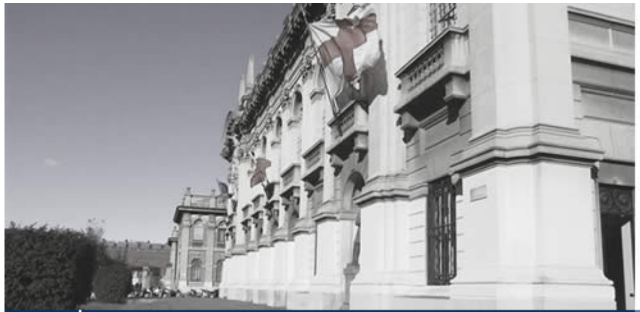

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Integration of OTM in an oxyfuel circulating fluidized bed boiler coal plant

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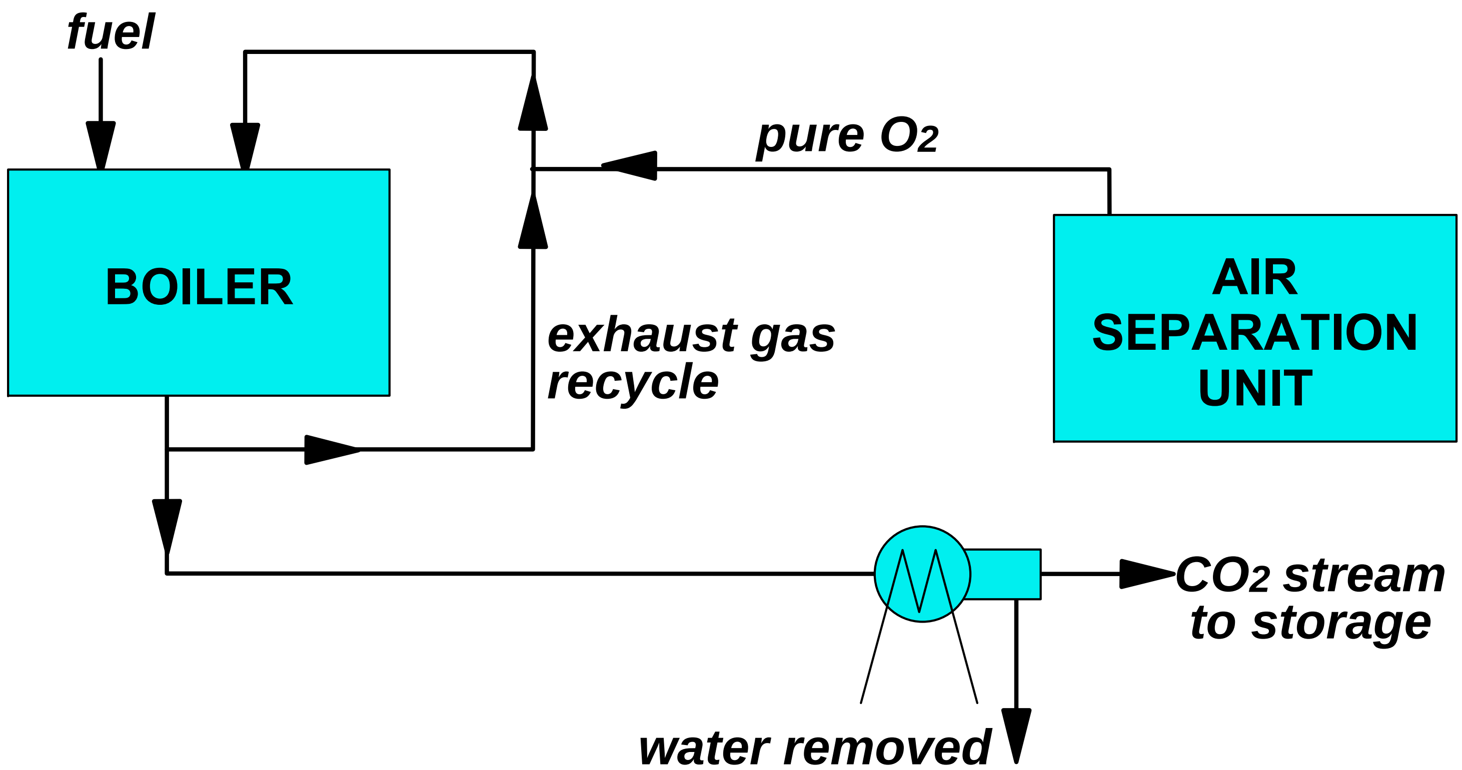
CO_2 Capture and Sequestration

- **CCS strategies allow a significant reduction of the CO_2 emissions to the environment from fossil fuel fired power plants**
- **Commercially ready technologies can be implemented NOW to build plants featuring CO_2 emissions lower than one tenth of the current standards**
- **Reduction of CO_2 emission is unavoidably related to:**
  - **decrease of fuel to electricity conversion efficiency**
  - **increase of plant capital cost**

  → cost of the electricity increases
- **Advanced technologies (like membranes) can be considered to mitigate these drawbacks**
- **Demoys project extensively studied the possible integration of MIEC membranes for O_2 and H_2 separations in plants for power generation and hydrogen production (25 configuration analyzed, both coal and natural gas fired)**
- **Just one configuration is illustrated in this presentation: oxygen combustion (oxyfuel), coal fired Rankine power plant**

Oxygen combustion

- Oxygen combustion aims to concentrate CO_2 in the exhaust stream by removing nitrogen from the oxidizer

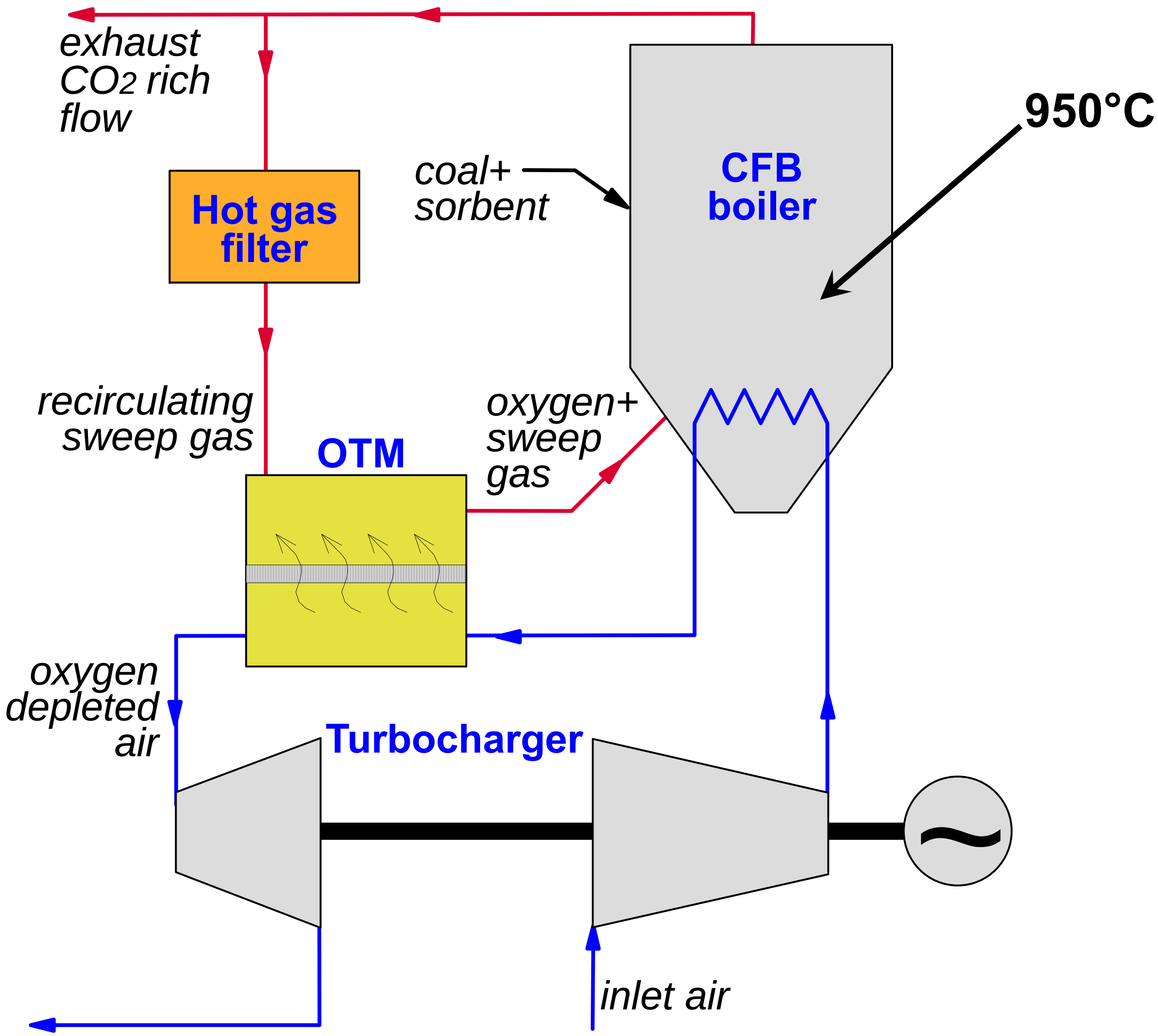


- If the membrane module is properly integrated in the power plant consumption for O_2 production reduces with respect to a cryogenic air separation unit (ASU) → higher plant efficiency

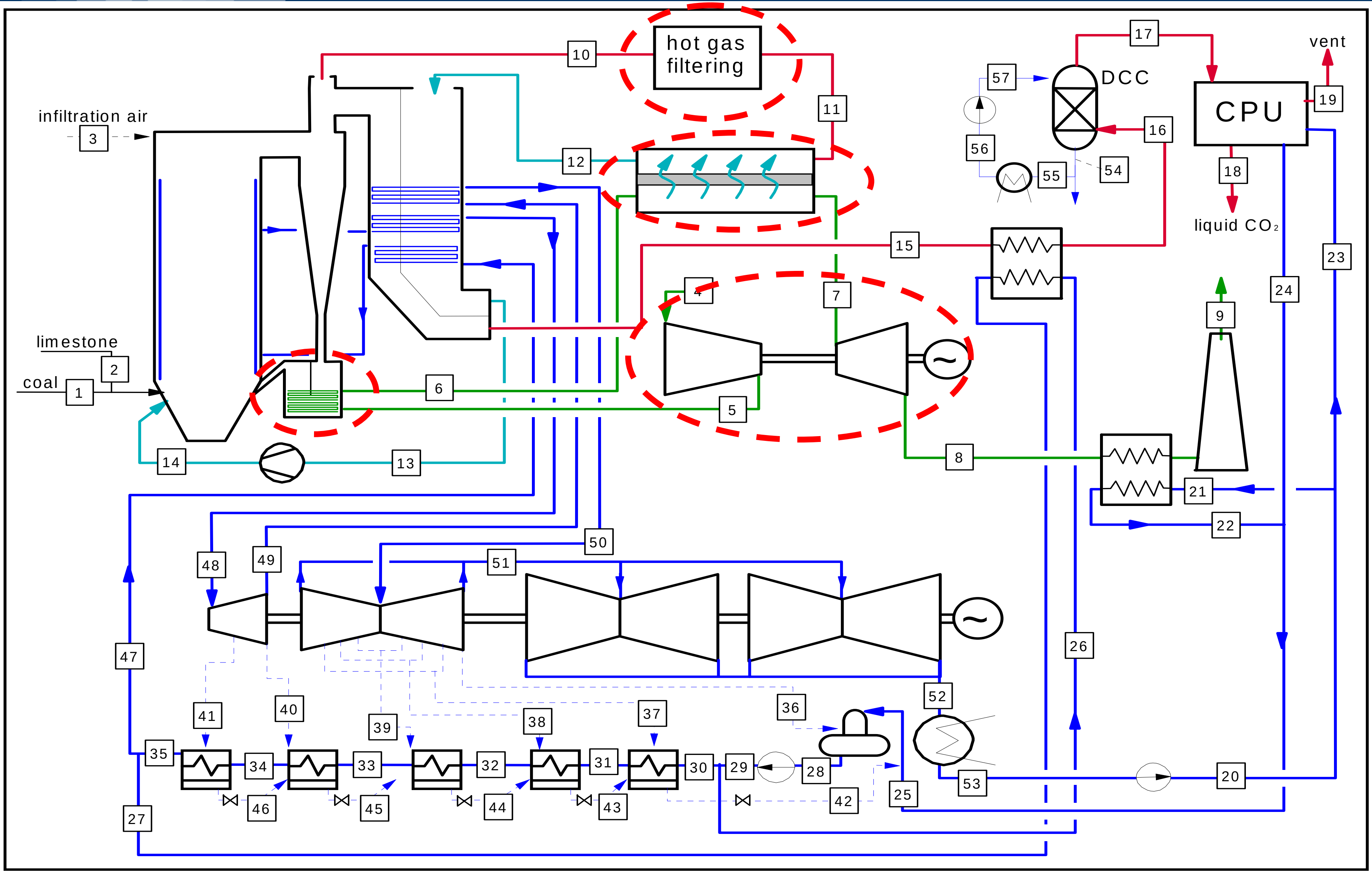
Background of this presentation

- **Integration of an oxygen transfer membrane module in a CFB boiler based power plant requires the specification of a number of design variables**
- **This presentation aims at showing how strongly this choice affects the economics of the plant**
- **An optimization carried out on a techno-economic basis as function of membrane properties and cost is eventually needed to set the design parameters**
- **Some reasons lead to prefer Circulating Fluidized Bed (CFB) boiler for arranging oxyfuel, coal fired steam power stations:**
  - **internal sulfur removal**
  - **low combustion temperature**
  - **reduced boiler volume**

Simplified power plant



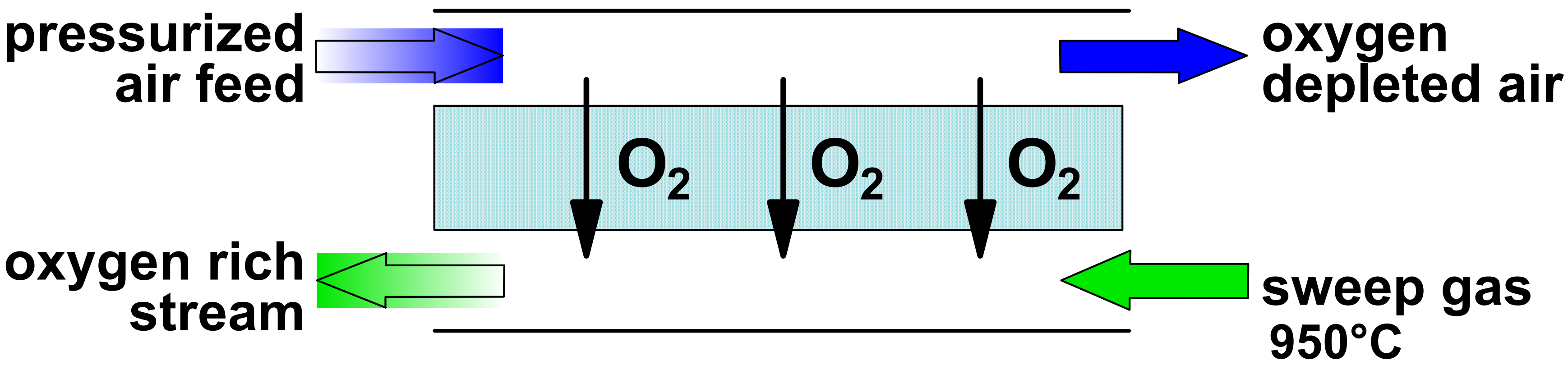
Complete power plant layout



Membrane module main design parameters

There are four main design parameters affecting size and operating conditions of the membrane module:

- **SR: O_2 Separation Ratio. Fraction of O_2 in the feed air stream separated by the membrane (i.e. mass flow rate on the feed side for a given permeated oxygen flow rate)**
- **$T_{FEED-IN}$: temperature of air stream at the membrane feed side inlet**
- **β: air compressor pressure ratio, i.e. pressure of the air stream at the membrane feed side inlet**
- **$x_{O2,PERM-OUT}$: O_2 concentration in the sweep gas stream at permeate side outlet (i.e. mass flow rate on the permeate side)**



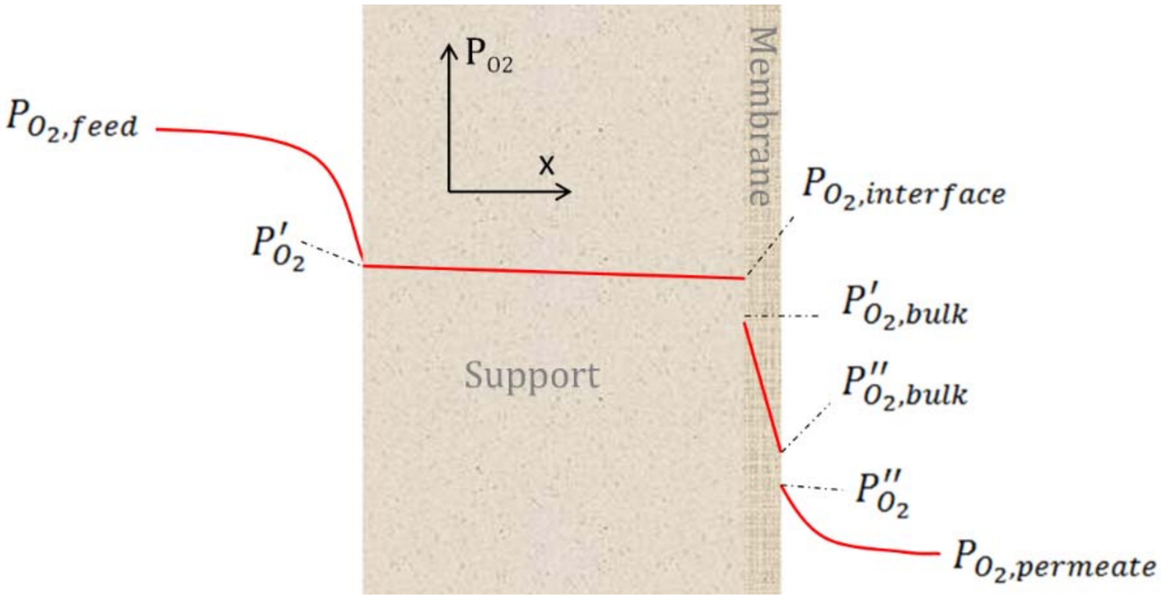
Oxygen membrane model

Six steps have been considered for oxygen permeation:

- **O_2 diffusion in the air channel**
- **O_2 diffusion across support**
- **O_2 adsorption and $O_2 \rightarrow 2O^{=}+4e^{-}$ dissociation**
- **$O^{=}$ diffusion across membrane**
- **$2O^{=}+4e^{-}$ association and O_2 desorption**
- **O_2 diffusion in the permeate stream**

