCFC	SOFC	DMFC
Electrolyte	Polymer Membrane	KOH	Phosphoric Acid	Molten Carbonate	Solid Oxide	Polymer Membrane
Temp. (°C)	70-80	80-100	200-220	600-650	800-1000	70-120
Corr.Den.	H	H	M	M	H	L
Reformer	External	External	External	Ext/Int	Ext/Int	Internal
Toll. CO ₂	Yes	No	Yes	Yes	Yes	Si
Toll. CO	No	No	No	Yes	Yes	Si
Applications	Space. Transp. Portable	Space Transp. Portable	Dist. Generation	Generaz. MW	Gen. Distrib.-MW	Transport.
FC Efficiency H ₂ LHV	50%	50%	50%	60%	60%	N.D.
PEMFC: Proton Exchange Membrane Fuel Cell			MCFC: Molten Carbonate Fuel Cell			
AFC: Alkaline Fuel Cell			SOFC: Solid Oxide Fuel Cell			
PAFC: Phosphoric Acid Fuel Cell			DMFC: Direct Methanol Fuel Cell			

High Temperature PEM

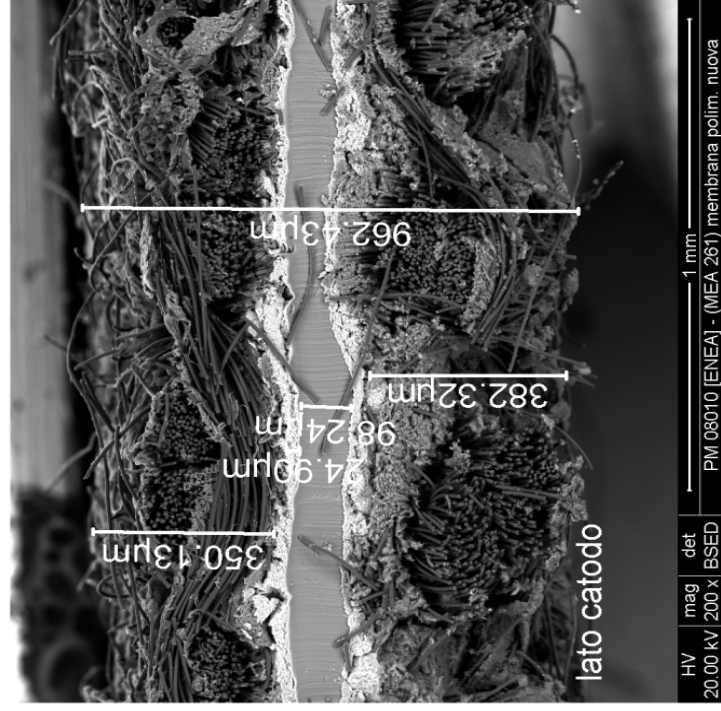
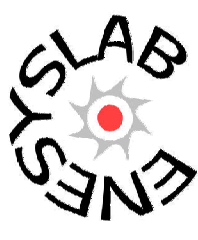


Low temperature PEM technology:

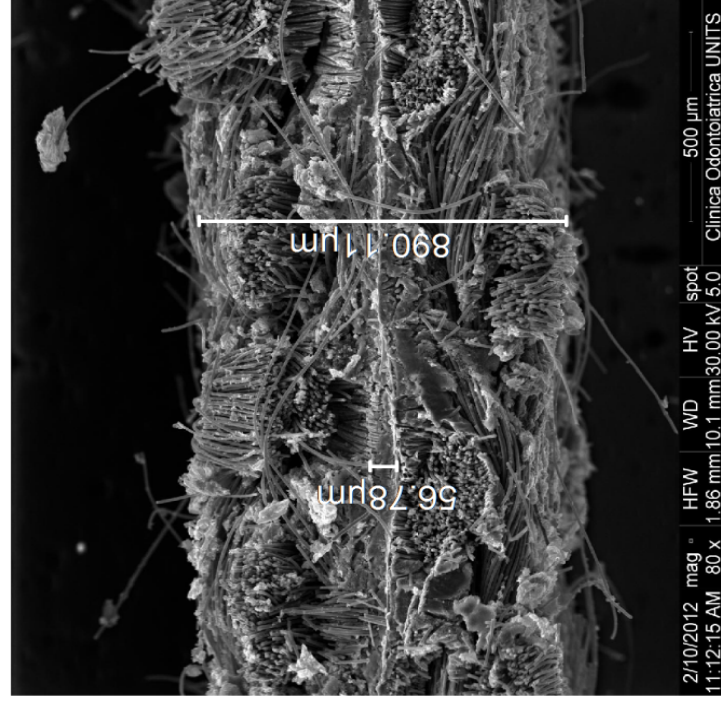


High temperature PEM technology:

MEA deformation



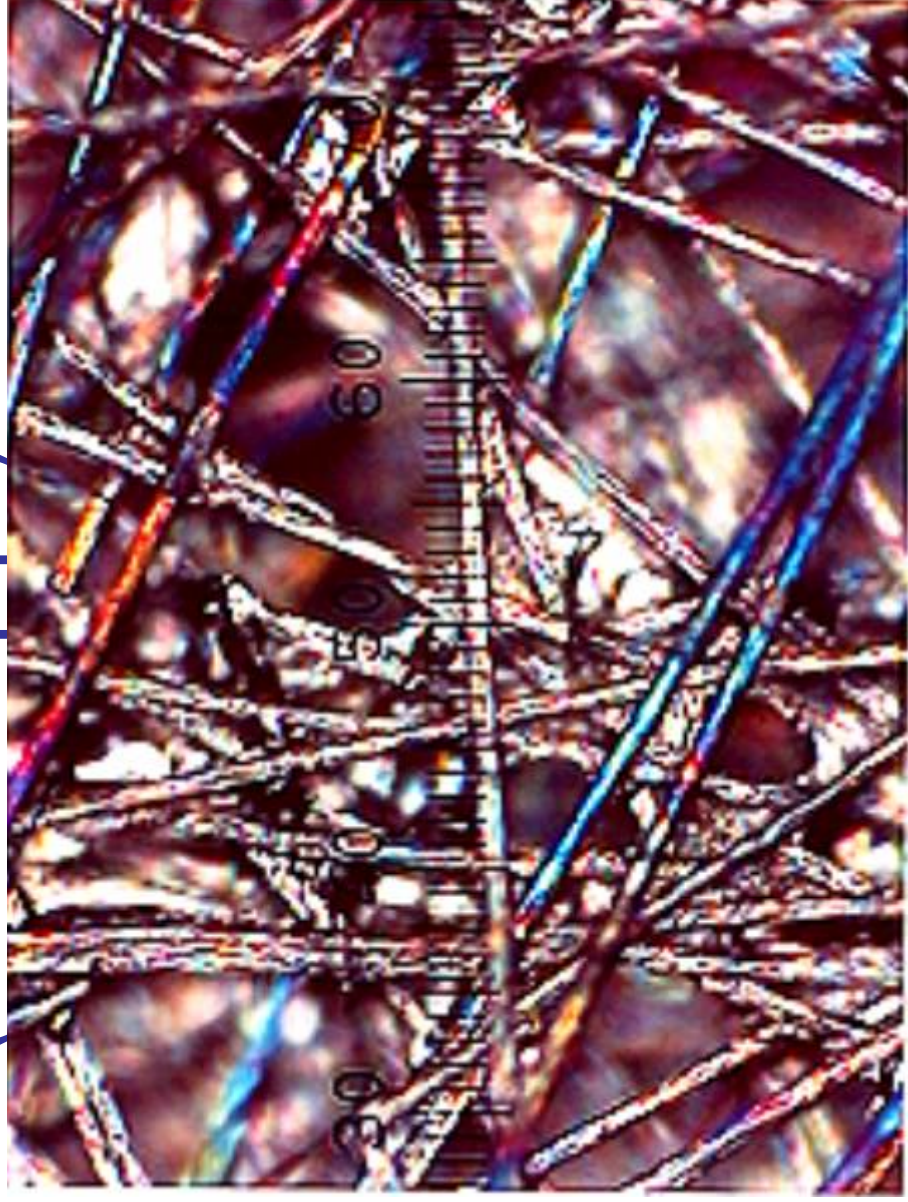
New MEA



Used MEA

FUEL CELL COMPONENTS - GDL

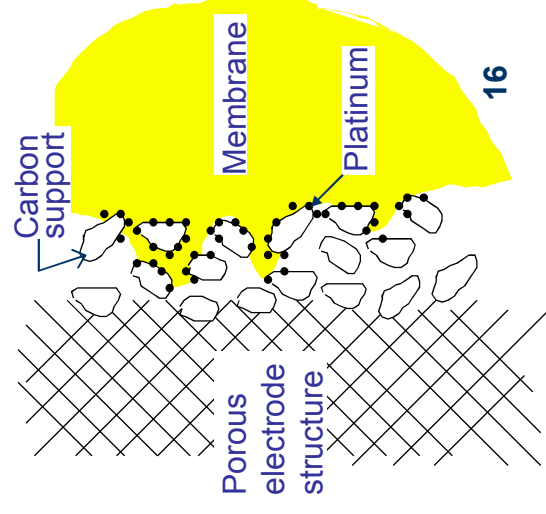
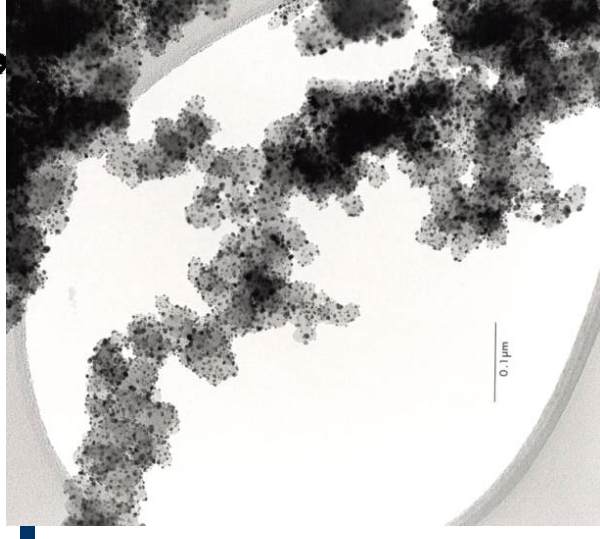
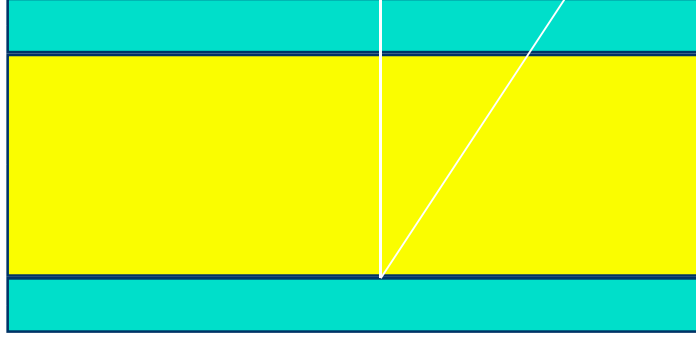
Porous electrode structure
Gas diffusion layer surface
(carbon fiber paper)



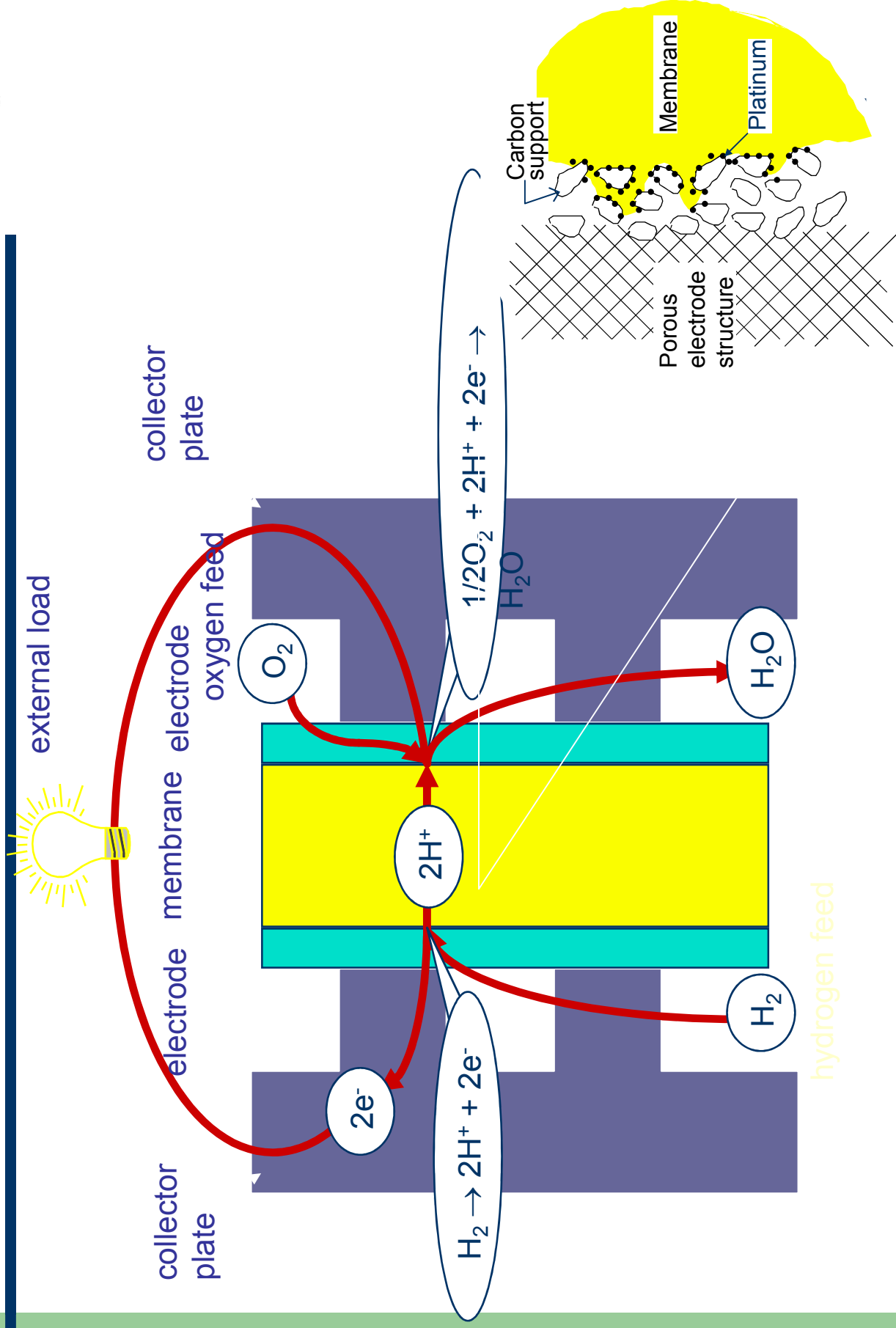
80 μm

PEM Fuel Cell: How does it work?

electrode membrane electrode

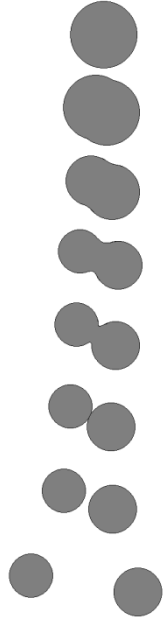


How does it work?

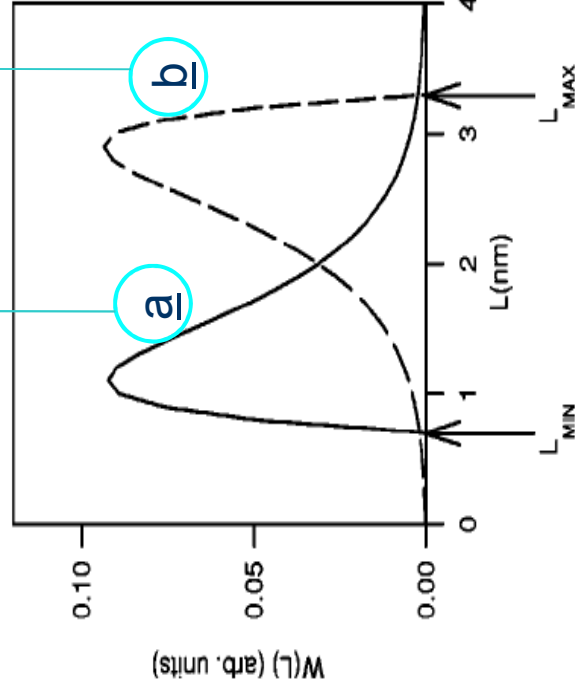
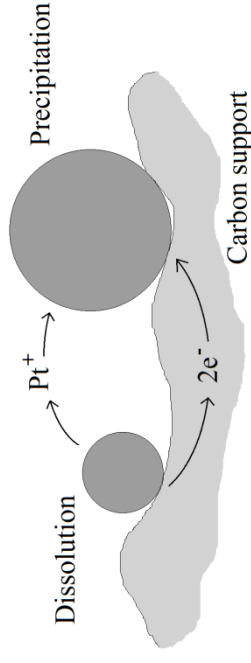


Degradation: catalyst particles growing

Coalescence



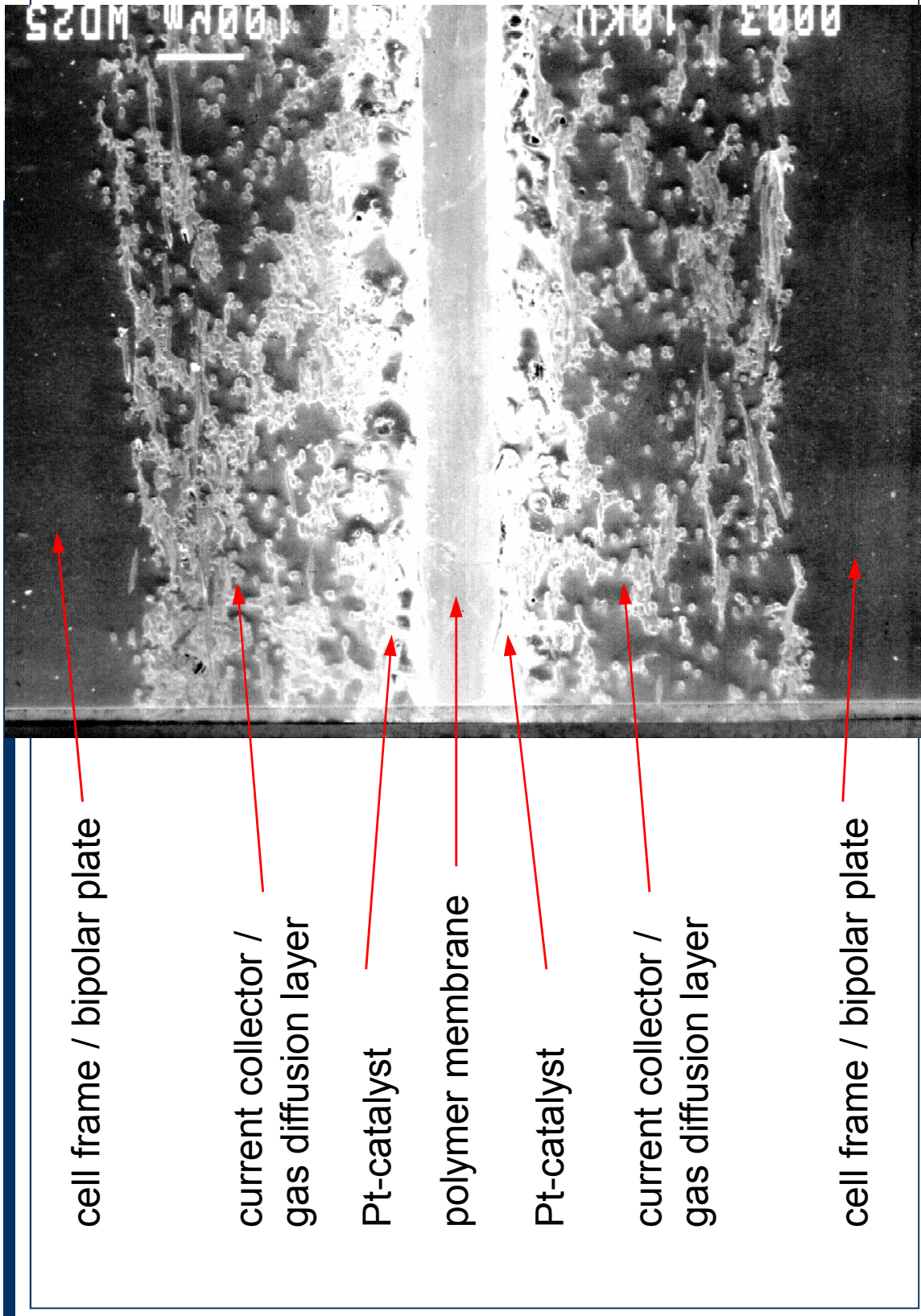
Ostwald ripening



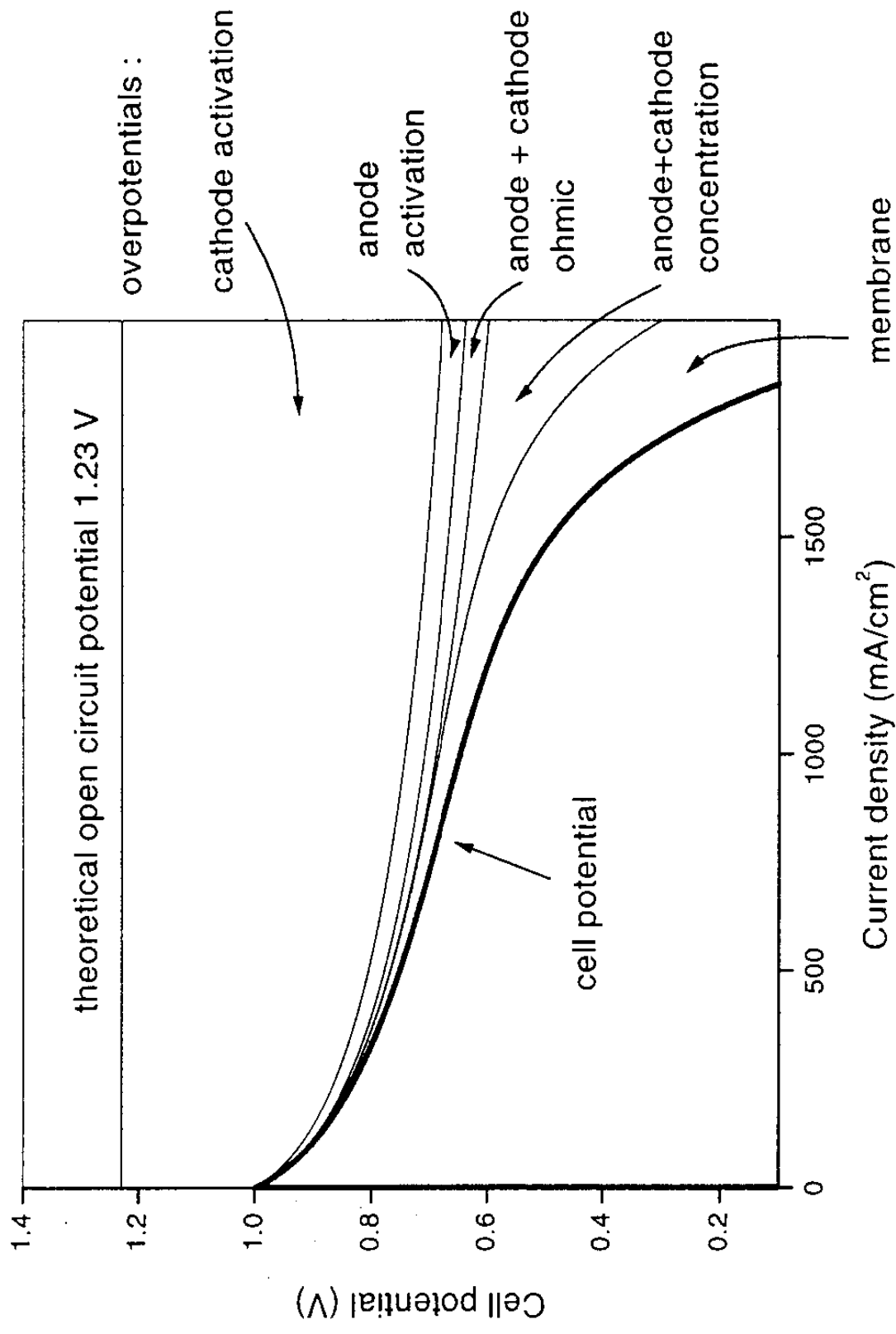
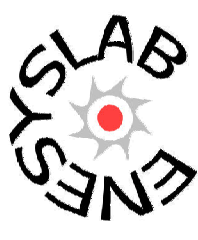
Particles size distribution

