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TWO MEMBRANE STAGES FOR CAPTURING CO_2 GENERATED BY COAL FIRED POWER PLANT

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The central aim of this paper is to create an economic and technical evaluation to capture carbon dioxide produced from coal-fired power plants by using two membrane stages. Many literature studies concentrate on using only the 1-single stage of the membrane due to the low CAPEX cost. Although the high CO_2 capture efficiency is obtained from one stage (90%), the CO_2 purity is relatively low (max. 70%). Therefore, another stage of the membrane module is investigated to examine the possibility of achieving high purity of CO_2. In this research, the membrane materials used for both stages are the same, for which the CO_2/N_2 selectivity used is 50 while the CO_2 permeability is 1,000 GPU. The characteristic of the coal-fired power plant is 1,000 MW using lignite as a fuel. As a result, the CO_2 purity in the 2nd stage increased by 26%, compared with the 1st membrane, reaching 95%. The total membrane electrical energy needed is about 53% of the overall output capacity of CFPP. The cost of the entire CFPP with membrane process is 2,190 M€.

Keywords: CO_2 capture, membrane, coal-fired power plant, parametrical optimization

Nomenclature

CP_1	First compressor pressure
CP_2	Second compressor pressure
MSA_1	First membrane surface area
MSA_2	Second membrane surface area
HPST	High Pressure Steam Turbine
MPST	Medium Pressure Steam Turbine
LPST	Low Pressure Steam Turbine

1. Introduction

Climate change resulting from large-scale industrial emissions (mainly CO_2) has become a global concern in recent years [1]. This serious ecological duty can be accomplished via different technical processes, such as raising the utilization of renewable energy sources, boosting the energy efficiency of both production & usage moves, or using carbon capture technologies [2]. According to the International Energy Agency (IEA), the main reason for CO_2 emissions is the power plants with coal fuel (37%). As assumed, coal will stay an essential source of

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electricity in the coming years, therefore, immediate development of carbon capture and storage (CCS) technologies is highly demanded [3-6]. To confirm the critical substantial element of treating CO_2 emissions, which increase universal temperature, the European Union (EU) started The Green Deal— an aspirant schedule striving to put the European land environment neuter by 2050 [7]. An intense study has concentrated on decreasing CO_2 emissions from large sources like fossil fuel power plants and other manufacturers (as cement) [8,9]. Presently, three CO_2 capture processes have been used: post-combustion, pre-combustion, and oxy-combustion [10].

Membrane starts to be an efficient solution and environmentally friendly technology to remove CO_2 in post-combustion processes. High permeability and selectivity are considerable criteria for choosing an efficient membrane for CO_2 capture [11,12]. Compressors or vacuum pumps are suggested to be used in the inlet and outlet streams of the membrane to raise the CO_2 capture efficiency. Thus, the high electrical power required for the membrane process is the essential impediment [13-15]. In addition, the membrane surface area plays a major role in influencing the capture rate and purity of carbon dioxide [16], as a consequence, 2-stages of the membrane modules are applied in this paper to control and increase CO_2 capture efficiency and purity.

This research achieved a techno-economic examination of 2-stages membrane application with the utilization of the auxiliary parts (compressor, vacuum pump) to obtain 90% CO_2 capture efficiency and CO_2 purity of 95% for the possibility of transport and storage. The configuration recommended was analyzed for a 1,000 MW thermal power plant using lignite coal as fuel.

2. Membrane system for CO_2 capture

Currently, different methods are used with various parameters to improve CO_2 capture technology. Due to the impurities that exist in the gas stream, a separation unit must be used, as shown in Figure (1), to avoid damage and expand the lifetime of the membrane [17]. To prevent the water drops issue, a drying component must be applied to the flue gas flow before arriving at the membrane unit [18].

This paper focused on integrating 2-stages of a membrane (Figure 2) into a conventional CFPP to reach high CO_2 efficiency (90%) and CO_2 purity of no less than 95% with the minimum power consumption value. Table (1) represents the main power plant characteristics. Furthermore, CO_2 captured stream must be compressed at high pressure (considered 70 bar) with a heat exchanger to achieve all the demands for CO_2 transport [9].

The membrane consists of a CA enzyme that was included in polyacrylamide polymer (PSF 50 K) by an improved method utilized in 2020 [19].