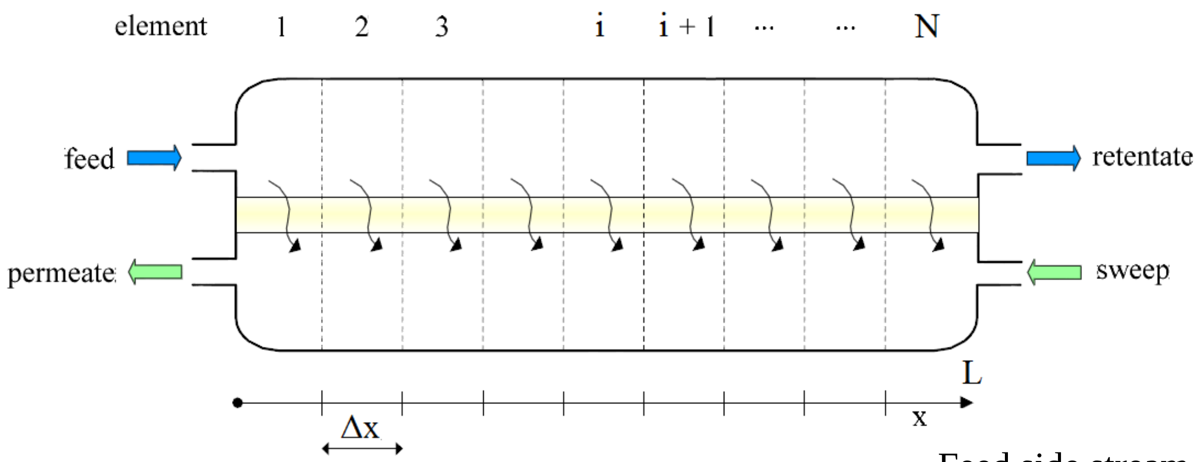
complete membrane resistance flux model

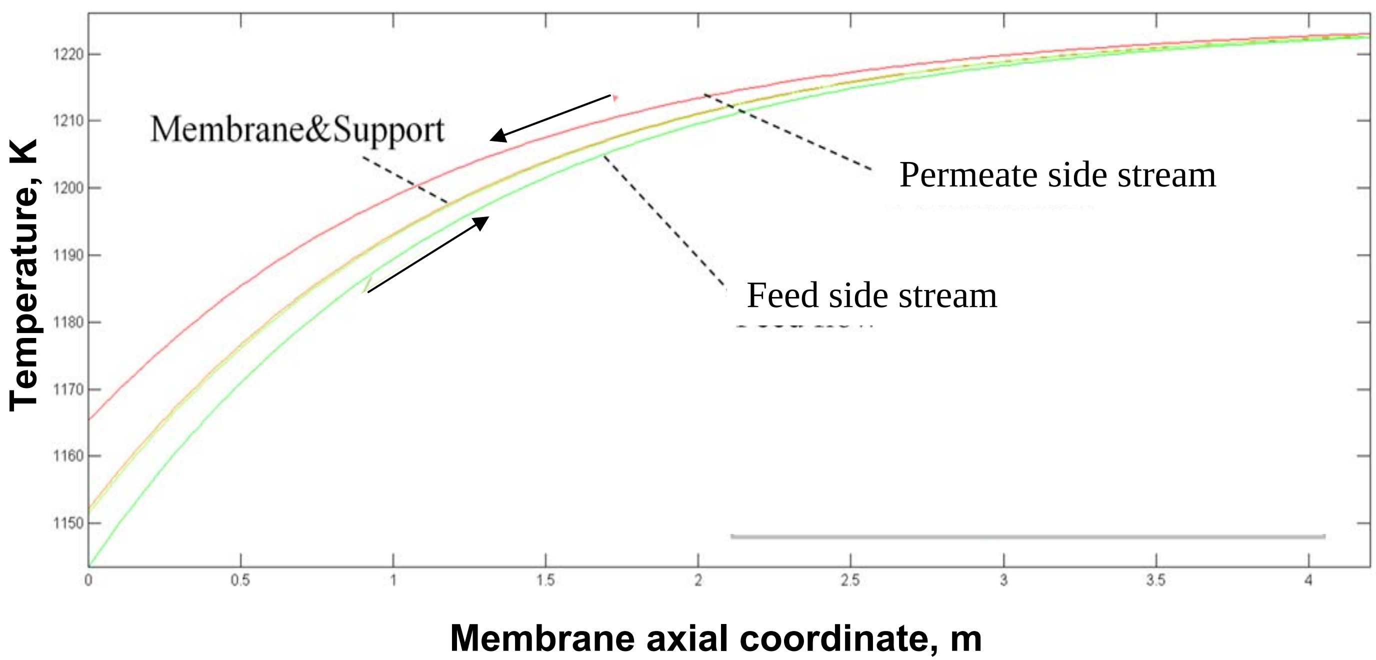
$$J_{O_2} = \frac{D_V k_r (P'^{0.5}_{O_2} - P''^{0.5}_{O_2})}{2Lk_f (P'_{O_2} P''_{O_2})^{0.5} + D_V (P'^{0.5}_{O_2} + P''^{0.5}_{O_2})}$$

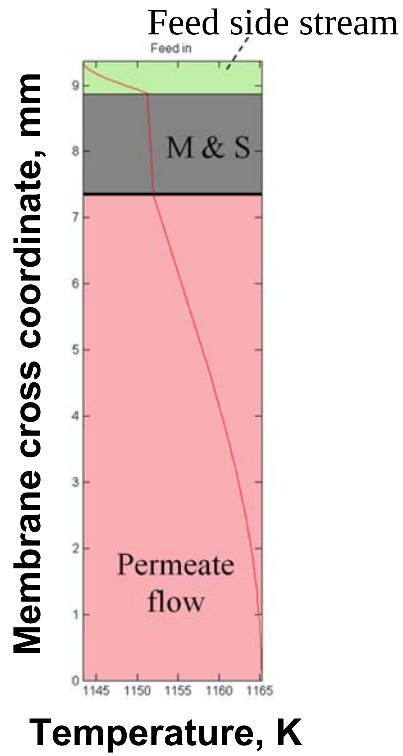


Module discretization

- **Simultaneous mass and heat transfer are modelled**
- **Extended 1D model solved with a finite difference code**
- **Planar counter- or co-current membrane arrangement**