Ascarelli method

FUEL CELL COMPONENTS - MEA



TYPES OF OVERPOTENTIALS



FUEL CELL EFFICIENCY

$$\eta = \frac{V * I}{m_c * LHV} = \left(\frac{nFE_{rev}}{LHV} \right) \left(\frac{V}{E_{rev}} \right) \left(\frac{I}{nF\gamma} \right) \left(\frac{\gamma}{m_c} \right)$$

- E_{rev} : THEORETICAL CELL VOLTAGE
- F : 96439 coulomb;
- n : ELECTRONS INVOLVED IN THE REACTION;
- LHV : LOWER HEATING VALUE;
- m_c : FUEL MOLAR FLOWRATE;
- V : CELL VOLTAGE;
- I : CURRENT INTENSITY;
- γ : USED FUEL MOLAR FLOWRATE;
- U_f : UTILIZATION FACTOR: $U_f = \gamma/m_c$.

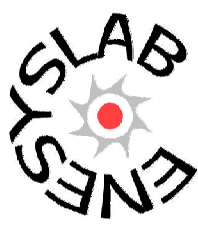
1- (nFE_{rev}/LHV) . IDEAL EFFICIENCY

2- (V/E_{rev}) . TAKES INTO ACCOUNT FOR ACTIVATION, OHMIC AND CONCENTRATION LOSSES

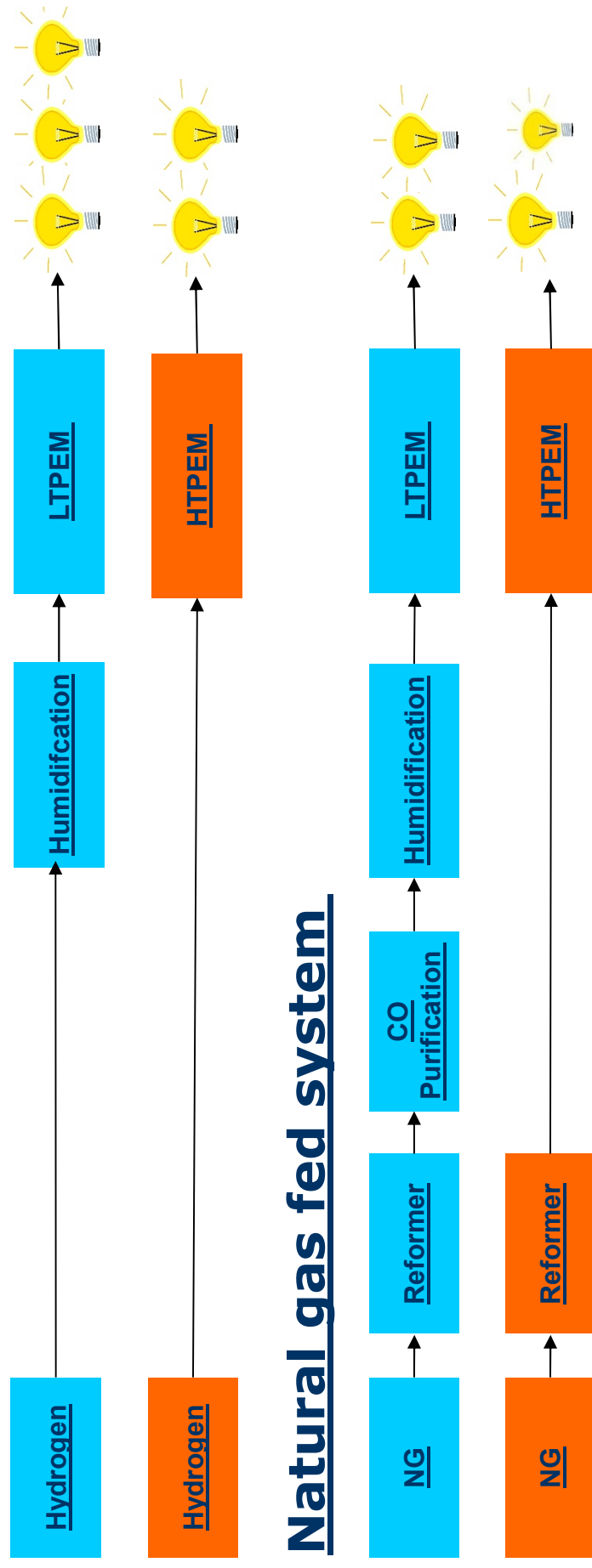
3- $(I/nF\gamma)$. PARASSITIC LOSSES

4- (γ/m_c) . UTILIZATION FACTOR

FUEL CELL EFFICIENCY

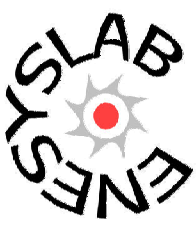


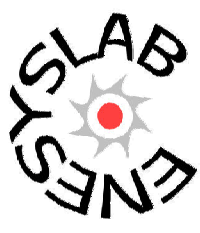
Hydrogen fed system



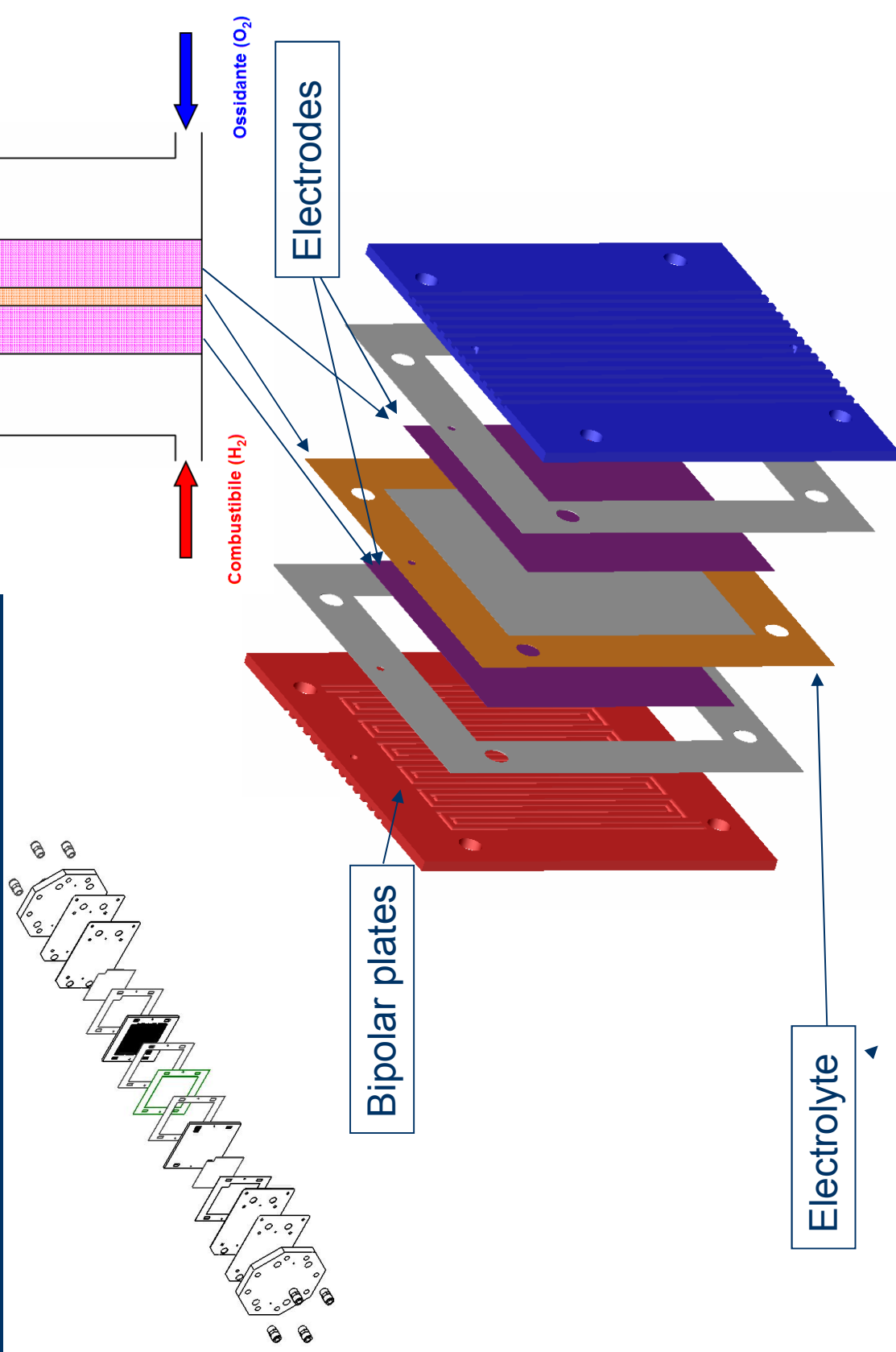
Topics

- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusion



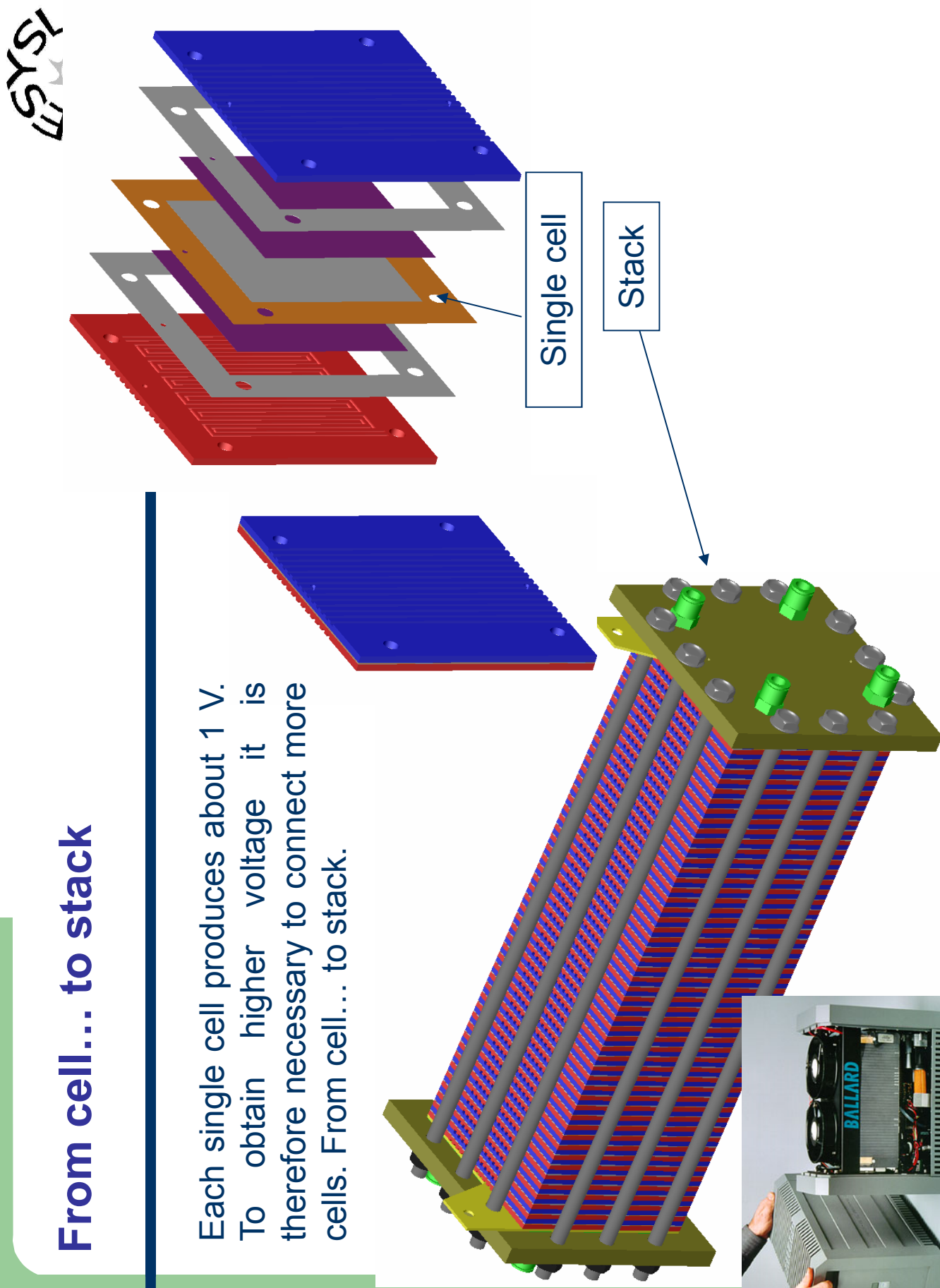


Fuel Cell Components

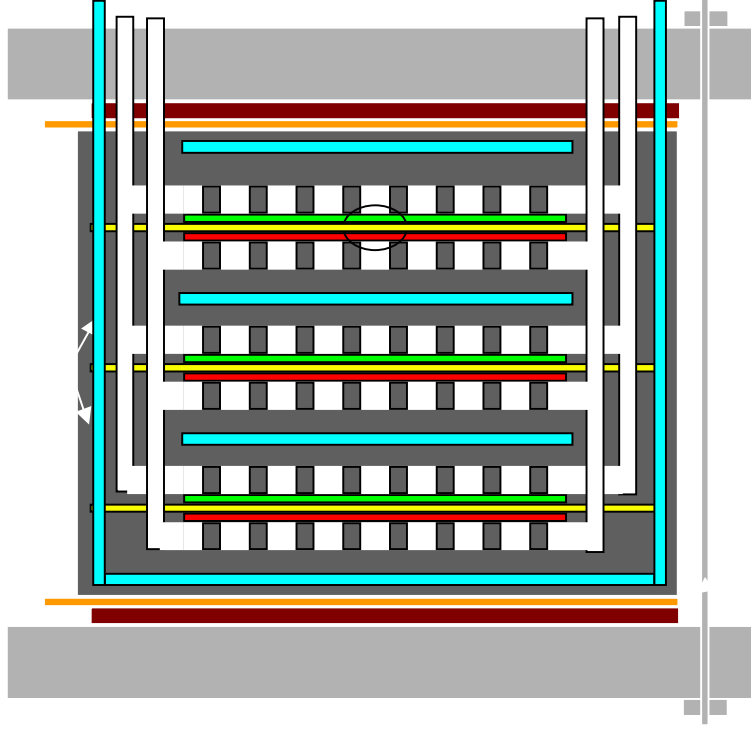


From cell... to stack

Each single cell produces about 1 V.
To obtain higher voltage it is
therefore necessary to connect more
cells. From cell... to stack.



Major stack components



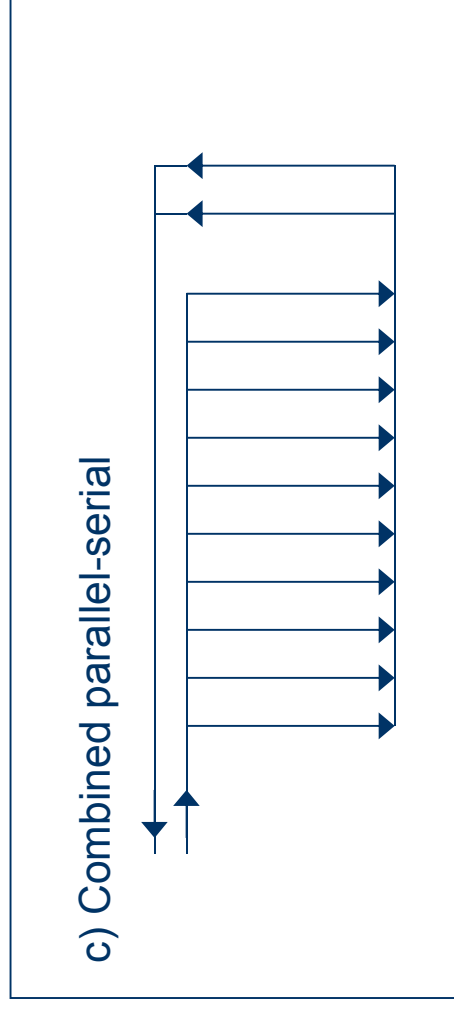
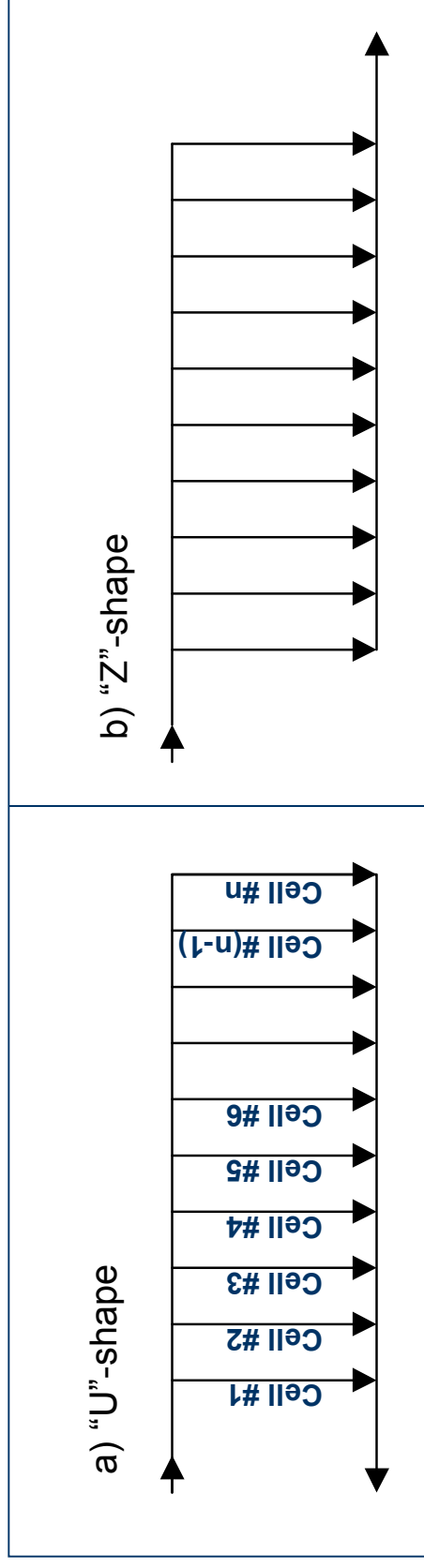
- Membrane
- Catalyst
- Catalyst support
- Catalyst layer
- Gas diffusion layer
- Gaskets/frames
- Flow field
- Separator/connector
- Bus plates/terminals
- End plates
- Clamping mechanism
- Fluid connections
- Manifolds
- Cooling plates/arrangements
- Humidification section (optional)

