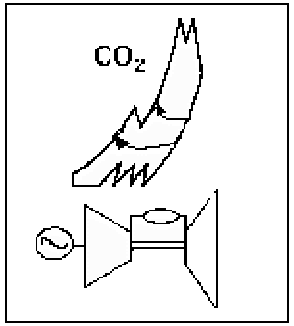

ZERO EMISSION (MATIANT) POWER CYCLES : PERFORMANCE AND COSTS

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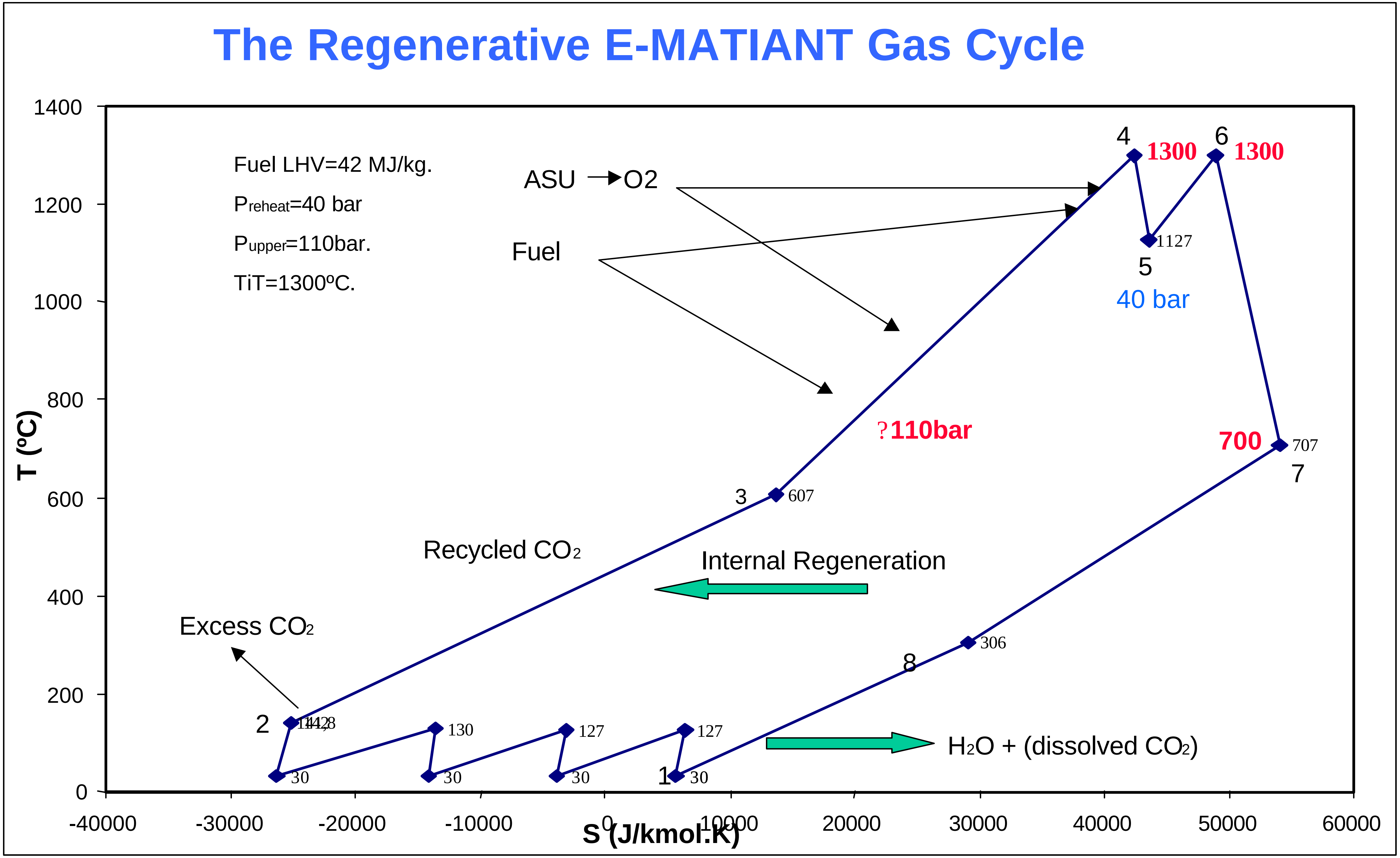
Rationale of oxy-fuel cycles for Near Zero Emission Power Generation