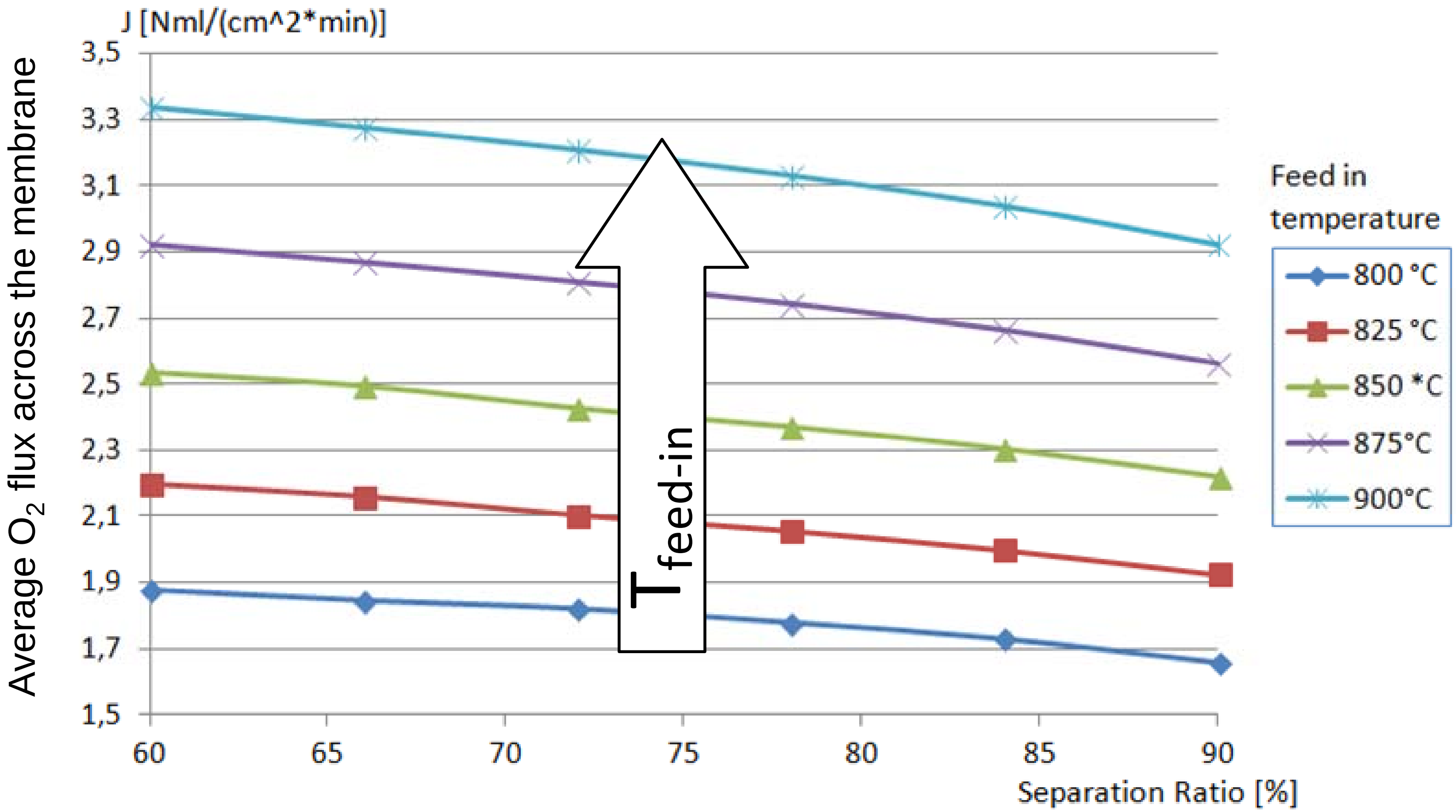




Effect of SR and $T_{FEED\text{-}IN}$

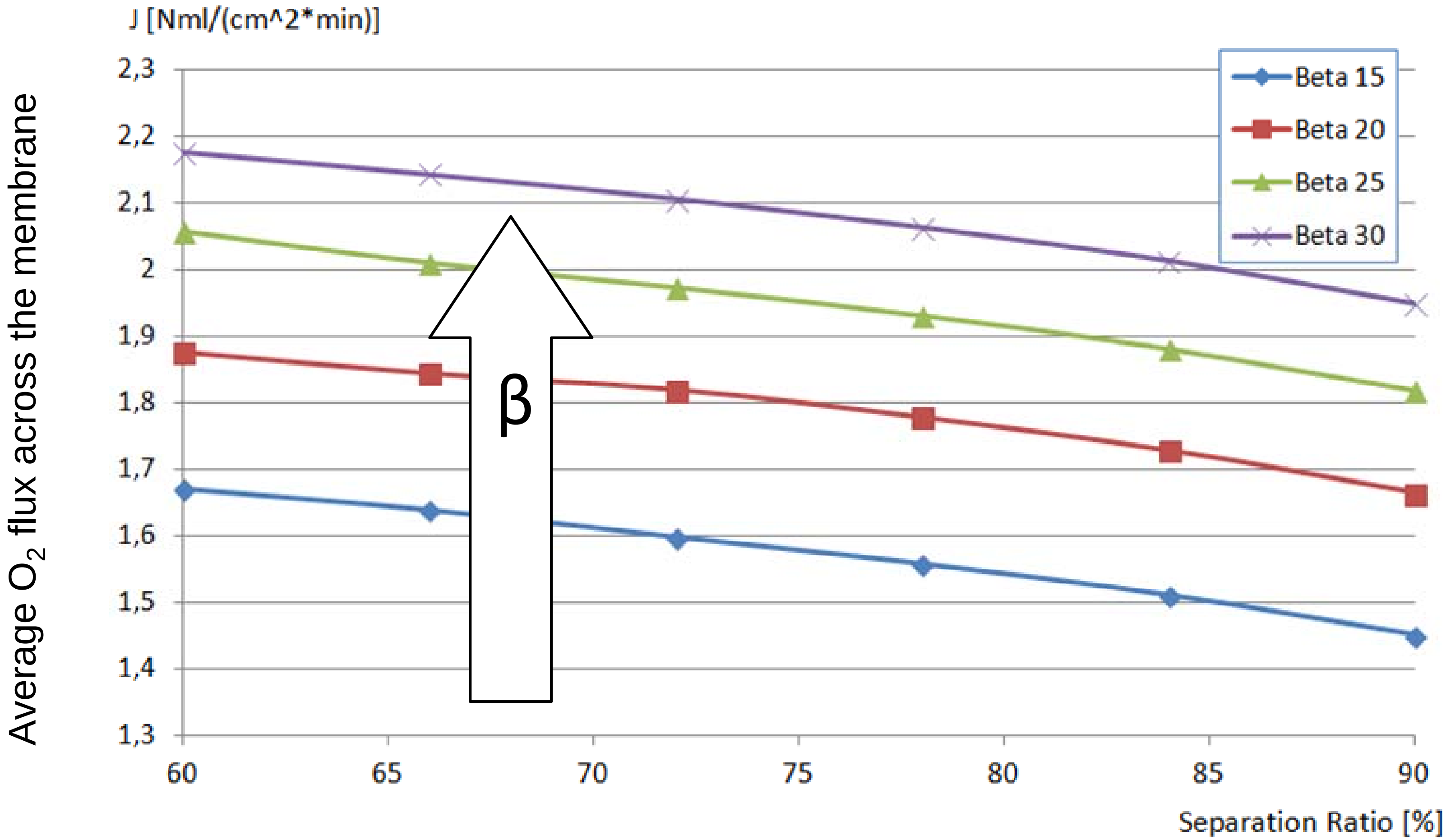
curves at constant permeated O_2 flow rate