MEA

Bi-polar plate

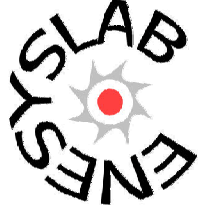
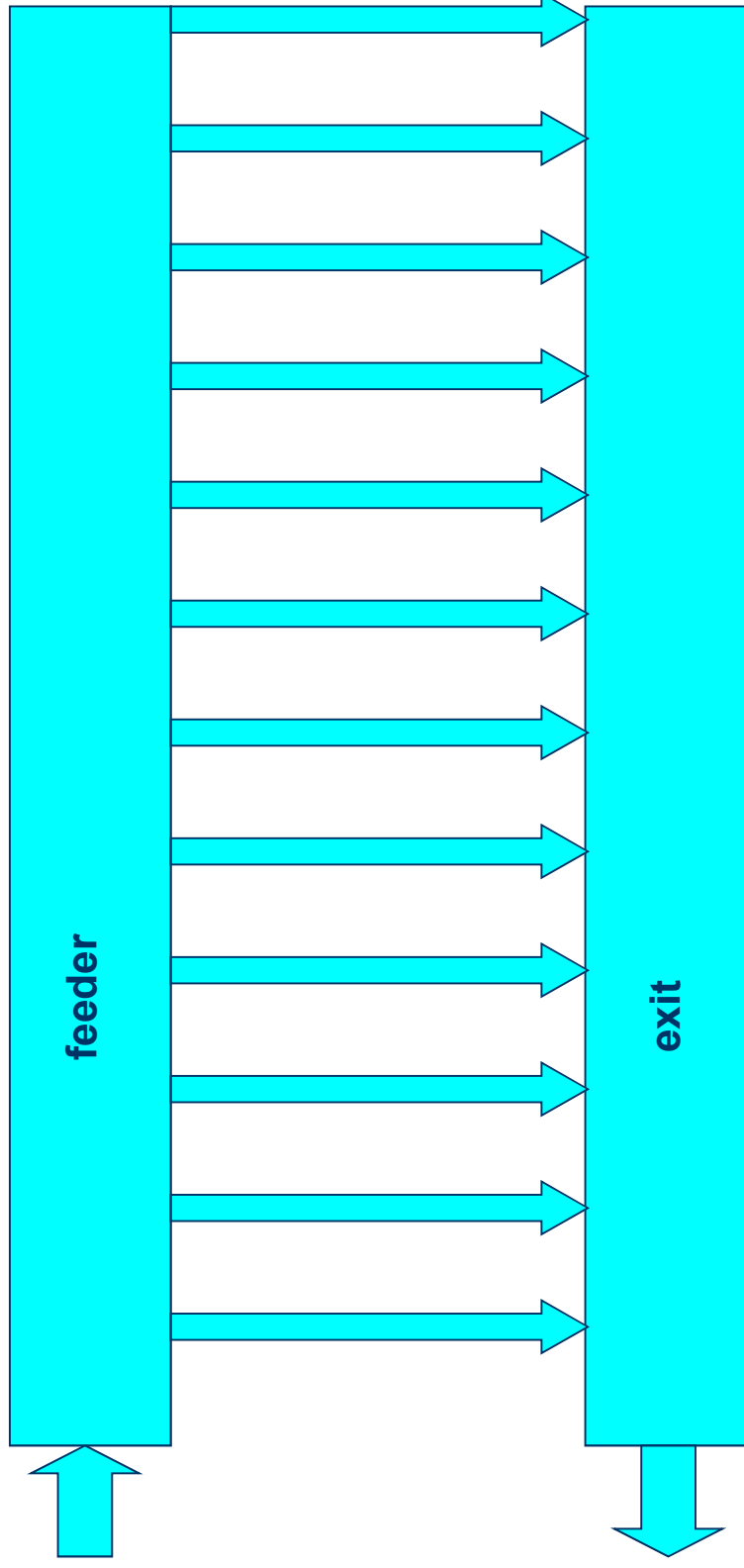
Stack design/engineering issues

- Uniform distribution of reactants to each cell

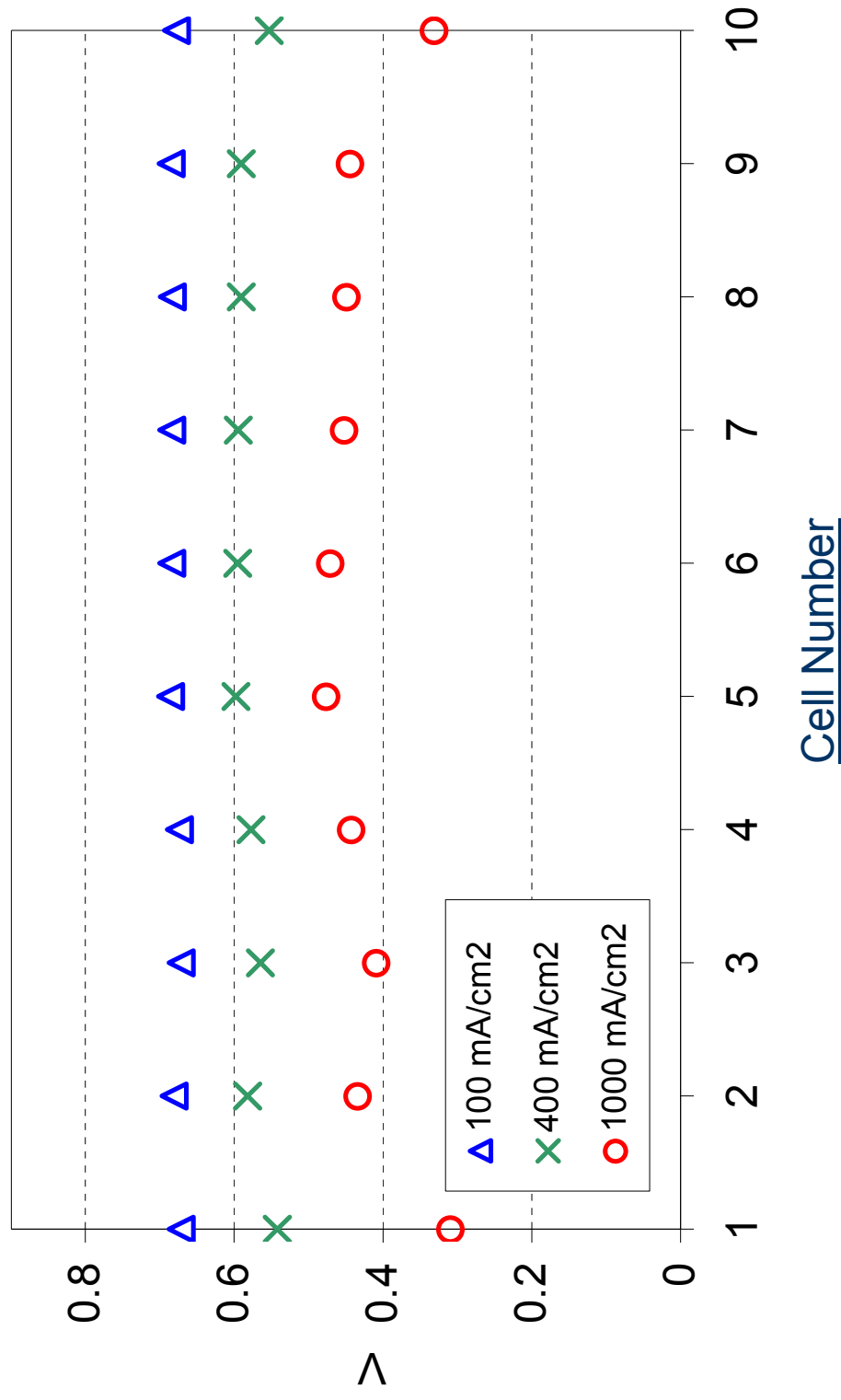
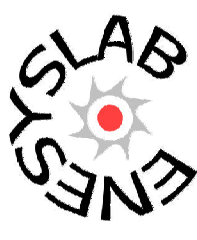


Pressure drop

$$\Delta P_{\text{feeder}} \ll \Delta P_{\text{cell}}$$

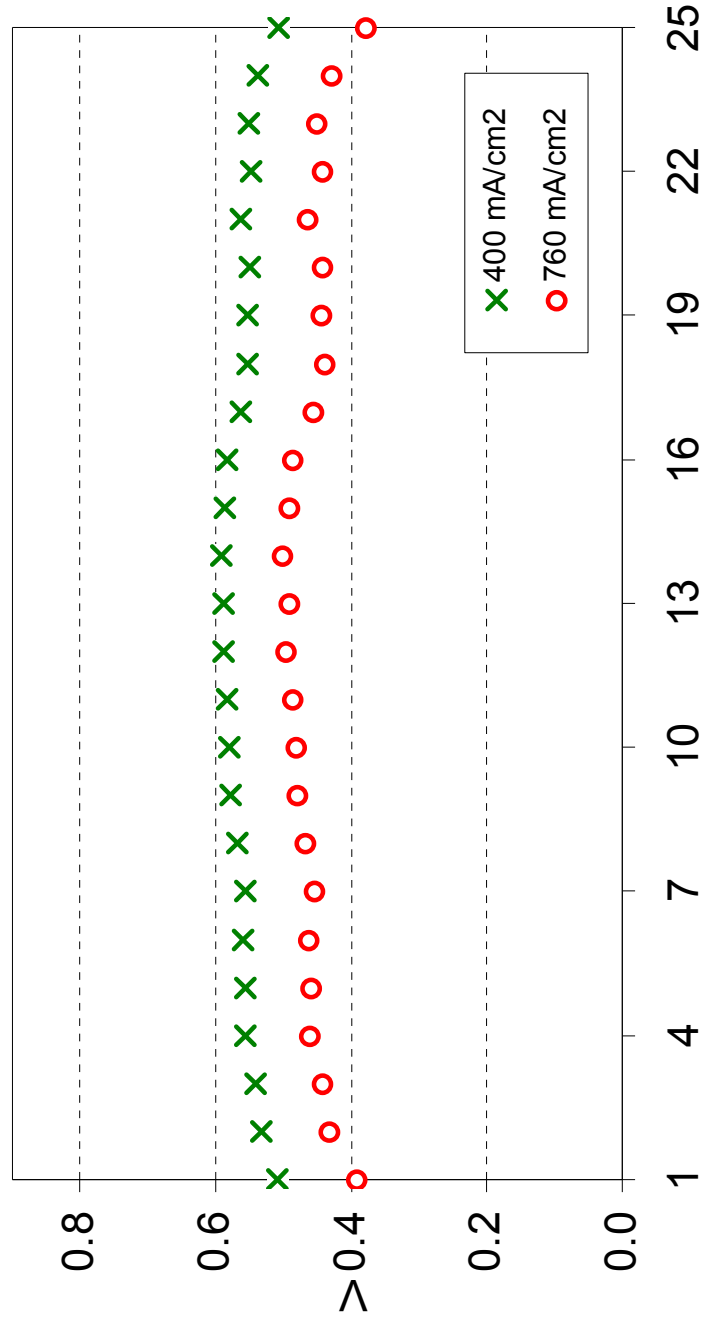
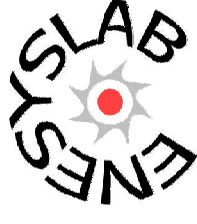


Stack Voltage Distribution



HT PEM, 160°C

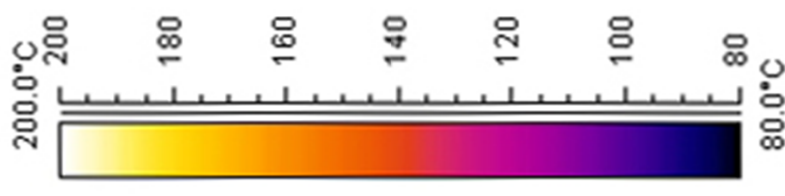
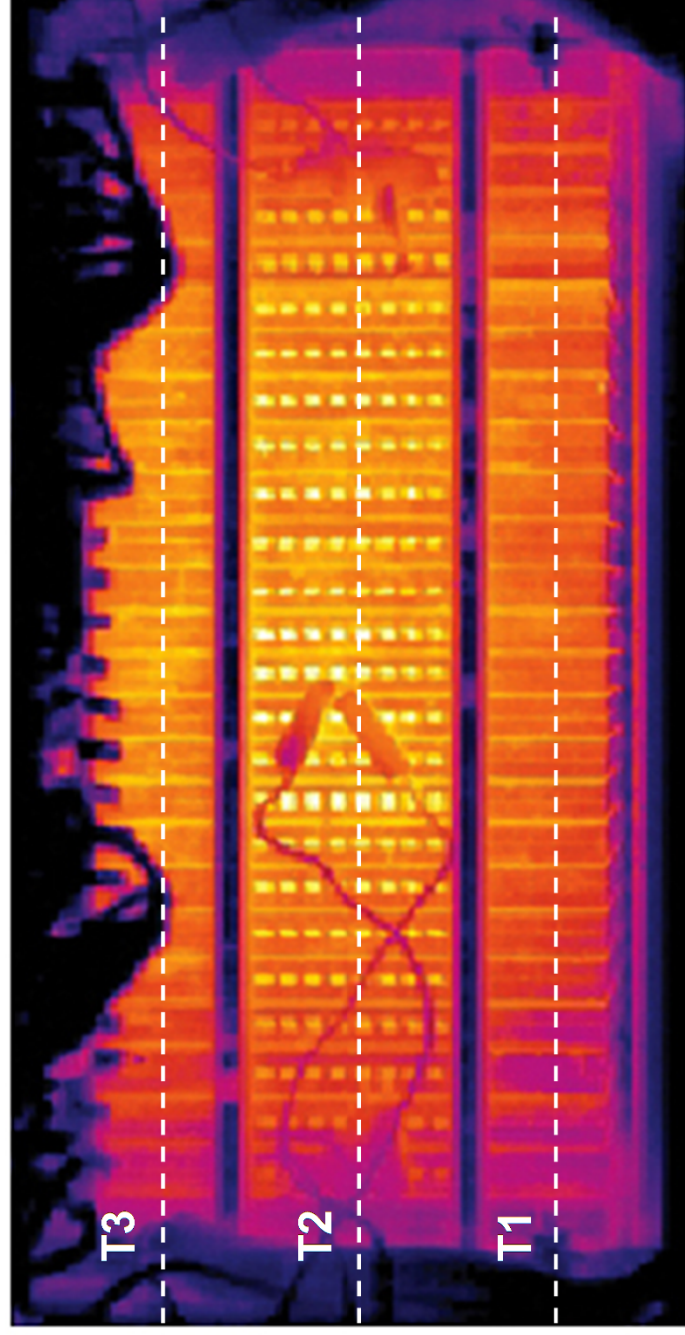
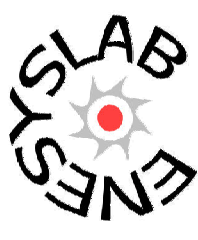
Stack Voltage Distribution



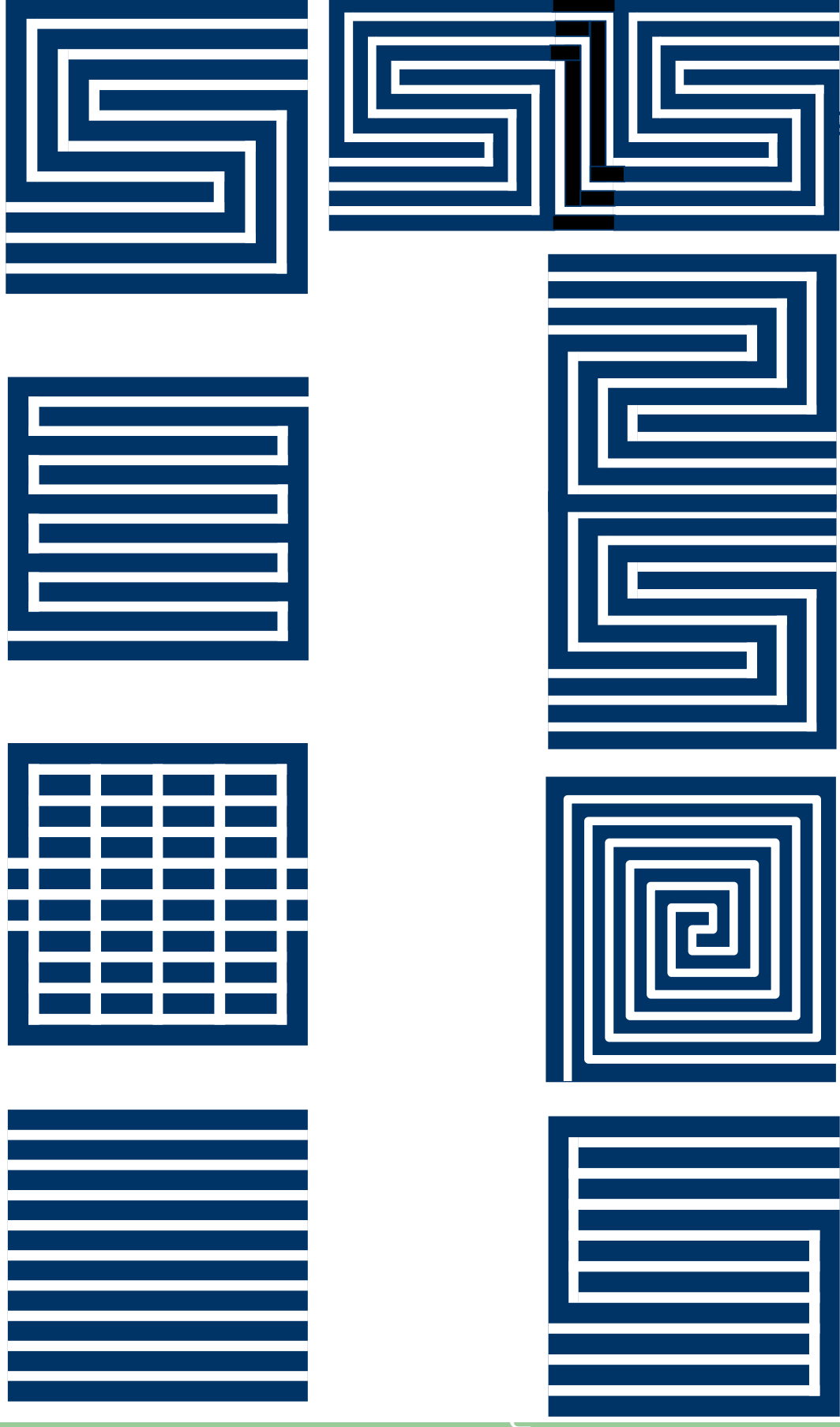
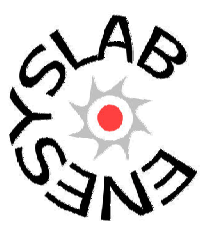
Cell Number

HT PEM, 160°C

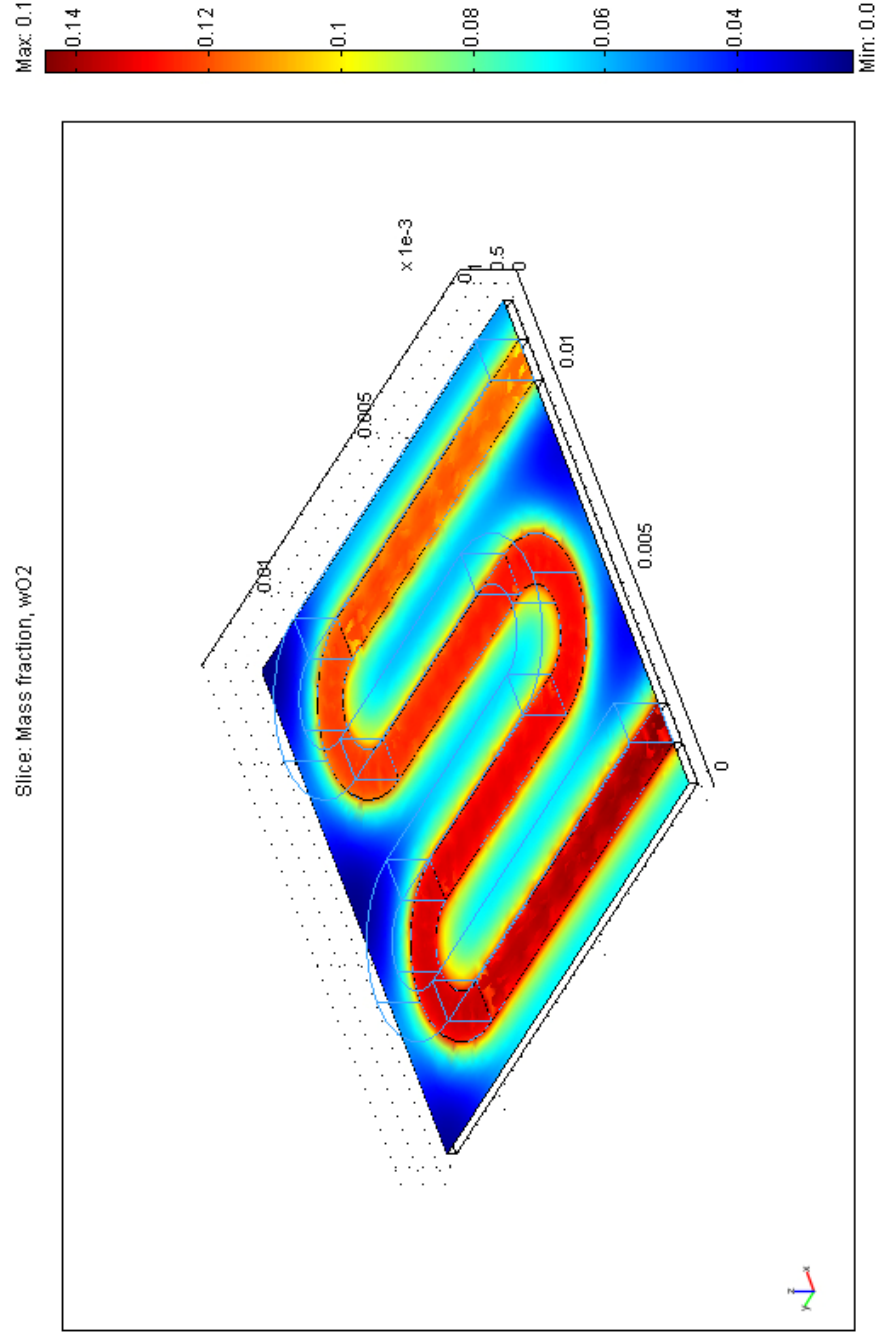
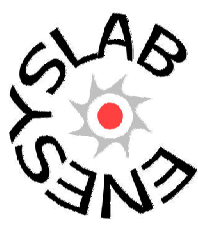
Stack Temperature Distribution



