National University of Science and Technology
POLITEHNICA Bucharest
Faculty of Energy Engineering
Department of Energy Generation and Use
Energy doctoral school

System Modelling, Simulation, and Cost-Effective Evaluation of Membrane and Hybrid CO2 Capture Integration

A Thesis submitted in partial fulfilment of the requirements of National University of Science and Technology Politehnica Bucharest, for the degree of Ph.D. in Energy Engineering

Eng. MAYTHAM ODAY MOHAMMED SALIH ALABID

PhD Supervisor: Prof. Dr. Eng. Cristian DINCA

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Abstract

Chapter 1- Introduction

Population growth, swift urbanization, and increasing manufacturing, especially in penurious states have caused to raise in human-stimulated carbon dioxide emissions. According to Our World in Data, greenhouse gases (GHG) are produced by around 50 billion tones every year, where 73.2% of total emissions are generated from energy utilization, 18.4% from agriculture forestry, and the last 8.4% is produced by wastes and industry. Intensive modification in the worldwide and domestic energy sectors will be fundamental to decreasing the atmospheric level of carbon dioxide. A unique study on global warming of 1.5 ºC was published by the Intergovernmental Panel on Climate Change (IPCC) in October 2018 that demonstrated the influence of global warming by a raise of 1.5 ◦C in universal temperature, which is related to the GHG. To achieve the agreement goal, the total carbon dioxide releases have to be reduced by around 45% from the 2010 scale to 2030 and accomplish no emissions in 2050. Several solutions have been researched regarding that crisis, such as migrating the power production from fossil fuels to renewable sources, enhancing existing plants energy efficiency, and integrating Carbon Capture and Storage (CCS) methods into power sectors.

Chapter 2- CO₂ Capture Systems

There are three common routes for recovering CO_2 from industrial facilities and fossil fuels, including petrol, coal, biomass, and natural gas: Post-combustion process, Pre-combustion process Oxy-combustion process. These processes are demonstrated in the summarized scheme in Figure 1.
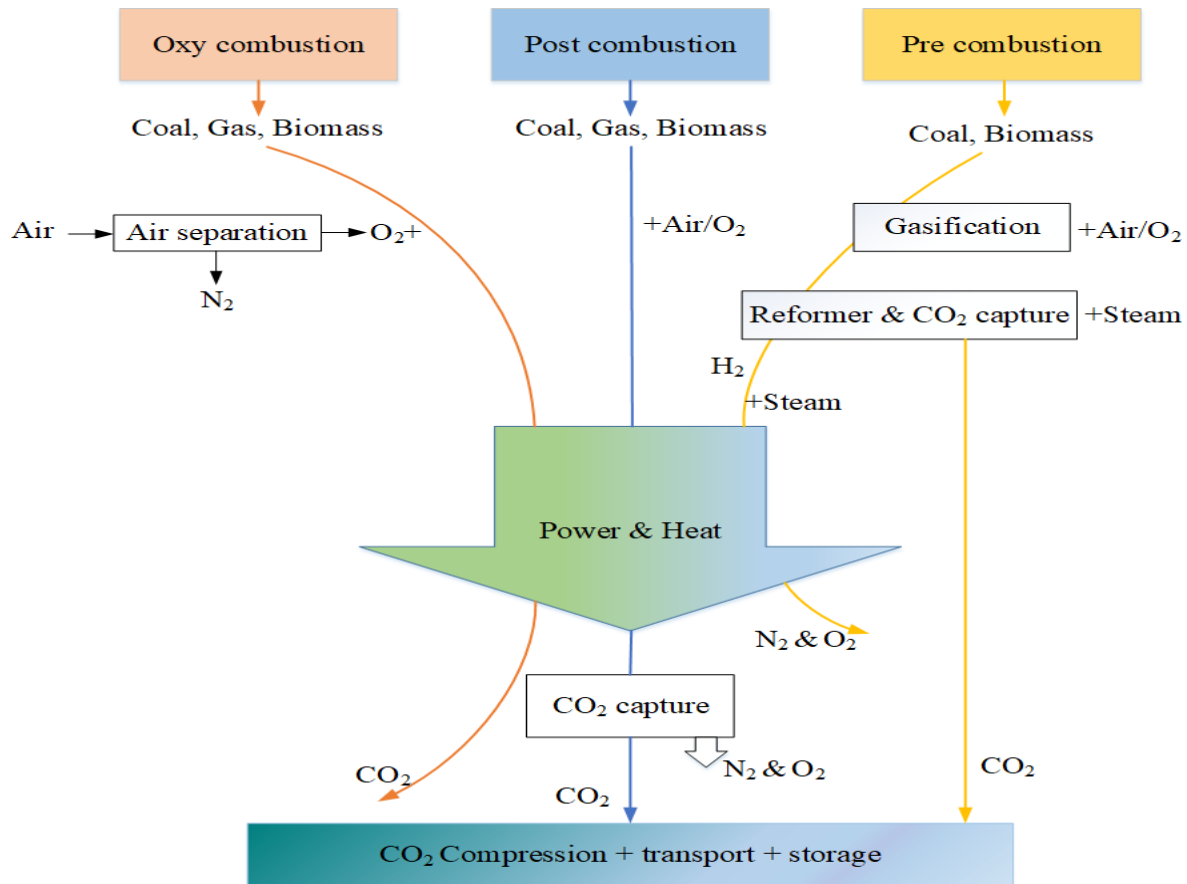
Figure 1. Carbon capture systems with different fuels.

Post-combustion process includes removing CO_2 from feed gas generated by combustion operations. This process is integrated into the present power plants without making major alterations, therefore it has the benefit of being easier to retrofit than the other CCS methods. In the post-combustion process, an electrostatic precipitator (ESP) is integrated to eliminate all the dust from hot exhaust gas that is released from the boiler. A desulphurization section (FGD) is then utilized for removing the sulfur byproducts. Technology for post-combustion CO_2 recovery is intended to purify the FGD exhaust flow. Recently, literature has focused on integrating CCS technologies into the post-combustion process, where that technology presented a potential approach to remove CO_2 from different gas mixtures.

Pre-combustion process suggests another solution for burning fuel in a combustor directly. Fuel is initially transformed into a syngas that is utilized for energy production. Before burning, carbon dioxide, generated through burning fossil fuels, is extracted and recovered. The pre-combustion notion involves removing CO_2 before combustion operation, where the syngas is generated by reforming/gasification of fuel with oxygen/air and steam. The concentrating ratio of CO_2 is usually 15 to 60% by volume, therefore, low energy is required compared to post-combustion process. Nevertheless, air separation and oxidation/gasification processes can increase the energy demand in the current system. Presently, the main literature concentrates on harnessing pre-combustion process to be combined with the Integrated Gasification Combine Cycle (IGCC).

In the oxy-combustion process, a highly concentrated oxygen flow (95-99% purity) is introduced to be combusted rather than air with the primary fuel, where the oxygen is separated from N_2 through a membrane or cryogenic method. Thus, feed gas usually has water vapor and carbon dioxide high concentrations (80%), which water vapor is removed by cooling and condensation which leaves a pure stream of CO_2. The high operational expense of generating O_2 and compressing carbon dioxide after combustion is this method's principal drawback.