Table 1

The fuel and CFPP indicators

Indicators	Units	Values
Coal features [20]	%	72.30 C, 13.89 Ash, 8 Moisture, 7.45 O, 4.11 H, 1.69 N, 0.56 S
Lower heating value	kJ/kg	28,141
CFPP features		
The pressure of the flow	bar	170
The temperature of the flow	°C	560
Low/medium/high-pressure turbine efficiency	%	87.8/91.6/84.9
Refrigerant pressure	bar	0.05
Water temperature in the condenser	°C	9.5
Combustion process efficiency	%	91
Rate of steam flow	t/h	914.5
Net CFPP efficiency	%	41.63
The pressure of flue gas	bar	1.013
The temperature of flue gas	°C	50
Gas stream rate	kmol/h	120,960
Flue gas fractions	%mole	
CO_2		13.12
N_2		80.80
O_2		6.05
SO_2		0.03

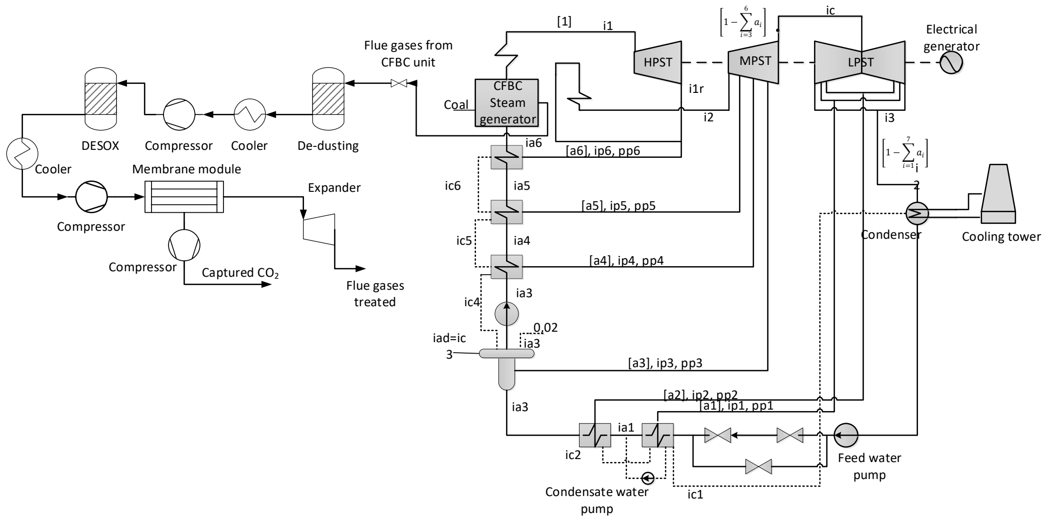

Fig. 1. Principle diagram of membrane integration in CFPP

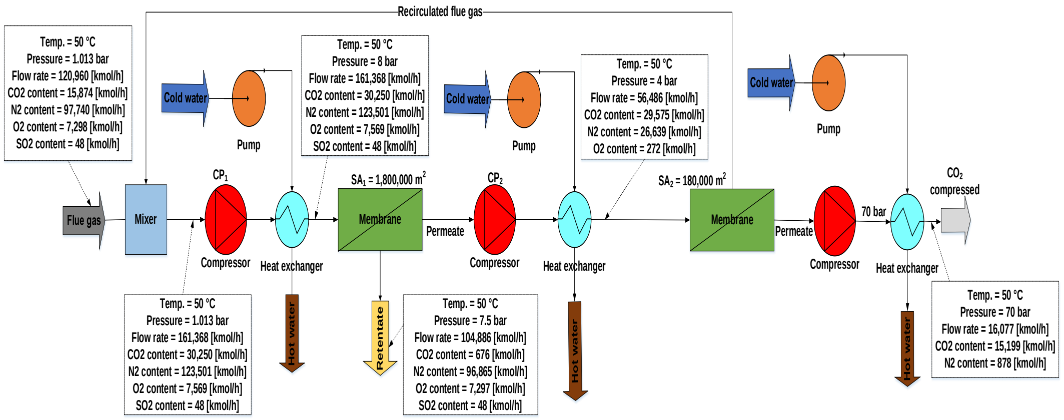

Fig. 2. 2-stages of the membrane scheme

Table (2) below demonstrates the specific membrane parameters used with the variations of the ancillary components like compressors.