- Use of nearly pure O_2 (+ Ar) as fuel oxidiser so that the flue gas is highly enriched in CO_2 : air separation required
- Use of CO_2 itself or of H_2O as the working fluid in a gas cycle and as thermal ballast for flame t° control in stoichiometric proportions
- Separation of CO_2 and H_2O is easy and there is no longer need for a very penalising scrubber separating CO_2 from N_2 in the flue gas
- Take advantage of the performance of most advanced GTs
- Two main options
  - O_2/ H_2O cycles : water cycle; Graz cycle
  - O_2/ CO_2 cycles : AZEP (Alstom/NorskHydro); HiOx (Aker Kvaerner); MATIANT



1-2: Intercooled staged compressor 2-3: Upper pressure cycle 3-4: HP Combustor chamber 4-5: HP Expander. 5-6: LP Combustion chamber. 6-7: LP Expander. 7-8: Internal regeneration. 8-1: Water cooler/separator.

✍ *Configurations of* O_2/CO_2 *MATIANT* cycles

1) E-MATIANT cycle: Ericsson-like CO_2 regenerative gas cycle

- ✍ Boundary conditions :
- ✍ TIT = 1300 °C
- ✍ LP turbine exhaust gas : 700 – 750 °C complying with t° limits of advanced materials in regenerator and HRSG
- ✍ Pinch point at regenerator inlet : 100°C
- ✍ Upper cycle pressure : > = 110 bar
- ✍ Reheat pressure : optimised 25- 40 bar
- ✍ ASU, extracted CO_2, fuel and oxygen compressors included in the system
- ✍ Cooling of hot components with extracted CO_2 or with compressed N_2 from ASU

✍ Net cycle efficiency : 40- 45%

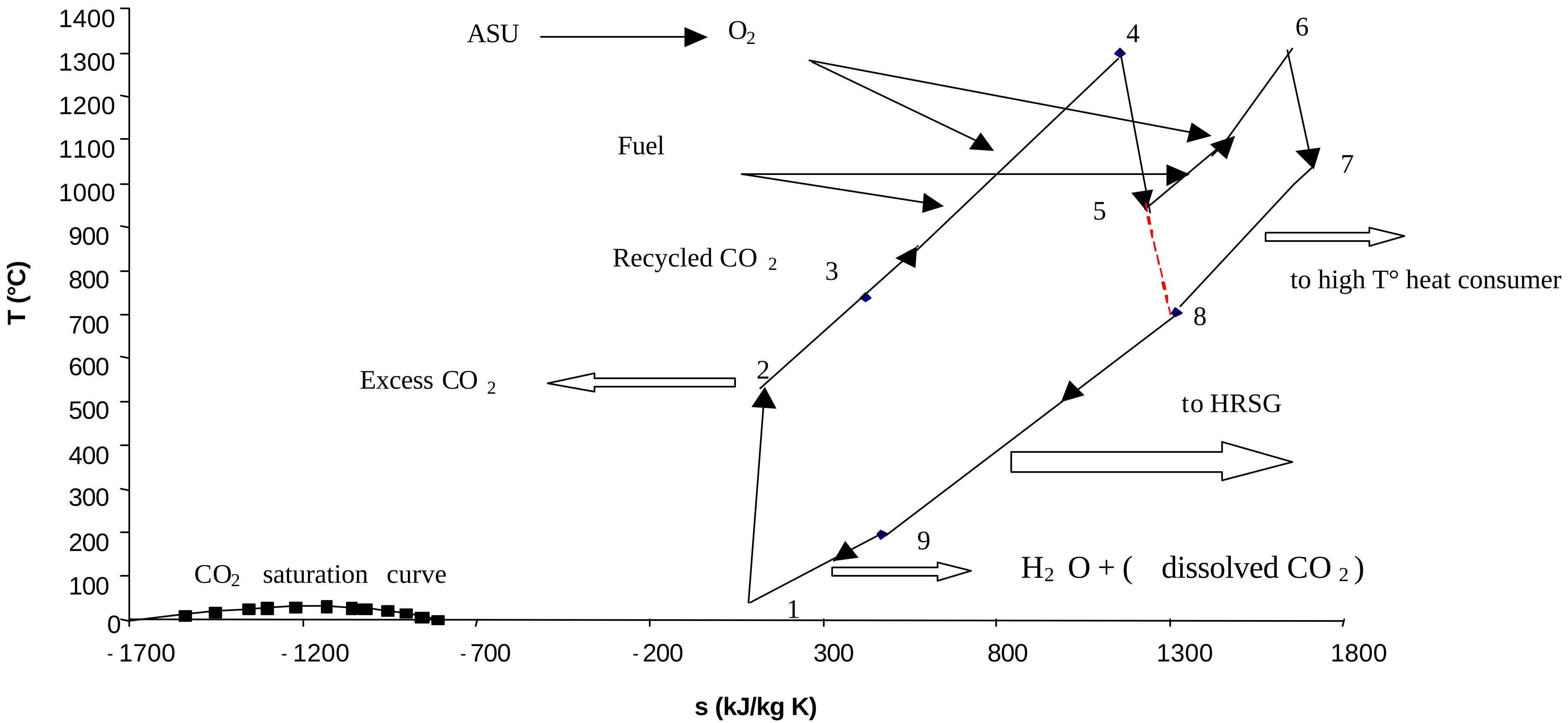
Improvements of O_2/CO_2 E-MATIANT cycles