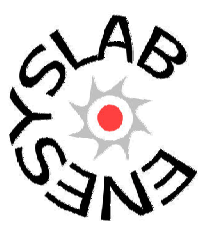
Flow field configurations



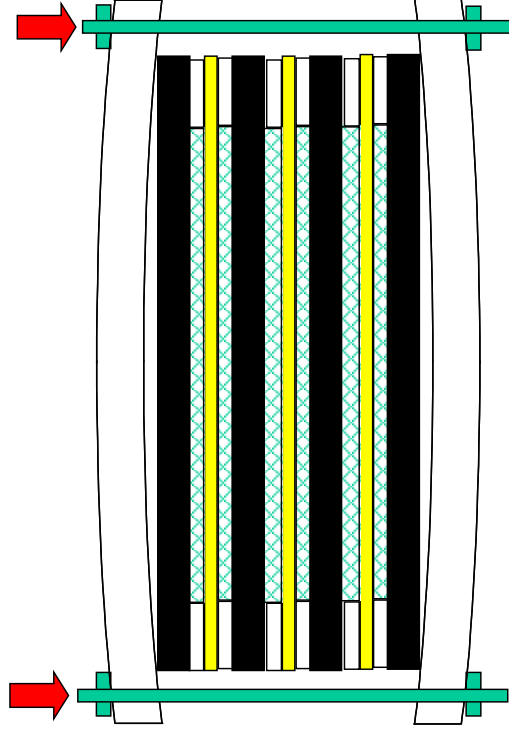
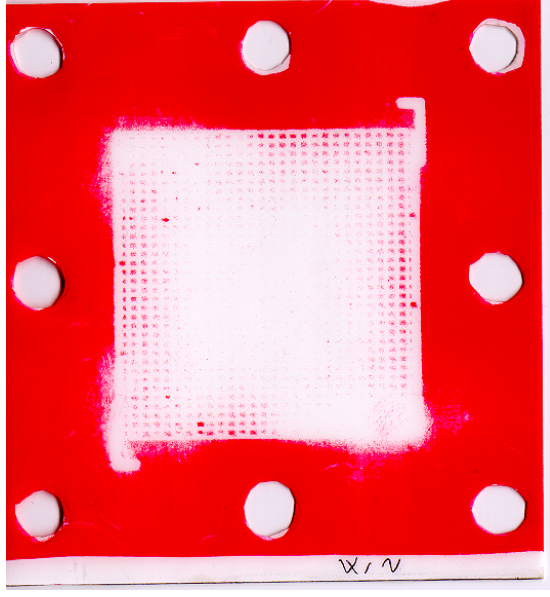
CFD can help



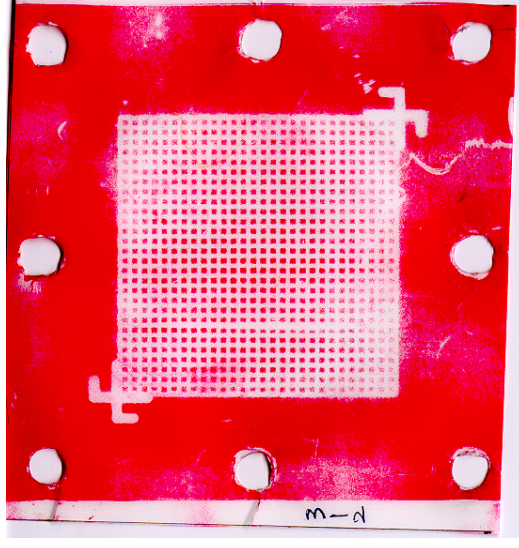
Cell/stack compression



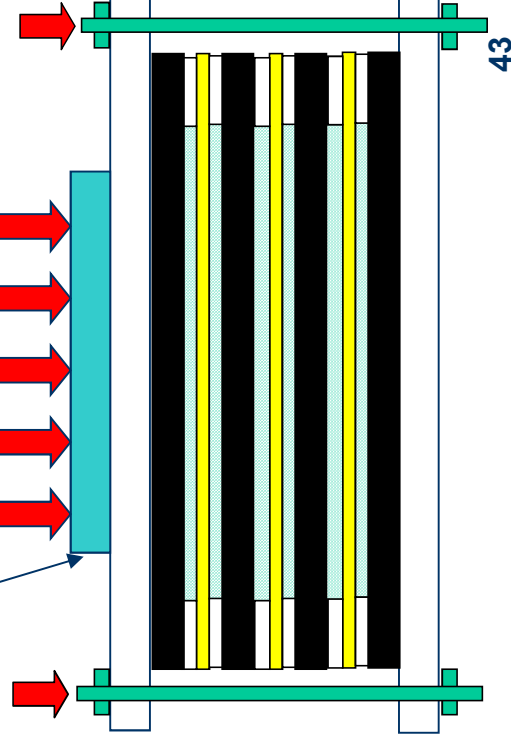
Non-uniform

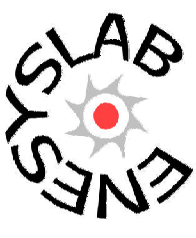


Uniform



Hydraulic or pneumatic piston



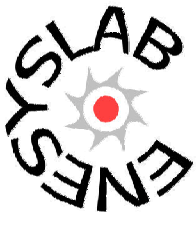


Stack design summary

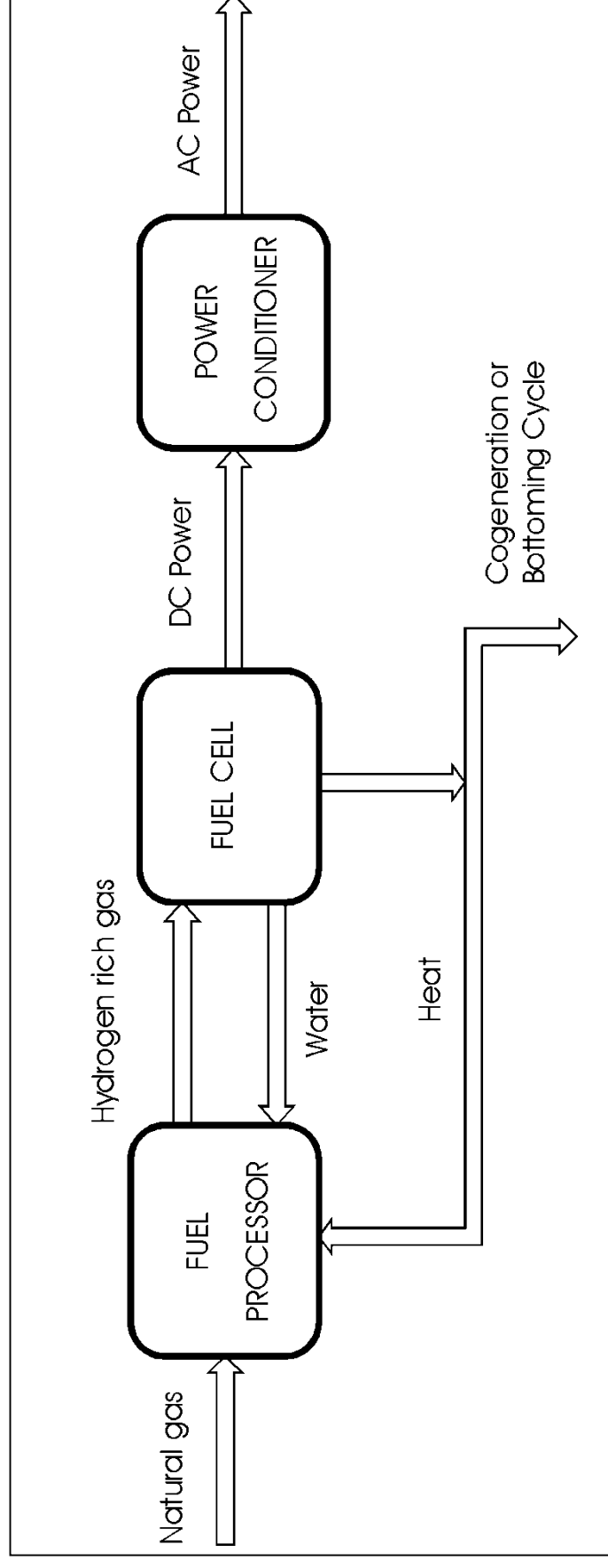
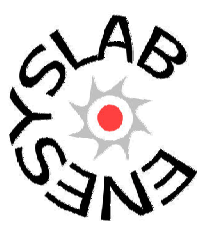
- A fuel cell stack is a simple, yet complex device
- Uniformity of local conditions is essential for good design
- Understanding of operating conditions is important
- Information may be gathered through modeling/numerical simulations and experimentally
- Selection of key parameters and conditions must be made from the system perspective

Topics

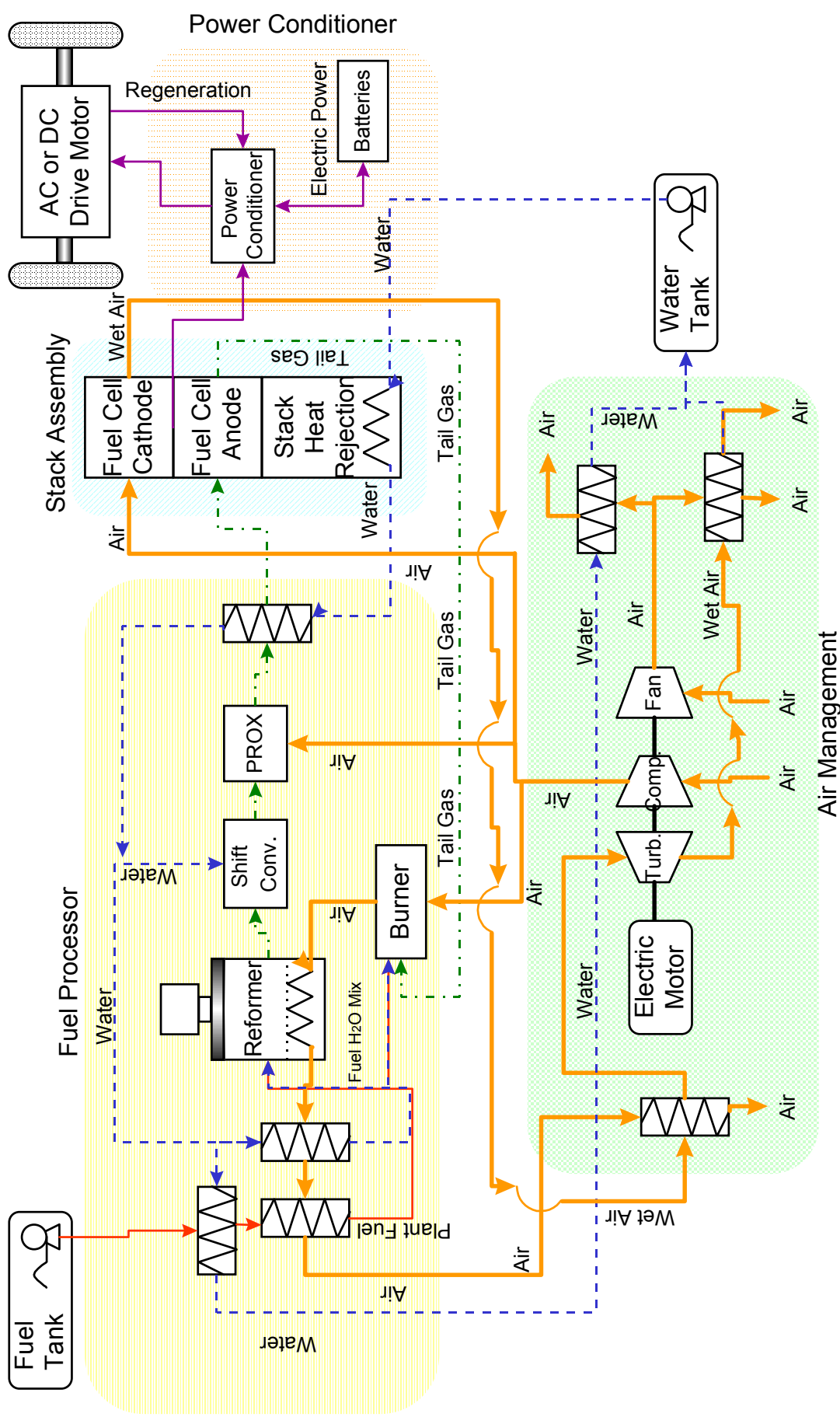
- EneSysLab at a glance
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- Conclusion



System design and integration



Sistem design and integration



Actual fuel cell system



back-pressure
regulator

DC/DC inverter

hydrogen tank



heat
exchangers

main load -
propulsion
motor

air
humidifier

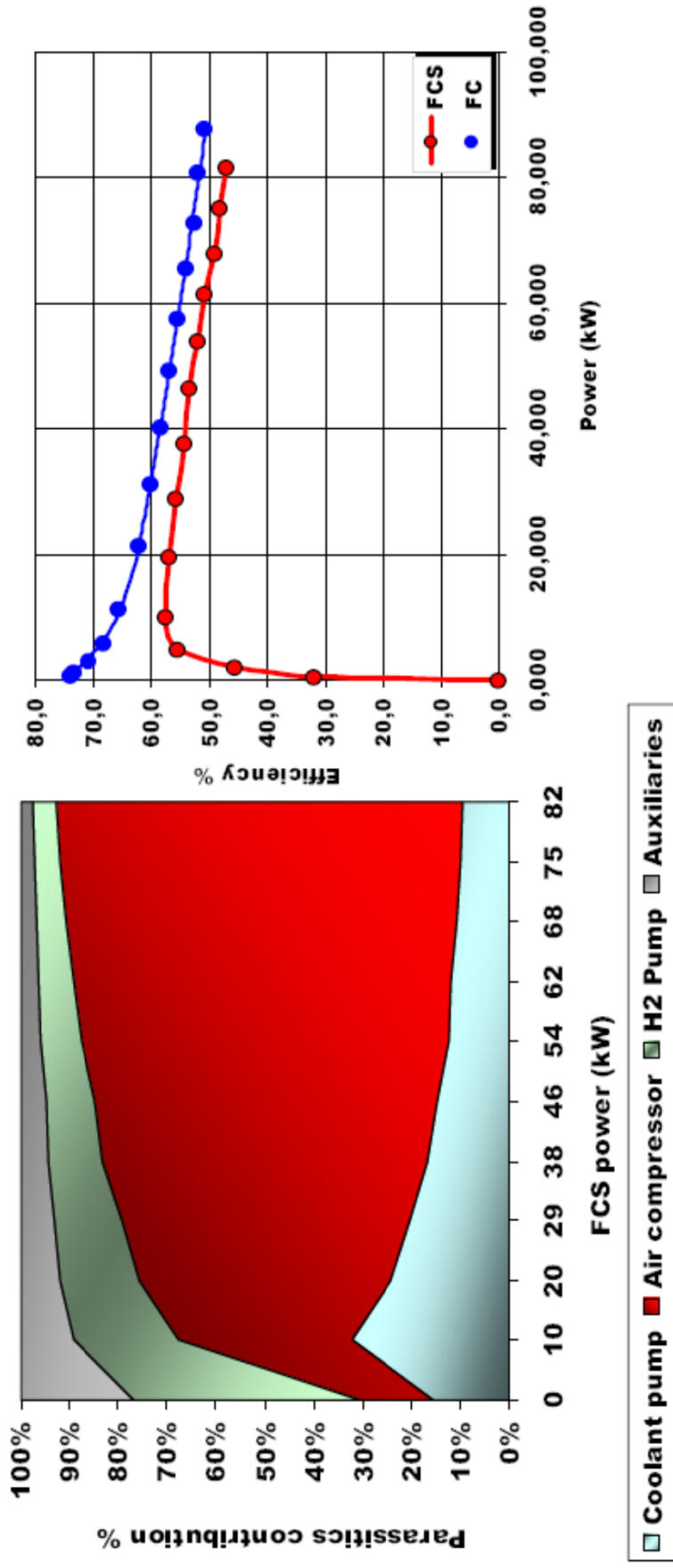
air compressor

battery

water tank

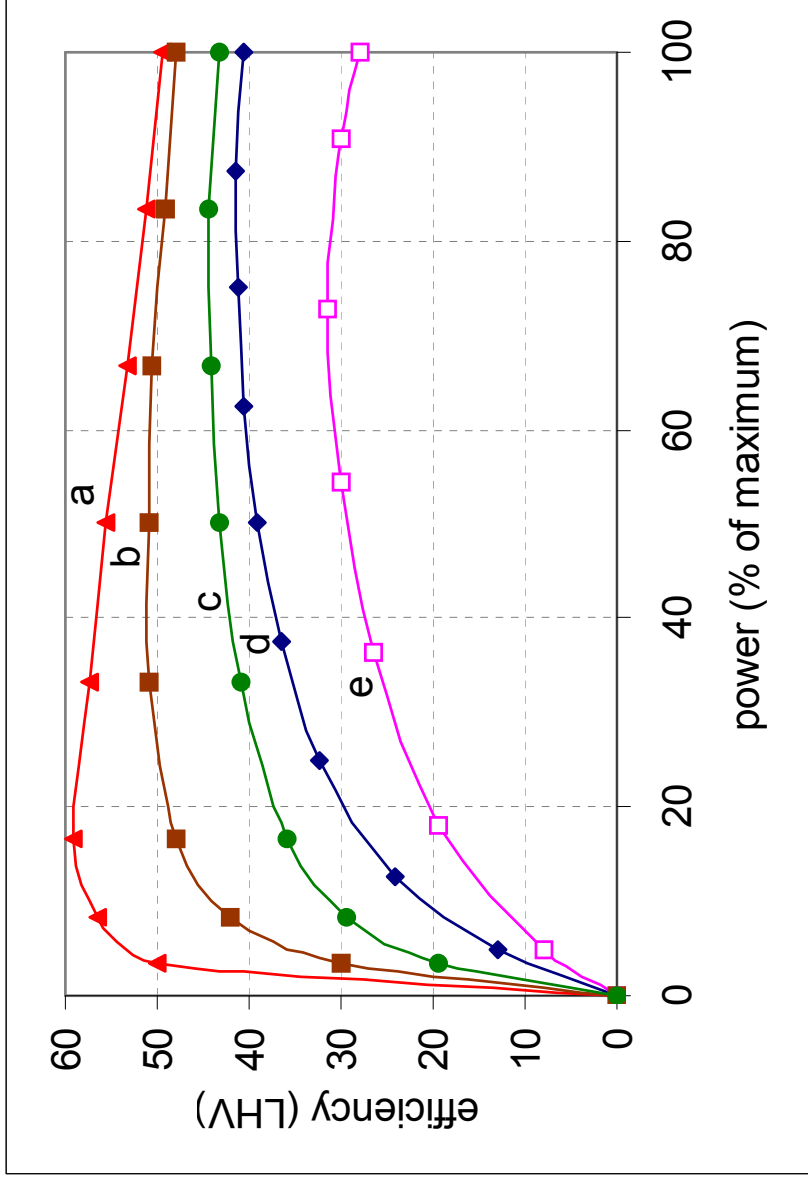
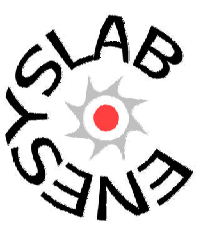
water pump

HDL 82 FCPM Efficiency Diagram



- 750 W of parasitic losses in IDLE MODE
- 6350 W of parasitic losses @ max power

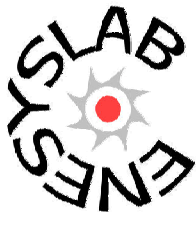
Efficiency of fuel cell vs. ICE



- a) Low pressure, low temperature fuel cell system
- b) High pressure, high temperature fuel cell system
- c) Fuel cell system with an on-board reformer
- d) Compression-ignition engine (diesel)
- e) Spark-ignition engine

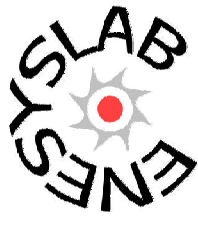
Topics

- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusion



Fuel Cell applications:

Status, Challenges and Perspectives



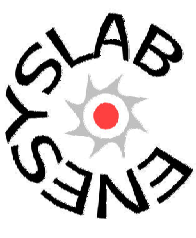
- **Space** in use for decades
- **(Sub)marine** in use
- **Automotive** demonstrations
- **Stationary Power** demonstrations
- **Portable Power** military
- **Battery Replacement** close to commercial

Why fuel cells?

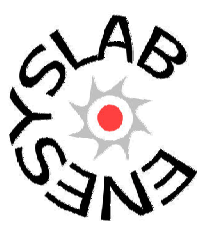
- Promise of high efficiency
- Promise of low or zero emissions
- Run on hydrogen/fuel may be produced from indigenous sources/issue of national security
- Simple/promise of low cost
- No moving parts/promise of long life
- Modular
- Quiet

Why PEM Fuel Cells?

