Carbon Sequestration in Unmined Coalbeds of Pakistan

Osama Ajaz*, LMK Resources Pakistan (Pvt) Limited, Islamabad, Pakistan; **Saleem Qadir Tunio**, Cyrpus International University, Nicosia, North Cyprus; **Jahangeer Zafar**, United Energy Pakistan Limited, Karachi, Pakistan

Abstract

Exponential increment in carbon dioxide (CO_2) emissions into the atmosphere has become a serious threat to global security. Many reports concluded that maintaining <2ºC is mandatory to avoid severe consequences associated with the environment and global warming. Pakistan is indexed in a region of high vulnerability to climate change. Thus, the country has faced severe reflection of the deteriorated environment in terms of drought, floods, and uncertain climatic conditions. The country's recent development has increased emissions as many power plants are being run on coal. It implies that significant efforts must be made to emphasize limiting emissions and environmental damage. Carbon storage technology is a way forward for continuous utilization of fossil fuels. Coalbeds ensure secure storage of CO_2 for long term. Carbon storage in subsurface beds will minimize the ongoing greater impact on environment of Pakistan. Thar Coalfield offers great potential for CO_2 storage due to the largest reserves in the country. This study contributes towards further steps needed for practical implementation of carbon capture and sequestration in Thar coalfield. The analogy among different coal sites for carbon storage was drawn to project potential of Thar coalfield along with other coalfields in Pakistan. Thar coalfield properties, being lignite in rank, resemble North Dakota coalfield, whereas some properties resemble Rajasthan coals. Hence, North Dakota coalfield and Rajasthan can be effective reference projects for practical implementation of CO_2 storage in Thar coalfields. The research study has recommended further directions for study to calculate exact amount of CO_2 storage. The study was concluded with the future implication of potential carbon storage in the coalfield of Thar.

Introduction

Rising greenhouse gas concentrations in atmosphere are causing a rapid increase in average temperatures globally. Evidence shows that global surface temperature rose 0.6U±0.2ºC over the 20th century (Balat and OZ 2007). The environment model projections suggest that temperature will rise sharply in the next century and this could go beyond 2ºC. To avoid such an increment in temperature, Intergovernmental Panel on Climate Change (IPCC) has stated that greenhouse gas (GHG) emissions should be reduced to 80% by 2050 (Li et al. 2019). Primarily CO_2 is responsible for alteration in environment and global warming (Nunes 2023). Among current viable mitigation environmental strategies, carbon capture gathered many interests of experts and policymakers that could enable the continuous use of fossil energy. Carbon sequestration with advanced technologies causes low (or almost zero) emissions into environment. Countries should emphasize this low emission to contribute to reaching a temperature of less than 2ºC by 2050.

Besides furnace oil, Pakistan's power sector has been relying on natural gas (having the lowest carbon intensity), and a lower fraction of coal (highest carbon intensity) for the purpose, which is in utter contrast to energy consumption for electricity generation worldwide. Thus, Pakistan has been a lesser contributor to CO_2

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*Corresponding author: osamaajaz99@gmail.com

emissions. However, modern life have changed fuel-type preferences and Pakistan has no alternative but to utilize only sizable coal reserves of 185 billion tons to meet increasing energy needs. Since coal is a high carbon-intensity fuel as shown in **Figure 1**, so emissions have drastically increased, as shown in **Figure 2**. The country's vulnerability to the effects of climate change is well documented and recognized. Over the last decade, repeated periods of extreme weather had a negative impact on the country's economic growth.

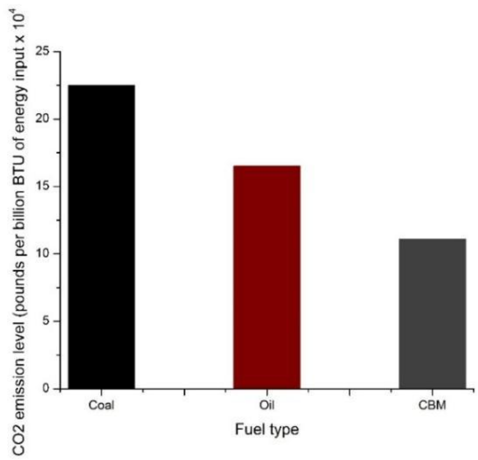

Figure 1—Carbon dioxide emissions for different fossil fuels (Carbon Dioxide Emissions Coefficients 2023).

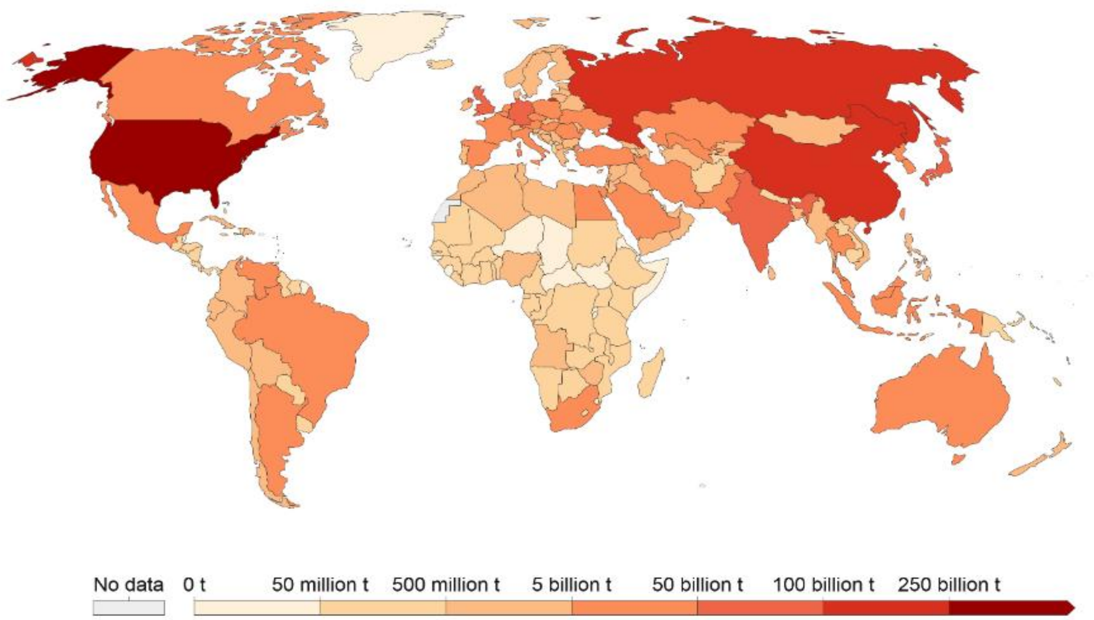

Figure 2—Annual CO_2 emissions from burning fossil fuel and cement production since 1970 (Our World in Data 2024).

Clean coal technology is a viable approach to adopt for medium-term planning in order to mitigate carbon emissions which are continuously on the rise. The creative energy and environmental framework design may help in reducing GHG emissions along with meeting energy demands. CO_2 capture extracted from different large-scale firms and deposited far below the ground provides a unique design and is widely adopted for the purpose. This prevents and eliminates a larger fraction of CO_2 exposure to the environment.

Carbon capture and storage appears to be a workable choice for removal of 50-85% of GHG emissions by 2050 (Shukla et al. 2020).

Role of GDP in CO_2 Emissions

Energy intensity is calculated on energy consumption per unit of GDP. This derives a direct relationship between energy use and CO_2 emissions. Higher CO_2 emissions reflect greater use of fossil fuel energy. CO_2 emissions and GDP are related as (Balat and OZ 2007),

$$CO_2 \text{ emissions} = \text{GDP} \times \text{Energy consumption per unit GDP} \times CO_2 \text{ emissions per unit energy consumption.} \quad (1)$$

The relation implies that a country having a higher GDP leads to higher CO_2 emissions, whereas developing countries tend to increase emissions with a higher GDP. To meet demands, electricity generation potential is being expanded in Pakistan and many plants are consuming coal as fuel.Thus, emissions are on the rise. This situation could lock the country into a carbon-intensive region due to emissions from coal. Whereas, increasing GDP guarantees the development of the country. Pakistan, like any other developing countries, tends to increase GDP, as shown in **Figure 3**, which results in increasing emissions as shown in **Figure 4**.

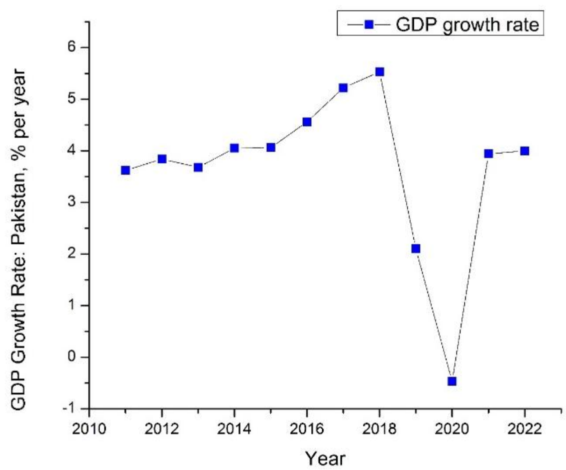

Figure 3—GDP of Pakistan over years (The World Bank 2024).

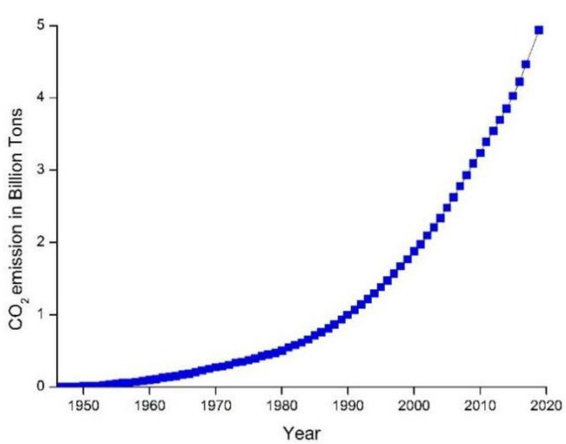

Figure 4—Cumulative CO_2 emissions from burning fossil fuel since 1970 by Pakistan (Our World in Data 2024).

Carbon Capture and Sequestration

Carbon capture and sequestration (CCS) technology is an important portfolio option in mitigating atmospheric greenhouse concentrations. The process consists of CO_2 capture from energy-related sources mainly power plants, cement plants, steel mills, and refineries. The captured CO_2 is then transported to storage sites and thus isolates CO_2 from the atmosphere in the long term. The capture and storage site should be near enough to minimize costs.

CO_2 Capture. CO_2 can be captured by any of the following technologies (Sifat and Haseli 2019):

1. Pre-combustion: CO_2 and hydrogen are separated from the primary fuel in a shift reaction. This hydrogen can be used as a fuel.
2. Oxy-fuel combustion: Oxygen is used for combustion instead of air for producing CO_2 and H_2O, after which water vapor is condensed and CO_2 is captured.
3. Post-combustion: It captures CO_2 combustion of a primary fuel in air.

CO_2 Storage. Following the capture process, CO_2 is stored underground so that it will remain stored preferably for hundreds to thousands of years. By this way, CO_2 is prevented from being exposed to the atmosphere. The geological structure must have the ability to contain CO_2 over a long period. **Table 1** shows international treaties that come into force for the geological storage of CO_2.

Table 1—International treaties for consideration of geological CO_2 storage 9 (Metz 2005).

Treaty	Adoption (Signature)	Entry into Force	Number of Parties/ratifications
UNFCCC	1992	1994	189
Kyoto Protocol (KP)	1997	2005	132*
UNCLOS	1982	1994	145
London Convention (LC)	1972	1975	80
London Protocol (LP)	1996	No	20* (26)
OSPAR	1992	1998	15
Basel Convention	1989	1992	162

*Several other countries have also announced that their ratification is under way.

There are differences in the physical features of oceans, geological formations, saline aquifers, and mineralized solids for the retention of CO_2. There could be a chance that injected gas leaks or is exposed to surface depending upon the subsurface structure. The amount of CO_2 stored over time interval is given by (Balat and OZ 2007):

$$\mathrm{CO_2\ stored} = \int_0^T \left(\mathrm{CO_2\ injected}(t) - \mathrm{CO_2 emitted}(t)\right)dt, \quad (2)$$

where t is time, and T is length of assessment time period.

Economics of CCS. The vital consideration for implementing CCS is the cost. The cost of capturing carbon depends upon the capturing mechanism, which is being optimized with the developments made in technology. The storage and monitoring are based on the geologic area, in which CO2 is injected for storage. However, transportation costs can be eliminated from the process, when the capture and storage sites are near or in the same area. This greatly reduces the whole cost. The cost of CCS, therefore, consists of (Balat and Oz 2007):

$$C_{ccs} = C_{capture} + C_{tranportation} + C_{storage} + C_{monitoring}, \qquad (3)$$

Capturing CO_2 from the power plant at Thar coalfield and then injecting it into the coalbed would reduce overall cost for CCS.

Potential Storage Sites

International treaties endorsed geological sites as reliable places for CO_2 storage. Following are underground formations that could be used for CO_2 storage,

1. Saline formations
2. Oil and natural gas reservoirs
3. Unmineable coal seams
4. