Using Carbon Capture and Storage Technology to Reduce CO2 Emissions from Power Systems

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***Abstract*—This study investigates the crucial role of Carbon Capture and Storage (CCS) technology in mitigating CO2 emissions from Poland's power systems. This is essential not only for meeting climate targets but also for maintaining energy security. The integration of CCS technology is seen as pivotal in addressing the dual challenge of reducing carbon emissions and ensuring a reliable and secure energy supply. Given the significant reliance on fossil fuels in Poland, particularly coal, which constitutes 77% of electricity generation and 53.4% of carbon emissions, this study assesses the potential of CCS adoption. Acknowledging natural gas as a transitional fuel, the focus is on evaluating the decarbonization potential of gas-fired power plants. The emphasis lies also in utilizing offshore aquifers in the Baltic Sea as a storage sink for CO2 emissions, drawing comparisons with the Sleipner benchmark.**

Keywords-Carbon Capture and Storage (CCS), Power Systems, Decarbonization, Natural Gas Combined Cycle (NGCC) Plants, Offshore Aquifers, Energy Efficiency.

I. INTRODUCTION

The urgency of transitioning to a low-carbon energy system stems from the alarming rate at which we are depleting our carbon budget. In the Figure 1 the historical budget reflects the cumulative amount of CO2 that has already contributed to global warming, whereas the remaining carbon budget represents the allowable amount of CO2 that can still be emitted to limit warming below specific temperature thresholds. The annual global emissions of CO2 currently stand at approximately 36.5 billion tonnes in 2022, resulting in an average daily emission of 100 million tonnes (0.1 billion tonnes), therefore every tonne counts. Hence, each individual tonne emitted counts, as every reduction contributes to mitigating climate change.

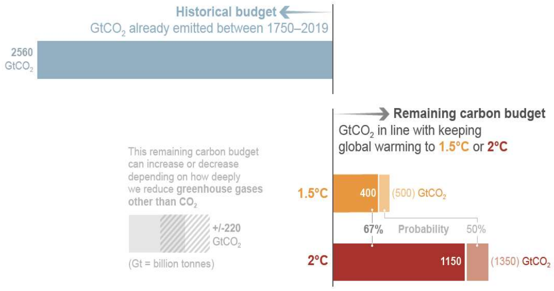


Figure 1. Various types of carbon budgets [1].

Therefore, developing a comprehensive transition plan for the entire coal value chain is crucial to align with the rapid energy transition required by 2030, promoting carbon neutrality and ensuring a just transition. This plan should prioritize the integration of CCS technologies, recognizing that fossil fuels will continue to play a role in power generation in Poland. This study focuses on deploying CCS as a transitional solution aligned with the IPCC statement, emphasizing the need to capture about 20% of global CO2 emissions to limit global warming below 2 °C. Applied to Poland, achieving this target requires injecting between 21 and 28 million tons of CO2 from commercial power plants alone, and 60 to 80 million tons of CO2 from all sectors into suitable underground storage sites each year by the end of the century[2].

Figure 2 depicts the distribution of total CO2 emissions in Poland for the year 2021. The sectors of Electricity, Heat Production, and Industry collectively contributed to 53.4% of the total emissions, amounting to 215.7 Mt of CO2. This share represents a significant portion of the overall emissions recorded for the year, which stood at 403.8 Mt of CO2 [2]. Figure 3 presents the dominant role of domestic coal-fired generation in Poland's electricity supply. In 2022, the country produced 178.8 TWh, with fossil fuels accounting for approximately 77% of the total production share[2].

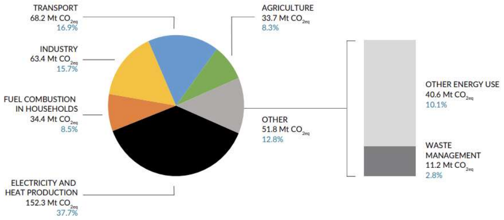


Figure 2. Structure of greenhouse gas emissions in Poland in 2021[2].