- Simple
- Quick start-up
- Fast response
- High efficiency
- High power density (kW/kg and kW/l)
- Zero emissions



Fuel cells have already been demonstrated in every imaginable application



- Automobiles
- Buses
- Scooters
- Bicycles
- Golf carts
- Space
- Airplanes
- Locomotives
- Boats
- Underwater vehicles
- Distributed power generation
- Cogeneration
- Back-up power
- Portable power

Patents 2002-2011

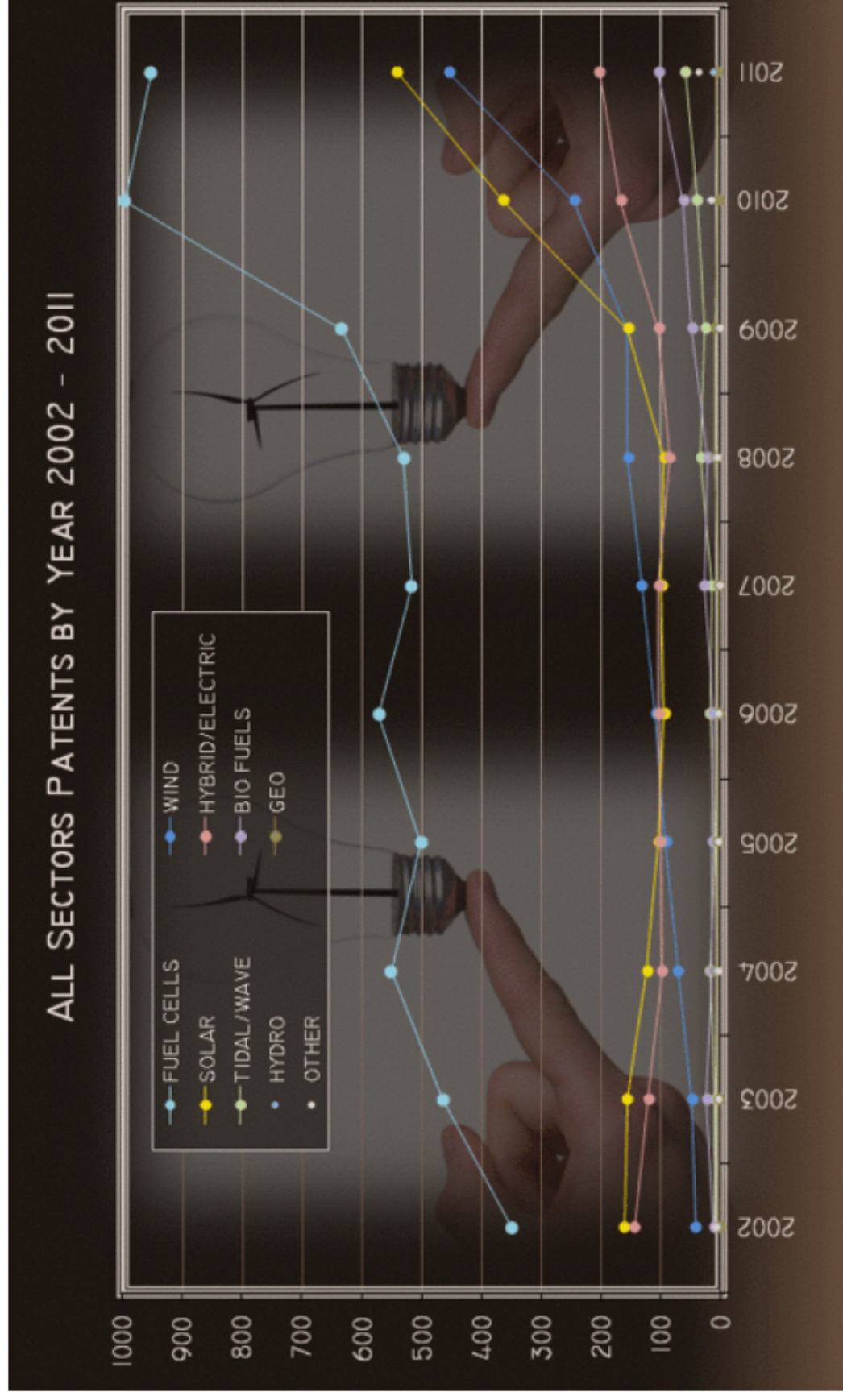
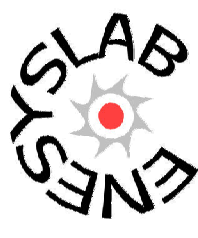


Figure 19: US Patent and Trademark Office Clean Energy Patent Awards By Sector, 2002-2011.
Source: Heslin Rothenberg Farley & Mesiti P.C.

DOE

Sesto 2013 - R. Taccani

Stationary power market

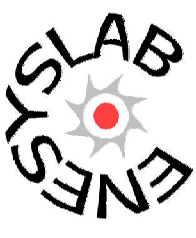
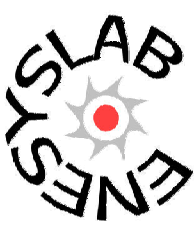


Table 8: Commercially Available Stationary Fuel Cells 2011			
Prime Power and mCHP			
Manufacturer	Product Name	Type	Output
Ballard	FCgen-1300	PEM	2 - 11 kW
	CLEARgen	PEM	Multiples of 500 kW
Bloom Energy	ES-5400	SOFC	100 kW
	ES-5700	SOFC	200 kW
Ceramic Fuel Cells	BlueGen	SOFC	2 kW
	Gennex	SOFC	1 kW
ClearEdge Power	ClearEdge 5	PEM	5 kW
	ClearEdge Plus	PEM	5 - 25 kW
ENEOS CellTech	ENE-FARM	PEM	250 - 700 W
FuelCell Energy	DFC 300	MCFC	300 kW
	DFC 1500	MCFC	1,400 kW
	DFC 3000	MCFC	2,800 kW
Heliocentris Fuel Cells AG	Nexa 1200	PEM	1.2 kW
Horizon	GreenHub Powerbox	PEM	500 W - 2 kW
Hydrogenics	HyPM Rack	PEM	Multiples of 10, 20, and 30 kW
	FCXR System	PEM	150 kW
Panasonic	ENE-FARM	PEM	250 - 700 W
Toshiba	ENE-FARM	PEM	250 - 700 W
UTC Power	PureCell Model 400	PAFC	400 kW

Back up and remote power market



Backup and Remote Power			
Manufacturer	Product Name	Type	Output
Altery Systems	Freedom Power System	PEM	5 – 30 kW
Ballard	FCgen 1020A CS	PEM	1.5 – 3.6 kW
ClearEdge Power	ClearEdge CP	PEM	10 kW
Dantherm Power	DBX 2000	PEM	1.7 kW
	DBX 5000	PEM	5 kW
	H-100	PEM	100 W
	H-1000	PEM	1 kW
Horizon	H-3000	PEM	3 kW
	H-5000	PEM	5 kW
	MiniPak	PEM	100 W
Hydrogenics	HyPM XR Power Modules	PEM	4, 8, and 12 kW
IdaTech	ElectraGen H2-I	PEM	2.5 - 5 kW
	ElectraGen ME	PEM	2.5 - 5 kW
Microcell	MGEN 1000	PEM	1 kW
	MGEN 3000	PEM	3 kW
	MGEN 5000	PEM	5 kW
ReliOn	E-200	PEM	175 W
	E-1100/E-1100v	PEM	1.1 kW
	E-2500	PEM	2.5 kW
	T-1000	PEM	600 W – 1.2 kW
SFC Energy	T-2000	PEM	600 W – 2 kW
	EFOY Pro Series 600, 1600, 2200	DMFC	25, 65, and 90 W

Fuel cells for transportation market

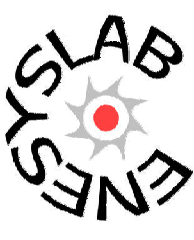
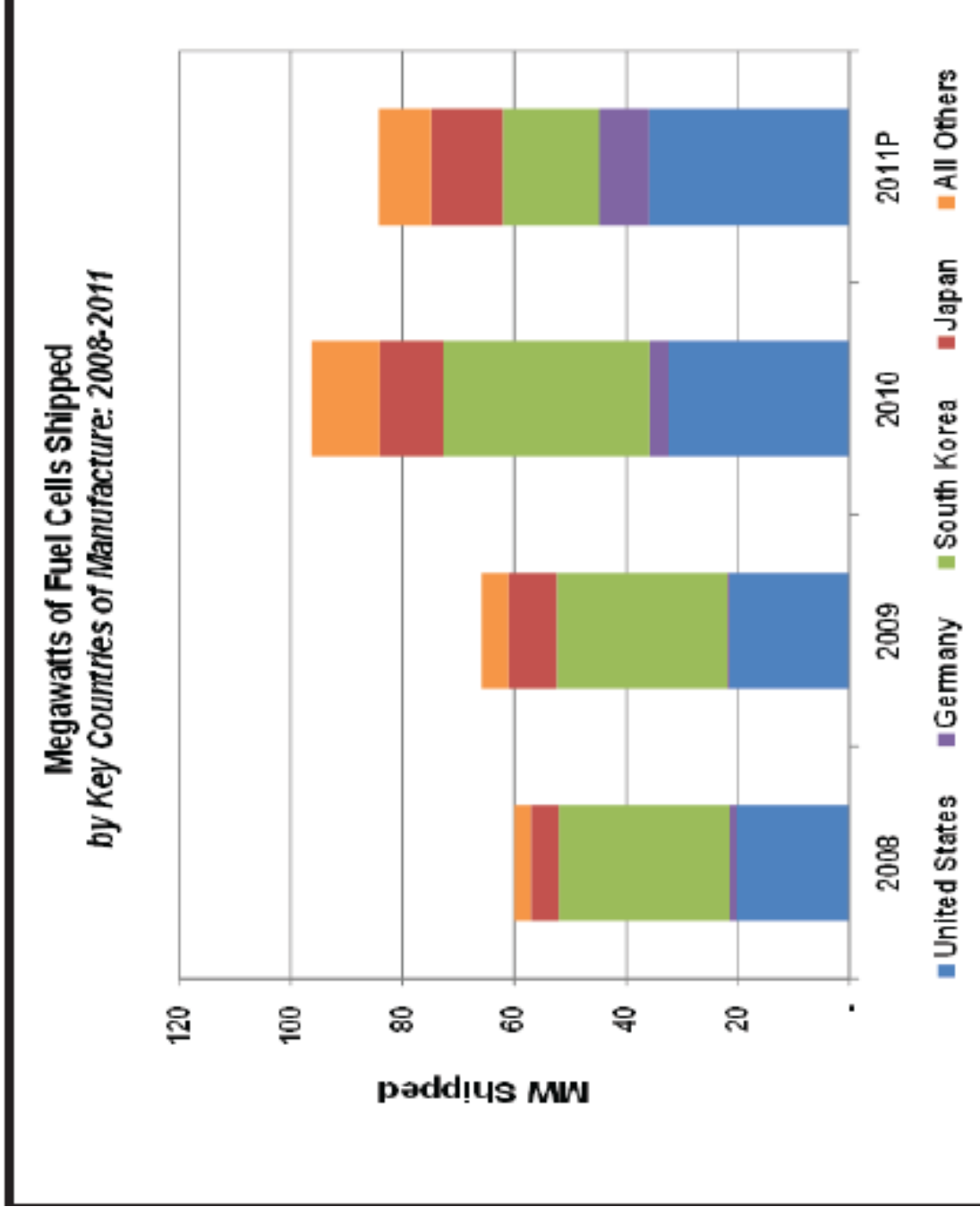
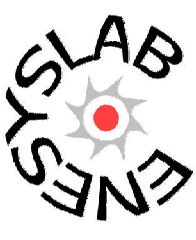


Table 15: Commercially Available Fuel Cells for Transportation 2011			
Manufacturer	Product Name	Type	Output
Ballard	FCvelocity-HD6	PEM	75 and 150 kW
Hydrogenics	HyPM HD Modules	PEM	4, 8, 12, 16, 33, and 100 kW
Nuvera	Andromeda Fuel Cell Stack	PEM	100 kW
	HDL-82 Power Module	PEM	82 kW
UTC Power	PureMotion 120	PEM	120 kW

MW of Fuel cells shipped



Fuel cell costs

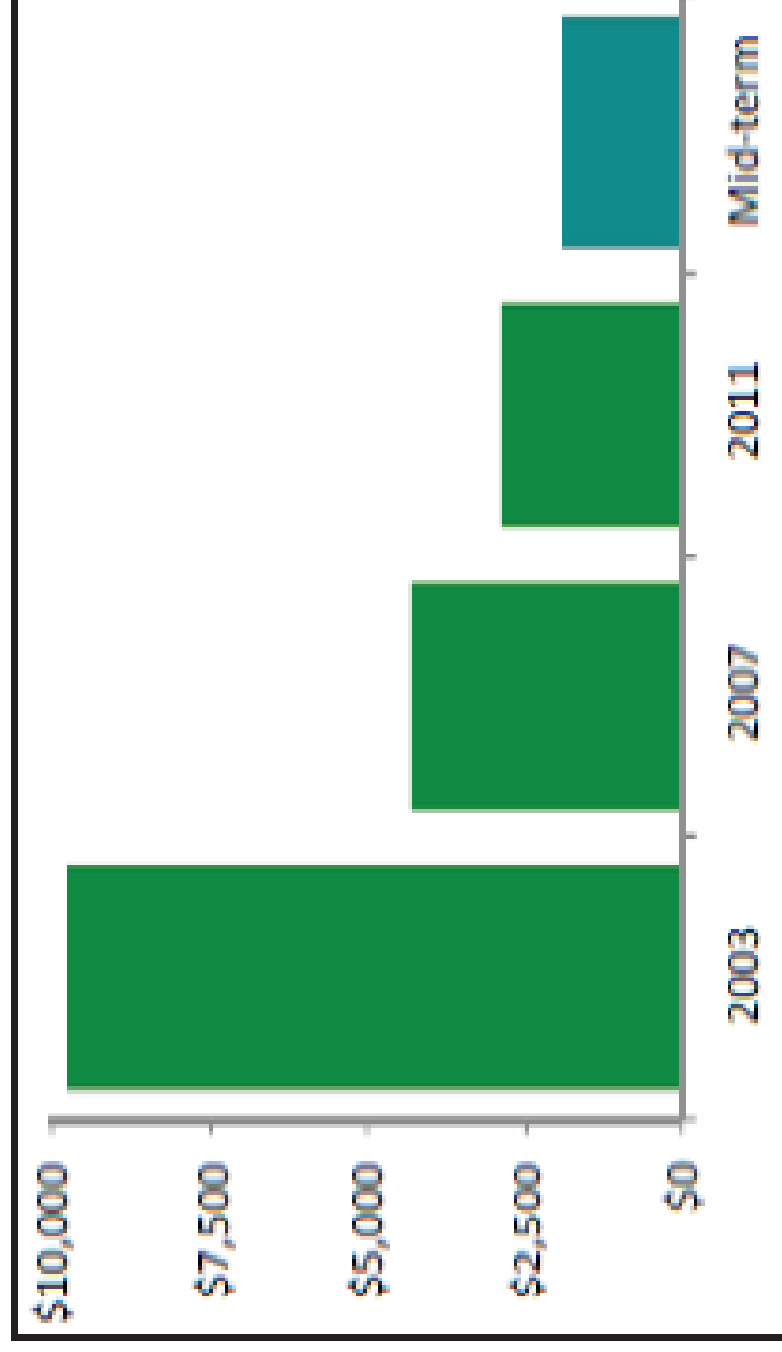
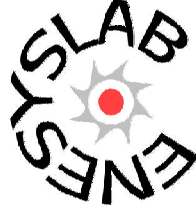
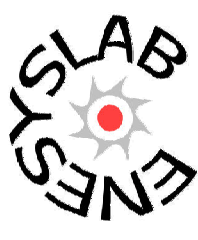


Figure 3: FuelCell Energy Cost Reduction.
Source: FuelCell Energy.

Fuel Cell Powered Fork Lifts

– Ideal Niche Market



Fuel Cell Powered Fork Lifts

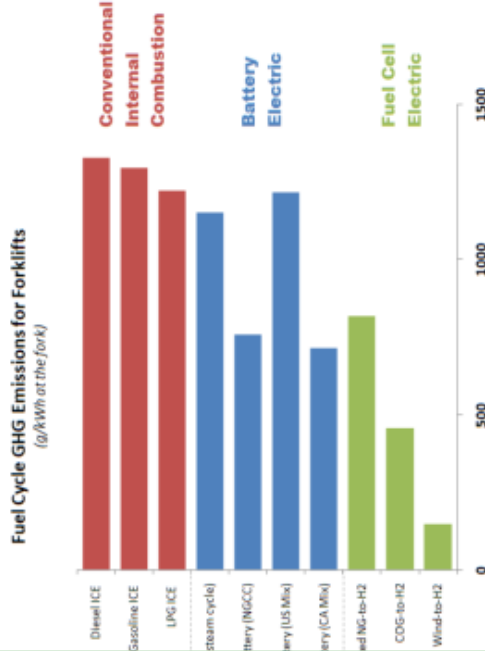
Ideal Niche Market



The Case for Forklifts*

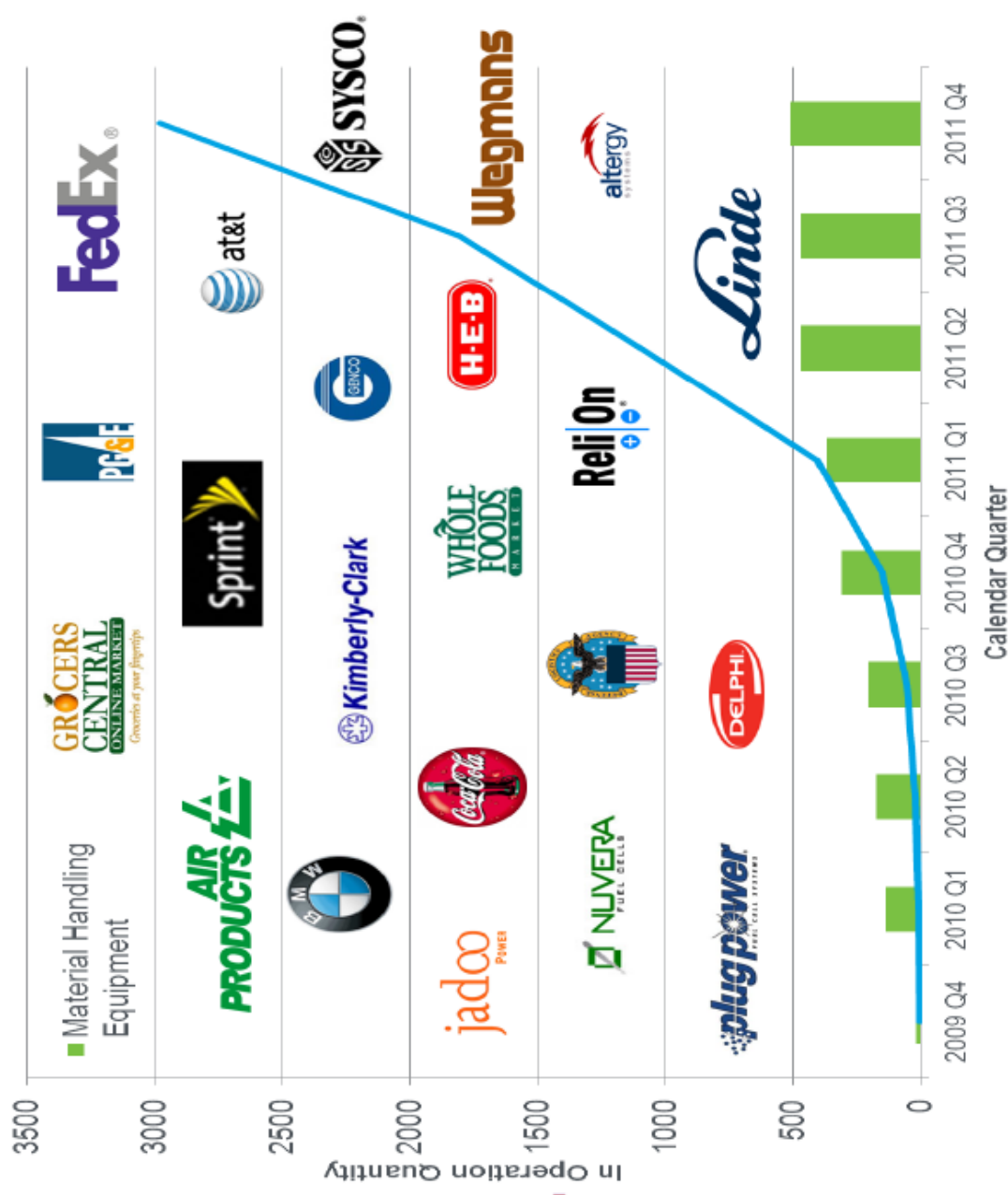
Compared to conventional forklifts, fuel cell forklifts have:

- 1.5 X lower maintenance cost
- 8 X lower refueling labor cost
- 2 X lower net present value of total system cost

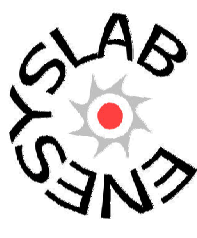


*Preliminary Analysis

Fuel Cell Lift Truck Purchases

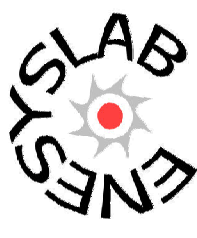


Nuvera Fuel Cells



Power	125	kW
Operating voltage	240-384	Volt
Transient response 10-90%	2	s
Dimension	210x550x900	mm
Weight	140	kg

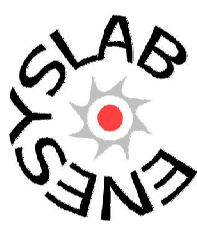
Ballard Fuel Cell



PRODUCT SPECIFICATIONS

Gross Power:		75 kW	150 kW
Performance:	DC voltage	275 – 400V	550 – 800V
	Maximum current	300A	300A
Physical:	Weight (dry)	< 350 kg (< 700 lbs)	< 400 kg (< 990 lbs)
	Length x width x height (without controller box)	1270 x 870 x 505 mm (50 x 34 x 20 in)	
	Volume	0.55m ³ (19.6 cubic ft)	
Fuel:	Gaseous hydrogen	Commercial grade (per SAE J2719)	
Oxidant:	Air		
Coolant:	50/50 Pure Ethylene Glycol and Water		
Operating Conditions:	Temperature (nominal)	63°C (149°F)	
	Fuel pressure (minimum)	12 barg	
	Air pressure (nominal)	1.2 barg	
Additional Features:	Control interface	CANbus	
	Enclosure	IP53	