- ✍ Recycling of the extracted water in the LP combustion chamber after superheating in the regenerator : increases the specific power output and efficiency (similarly to STIG GTs)
- ✍ Use as a CC: adiabatic compressor and HRSG with advanced steam turbines (3PR, supercritical steam, 700°C) : **?** > 50%
- ✍ Use as an IGCC : addition of a gasification unit and a syngas clean-up unit upwards of the GT combustion chambers. Asset: the ASU is already existing; no need for a shift reaction of CO in the syngas and separation of CO_2 and H_2 : **?** ~ 42- 45%
- ✍ Integration of a high t° fuel cell SOFC by the use of the sensible heat in hot exhaust flue gas (900°C) for preheating of fuel, O_2 and water/steam : **?** ~ 47-49%
- ✍ Integration of a high t° conducting membranes (ITM or OTM) for oxygen production (900°C) : **?** ~ 45%
- ✍ Integration of cogeneration

Modelling of the cycles : CO_2 properties

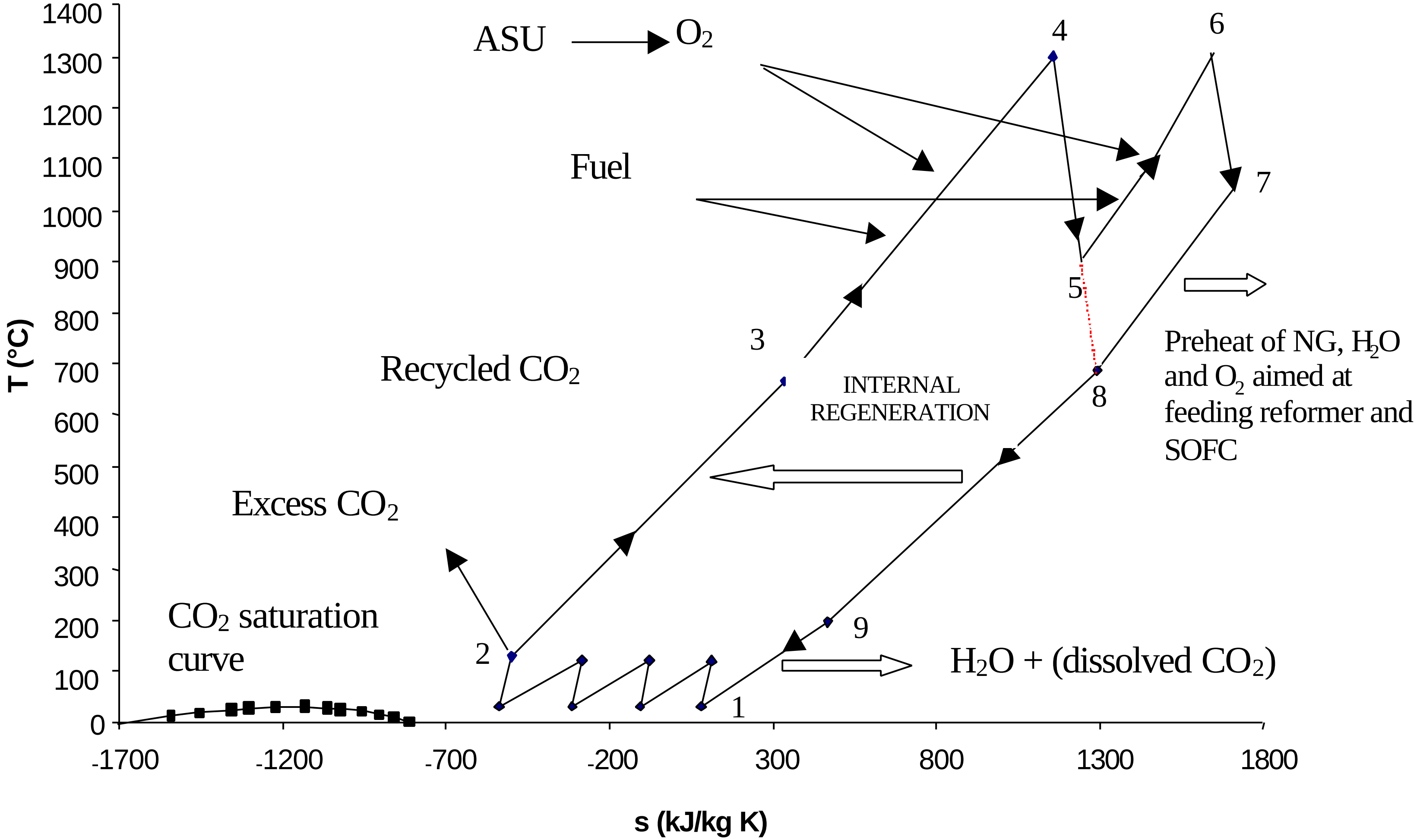
- ? Heavier than air and water (molecular weight: 44 against 29 for air and 18 for steam)
- ? Lower specific heat Cp than water (nearly the half) but roughly the same as air (for sizing of heat exchangers). Lower than air in the compression zone
- ? Lower adiabatic exponent ? = Cp/Cv (for sizing of turbomachines): less compressible than air and steam
- ? Low critical point (73 bar; 31°C) against 221 bar; 375°C for water
- ? Higher density than water and lower in gaseous state than steam (influence on the dimensions of components)
- ? Chemically reactive (interaction with storage medium)
- ? **Supercritical CO_2 behaves like a liquid (density) and like a gas (viscosity)**

