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Review

The Potential of CO_2 Capture and Storage Technology in South Africa's Coal-Fired Thermal Power Plants

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Abstract: The global atmospheric concentration of anthropogenic gases, such as carbon dioxide, has increased substantially over the past few decades due to the high level of industrialization and urbanization that is occurring in developing countries, like South Africa. This has escalated the challenges of global warming. In South Africa, carbon capture and storage (CCS) from coal-fired power plants is attracting increasing attention as an alternative approach towards the mitigation of carbon dioxide emission. Therefore, innovative strategies and process optimization of CCS systems is essential in order to improve the process efficiency of this technology in South Africa. This review assesses the potential of CCS as an alternative approach to reducing the amount CO_2 emitted from the South African coal-fired power plants. It examines the various CCS processes that could be used for capturing the emitted CO_2. Finally, it proposes the use of new adsorbents that could be incorporated towards the improvement of CCS technology.

Keywords: CO_2 capture and storage; climate change; coal-fired power plants; South Africa

1. Introduction

Over the past decade, global carbon dioxide emissions have significantly increased by approximately 2.7%, which is 60% more than that of the late 20th century [1]. South Africa is among the countries that are highly affected by carbon emissions; the country is the leading CO_2 emitter in Africa and is ranked amongst the top twelve emitters in the world [2]. The country's emissions are intensified by the energy and manufacturing sectors, which release huge amounts of CO_2 into the atmosphere. For instance, an estimated 367.6 million tons of CO_2 were emitted by South Africa in 2011; this value increased to 476 million tons in 2015. Most of the country's CO_2 emissions are derived from the burning of coal [3]. Thus, future projections show that carbon emissions will continue to increase unless there is acceleration in the formation of carbon-neutral technologies that will reduce this problem or incorporate CO_2 capture technologies from major emitting sources, such as the coal-fired thermal power plants.

Moreover, there has been a significant decline in the country's agricultural output due to low rainfall seasons and temperature rise, which is caused by climate change [4]. Many parts of South Africa are experiencing drought and are therefore no longer suitable for commercial farming. Studies have reported that carbon emissions if not curtailed will have the following devastating effects: (i) South Africa's coastal region is expected to have an atmospheric temperature rise of 2 °C by 2050 and 4 °C by 2100; (ii) the country's interior region is also expected to increase by 4 °C in 2050 and 7 °C in 2100; (iii) this will affect the country's food security; (iv) alien invasive plants might increase and negatively affect the country's water resources; (v) this will likely exacerbate health issues due to droughts and floods; diseases, such as malaria and cholera, have been linked to extreme weather patterns; and (vi) bushlands and various commercial plantations will be vulnerable to wildfires [4]. It is estimated that in order to reduce global warming or limit global average temperatures by 2 °C in 2050, global CO_2 emissions should be reduced by at least 50% [5]. Currently, a range of options that could help to mitigate climate change are being considered worldwide, including carbon capture and storage technology (CCS) [6]. CCS technology can contribute towards the reduction of carbon emissions, thus allowing the continual use of coal-dependent energy markets, like South Africa. The aim of CCS is to capture carbon emissions from point sources, such as coal-fired power plants and industrial processes, to prevent it from being released into the atmosphere [7]. The captured CO_2 can be used for enhanced oil recovery; it can be utilized in chemical and beverage industries for the preservation of drinks. Alternatively, it can be stored in underground rocks or deep ocean waters [8]. Devilliers et al. [9] highlighted that South Africa's economy is primarily dependent on coal reserves for energy supply, and therefore, its utilization is envisaged to continue for the next three decades. In addition, 75% of the country's primary energy supply and 93% of the electricity are derived from coal reserves. The drawback about coal reserves is that they are escalating the country's CO_2 emissions and consequently contributing to environmental degradation, i.e., more than 80% of the country's carbon footprint is produced from the coal-fired power plants [10,11].

The integration of clean and sustainable energy technologies in South Africa requires solutions that deal with high CO_2-emitting sources, such as coal-fired thermal power plants [12]. This implies that sustainability assessment of CCS technology is an important aspect of climate policy, especially in highly industrialized countries, like South Africa [13]. Nonetheless, CCS has some technical and economic barriers that must be addressed before it can be implemented on the industrial scale, which include high capital incentives and leakage problems. CCS is also hindered by economic, social and legal barriers [14]. Besides, some countries have limited geological storage capacity for CO_2 capture [15]. The development of CCS is still in its infancy in South Africa, implying that there are no frameworks for this technology [16]. Against this background, this review examines the potential of CCS technology for mitigating CO_2 emitted from coal-fired thermal power plants in South Africa. It investigates the various CCS methods that could be applied to capture the CO_2 generated from these coal-fired power plants. Lastly, it recommends the use of new adsorbents that could be utilized towards the implementation of CCS systems in South African coal-fired thermal power plants and also the retrofitting of capture devices into the existing coal-fired thermal power plants.

2. Technological Routes for CO_2 Capture

The efficient capture of anthropogenic CO_2 emitted from large point sources such as power plants, is seen as an important strategy that can be used to significantly reduce the level of atmospheric CO_2. This is because the generation of CO_2 is inherent in the combustion of hydrocarbon fuels, which is a daily occurrence in South Africa's coal-fired thermal power plants [17–28]. Currently, pre-combustion, post-combustion and oxy-fuel combustion captures are the three basic technological routes used to capture CO_2 [29–36]. These technological routes are discussed below on a broader note and related to their possible implementation in South African coal-fired thermal power plants.

2.1. Post-Combustion

This capture technology involves the separation of CO_2 from waste gas streams after the conversion of the carbon source of CO_2 [37–40]. This method is very effective at capturing CO_2 from power plants. It is also known as post-conversion capture, but when applied in power plants, it is referred to as post-combustion capture [41]. The post-combustion method of CO_2 capture includes solvent absorption, solid sorbent adsorption, membranes and cryogenic separation [42,43]. Out of all of these options, CO_2 absorption by monoethanolamine is extensively used and referred to as a very mature technology [44]. The post-combustion capture is still considered as the most mature capture route, because it has a good reputation within many industrial applications and also a better operational flexibility [45–48]. The post-combustion capture technology is mostly used in power plants because it has the possibility of retrofitting in existing power plants, such as the South African coal-fired thermal power plants. The South African energy sector is mainly driven by coal, and the sustainable use of coal in these power plants must continue in order to avoid escalating the price of electricity. On this note, retrofitting CO_2 capture devices in the already existing coal-fired power plants in South Africa becomes a viable option in order to curtail CO_2 emission to the atmosphere. Since the post-combustion technology allows for possible retrofitting, it becomes a promising technology that can be implemented in the South African coal-fired thermal power plants with no associated increase in the price of electricity, because coal will still remain the primary source of electricity in the country, and carbon emissions from this sector will be reduced drastically.

2.2. Pre-Combustion

The pre-combustion capture refers to capturing CO_2 generated as an undesired co-product of a conversion process [49–54]. In the pre-combustion capture, fuel from the power plant is reacted with oxygen to generate a syngas mixture, which is carried out in the gasification step [55–60]. Carbon dioxide is then reacted with steam in the second step to produce CO_2 and H_2 before the CO_2 is finally separated using a physical or chemical absorption process [61–65]. The pre-combustion capture technique incurs high costs for chemical solvent regeneration. However, for physical solvents, the costs are lower because they are regenerated by pressure reduction instead of using heat. Physical solvents are most suitable for use at high operating pressure and low temperatures, and it is more efficient when the CO_2 streams in the power plants are more concentrated [66–70]. In the context of CO_2 capture from the South African coal-fired power plants, the pre-combustion technology cannot be fully implemented because it has a high energy requirement with no option of retrofitting capture devices into existing power plants. This invariably means that the implementation of this technology will only be feasible in newly-built power plants and cannot be implemented in the already existing coal-fired thermal power plants in South Africa. This makes the pre-combustion CO_2 capture technology more expensive and difficult to implement in the South African power sector.

2.3. Oxy-Fuel

In the oxy-fuel combustion technological approach for CO_2 capture, flue gas consisting of pure oxygen is burnt. This technological route produces a flue gas stream that is highly saturated with CO_2 [71–76]. This technology also produces flame with an excessively high temperature because, theoretically, if fossil fuel (coal) is burnt in pure oxygen, much heat is produced [77–89]. The pure oxygen is produced by cryogenics. This technique is a modification of the pulverized coal-fired power plant in South Africa. It involves burning coal in nearly pure oxygen. The main advantage of the oxy-fuel CO_2 capture technique is that the flue gas is available at a high CO_2 concentration of approximately 75.7 mol%, thereby reducing compression costs and facilitating efficient CO_2 removal [90–104]. Although this technology appears promising if implemented for CO_2 capture in power plants, its possibility of implementation in the South African coal-fired power plants is quite slim because burning coal in pure oxygen instead of air on a large scale is very expensive. This will in turn increase the cost of electricity in South Africa. Therefore, it is not a suitable technological route for CO_2 capture in South Africa.

3. Separation Technologies during Post-Combustion CO_2 Capture

The preference of one technological route over others could be attributed to its ease of access, its possibility of the capture process, retrofitting to existing power plants, the maturity level of such a technological route and the period needed for the implementation of such technology [105]. Currently, there is a wide range of CO_2 capture and separation techniques from gas streams, which could be implemented in the South African coal-fired thermal power plants. They are based on physical and chemical processes, which include adsorption, absorption, cryogenic and membrane separation technologies. They are discussed below.

3.1. Cryogenic Separation

The cryogenic separation method for CO_2 capture is mainly based on the principle of condensation and cooling [106–110]. It is mostly applied in CO_2 capture systems where the gas streams contain a high concentration of CO_2. The challenge about cryogenic separation is that it cannot be used in CO_2 capture from power plants because the power plants have a more dilute CO_2 stream [111,112]. Another setback is that this technology is energy intensive, i.e., it requires high amounts of energy for CO_2 separation. The concentration of CO_2 from South African coal-fired power plants is quite low, thereby rendering this CO_2 separation method difficult to implement in South Africa. Furthermore, cryogenic separation is best carried out at very low temperatures [113–119]. However, it is difficult to attain very low temperatures in coal-fired power plants that will be suitable for CO_2 capture using this technique. In most cryogenic separation processes, various components in gas mixtures are separated by a series of compression, refrigeration and separation steps [120]. Impurities lower the phase transition temperature of CO_2 in cryogenic separation processes to as low as -80 °C. In this case, the refrigeration energy penalty increases substantially, and there is a huge possibility of CO_2 frost formation, which is a threat to equipment safety [120–123]. As a result, another technology that is economically viable and less energy intensive needs to be investigated.

