POLITECNICO
MILANO 1863

Terminology: Waste-To-Energy (WTE) ↔ Energy from Waste (EfW)

1) **Energy recovery is an essential ingredient of sustainable waste management**

2) **EfW with grate combustors and steam Rankine cycle dominates the production of electricity and heat from waste**

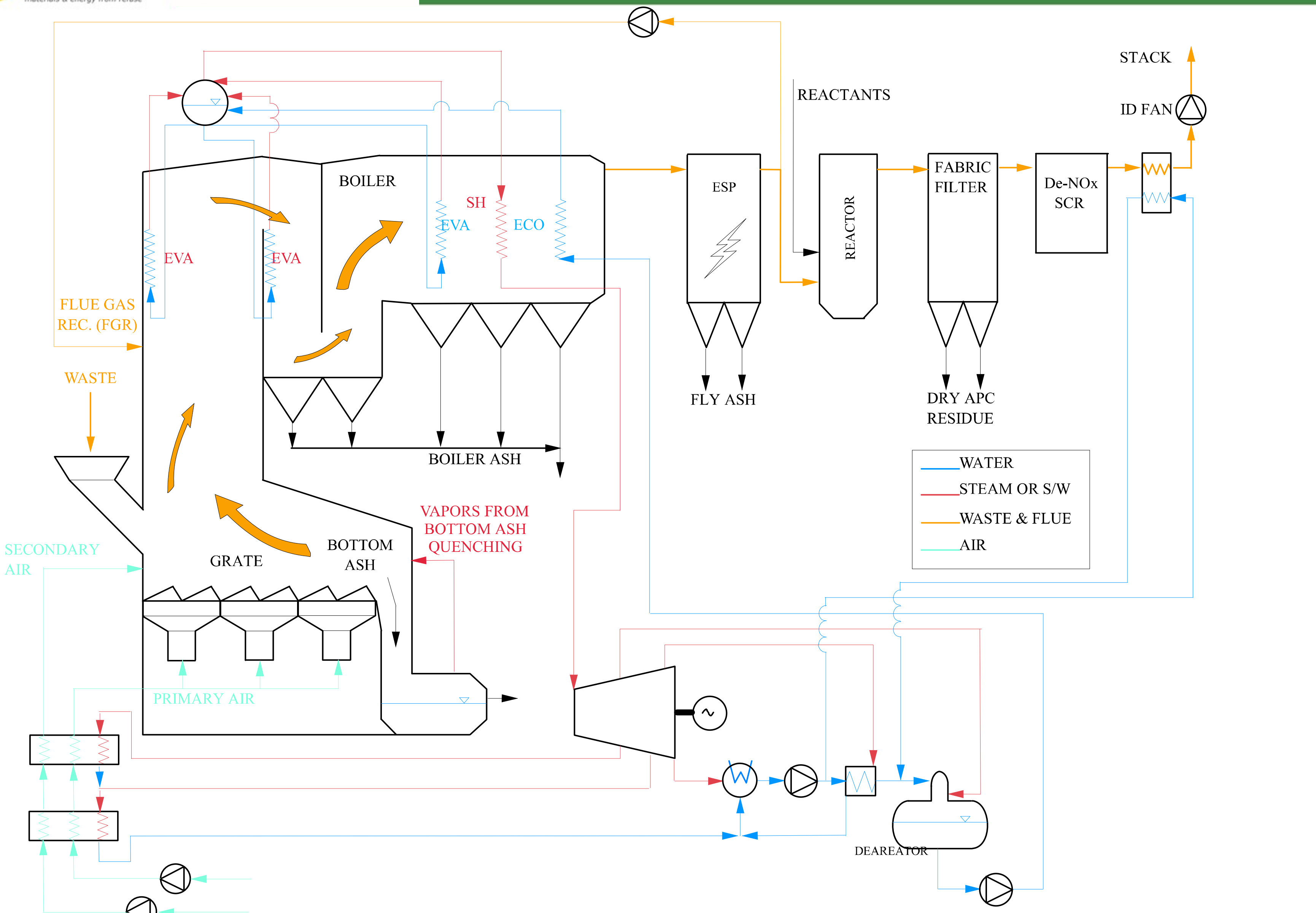
3) **Net Life-Cycle fossil CO_2 emissions from EfW plants are low – even negative in several instances - but the goals set by the Paris agreement call for further efforts**

4) **Reducing direct CO_2 emissions from EfW plants can further improve their environmental compatibility and improve their acceptance by the public opinion**

5) **Post-combustion CO_2 capture appears the most suitable technology to reduce direct CO_2 emissions from EfW plants**

6) **This work aims at assessing the performances achievable by post-combustion capture via Molten Carbonate Fuel Cells (MCFC)**

EfW plant


STACK
ID FAN
REACTANTS
BOILER
SH
EVA
ECO
EVA
EVA
ESP
REACTOR
FABRIC FILTER
De-NOx SCR
FLUE GAS REC. (FGR)
WASTE
FLY ASH
DRY APC RESIDUE
BOILER ASH
WATER
STEAM OR S/W
WASTE & FLUE
AIR
VAPORS FROM BOTTOM ASH QUENCHING
BOTTOM ASH
GRATE
SECONDARY AIR
PRIMARY AIR
DEAREATOR

EfW plant

Nominal thermal capacity, MW_{LHV}	200.0
No. of parallel lines	3
Design LHV, MJ/kg	10.34*
Waste throughput, t/h	69.6
Treatment capacity (@ 8,000 h/y), kt/y	557.0
Steam pressure, bar(a)	50.0
Steam temperature, °C	440
Nominal steam production, t/h	233.9
Nominal condensing pressure, bar(a)	0.05
Nominal gross power, MW_E	63.0
Nominal net power, MW_E	56.1