Combined Cycle based on a O_2/CO_2 Brayton–like gas cycle : CC-MATIANT cycle



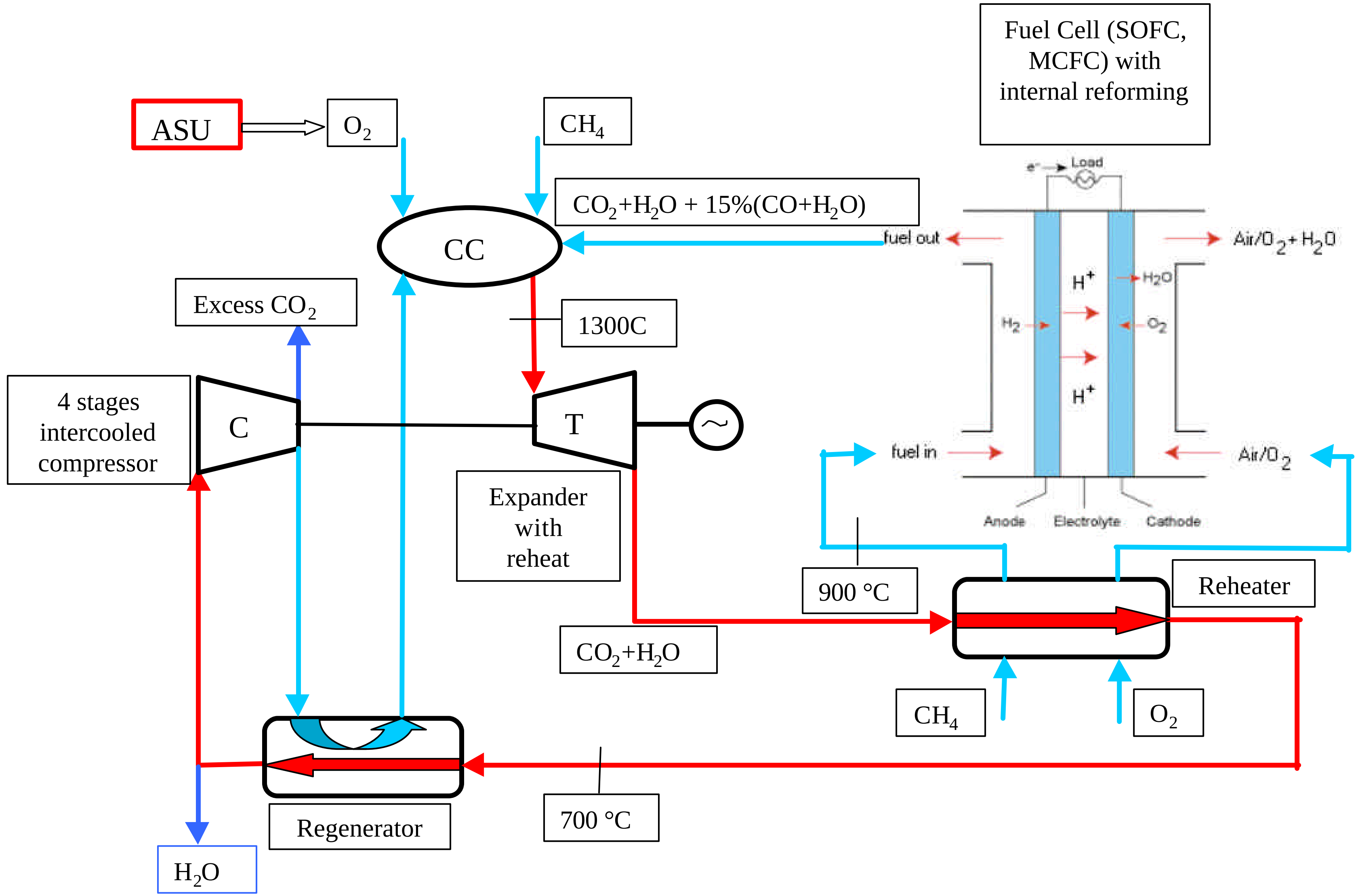
Combined Cycle : O_2/CO_2 regenerative Brayton – like gas cycle with reheat and steam cycle with HRSG.
1-2 : adiabatic compressor ; 2-3 : upper pressure cycle ; 3-4 : HP combustion chamber ; 4-5 : HP expander ;
5-6 : LP combustion chamber ; 6-7 : LP expander ; 9-1 : water cooler/separator ; 4-5-8 : non reheated expansion.