Various methods have been researched to minimize CO_2 releases from different providers, including changing the fuel of high CO_2 content with lower one, switching to renewable energy from fossil sources, improving the plants' efficiency, and utilizing CO_2 capture technologies. Absorption, adsorption, membranes, cryogenic, and hybrid uses of such methods can all be harnessed for carbon dioxide capture, based on the capture system. The absorption processes of CO_2 capture rely on whether the solvent interacts chemically with CO_2 to produce chemical substances, where the gas can be captured later, or if the solvent absorbs the sorbate without undergoing a chemical process. Chemical and physical absorption are the titles of these two unique methods, respectively. The chemical absorption process (CAP) of CO_2 recovery depends on the exothermic reaction of a solvent with CO_2

that exists in exhausts, preferred at low temperatures. Subsequently, at elevated temperatures, the reaction becomes the opposite in an event known as "stripping" or "regeneration". This method works particularly well for recovering carbon dioxide at modest pressures, where the most prevalent solvents are amine or carbonate solutions. The closest commercially available and highly effective CO_2 removal and storage method is the post combustion process. The most well-known initial amine solvent, monoethanolamine (MEA), is particularly notable for its affordable cost and strong chemical interaction with carbon dioxide. Another advantage of this technology is that it is appropriate for updating the current power stations. Nevertheless, this technology has many drawbacks like low CO_2 loading capacity, large equipment size, amine degradation by the existence of acid gases in the feed gas, and a high rate of machine corrosion, in addition to great energy consumption during the regeneration process.

Physical absorption depends on Henry's Law, where the carbon dioxide's great pressure and poor temperature allow the gas to be absorbed and can be desorbed by pressure reduction and raising the temperature. The primary disadvantage of utilizing the current method is the substantial energy required to compress supply gas to elevated pressures. Certain utilizations, like carbon capture from natural gas, cannot be affected by this challenge since the stream of gas is not required to be pressed because it can originate at a high pressure (more than 100 bar).

Adsorption is another way to capture carbon dioxide from feed gases provided by different sources. Unlike processes of absorption that utilize liquid solvents, the adsorption process uses a solid sorbent to trap carbon dioxide on its outer layer. One of the drawbacks of this process is that it is unable to treat extremely high carbon dioxide levels, which are typically between 0.04% - 1.5%. The majority of power stations contain flue gases with approximately 15% carbon dioxide levels in them. The second is that adsorption occurs in a slow process. Another disadvantage is that existing sorbents, whose

capacity is dependent on pore size, are not sufficiently selective to separate carbon dioxide from feed gases.

Membrane gas separation process is believed to be an applicable and optimistic method for carbon dioxide reduction that can compete with the conventional CO_2 separation processes regarding energy penalties and price. Membrane technology is appealing for carbon dioxide recovery because of its characteristics such as simple structure, clean energy, and environmentally friendly nature. The fundamental drawback of membranes is that they perform worse at lower CO_2 concentrations. Membrane CO_2 capture process can be integrated with different applications like CFPP, natural gas, and different chemical industries. The membrane gas separation process, which is investigated in the present article, is believed to be an applicable and optimistic method for carbon dioxide reduction that can compete with the conventional CO_2 separation processes regarding energy penalties and price. However, polymeric materials are the most mature materials harnessed for CO_2 removal in solution diffusion mechanism.

Cryogenic separation includes a physical capturing procedure that captures carbon dioxide under exceedingly low temperatures. The essential disadvantages of cryogenic process involve the elevation of refrigeration energy consumption, specifically for dilute gas flows, and the blockages caused by some components' presence like water, that must be separated before cooling units.

Chapter 3- Membrane Optimization for CO_2 Capture

Different standards should be taken into consideration such as a high capture rate and low operating costs to improve the carbon dioxide recovery process. Moreover, the essential part is played by the membrane process flexibility in choosing the best configuration for the CO_2 capture process. Membrane removal technology with 1 to 3 configuration modules has been optimized with a numerical model that uses the algorithm shown in Figure 2 for specific membrane parameters.
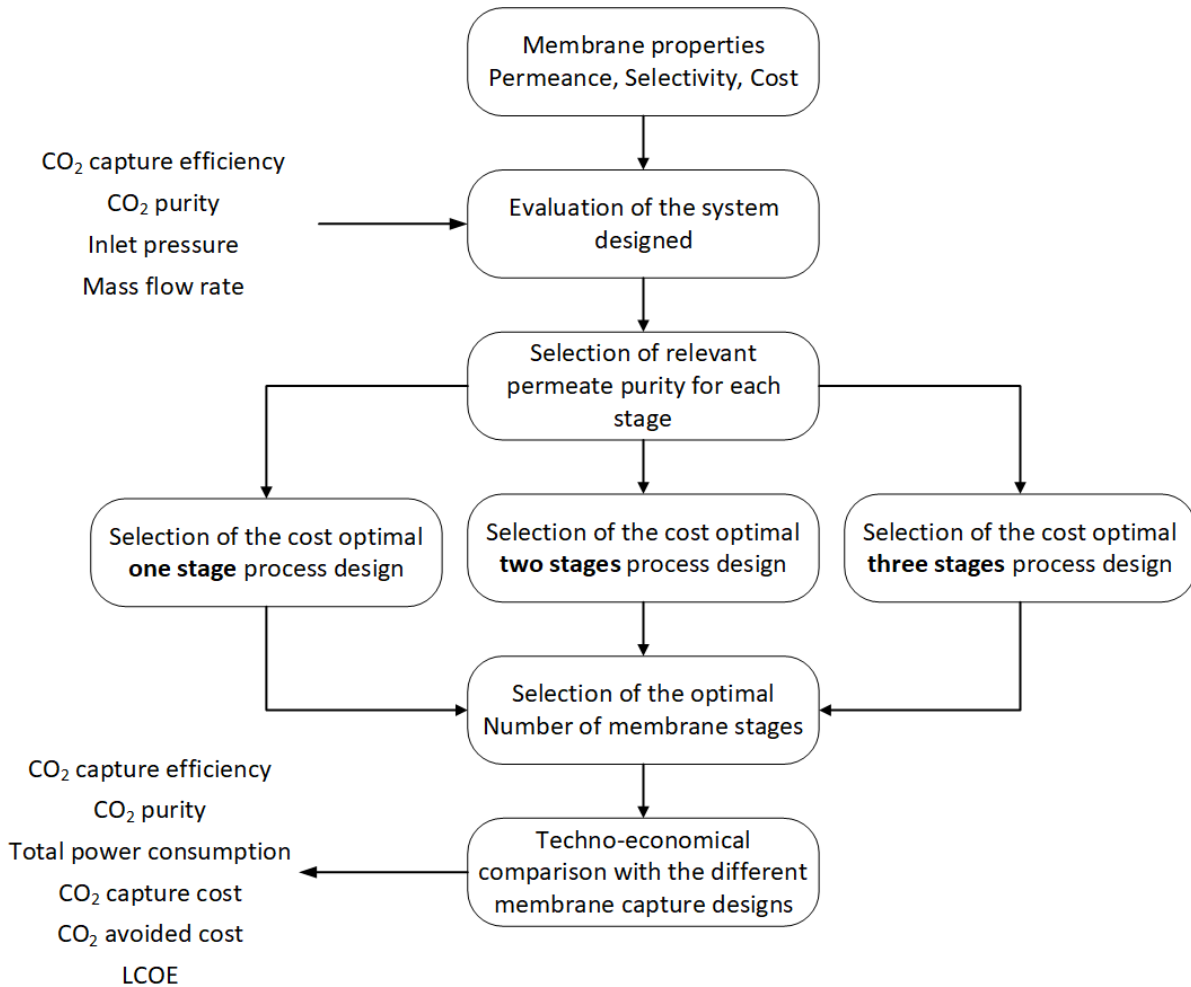
Figure 2. Optimization algorithm for determining and assessing the most economical membrane configuration.