** Reference waste taken from Consonni & Viganò, WM 2011.*

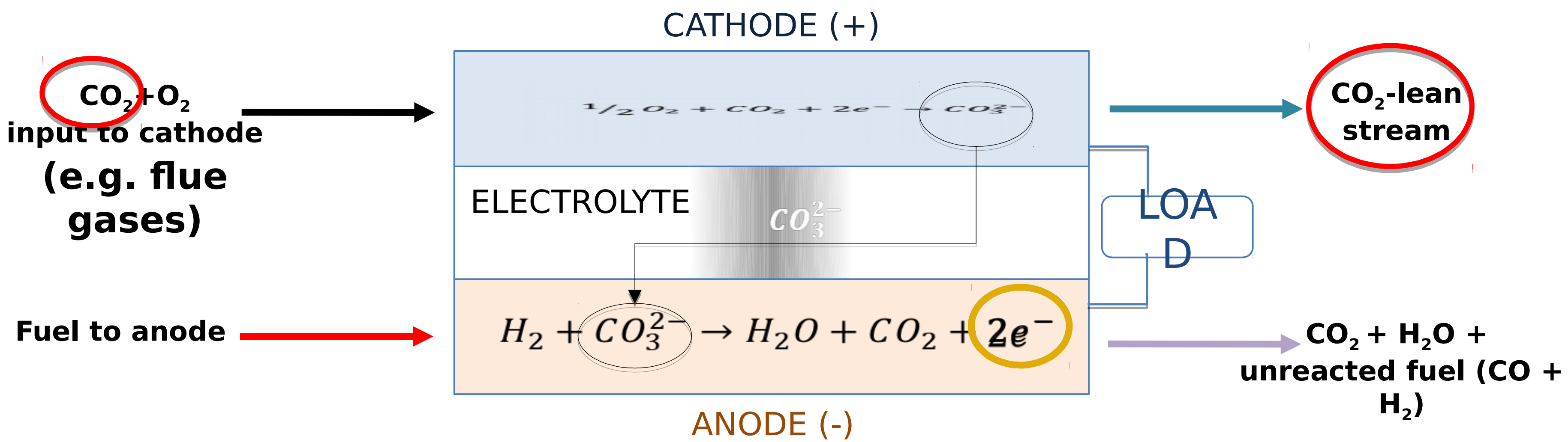
"Only electricity" mode	
Gross el. eff., $\%_{LHV}$	31.5
Net el. eff., $\%_{LHV}$	28.1
Estimated R1	0.75

Expected emission levels*	
CO, mg/m_N^3	5.0
SO_2, mg/m_N^3	0.5
NO_X, mg/m_N^3	35.0
HCl, mg/m_N^3	2.0
HF, mg/m_N^3	0.1
PM, mg/m_N^3	0.3

** Dry gas @ 11% O_2 content*

- Grate combustor with integrated boiler.
- Dry Air Pollution Control (APC) system with use of $NaHCO_3$.
- Low temperature (~180 °C) "tail end" SCR with NH_3 solution.

Molten Carbonate Fuel Cell



Temperature range: **600-650°C**

- Overall REDOX $H_2 + 1/2\ O_2 + CO_{2,cathode} \rightarrow H_2O + CO_{2,anode} + heat$
- Steam reforming $C_nH_m + nH_2O + \boldsymbol{heat} \rightarrow \left(\frac{m}{2} + n\right) H_2 + nCO$
- Water gas shift $CO + H_2O \leftrightarrow H_2 + CO_2 + \boldsymbol{heat}$

Overall exothermic
(in this application)

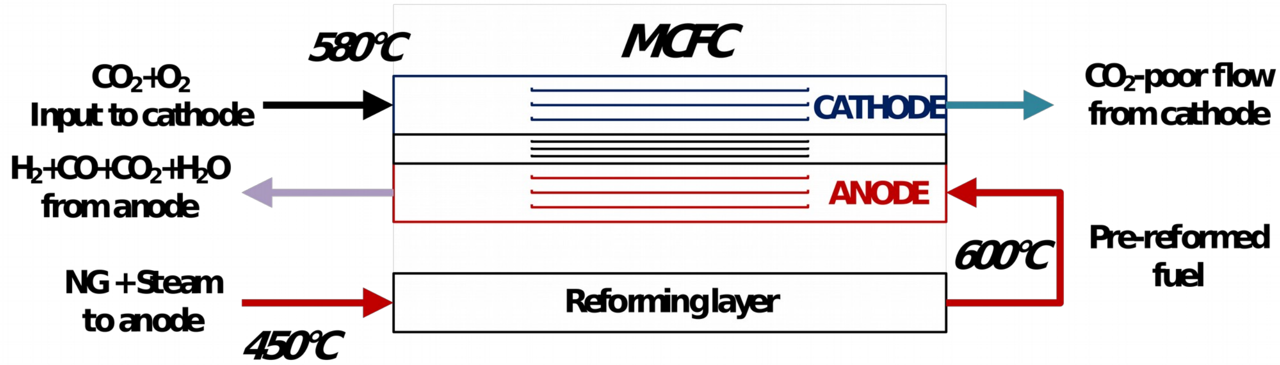
$$\eta_{el,MCFC} \propto V_{cell} = E_{Nerst} - \Delta V_{losses}$$