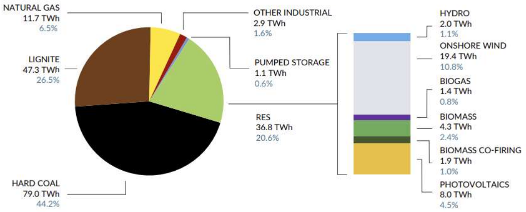


Figure 3. Electricity production in Poland 2022[2].

II. LITERATURE REVIEW

Carbon capture, utilisation and storage (CCUS) is a focused approach as a climate change mitigation strategy. The process begins with the capture of CO2 emissions from major industrial point sources, including operations such as cement and chemical production, coal and biomass plants. Using a variety of capture methods, such as post-combustion and pre-combustion techniques, CCUS effectively removes CO2 before it is released into the atmosphere. The captured CO2 is then purified and compressed, transforming it into a liquid state. What sets the CCUS apart is its versatility; beyond storage, there is a growing emphasis on carbon utilisation. This involves reusing captured CO2 for industrial applications or converting it into valuable products, fostering a circular carbon economy.

After capture and utilisation, the final stage is to transport the CO2 to suitable storage sites. Typically, underground geological formations, such as depleted oil and gas fields, coal beds or saline aquifer formations, serve as safe storage sites. Transportation itself is via pipelines, ships or tankers, and ship transport is emerging as a viable alternative for many regions of the world. Indeed, the entire process of CCUS, as illustrated in Figure 4, holds the potential to address global emissions and fostering a more sustainable future.

The utilization aspect of CCUS will not be addressed further in this work. The focus will be limited to the Capture and Storage stages of the process, henceforth referred to as CCS.

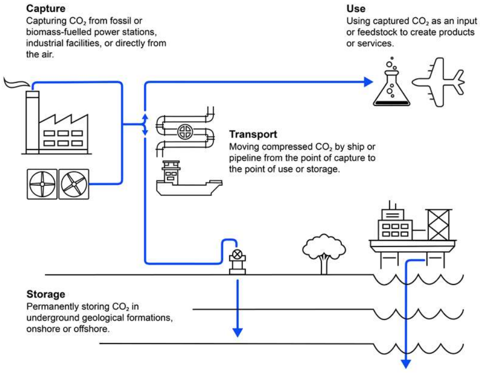


Figure 4. Schematic of CCUS[16]

III. METHODOLOGY

The work emphasizes the need for sustainable solutions that balance environmental concerns with energy security while closing the loop on CO2 emissions. By integrating surface capture processes and underground storage, the research aims to develop a comprehensive approach to efficiently capture and store CO2 emissions while prioritizing energy efficiency. Computer simulations, employing IPSEpro, calculate heat and mass balances, allowing the evaluation of amine-based CO2 capture systems and the energy efficiency of power plants. The Integrated Environmental Control Model (IECM) facilitates the analysis of modelled emissions from the Natural Gas Combined Cycle (NGCC) power plant, providing insights into CO2 dynamics for informed decision-making in implementing CCS projects. This research contributes to advancing CCS technologies, supporting the transition to sustainable, low-carbon energy systems in Poland.

The work develops comprehensive numerical models for two complementary levels. Firstly, at the surface facility, with the integration of the NGCC power plant and the CO2 capture unit to achieve the most optimal arrangement. This involves simulating various configurations to determine the most efficient and effective setup. Secondly, it is crucial to simulate CO2 injection and storage in the available underground sinks within Poland. These simulations will help define the necessary number of wells and appropriate injection volumes, ensuring the safe and efficient sequestration of CO2. Surface and underground integrations will greatly enhance and complement the research project on CCS conducted in this work.

IV. SCENARIO BUILD-UP

The Case Study power station, is a 465-MW gas-fired facility. By adopting co-generation principles, the plant not only generates electricity but also harnesses useful heat, maximizing energy utilization and contributing to reduced emissions. The NGCC power plant is a power generation facility that utilizes both gas turbines and steam turbines to produce electricity. The plant operates in two main cycles: the gas turbine cycle and the steam turbine cycle, which are combined to maximize efficiency and power generation. The combination of the gas turbine and steam turbine cycles significantly improves the overall efficiency of the power plant compared to a standalone gas turbine plant. Figure 5 shows the general scheme of the NGCC power plant integrated with CCS.

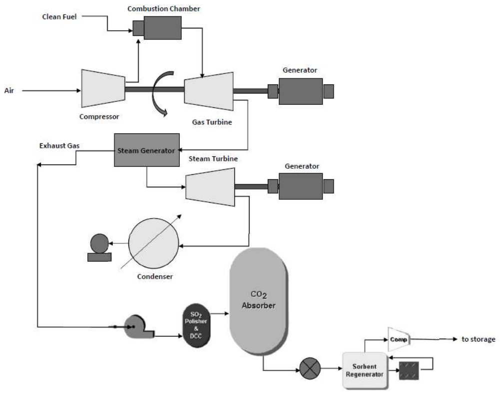


Figure 5. Diagram of the case study NGCC Power Plant with CCS

Table 1 presents a comprehensive summary of the operational parameters of the case study NGCC Power Plant operating at nominal load of 100% with production of steam 110 t/h of heat flow without CO2 capture. This table encompasses critical metrics that characterize the plant's performance, such as the efficiency, and energy utilization. The real data collected from the power plant serves as the foundation for analysis, while measured and simulated data provide insights into the potential outcomes of implementing CCS technology.

TABLE I. SUMMARY OF OPERATING PARAMETERS OF NGCC

Parameter	***Data from the installation***	***Simulation Data***
Gross gas turbine electrical power, MWe	300,0	301,12
Gross steam turbine electrical power, MWe	146,36	133,55
Total gross electric power, MWe	446,36	434,67
Gross power plant efficiency (referenced to LHV), %.	55,18	54,58
Gas turbine gross power generation efficiency referenced to LHV (LHV combustion turbine efficiency), %	-	37,79
Gross power generation efficiency of a steam turbine (steam turbine cycle efficiency), %	38,96	31,04
Gas mass flow rate, kg/s	15,89	15,89

The operational parameters include the gross electrical power from both the gas and steam turbines, as well as their generation efficiency, the gross power plant efficiency, fuel consumption, steam turbine heat rate and gas mass flow rate to the system. These parameters are assessed both in the existing setup and in the simulated scenario with integrated CCS. The modelling is focused on the impact of CCS integration on the plant's operational parameters, particularly focusing on changes in efficiency, energy consumption, and power generation.

The storage assessment covers the examination of two offshore saline aquifers, Block N(B) and Block E, against Sleipner characteristics, using IECM. Within the framework of this thesis, the objective is to provide valuable information to close the loop of the 1 million tonnes of CO2 emissions from the NGCC power plant obtained above 80% capture rate. This involves estimating the CO2 storage potential and identifying a suitable storage site to effectively sequester CO2 back to its original source. It is noteworthy that while aquifers in the Mid-Polish Mesozoic Basin, particularly in the Lower Jurassic, have a higher storage capacity than those in the Baltic Basin, their onshore location and existing constraints have excluded them from the modelling process. Table 2 summarize the model input parameters for Block N(B), Block E, and Sleipner

TABLE II. REFERENCE MODEL INPUT PARAMETERS

Model Parameters	***Unit***	***Block N(B)***	***Block E***	***Sleipner Utsira*** [4, 5]
Area	km2	2200		
Reservoir thickness	m	70	1000	26100
Depth	m	2200	100	200 - 300
Average permeability	mD	50	2060	800
Average porosity	%	10	200	1100 - 5000
Temperature	°C	60	15	27- 42
Reservoir pressure	Mpa	20	55	29 – 35.5

V. RESULTS SUMMARY

A. *Case Scenario for CO2 Capture*

The modelled gas and steam turbines collectively generate a total gross electric power of 446.36 MWe, with a steam flow rate of 110 tons per hour. The process involves varying the proportion of exhaust gas recovery from the plant, ranging from 5% to 100%. The capture process occurs at the MEA unit, maintained at 40 °C and 1.20 bar. Table 3 explain the impact on electricity generation, considering the scenario with CCS.

