Critical Assessment of Membrane Technology Integration in a Coal-Fired Power Plant

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Abstract: Despite the many technologies for CO\textsubscript{2} capture (e.g., chemical or physical absorption or adsorption), researchers are looking to develop other technologies that can reduce CAPEX and OPEX costs as well as the energy requirements associated with their integration into thermal power plants. The aim of this paper was to analyze the technical and economic integration of spiral wound membranes in a coal-fired power plant with an installed capacity of 330 MW (the case of the Rovinari power plant—in Romania). The study modeled energy processes using CHEMCAD version 8.1 software and polymer membranes developed in the CO\textsubscript{2} Hybrid research project. Thus, different configurations such as a single membrane step with and without the use of a vacuum pump and two membrane steps placed in series were analyzed. In all cases, a compressor placed before the membrane system was considered. The use of two serialized stages allows for both high efficiency (minimum 90%) and CO\textsubscript{2} purity of a minimum of 95%. However, the overall plant efficiency decreased from 45.78 to 23.96% and the LCOE increased from 75.6 to 170 €/kWh. The energy consumption required to capture 1 kg of CO\textsubscript{2} is 2.46 MJ\textsubscript{el} and 4.52 MJ\textsubscript{th}.

Keywords: membrane technologies; CO\textsubscript{2} capture; post-combustion processes; economical assessment; process integration

1. Introduction

In the past decade, considerable improvements in polymeric membrane materials for gas separation processes have been observed, where many types of polymer materials have been manufactured. Consequently, their transport properties could provide an energy-efficient path for wide-range gas separations. Due to the urgent demand to mitigate CO\textsubscript{2} emissions from the application of fossil fuels, these planned research potentials have been vastly catalyzed. In general, CCS technologies are believed to be a successful technological solution to reduce the environmental and economic carbon dioxide influences, comprising climate change [1]. The classical process for CO\textsubscript{2} capture, which is based on amine absorption, demands high energy, needs high capital and operating cost, and causes corrosion and environmental troubles in addition to some operational problems. As a result, the membrane is used due to high energy efficiency, operational plainness, system consolidation, and capability to beat thermodynamic solubility restrictions. As a rule, a membrane is a thin interphase layer that plays a significant role in separating two phases [2,3].

Presently, various CO\textsubscript{2} capture processes have been used based on either ejecting CO\textsubscript{2} from flue gas (post-combustion), from syngas (pre-combustion), or injecting pure O\textsubscript{2} instead of air (oxy-fuel combustion) which provides a high CO\textsubscript{2} flow [4–7].

So far, different membranes have been enhanced and characterized by high permeability and selectivity to achieve a high CO\textsubscript{2} capture process. Various types of membrane materials such as inorganic membranes, common polymers, carbon molecular sieve membranes, mixed matrix membranes, fixed site-carrier (FSC) membranes, and carbon molecular sieve
membranes have been utilized for CO₂ separation operation [8]. Nevertheless, to provide a commercially viable membrane to capture CO₂ and contend with the classical amine absorption process, membrane technology must have a relatively low power consumption and low particular capture cost conjointly with an acceptable stability exposure to impurities such as SO₂ and NOₓ, which are generally included in the flue gas stream [8].

Over the last decade, preferable polymeric materials with enhanced CO₂ permeability and selectivity have been vastly researched. Generally, more permeable polymers lead to less selectivity and vice versa, similar to a trade-off relationship. In any case, most polymeric materials depend on the solution-diffusion mechanism in which this trade-off is heavily rooted [9,10].

Processability is a basic demand for an effective industrial gas separation membrane. Dense polymers are suitable membrane materials whereas most commercial membranes are manufactured from polymers with low-cost and good scalability, as a result of the credible fabrication of a fine selective layer of 0.1–10 µm and membrane surface area at a range of (1000–1,000,000 m²) [11]. The simplest model utilized to demonstrate and predict the gas permeation process via the dense membrane is the solution-diffusion model, where a molecule can transport from one side of the material to another by a concentration gradient. In typical, the separation can be obtained by the difference in solubility and/or diffusivity. The solubility of specific gases relies on their condensability and affinity to the membrane material. Generally, the molecule condensability expands by increasing critical temperature [12]. On the other hand, the diffusion of a gas molecule depends on the space between two chains, where the chain piece’s random motion permits small kinetic diameter molecules to diffuse through [13]. As a result, the molecule diffusivity increases by the decrease of kinetic diameter. Table 1 demonstrates the physical properties of different gases.

### Table 1. Physical properties of different gases [14].

| Gas   | Kinetic Diameter/µm | Critical Temperature/°C |
|-------|----------------------|-------------------------|
| CO₂   | 0.330                | 304.1                   |
| N₂    | 0.364                | 126.2                   |
| H₂    | 0.289                | 33.2                    |
| CH₄   | 0.380                | 190.6                   |

### 2. Solution-Diffusion Polymeric Membranes

In this part, the current advances for polymers that are eligible for selective CO₂ separation based on the mechanism of solution diffusion are researched. Five types of polymers are involved: polyethylene oxide (PEO), perfluoro polymers, polymers of intrinsic microporosity (PIMs), thermally rearranged (TR), and iptycene-containing polymers. These types are sorted depending on the discovery period or application in the gas separation process. Polymer string hardness is the main factor that affects this sequence, from the rubbery PEO to the vitreous TR polymers. In addition, the iptycene-containing polymers are derived/adjusted polymers through the integration of iptycene-containing moieties [15].

#### 2.1. PEO-Based Membranes

Despite the CO₂ molecule being non-polar, the different distribution of charges inside gives the molecule a quadrupole moment [16]. In poly (ethylene oxide) (PEO), the polar ether connection (–C–C–O–) is noticed to have a high affinity to CO₂ [17]. Thus, PEO-based polymers offer a major CO₂ solubility, and CO₂ selectivity typically derives from the solubility selectivity. However, one drawback that has been observed is the high degree of crystallinity in pure PEO or in materials related to PEO. Due to the polar ether groups inclination to compose powerful hydrogen bonding, which leads to a compact chain packing [18]. The crystalline area that formed obstructs the diffusion of CO₂ and ultimately restrains the membrane permeability. Weak mechanical strength is also a result of high crystallinity. To compensate for these restrictions, different processes have been...
applied, including (1) block copolymerization with other rigid pieces, (2) combining with low MW poly (ethylene glycol) (PEG) and its derivatives, and (3) crosslinking to compose a highly branched PEO polymer network [19]. In addition to providing noticeably permeable PEO membrane materials, these efforts also drive a remarkable understanding of the nanostructures of the PEO polymers. Generally, the most accepted process to prevent the high crystallinity of PEO is to block the copolymerization of PEO with rigid pieces [11,20].

Table 2 demonstrates the permeabilities of CO$_2$ and CO$_2$/gas selectivities of the PEO polymers based on various strategies.

Table 2. Transport properties of specific PEO polymers.

| Strategy   | Material                                      | T/°C | CO$_2$ Permeability/Barrer | (CO$_2$/N$_2$) Selectivity | (CO$_2$/H$_2$) Selectivity |
|------------|-----------------------------------------------|------|---------------------------|---------------------------|---------------------------|
| Copolymer  | PEO-b-PA6 [14]                                | 35   | 120                       | 51.4                      | 9.8                       |
|            | PEO-b-PBT [20]                                | 35   | 150                       | 51.5                      | 10.3                      |
|            | PEO-ran-PPO T6T6T [21]                        | 35   | 470                       | 43                        | 10                        |
|            | Pent-PI-PEO2000 [22]                          | 35   | 39                        | 36                        | 4.1                       |
|            | PEO-b-PBT on PDMS [23]                        | 30   | 1815 *                    | 50                        | -                         |
| Blending   | PEO-b-PS [24]                                 | 70   | 20,400 *                  | 27.7                      | -                         |
|            | PEO-PBT/PEG200 [20]                           | 30   | 208                       | 48.7                      | 11.6                      |
|            | PEO-PBT/PEG-BE [20]                           | 35   | 400                       | 50.1                      | 11.8                      |
| Crosslinking| PEO-PBT/PEG-DME [25]                          | 45   | 896                       | 36                        | 10.6                      |
|            | PEO-amine/PEO-epoxy [27]                      | 35   | 376                       | 53                        | 10                        |

* GPU.

The PEO block copolymers commonly demonstrated a CO$_2$ permeability around 100–200 Barrers with the selectivity of CO$_2$/N$_2$ about 50 at 25 °C. Monodisperse tetra-amide (T6T6T) and pentiptycene-based polyimide (pent-PI) are kinds of many new hard segments that were incorporated with PEO to assemble ultra-permeable PEO-based copolymers [22,23]. The self-synthesis trait of the PEO-based block copolymer was also largely studied. A polymer chain rearrangement was noticed by Yave et al. when an ultrathin selective layer was covered onto a hydrophobic PDMS face, resulting in a high CO$_2$ permeance of 1815 GPU with a CO$_2$/N$_2$ selectivity around 50 at 30 °C [23]. Xue et al. assembled a PEO–polystyrene (PS) block copolymer, where cylindrical PEO domains are formed, which provide intense CO$_2$ permeance of 20,400 GPU with a CO$_2$/N$_2$ selectivity around 27.7 at 70 °C [24].

Another strategy that is utilized to increase the ether content in the polymer matrix is known as blending. A 100–2 000 MW short-chain PEG was established in a PEO-based copolymer via polymer chain tangle, which improved the CO$_2$ solubility and broke the compact packing of the PEO piece in the copolymer. The strong hydrogen bonding among the ether kinds can be reduced due to the tip parts on PEG that supplied another control. As a result, PEG moieties with end parts, such as methyl ether, ally ether, divinyl ether, and butyl ether, were researched [23].

The crosslinking process indicates the bottom-up assembly of extreme branches of PEO or PEO-based copolymers by the polymerization of ethylene oxide monomer or oligomer. In this process, the primary work was based on different methacrylate monomers, where the crosslinking mitigated the crystallinity and enhanced the film-forming capacity [28]. Kline et al. demonstrated that the crosslinking density and heterogeneity could be adjusted via the platform of poly (ethylene glycol) diglycidyl ether and polyether diamine, where the heterogeneity crosslinking enhanced the permeability of CO$_2$ [27]. In Figure 1, unimodal, bimodal, and clustered PEO networks are assembled.
PEO-based polymers have the main commercial potential, due to the high CO₂ permeance that has been presented in thin-film-composite membranes under specific testing conditions. Furthermore, the various PEO-based materials that have demonstrated practicable selectivities at an operating temperature of more than 35 °C are of special significance [24,29].

2.2. Perfluoro-Polymers

These are a group of glassy hydrocarbon polymers with added fluorine atoms instead of all or most hydrogen atoms. Due to the powerful C–C and C–F covalent bonds, Perfluoro-polymers are resistant to many chemicals, which leads to these polymers being typical for applications that are submitted to hostile situations [30]. One of the drawbacks is their semicrystalline nature and low solvent processability, which largely obstruct the development of the polymers in gas separation. In the mid-1980s, the gas permeation data were obtained through the introduction of many amorphous perfluoro-polymers with specific trade names, such as Teflon™ AF, Hyflon™ AD, and Cytop™. In Figure 2, the chemical structures of these perfluoro-polymers, which are commercially obtainable, are demonstrated. They are either cyclic homopolymers or copolymers of tetra-fluoro ethylene and perfluoro odioxole, where they are known for their elevated gas permeability because of the pre-existing micro channels [31]. The properties of these glassy perfluoro-polymers are shown in Table 3, listed from the most permeable Teflon™ AF2400 to the least permeable Cytop™.
Table 3. Transport properties of specific perfluoro-polymers.

| Strategy  | Material               | P (CO$_2$/atm) | T/°C | CO$_2$ Permeability /Barrer | CO$_2$/H$_2$ Selectivity | CO$_2$/N$_2$ Selectivity |
|-----------|------------------------|----------------|------|-----------------------------|--------------------------|---------------------------|
| Commercial| Teflon™ AF2400 [32]    | 1              | 35   | 2200                        | 4.6                      | 0.96                      |
| Commercial| Teflon™ AF1600 [33]    | 1              | 35   | 520                         | 4.7                      | 1.06                      |
| Commercial| Hyflon™ AD80 [34]      | 3              | 35   | 473                         | 6.1                      | 1.19                      |
| Commercial| Hyflon™ AD60 [34]      | 3              | 35   | 124                         | 7.3                      | 1.63                      |
| Commercial| Cytop™ [34]            | 1              | 35   | 35                          | 7                        | 1.69                      |
| Commercial| Teflon™ AF2400 [35]    | 4.4            | 35   | 13,000 *                   | 4.8                      | 0.81                      |
| Commercial| Hyflon™ AD60 [35]      | 4.4            | 22   | 1330 *                     | 7.3                      | 1.28                      |
| Homopolymer| Poly(PFMD) [36]        | 4.4            | 35   | 5.9                         | 8.3                      | 8.47                      |
| Copolymer | Poly(PFMM-co-PFMD) [37]| 4.4            | 35   | 58                          | 7.5                      | 4.1                       |
| Copolymer | Poly(PFMM-co-CTFE) [37]| 4.4            | 22   | 403 *                      | 9.1                      | 2.9                       |

* GPU.

2.3. Polymers of Intrinsic Microporosity (PIMs)

PIMs are a kind of glassy polymer with hard and twisted macromolecular backbone structures, which were originally reported by Budd and McKeown [38]. Unlike other porous organic polymers, PIMs are solution-treatable [38]. They are generated from the locations of twisting or spiro centers, where the poor molecular packing is induced by the restricted chain turnover of the component macromolecules, performing interconnected holes of smaller than 2 nm [39]. The substantial microporosity of this kind of polymer produces a less than 20% fractional free volume (FFV), resulting in elevated gas permeability [40]. The substantial microporosity of this kind of polymer produces a less than 20% fractional free volume (FFV), resulting in elevated gas permeability. These advantages swiftly stimulated concentrated research potential to assemble various PIMs to enhance the gas permeability and selectivity [38]. Table 4 represents the transport properties of the newly improved PIMs, involving spirobiindane (SBI)-based PIMs, Tröger’s base (TB)-based PIMs, polyimide (PI)-based PIMs, and some other differences. The crosslinking strategy to handle the fast physical aging is also summarized.

The kinks of the PIMs polymer backbone were primarily recognized through inserting the SBI moiety with large pendant sets. SPI can be defined as a molecule with two indanes linked by a spiro carbon center. The SPI piece is generally polymerized with a halogen-including aromatic monomer, which results in the first PIMs used in gas separation membranes, such as PIM-1 and PIM-7 [41,42]. In PIMs, the gas permeation follows the solution-diffusion mechanism. The CO$_2$/H$_2$ selectivity is around 1-3, which is due to the size sieving trait that prefers the diffusion of H2. A spiro-fluorene (SBF) element could replace the SBI center, resulting in PIM-SBF offering low chain flexibility and an ultrahigh CO$_2$ permeability of 13,900 Barrers [43]. Recently, big tetra methyl tetra hydro naphthalene (TMN) units were fused into the SBI units in PIM-1, leading to less conformational flexibility and resulting in higher CO$_2$ permeability of 17,500 Barrers [44].

Unlike the SBI-based PIMs, Tröger-base (TB), a hard bicyclic unit, has been applied to PIMs. Diamino aromatic polymers with bicyclic rings, such as ethano-anthracene (EA) and triptycene (Trip), are integrated with or without SBI centers to compose an extremely twisted network. The TB group supplies extra Langmuir affinity toward CO$_2$, which enhances CO$_2$ selectivity [45]. The contortion sites can be within either the diamine [46] or the dianhydride [47]. Regardless of the utilization of different chemistry for PIM assembly, various enhanced PIMs have been notified by integrating bulky side groups including aromatic rings, such as the hexaphenylbenzene (HPB) unit that is used to reduce physical aging [48]. Carta et al. notified the CO$_2$ permeability of 333,000 Barrers with a CO$_2$/N$_2$ selectivity of 14.9 through fusing bulky TMN and Trip into PIM [44]. Similar to other glassy polymers that have high free volume, PIMs suffer from physical aging, where the
repose of the nonequilibrium series leads to the damage of permeability over time [49]. One intensively studied process is crosslinking to provide a more solid polymer network. For PIM-1, different crosslinking methods are used, e.g., thermal, UV, and chemical crosslinking, which are explained in detail in [50–52]. Driven by the high cost of the membrane, some polymeric materials have been blended with PIMs, such as carboxylate PIM-1 in Ultem and Matrimid as extremely permeable nanofillers, to mitigate the manufacturing cost as well as raise the gas selectivity [53,54]. Jue et al. found a defect-free HF asymmetric PIM-1 membrane created by phase inversion. A skin layer was provided, and CO₂ permeance of 360 GPU and 27.7 CO₂/N₂ selectivity were gained [55].

| Strategy  | Material                  | P (CO₂)/atm | T/°C | CO₂ Permeability /Barrer | (CO₂/N₂) Selectivity | (CO₂/H₂) Selectivity |
|----------|---------------------------|-------------|------|--------------------------|----------------------|----------------------|
| SBI-based PIMs | PIM-1 alcohol-treated [41] | 1           | 30   | 11,200                   | 18.4                 | 3.4                  |
|           | PIM-7 [42]                | 0.2         | 30   | 1100                     | 26                   | 1.3                  |
|           | PIM-SBF [43]              | 1           | 25   | 13,900                   | 17.7                 | 2.2                  |
|           | PIM-TMN-SBI [44]          | 1           | 25   | 17,500                   | 16.2                 | 2.4                  |
| TB-based PIMs | PIM-EA-TB [56]           | 1           | 25   | 7140                     | 13.6                 | 0.92                 |
|           | PIM-SBI-TB [42]           | 1           | 25   | 2900                     | 12.5                 | 1.3                  |
|           | PIM-Trip-TB [57]          | 1           | 25   | 9709                     | 15.9                 | 1.2                  |
| PI-based PIMs | PIM-SBI-PI [47]          | 1           | 25   | 8210                     | 18.7                 | 3.1                  |
|           | PIM-EA-PI [46]            | 1           | 25   | 7340                     | 19.9                 | 1.7                  |
|           | 6FDA-DAT1-OH [58]         | 2           | 35   | 47                       | 25.9                 | 0.37                 |
| PIMs wo SBI | PIM-TMN-Trip [44]         | 1           | 25   | 33,300                   | 14.9                 | 2                    |
|           | PIM-HPB [48]              | 1           | 25   | 1800                     | 20                   | 7                    |
| Crosslinking | TOX-PIM-1 (thermal) [50]  | 4           | 22   | 5100                     | 18.1                 | 1.7                  |
|           | PIM-1 (UV) [51]           | 4           | 22   | 6374                     | 21.6                 | 2.1                  |
|           | PAH-PIM-1 (chemical) [52] | 1           | 20   | 150                      | 22.1                 | -                    |
| Blending  | C-PIM-1/Matrimid [54]     | 3.5         | 35   | 2268                     | 18.7                 | 1.4                  |
|           | PIM-1/Ultem [53]          | 3.5         | 35   | 3276                     | 21.1                 | -                    |
|           | PIM-1/POSS-PEG [59]       | 1           | 30   | 1309                     | 31                   | -                    |
|           | PIM-1/HCP [60]            | 2           | 25   | 19,086                   | 11.6                 | -                    |
| Membrane  | PIM-1 HF [55]             | 6.9         | 35   | 360 *                     | 27.7                 | 1                    |

* GPU.

2.4. Thermally Rearranged (TR) Polymers

Thermally rearranged (TR) polymers are harder and planer macromolecules that can be composed by the thermal rearrangement of polyamide (PAs) or ortho-functionalized polyimides (PIs), which were first found by Park et al. [61]. Generally, the TR polymers are characterized by unprecedented polymer chain hardness and a tight bore size distribution, as a result of the microporous nature which occurs due to the high torsional energy fence versus turnover between the phenylene-heterocyclic circles. The main ancestors for the TR conversion are ortho-functionalized PIs or PAs, as shown in Figure 3 below.

When the temperature rises above 350 °C, an intramolecular cyclization is started, and a hard polymer, such as polybenzoxazole (PBO), polybenzimidazole (PBI), or polypyrrolone (PPL), is composed if the ortho-functional set is amino or hydroxyl [62]. The TR polymers obtained from the polycondensation of hydroxy-diamine and diacid chloride are named TR-β, while the ones from the polycondensation of dianhydride and ortho-functional diamine are designated TR-α [62]. The transport properties of various selected TR polymers are shown in Table 5.
Figure 3. Thermal rearrangement of (1) TR-α, where the ancestor is an ortho-functional polyimide (PI), and (2) TR-β, where the ancestor is an ortho-functional polyamide (PA) [62].

Table 5. The transport properties of various selected TR polymers.

| Strategy    | Material                      | P (CO$_2$/atm) | T/°C | CO$_2$ Permeability /Barrer | (CO$_2$/N$_2$) Selectivity | (CO$_2$/H$_2$) Selectivity |
|-------------|-------------------------------|----------------|------|-----------------------------|----------------------------|----------------------------|
| TR-α-PBO    | 6FDA + bisAPAF [61]           | 10             | 35   | 4045                        | 25.9                       | 1.4                        |
|             | 6FDA + bisAPAF [63]           | 1              | 25   | 4201                        | 14.8                       | 1                          |
|             | 6FDA + bisAPAF + ADHAB [64]   | 3              | 30   | 151                         | 21                         | 1                          |
|             | 6FDA + HAB [65]               | 1              | 35   | 2.9                         | 29                         | 0                          |
| TR-α-PBI    | 6FDA + DAB [66]               | 1              | 25   | 1624                        | 26.2                       | 0.91                       |
| TR-β-PBO    | BPDC + bisAPAF [67]           | 10             | 35   | 532                         | 17.6                       | 1                          |
| Crosslinking| 6FDA + bisAPAF + DABA/diol [68] | 1          | 25   | 746                         | 25.2                       | 1.2                        |
|             | 6FDA + bisAPAF + DABA [69]    | 1              | 25   | 491                         | 24.3                       | 1                          |
| Copolymer   | 6FDA + bisAPAF + DAM [70]     | 0              | 35   | 137                         | 21.6                       | 0.78                       |
|             | 6FDA + HAB + 4MPD [71]        | 10             | 35   | 226                         | 10.5                       | -                          |
| TR-labile PI| 6FDA + DABA + βCD [72]        | 10             | 35   | 2707                        | 15.3                       | 0.34                       |
|             | 6FDA + durene + DABA + γCD [73]| 2           | 35   | 1024                        | 18.2                       | 0.24                       |
| TR w/SBI    | TR-PIM-1 [74]                 | 1              | 35   | 675                         | 23                         | 1.6                        |
|             | TR-PIM-2 [74]                 | 1              | 35   | 263                         | 24                         | 1                          |
| TR HF       | 6FDA + bisAPAF [75]           | 1              | 25   | 2326 *                      | 20                         | 1.2                        |
|             | 6FDA + bisAPAF [76]           | 1              | 25   | 2500 *                      | 16                         | 1.2                        |

* GPU.

2.5. Iptycene-Containing Polymers

The two molecules belonging to the iptycene family are triptycene (Trip) and pentipentylene (Pent), where the iptycene family is a group of three-dimensional molecules with arene identities integrated into the (2,2,2)bicyclooctatriene bridgehead method [77]. The iptycene membrane is unique due to the slits (blades) of the benzene creating an interior free volume, which can be compared to the kinetic diameters of the light gases in Table 1. The internal free volume, because of its shape and persisting nature, is not subjected to collapse, and low physical aging is obtained [78]. When the huge iptycenes are integrated into other polymer systems, the polymer chain packing is damaged and the overall free volume is increased [44]. Weidman et al. that proposed iptycene polymers can be classified into three categories: non-ladder, semi-ladder, and ladder, depending on the backbone architecture [79]. The categories are reviewed more systematically in Table 6.
Table 6. Transport properties of specific iptycene-containing polymers.

| Strategy  | Material                  | P (CO₂/atm) | T/°C | CO₂ Permeability/Barrer | (CO₂/N₂) Selectivity | (CO₂/H₂) Selectivity |
|-----------|---------------------------|-------------|------|-------------------------|-----------------------|-----------------------|
| Non-ladder| 6FDA + DATRI [80]         | 1           | 35   | 189                     | 23.3                  | 0.73                  |
|           | 6FDA + DAT2 [49]          | 2           | 35   | 210                     | 23.3                  | 0.74                  |
|           | 6FDA + PPDA(CF3) [81]     | 1           | 35   | 132                     | 19                    | 0.7                   |
|           | TPDAn + 6FAP [82]         | 1           | 35   | 4.7                     | 25                    | 0                     |
|           | TPHA-TC [83]              | 11          | 35   | 270                     | -                     | -                     |
| Semi-ladder| KAUST-PI-1 [84]           | 2           | 35   | 2 389                   | 22.3                  | 0.6                   |
|           | KAUST-PI-2 [84]           | 2           | 35   | 2 071                   | 21.1                  | 0.87                  |
|           | 6FDA + PAF [85]           | 2           | 35   | 6.8                     | -                     | -                     |
|           | TPDA + APAF [85]          | 2           | 35   | 46                      | -                     | -                     |
|           | PBIBI + PPD [86]          | 1           | 25   | 137.2                   | 27.8                  | -                     |
| Ladder    | PIM-Trip-TB [87]          | 1           | 25   | 9 709                   | 15.4                  | 1.2                   |
|           | PIM-Btrip-TB [87]         | 1           | 25   | 13 200                  | 14.2                  | 1.3                   |

3. Membrane Technology for CO₂ Capture

To improve the CO₂ capture system, several standards should be taken into consideration, such as high capture rate and low operating costs. Moreover, the flexibility of the membrane system plays the main role to choose the best configuration for the CO₂ capture process. Presently, several procedures are utilized with different parameters to optimize CO₂ capture technology. The membrane process requires a high separation of acid gases and impurities that are commonly part of the flue gas stream to avert harmful issues and extend its lifetime [88]. Figure 4 shows the membrane system used, with the acid gas separation process, which is integrated with a coal-fired power plant (CFPP).

Figure 4. Principle diagram of membrane integration in CFPP.
The low volumetric fraction of CO$_2$, contrasted with a high volume of the flue gas stream to be treated, is the essential challenge for the post-combustion capture process, which drives a low driving force of CO$_2$ permeation. To overcome the low motive force in the membrane process fused into post-combustion CO$_2$ capture technology, either a compressor before the membrane module or a vacuum pump in the permeate flow side, or both together, can be used [89]. As a result, the flue gas stream must be dried before entering the compression station to avoid troubles caused by water droplets.

In this paper, three different schemes with several parameters have been presented, either by using 1-single stage (with and without a vacuum pump) or 2-stages of the membrane to obtain both goals of 90% carbon capture rate and at least 95% purity of CO$_2$ captured. High purity is required for the transportation purposes and for other goals such as enhance oil recovery (EOR) [90]. As can be noticed, the flue gases must be compressed before any membrane module to produce sufficient driving force for CO$_2$ separation. As researched further, membrane surface area and energy consumption demonstrate important factors of any membrane module for CO$_2$ capture. Designing the CO$_2$ separation system utilizing membrane reveals the size of the membrane technology, such as the required surface area and the suitable configuration to achieve the CO$_2$ purity goal (min. 95 mole %) with the lowest power consumption. In general, the efficiency of the process relies essentially on the compression ratio of the flue gas, membrane permeability, and membrane surface area. On the other hand, the purity of the CO$_2$ stream depends on membrane selectivity, capture efficiency, and CO$_2$ content in the combustion gases. This analysis concentrated on designing the optimal process with minimal energy and surface area needed to reach the proposed project targets.

In the research project (13/2020) a currently developed procedure was utilized to embed CA enzyme into polyacrylamide polymer (PSF 50 K) [91]. Generally, the lifetime of the membrane is 5 years, and after this period the membrane performance will decrease and the material must be replaced [8,92]. The permeability and selectivity for different gases are mentioned in Table 7.

The objective of this article is to evaluate and compare the performance of a 1-single stage and 2-stages membrane unit fused into a conventional CFPP. The flue gas temperature and pressure treated in this study are 50 °C-1.015 bar, respectively (Table 7). Moreover, a high compressor pressure must be utilized in four stages (in this study we assumed it 70 bar) to compress and prepare CO$_2$ captured for transportation goals with an inter-cooling process to reduce the high temperature generated from the high-pressure compressor [93] in order to accomplish all the demands for CO$_2$ transport.

Three configurations for integrating membrane technology in CFPP, where the variations for these configurations are demonstrated in the membrane parameters section of the Table 7, are proposed as follows:

A. 1-single membrane with a compression station before the membrane inlet, see Figure 5;
B. 1-single membrane with a compression station before the membrane and a vacuum pump on the permeate flow side, see Figure 6;
C. 2-stages of a membrane with different compressors and vacuum pumps, check Figure 7.

In general, for a specific CO$_2$ capture efficiency, the operation at a high-pressure difference across the membrane shows more power consumption required, a smaller membrane surface area, and higher CO$_2$ purity until specific pressure. Furthermore, the performance at a lower pressure difference implies lower energy consumption, larger membrane surface area, and lower CO$_2$ purity.
Table 7. The main parameters of CFPP and membrane.

| Parameters                                            | Main Data                                                                 |
|-------------------------------------------------------|---------------------------------------------------------------------------|
| Fuel characteristics [94]                             | 72.30% C, 4.11% H, 1.69% N, 7.45% O, 0.56% S, 13.89% ash; Moisture: 8%; Lower heating value: 28,141 kJ/kg |
| **CFPP parameter**                                    |                                                                           |
| Steam temperature/pressure, [°C/bar]                  | 585/290                                                                   |
| Efficiency in high/medium/low-pressure steam turbine, [%] | 84.9/91.6/87.8                                                           |
| Condensing pressure, [bar]                            | 0.05                                                                      |
| Heating water in the condenser, [°C]                  | 9.5                                                                       |
| Coal combustion efficiency in the steam generator, [%] | 91                                                                        |
| Steam flow rate, [t/h]                                | 914.5                                                                     |
| Net power plant efficiency, [%]                       | 45.78                                                                     |
| **Flue gas Parameters**                               |                                                                           |
| Temperature/pressure [°C/bar]                         | 50/1.013                                                                  |
| Flue gas flow, [kmol/h]                               | 40,320                                                                    |
| CO₂ permeance, [GPU]                                  | 13.12                                                                    |
| N₂ permeance, [GPU]                                   | 80.80                                                                    |
| O₂ permeance, [GPU]                                   | 6.03                                                                     |
| SO₂ permeance, [GPU]                                  | 0.04                                                                     |
| **Membrane parameters [95]**                          |                                                                           |
| Membrane material characteristics                     | Spiral wound in counter current                                           |
| CO₂ permeance, [GPU]                                  | 1000                                                                     |
| N₂ permeance, [GPU]                                   | 20                                                                        |
| CO₂ / N₂ selectivity                                  | 50                                                                        |
| Compressor/vacuum pump efficiency, [%]                | 90                                                                        |
| Variations of different membrane parameters simulated |                                                                           |
| 1st Compressor pressure, [bar]                        | 1.5–10                                                                   |
| Vacuum pump pressure (case B), [bar]                  | 0.5–0.05                                                                 |
| 2nd Compressor pressure (case C), [bar]               | 2–10                                                                     |
| 1st membrane surface, [m²]                            | 100,000–1,000,000                                                         |
| 2nd membrane surface (case C), [m²]                   | 5000–100,000                                                             |

Figure 5. Single-stage scheme of a membrane with only a compression station.
4. Decarbonized Coal-Based Super-Critical Power Plants, Main Design Characteristics, and Assessment Methodology

As a targeted industrial process to be decarbonized by membrane systems, a 330 MW net output coal power plant was investigated, using lignite coal as a fuel. The decarbonization yield is 90% the same as most of the CCS projects [93]. As can be distinguished from Figure 4, the flue gas out of the coal combustion process must be subjected to particulate matter (NO\textsubscript{x} and SO\textsubscript{x}) removal before the CO\textsubscript{2} capture process.

Table 7 presents the main technical assumptions of investigated CFPP and membrane. All processes were modeled and simulated by using ChemCAD software. The paper analyzed different parameters of the compressor pressure, membrane surface area, and vacuum pump pressure (if used) in many cases to estimate the techno-economic influence of the analyzed CO\textsubscript{2} capture solutions and achieve the membrane efficiency of 90% and CO\textsubscript{2} purity of 95% with at least the minimum energy consumption required. However, power consumption in membrane technology is only the energy required for the main driving machines such as compressors and vacuum pumps.

To evaluate the techno-economic influence of the analyzed CO\textsubscript{2} capture solutions, the following indicators have been proposed [96]:

![Figure 6. Single-stage scheme of a membrane with a compressor station and a vacuum pump.](image1)

![Figure 7. Two stages of a membrane with different compression stations.](image2)
SPECCA—specific primary energy consumption for avoiding CO₂ emissions;

\[
\text{SPECCA} = \frac{3600 \cdot \left( \frac{1}{\eta_{\text{CCS}}} - \frac{1}{\eta_{\text{base}}} \right)}{P_{\text{base}} - P_{\text{CCS}}},
\]

where \(\eta_{\text{base}}\): the overall efficiency of energy solutions without CCS technology,
\(\eta_{\text{CCS}}\): the overall efficiency of energy solutions with CCS technology,
\(P_{\text{base}}\): the CO₂ pollutant in kg/kWh produced by the CFPP without capture technology,
\(P_{\text{CCS}}\): the CO₂ pollutant in kg/kWh produced by the CFPP with capture technology.

SEPCCAs, \(m\)—takes into account the energy penalty \((\eta_{\text{base}} - \eta_{\text{CCS}})\) of the energy solution because of the extra heat consumption demanded in the chemical absorption process (SPECCA\(_s\)—Equation (2)), and the electricity consumption required by the capture process using membranes (SPECCA\(_m\)—Equation (3));

\[
\text{SPECCA}_s = \frac{3600 \cdot (\eta_{\text{base}} - \eta_{\text{CCS}})}{\eta_{\text{base}} \cdot P_{\text{base}} - \eta_{\text{CCS}} \cdot P_{\text{CCS}}},
\]

\[
\text{SPECCA}_m = \frac{3600 \cdot (W_{\text{base,net}} - W_{\text{CCS,net}})}{W_{\text{base,net}} \cdot P_{\text{base}} - W_{\text{CCS,net}} \cdot P_{\text{CCS}}},
\]

where \(W_{\text{base,net}}\): the net power generated for the energy solution without capture solution;
\(W_{\text{CCS,net}}\): the net power generated for the energy solution with capture solution.

The levelized cost of electricity (LCOE) was calculated by Equation (4), considering the annualized CAPEX and OPEX costs, a specified CO₂ recovery (\(\varphi_{\text{CO}_2}\)), and the CO₂ recovery flow (\(\text{CO}_2\text{CCS}\)), where 6570 demonstrates 75% of annual capacity of hours:

\[
\text{LCOE} = \frac{\text{CAPEX} + \text{OPEX}}{6570 \cdot \varphi_{\text{CO}_2} \cdot \text{CO}_2\text{CCS}}
\]

Both recovery and avoided costs of CO₂ indicators are calculated by taking the consideration LCOE, \(\text{CO}_2\text{CCS}\), and specific CO₂ emissions for energy solution with and without CCS solution:

\[
\text{CO}_2\text{rc} = \frac{\text{LCOE}_{\text{CCS}} - \text{LCOE}_{\text{base}}}{\text{CO}_2\text{ recovery}}
\]

\[
\text{CO}_2\text{ac} = \frac{\text{LCOE}_{\text{CCS}} - \text{LCOE}_{\text{base}}}{\text{CO}_2\text{base} - \text{CO}_2\text{CCS}}
\]

In order to set the economic indicators, several data on the unit costs of the components are presented in Table 8. The presented costs are calibrated to the year 2022 based on the index demonstrated on the Chemical Engineering online site [97].

In order to be able to determine whether an investment project, in this case, the CFPP with and without CO₂ capture, is economically appropriate, an economic and financial analysis is required that considers all cash flows in and out of the established meter. The economic and financial indicators calculated in this analysis are as follows:

Net present value (NPV) calculated with Equation (7):

\[
\text{NPV} = \sum_{i=1}^{n_f} \left( \frac{\text{IN}_i - C_i - A_i}{(1 + r)^i} \right) - \sum_{i=1}^{n_r} \text{I}_i \cdot (1 + r)^i, \ \€
\]

where \(\text{IN}_i\): the realized revenues for a year \(i\) (\(€/\text{year}\)); \(C_i\): the operating and maintenance expenses for the year \(i\), with taxes and duties but without depreciation (\(€/\text{year}\)); \(A_i\): the annuity for the year \(i\), if a loan was taken (\(€/\text{year}\)); \(\text{I}_i\): the realized equity investment for the year \(i\) (\(€/\text{year}\)); \(r\): the discount rate, which for the energy sector is 8%. 
Table 8. Main assumptions concerning the economic indicators.

| Indicators | Main Data |
|------------|-----------|
| Availability factor, % | 85 |
| Electricity price, €/MWh | 160 |
| CO₂ tax, €/t [98] | 82 |
| Annual hours, h/year | 7446 (85/100·8760) |

| Membrane capture unit | |
| Membrane-specific cost, €/m² | 50 |
| Membrane lifetime, years | 5 |
| Flue gas, and inter-stage compressor, €/kW | 850 |
| Vacuum pump, €/kW | 1300 |
| CO₂ pump, €/kW | 1350 |
| CO₂ compressor, €/kW | 1800 |
| Membrane replacement cost | 20% of the membrane cost |
| Labor cost, €/h | 15 |
| CO₂ stream compression | |
| CO₂ compressor, M€ | 11.7 |
| Compressor inter-stage coolers and separators, M€ | 0.87 |

Internal rate of return (IRR) was determined utilizing Equation (8).

\[
NPV = \sum_{i=1}^{n} \frac{IN_i - C_i - I_i}{(1 + IRR)^i} = 0, \quad (8)
\]

IRR for an investment project is equal to the discount rate for which NPV is 0.

Discounted payback period (DPP) was determined by Equation (9).

\[
NPV = \sum_{i=1}^{DPP} \frac{IN_i - C_i - I_i}{(1 + r)^i}, \quad (9)
\]

DPP is the period of time after which the initial investment is recovered.

The profitability index (IP) was calculated using Equation (10)

\[
IP = \frac{NPV + IA}{IA}, \quad (10)
\]

where IA: the discounted investment. An investment project is economically efficient if IP ≥ 1; for IP < 1 the project is economically inefficient.

5. Results and Discussion

In Case A (no vacuum pump used), various compressor pressures (1.5–10 bar) were used, while all other parameters were fixed. CO₂ capture efficiency rose visibly with the increase of 1st compressor pressure (CP₁), and the power consumption value rose as well. On the other hand, when CP₁ was fixed and 1st membrane surface (SA₁) differed from 100,000 to 1,000,000 m², CO₂ capture efficiency and power consumption increased significantly depending on the raising of CO₂ captured. The 90% efficiency required for the process was obtained at 8.5 bar and 300,000 m² SA₁, while the energy consumption at this point was about 153 MW, and CO₂ purity was 49%. However, the maximum CO₂ purity achieved was 64% at 9.5 bar and 100,000 m², which is quite low. The results show increasing the membrane surface area leads to a decrease in CO₂ purity due to the other particles (e.g., N₂) that pass through the membrane with CO₂ molecules at a higher membrane surface.

Case B demonstrates the utilization of vacuum pump (VP) pressures (0.05–0.5 bar) while the other parameters are constant. The results showed an obvious increase in
CO₂ capture efficiency when VP pressure decreased due to the high-pressure difference across the membrane unit. Thus, the power consumption value rose with the decrease of VP pressure. The 90% efficiency required for the process was obtained at 5.5 bar CP₁, 200,000 m² membrane SA₁, and 0.15 bar VP pressure. At the same parameters, the CO₂ purity was 68% and power consumption was about 145 MW. Moreover, the highest CO₂ purity value was achieved at 2 bar CP₁, 0.05 bar VP pressure, and 100,000 m², which is 84%.

Since CO₂ capture efficiency requires a large surface area and CO₂ purity needs a low surface area to be high, 2-stages of membrane units have been recommended to manipulate and increase both the values of CO₂ capture efficiency and CO₂ purity (case C).

In case C, different parameters of CP₁ (2–10 bar) were used where all other parameters were constant. Consequently, the CO₂ capture efficiency increased obviously with increasing CP₁, and the power consumption rose as well. The 2nd compressor pressure (CP₂) rose from 2 to 10 bar while fixing all other components, influenced and increased the 2nd membrane efficiency, and also impacted the CO₂ purity. The moment when SA₁ increased and all other parameters were constant, CO₂ capture efficiency and power consumption rose excessively due to the CO₂ captured rising. On the other hand, the leading factor that influenced the CO₂ purity was the 2nd membrane surface (SA₂), which increased from 5000 to 100,000 m², where CO₂ purity decreased constantly with the increase of the surface area. The efficiency and CO₂ purity required for the process (90%, and 95%, respectively) were achieved at 8 bar CP₁, 4 bar CP₂, 600,000 m² SA₁, and 40,000 m² of SA₂. Moreover, the energy consumed in this case was around 189 MW, which is almost 57% of the total output of energy (330 MW). As shown in Figure 7, the flue gas exits from the second membrane has to be sent back to the mixer as a recirculated flue gas in order to increase CO₂ capture efficiency.

The parameters (such as VP, SA₁, and CP₁) were selected and fixed for all the following figures only to illustrate the variations among the variants.

In Figure 8, the influence of VP and CP₁ on CO₂ capture efficiency was analyzed. In the (no vacuum) line, the maximum capture efficiency value achieved was 87% at high CP₁ (10 bar), while in 0.05 bar VP, the efficiency was much more than other efficiencies, reaching 99.9% at 10 bar CP₁ due to the high-pressure difference around the membrane. The impact of reducing VP on process efficiency was also clearly apparent. Moreover, it was also demonstrated that CO₂ capture efficiency increases when CP₁ increases successively because of the high CO₂ content passed via the membrane unit.

![Figure 8](image_url)

**Figure 8.** CO₂ capture efficiency regarding different 1st compressor and vacuum pump pressure values for 1-stage (case A, B) at 200,000 m² of 1st membrane surface.
Figure 9 presents how the CO\textsubscript{2} purity differs based on the compressor and vacuum pump pressure. The necessity of utilizing a vacuum pump is clear to increase CO\textsubscript{2} purity, where the highest amount achieved in no vacuum case is 62%. This value is poor compared with CO\textsubscript{2} purity after using different vacuum pump pressures. On the other hand, increasing compressor pressure value leads to high CO\textsubscript{2} purity till a specific value of the pressure where other molecules (such as N\textsubscript{2}) will pass through the membrane decreasing CO\textsubscript{2} purity.

![Figure 9. CO\textsubscript{2} purity variation regarding vacuum pump for 1-stage (case A, B) at different 1st compressor pressures and 200,000 m\textsuperscript{2} of 1st membrane surface.](image)

The impact of increasing vacuum pump pressure on CO\textsubscript{2} capture efficiency at various CP\textsubscript{1} is demonstrated below in Figure 10. The efficiency lines go down decreasingly at different CP\textsubscript{1}, as a result of the reduction of the pressure difference across the membrane. For example, CO\textsubscript{2} capture efficiency at the point where CP\textsubscript{1} and VP\textsubscript{1} are 10, 0.5 bar, respectively, is higher than what is at 5.5 bar CP\textsubscript{1} and VP\textsubscript{1} of 0.05 bar due to the high pressure difference.

![Figure 10. The vacuum pressure difference influence on CO\textsubscript{2} capture efficiency for 1-stage (case A, B) at 200,000 m\textsuperscript{2} of 1st membrane surface.](image)
In Figure 11, the CO₂ capture efficiency rises directly when the membrane surface increases in various CP₁ values. At 10 bar CP₁, it is evident that the efficiency over different membrane surface areas is almost steady at 100% due to the flow that is almost fully captured and being passed through the membrane.

Figure 11. First membrane surface and 1st compressor pressure influence on CO₂ capture efficiency for 1-stage (case A, B) at 0.5 of vacuum pump pressure.

Figure 12 demonstrates the influence of the membrane surface at different compressor pressures. The power consumption increases continuously as the membrane surface increases at any CP₁ (1.5–10 bar); it is also noticeable that the power consumption columns are taller when the CP₁ rises due to the high gas flow that passed through the membrane unit. Typically, the power consumption required relies basically on the compressor and vacuum pump energy, and also on the power needed to compress the CO₂ stream at 70 bar which increases constantly with the rise of the membrane surface.

Figure 12. First membrane surface and 1st compressor pressure influence on power consumption for 1-stage (case A, B) and 0.5 bar of vacuum pump pressure.
In Figure 13, the impact of the SA$_1$ with various CP$_1$ on CO$_2$ purity has been examined, where the purity reduced slightly at 1.5 bar because of the low compressor pressure value utilized, while at 5 bar the CO$_2$ purity level was favorable in 100,000 m$^2$ of SA$_1$, almost 70% mole. As discussed before in the results section (case A), when the membrane surface increases the CO$_2$ purity decreases constantly.

![Figure 13. The effect of 1st membrane surface with different 1st compressor pressure on CO$_2$ purity for 1-stage (case A, B) and 0.5 bar of vacuum pump pressure.](image)

Figure 13. The effect of 1st membrane surface with different 1st compressor pressure on CO$_2$ purity for 1-stage (case A, B) and 0.5 bar of vacuum pump pressure.

Figure 14 below shows the effect of CP$_2$ on CO$_2$ capture efficiency in different CP$_1$. It is noticeable that CO$_2$ capture efficiency increases crucially when the CP$_1$ rises, reaching almost 100% at 10 bar and CP$_2$ at 4 bar. The figure also demonstrates that CP$_2$ has a low impact on CO$_2$ capture efficiency due to its location after the 1st membrane unit (see Figure 7). The explication of that tiny decrease in CO$_2$ capture efficiency regarding CP$_2$ is that the increase of CP$_2$ leads to a rise in the 2nd membrane CO$_2$ efficiency which drives a decrease in the recirculated flow to the mixer, finally reducing the flow rate entering the 1st membrane.

![Figure 14. The impact of 2nd compressor pressure on CO$_2$ capture efficiency for 2-stages at 600,000 and 40,000 m$^2$ (1st membrane surface and 2nd membrane surface, respectively).](image)
Figure 15 represents the influence of different SA1 on CO2 capture efficiency. The CO2 capture efficiency line goes up obviously with the increase of SA1 because of the high stream flow passed via the membrane at a higher membrane surface, obtaining almost 95% at 600,000 m².

![Figure 15. The 1st membrane surface effect on CO2 capture efficiency for 2-stages of the membrane at 8 bar of 1st compressor pressure, 4 bar of 2nd compressor pressure, and 40,000 m² of 2nd membrane surface.](image)

In Figure 16, the impact of CP1 on power consumption at different CP2 has been shown. The main factor that influences the total power consumption rate is CP1 because of the recirculated flue gas that fuses with the primary flue stream to generate a high flow rate that boosts the power needed to pressure the flow at the 1st compressor. Since the high CP2 pressures increase the 2nd membrane efficiency, the low recirculated flow decreases constantly, thus providing a lower flow rate entering the 1st compressor, which demonstrates why power consumption reduces at high CP2.

![Figure 16. The total power consumption required for 2-stages of the membrane (case C) regarding different 1st and 2nd compressor pressures at SA1 of 600,000 m² and SA2 of 20,000 m².](image)
Figure 17 shows the effect of the 2nd membrane surface area on CO₂ purity at different CP₂. All CO₂ purity lines go down permanently with the increase of membrane surface due to the transit of other components that pass through larger membrane surface (like N₂) producing low CO₂ purity. Furthermore, the CP₂ affects CO₂ purity, where higher CP₂ leads to less CO₂ purity.

Figure 17. CO₂ purity at different 2nd compressor pressures for 2-stages of the membrane regarding 2nd membrane surface at SA₁ of 600,000 m² and CP₁ of 6 bar.

Figure 18 below represents the CO₂ purity difference between the 1st and 2nd stages regarding various CP₂. Firstly, it is distinguished that the CO₂ purity of the 2nd membrane is much higher than that of the first because of the low surface area (20,000 m²) used in the 2nd membrane, which shows the significance of utilizing 2-stages of membrane unit. Typically, CO₂ purity is reduced at high pressures. The influence of high CP₂ on the 2nd membrane is more than in the first due to its location (see Figure 7).

Figure 18. The difference in CO₂ purity at CP₁ of 4 bar, SA₁ of 600,000 m², and SA₂ of 20,000 m² regarding various 2nd compressor pressures.
On the other hand, Figure 19 demonstrates the variation of CO$_2$ purity of single-stage (with and without vacuum pump) and 2-stages membrane based on 1st compressor pressure. Low CO$_2$ purity is remarkable in the 1-stage of the membrane (with and without a vacuum pump) due to the high membrane surface used ($400,000 \text{ m}^2$). Integrated 2-stages of membrane increase the CO$_2$ purity with the rise of CP$_1$ reaching almost 99% at 6 bar. It is observable that all the steam flow contents which passed through the 2nd membrane are CO$_2$ molecules. However, the usage of the 2nd stage of the membrane is highly recommended to increase CO$_2$ purity.

Figure 19. The variation of CO$_2$ purity at $400,000 \text{ m}^2$ of SA$_1$ and $5000 \text{ m}^2$ of SA$_2$ based on 1st compressor pressure.

Figure 20 exhibits how the CO$_2$ capture efficiency of single-stage (with and without a vacuum pump) and the 2-stage membrane is affected by 1st compressor pressure. The CO$_2$ capture efficiency line of single-stage with vacuum is remarkably higher than other lines, where the usage of a vacuum pump increases the pressure difference across the membrane unit, producing high CO$_2$ capture efficiency.

Figure 20. CO$_2$ capture efficiency variation at $200,000 \text{ m}^2$ of SA$_1$, 0.25 bar of VP pressure, CP$_2$ of 4 bar, and SA$_2$ of $20,000 \text{ m}^2$ based on different 1st compressor pressure.
Figure 21 demonstrates the impact of 1st compressor pressure on power plant efficiency at different 1-single stage membrane surfaces. As shown, high compressor pressure increases the energy consumption required for CCS, which drives to decrease the power plant efficiency. As described before, a high membrane surface such as 700,000 m$^2$ increases CO$_2$ capture efficiency, therefore, generating a significant demand for energy to compress the CO$_2$ flow. Thus, the power plant efficiency decreases.

Figure 21. Power plant efficiency depending on 1st compressor pressure and different 1st membrane surfaces.