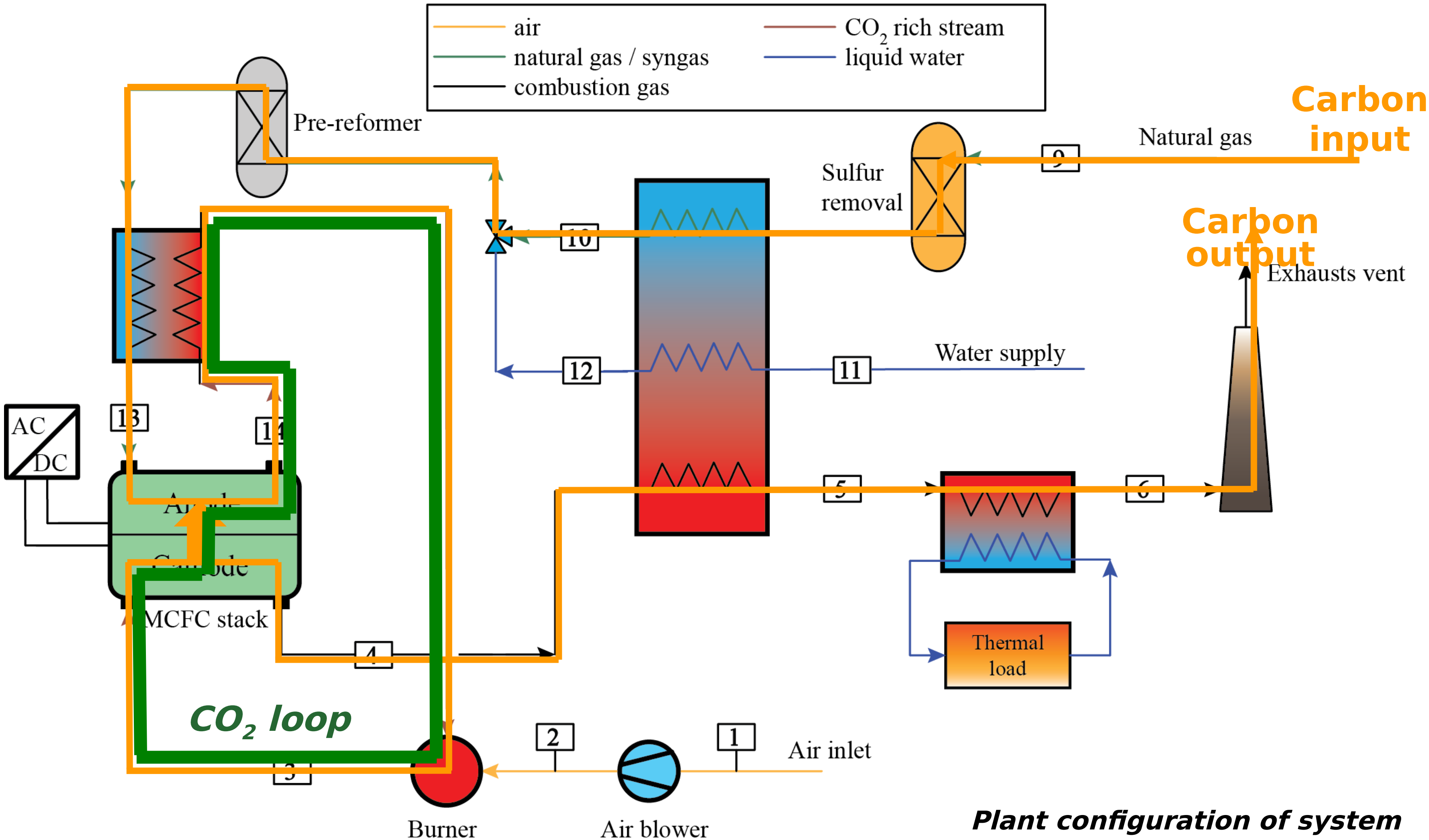
$$E_{Nerst} = \frac{\Delta G}{nF} + \frac{RT}{nF} ln\left(\frac{x_{H_2an}\,(x_{O_2cath})^{0.5}\,x_{CO_2cath}}{x_{H_2Oan}\,x_{CO_2an}}\right)$$

Basic features of the MCFC

In a MCFC carbonate ions ($CO_3^{=}$) permeate through a Li-K solid matrix electrolyte supported by porous aluminate ($LiAlO_2$) for stability and strength increase. H_2 is fed to the anode (Ni), O_2 and CO_2 to the cathode (NiO)