As the exhaust gas recovery rate increases, the gross power begins to decrease. On average, it drops by 4.27 MW of the electric power allocated for CCS requirements and the NGCC power plant's own needs, resulting in a 1.07% reduction in energy production. This trend becomes more pronounced with higher exhaust gas recovery rates as seen in Table III. For instance, at a 50% recovery rate, CCS requires 17.28 MW of power, causing a 3.96% decrease in gross power, equivalent to 392.87 MW compared to the starting value. Beyond 80% recovery, there's a notable shift in energy consumption for CCS. The average reduction in energy consumption between 5% and 80% recovery is approximately 4.3 MW for CCS. However, from 80% to 100% recovery, this decreases to 1.63 MW or 0.44% reduction in power generation. In general, the total net power with CCS (MW) peaks at 100% exhaust gas recovery, resulting in a decrease of 31.73 MW, with 28.91 MW used by CCS equipment. This represents 6.63% of the total power produced by the NGCC power plant. To put it in perspective, against the initial simulated total gross electrical output of 434,67MW, achieving 100% CO2 recovery from the exhaust gas results in a net output of 363.47 MW, which includes all CCS requirements and auxiliary equipment. This net output dedicated to CO2 capture and own auxiliary equipment accounts for 7.3% of the NGCC power plant's total power production.

TABLE III. Reference Model Input Parameters

Share of exhaust gas recovery	NGCC Own Needs (MW)	Exhaust gas compression to 1.2 bar (MW)	CO2 compression (MW)	Total Electric power for CCS purposes (MW)	Net electrical power with CCS (MW)
5%	2.82	0.86	0.59	4.27	431.35
10%	2.82	1.72	1.17	5.71	427.04
15%	2.82	2.57	1.76	7.16	422.74
20%	2.82	3.43	2.35	8.60	418.45
25%	2.82	4.29	2.94	10.05	414.17
30%	2.82	5.15	3.52	11.49	409.90
35%	2.82	6.01	4.11	12.94	405.64
40%	2.82	6.87	4.70	14.38	401.37
45%	2.82	7.72	5.28	15.83	397.12
50%	2.82	8.58	5.87	17.28	392.87
55%	2.82	9.44	6.46	18.72	388.62
60%	2.82	10.30	7.05	20.17	384.37
65%	2.82	11.16	7.63	21.61	380.12
70%	2.82	12.02	8.22	23.06	375.88
75%	2.82	12.87	8.81	24.50	371.63
80%	2.82	13.73	9.40	25.95	370.00
85%	2.82	14.59	9.98	27.39	368.36
90%	2.82	15.45	10.57	28.84	366.73
95%	2.82	16.31	11.16	30.28	365.11
100%	2.82	17.16	11.74	31.73	363.47

Figure 6, presented on a logarithmic scale, illustrates that the power generation from the gas turbine remains constant at 301.12 MW. Meanwhile, all the energy needed to fulfil the plant's energy-related demands is sourced from the steam turbine. This is particularly notable when considering 100% exhaust gas recovery, where the steam turbine's total energy consumption reaches 31.73 MW.

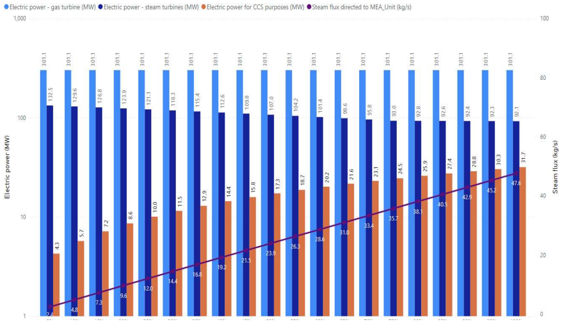


Figure 6. Power and steam used for CCS purposes

To put this in perspective, when compared to the initial conditions, where the gross electrical power of the steam turbine was 133.55 MWe, as indicated in Table I, this energy demand represents 23.4% of the total electrical power. This is equivalent to a steam flow rate of 48 kg/s, which is utilized at the MEA unit for CCS operations.