Figure 22 shows a comparison of power plant efficiencies regarding 1-stage (no vacuum used), 1-stage (with vacuum), and 2-stages of the membrane. As mentioned above, high compressor pressure decreases the power plant efficiency either for the 1-single stage or 2-stages of the membrane. As shown, the power plant efficiency of 2-stages is higher than the efficiency of one stage due to the lower energy demanded for the 2-stage of membrane case.

Figure 22. Power plant efficiency variation of 1-single stage (with and without VP) depending on 1st compressor pressure at 200,000 m$^2$ SA$_1$, 40,000 m$^2$ SA$_2$, and 4 bar of CP$_2$. 
Figure 23 represents the difference in capital cost of various membrane surfaces of the 1-single stage based on different 1st compressor pressure. The capital cost lines of the surfaces increase and go up noticeably achieving 10,000 €/kWh at 10 bar of 700,000 m². High surfaces raise the capital cost and also high compressor pressure influences the cost due to the high CO₂ content passed through the membrane, which increases the power consumption required.

![Figure 23. 1st compressor pressure effect on the capital cost at different surfaces area.](image)

The influence of SA₁ on CO₂ capture efficiency of one (with and without VP) and 2-stages of the membrane is shown in Figure 24. The case where the 1-single stage of the membrane with vacuum is used has the highest values of CO₂ capture efficiency due to the high-pressure difference across the membrane unit. At 400,000 m² of SA₁, 1-stage (with vacuum) of membrane achieved almost 100% CO₂ capture efficiency. While, in the same point, CO₂ capture efficiency is less by around 6% and 13% for 1-stage (no vacuum) and 2-stages of the membrane, respectively.

![Figure 24. The impact of 1st membrane surface on CO₂ capture efficiency of 1 and 2-stages of membrane at 8 bar CP₁, 4 bar CP₂, and 40,000 m² of SA₂.](image)
Figure 25 exhibits the variation of power plant efficiency of single-stage (with and without vacuum pump) and 2-stages of membrane regarding SA$_1$. As noticed from the figure, at 200,000 m$^2$, the power plant efficiency for 2-stages and no vacuum case of the membrane are almost the same, which are the highest, while utilization of vacuum pump in the 1-stage reduces the power plant efficiency by around 16% because of the low power consumption needed for capture CO$_2$ comparing with 1-stage no vacuum case. By increasing SA$_1$ the power plant efficiency lines of all stages go down constantly due to the increase of CO$_2$ capture efficiency with SA$_1$ increase, which leads to high demands of energy.

Figure 25. The impact of 1st membrane surface on power plant efficiency of 1 and 2-stages of membrane at 8 bar CP$_1$, 4 bar CP$_2$, and 40,000 m$^2$ of SA$_2$.

Figure 26 represents the effect of SA$_1$ on discounted payback period (DPP) of 1-stage (with and without vacuum pump) and 2-stages of the membrane. The SA$_1$ of 1-stage (no vacuum) of the membrane has a low influence on DPP, which is the best case due to the low requirements of energy for CO$_2$ capture compared with other cases. It is observable that increasing SA$_1$ leads to an increase in DPP because of the high demand for power consumption.

Figure 26. The variation of DPP of 1-stage (with and without VP) and 2-stage of the membrane at 8 bar CP$_1$, 4 bar CP$_2$, and 40,000 m$^2$ of SA$_2$. 
To evaluate the technical and economic assessment for the case A, the different parameters in Table 9 are chosen based on the optimum results of CO\textsubscript{2} capture efficiency, CO\textsubscript{2} purity, and power consumption (Figure 27). To abbreviate the surface area and compressor pressure parameters of case A, it was considered that case A\textsubscript{12} represents 200,000 m\textsuperscript{2} of 1st membrane surface and 8 bar of 1st compressor pressure, and case A\textsubscript{13} represents 200,000 m\textsuperscript{2} of 1st membrane surface and 10 bar of 1st compressor pressure. For 400,000 m\textsuperscript{2} SA\textsubscript{1} and 6 bar of CP\textsubscript{1}, the abbreviation is A\textsubscript{21} and along with others.

Table 9. The specific parameters were chosen for the technical and economical assessment of a single-stage of membrane technology (no vacuum pump used), case (A).

| 1st Membrane Surface | m\textsuperscript{2} | 200,000 (A\textsubscript{1}) | 400,000 (A\textsubscript{2}) | 500,000 (A\textsubscript{3}) |
|----------------------|----------------------|-----------------------------|-----------------------------|-----------------------------|
| 1st compressor pressure | Bar | 8 | 10 | 6 | 8 | 10 | 6 | 8 | 10 |
| Case abbreviation | - | A\textsubscript{12} | A\textsubscript{13} | A\textsubscript{21} | A\textsubscript{22} | A\textsubscript{23} | A\textsubscript{31} | A\textsubscript{32} | A\textsubscript{33} |
| CO\textsubscript{2} efficiency | % | 73.14 | 87.43 | 75.85 | 94.16 | 99.23 | 84.14 | 97.82 | 99.9 |
| CO\textsubscript{2} purity | % | 56.67 | 54.63 | 49.03 | 45.62 | 40.49 | 46.05 | 41.06 | 35.41 |
| Power consumption | MW | 133 | 156 | 126 | 159 | 185 | 135 | 169 | 198 |
| CO\textsubscript{2} captured/Membrane area | kmol/m\textsuperscript{2} h | 0.019 | 0.023 | 0.010 | 0.012 | 0.013 | 0.008 | 0.010 | 0.010 |

Figure 27. LCOE variation according to different parameters.

Table 10 demonstrates the evaluation and economical estimation with the analyzed solutions considering the indicators presented above of single-stage membrane technology. By fusing the single-stage of the membrane without vacuum pump utilization, the net power plant efficiency decreases by (31–50%) based on the membrane surface and compressor pressure values utilized. Generally, increasing the membrane surface or compressor station unit drives an increase in the power plant efficiency loss. As demonstrated in the paper, the electrical consumption required for a membrane system increases vastly with the increase of CP\textsubscript{1} in addition to membrane surface impact. The LCOE increases with the increase of membrane surface from 200,000 to 500,000 m\textsuperscript{2} of (44–56%) at compressor pressure of 8 bar. The CO\textsubscript{2} avoided cost is higher on the 200,000 m\textsuperscript{2} membrane surface than on other surfaces at the same compressor pressure due to the low power required to capture CO\textsubscript{2}.
Table 10. The evaluation of the CFPP system with a single-stage of membrane technology (no vacuum pump used).

| Parameters                        | Power Plant | A12 | A13 | A21 | A22 | A23 | A31 | A32 | A33 |
|----------------------------------|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Fuel feedstock, (t/h)            | 92.22       | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 |
| CO₂ capture efficiency, (%)      | n.a.        | 73.14 | 87.43 | 75.85 | 94.16 | 99.23 | 84.14 | 97.82 | 99.90 |
| Net power generated, (MW)        | 330         | 202.5 | 179.3 | 210 | 177 | 150.5 | 201 | 166 | 137.5 |
| Net power plant efficiency, (%)  | 45.78       | 31.72 | 28.51 | 32.74 | 28.18 | 24.51 | 31.46 | 26.67 | 22.71 |
| Capital costs per net electrical capacity, (€/kWh) | 2754 | 5347 | 6037 | 5265 | 6243 | 7340 | 5562 | 67,189 | 8112 |
| CO₂ emission factor, (kg/MWh)    | 741.15      | 324.43 | 171.42 | 281.51 | 80.73 | 12.51 | 193.39 | 45.78 | 31.72 |
| CO₂ captured, (kg/MWh)           | n.a.        | 883.41 | 1192 | 884.15 | 1302 | 1613 | 1026 | 1441 | 1777 |
| Power consumption of membrane plant, (kWe) | n.a.        | 132,990 | 156,140 | 125,660 | 158,550 | 184,980 | 134,900 | 169,430 | 197,950 |
| CO₂ avoided cost (€/t)           | n.a.        | 147.92 | 113.79 | 121.29 | 92.95 | 109.64 | 100.34 | 128.82 | 128.82 |
| CO₂ captured cost (€/t)          | n.a.        | 69.77 | 54.37 | 63.05 | 47.16 | 49.54 | 53.57 | 46.82 | 53.61 |

By presuming the CO₂ tax is 82 €/ton and retail electricity cost is 160 €/MWh and considering that all carbon certificates are sold, the assumptions for all cases are in the Tables below. The economic evaluation of the 1-single stage of the membrane (no vacuum used) was analyzed in Table 11. As summarized, by increasing the membrane surface from 200,000 to 500,000 m² at the same compressor pressure, the net present value increases at 400,000 m² by around 25%, then reduces by 1% at 500,000 m² membrane surface due to the increase of energy consumption needed for the CO₂ capture process.

Table 11. The economical assessment of the CFPP system with a single-stage of membrane technology (no vacuum pump used).

| Parameters          | Units | A12 | A13 | A21 | A22 | A23 | A31 | A32 | A33 |
|---------------------|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| NPV [M€]            | 813   | 963 | 922 | 1087 | 985 | 1035 | 1073 | 880 |
| VNA [M€]            | 753   | 892 | 853 | 1006 | 912 | 958 | 994 | 815 |
| IRR [%]             | 0.16  | 0.17 | 0.17 | 0.18 | 0.17 | 0.18 | 0.18 | 0.16 |
| UPP [year]          | 7.60  | 7.18 | 7.34 | 6.93 | 7.18 | 7.08 | 6.99 | 7.48 |
| DPP [year]          | 10.16 | 9.34 | 9.65 | 8.87 | 9.33 | 9.14 | 8.97 | 9.91 |
| PI [-]              | 1.75  | 1.89 | 1.83 | 1.98 | 1.89 | 1.93 | 1.96 | 1.79 |

To evaluate the technical and economic assessment for the case B, the different parameters in Table 12 are chosen based on the optimum results of CO₂ capture efficiency, CO₂ purity, and power consumption.