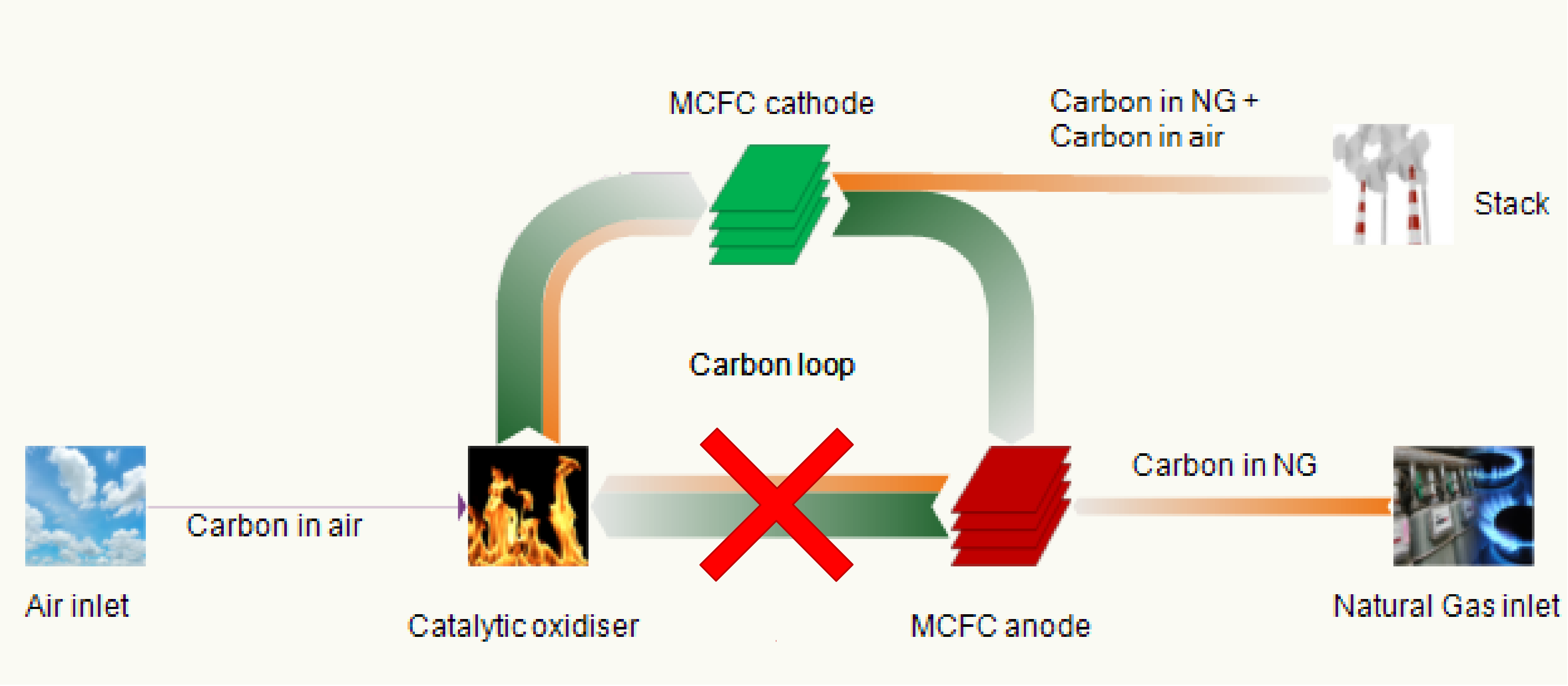
- ↑ ✓ High efficiency (>50% LHV)
- ↑ ✓ Suitable for CCS applications in power and industrial plants
- ↑ ✓ Operating temp. (650°C) favors internal reforming cheap catalyst
- ↑ ✓ Internal reforming increases fuel flexibility (variety of hydrocarbons)
- ↑ ✗ Low NO_x (electroreduction) and SO_2/H_2S (must be removed upstream)
- ↓ ✗ Low material durability (corrosion) and low tolerance to contaminants
- ↓ ✗ Costs and durability





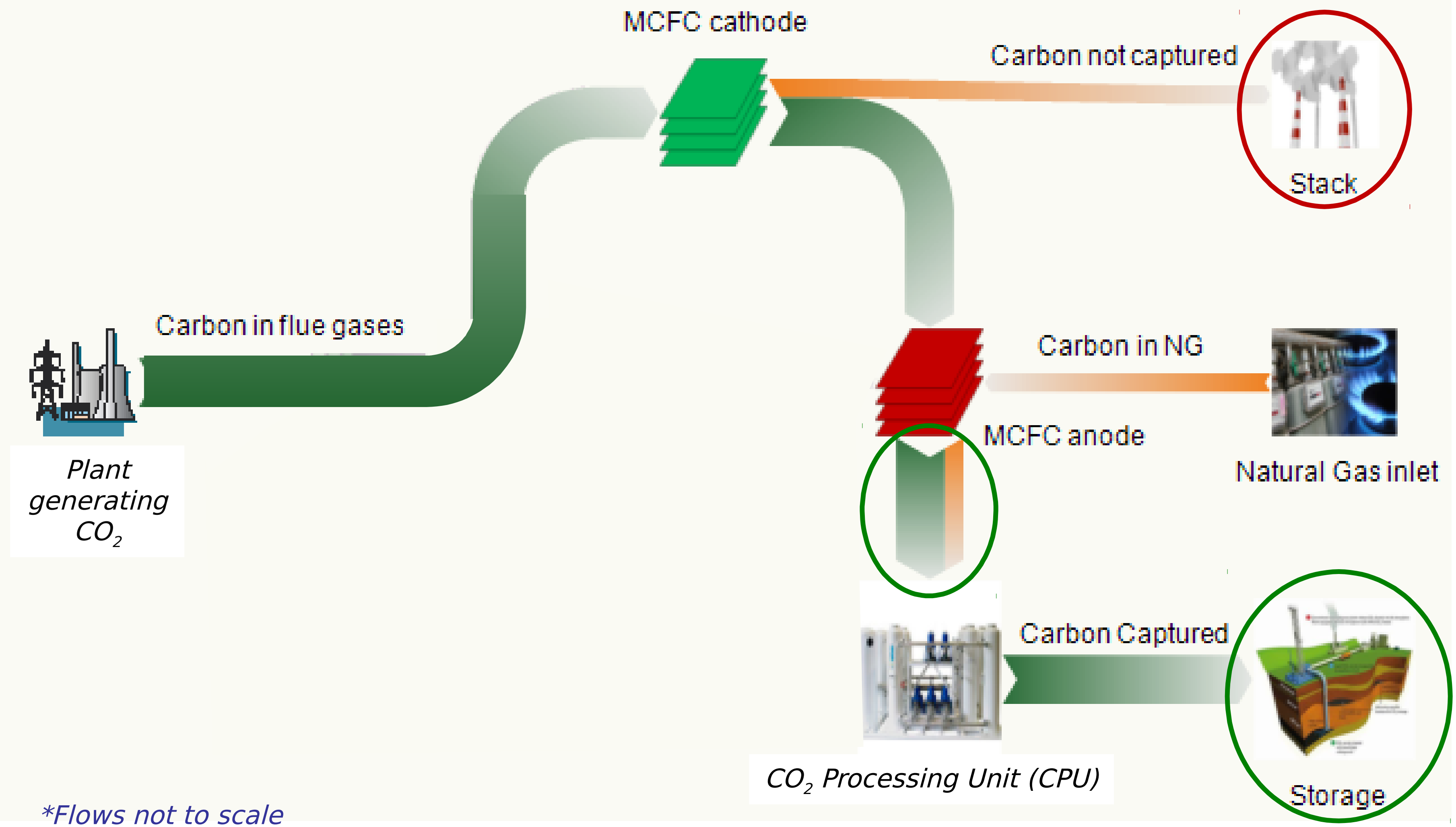
Plant configuration of system offered by Fuel Cell Energy (FCE)