In this study, several configurations are utilized with different parameters to optimize CO_2 capture technology, see Figure 3. Furthermore, an elevated compressor pressure (assumed to be 70 bar) was used at each design considered to compress CO_2 removed from the gas mixture and to be prepared for the next step (storage or direct use). After that compression unit, a heat exchanger unit is recommended to mitigate the elevated temperature resulting from the high-pressure compressor. The required power needed for the membrane auxiliaries (compressors, vacuum pumps) was provided by the power station. The polyacrylamide polymer was integrated with an enzyme called CA in a research project (CO_2 hybrid project) examined in 2020, this material was selected for the current research due to specific advantages such as its characteristic of high permeability and selectivity. CHEMCAD model

8.1 is the simulation platform harnessed to investigate all the operations in the present thesis. However, in each membrane configuration simulated, various values of compressors, and vacuum pumps, were examined to determine the optimum CO_2 capture efficiency and purity at a lower cost. This research also evaluates the impact of different CO_2 permeabilities (300; 1000; 3000 GPU) for post-combustion CO_2 recovery used in fuel-based supercritical electricity production.
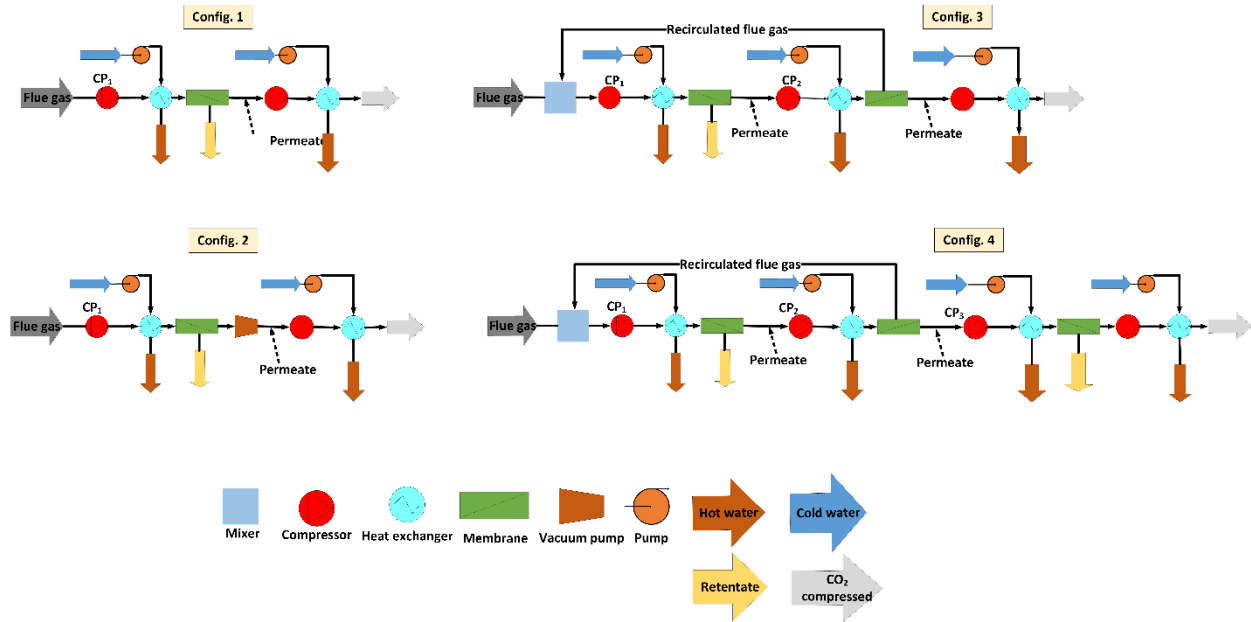

Figure 3. The schematic diagram of each configuration considered.

Figure 3 (Configs. 1 and 2) represents the scheme considered for a membrane single stage with and without the usage of a vacuum pump. The gas mixture (containing CO_2) produced from different sources was introduced into a compression unit with a specific value to enhance the driving force for carbon dioxide recovery. Then, the compressed flow passes through a heat exchanger to reduce temperature to around 50 °C to mitigate the high temperature generated from the compressor, subsequently introduced into the membrane stage. A vacuum pump was used to boost the capture rate by increasing the driving force along the module. The utilization of compression and/or vacuum pump units is fundamental in membrane systems for CO_2 separation to compensate for the low carbon dioxide content and low pressure in feed gas. For the two membrane stages, see Figure 3 (config. 3), the second

membrane module was harnessed to treat the flow permeated from the first membrane module. For the current design, two compression units were utilized before each membrane without vacuum pump utilization. The main purpose of harnessing a compression unit before the 2nd membrane stage was to improve the module's efficiency. The recirculated stream was considered from the retentate stream of second stage to improve the rate of the recovery process. Two membrane units were designed to overcome the low results in carbon dioxide purity by introducing a low surface for the second membrane unit. Multi-stage membrane system designs and recycle flow utilization are substantially required to obtain a high carbon dioxide recovery efficiency with elevated concentration. Figure 3 (config. 4) presents the system design assumed for the CO_2 capture simulation. The main reason for integrating a third membrane stage was to examine its impact on reducing the process power consumption at the same CO_2 removal efficiency and purity.

Based on membrane stages, various membrane system configurations are modeled and studied for different power plants (coal fired power plants and biomass gasification) in post- and pre-combustion carbon dioxide recovery. Membrane for the carbon capture process must achieve a 90% removal efficiency of CO_2 with a concentration of more than 95%, High purity is required for transportation purposes and other goals such as enhanced oil recovery (EOR). The simulation of the proposed technology is demonstrated for sensitivity analyses of the main indicators' effect on the capture efficiency, such as pressure difference across the membrane, CO_2 permeance, flue gas characteristics, membrane surface areas, and the recirculated flue gas. Furthermore, the sensitivity investigation was implemented for a single indicator or various indicators' impact on the requested target. The essential influence of each parameter has been researched.

The low volumetric fraction of CO_2, contrasted with a high flue gas rate, is the essential difficulty for post-combustion capture process, which drives a low driving force of carbon dioxide recovered. To overcome the low motive force in the membrane process fused into post-combustion CO_2 capture technology, either a compressor before the module of membrane or a vacuum pump in the

captured flow side, or both together, can be used. Figure 4 presents the membrane technology utilized in post-combustion process, together with the CFPP used acid gas separation procedure.
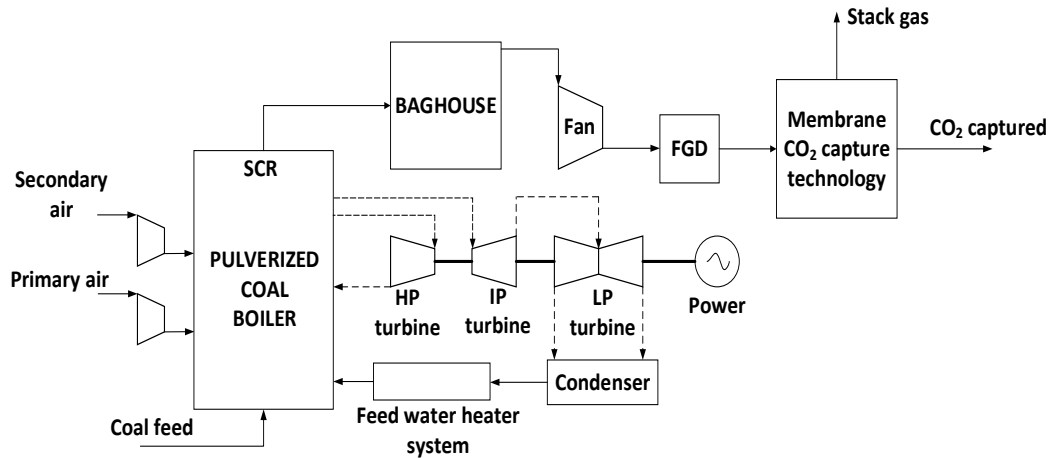

Figure 4. Principle diagram of the integrated membrane into CFPP.