When examining the power plant data presented in Table I related to the gross power plant efficiency (measured relative to the Lower Heating Value, LHV) in the NGCC power plant simulation stands at 54.58% when operating without CCS. However, when we introduce CCS into the equation, this efficiency metric undergoes notable changes, as depicted in Figure 7. Initially, at a 5% exhaust gas recovery rate, the net efficiency is measured at 55.05%, which represents a decrease of 0.43% compared to the efficiency when no gas recovery is in place. The rate at which the efficiency goes down keep steady at an average of 0.54% every 5% steps of capture rate from 5% until 75%. Remarkably, as the CO2 recovery rate is increased to 80%, there is a change in this trend. The average values decreased from 0.54% to 0.21% per 5% of capture share. Then, as the CO2 capture rate reaches 100%, the final efficiency figure is 46.39%. This signifies an overall decrease of 9.09% in efficiency when CCS is implemented in the NGCC power plant.

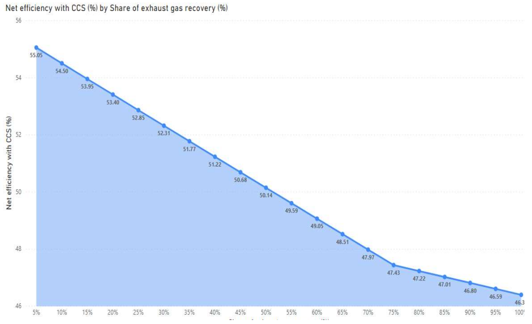
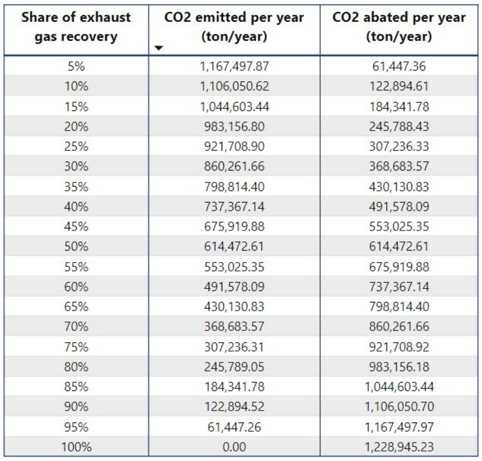


Figure 7. Net efficiency of the NGCC Power Plant with CCS

Related the CO2 emissions, the total modelled exhaust gas stream remains constant at 671.03 kg/s throughout the operation of the NGCC power plant, the flue gas stream is diverted from the chimney and directed to the MEA unit. At 100% of the flue gas flow through the MEA unit, the process yields a pure CO2 stream of 38.97 kg/s out of the 671.03 kg/s of exhaust gases. This value translates to an annual potential CO2 reduction of 1,228,945.228 tons if the amine-based CCS technology, examined in this project, were to be retrofitted at the NGCC power plant case scenario.

In Table IV capture rate starts at a conservative 5%, effectively capturing 61.447,36 tons of CO2 per year. The importance of this capture becomes more evident when the rate reaches 40%, which translates into an annual abatement of approximately 500 kilotons of CO2. However, the true impact takes place at an 80% capture rate, where a substantial reduction of nearly 1 million tonnes of CO2 per year is achieved. This reduction represents a significant contribution to mitigating climate change, particularly within the Polish context, marking an important milestone in carbon abatement within the power sector.

TABLE IV. REFERENCE MODEL INPUT PARAMETERS



Share of exhaust gas recovery	CO2 emitted per year (ton/year)	CO2 abated per year (ton/year)
5%	1,167,497.87	61,447.36
10%	1,106,050.62	122,894.61
15%	1,044,603.44	184,341.78
20%	983,156.80	245,788.43
25%	921,708.90	307,236.33
30%	860,261.66	368,683.57
35%	798,814.40	430,130.83
40%	737,367.14	491,578.09
45%	675,919.88	553,025.35
50%	614,472.61	614,472.61
55%	553,025.35	675,919.88
60%	491,578.09	737,367.14
65%	430,130.83	798,814.40
70%	368,683.57	860,261.66
75%	307,236.31	921,708.92
80%	245,789.05	983,156.18
85%	184,341.78	1,044,603.44
90%	122,894.52	1,106,050.70
95%	61,447.26	1,167,497.97
100%	0.00	1,228,945.23