3.2. Membrane Separation

Corti et al. [65] investigated CO_2 capture using membranes and concluded that the application of CO_2 capture from flue gases using membranes can only be competitive if the CO_2 concentration in the flue gas is higher than 10%. CO_2 capture using membranes operates on the principle of differences in the physical or chemical interaction between the CO_2 gas and the membrane for which the membrane is designed in such a way as to allow one gas to pass through faster than the other. The membrane modules can also be used as a gas absorption column or as a conventional membrane separation unit [124–128]. Although the membrane technology is relatively new, it requires high energy during separation, and it is widely known for its poor selectivity [129–135]. This poses a major disadvantage for CO_2 capture using membranes [136–138]. More so, this technology uses either inorganic ceramic membranes or organic polymeric membranes [139,140]. Ceramic membranes are quite expensive; however, it is very difficult to achieve a high degree of separation of CO_2 and a high purity of CO_2 at the same time with CO_2 in the flue gas through a single-stage ceramic or polymeric membrane. This is another major limitation of this CO_2 capture technology. This technology for post-combustion CO_2 capture is not suitable for implementation in the South African coal-fired power plants owing to its expensive nature if ceramic membranes are used and fouling in the case of polymeric membranes. Although the polymeric membranes have excellent selectivity and permeability for CO_2 capture, they have very low thermal stability and these membranes may be plasticized with the influence of CO_2 in the membrane. Therefore, application of the membrane technology for post-combustion CO_2 capture in power plants similar to the South African coal-fired thermal power plants is limited. Efficient capture technologies for CO_2 with low cost and high CO_2 capture potential, as well as selectivity need to be studied further as an alternative to the use of membranes for post-combustion CO_2 capture [141].

3.3. Absorption

The absorption technology involves the use of chemical solvents to capture CO_2. It is a well-researched, robust, mature technology, and it is widely applied industrially. It is sub-divided into physical and chemical absorption. The former is temperature and pressure dependent, and the absorption of CO_2 from the flue gas occurs at high pressure and low temperature. Whereas in the latter, the absorption of CO_2 from the flue gas depends on the acid-base neutralization reaction using basic solvents [142–145]. The most commonly-used solvents for absorption of CO_2 from flue gases are basically amines [146], chilled methanol [147] and ammonia solution [148]. Even though the absorption technology is considered as a mature technology for CO_2 capture, the use of solvents for this technology makes it corrosive and energy intensive due to high energy demands during solvent regeneration, and it is also expensive. The major limitation of this technique is that it uses liquid absorbents, which corrode piping in power plants; as such, it is not very suitable for adoption in the South African coal-fired power plants. Consequently, the adsorption technology that uses solid adsorbents for CO_2 capture is highly recommended for use in most South-African coal-fired power plants because it is not corrosive, the least expensive and has minimum energy requirements for the regeneration of the solid adsorbents [149]. Liquids, such as monoethanolamine, react readily with CO_2, but because heat must be applied to remove CO_2 from the resulting liquid, the process is not economically viable for implementation in power plants. If the approach were applied to every power station in the South Africa, CO_2 capture could cost 30% of the country's growth in gross domestic product each year [150]. Less expensive methods for capturing CO_2 and hydrocarbon emissions with minimal energy costs need to be investigated.

In order to reduce the high thermal energy consumption in the power plants, the concentration of monoethanolamine used during the post-combustion CO_2 capture process should be increased, and better corrosion inhibitors should be used to eliminate the high corrosive effect of monoethanolamine as a solvent for the CO_2 capture by absorption. Figure 1 shows a summary of various CO_2 capture and separation technologies for post-combustion CO_2 capture.