The fundamental feature of using biomass is the fact that biomass absorbs CO_2 during its growth, which is equal to that produced in the combustion step. The most efficient path to utilize biomass is by gasification. Integration of a biomass gasification method with an efficient combined cycle plant is a promising potential choice for CO_2-neutral energy production. The energy losses for the CO_2 recovery process are recompensed by extra carbon dioxide capture, producing a fine CO_2-negative power plant. However, the gasification method of using biomass as fuel and the combined cycle with the carbon removal operation is a potentially promising technology to meet the carbon reduction goal to face the threats of climate change. In the state of solid fuels (as biomass), the pre-combustion recovery method is preferable due to both the carbon dioxide molecules in the syngas (more than 20%) and the pressure of the gas (20–50 bar). These values could be obtained using O_2 instead of air, which is better than the state of post-combustion recovery. A classical pre-combustion CO_2 removal system needs a gasification section, as shown in Figure 5. In terms of the gasification process, solid fuel is modified to syngas enriched with carbon monoxide and hydrogen. After particulate elimination through a cyclone separation section, syngas are then sent to the water gas shift (WGS) section, where carbon monoxide interacts with the vapor to produce a mixture of CO_2 and H_2.

Then, the mixture is processed in desulphurization and carbon dioxide separation methods (e.g., membrane), generating a fuel full of H_2 that can be utilized in several ways, for instance in gas turbines or interior burning engines.
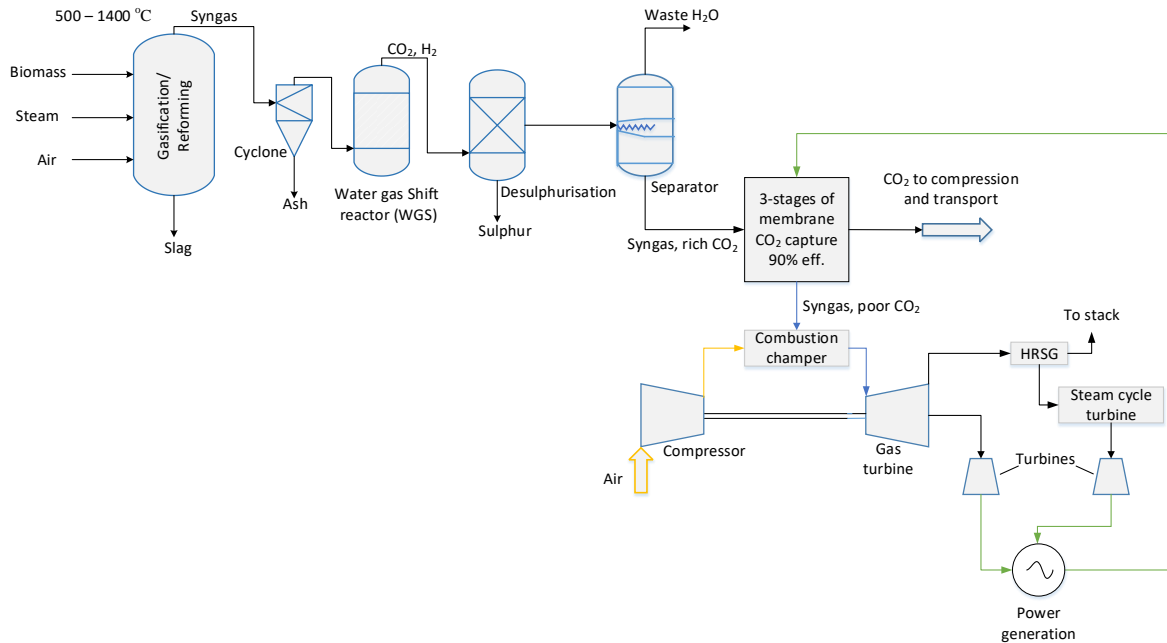

Figure 5. Scheme diagram of BIGCC with pre-combustion CO_2 recovery.

To defeat the drawbacks of each system, the hybrid CO_2 recovery system (membrane-chemical absorption) was studied in the current application. The hybrid systems use membrane process properties to recover carbon dioxide whereas the absorption method is utilized to perform the desired specification. Since the carbon dioxide recovery process is not completely developed in industries from a commercial point of view, studying techno-economic evaluation would be profitable to rise the research comprehension for the features and drawbacks of hybrid CO_2 removal systems. Nevertheless, assessing the execution of hybrid recovery technologies and their economic influence is convoluted due to several factors and the complicated process designs that must be assumed concurrently. When solvent regeneration is combined with membrane technology, the carbon dioxide removal systems are affected by different variables such as flue gas variation and CO_2 fraction in the feed gas, and the molecules' number that must be considered for integration. Despite the membrane-solvent hybrid

carbon dioxide recovery system has been researched, a detailed study of the combined process with the carbon dioxide emissions in an organized and comprehensive style has not been carried out. Most of the investigations currently have concentrated on the hybrid method's advantages like mitigating the energy requirements. Nevertheless, a full economic assessment has not been investigated, therefore, the present conception of hybrid systems is bounded. The hybrid system aims to analyze pre-combustion CO_2 removal from syngas flow emitted by BIGCC with competing systems like membrane, solvent regeneration, and their hybrid method. Two schemes of spiral wound membrane and CAP were investigated for the goal of capturing CO_2 with high purity. A membrane–solvent hybrid system was investigated posteriorly for the configuration statement. The research purpose is to evaluate membrane and chemical absorption performance with the gasification process that used either air or oxygen as an oxidizing agent, see Figure 6, for the target of 90% efficiency (most researchers' main purpose) of the CO_2 releases with a purity of 99%, this purity is recommended for different industrial uses.
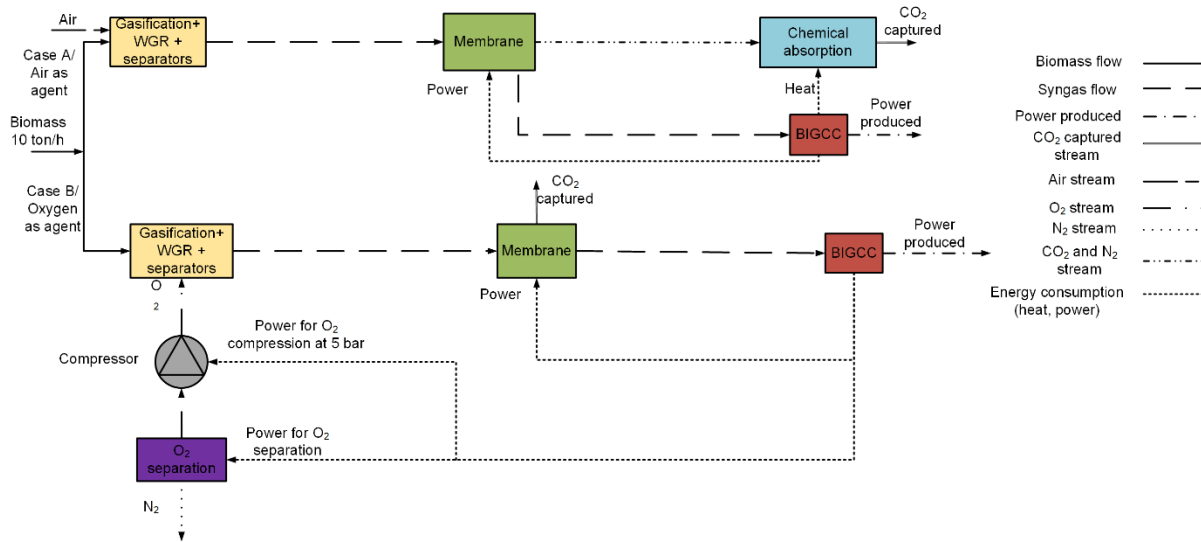