From commercial MCFC to carbon capture



**Flows not to scale*

From commercial MCFC to carbon capture



*Flows not to scale

CO_2 Capture by MCFCs

Maurizio Spinelli[1]
Politecnico di Milano, Via Lambruschini 4, Milano 20156, Italy
e-mail: maurizio.spinelli@polimi.it
Stefano Campanari
Politecnico di Milano, Via Lambruschini 4, Milano 20156, Italy
e-mail: stefano.campanari@polimi.it
Stefano Consonni
Politecnico di Milano, Via Lambruschini 4, Milano 20156, Italy
e-mail: stefano.consonni@polimi.it
Matteo C. Romano
Politecnico di Milano, Via Lambruschini 4, Milano 20156, Italy
e-mail: matteo.romano@polimi.it
Thomas Kreutz
Princeton Environmental Institute, Princeton University, Princeton, NJ 08544
e-mail: kreutz@princeton.edu
Hossein Ghezel-Ayagh
Fuel Cell Energy, Inc., 3 Great Pasture Road, Danbury, CT 06813
e-mail: hghezel@fce.com
Stephen Jolly
Fuel Cell Energy, Inc.,

Molten Carbonate Fuel Cells for Retrofitting Postcombustion CO_2 Capture in Coal and Natural Gas Power Plants

The state-of-the-art conventional technology for postcombustion capture of CO_2 from fossil-fueled power plants is based on chemical solvents, which requires substantial energy consumption for regeneration. A promising alternative, available in the near future, is the application of molten carbonate fuel cells (MCFC) for CO_2 separation from postcombustion flue gases. Previous studies related to this technology showed both high efficiency and high carbon capture rates, especially when the fuel cell is thermally integrated in the flue gas path of a natural gas-fired combined cycle or an integrated gasification combined cycle plant. This work compares the application of MCFC-based CO_2 separation process to pulverized coal fired steam cycles (PCC) and natural gas combined cycles (NGCC) as a "retrofit" to the original power plant. Mass and energy balances are calculated through detailed models for both power plants, with fuel cell behavior simulated using a 0D model calibrated against manufacturers' specifications and based on experimental measurements, specifically carried out to support this study. The resulting analysis includes a comparison of the energy efficiency and CO_2 separation efficiency as well as an economic comparison of the cost of CO_2 avoided (CCA) under several economic scenarios. The proposed configurations reveal promising performance, exhibiting very competitive efficiency and economic metrics in comparison with conventional capture technologies. Application as a MCFC retrofit yields a very limited (< decrease in efficiency for both power plants (PCC and NGCC), a strong redu (>80%) in CO_2 emission and a competitive cost for CO_2 avoided (25–40 €/ton).
[DOI: 10.1115/1.4038601]

ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 63 (2014) 6517 – 6526
Energy Procedia
GHGT-12

Application of Molten Carbonate Fuel Cells in Cement Plants for CO_2 Capture and Clean Power Generation

Maurizio Spinelli[a], Matteo C. Romano[a]*, Stefano Consonni[a], Stefano Campanari[a]
Maurizio Marchi[b], Giovanni Cinti[b]
[a]Politecnico di Milano, Department of Energy, via Lambruschini 4, 20156 Milano, Italy
[b]C.T.G. - Italcementi Group, via Camozzi 124, 24121 Bergamo, Italy

ELSEVIER
Contents lists available at ScienceDirect
International Journal of Greenhouse Gas Control
journal homepage: www.elsevier.com/locate/ijggc

ELSEVIER
Contents lists available at ScienceDirect
International Journal of Greenhouse Gas
journal homepage: www.elsevier.com/locate/ij