$\beta = 20$, $x_{O2,PERM\text{-}OUT} = 40\%$



Effect of SR and air pressure (β)

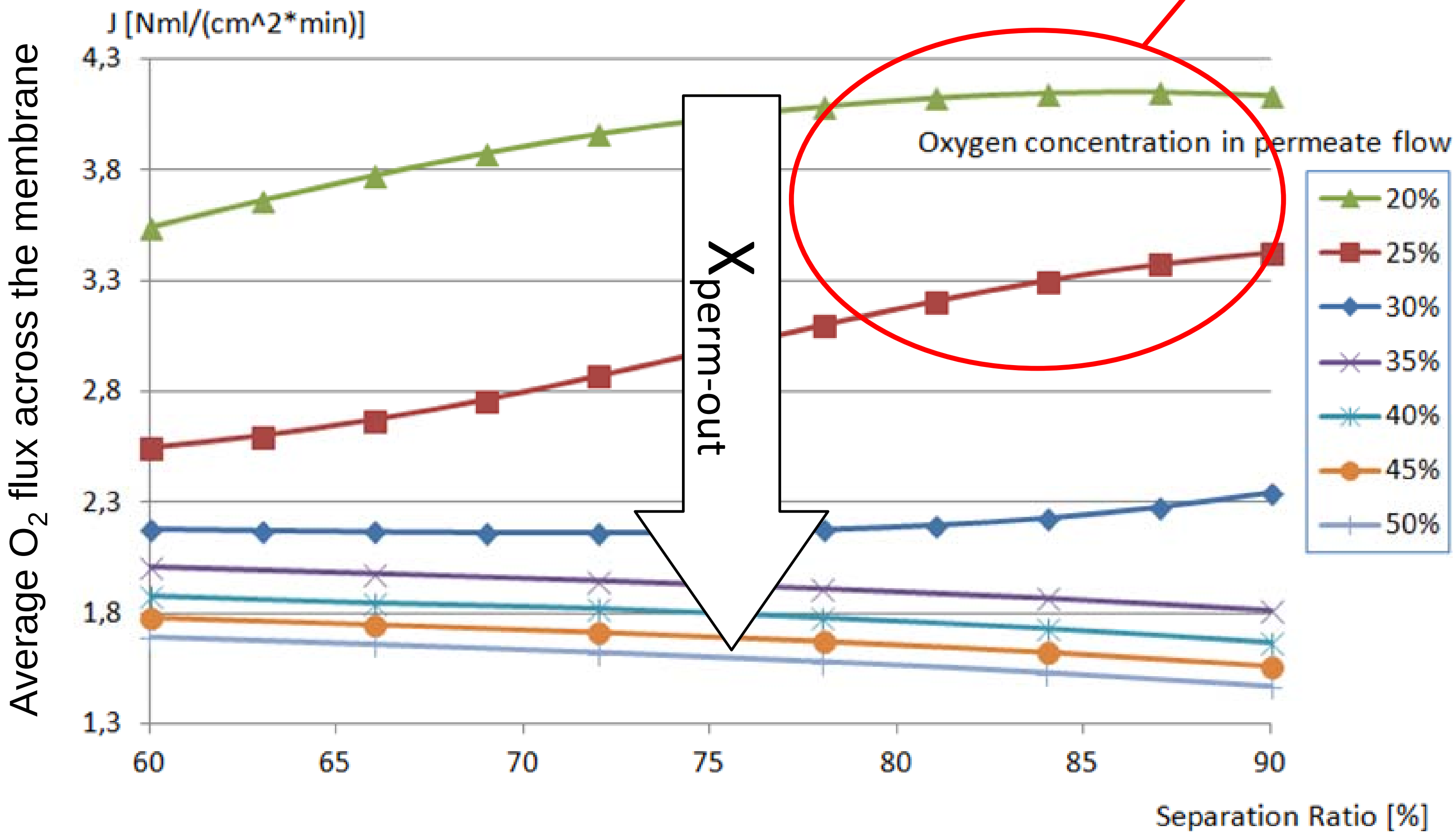
curves at constant permeated O_2 flow rate
$T_{FEED,IN}$ = 800°C, $x_{O2,PERM\text{-}OUT}$ = 40%