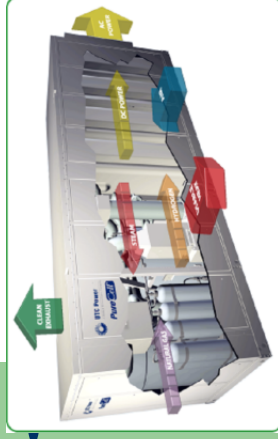
Distributed cogeneration



Panasonic

Launch date	New model	
	April 1, 2011 (scheduled)	
Performance	Electricity generation output	250W-750W
	Rated generation efficiency	40% (LHV) 36% (HHV)
	Rated heat recovery efficiency	50% (LHV) 45% (HHV)
	Water tank capacity	200 liters
	Fuel cell unit	H1,883mm × W315mm × D480mm
Dimensions	Hot water unit	H1,883mm × W750mm × D480mm
	Fuel cell unit	100kg
Weight	Hot water unit	125kg
	Installation area	Approx. 2.0m ²
Recommended retail price (including tax; not including installation)		2,761,500 yen
Maintenance support		10 years
		F

UTC Pure cell System

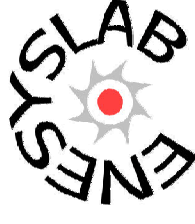


Fuel requirements

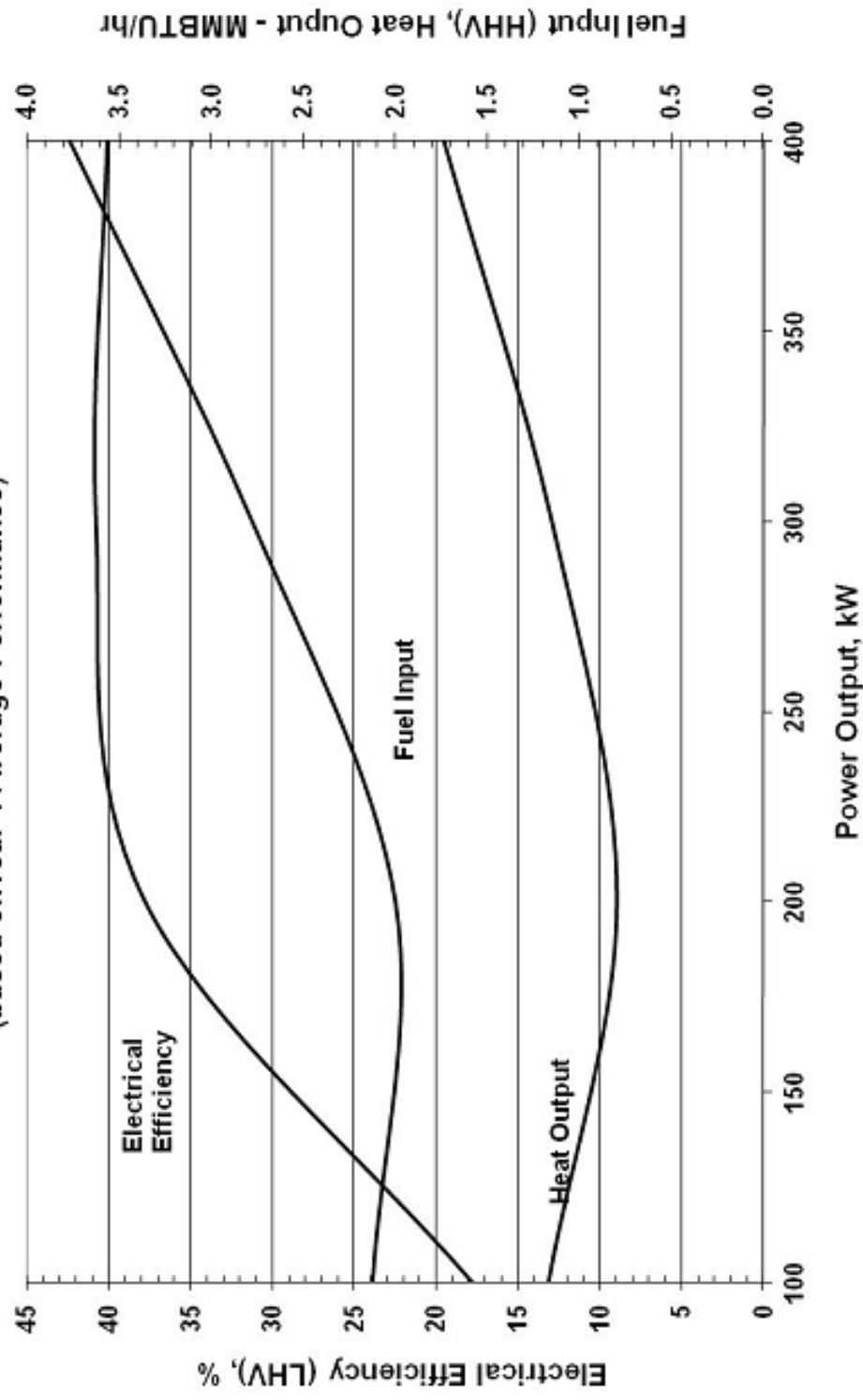


Model 400 Pure Cell® System				
Basic data				
Power module		Cooling module		
Dimensions [mm]	8738 x 2540 x 3023	Dimensions [mm]	4851 x 2388 x 1829	
Weight [kg]	27240	Weight [kg]	1448	
System				
N° of cells	PAFC, 376 x 4 stacks			
System power [kW]	400 (350 in grid independent mode)			
Output voltage [V]	480 / 60 Hz / 3 phase			
System efficiency [%]	40 BOL, 38 average 10 years, LHV			
Fuel type	Natural gas			
Fuel in [Nm³/h]	127.43 EOL			
Fuel pressure [mbar(g)]	24.91 – 34.87			
Emissions				
NO _x [g/MWh]	9.07			
CO [g/MWh]	9.07			
CO ₂ [kg/MWh]	499			
SO _x [g/MWh]	Negligible			
PM [g/MWh]	Negligible			
VOCs [g/MWh]	9.07			
Water consumption	None (up to 29 °C ambient)			
Water discharge	None (normal operating conditions)			
Noise	< 65 dBA @ 10 m			
Ambient operating temperature [°C]	From -29 to 45			

UTC Pure 400

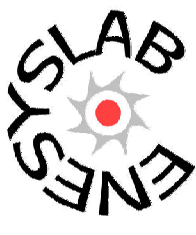


Model 400 Performance vs Power Output
(based on Year 1 Average Performance)

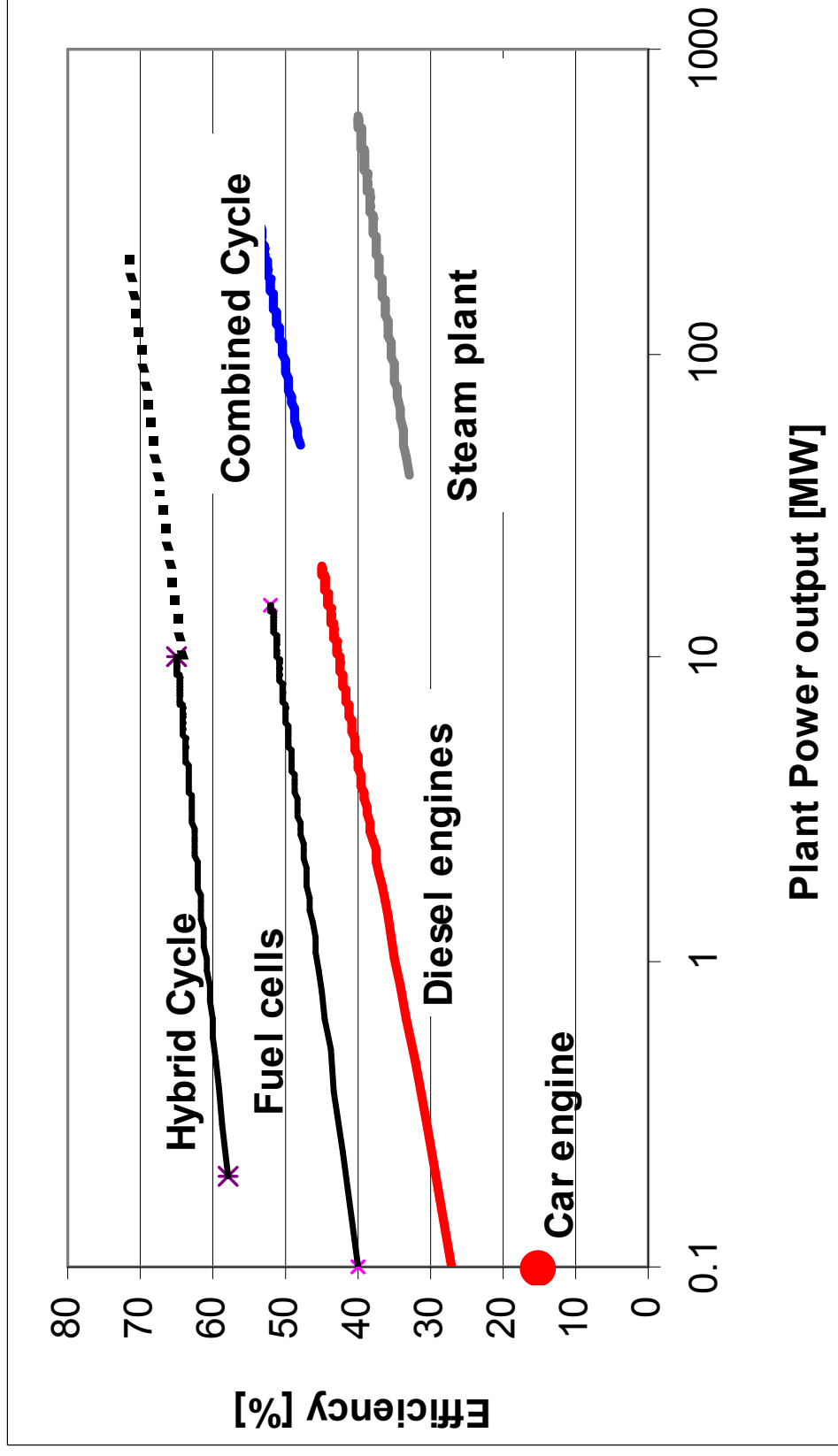
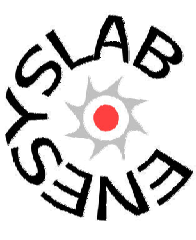


Topics

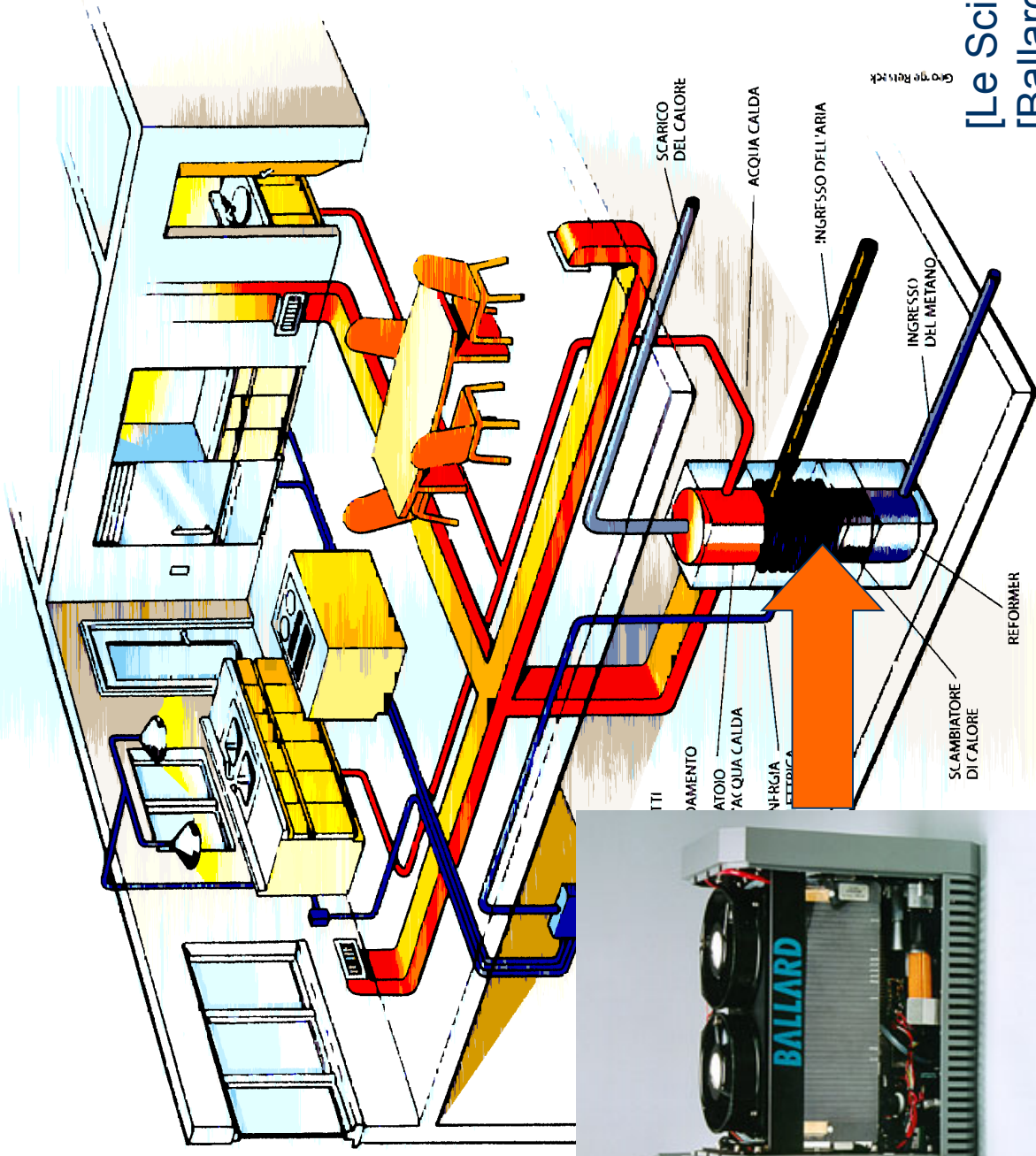
- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusion



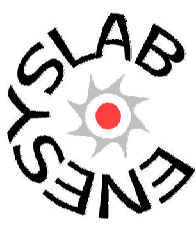
POWER PLANTS EFFICIENCIES



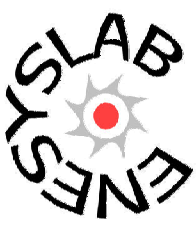
DOMESTIC COGENERATION



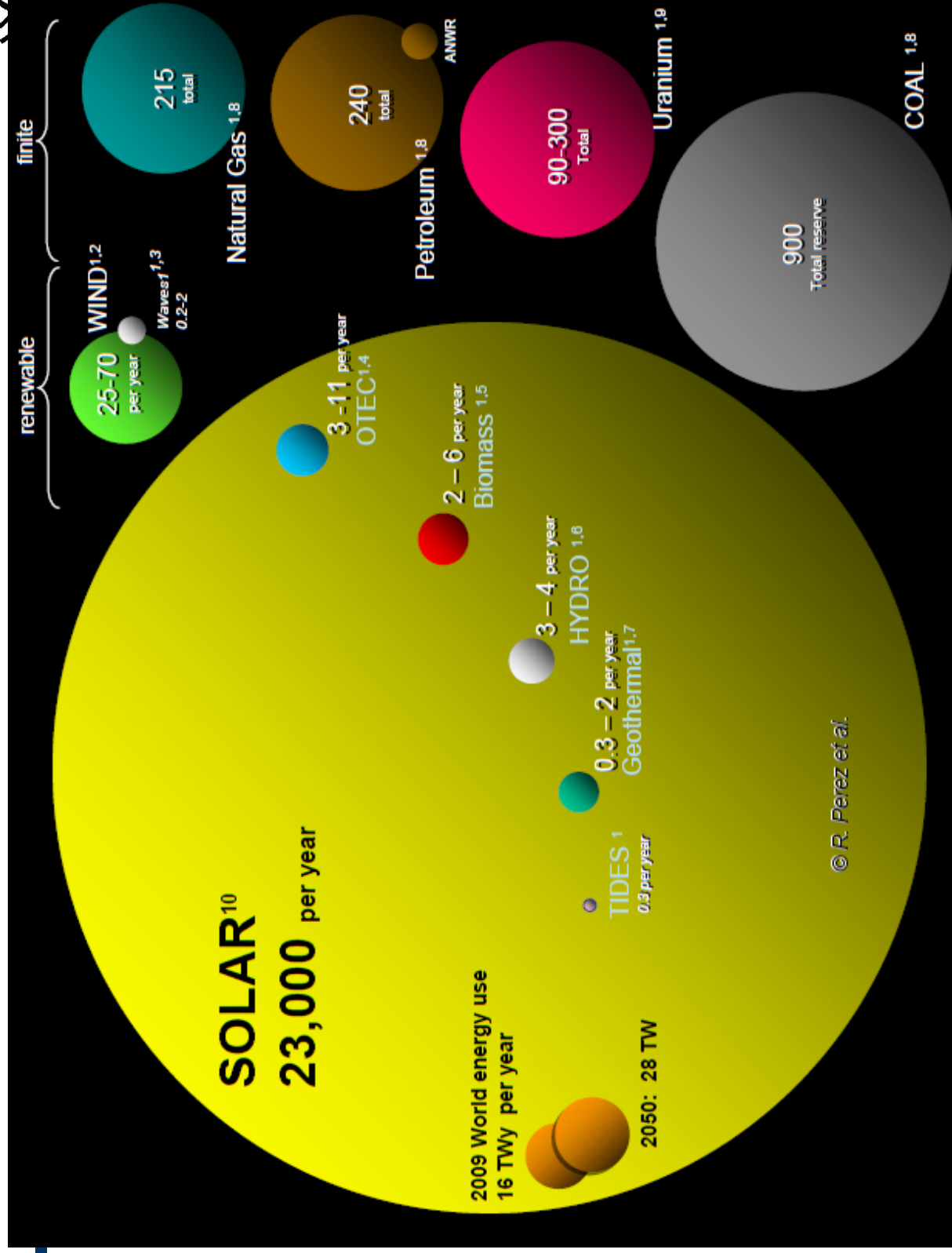
Conclusions



- **Fuel cells are:**
 - versatile (many possible applications)
 - efficient
 - clean (when use hydrogen as fuel)
 - modular
- **Fuel cells are close to commercialization**
 - niche market opportunities
- **Few technical challenges, but no show-stoppers**
- **Fuel cells are only a part of a bigger system –**
 - Difficulties in market penetration of individual technologies
- **Fuel cells may be the enabling technology to pave the road toward hydrogen economy**



Introducing solar thermal



Process heat

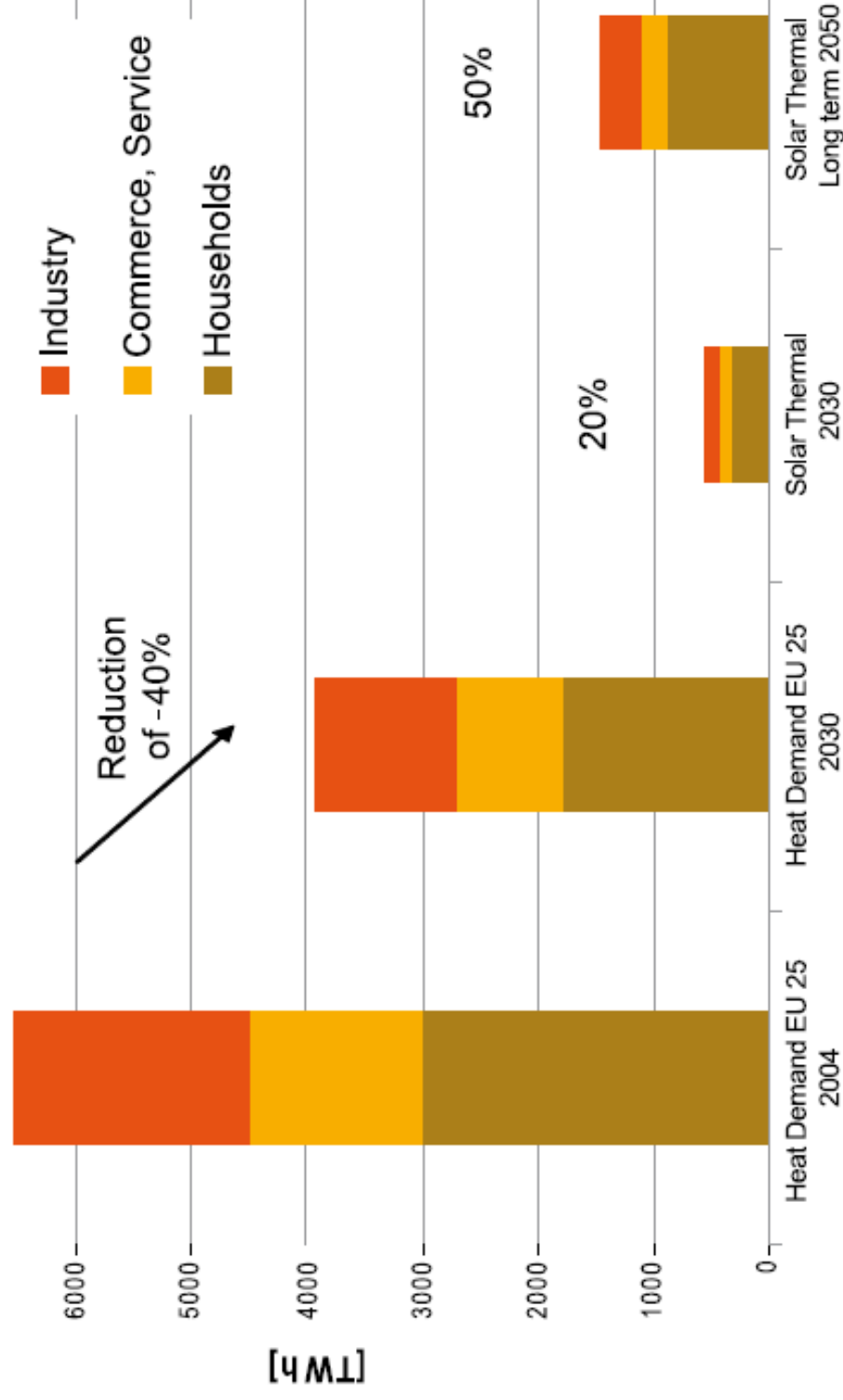
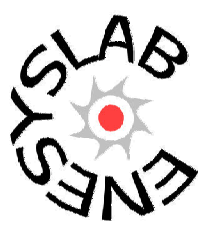