Table 2

The main parameters of membrane

Membrane parameters	Units	Values
CO_2; N_2 permeance	GPU	1,000; 20
CO_2/N_2 selectivity	-	50
Compressors efficiency	%	90
First compressor pressure	bar	2 - 10
Second compressor pressure	bar	2 - 10
First membrane area	m^2	600,000 – 1,800,000
Second membrane area	m^2	15,000 – 300,000

3. Economic parameters of CO_2 captured

The membrane process for CO_2 capture was simulated by utilizing ChemCAD software depending on the data obtained from the process modeling of the CFPP. The most common parameters that are used to estimate the economic level of the CO_2 capture process are as follows [21]:

SPECCA represents the particular main power demanded to avert carbon emissions;

$$SPECCA = \frac{3600 \times \left(\frac{1}{\eta_{CCS}} - \frac{1}{\eta_{Nocapture}}\right)}{P_{Nocapture} - P_{CCS}}, \qquad (1)$$

Where η_{CCS} and $\eta_{Nocapture}$ represent the overall efficiency with and without CCS technology, while $P_{Nocapture}$ and P_{CCS} demonstrate the CO_2 emissions produced from the power plant with and without CCS.

$SPECCA_m$ can be calculated by counting the electrical energy required to capture CO_2 $(\eta_{base} - \eta_{CCS})$;

$$SPECCA_m = \frac{3600 \times (W_{Nocapture,net} - W_{CCS,net})}{W_{Nocapture,net} \times P_{Nocapture} - W_{CCS,net} \times P_{CCS}}, \quad (2)$$

The Levelized cost of electricity $LCOE$ can be computed regarding the $OPEX$ and $CAPEX$ prices;

$$LCOE = \frac{CAPEX + OPEX}{AnnualLife \times \vartheta_{CO2} \times CO_{2CCS}}, \quad (3)$$

Where ϑ_{CO2} represents CO_2 recovery, CO_{2CCS} CO_2 recovery stream, annual lifetime is considered as 75% of the total working hours, which is 6,570 h.

Eq. (4,5) represents the calculations to obtain the carbon dioxide capture recovery and avoided prices;

$$CO_2rp = \frac{LCOE_{CCS} - LCOE_{Nocapture}}{CO_2removed}, \quad (4)$$

$$CO_2ap = \frac{LCOE_{CCS} - LCOE_{Nocapture}}{CO_{2Nocapture} - CO_{2CCS}}, \quad (5)$$

Table (3) exhibits various element prices used in the capture process to calculate the following economic indicators in equations (6-8).

Table 3 **Essential economic factors [22]**

Items	Units	Values
Availability indicator	%	85
Annual working period	h/year	6,570
Cost of electric energy	€/MWh	160
CO_2 fee [23]	€/t	66
Cost of the membrane module	€/m^2	50
Duration of membrane life	Years	5
Cost of the compressor in inter-stage	€/kW	850
Cost of CO_2 compressor	€/kW	1,800
Price of membrane maintenance		Estimated 20% of the membrane value
Price of the employment	€/h	15
Price of CO_2 captured compressor	M€	11.7
Cost of the separator and cooler compressor	M€	0.87

Net present value (NPV) was calculated by eq. 6:

$$NPV = \sum_{i=1}^{n_f} \frac{IN_i - C_i - A_i}{(1+r)^i} - \sum_{i=1}^{n_r} I_i \times (1+r)^i \,, \tag{6}$$

which: IN_i represents the profits obtained in a year i; C_i the cost of operating and replacements with taxes per year; A_i the installment per year; I_i the achieved funding per year; and r the reduction average which is 8% regarding the energy sector.

Eq. (7) determines the Internal Rate of Return (IRR), where NPV is zero regarding an investment plan due to the equality between r and IRR;

$$NPV = \sum_{i=1}^{n} \frac{IN_i - C_i - I_i}{(1+IRR)^i} = 0 \,, \tag{7}$$

Discounted Payback Period (DPP) is the required specific time to obtain the investment cost back and can be calculated by eq. 8.

$$NPV = \sum_{i=1}^{DPP} \frac{IN_i - C_i - I_i}{(1+r)^i} \,, \tag{8}$$

In terms of the efficiency economics of the project, the profitability index (IP), determined in eq. 9, must be more than 1 which implies the project is profitable and vice versa.

$$IP = \frac{NPV + IA}{IA} \tag{9}$$

Where IA is the reduction of investment.