Figure 6. Scheme of pre-combustion carbon capture in BIGCC.

The syngas obtained after the membrane process (the retentate stream) were directly introduced to the combined cycle for electricity generation. The back-pressure steam turbine's steam (5 bar) was utilized either to provide heat energy for solvent regeneration (case A) or to cover the WGR (water gas

shift reactor) requirements for case B. In case A, the steam required for WGR was generated from HRSG (heat recovery steam generator), where 500 kg/h of natural gas was used.

Chapter 4- Technical and Economical Assessment

This research also investigated the connection between the CO_2 removal price and the amount of CO_2 in gas feed flow. For each case, the power consumption demanded for the membrane process, operational expenditures (OPEX), and capital expenditure (CAPEX) were computed and compared. Furthermore, based on the CAPEX and OPEX and considering a 25-year project period, the levelized cost of electricity (LCOE) was calculated. For each case, the CO_2 avoided and capture costs were determined. Ultimately, a financial analysis, mainly net present value (NPV) and discount payback period (DPP) was studied to consider all cash flows in and out of the established meter to decide whether an investment project is economically feasible.

Chapter 5- Results and Discussion

5.1 Membrane Integration into Coal Fired Power Plants

The results showed that integration of a single membrane stage can be considered sufficient for projects with low CO_2 purity requirements. The first compressor pressure is the master component that manipulates carbon dioxide capture rate, the power required, and the purity of the CO_2 removed. Carbon dioxide purity is also impacted by the increase in first compressor pressure by around 17% at the same first membrane surface. The results showed that increasing the pressure variation along the membrane stage leads to a reduction in the membrane area constantly, therefore decreasing the total annual cost. The first membrane area has a senior direct impact on the whole recovery rate, for example, increasing the first membrane surface from 200,000 to 600,000 m^2 showed a rise in CO_2 capture efficiency by approximately 31% at the same compressor pressure, see Figure 7.
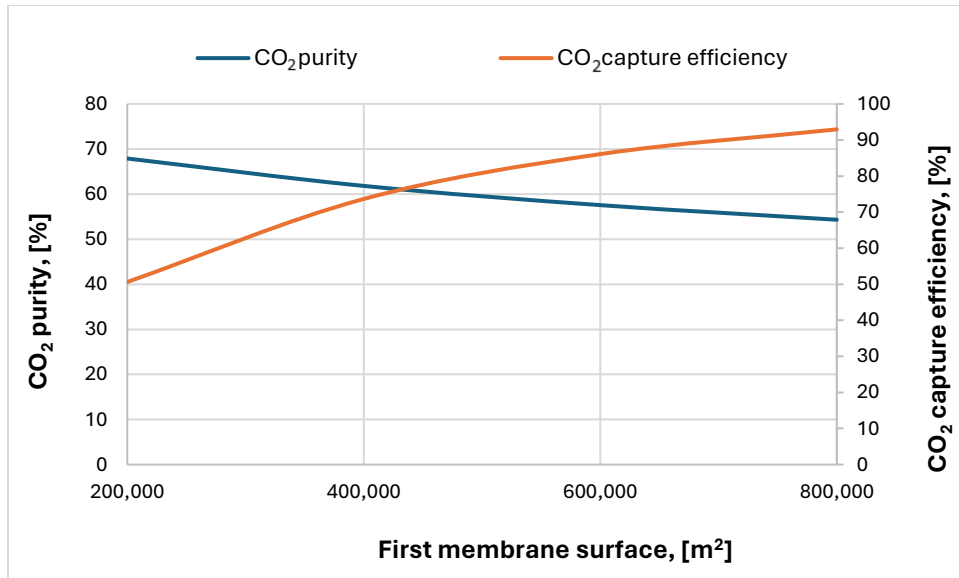
Figure 7. The variation of CO_2 capture rate and purity regarding different first membrane surfaces used in 600 MW CFPP.

Furthermore, the simulations revealed that increasing the membrane stages granted the advantage of raising the purity of CO_2 recovered due to the usage of second membrane unit with a lower surface area. The process design of two-stage configuration is an efficient process for projects with 95% purity demands at a carbon dioxide permeability of 1000 – 3000 GPU. High compressor pressure increases the power required for membrane process, which decreases the power plant efficiency. Figure 8 represents the total power plant efficiency loss after using membrane CO_2 capture technology. The membrane system parameters were used based on the optimum case obtained from 2-stages configuration. The net power plant efficiency is reduced by around 21.82%, that percentage is divided into 17.46 to the energy required for compressors and VPs to capture the CO_2 and 4.36% for CO_2 captured compression units to prepare the gas for storage and transportation.
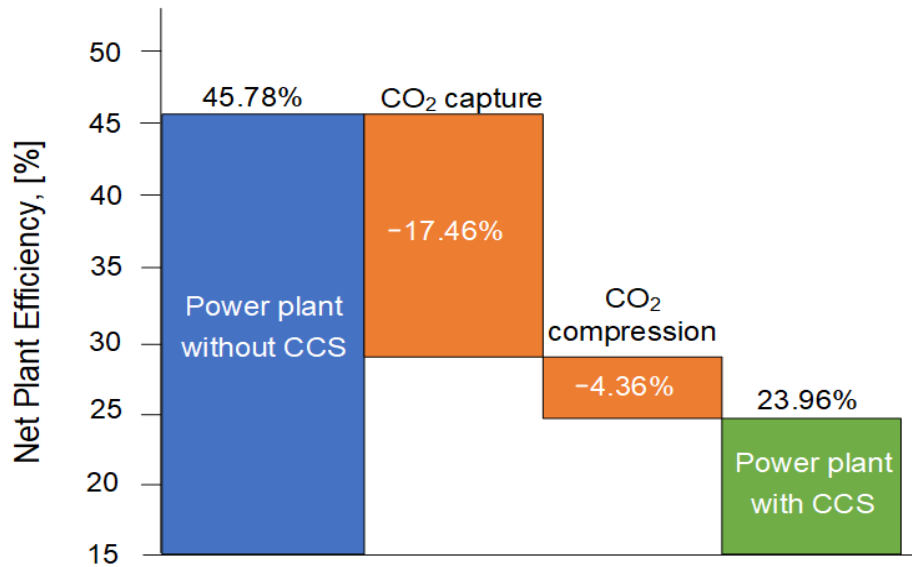
Figure 8. Efficiency loss after membrane integration into 330 MW CFPP.