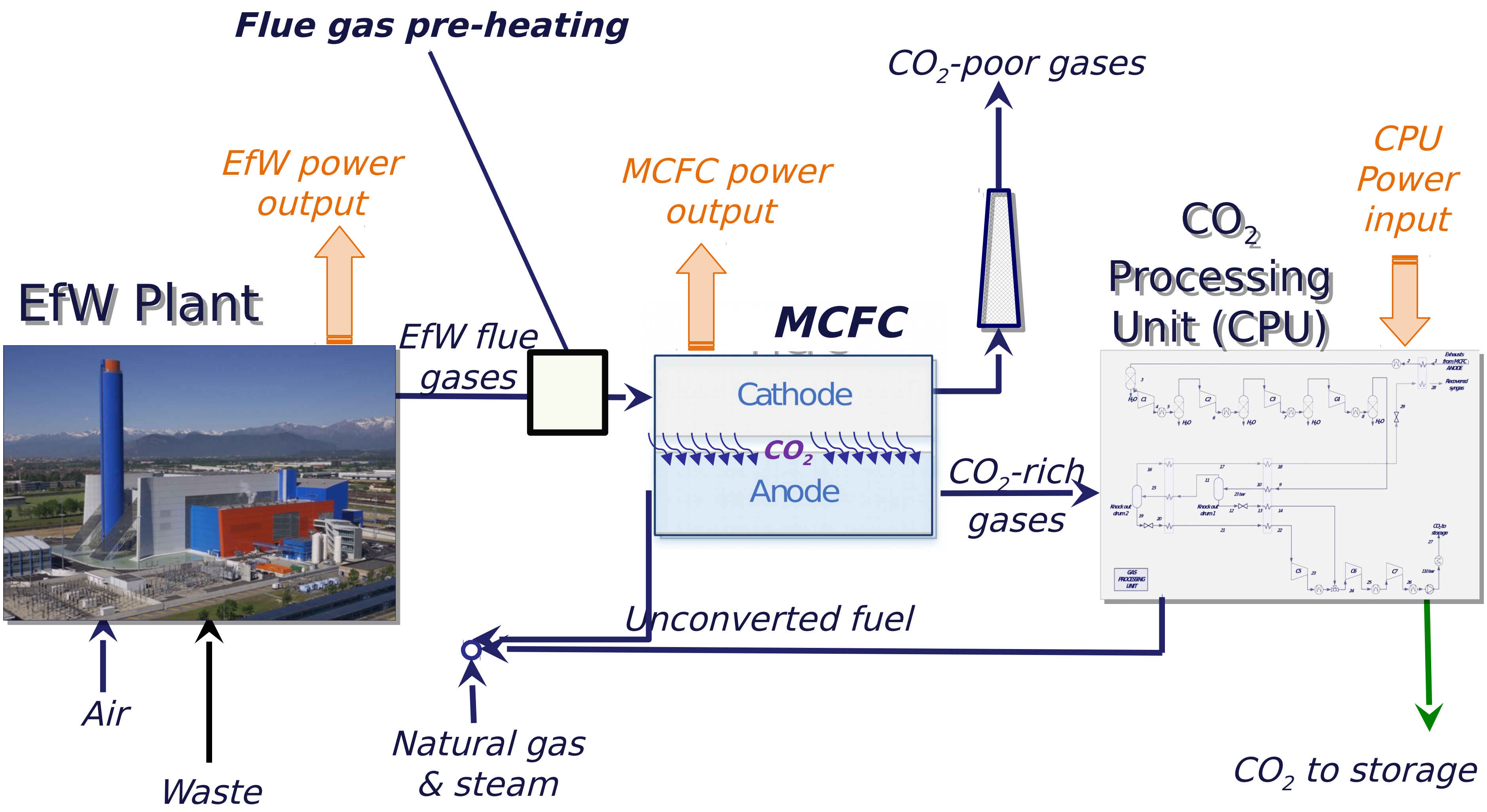
Molten Carbonate Fuel Cells retrofits for CO_2 capture and enhanced energy production in the steel industry

Luca Mastropasqua[a,*], Lorenzo Pierangelo[a,b], Maurizio Spinelli[b], Matteo C. Romano[a], Stefano Campanari[a], Stefano Consonni[a,b]
[a] Politecnico di Milano, Department of Energy, Via Lambruschini 4, 20156 Milan, Italy
[b] LEAP scarl, via Nino Bixio 27C, 29121, Piacenza, Italy

CO_2 capture from combined cycles integrated with Molten Carbonate Fuel Cells

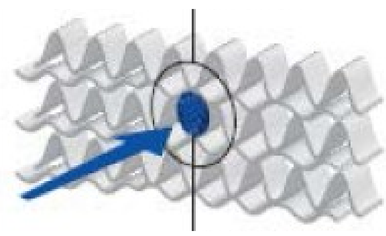
Stefano Campanari *, Paolo Chiesa, Giampaolo Manzolini
Politecnico di Milano, Dipartimento di Energia, Via Lambruschini 4, 20156 Milano, Italy