Table 13 summarizes the assessment with the examined solutions based on the indicators shown above at a 1-stage of membrane technology with vacuum pump usage. In all analyses, the vacuum pump pressure was assumed to be 0.25 bar. After the integration, the net power plant efficiency decreased by 42% at 200,000 m² and 8 bar, then reduced constantly, reaching mitigation of 59% of the main net power plant efficiency at 500,000 m². As explained in the paper, the high pressure difference across the membrane module guides an increase in the power plant efficiency loss. The table shows that LCOE increases by
23% with the increase of membrane surface from 200,000 to 400,000 m$^2$ and by 16% with the increase from 400,000 to 500,000 m$^2$ due to the high demands of energy CO$_2$ capture. In terms of CO$_2$ avoided cost, for the 200,000 m$^2$ membrane surface the cost is less than 400,000 and 500,000 m$^2$ by around 33% and 49%, respectively, at compressor pressure 8 bar because of the low energy required for the CO$_2$ capture process.

Table 12. The specific parameters were chosen for the technical and economical assessment of a single-stage of membrane technology (with a vacuum pump), case (B).

| 1st Membrane Surface | m$^2$ | 200,000 (B$_1$) | 400,000 (B$_2$) | 500,000 (B$_3$) |
|----------------------|-------|----------------|----------------|----------------|
| 1st compressor pressure | Bar   | 6  | 8  | 10  | 6  | 8  | 10  | 6  | 8  | 10  |
| Case abbreviation   |       | B$_{11}$ | B$_{12}$ | B$_{13}$ | B$_{21}$ | B$_{22}$ | B$_{23}$ | B$_{31}$ | B$_{32}$ | B$_{33}$ |
| CO$_2$ efficiency    | %     | 88.27 | 96.17 | 98.93 | 98.78 | 99.90 | 100 | 99.70 | 99.99 | 100 |
| CO$_2$ purity        | %     | 55.45 | 56.67 | 54.63 | 51.88 | 44.35 | 38.6 | 46.48 | 38.92 | 33.47 |
| Power consumption    | MW    | 142 | 171 | 195 | 173 | 209 | 242 | 187 | 228 | 265 |
| CO$_2$ captured/Membrane area | kmol/m$^2$·h | 0.023 | 0.025 | 0.026 | 0.013 | 0.013 | 0.013 | 0.010 | 0.010 | 0.010 |

Table 13. The evaluation and economical assessment of the CFPP system with a single-stage of membrane technology (vacuum pump used).

| Parameters | Power Plant | B$_{11}$ | B$_{12}$ | B$_{13}$ | B$_{21}$ | B$_{22}$ | B$_{23}$ | B$_{31}$ | B$_{32}$ | B$_{33}$ |
|------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Fuel feedstock, (t/h) | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 |
| CO$_2$ capture efficiency, (%) | n.a. | 88.27 | 96.17 | 98.93 | 98.78 | 99.90 | 100 | 99.70 | 99.99 | 100 |
| Net power generated, (MW) | 330 | 194 | 164.5 | 140.5 | 162 | 126 | 93.5 | 148 | 107.7 | 70 |
| Net power plant efficiency, (%) | 45.78 | 30.49 | 26.46 | 23.13 | 26.14 | 21.16 | 16.60 | 24.21 | 18.57 | 13.35 |
| Capital costs per net electrical capacity, (€/kWh) | 2754 | 5592 | 6851 | 7705 | 6809 | 8744 | 11,819 | 7521 | 10,360 | 15,932 |
| CO$_2$ emission factor, (kg/MWh) | 741.15 | 148.19 | 56.94 | 18.62 | 18.39 | 1.94 | 0.00 | 4.95 | 0.23 | 0.00 |
| CO$_2$ captured, (kg/MWh) | n.a. | 1115 | 1429.7 | 1722 | 1489 | 1934 | 2617 | 1644 | 2271 | 2493 |
| Power consumption of membrane plant, (kWe) | n.a. | 141,890 | 170,960 | 194,970 | 173,240 | 209,150 | 242,020 | 187,150 | 227,790 | 265,460 |
| Membrane power consumption, (kWh/tCO$_2$) | n.a. | 657.22 | 726.82 | 805.77 | 717.06 | 855.98 | 989.52 | 767.48 | 931.43 | 1085.4 |
| LCOE$_{tax}$, (€/kWh) | 0.0756 | 0.13 | 0.1434 | 0.1650 | 0.1444 | 0.1852 | 0.2518 | 0.1583 | 0.22 | 0.34 |
| SPECCA$_m$, (MJ/kg) | n.a. | 3.54 | 4.02 | 4.47 | 3.97 | 4.73 | 5.28 | 4.26 | 5.07 | 5.47 |
| SEPPCA$_s$, (Mjel/kg) | n.a. | 1.87 | 2.15 | 2.43 | 2.11 | 2.62 | 3.10 | 2.30 | 2.89 | 3.44 |
| CO$_2$ avoided cost (€/t) | n.a. | 89.91 | 99.12 | 123.75 | 95.21 | 148.21 | 237.70 | 112.35 | 194.04 | 356.69 |
| CO$_2$ captured cost (€/t) | n.a. | 47.81 | 47.44 | 51.93 | 46.21 | 56.65 | 67.32 | 50.32 | 63.31 | 75.69 |

Table 14 demonstrates the economic evaluation for different parameters which were examined. The net present value in the economic assessment decreases by 24% when the membrane surface increases from 200,000 to 400,000 m$^2$, and also decreases if the surface differs from 400,000 to 500,000 m$^2$ by around 21% at 8 bar CP$_1$. On the other hand, the DDP scale increases with the membrane surface increase reaching 15.5 years at 500,000 m$^2$ due to the high power consumption that increases with the rise of SA$_1$. 
Table 14. The economic assessment of the CFPP system with a single-stage of membrane technology (vacuum pump used).

| Parameters          | Units | B_{11} | B_{12} | B_{13} | B_{21} | B_{22} | B_{23} | B_{31} | B_{32} | B_{33} |
|---------------------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| NPV [M€]            |       | 1106   | 1050   | 912    | 1074   | 794    | 516    | 968    | 627    | 306    |
| VNA [M€]            |       | 1024   | 972    | 844    | 994    | 736    | 478    | 896    | 581    | 283    |
| IRR [%]             |       | 0.19   | 0.18   | 0.17   | 0.18   | 0.16   | 0.13   | 0.17   | 0.14   | 0.11   |
| UPP [year]          |       | 6.84   | 6.97   | 7.32   | 6.96   | 7.71   | 8.72   | 7.25   | 8.30   | 9.76   |
| DPP [year]          |       | 8.70   | 8.93   | 9.60   | 8.92   | 10.38  | 12.64  | 9.46   | 11.65  | 15.5   |
| PI [-]              |       | 2.02   | 1.97   | 1.84   | 1.97   | 1.72   | 1.47   | 1.87   | 1.56   | 1.27   |

Table 14 shows the economic estimation of 2-stages of membrane integrated into CFPP. As demonstrated, increasing SA_{1} drives the decrease of the net power plant efficiency by 14% when the surface is increased from 200,000 to 600,000 m² at 6 bar of CP_{1}. Integrating 2-stages of the membrane increases the LCOE by about 50% at 8 bar compressor pressure and 400,000 m² membrane surface. By considering the impact of CP_{1} on CO_{2} avoided cost, the values of the cost decrease with CP_{1} increasing (6–10 bar) by around 66% at 200,000 m² of SA_{1}.

In terms of economic assessment of 2-stages of the membrane, Table 17 summarizes it, where the net present value decreases with the increase of SA_{1} from 200,000 to 600,000 m² by 59%. It is noticeable that increasing SA_{1} impacts directly on the DPP, where DPP decreases from almost 15 to 11 years with the rise of SA_{1} 200,000–600,000 m².

The sensitivity assessment for 1-stage, no vacuum, SA_{1} of 500,000 m², CP_{1} 6 bar is given (as an example). For all cases, the variation is approximately the same. The influence of the CO_{2} tax and the CO_{2} capture efficiency on the levelized cost of electricity is remarkable. Taking into account that CO_{2} avoided cost is over 100 €/t for almost all cases, we calculated a possible 140 €/t of CO_{2} tax which allows us to increase the profitability index from 1.93 to 2.44.

Different economic parameters of 1- and 2-stages of the membrane are compared in Table 18 considering the optimal CO_{2} capture efficiency and purity. According to the table, increasing the membrane stages leads to an increase in CO_{2} purity, but at the same time increases the power consumption and investment cost of the project, which is also due to the usage of more equipment that requires energy to function.

In order to provide a clear vision regarding modeling using the CHEMCAD process with membrane, a comparison between the current and other papers studied from technical and economical points of view has been presented in Table 19 below.

The current paper focused on using membrane technology integrated into CFPP in the coming years (at least 5 years); in that time, regarding the improvements of pieces of equipment and performance, we believe the efficiency of equipment (such as compressors and
vacuum pumps) could be enhanced. However, the difference between using a compressor or pump efficiency of 90% instead of 85% leads to 6% decrease in the energy consumption at the CO$_2$ capture efficiency of 90%.

**Table 16.** The evaluation and economical assessment of the CFPP system with 2-stages of membrane technology.

| Parameters | Power Plant | C$_{11}$ | C$_{12}$ | C$_{13}$ | C$_{21}$ | C$_{22}$ | C$_{23}$ | C$_{31}$ | C$_{32}$ | C$_{33}$ |
|------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Fuel feedstock, (t/h) | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 | 92.22 |
| CO$_2$ capture efficiency, (%) | n.a. | 43.21 | 65.78 | 80.57 | 64.52 | 86.08 | 95.56 | 78.00 | 94.85 | 99.26 |
| Net power generated, (MW) | 330 | 233 | 203 | 176 | 214 | 174 | 138 | 196 | 147 | 102 |
| Net power plant efficiency, (%) | 45.78 | 36.00 | 31.74 | 28.00 | 33.36 | 27.75 | 22.71 | 30.81 | 23.96 | 17.79 |
| Capital costs per net electrical capacity, (€/kWh) | 2754 | 4659 | 5365 | 6188 | 5176 | 6380 | 8066 | 5774 | 7717 | 11,085 |
| CO$_2$ emission factor, (kg/MWh) | 741.15 | 595.25 | 413.08 | 270.53 | 404.98 | 195.85 | 78.97 | 274.67 | 85.94 | 17.74 |
| CO$_2$ captured, (kg/MWh) | n.a. | 452.91 | 794.05 | 1,121.79 | 736.46 | 1,211 | 1,700 | 973.83 | 1,583 | 2,379 |
| Power consumption of membrane plant, (MWe) | n.a. | 102 | 133 | 160 | 121 | 162 | 198 | 140 | 189 | 233 |
| Membrane power consumption, (kWh/tCO$_2$) | n.a. | 966.46 | 825.86 | 811.02 | 768.10 | 767.80 | 847.07 | 731.67 | 814.36 | 961.61 |
| LCOE$_{tax}$, (€/kWh) | 0.0756 | 0.14 | 0.14 | 0.15 | 0.14 | 0.15 | 0.18 | 0.14 | 0.17 | 0.24 |
| SPECCA$_m$, (MJth/kg) | n.a. | 4.71 | 4.38 | 4.45 | 3.98 | 4.22 | 4.70 | 3.92 | 4.52 | 5.20 |
| SEPCCA$_s$, (MJel/kg) | n.a. | 2.82 | 2.43 | 2.43 | 2.19 | 2.28 | 2.58 | 2.12 | 2.46 | 3.00 |
| CO$_2$ avoided cost (€/t) | n.a. | 462.77 | 209.65 | 160.77 | 188.22 | 134.10 | 151.91 | 139.99 | 141.19 | 220.86 |
| CO$_2$ captured cost (€/t) | n.a. | 149.07 | 86.62 | 67.45 | 85.91 | 60.38 | 59.18 | 67.06 | 58.44 | 67.15 |