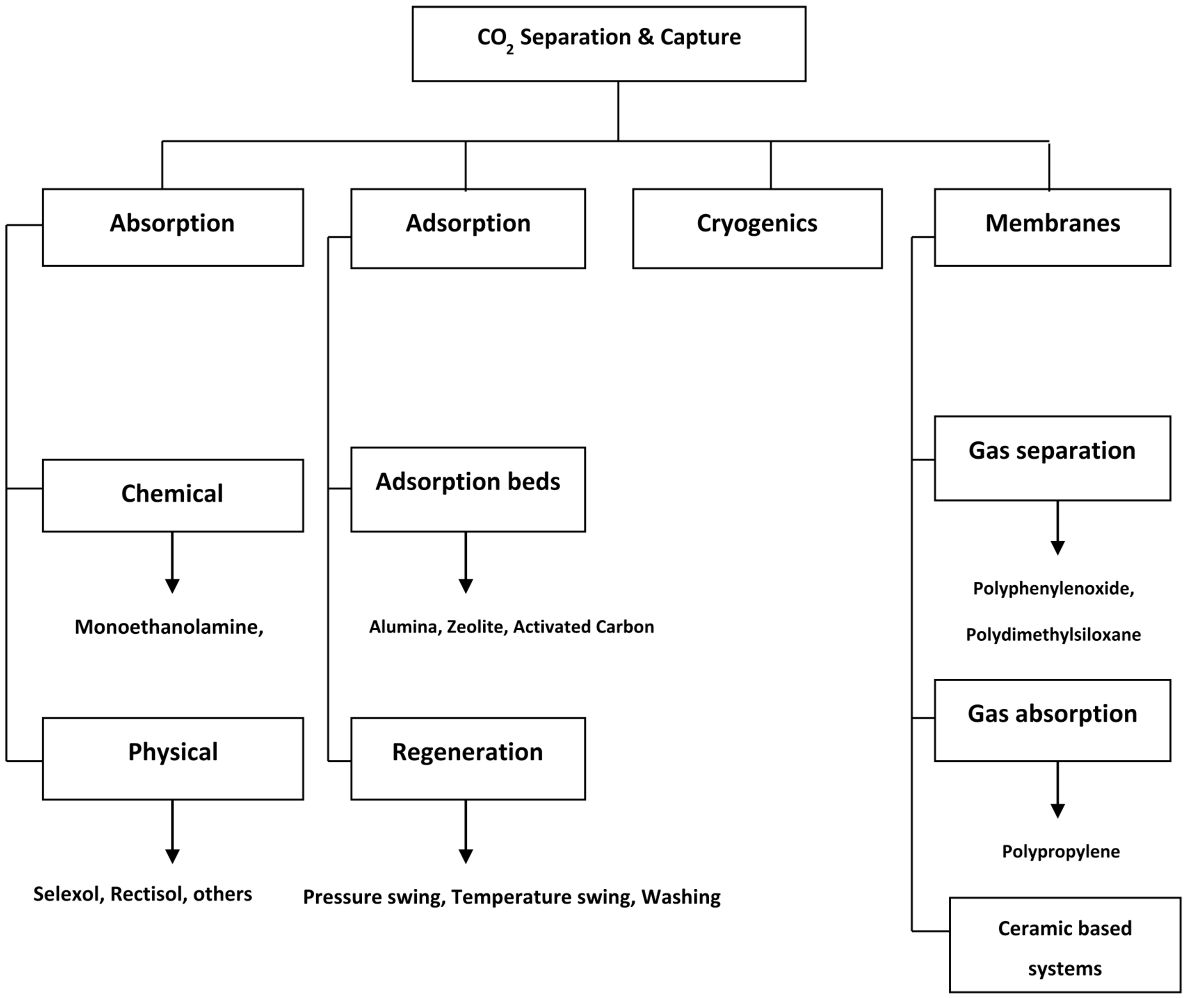

Figure 1. Different CO_2 separation and capture technologies for post-combustion CO_2 capture [82].

3.4. Adsorption

This technology is extensively used in chemical and environmental processes. It uses various adsorbents such as zeolites, activated carbon, polyaspartamide, metal oxides; porous silicates, metal organic frameworks and chitosan for CO_2 capture [151]. However, CO_2 capture by adsorption using activated carbon fibers and a carbon fiber component is regarded as an efficient approach when used in power plants [152]. Adsorption technology is attracting increasing attention due to its characteristics, which include minimum energy requirements, easy maintenance, simple operation and flexibility [153]. Amongst the adsorption processes reported in literature, temperature swing adsorption (TSA) is an advantageous process because it is inexpensive and uses less thermal energy. Therefore, it can reduce the operating costs if it is incorporated into coal-fired plants [154]. However, it requires longer cooling and heating times for CO_2 capture [155]. Meanwhile, vacuum swing adsorption (VSA) is more economically viable than pressure swing adsorption (PSA) in post-combustion for CO_2 capture [156]. Nevertheless, it has its own drawbacks, such as its sensitivity to feed gas temperature. More heat treatment might be needed to condition the flue gas before injecting it to the VSA plant; this affects the separation efficiency and process economics. PSA has been shown to be a promising technology in recent years because it can use a wide range of temperatures and pressures and requires minimum energy. Another advantage is that it requires low investment costs [157]. The adsorption technology also has its disadvantages, such as poor heat transfer, especially in packed beds, and slow kinetics, but the advantages of this technology far out-weigh its disadvantages [158]. There is potential in the implementation of this technology in the South African coal-fired power plants because of its ease of regeneration of the adsorbent using pressure modulation with reduced energy requirements.