The regenerative E-MATIANT gas cycle

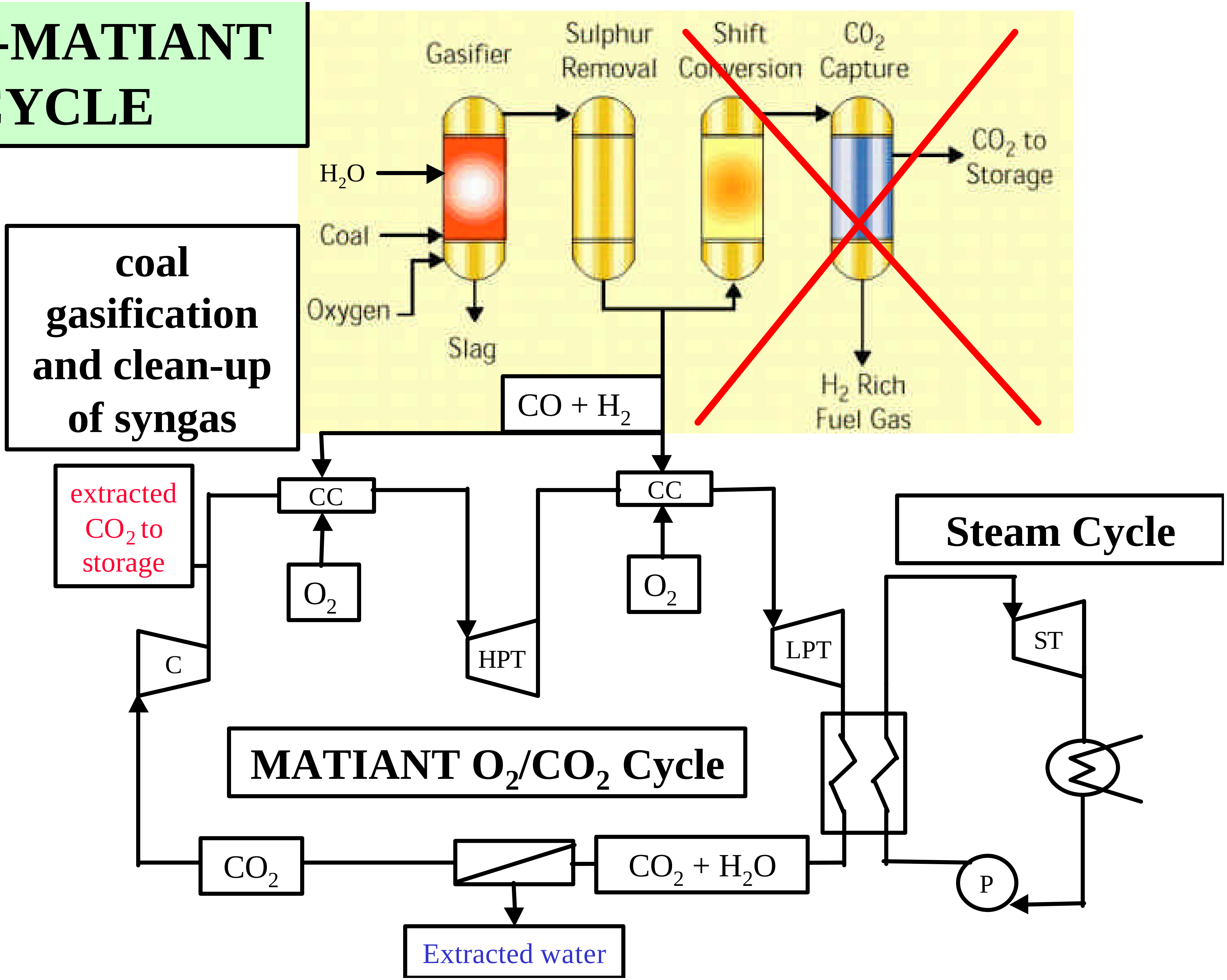


1-2 : intercooled staged compressor ; 2-3 : upper pressure cycle ; 3-4 : HP combustion chamber ; 4-5 : HP expander ; 5-6 : LP combustion chamber ; 6-7 : LP expander ; 9-1 : water cooler/separator ; 4-5-8 : non reheated expansion.

FUEL CELL – MATIANT CYCLE



IGCC-MATIANT CYCLE



Oxygen production is a critical issue

State-of-the-art: Cryogenics (double column for air distillation)

Advanced systems

Membranes (barodiffusion transport of O ions through high t° 600-1000°C dense conducting ceramic membranes under differential pressure)

Ceramic Autothermal Recovery (CAR) : based on O_2 storage in and release from peroviskite at high t°; O_2 is stored in a first bed, the outlet being a N_2 rich waste; in a second bed, O_2 is released by a purge gas CO_2+H_2O, the outlet being a mixture $O_2 + CO_2 + H_2O$ like in a Matiant cycle

COST OF CAPTURE or MITIGATION COST

Definition : ratio of increase of the electricity production cost ?COE (c€/kWh) and of CO_2 emission reduction ?E (gCO_2/kWh) for the same power output

MC (Mitigation Cost) = ?COE/ ?E (€/ton CO_2 avoided)

- ✍ COE_{st} = [I (capital cost/y) + O&M/y + F_{st} (fuel cost/y)]/PE (production/year)

  F_{st} = (€/kWh) = fuel cost (€/GJ)/ $?_{st}$ (kWh/GJ)