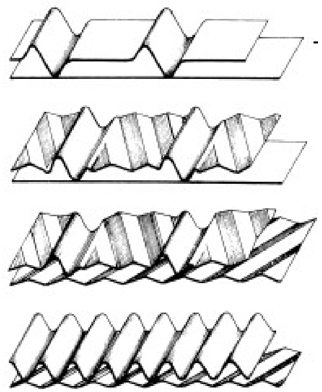
Plant configuration

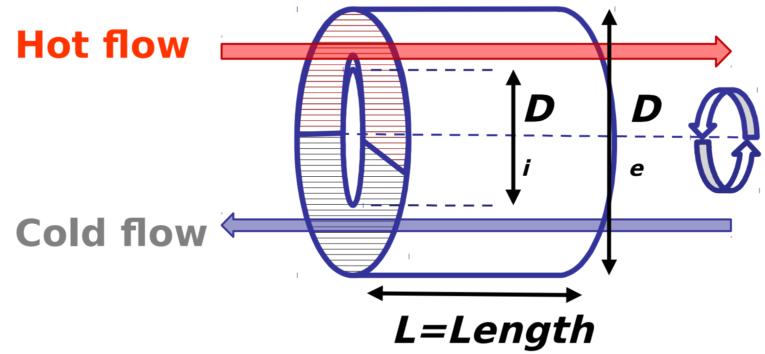


Flue gas preheating ahead of

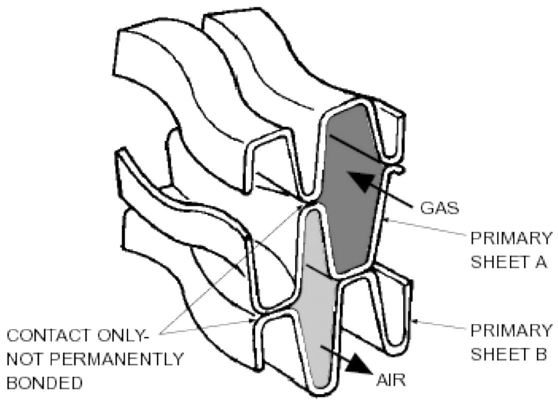
___Option 1 – LJUNGSTROM REGENERATOR___

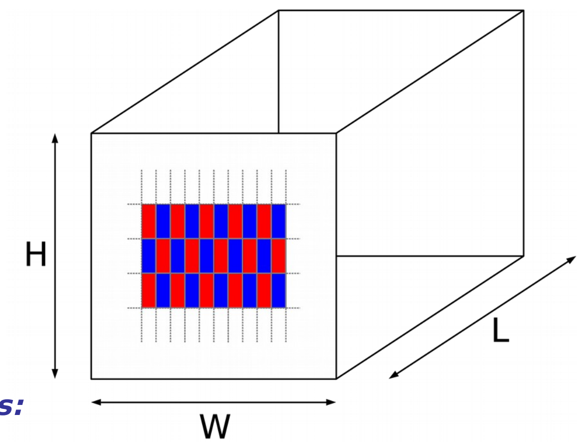






___Option 2 - COMPACT HEAT EXCHANGER___





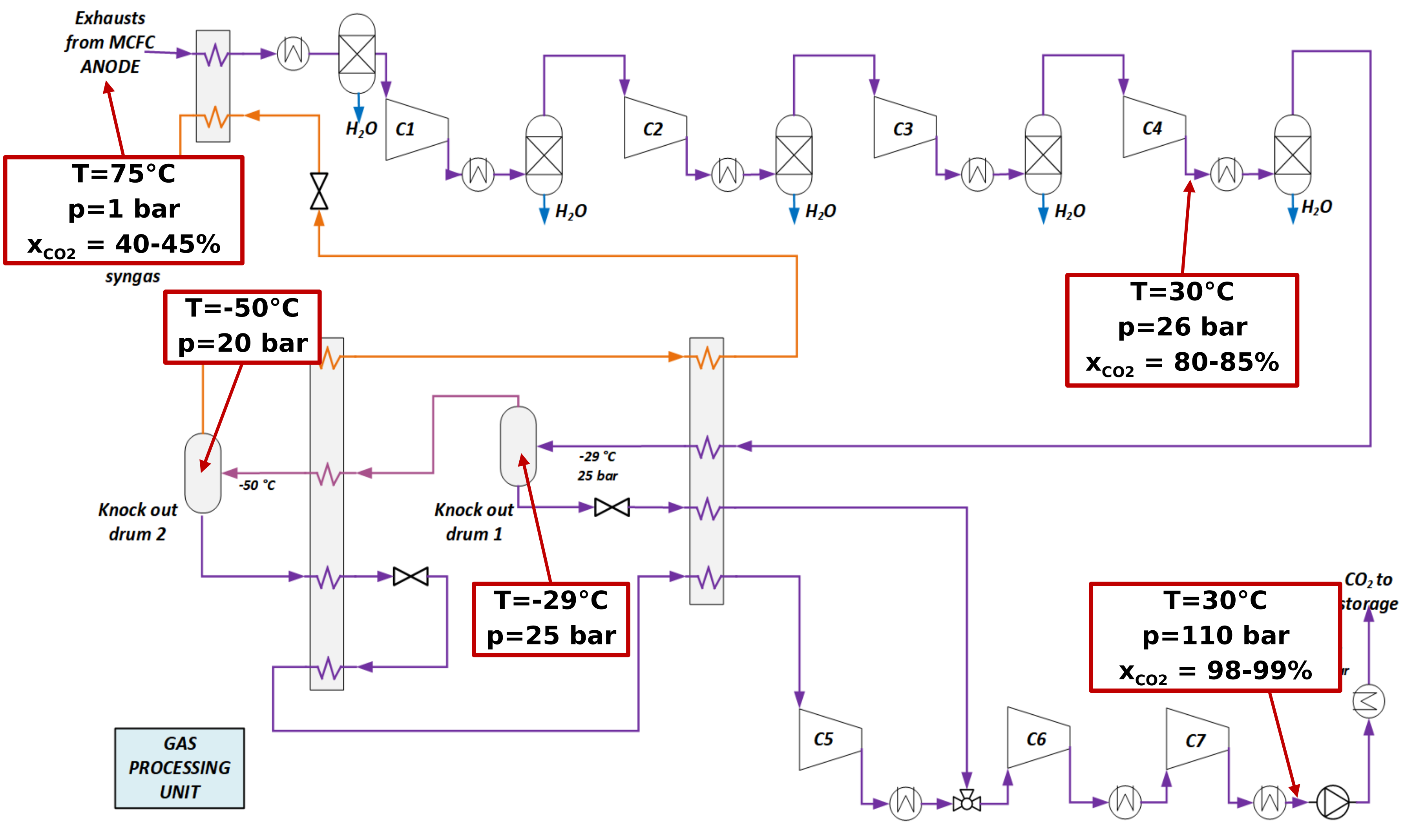
Features:

- ✓ ***Stamped and folded metal foil***
- ✓ ***Chessboard arrangement - Square matrix***
- ✓ ***Counter-flow configuration***

INDUSTRIAL REFERENCE:

Heat exchanger type like Solar Mercury 50 GT's recuperator

CO_2 Processing Unit (CPU)