4. Results and discussion

Utilizing different values for 1st compressor pressure (CP_1) starting from 2 to 10 bar showed a clear increase in the rate of CO_2 capture process regarding CP_1 excess, in addition to the higher electric power consumption required. The second compressor (CP_2) elevation influenced CO_2 purity and increased the second membrane module efficiency. Higher amounts of 1st membrane surface (MSA_1) led to an enormous increase in carbon capture rate and electrical energy because of the high CO_2 captured. In the current design (Figure 2), the main factor that affected the CO_2 purity was the 2nd membrane surface (MSA_2), where the purity decreased constantly with higher MSA_2. The point where the considered capture rate and purity of CO_2 for the paper are obtained was at CP_1 and CP_2 of 8, 4 bar respectively; 1,800,000 m^2 MSA_1; and 180,000 m^2 MSA_2. On the other hand, the electrical energy needed was about 537 MW which represents 53% of the overall CFPP capacity (1,000 MW).

All the indicators (e.g., CP_1, MSA_1, etc.) used for the coming figures were chosen only to present variations regarding the selected parameter.

Figure (3) below demonstrates the impact of CP_1 on CO_2 capture efficiency. It's remarkable that increasing CP_1 significantly led to a higher CO_2 capture rate, which can be explained by the high pressure across the first membrane module. The second compressor has a considerable impact on the second membrane efficiency, where higher CP_1 produced a reduction in the stream that enters the mixer, which eventually decreased the amount of flue gas passing through the first membrane component. The figure's other indicators used were 1,800,000 and 180,000 m^2 for MSA_1 and MSA_2 respectively.

Increasing MSA_1 directly affected the capture rate as presented in Figure (4), where all other components were constant at 8, 4 bar (CP_1, CP_2 respectively), and 180,000 m^2 MSA_2. The CO_2 capture process rate values increased with the rise of MSA_1 due to the elevated flue gas stream exceeding the first membrane unit, which at the surface area of 1,800,000 m^2 reaches around 95%.

At MSA_1 = 1,800,000 m^2 and CP_1= 8 bar, Figure (5) represents the effect of the MSA_2 on CO_2 purity at various CP_2. As demonstrated in the figure, a bigger membrane area allowed CO_2 and other particles, such as N_2, to go via the membrane unit generating a mitigation in CO_2 purity. Moreover, CP_2 influenced CO_2 purity, where higher CP_2 produced less CO_2 purity.

Figure (6) below demonstrates the impact of CP_2 on the CO_2 purity of the first and the second membrane modules at CP_1= 8 bar, MSA_1= 1,800,000 m^2, and MSA_2= 180,000 m^2. Firstly, it's noticeable that the CO_2 purity after the second membrane was better than the first due to the low surface area (180,000 m^2) utilized in the process compared with 1,800,000 m^2 of MSA_1, which demonstrates the importance of using a second membrane module. However, higher pressure values helped to reduce CO_2 purity due to molecules passing with CO_2 particles.