- ✍ COE_{ZEP}= [I(ZEP unit) + $O\&M_{ZEP}$+ F_{ZEP}]/PE with F_{ZEP} (€/kWh) = fuel cost (€/GJ)/$?_{ZEP}$ (kWh/GJ)

- ✍ ?E =E_{st} - E_{ZEP} = E_{st} x (1 – R) *(R >= 98%)* for the same power output

  Reference NGCC $?_{st}$ = *55%;* E_{st} = *350* gCO_2/kWh

MITIGATION COST

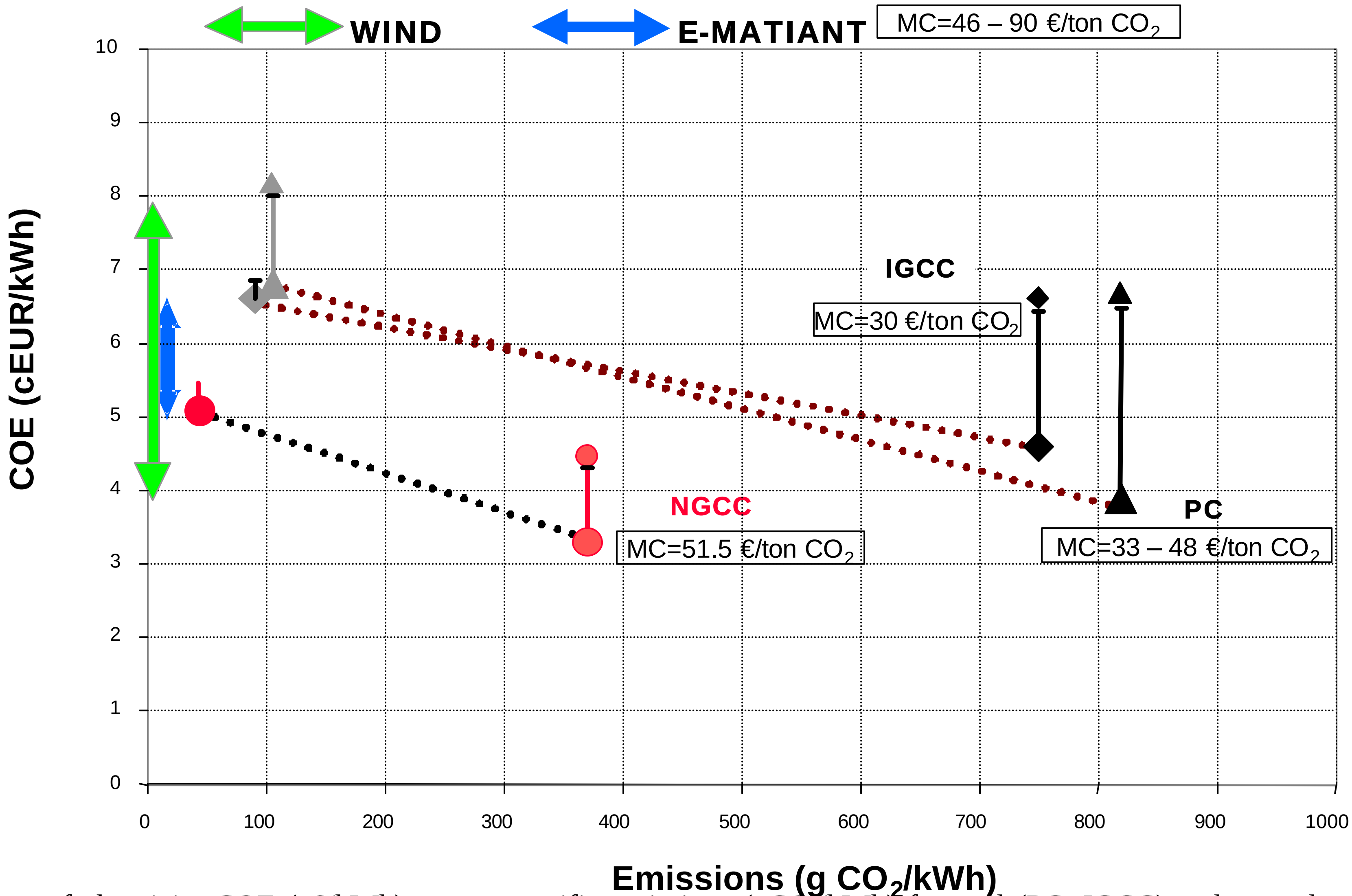
Total COE (production cost + external cost due to impact of acid oxides on the environment) for a E-MATIANT plant 5 –7 cent€/kWh