B. *Case Scenario for CO2 Storage*

Poland has considerable storage potential, as indicated by the assessment conducted in the framework of the EU GeoCapacity project [3]. Unfortunately, current challenges are derived from strict regulations that pose hurdles to the implementation of CCS projects. These regulations are mainly contained in the Law on Geology and Mining, together with ensuing Regulations. This Act delimits the specific regions in which a subsurface carbon dioxide storage site may be located, currently limited to offshore areas as defined in regulations set by the Minister responsible for environmental affairs. Current, this comprises a single depleted hydrocarbon field located within Poland's exclusive economic zone in the Baltic Sea. Although the estimated storage potential in saline aquifers is enormous, it remains largely uncharacterized, estimated at approximately 14,495 Mt and distributed over several structures/sites (I, II, III, IV, V, VI, VII, VIII), as shown in Figure 8, which illustrates the state of knowledge on CO2 geological storage possibilities in Poland [4].

Figure 8. Possibilities of CO2 geological storage in Poland [4]

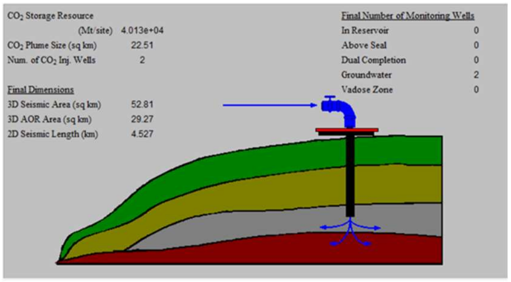
Hence, the legislation restricts usable storage sites to zone VIII, which covers only the Łeba-Baltic Sea region, including offshore areas. This limitation mainly concerns the CO2 emission potential of the northern parts of the country [5].

In Zone VIII, the primary aquifer is the Cambrian, extending across both offshore and onshore areas. The Cambrian reservoir represents the base of the Baltic Basin sedimentary infill. The reservoir consists of quartz sandstones with underlying siltstones and shales. In terms of hydrocarbon fields suitable for CO2 storage, the only offshore oil field currently identified for this purpose is the depleted B3 field (74.12% recovered reserves) of the middle Cambrian, located about 70 km north of the northernmost part of the Polish coast within the exclusive economic zone in the Baltic Sea and operated by LOTOS Petrobaltic. The estimated storage capacity of the B3 field is 7.0 Mt. 64. Regarding offshore saline aquifers, Table II outlines the parameters for two structures situated in sector VIII within the Middle Cambrian formation with larger storage capacity, Block N(B) and Block E. Therefore, CO2 storage within saline aquifers is the optimal choice in the Baltic Basin, given its large capacity compared to hydrocarbon fields.

Hence, the Sleipner project stands out as one of the most compelling examples of CCS technology. It has proven the feasibility and safety of geological storage of CO2 in saline aquifers. It therefore serves as a key reference for the implementation of CCS in Poland in the offshore Baltic Sea area and plays a crucial role in the country's efforts to reduce CO2 emissions from industrial and energy operations.

For all cases, a uniform storage coefficient of 2.6%[6] was defined, as per the technical report conducted by the IEA Greenhouse Gas R&D Program for carbon dioxide storage in deep saline formations. Additionally, the average injection rate was standardized at 1 Mt CO2 per year, aligning with the CO2 recovery share of 85%, as obtained from Table IV.

Based on the CO2 storage capacity findings derived from the specified properties for Sleipner, Figure 9 illustrates that approximately 40,130 Mt of CO2 can be effectively stored in the reservoir. This entails the deployment of a minimum of two CO2 injection wells to accommodate a plume size of 22.51 km².