**Table 17.** The economic assessment of the CFPP system with 2-stages of membrane technology.

| Parameters | Units | C$_{11}$ | C$_{12}$ | C$_{13}$ | C$_{21}$ | C$_{22}$ | C$_{23}$ | C$_{31}$ | C$_{32}$ | C$_{33}$ |
|------------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| NPV | [M€] | 343 | 630 | 761 | 679 | 859 | 780 | 831 | 820 | 547 |
| IRR | [%] | 0.12 | 0.14 | 0.15 | 0.15 | 0.16 | 0.16 | 0.16 | 0.16 | 0.13 |
| UPP | [year] | 9.51 | 8.22 | 7.78 | 8.09 | 7.53 | 7.76 | 7.66 | 7.69 | 8.64 |
| DPP | [year] | 14.76 | 11.49 | 10.52 | 11.20 | 10.00 | 10.49 | 10.27 | 10.34 | 12.45 |
| PI | [-] | 1.32 | 1.58 | 1.70 | 1.61 | 1.77 | 1.70 | 1.73 | 1.73 | 1.45 |

**Table 18.** A comparison 1- and 2-stages of membrane regarding different parameters.

| Parameters | Units | 1-Stage (without Vacuum) | 1-Stage (with Vacuum) | 2-Stages |
|------------|-------|--------------------------|-----------------------|----------|
| CO$_2$ capture efficiency | % | 94.16 | 96.17 | 94.85 |
| CO$_2$ purity | % | 45.62 | 56.67 | 96.85 |
| Power consumption | MW | 159 | 171 | 189 |
| LCOE$_{tax}$ | €/kWh | 0.1370 | 0.1434 | 0.17 |
| CO$_2$ avoided cost | €/t | 92.95 | 99.12 | 141.19 |
| CO$_2$ captured cost | €/t | 47.16 | 47.44 | 58.44 |
| NPV | M€ | 1087 | 1050 | 820 |
Table 19. The comparison of the current paper and different papers regarding technical and economical parameters.

| Parameters                                | Current Study | Study 1 | Study 2 | Study 3 | Study 4 |
|-------------------------------------------|---------------|---------|---------|---------|---------|
| Fuel feedstock, [t/h]                    | 92.22         | n.a.    | n.a.    | n.a.    | n.a.    |
| CO₂ capture efficiency, [%]              | 94.85         | 90.01   | 67      | 90      | 90      |
| CO₂ purity, [%]                           | 96.85         | 95.67   | 88      | 95      | 95      |
| CO₂ permeance, [GPU]                     | 1000          | 740     | 270     | 100     | 1000    |
| CO₂/N₂ selectivity                       | 50            | 135     | 34      | 43      | 50      |
| 1st, 2nd Compressor pressure, [bar]      | 8, 4          | 2.5     | 5       | 1       | n.a.    |
| 1st, 2nd vacuum pump pressure, [bar]     | No utilization| 0.25    | n.a.    | n.a.    | n.a.    |
| Flue gas flow, [kmol/h]                  | 40,320        | 9580    | 6690    | n.a.    | 500 *   |
| Net power plant efficiency, [%]          | 23.96         | 35.5    | n.a.    | n.a.    | n.a.    |
| Capital costs per net electrical capacity, [€/kWh] | 7717         | n.a.    | n.a.    | n.a.    | n.a.    |
| CO₂ emission factor, [kg/MWh]            | 85.94         | n.a.    | n.a.    | n.a.    | n.a.    |
| Power consumption of membrane plant, [MWe]| 189           | 165     | 137     | n.a.    | 145     |
| LCOE_tax, [€/kWh]                        | 0.17          | n.a.    | n.a.    | n.a.    | n.a.    |
| SPECCAₘ, [MJth/kg]                       | 4.52          | n.a.    | n.a.    | n.a.    | n.a.    |
| SEPCCAₛ, [MJel/kg]                       | 2.46          | 1.09    | n.a.    | n.a.    | n.a.    |
| CO₂ avoided cost [€/t]                   | 141.19        | 47.40   | 197     | n.a.    | n.a.    |
| CO₂ captured cost [€/t]                  | 58.44         | 47.11   | n.a.    | 72      | 39      |

* m³/s.

Study_1 represents a paper studied by Xuezhong He and May-Britt Hägg [8], while study_2 demonstrates a research article authored by Xuezhong He; Jon Arvid Lie; Edel Sheridan; and May-Britt Häg [99], study_3 exhibits an article studied by Van der Sluus; Hendriks; and K. Blok [100], and study_4 shows a paper studied by Merkel; Lin H; Wei X; and Baker [101]. The current study shows an increase regarding the economic side compared with study_1 due to the elevated flue rate, which is almost 76% higher, which also explains why the power consumption of the present paper is larger as well. On the other hand, the capture efficiency and purity of CO₂ is more than the others because of the high CO₂ permeance and the 1st compressor pressure used.

6. Conclusions

The aim of this paper was to assess and compare 1-single stage (with and without usage of vacuum pump) and 2-stages of membrane performance, from a technical and economical point of view, integrated into a 330 MW coal-based super-critical power plant with different configurations and parameters to achieve 90% CO₂ capture efficiency and CO₂ purity of at least 95%.

The application of a 1-single stage of the membrane with and without a vacuum pump station is remarkably undesirable due to neither the low CO₂ capture efficiency and CO₂ purity when no vacuum is used nor the poor CO₂ purity when a vacuum station is harnessed. The required CO₂ capture efficiency (90%) is obtained at 8.5 bar CP₁ and 300,000 m² of SA₁ when no vacuum is utilized. At this point, CO₂ purity attained was 50%, which is extremely low. The moment a vacuum pump is utilized, CO₂ capture efficiency and CO₂ purity can be improved. A 90% CO₂ capture efficiency can be obtained at 4.5 bar CP₁ and 200,000 m² of SA₁. At the same point, the power consumption is 10% less than no vacuum station used at 90% capture efficiency. The fundamental obstacle that has been examined is the low value of CO₂ purity at any parameters utilized (84% mole max); therefore, a 2nd stage of the membrane with lower surface areas has been suggested to enhance the CO₂ purity. The results show that CO₂ purity has increased by almost 16%
reaching 97% at 6 bar CP\textsubscript{1}, 4 bar CP\textsubscript{2}, SA\textsubscript{1} of 600,000 m\textsuperscript{2}, and SA\textsubscript{2} of 40,000 m\textsuperscript{2}. On the other hand, CO\textsubscript{2} capture efficiency at this point is around 93%, which is the required level. However, high CP\textsubscript{1} is a considerable factor in boosting the carbon capture rate. By increasing the CP\textsubscript{1} from 4 to 6 bar, CO\textsubscript{2} capture efficiency rises by around 51%, and this value has been obtained at 600,000 m\textsuperscript{2} of SA\textsubscript{1}. The SA\textsubscript{1} impacts the CO\textsubscript{2} capture rate as well, for example increasing the SA\textsubscript{1} from 200,000 m\textsuperscript{2} to 600,000 m\textsuperscript{2} drives a rise in CO\textsubscript{2} capture efficiency by approximately 31%. At the suitable parameters to achieve 93% and 97% of CO\textsubscript{2} capture efficiency and CO\textsubscript{2} purity, respectively, the power consumption required for the process is around 57% of the total plant energy (330 MW).

One of the main influences on the economic section is SA\textsubscript{1}, where increasing the surface drives an increase in CO\textsubscript{2} captured constantly which means higher electrical energy required. Moreover, CP\textsubscript{1} has a senior role in affecting the economic side, where high CP\textsubscript{1} leads to an increase in investment cost. The LCOE is highly influenced by increasing CP\textsubscript{1}, where raising CP\textsubscript{1} 2–6 bar leads to an increase of 42% at the 2-stages of the membrane and 600,000 m\textsuperscript{2} SA\textsubscript{1}. However, at the optimum point where 93% and 97% of CO\textsubscript{2} capture efficiency and CO\textsubscript{2} purity, respectively, has achieved, the economic assessments are credible from DPP, CO\textsubscript{2} avoided, and LCOE points of view. In applicable future growth methods, the increase of CO\textsubscript{2} permeability is a significant factor to consider.

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**Nomenclature**

| Abbreviation | Description |
|--------------|-------------|
| CFBC         | Circulating Fluidized Bed Combustion |
| DeSOX        | Desulfurization System |
| HPST         | High-Pressure Steam Turbine |
| MPST         | Medium-Pressure Steam Turbine |
| LPST         | Low-Pressure Steam Turbine |
| CCS          | Carbon Capture System |
| CFP          | Coal-Fired Power Plant |
| LHV          | Lower Heating Value |
| LCOE         | Levelized Cost of Electricity |
| NPV          | Net Present Value |
| IRR          | Internal Rate of Return |
| DPP          | Discounted Payback Period |
| PI           | Profitability Index |
| SA\textsubscript{1} | 1st Membrane Surface Area |
| SA\textsubscript{2} | 2nd Membrane Surface Area |
| CP\textsubscript{1} | 1st Compressor Pressure |
| CP\textsubscript{2} | 2nd Compressor Pressure |
| VP           | Vacuum Pump |
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