Figure 2: Contribution of solar thermal to EU heat demand by sector, assuming that the total heat demand can be reduced by energy conservation and a 40% increase in efficiency by 2030. (Source: AEE INTEC, 2008)

Heat “quality”

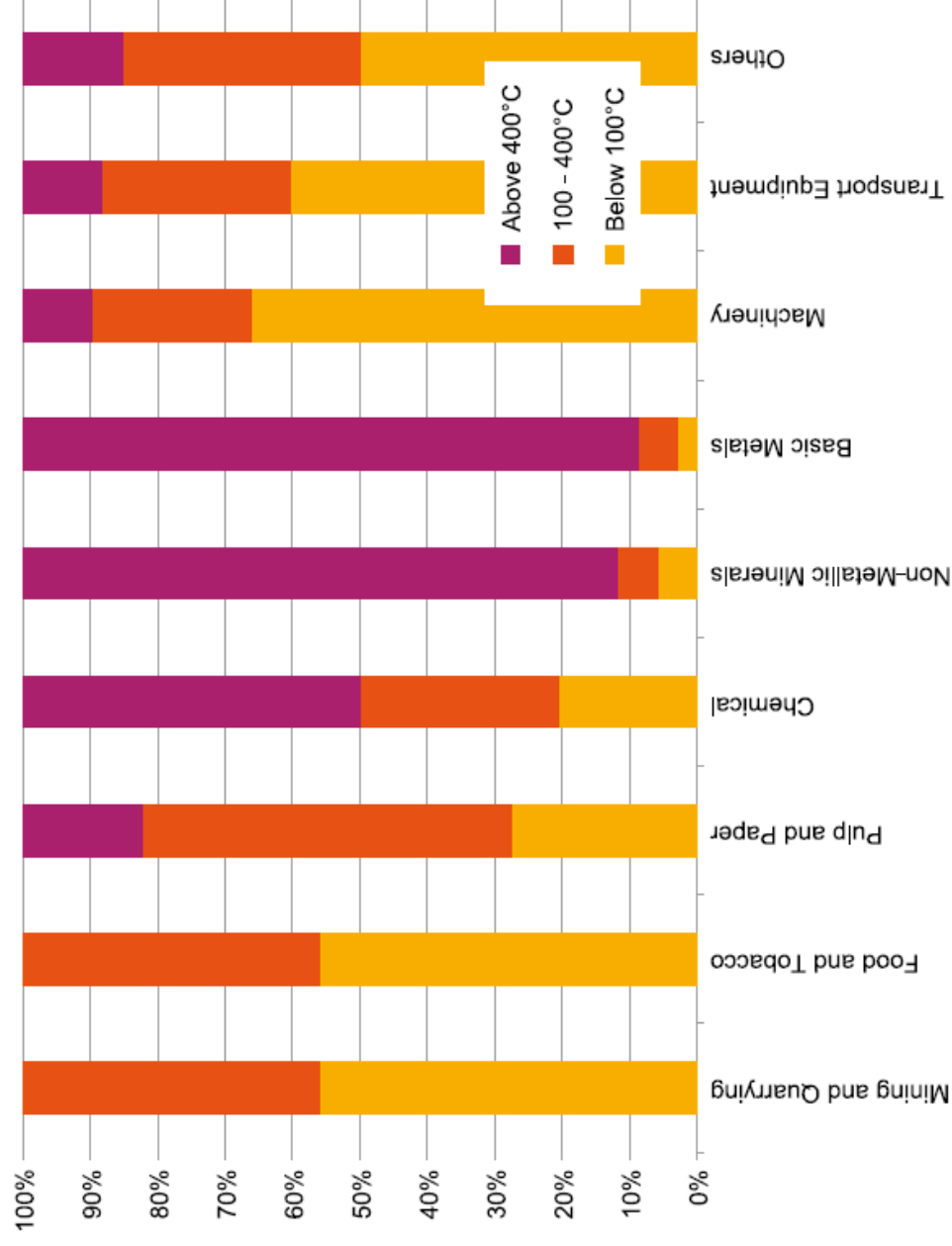
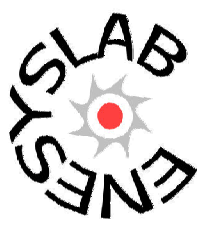
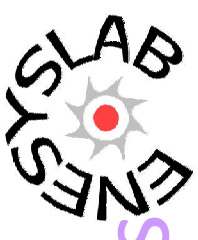


Figure 20: Processes at different temperature levels in different industry sectors; Data for 2003, 32 Countries: EU25 + Bulgaria, Romania, Turkey, Croatia, Iceland, Norway and Switzerland. (Source: ECOHEATCOOL (IEE ALTENER Project), The European Heat Market, Work Package 1, Final Report published by Euroheat & Power)

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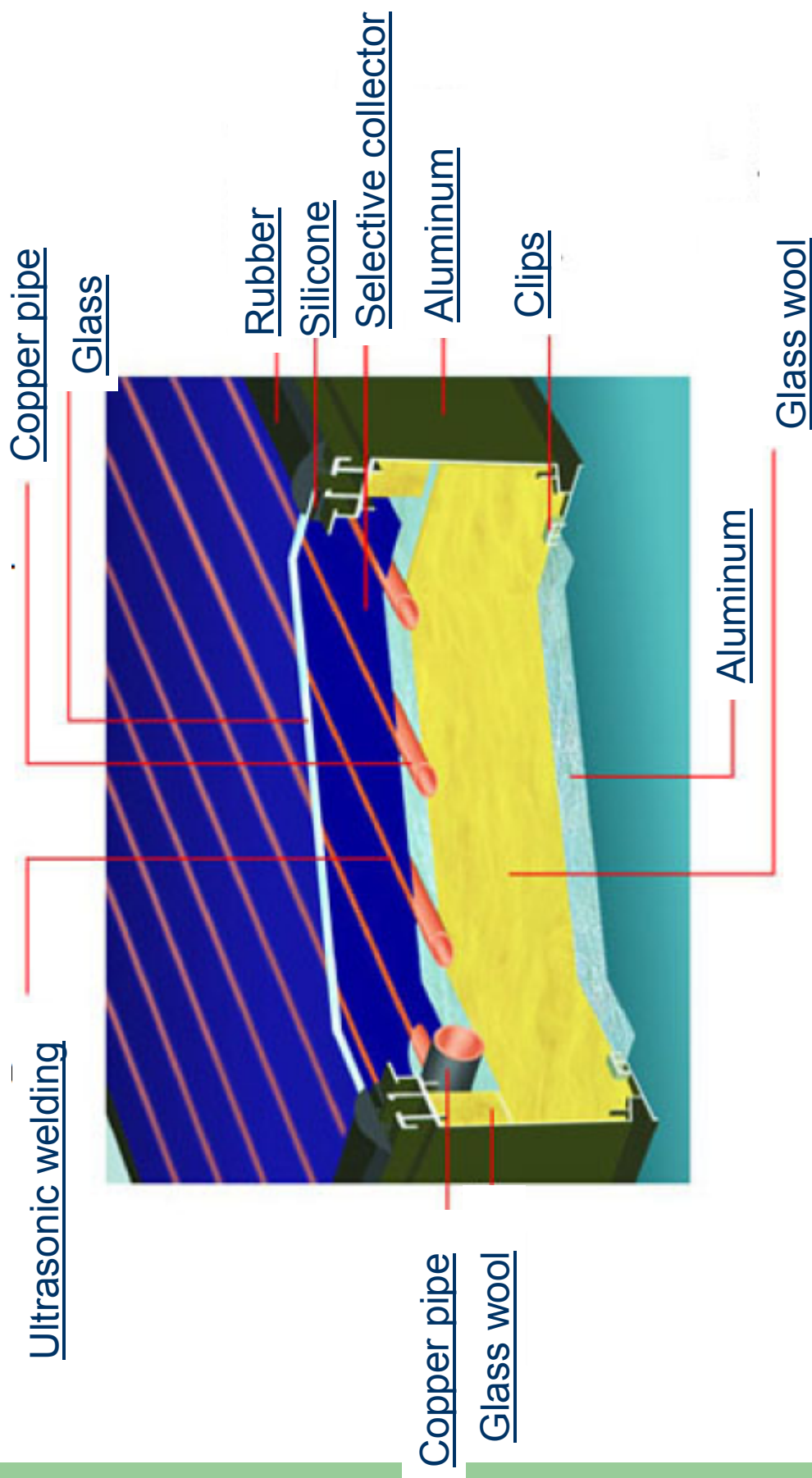
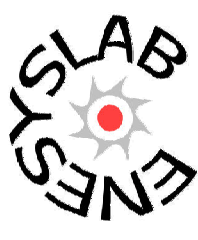


Solar Collectors

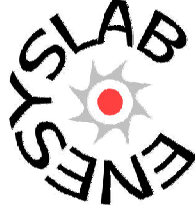
- Flat plate collectors
- Vacuum tubes
 - Heat pipes
 - Vacuum tube forced circulation



Flat Plate Collectors



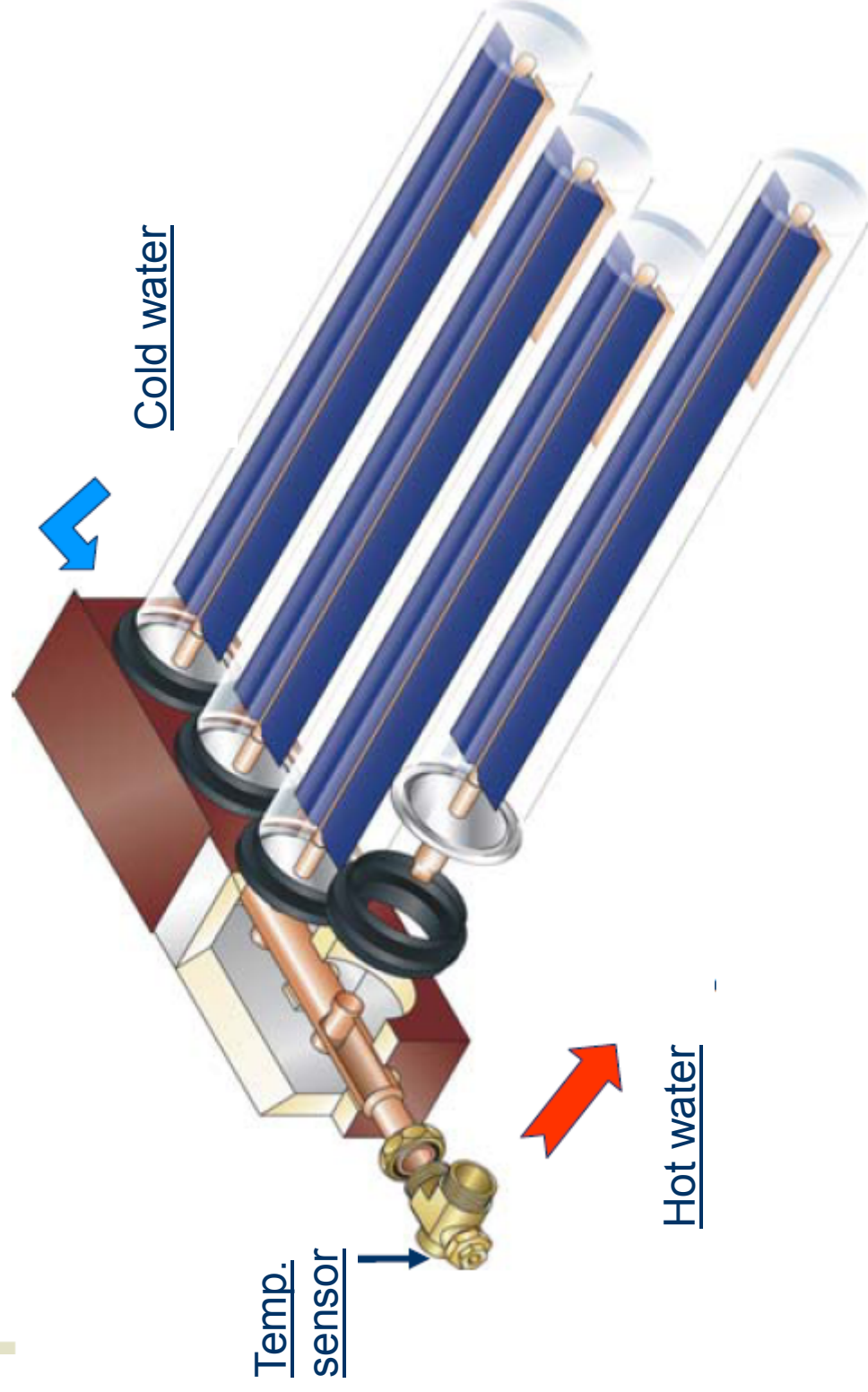
Flat Plate Collectors



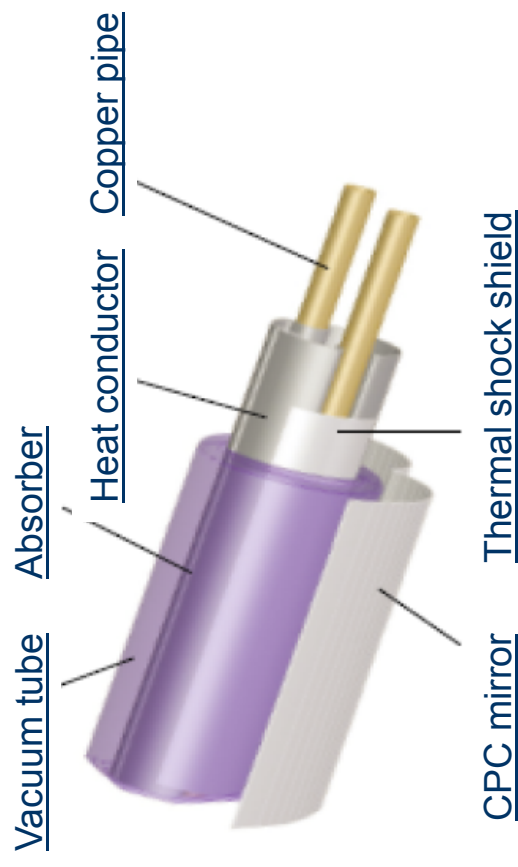
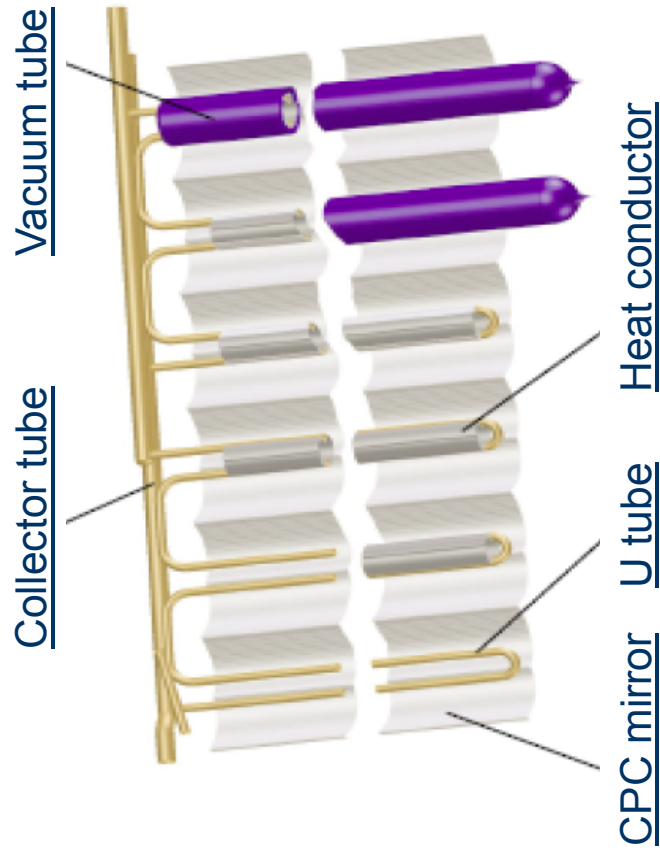
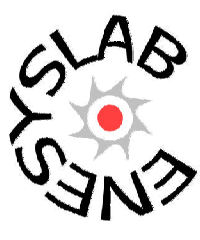
Specifications IDMK

Name	IDMK25	IDMK12
Collector type	pre-assembled collector	
Installation type	in-roof	
Gross surface area	2.52m ²	1.25m ²
Opening surface area	2.32m ²	1.10m ²
Absorber surface area	2.28m ²	1.08m ²
Height	2058mm	1015mm
Width	1227mm	1227mm
Depth	105mm	105mm
Empty weight	49kg	25kg
Collector capacity	1.7l	1.2l
Connections	1" or Cu22 screw connection	
Absorber	structure, copper full-surface absorber with highly-selective vacuum coating	
Wiring	Harp wiring	
Absorption (α)	0.95	
Emission (ϵ)	0.05	
Housing	wooden frame with aluminium section, 4 mm hardboard	
Heat insulation	50mm mineral wool	
Collector glazing	3,2mm tempered solar safety glass	
No. plates	1	
Conversion factor η_0	0.79	
Angle correction factor K_{50°	0.93	
Minimum output	525kWh/(m ² a)	
Max. operating pressure	10 bar	
Idle temperature	180 °C plus ambient temperature	
Recommended throughput	15 - 40l/h per m ²	
Module wiring	max. 6 in series	
Min. collector angle	20°	
Max. collector angle	65°	

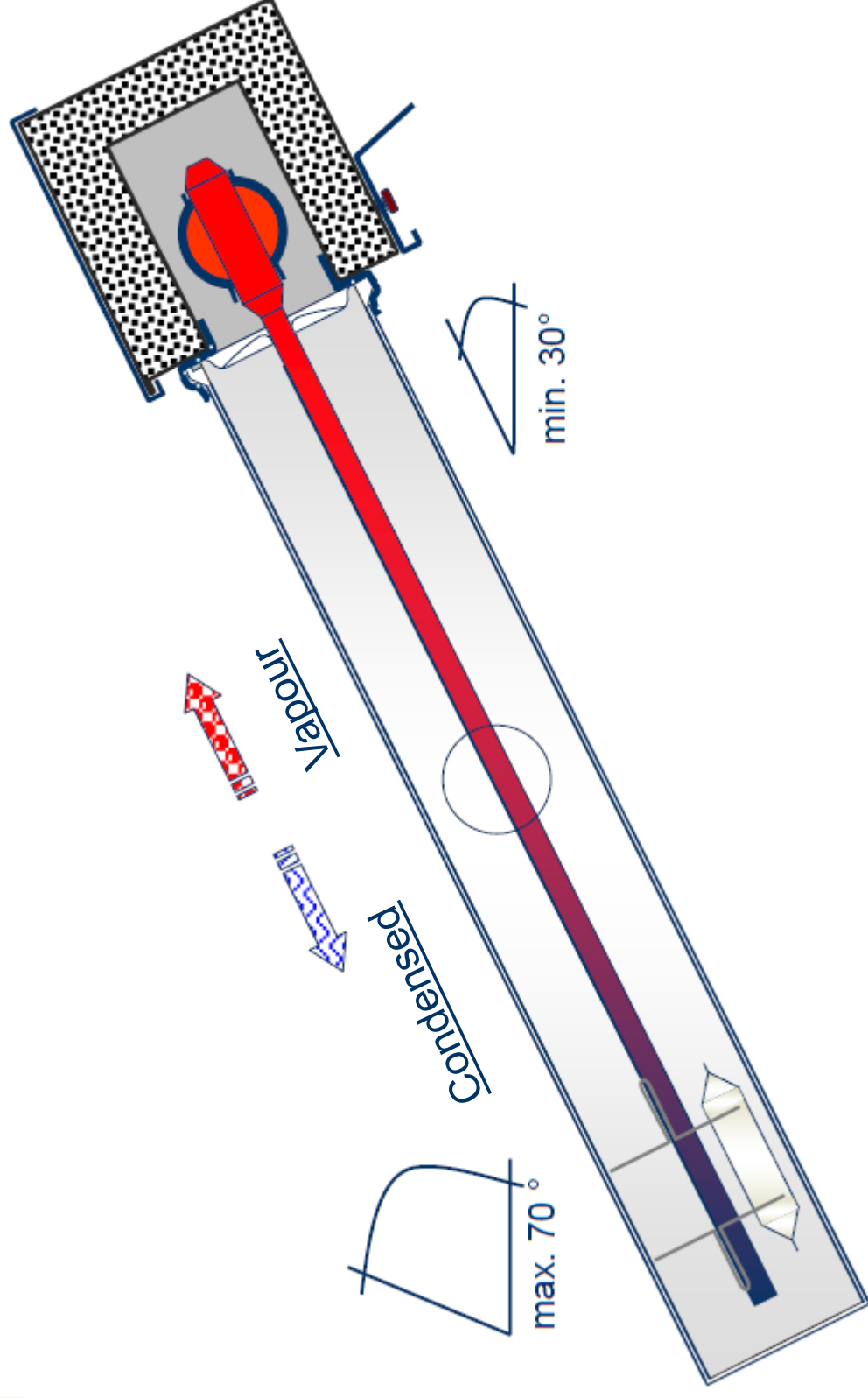
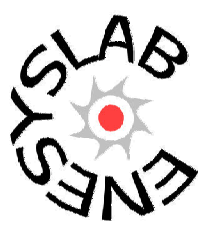
Heat Pipes