Assumptions

EfW Operating conditions	
Primary energy input, MW_{LHV}	200
Net electric power, MW_e	54.9

EfW Effluents properties

Flow rate	Temperature	Pressure	Composition, %vol				
kg/s	°C	bar	Ar	CO_2	O_2	N_2	H_2O
137.9	61.3	1.01	0.8	8.86	7	67.1	16.24

MCFC operating conditions	
Current density	1500 A/m^2
Voltage	0.65-0.72 V
Fuel utilization factor	75%
Steam to carbon ratio	2
Inlet temperature (pre-reformer layer)	450°C
Inlet temperature (anode)	600°C
Inlet temperature (cathode)	575°C
Outlet temperature (anode and cathode)	645°C
Pressure losses on anode / cathode sides	3 kPa /2kPa
Heat losses (% input thermal power)	1%
DC/AC electrical efficiency	97%
Minimum CO_2 molar fraction at cathode outlet	1%
Minimum O_2 molar fraction at cathode outlet [%]	2.5%

Results

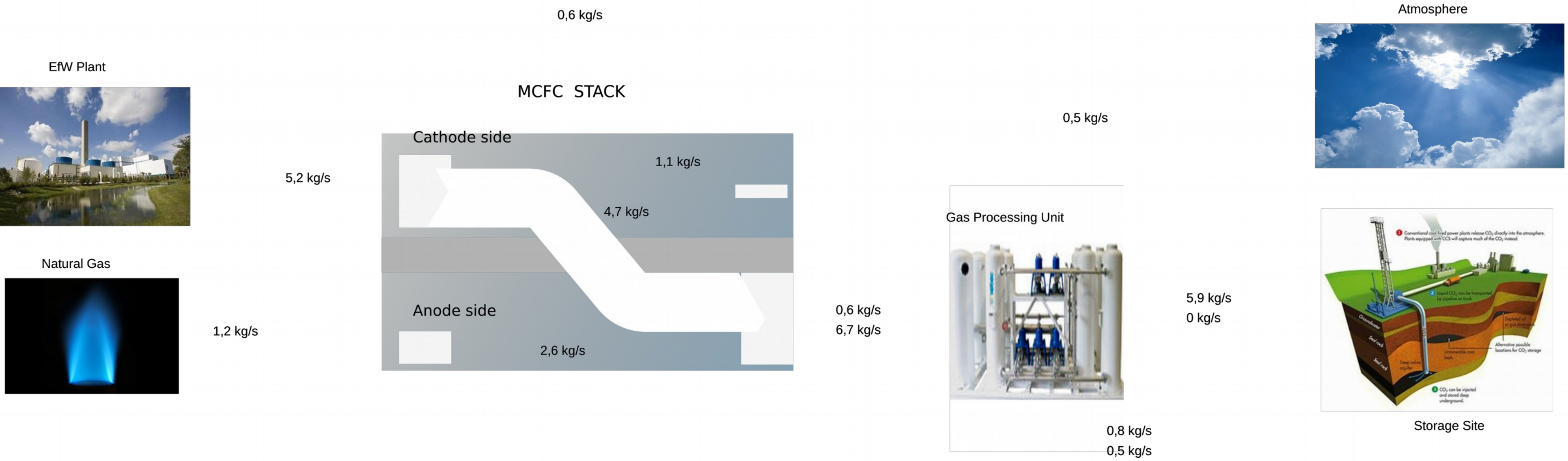
RESULTS	Ref. EfW	EfW+1 MCFC	EfW+2 MCFC
EfW gross electric power*, MW	63.0	64.1	64.1
EfW net electric power*, MW	56.1	54.9	54.9
MCFC gross electric power, MW	-	47	50.2
CO_2 capture and other auxiliary consumptions, MW	-	-14.4	-12.8
Overall net electric power, MW	56.1	87.5	92.3
Natural gas consumption, MW_{LHV}	-	79.5	79.4
1st law energy efficiency, $\%_{LHV}$	28.1	31.3	33.0
NG marginal efficiency, $\%_{LHV}$	-	39.5	47.1
Biogenic CO_2 released by waste combustion+, kg/s	9.7	9.7	9.7
Captured CO_2, kg/s	-	21.6	21.7
Emitted CO_2, kg/s	19.1	1.90	1.9
Fossil CO_2 emission, kg/s	9.4	-7.8	-7.8
Avoided fossil CO_2 emission§, kg/s	-	10.8	11.2
Primary energy consumption for CO_2 capture§, MW_{LHV}	-	27.2	19.1
SPECCA§, MJ_{LHV}/kg_{CO2}	-	2.52	1.70

** Including extra power production due to heat recovery from additional flue gas cooling and extra consumption due to the increased head of the ID fan.*

+ By assuming 51% of carbon in the waste is biogenic.

§ By assuming reference efficiency for electricity from NG of $60\%_{LHV}$.

Carbon balance – single stack



Conclusions / perspectives

1) The use of MCFCs as post-combustion capture technology for EfW plants can yield interesting outcomes in terms of both carbon capture and performances

2) For a large scale EfW plant, fossil CO2 emissions become negative, making the EfW+MCFC plant a CARBON SINK rather than a carbon emitter

3) For the case study considered here - EfW with combustion power 200 MW_{LHV} - net power production increases by 55-65%, at the expense of a natural gas consumption for the MCFC of about 80 MW_{LHV}, i.e. about 40% of the energy input from waste

4) Crucial issue to be verified for technical feasibility is the capability to achieve EfW flue gas purity compatible with the requirements of the fuel cell

5) Additional crucial issue to be verified for industrial feasibility is capital and operating costs

Thank you

for your attention !

www.mater.polimi.it