4. The South African Power Sector

4.1. Power Generation in South Africa

South Africa has different options for power generation, which include nuclear energy, hydroelectric energy and wind energy [143]. South Africa is a main supplier of almost two-thirds of the electricity used in the African continent, and it falls among the top four least expensive electricity-producing nations globally. Over 90% of South Africa's electricity is generated from its coal-fired thermal power stations; 5% is generated from nuclear power plants, i.e., the Koeberg nuclear power station in Cape Town; and a further 5% of electricity is generated in hydroelectric power stations. However, there are only a few economic hydro sites that could be used for significant power generation in South Africa [147]. Approximately 52,017 MW of electricity are generated in South Africa, out of which 42,691 MW are generated from the combustion of fossil fuels, like coal. The remaining 9326 MW of electricity are generated from renewable, nuclear and hydro-electric stations, which are low CO_2-emitting power generation sources [16].

4.2. An Outlook for the South African Coal-Fired Power Plants

The major CO_2-emitting industries in South Africa are situated in the provinces of Gauteng, Mpumalanga and Free State. These regions form South Africa's coal mining sector, and most coal-fired powered plants are situated in these provinces, as well [17]. The electricity sector is predominantly dependent on coal energy, thereby making South Africa's coal-fired thermal power plants the largest CO_2 emitters in the country. Coal-fired power plants generate more than 90% of South Africa's electricity through the country's power parastatal, i.e., Electricity Supply Commission (ESKOM). Since 2008, new coal-fired power plants have been established in the coal-rich provinces of Mpumalanga and Limpopo. The Camden Power Station, which is located in Mpumalanga, generates about 156 megawatts of electricity, and it was established in 2008. The Grootveli Station was established in 2011 and has a production capacity of 1180 megawatts; it is also situated in Mpumalanga. Currently, two major coal-fired power plants are under construction, these include the Kusile and Medupi power plants, which are expected to generate about 794–4764 megawatts of electricity supply in 2015–2020 [18].

The utilization of coal energy is expected to continue for the next decades because the country has enormous coal reserves, and this source of energy is inexpensive compared to other hydrocarbon fuels [19,20]. The country's power utility, Electricity Supply Commission (ESKOM) is listed amongst the highest CO_2-emitting companies in the world due to its use of pulverized coal combustion plants for power generation [21]. In 2010, South African coal-fired thermal power plants were among the highest CO_2 emitters in the world, as depicted in Table 1, i.e., South Africa was ranked ninth and generated 218 million tons of CO_2, with a total energy production of 215,000 GWh, out of which 93.4% was derived from coal. Therefore, mitigation strategies are highly emphasized by the South African government as a result of its heavy reliance on coal for electricity generation [21]. Consequently, the implementation of CCS technology is mandatory in South Africa's coal-intensive energy-grid in order to address the challenges of carbon emissions.

Table 1. World's largest CO_2 emitting coal-fired power plants by country.

Rank	Country	CO_2 Emitted (Megatons)	Energy Produced (GWh)	Fossil Fuel Power (%)	Reference
1	China	3120	3,620,000	82.5	[22]
2	USA	2820	4,190,000	68.8	[23]
3	India	638	719,000	76.3	[24]
4	Russia	478	896,000	63.4	[25]
5	Germany	429	636,000	62.1	[26]
6	Japan	414	1,030,000	33.2	[27]
7	U.K.	227	370,000	71.4	[28]
8	Australia	224	228,000	90.1	[29]
9	South Africa	218	215,000	93.4	[30]
10	South Korea	192	392,000	44.3	[31]

5. The Potential of CO_2 Capture and Storage in South Africa

South Africa is amongst the fast developing nations in the world and has a power sector that is mostly dependent on coal, i.e., the country generates up to 224 million tons of coal per annum. Owing to the country's strong commitment to sustainable energy development, it is necessary to understand the need for climate change mitigation options in the country's economic, social and environmental dimensions. With South Africa's high dependence on coal energy and the presence of streams of pure carbon dioxide in its coal-fired power plants, the application of CCS systems will be an attractive option to curtail the unfettered release of CO_2 into the atmosphere by the South African power sector [32]. The country's climate policy is deeply rooted in a strong commitment to a multilateral process under the Kyoto Protocol and the United Nation's Framework Convention on Climate Change (UNFCCC). South Africa is also a signatory to both the Kyoto Protocol and the United Nation's Framework on Climate Change; the country is committed to introducing measures to mitigate climate change, albeit it does not have quantifiable emission reduction targets under the Kyoto Protocol. Therefore, the country can benefit immensely by switching to a clean and sustainable energy development path through the CCS approach [33]. It can offer an environmentally-benign alternative in the utilization of coal energy in coal-fired power plants. Coal can still be used to fuel the power plants and yet reduce the emission of greenhouse gases like CO_2, instead of the so-called "business-as-usual" approach in which it is released into the atmosphere.