Effect of SR and $x_{O2,PERM-OUT}$

curves at constant permeated O_2 flow rate
β = 20, $T_{FEED,IN}$ = 800°C

High sweep gas/air flow ratio
→ high average membrane temperature

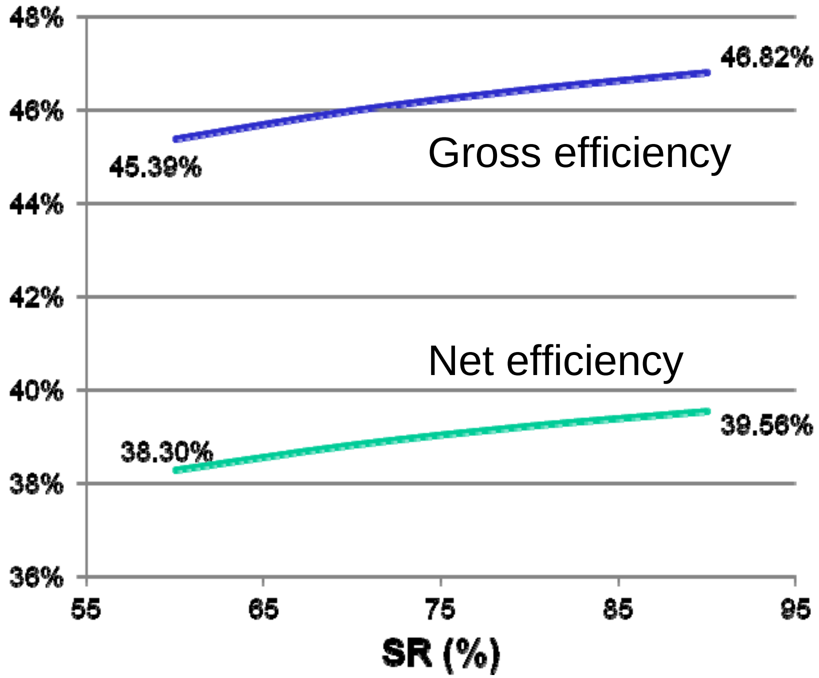


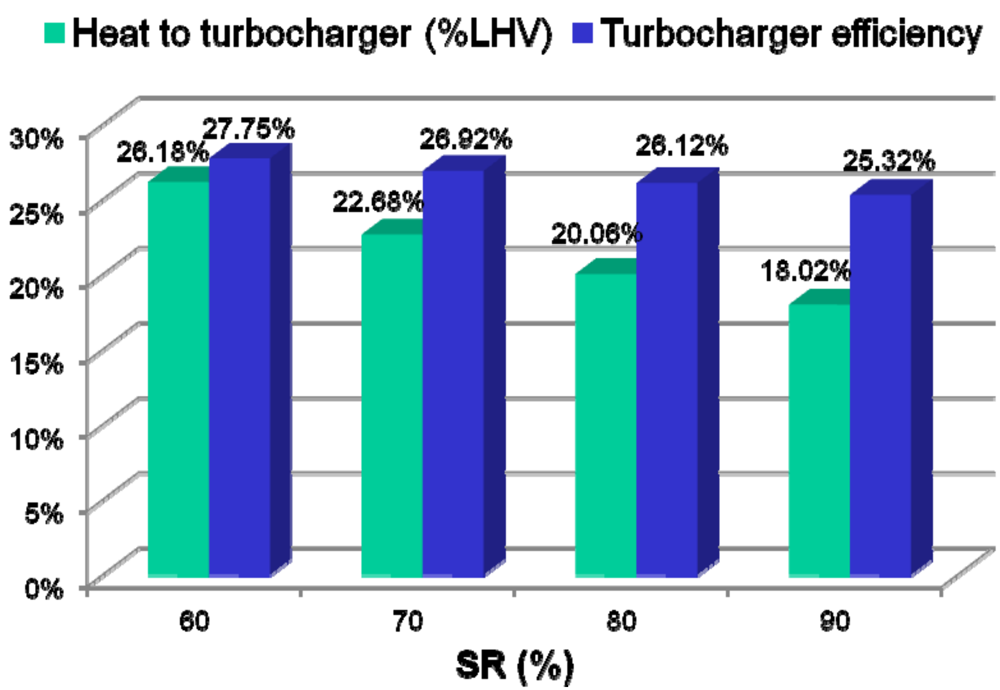
Sensitivity analysis

Influence of the O_2 separation ratio on the plant efficiency:

Higher SR → lower compressed air flow rate for a given O_2 production

- **→ Lower heat transferred in the air heat exchanger**
- **→ Lower heat input to the gas cycle (which results less efficient than heat released to the steam cycle)**
- **→ Higher net plant efficiency**





Base case assumptions

Base case defined on the basis of a “tentative” OTM design parameters and operating variables:

- **O_2 separation ratio**
  SR = 80%
- **Temperature of air stream at the feed side inlet:**
  $T_{FEED\text{-}IN}$ = 800°C
- **Air compressor pressure ratio:**
  β = 20
- **O_2 concentration in the sweep gas stream at permeate side outlet:**
  $x_{O2,PERM\text{-}OUT}$ = 30%

Performance of reference cases

	air-CFB	ASU oxy-CFB	OTM oxy-CFB
Electric power balance, MW			
Steam turbine	814	717	693
ASU/Turbocharger	----	-85.6	37.0
CO_2 compression	----	-55.1	-60.2
Fans	-17.8	-11.9	-22.9
Other auxiliaries	-36.7	-33.2	-31.2
Net electric plant output, MW	760	532	616
Coal thermal input, MW_{LHV}	1708	1436	1574
Net electric efficiency (LHV), %	44.5	37.0	39.1
Carbon capture ratio, %	----	91.6	96.2
CO_2 specific emission, kg/MWh	788.9	79.6	34.0
CO_2 avoided, %	----	89.9	95.7
SPECCA, MJ_{LHV}/kg_{CO2}	----	2.30	1.47

SPECCA index: specific primary energy consumption for CO_2 avoided

$$\text{SPECCA}\ [\text{MJ}_{\text{LHV}}/\text{kg}_{\text{CO2}}] = \frac{3600 \cdot ((1/\eta) - (1/\eta_{\text{ref}}))}{E_{\text{CO2,ref}} - E_{\text{CO2}}}$$

Cost analysis of reference cases

- a comprehensive economic model has been implemented
- the economic model includes equipment cost estimation for non conventional components (i.e. the membrane modules, high temperature heat exchanger and ceramic filters, turbocharger)
- cost of membrane module assumed at 1000 €/m²

	air-CFB	ASU oxy-CFB	OTM oxy-CFB
Net electric plant output, MW	760	532	616
Net electric efficiency (LHV), %	44.5	37.0	39.1
Carbon capture ratio, %	----	91.6	96.2
CO_2 specific emission, g/kWh	788.9	79.6	34.0
CO_2 avoided, %	----	89.9	95.7
Total plant cost, M€	1142	1323	1681
Plant specific cost, €/kW	1503	2489	2730
Level. cost of electricity, €/MWh			
Investment	46.4	76.8	84.3
Fuel	22.7	27.3	25.9
O&M	10.6	20.9	36.5
Total cost of electricity	79.8	125.0	146.6
Cost of avoided CO_2, €/tonn	----	63.7	88.5

Economic optimization

The sensitivity analysis showed that design parameters and operating conditions of the membrane module heavily influence the cost of of the module itself and other different components. For example:

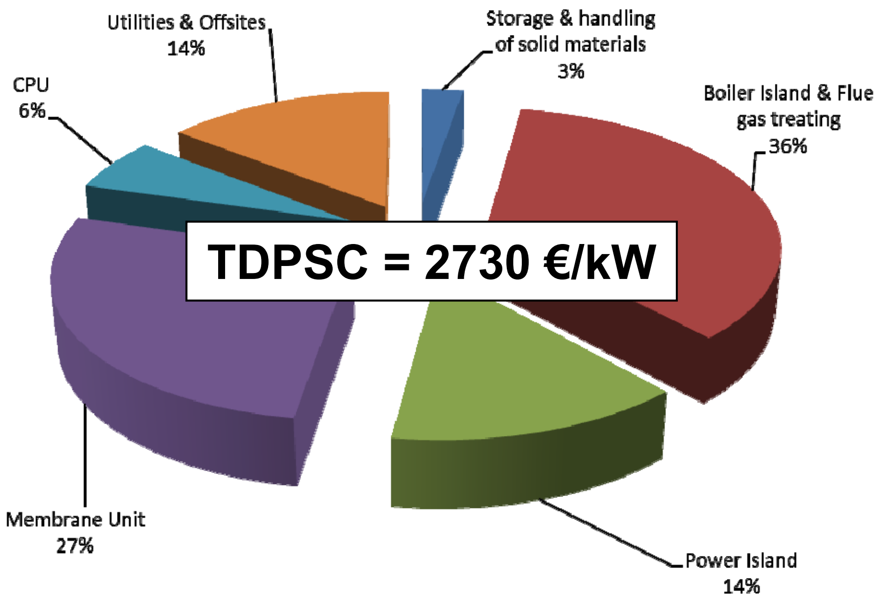
- **If OTM feed air temperature ($T_{FEED,IN}$) ↑:**
  - ➔ **cost of high temperature heat exchanger ↑**
  - ➔ **cost of OTM ↓**
- **If O_2 separation ratio (SR) ↑ then air flow rate ↓:**
  - ➔ **plant efficiency ↑ (less heat to the gas cycle)**
  - ➔ **size and cost of turbomachines and high T heat exchanger ↓**
  - ➔ **OTM area ↑ ↓ (depending on $x_{O2,PERM-OUT}$)**
- **If compressor pressure ratio (β) ↑:**
  - ➔ **number of stages and cost of turbomachines ↑**
  - ➔ **OTM area ↓**
- **If $x_{O2,PERM-OUT}$ ↓ then recirculated exhaust (sweep) gas flow rate ↑**
  - ➔ **OTM area ↓**
  - ➔ **High temperature filtering surface ↑**
  - ➔ **CFB boiler cross section ↑**
  - ➔ **recycle fan power ↑**

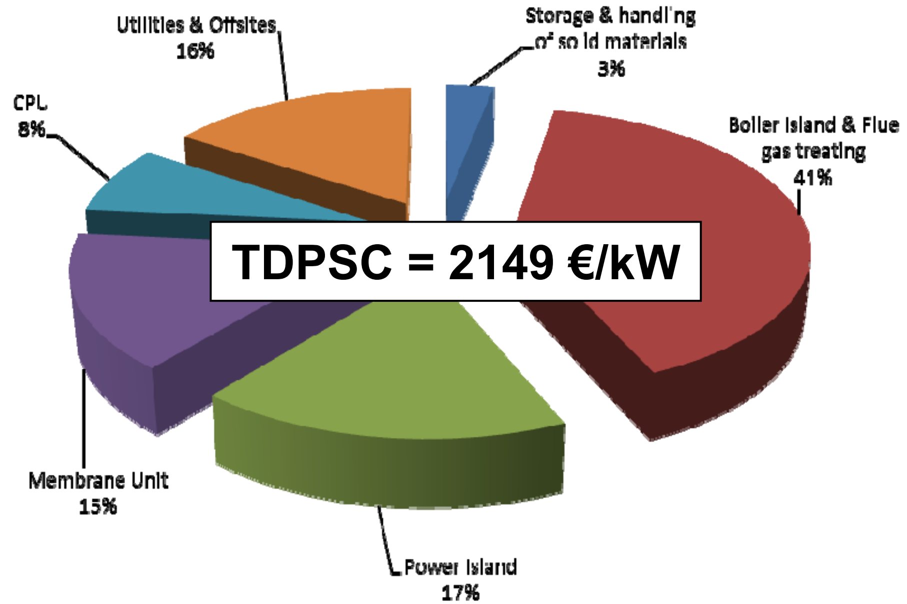
Result of optimization

	"Tentative" base case	Optimized case
Optimization variables		
Oxygen separation ratio (SR), %	80	88.6
Temperature $T_{FEED,IN}$, °C	800	870
Compressor pressure ratio β	20	17.9
O_2 concentration $x_{O2,PERM-OUT}$, %	30	21
Achieved performance		
Average oxygen flux, Nml/cm²-min	1.65	4.01
Net electric plant output, MW	616	639
Net electric efficiency (LHV), %	39.1	39.1
Carbon capture ratio, %	96.2	95.3
CO_2 specific emission, g/kWh	34.0	42.3
CO_2 avoided, %	96.2	94.6

Economic improvement

	"Tentative" base case	Optimized case	difference
Total plant direct cost, M€	1681	1374	
Plant specific cost, €/kW	2730	2149	-21%
Level. cost of electricity, €/MWh			
Investment	84.3	66.3	
Fuel	25.9	25.9	
O&M	36.5	30.1	
Total cost of electricity	146.6	122.4	-17%
Cost of avoided CO_2, €/tonn	83.0	57.0	-36%





Conclusions

- Membrane module represents a significant fraction (15-30%) of the total plant cost of an oxyfuel Circulating Fluidized Boiler based power station
- Membrane technological features (permeability, specific cost - €/m^2, temperature resistance, operating life) have a strong influence on plant design parameters
- Specification of membrane design parameters and operating conditions involves economic optimization of the whole plant
- A change in the membrane characteristics eventually moves the optimal conditions and requires different design specs of the membrane module
- The number of parameters to be considered makes hard a "tentative" selection of the membrane module design specs
- In the specific case considered, multi-variable economic optimization led to plant configuration featuring:
  - air stream temperature at the feed side inlet included in the range 860-880°C
  - membrane separation ratio included in the range 80-90%
  - high sweep gas flow rate (i.e. low O_2 concentration)
- The optimized OTM case shows a cost of avoided CO_2 of 57 €/tonn. It is about 10% less than the cost of the corresponding plant based on cryogenic air separation unit

Thank you

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