To estimate the action of the recirculated flue gas from the 2nd membrane on CO_2 capture efficiency, three cases of recycling flue gas stream have been examined in Figure 9 as follows:

Case 1. Recycle flue gas from the 2nd membrane.

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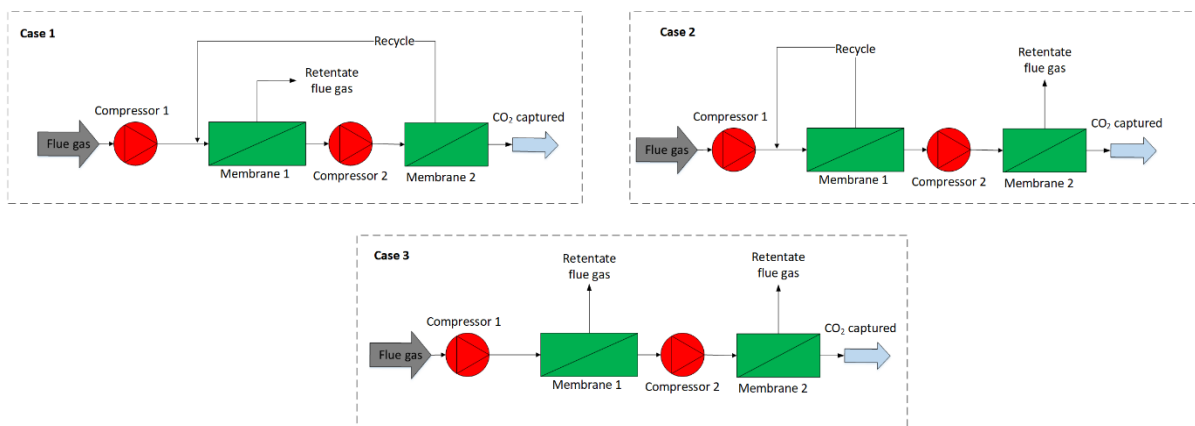
Case 3. No flue gas is recycled.

Figure 9. Cases of the recycled stream flow utilized in 330 MW CFPP.

Table 1. The score of the three cases examined, in 330 MW CFPP, at specific indicators.

Cases	Units	Case 1	Case 2	Case 3
CO_2 capture efficiency	%	94.85	37.91	43.94

CO$_2$ purity	%	96.85	90.33	87.01
Power consumption	MW	189	47,369	134

As shown in Table 1, case 1, where the recirculated flow stream is located on the 2nd membrane retentate side, is ideal because of the high carbon dioxide recovery efficiency and its purity. In case 2, carbon dioxide recovery efficiency is extremely low because of the low SA$_2$ (40,000 m^2). As a consequence of the high recirculated flow from the 1st membrane unit to the primary flow side, the CP$_1$ energy is completely enormous, which raises the power consumption demanded (47,369 MW). Case 3 shows an excessively low CO$_2$ capture efficiency (43.9 %) due to the 2 sides retentate flow.

Nevertheless, the proposed design of two stages was observed to be non-economically convenient for a system of 99% CO$_2$ purity, due to the high energy consumption that increases the capture cost. Based on the simulation, integrating three units of membranes helped the whole process to gain 90, and 99% rates of efficiency and purity with around 12% lower power than the usage of two stages at the same flue gas characteristics. The recirculated flue stream from the second membrane reduced the CO$_2$ stream released to the atmosphere, where that structure improved the process with a high carbon dioxide removal rate and purity. The recycle flue stream designed from the second membrane unit increased CO$_2$ capture efficiency by around 54%. The results obtained showed increasing CO$_2$ permeance demonstrate greater CO$_2$ capture rate and purity and lower membrane area. Even though higher CO$_2$ purity may be procured for materials of high CO$_2$ permeability, the power consumption is higher and may not be favorable economically. Table 2 below shows the main results of the membrane configurations assumed.

Table 2. The configurations main results.

Configurations	Units	Config. 1	Config. 2	Config. 3	Config. 4
CO$_2$ capture rate	%	90.1	90.3	90.0	90.7
Power needed	MW	289.1	238.5	340.6	298.3
CO$_2$ purity	%	45.6	73.3	99.1	99.7

LCOE	EUR/MWh	137	109	157	134
CO_2 captured cost	EUR/t	47.16	35.44	62.47	51.82
CO_2 avoided cost	EUR/t	51.3	52.16	134.4	93.82

Regardless of membrane CO_2 permeability, the compression section in a membrane system is the most significant contributor to LCOE due to the poor CO_2 pressure difference in feed gas across the membrane unit. Improving CO_2 inlet partial pressure in an efficient technique is fundamental to reducing LCOE. High surface area raises the capital cost (CAPEX) and high compressor pressure influences the operating cost (OPEX) due to the high CO_2 content passed through the membrane, which increases the power consumption required. By increasing membrane area, the power plant efficiency goes down constantly due to the increase of CO_2 capture efficiency with membrane area increase, which leads to high demands of power. Finally, the increase in power consumption led to a rise in discount payback period (DPP).

Figure 10 below shows the accumulated cash flow of different membrane schemes integrated into the coal power plant throughout its duration (25 years). After almost 8 years, the investment cost will be recovered in the case of 1-single stage. Integrating 3-stages decreased the period of investment recovery by approximately 13% compared with using 2-membrane stages.

Figure 11 below demonstrates the effect of CAPEX, fuel, and other various indicators price on LCOE at CFPP with the integration of the third case of membrane scheme. The impact of the CAPEX and plant capacity factors is distinguished on the LCOE, where LCOE differed from almost 124 to 143 EUR/MWh by modification CAPEX price +/-10%.
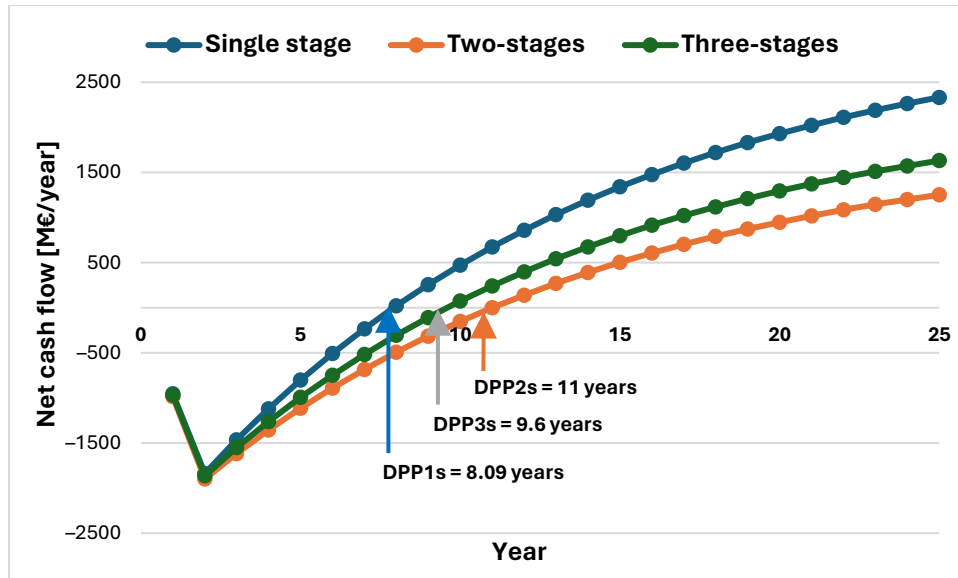
Figure 10. Discount payback period regarding the three cases of accumulated cash flow used in 600 MW CFPP.
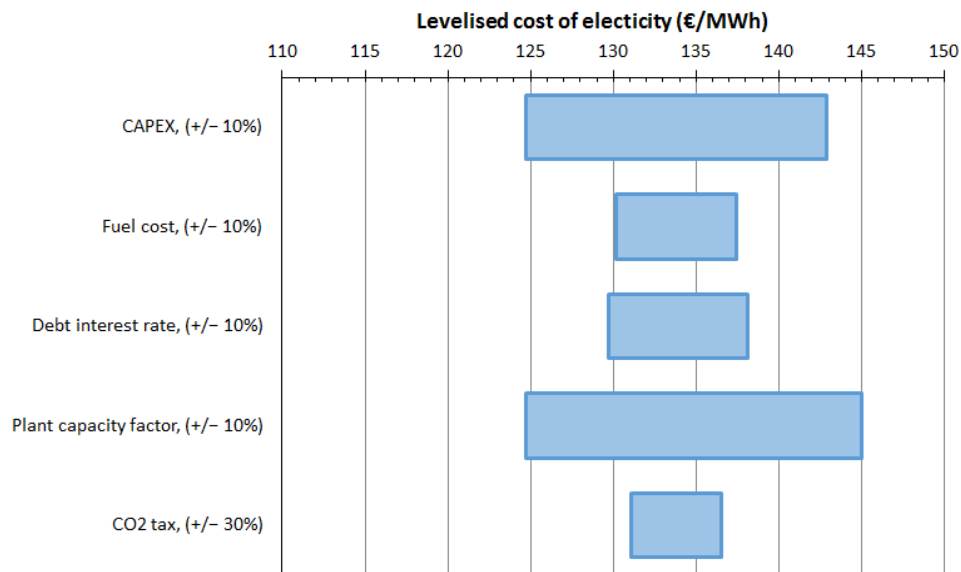
Figure 11. Influence of different factors used in 600 MW CFPP on LCOE.