CO_2 Storage Resource (Mt/site) 4.013e+04
CO_2 Plume Size (sq km) 22.51
Num. of CO_2 Inj. Wells 2

Final Dimensions
3D Seismic Area (sq km) 52.81
3D AOR Area (sq km) 29.27
2D Seismic Length (km) 4.527

Final Number of Monitoring Wells
In Reservoir 0
Above Seal 0
Dual Completion 0
Groundwater 2
Vadose Zone 0

Figure 9. CO2 Storage Diagram for Sleipner

In relation to Block N(B) and Block E, Figures 10 and 11 depict that, based on the properties used, these offshore aquifers have the potential to store 367 and 360.9 Mt of CO2, requiring 3 and 2 injection wells, respectively. The size of the CO2 plume for Block N(B) is 204.8 km², while for Block E, it is 94.51 km².

The plume size for the Baltic Sea aquifers is significantly higher than that for the North Sea one, attributed to the smaller size of the storage area for the Baltics.

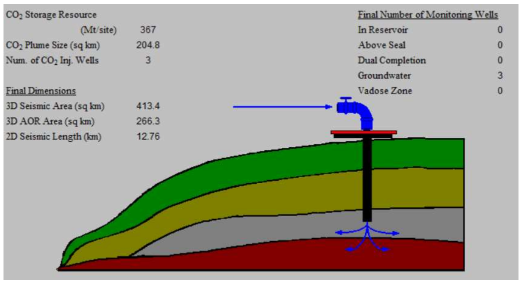


Figure 10. CO2 Storage Diagram for Block N(B)

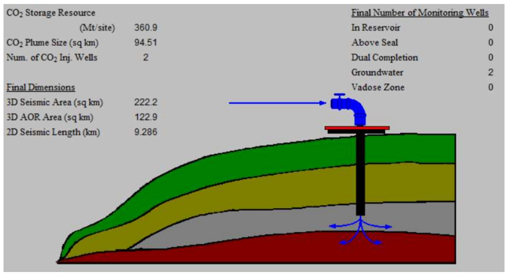


Figure 11. CO2 Storage Diagram for Block E

VI. CONCLUSIONS

The integration of CCS technology impacts the NGCC Power Plant's operational parameters, particularly in terms of efficiency, energy consumption, and power generation. CCS technology comes with increased energy demands, primarily for the capture and compression of CO2. The energy-intensive nature of CO2 capture presents a notable challenge. As the CO2 recovery rate increases, the net efficiency of the power plant decreases. Specifically, at a 100% CO2 recovery rate, the overall efficiency decreases by 9.09%. This reduction in efficiency is primarily attributed to the energy requirements of CCS operations, underscoring the trade-off between reducing emissions and maintaining energy efficiency. It is advisable to set the capture rate for the NGCC at a level higher than 80%, as there is no significant impact on efficiency beyond this threshold.

Regarding storage capacities, the Baltic Sea area in Poland holds promising potential to develop into a significant CCS complex. Such a complex could play a pivotal role in capturing CO2 emissions from industrial facilities and transporting them to offshore storage sites for permanent containment, mirroring successful models like The Northern Lights CCS project in Norway. However, a comprehensive exploration of the potential and conditions for geological storage in the Baltic Sea Region requires a cooperative effort with other nations sharing this area of interest. Establishing a fundamental regional network of CCS is essential, as it has the potential to collaboratively drive the deployment of CCS initiatives. Notably, on the Polish side of the Baltic Sea Area, the presence of Paleozoic sedimentary basins and Cambrian reservoirs, located deeper than 800m below the seabed, presents promising candidates for CO2 storage sites and, there are also offshore facilities in this region, such as those of LOTOS Petrobaltic S.A., which could potentially be used to develop CCS projects.

One of the most significant barriers to the widespread deployment of carbon capture technologies is the high associated costs, particularly in terms of equipment and energy required for the capture and compression phases of CO2. Therefore, integrating CCS projects in industrial clusters, including sectors like steel manufacturing, cement production, hydrogen and petrochemicals, becomes advantageous. In pursuing this initiative, attention should extend to critical aspects such as evaluating public communication and community acceptance, as well as harmonizing legal frameworks and regulations to facilitate efficient operations and compliance. These considerations can significantly favor the establishment of industrial CCS hubs and clusters, leading to a noteworthy reduction in the unit cost of CO2 storage through economies of scale. Moreover, such integrated projects offer commercial synergies that effectively mitigate investment risk playing also a strategically role in reducing CO2 emissions within the power sector in Poland.

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