The theoretical maximum amount of capturable CO_2 in South Africa is approximately 64% of all anthropogenic CO_2 released [34–36]. Table 2 presents a breakdown of CO_2 contributing sources in South Africa and the amounts of CO_2 that are likely and unlikely to be captured if CCS technology were employed. It can be observed from Figure 2 that a higher percentage of CO_2 emitted in South Africa is capturable, and the majority of CO_2 emissions are generated by the power sector. Therefore, CCS technology would play a pivotal role in curbing the environmental pollution and health hazards caused by anthropogenic greenhouse gases, such as CO_2. A report from Engelbrecht et al. [35] indicated that CCS systems can significantly reduce South Africa's CO_2 emissions if they are incorporated in coal-fired electricity-generating power plants [37]. The realization of CCS has been hampered by economic constraints, and its implementation has been discouraged in most developing countries due to high costs. Other barriers include lack of a framework, legislation and regulation from governments. Nonetheless, South Africa is a fast developing nation with sound economic policies that can fully implement CCS technology in these power plants, which is the country's major CO_2 emitter [14]. Furthermore, the implementation of CCS is economically feasible in South Africa, because it will primarily focus on coal-fired power plants, which will be less expensive than incorporating it in all sectors. South Africa can acquire skills from countries where the CCS technology is already functional and from sources like the European Directive on the Geological Storage of Carbon Dioxide (CCS Directive 2009/31/EC), which focuses on the geological storage of CO_2.

Table 2. Sources of CO_2 emissions in South Africa [35–37].

Source of Likely Capturable CO_2	Amount of CO_2 (Mt/a)	Source of Unlikely to Be Capturable	Amount of CO_2 (Mt/a)
Electricity generation	137	Municipal wastes	9
Process industries	24	Agricultural wastes	41
Other energy production companies	26	Other wastes	36
Manufacturing companies	26	Thermal energy production	32
Total capturable CO_2	213	Total uncapturable CO_2	118
Total capturable and uncapturable CO_2	331		
Percentage capturable CO_2	64.40%		
Percentage uncapturable CO_2	35.60%		

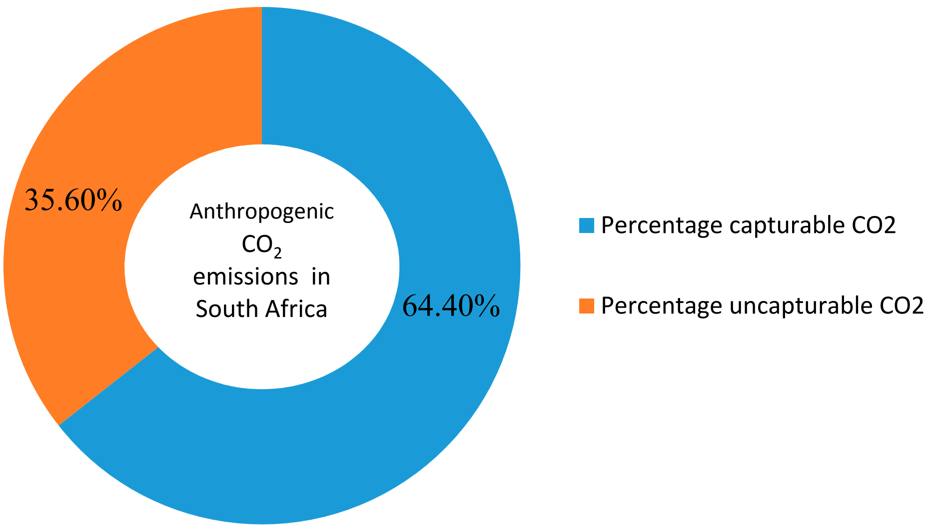

Figure 2. Percentage of capturable and uncapturable CO_2 in South Africa.

6. Geological Storage of CO_2

When CO_2 is successfully captured from these coal-fired power plants, it can be stored in natural areas, like geological formations, where it is trapped below impermeable rocks and retained in pore spaces after being dissolved by underground water [159,160]. This method of storing CO_2 has a long residence time. It can also be stored in geological formations, such as unused deep saline aquifers. According to literature reports, the geological storage of CO_2 is currently considered as the most viable option for storing captured CO_2 in large quantities [161,162]. Geological storage formations can store up to 10 million tons of CO_2 for a long period of time [163]. However, good geological sites for CO_2 storage must have: (i) appropriate thickness and porosity; (ii) the reservoir rock must be permeable and (iii) the cap-rock must be in a stable geological environment, as well as having a good sealing capability. Depleted or almost depleted oil and gas reservoirs, saline aquifers and un-mineable coal beds are the three major geological formations commonly considered for CO_2 storage [164]. Storing

CO_2 in deep oceans is another option for CO_2 storage; however, it poses environmental concerns, such as eutrophication and ocean acidification. Captured CO_2 could be stored in oceans by releasing it into deep ocean waters of a minimum depth of 1000 m below sea level. This form of CO_2 storage is feasible because cold-deep sea waters are unsaturated with CO_2 and subsequently have a significant potential of dissolving it. This is based on the principle that CO_2 becomes super critical below certain depths with a liquid-like density; and also, it is less buoyant than water [165]. However, as stated earlier, the major disadvantages of this option are the environmental challenges attributed to it.

South Africa has more geological formations than deep waters; therefore, the suitable option of storing the captured CO_2 from coal-fired power plants is by using geological formations, like deep saline aquifers at 700–1000 m below ground level. Carbon dioxide is soluble in water; there are natural exchanges of CO_2 between the atmosphere and waters at the ocean surface that occur until equilibrium is reached. If the atmospheric concentration of CO_2 increases, the ocean gradually takes up additional CO_2. In this way, the oceans have absorbed about 500 Gt CO_2 of the total 1300 Gt CO_2 of anthropogenic emissions released to the atmosphere over the past 200 years [166]. As a result of the increased atmospheric CO_2 concentrations from human activities relative to pre-industrial levels, the oceans are currently absorbing CO_2 at a rate of 7 Gt CO_2 per year. Most of this carbon dioxide now resides in the upper ocean and thus far, has resulted in a decrease in pH of about 0.1 at the ocean surface because of the acidic nature of CO_2 in water. To date, there has been virtually no change in pH in the deep ocean. Models predict that over the next several centuries, the oceans will eventually take up most of the CO_2 released to the atmosphere as CO_2 is dissolved at the ocean surface and subsequently mixed with deep ocean waters [167]. South Africa has various locations with great potential for CO_2 storage. For instance, the Karoo basin, which covers the Eastern Cape, Northern Cape, Free State, KwaZulu-Natal and the Mpumalanga provinces of South Africa, are very promising geological storage sites for the captured CO_2. The orange basin of Western South Africa around Durban and Zululand is another storage site available for the captured CO_2 from these power plants.

7. An Overview of CO_2 Capture Using Solid Adsorbents

CO_2 emissions from coal-fired power plants can be captured using solid adsorbents. Even though it is less mature than the absorption method, it is inexpensive, has minimum energy requirements and uses non-corrosive materials. Adsorption of CO_2 can be achieved by using various solid support systems, such as activated carbon, zeolites, carbon molecular sieves and polymeric adsorbents like amine-grafted polyaspartamide [168]. According to Chaffee et al. [165], physical adsorption of CO_2 using solid adsorbents require less energy as compared to other CO_2 capture systems. Physical adsorption of CO_2 requires about 0.09 KWh/kg CO_2 with equal pressure in the feed and product streams, which is by far smaller than the chemical adsorption, which requires about 0.34 KWh/kg CO_2. Yang et al. [166] conducted a study on modeling the physical adsorption of CO_2 using solid physical adsorbents and investigated CO_2 capture via the pressure swing adsorption methods using activated carbon, zeolite13X, and concluded that the adsorption technology is less expensive and less energy intensive for capturing CO_2. Similar findings were also confirmed by Othman et al. [167] when using molecular sieves and activated carbon materials. Rivas et al. [168] indicated that solid adsorbents are more efficient than liquid systems. For example, solid adsorbents exhibit better performance at partial pressures greater than 50 KPa of CO_2 [169–172]. However, liquid absorbents stabilize when coupled to chemical absorbents. Since the adsorption of gases is favored by higher pressures and lower temperatures, CO_2 capture from these power plants need to be carried out at high pressures; therefore, the adsorption technology will be ideal for effective CO_2 capture.

Physical adsorbents have also been proven to capture CO_2; they have a high affinity for CO_2. However, the purity of the gas decreases during the downstream process [173]. It was indicated that activated carbon and polymer-based adsorbents are the best type of physical adsorbents to be used for CO_2 capture. They produce about a 75%–80% pure CO_2 stream at a recovery of 90% [174]. Adsorption systems do not use high energy, and the recovery is far less than the chemical absorption methods [175].

Furthermore, polymer adsorption systems have been shown to bind CO_2. A study conducted by Diaf and Beckman [176] assessed the effects of polymers on CO_2 capture using primary, secondary and tertiary amine-based polymers, concluded that CO_2 binds strongly on basic amines and proposed ethylene diamine (EDA) as the most efficient amine compound for polymer system. Similar findings were also confirmed by Seckin et al. [177]; the authors used 1, 4, 5, 6-tetrahydropyrimidine polymer compound to capture CO_2 and concluded that this method was more feasible compared to other CO_2 capture methods. The effectiveness of CO_2 binding was due to the 1:1 nature of amidine groups in the 1, 4, 5, 6-tetrahydropyrimidine [174]. These findings could pave the way for the use of carbon dioxide capture technologies via amidine systems [175]. Recently, a novel polymer-based adsorbent "polyaspartamide" from polysuccinimide was identified as a promising adsorbent for CO_2 capture because of its ability to selectively adsorb gases; this is due to its molecular sieving characteristics [176]. The adsorbent was suggested in this study in order to address the limitations of conventional wet solvent processes for CO_2 capture at the pilot scale, such as high costs, high energy requirements and the generation of large quantities of water and sludge from the process [177]. Thus, the application of adsorption technology for CO_2 capture using amine-grafted polymer-based adsorbents is highly encouraged because it is a dry process and has fewer challenges as compared to the conventional process, which uses solvents for CO_2 capture.

8. Challenges Facing CO_2 Capture and Storage in South Africa

8.1. Economic Challenges

The implementation of CCS technology has been hindered mainly by financial constraints. The prices of incorporating CCS in power systems ranges between 30% and 70% depending on the method of CO_2 capture used [178,179]. Maver [180] showed that the challenges facing the implementation of CCS globally centers on economic, social and legal barriers; economic barriers in the sense that CCS is expensive and cannot be implemented by most developing countries. Nonetheless, South Africa is amongst the fast developing nations that have good economic frameworks and policies for successful implementation of CCS in its coal-fired power plants. There has also been some skepticism with regards to the deployment of CCS technology in South Africa; it has been debated that its implementation will threaten the country's efforts of developing renewable and sustainable energy resources because they also require huge financial incentives from the government [180]. Nevertheless, the CO_2 generated from the country's coal-fired thermal power plants is causing many challenges associated with environmental pollution and health hazards. It is essential to establish regulatory frameworks that will oversee this technology in South Africa [100]. Moreover, some of the economic barriers could be overcome by creating CCS financing mechanisms, whereby CO_2-emitting industries, e.g., Electricity Supply Commission (ESKOM) could contribute towards its financial development. A collaborative effort between various stakeholders can also accelerate its implementation [181].

8.2. Environmental Challenges

There are many environmental concerns associated with CCS; these include contamination of groundwater as a result of CO_2 leakage and the occurrence of earthquakes that might be caused by the sequestrated CO_2 due to pressure build-up [182]. The sequestrated CO_2 might be leaked into the atmosphere if it is stored in underground rocks and therefore escalates the problems of climate change. In addition, leakage could negatively affect soil quality; trees and other vegetation if stored underground [183]. In South Africa, this challenge could be surmounted because apart from storing the captured CO_2 in underground rocks, it can also be stored in the available basins listed in the previous chapters in this study. South Africa has abundant geological formations and un-mineable coal fields where captured CO_2 can be stored without infringing on environmental safety [184].

8.3. Social Challenges

The implementation of CCS may invigorate public debate because this technology is relatively new in South Africa and thus requires extensive research. Its long-term effects on the environment and people are not yet fully known. However, public awareness is essential in order to highlight its advantages, such as mitigation of CO_2 emissions and environmental degradation. This might in turn stimulate the interests of various stakeholders, which might contribute towards its implementation in South Africa [185]. South Africa through the South African Center for Carbon Capture and Storage (SACCCS) is creating public awareness on the need to curtail the indiscriminate emission of CO_2 in this region.

9. Conclusions and Recommendations

South Africa is a fast-developing nation with an energy economy that is highly dependent on coal, and it is apparent that the country has the potential for the implementation of CCS in the power sector. The potential for CO_2 capture lies in the major emitting sources, such as the electricity-generating coal-fired power plants, which are a major emitting source, as pointed out in this study. The establishment of the South African Center for Carbon Capture and Storage (SACCCS) illustrates the potential of the implementation of this technology in South Africa's power sector. There are various barriers facing the implementation of CCS globally. Nonetheless, it can be inferred that South Africa is a country with a strong commitment to sustainable and renewable energy and also a signatory to the Kyoto Protocol, as highlighted earlier in this review. This nation is working towards curtailing its carbon footprint by shifting its focus to major sources of CO_2 emission, such as the country's coal-fired thermal power plants. More so, it has included CCS policies into its legislation and has mandated SACCCS to oversee its implementation. This clearly brings to light that there is a huge potential of implementing CCS in the country's coal-fired thermal power plants. Thus, this review presented the potential of CCS technology in South African coal-fired power plants. The pressing challenges related to CO_2 emissions necessitate the search for clean and sustainable energy technologies, such as CCS in South Africa. The potential for CO_2 capture lies in the major emitting sources, which are the electricity-generating coal-fired power plants. The most suitable CO_2 capture route for the South African coal-fired power plants is post-combustion CO_2 capture, because it allows for easy retrofitting of capture devices in the existing coal-fired power plants. Adsorption technology using solid polymer-based adsorbents will be ideal and more economically viable for CO_2 capture in the South African coal-fired power plants.

The following recommendations are proposed for the implementation of CCS in South Africa's coal-fired power plants:

- ❖ The implementation of CCS has been stagnant in South African coal-fired power plants due to financial barriers, the lack of frameworks and the lack of technical expertise. Nonetheless, this challenge can be overcome by using solid inexpensive composite adsorbents, which have been shown in recent years to be economically viable, towards the improvement of CCS processes.
- ❖ Chemical absorbents, such as monoethanolamine, are extensively used in CO_2 capture. However, they have some limitations in terms of solvent capacity; it is therefore recommended that if the absorption technology must be used in post-combustion CO_2 capture from these South African power plants, a chemical absorbent with higher loading capacity, such as amine 2-amino-2-methyl-1-propanol (AMP) should be employed. Alternatively, the monoethanolamine can be coupled with activators, such as piperazine (PZ), to improve its efficiency, but if the adsorbents will be used as suggested by this study, these adsorbents should be impregnated with amine-rich materials, such as chitosan and polysuccinimide, because they increase the adsorbent's affinity for CO_2. Possible solid sorbents that could be used for CO_2 capture in the South African power plants include carbon nanotubes with chitosan impregnation, amine-grafted polyaspartamide, Sodalite-Zeolite Metal Organic Framework/chitosan composite materials, etc.

❖ Given the fact that the post-combustion CO_2 capture technology is highly embraced, its overall system performance with regards to South Africa's coal-fired power plants should be assessed by using pilot-plant experimental results from these power plants, and these results should be validated for their accuracy.

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