5.2 Membrane Integration into BIGCC

Table 3 presents an evaluation differentiation between the BIGCC power plant without the utilization of the membrane pre-combustion process.

Table 3. The technical and economical estimation of BIGCC (50 MW) with and without membrane process.

Parameter	Unit	BIGCC Single	BIGCC with Membrane
Introduced biomass	t/h	31.86	31.86

Global efficiency (LHV syngas)	%	62.20	37.60
Global efficiency (LHV biomass)	%	29.80	18.04
Net power produced	kW	50,000	30,245
CO_2 recovery factor	kg/MWh	0.00	−822.63
CO_2 recovered	kg/MWh	n.a.	939.11
Electricity needed for membrane process	kWe	n.a.	19,700
Membrane power consumption	kWh/tCO_2	n.a.	694
LCOE_rate	EUR/kWh	0.0974	0.1410
SEPCCA	MJel/kg	n.a.	2.86
CO_2 avoided price	EUR/t	n.a.	52.94
CO_2 captured price	EUR/t	n.a.	46.37

The moment when the membrane system was integrated with the BIGCC power station, the net energy generated was reduced by about 60% due to the extra power demanded by the auxiliary components used in the membrane (such as compressors). As already mentioned, biomass is a neutral fuel that absorbs CO_2 during its growth for photosynthesis, which elucidates why the carbon dioxide recovery factor is minus after utilizing the capture technology. The Integrated membrane process caused a significant increase in LCOE of 69%, which can be explained by the several items used to remove carbon dioxide from the syngas flow.

5.3 Hybrid Polymeric Membrane – Chemical Absorption System for Pre-Combustion CO_2 Capture

Regarding the value used, carbon dioxide in the syngas is 23.9% of the syngas flow, and the CO_2 produced from CO exits in the syngas is 319.8 kg/h (as it is in Figure 12), therefore, CO_2 generated after syngas and combustion process is 6336.4 kg/h, which represents the amount of CO_2 absorbed during biomass growth (photosynthesis process).
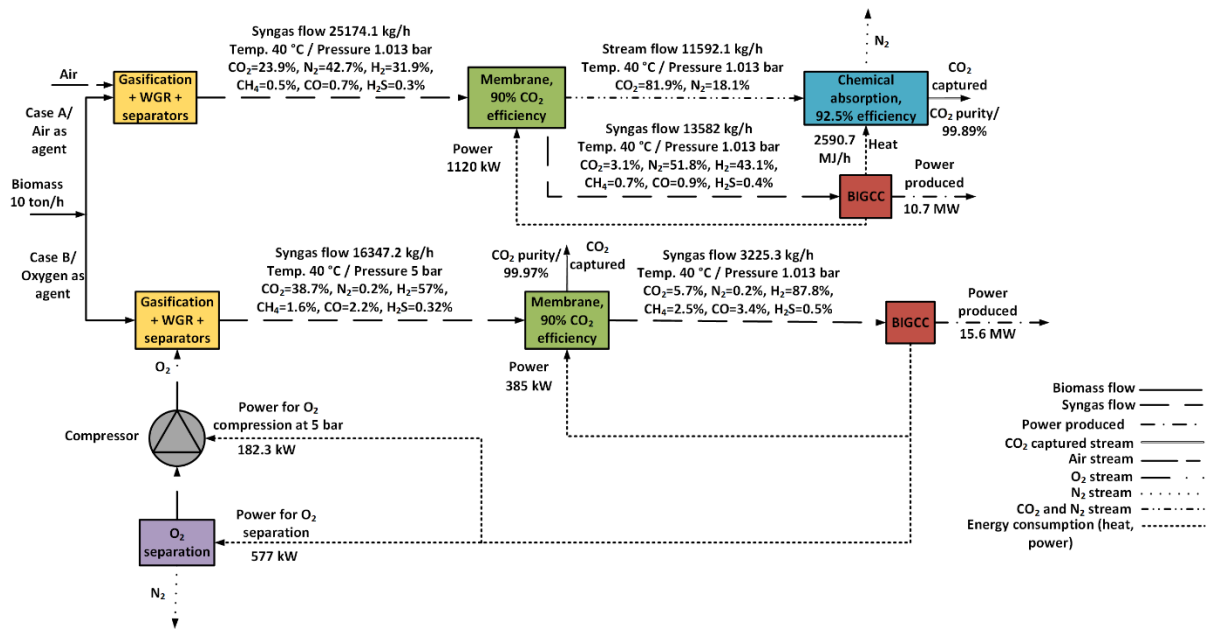
Figure 12. The main results of the two cases proposed at hybrid capture system.

The CO_2 emissions generated by the primary energy for biomass preparation and transport to the power plant were not considered. Table 4 shows the optimum results of each case simulated and modeled.

Table 4. The essential results regarding the four cases examined at hybrid capture system.