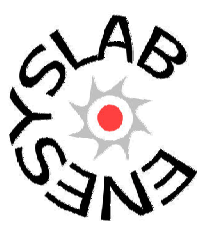
Vacuum Tube Forced Circulation



Heat Pipes



Vacuum Tube Forced Circulation

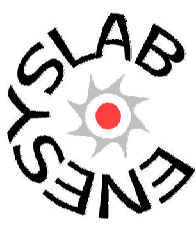


Specifications VK25

Name	VK25
Collector type	evacuated tube collector
Installation type	roof mounted
Gross surface area	2.57m ²
Opening surface area	2.21m ²
Absorber surface area *	2.36m ²
Height	1647mm
Width	1560mm
Depth	107mm
Empty weight	42kg
Collector capacity	2.3l
Connections	3/4" flat sealing
Absorber	aluminium
Wiring	direct flow U pipes (Cu pipes in evacuated tubes), parallel switching
Absorption (α)	0.96
Emission (ϵ)	0.06
Housing	aluminium
Heat insulation	tube: evacuated; collector: mineral wool
Collector glazing	evacuated tubes (borosilicate glass)
No. plates	14 evacuated tubes
Conversion factor η_0	0.64
Angle correction factor K_{50°	0.947
Minimum output	525kWh/(m ² a)
Max. operating pressure	10bar
Idle temperature	270° C plus ambient temperature
Recommended throughput	ca. 15 - 30l/h per m ²
Module wiring	max. 6 in series
Min. collector angle	15°
Max. collector angle	75°

*) jacket surface area of inner tubes

Collectors choiche



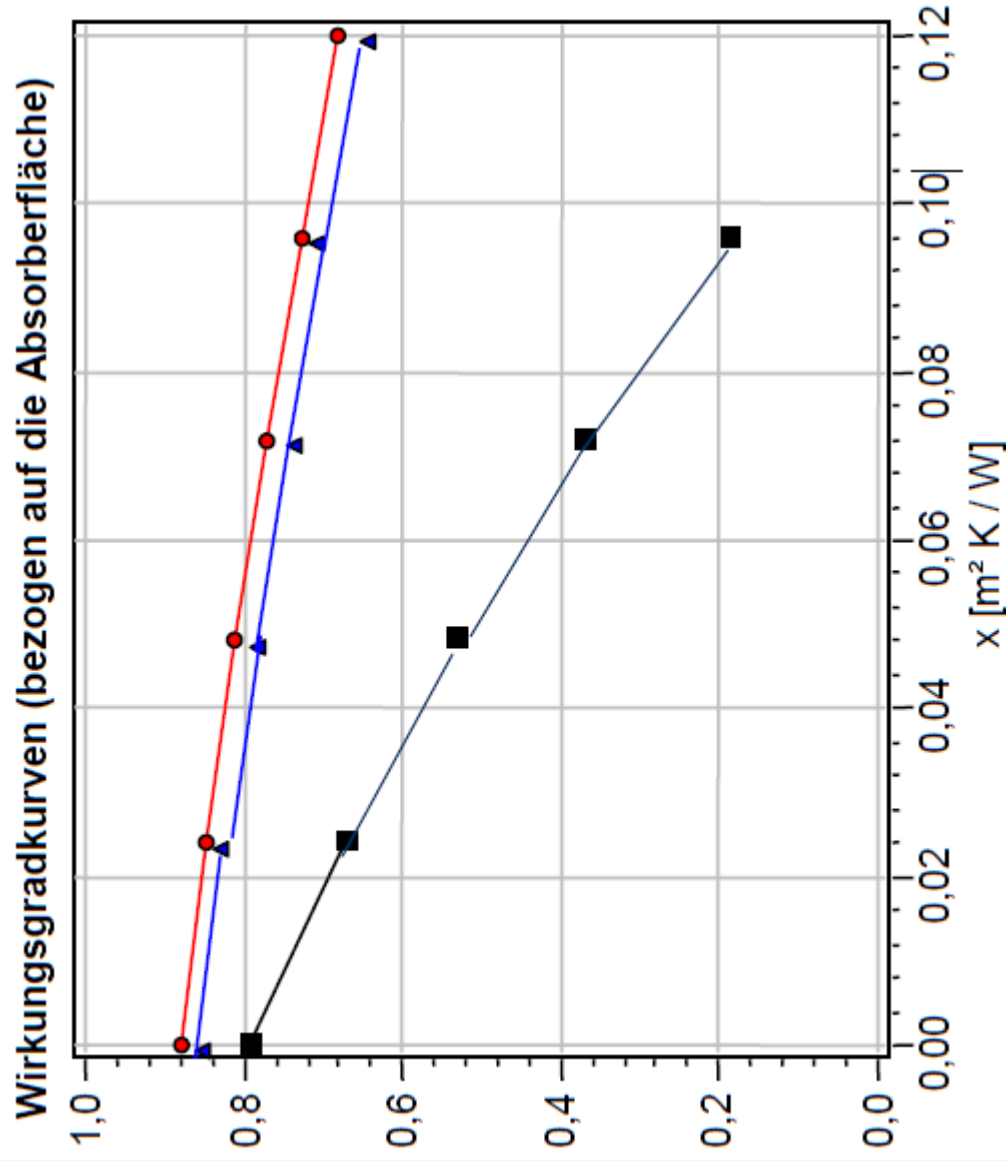
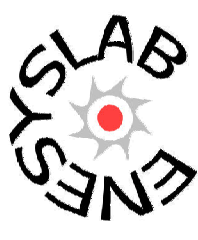
Flat collectors

- Low/medium grade heat required
- Lower cost
- Bigger collector surface required
- Easier integration in roof/structures
- Good efficiency required mainly with high ambient temperature

Vacuum tube

- High/medium grade heat required
- Higher cost
- Smaller collector surface required
- Integration in roof/structures more difficult
- Good efficiency required with low ambient temperature as well

Collector efficiency

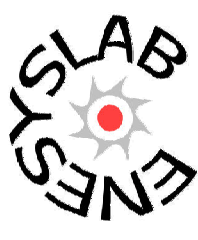


- Flat collector
- Heat pipe
- ▲— Vacuum tube forced circulation

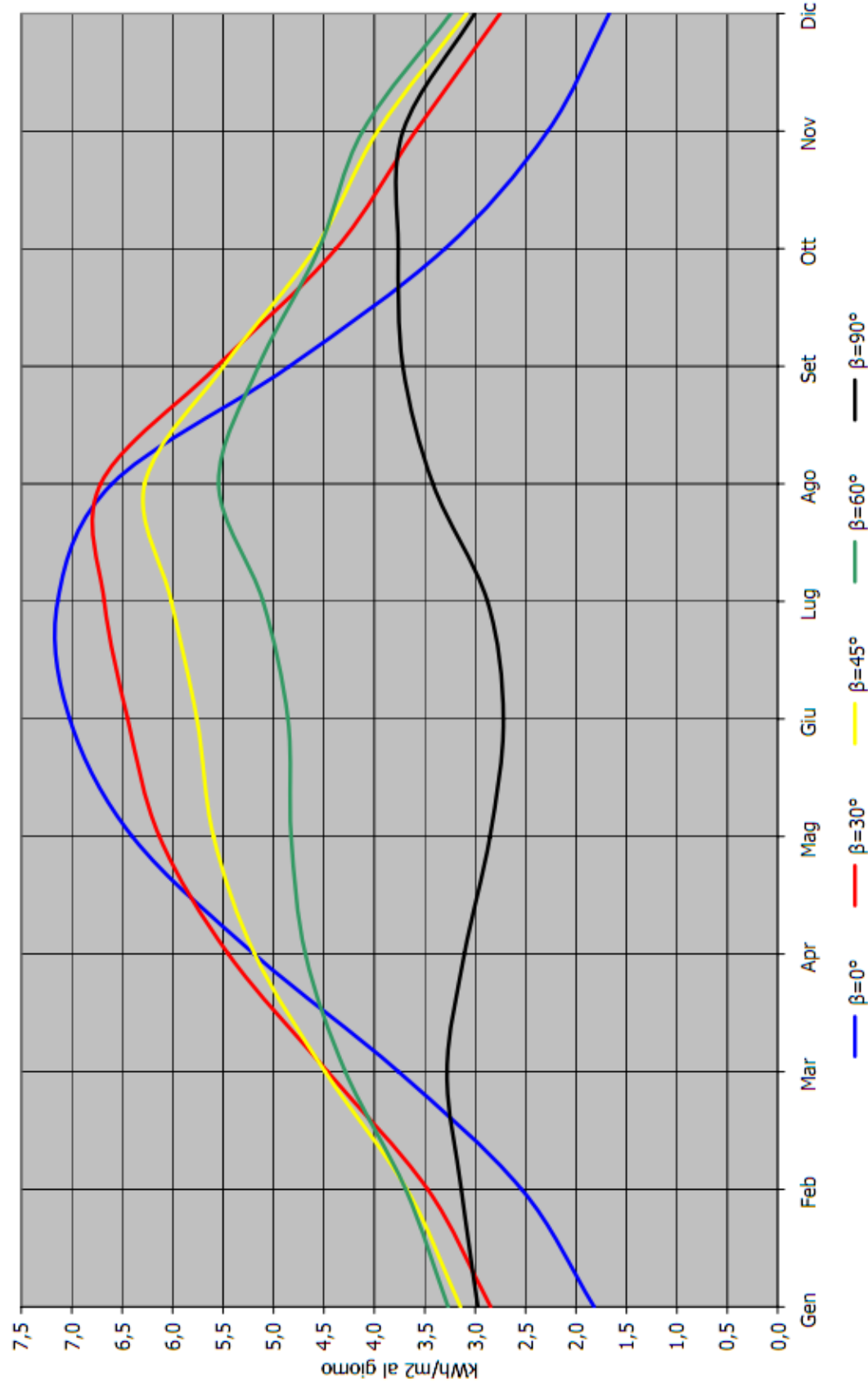
$$\eta(x) = \eta_0 - a_1 \cdot x - a_2 \cdot x^2 \cdot G_k$$

$$x = (T_m - T_a) / G_k$$

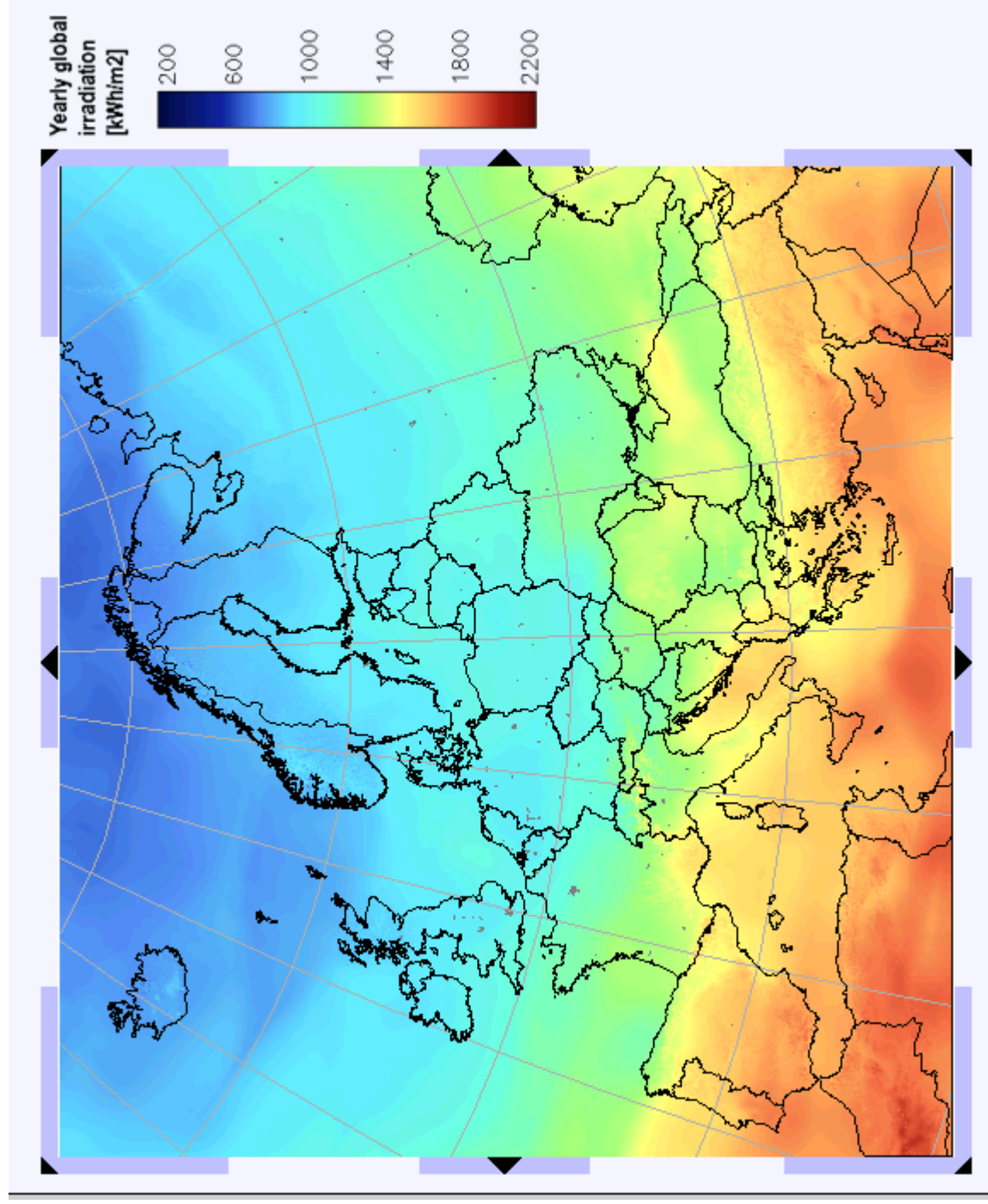
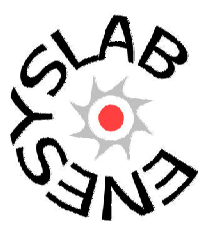
Solar Thermal Design



Total irradiation. Collector facing South



Solar Thermal Design



Solar Cooling

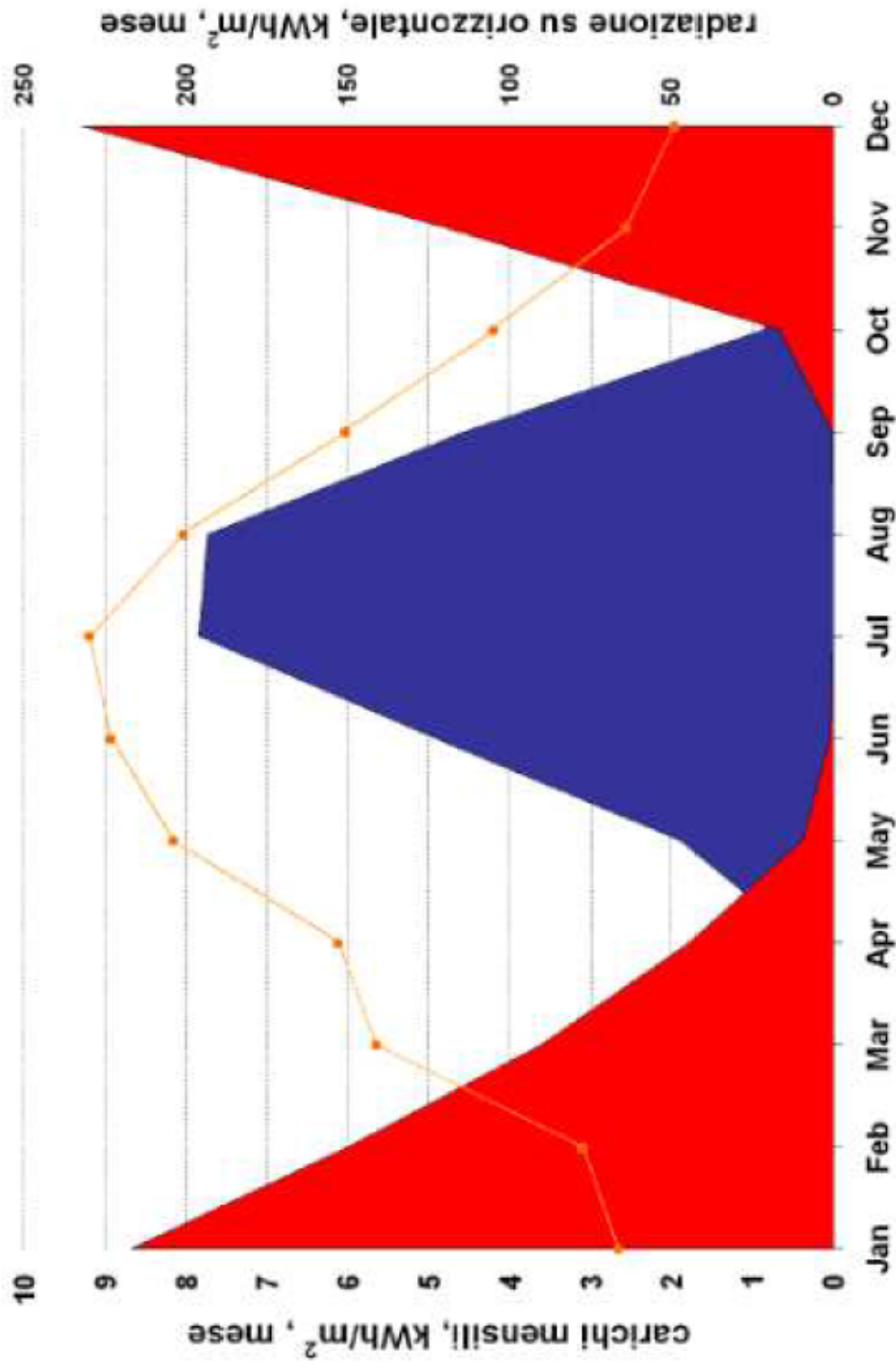
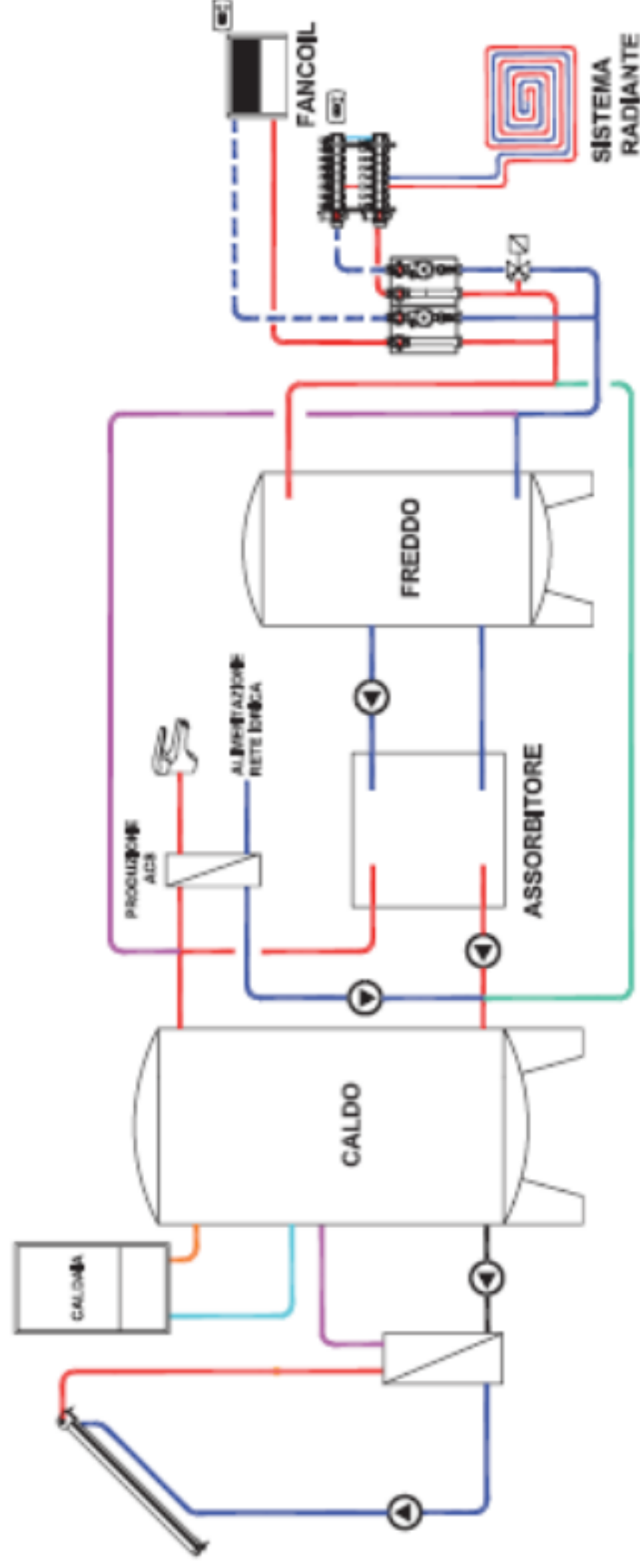
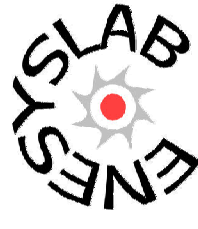


Fig. 1.1 – Andamento richiesta energia frigorifera.

Solar Cooling





REFERENCES (selection)

- Periodicals
 - Fuel cell Bulletin, Elsevier Science
 - Fuel Cell Technology News, BCC
 - Int. J. Hydrogen Energy, Elsevier
 - J. of Power Sources, Elsevier
 - J. of Energy Resources Technology, Elsevier
 - ...
- WEB
 - Fuel Cell 2000 – <http://www.fuelcells.org>
 - CA FC Partnership <http://www.drivingthefuture.org>
 - DOE <http://www.fetc.doe.gov>
 - HyWeb <http://www.hydrogen.org...>
- Codes and standards
 - American National Standards Institute (ANSI) Z21.83