+ 50-100% above the total COE of a standard NGCC of the same power output

Is comparable to total COE of wind energy

(‘4-8 cent€/kWh)

✍ **MC of the E-MATIANT cycle is 45 – 90 €/ton CO_2 avoided and is in the same range of that of natural gas and coal fired plants with capture by chemical absorption in the flue gas (40 – 60 €/ton CO_2 avoided) of the same power output**



Cost of electricity COE (c€/kWh) versus specific emissions (gCO_2/kWh) for coal (PC, IGCC) and natural gas (NGCC, E-MATIANT) power plants without and with capture and without and with the external costs (vertical bars). The mitigation costs (the slope of the straight lines) are mentioned for each technology.

Technical issues in ZEP cycles

- ✍The technical issues are linked to the composition of the working fluid:design of turbomachines operating on CO_2 / H_2O; development of materials and cooling techniques
- ✍Cooling systems of CO_2 expanders and combustors at 1300°C and higher
- ✍Combustion in pure O_2 in a CO_2 atmosphere under pressure,in stoichiometric conditions ✍ the flame stability is demonstrated at 1 bar
- ✍ Chemical behaviour of CO_2
- ✍Oxygen production using high temperature membranes; chemical looping combustion
- ✍Development of high temperature steam turbines (700°C in supercritical ST)

Advantages of ZEP cycles

- ✍Low emission of CO_2 AND of NO_x, SO_2 and particulates (lower than in flue gas and fuel decarbonisation)
- ✍Low degree of complexity (availability and reliability)
- ✍ High fuel flexibility : fossil fuels , biomass and hydrogen
- ✍Performance improvements by the use of advanced GTs
- ✍Possible integration of high t° fuel cells
- ✍No use of chemicals for capture (no emission of solvents)
- ✍No waste products (possibly toxic) to dispose of
- ✍High purity of the delivered CO_2 (no impurities from the fuel like sulfur, metals....)
- ✍Easy separation of CO_2 and H_2O in coolers or condensers
- ✍ Potential for use at small and large scale in off- and on shore applications

Challenges of ZEP cycles

Improvement of efficiency and reduction of costs

- ?Use of other O_2 production than cryogenics such as the integration of high t° membranes (OTM or ITM based on partial pressure difference; CAR based on O_2 storage on peroviskite in 2 beds in cycling operation)
- ?Possible sale of N_2 or recycling for cooling purposes (GT blades and walls)
- ? Integration of CO_2 sequestration (EOR; ERCBM)
- ?Development of new components, new materials (membranes) and coatings

Conclusions

- ✍ZEP cycles are only designed for CO_2 emission mitigation but at the same time they do not release other pollutants such as NO_x.
- ✍Extracted CO_2 purity for re-use and sequestration is above 99%
- ✍The various types of O_2 /CO_2 MATIANT cycles have 40-5O% efficiencies (10%pts below current CC) and very low specific emissions (5-6 gCO_2/kWh) corresponding to above 98% retention
- ✍ Technical issues are solvable and MATIANT cycles are feasible
- ✍ Costs are acceptable as they are comparable to wind energy and capture coal and natural gas fired plants. Cost effectiveness is expected in a near future, in the framework of regulations on emissions and of fiscal measures (taxes, emission permits trading, green certificates.)

MATIANT cycles based plants are technically feasible at an acceptable cost with a very low environmental impact.

FUTURE OBJECTIVES

- ✍ **Need for cheap O_2 production (cryogenics; O_2 or ion transport through dense ceramic membranes; chemical looping; ceramic auto-thermal recovery(CAR); other)**

- ✍ **Need for high efficiencies and cost reductions in the long run by a full integration, especially of an air separation unit and of CO_2 re-use (EOR; ERCBM) and sequestration**

- ✍ **Need for R&D,D to demonstrate the concept in a pilot plant by 2015**