Cases	Case A		Case B	
	No CO_2 capture	With CO_2 capture	No CO_2 capture	With CO_2 capture
Biomass flow, ton/h	10	10	10	10
Heat flow with syngas, kW	24,979	24,979	8698	8698
CO_2 emissions for biomass growth, kg/h	6336.4	6336.4	7534.5	7534.5
CO_2 emissions from natural gas usage, kg/h	No use	1380.3	No use	No use
Total CO_2 emissions, kg/h	6336.4	2013.9	7534.5	753.45
Membrane surface area, m^2	-	25,000	-	2500
Compressor pressure, bar	-	2.2	-	No use
Vacuum pump pressure, bar	-	0.25	-	0.25
L/G ratio for Chemical absorption, mole/mole	-	12.4	-	No use
Solvent flow, kmol/h	-	350	-	No use
Energy consumption for chemical absorption, MJ/kg	-	3.9	-	No use
Power of gas turbine, kW	8968.2	8968.2	12,234.4	12,234.4
Power of steam turbine, kW	2896.2	2896.2	4559.1	4559.1
Global efficiency, %	42.0	38.0	42.3	41.3
CO_2 factor, kg/MWh	-	-435.5	-	-877.4

NPV, million EUR	9152	67,411	32,470	124,830
DPP, years	17.73	8.17	8.07	4.5
Profitability index	1.18	2.15	1.62	3.87
LCOE, EUR/MWh	157	142.5	135.3	86.1

The CO_2 factor for case A is higher than the other case due to extra CO_2 produced by natural gas combustion. The global efficiency in case A was reduced by CCS utilization, where both electrical and thermal energy was consumed for the membrane and solvent regeneration process. On the other hand, the global efficiency in case B wasn't highly influenced by using CCS because of the low energy required for the membrane VP (385 kW).

In case A, the gasification process occurred with atmospheric pressure, so no electricity was required to compress the stoichiometric air stream. The syngas produced have a high flow rate, therefore, a compressor was utilized before the membrane stage to raise the CO_2 removal efficiency and that increased the electricity needed. Even though CAP helped raise the purity of CO_2 recovery, it increased CAPEX cost and mitigated the total combined cycle power generation due to the heat energy required. On the other hand, the usage of O_2 as an oxidizing agent has the advantage of no CAP utilization in the process due to the high purity (99.9%) achieved after the membrane stage, which enhanced the reduction of CAPEX cost in case B. In contrast to case A, electrical energy was needed for O_2 separation which can be considered a power consumption from the combined cycle. However, the integration of a 5-bar compressor in the O_2 stream (in gasification) generated the syngas at high pressure where no need to provide high electricity for the membrane stage as in the air case. Consequently, the electricity produced in case B is greater than that produced in case A.

5.4 Solutions to Improve the CO_2 Capture Process

Utilizing an energy recovery system (expander) in the N_2 rich stream improved the full capture system regarding economical assessment. The CO_2 avoided cost was reduced by 34% after integration of the expander in the same process configuration due to the energy recovered which decreased the power consumption for the capture method, see Figure 13. However, expander integration in membrane

CO_2 capture system illustrated a more profitable project by around 11% compared to the same project without the expander unit.
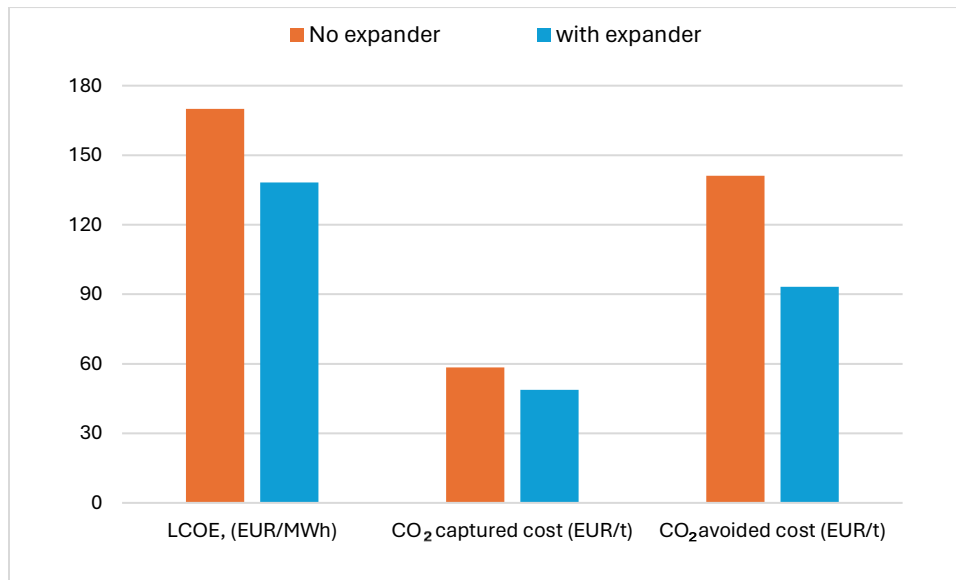

Figure 13. The comparison of the project's different economic indicators based on expander utilization.

5.4 Validation of Current Results with Different CO_2 Technologies in Post- and Pre-Combustion Systems from Literature

Validation of the results for post- and pre-combustion systems was performed by comparing the current research results with the results obtained in the literature to present a net perception concerning a model that utilizes the CHEMCAD program with membrane technology. Table 5 below shows a detailed comparison between recent research outcomes based on membrane and other articles already published regarding different CO_2 capture technologies (CAP, physical absorption) in post/pre combustion process for various substantial parameters.

Table 5. Post/pre- combustion system comparison of different CO_2 capture processes (literature) with current research results.

Parameters	Post-combustion			Pre-combustion		
	Current results	CAP (1)	CAP (2)	Current results	CAP (3)	Physical absorption
CO_2 capture efficiency, (%)	90	85	90	90	90	95

CO$_2$ purity, (%)	96.8	99.5	95	99	95	99
Efficiency loss, (%)	37.3	n.a.	n.a.	39.4	n.a.	n.a.
LCOE, (EUR/MWh)	138	130	75	141	148	142
CO$_2$ avoided cost, (EUR/t)	93.28	86.4	37.1	52.94	60.4	67.22
CO$_2$ captured cost, (EUR/t)	48.77	n.a.	31.4	46.37	n.a.	58.4

In the post-combustion process, membrane carbon dioxide removal technology requires more improvements to compete with CAP, where the main techno-economic parameters show progress in solvent regeneration technology. The recent outcomes based on membrane technology in the pre-combustion process demonstrate more efficient techno-economic parameters than other CO$_2$ capture technologies (CAP, physical absorption).

Chapter 6- Conclusions

1. Integration of a single membrane stage can be considered sufficient for projects with low CO$_2$ purity requirements. However, it was discovered that the membrane single-stage system must be further integrated with another membrane unit or with another separation system to improve the carbon dioxide capture concentration.

2. The optimal configuration in this analysis is membranes in two stages with compressors from an economical point of view, where the project is approximately 40% more profitable.

3. The results showed that increasing the pressure difference across the membrane stage leads to a reduction in the membrane area constantly, therefore decreasing the total annual cost.

4. For 99% CO$_2$ purity, the membrane process design with three stages instead of two can save around 15% and 17% in LCOE and CO$_2$ capture cost, respectively.

5. Utilizing a CO2-capture membrane system with high CO_2 permeability material (3000 instead of 1000 GPU) at large-scale power improves the capture efficiency by around 53%.

6. Integrating an expander in the retentate flow reduced the LCOE and CO_2 captured cost by 18% and 20%, respectively.

7. It is not convenient to have a hybrid process (membrane & chemical absorption) for CO_2 capture system because membrane module has a prohibitive cost (currently), and the hybridization suffers of high investment cost either the membrane process is integrated before or after chemical absorption. If chemical absorption is placed before membrane technology, the investment cost would increase compared with using only chemical absorption. If the chemical absorption integrated after membrane, the chemical solvent suffers from high cost due to the high CO_2 concentration permeating from membrane (60% purity), whereas the solvent is more efficient with a low CO_2 concentration (3-15%), therefore, it is more efficient to add another membrane stage instead of chemical absorption process.