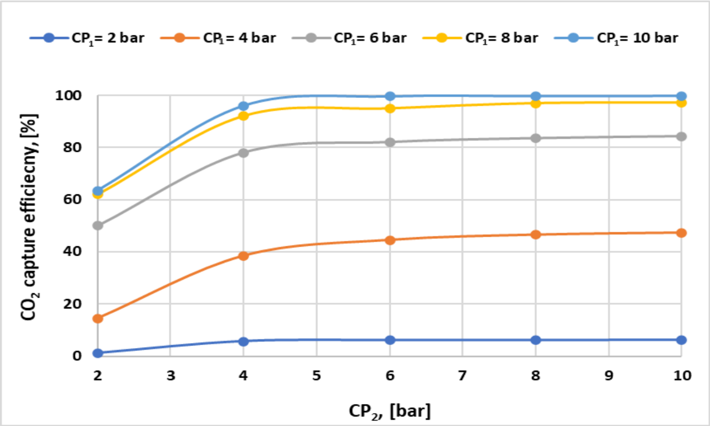

Fig. 3. The effect of CP_1 on CO_2 capture efficiency at different CP_2

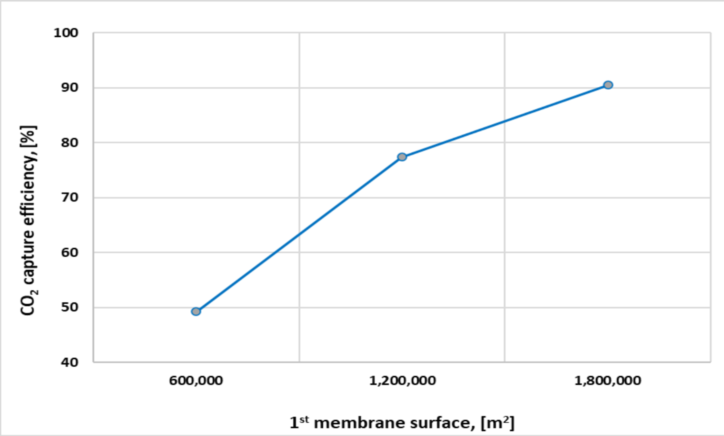

Fig. 4. MSA_1 impact on CO_2 capture efficiency

Figure (7) exhibits the first compressor influence on power consumption at various CP_2, MSA_1 1,800,000 m^2, and MSA_2 180,000 m^2. The first compressor can be considered as the base indicator that impacts the total electrical energy needed due to the high flue gas stream going through it, which was a combination of the flow coming from the combustion process and the retentate stream from the second membrane. The reduction of the required power regarding higher values of the second compressor can be clarified due to the boost of the second membrane efficiency which mitigates its retentate flow side.

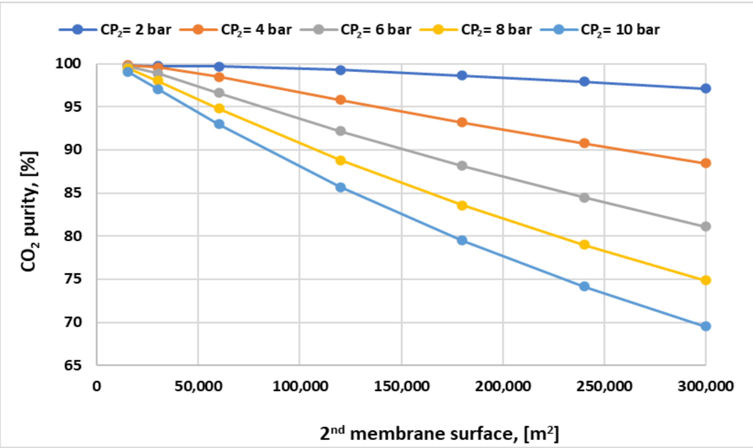

Fig. 5. CO_2 purity variation regarding different MSA_2

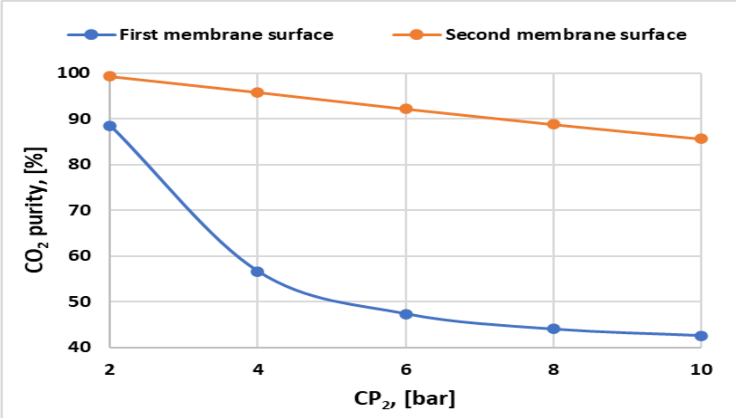

Figure 6. The impact of CP_2 on CO_2 purity at different membrane units

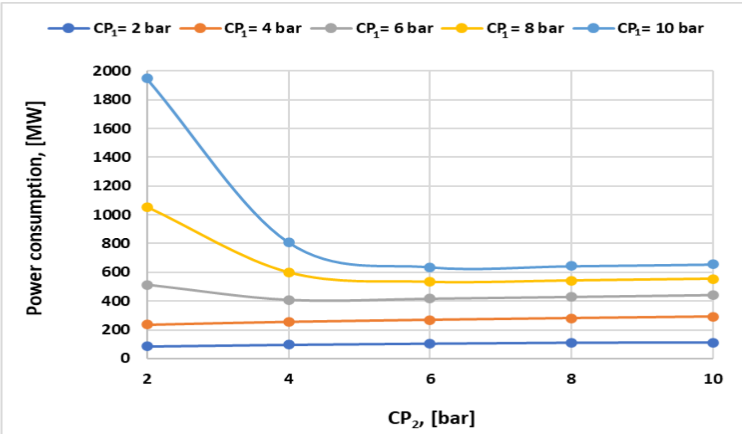

Figure 7. Total power consumption regarding different CP_1 and CP_2

To estimate the action of the recirculated flue gas from the 2nd membrane on CO_2 capture efficiency, three cases of recycled flue gas stream were examined (Figure 8) as follows:

1. Recycle flue gas from the 2nd membrane
2. Recycle flue gas from the 1st membrane
3. No flue gas recycled

The parameters used for all cases are CP_1 = 8 bar, CP_2 = 4 bar, MSA_1 = 1,800,000 m^2, and MSA_2 = 180,000 m^2.

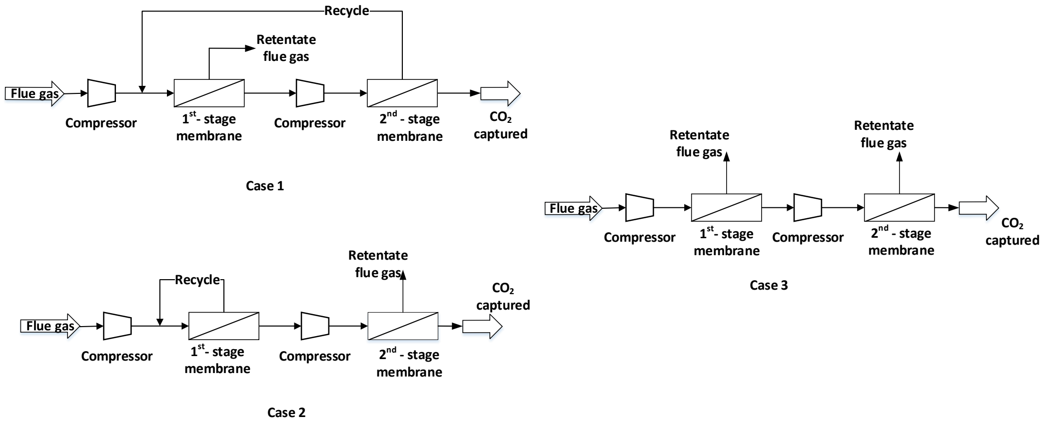

Fig. 8. Cases of the recycled flue gas flow

Table 4

The score of the 3 cases examined at specific indicators

Cases	Units	Case 1	Case 2	Case 3
CO_2 capture efficiency	%	95.7	37.9	43.9
CO_2 purity	%	95	90.3	87
Power consumption	MW	537	234,589	383

As shown in Table (4), case 1, where the recirculated flow stream was located on the 2nd membrane retentate side, was an ideal case due to the high CO_2 capture efficiency and CO_2 purity. In case 2, CO_2 capture efficiency was extremely low because of the low MSA_2 (180,000 m^2). As a consequence of the high recirculated flow from the 1st membrane unit to the primary flow side, the CP_1 energy was completely enormous, which raised the power consumption demanded (234,589 MW). Case 3 showed an excessively low CO_2 capture efficiency (43.9 %) due to the two sides of retentate flow.

Due to the low technical results of both cases (2,3), Table (5) represents the economic estimation for case 1 analyzed, in which the case achieved 95.7% and 95% of CO_2 capture efficiency and CO_2 purity, respectively.

Table 5

Economical evaluation of two membrane stages for CFPP integration

Indicators	Case 1
NPV, M€	2 190
IRR, %	14.28
UPP, year	8.23
DPP, year	11.51
PI, -	1.58

By taking into consideration that all carbon certificates are sold and supposing a CO_2 tax of 66 €/ton, the 2-stages of membrane recover the investment (DPP) over 11.5 years due to the high membrane surface area used to obtain CO_2

capture efficiency of 95%. To reduce the DPP, CO_2 capture efficiency must be decreased to the reference value (90 %).

5. Conclusions

This work evaluates the prospects of the 2-stages membrane system integrated into 1,000 MW coal-based super-critical power plants to achieve a high CO_2 capture rate and purity of no less than 95% at different parameters.

High CP_1 is a substantial factor in boosting CO_2 capture efficiency, where raising the pressure value 6 to 8 bar drives to raise carbon capture rate by 16%, both values were obtained at 1,800,000 m^2. The membrane surface affects the carbon capture efficiency, where boosting the MSA_1 600,000 to 1,800,000 m^2 guides to raising CO_2 capture efficiency by approximately 29%. As the CO_2 purity demanded a low membrane surface and less compressor pressure, 2-stages of membrane module were utilized, and the 2^{nd} membrane unit was designed with a lower surface area. The electrical energy consumption needed to obtain 95% for both CO_2 efficiency and purity was about 537 MW, which is high due to the elevated demands of the compressors used. The recycle flue stream designed from the 2^{nd} membrane unit increased CO_2 capture efficiency by around 54%. The net present value was high due to the high-power consumption required for the capture process. In relevant future evolution ways, raising CO_2 permeance is the most considerable element to develop.

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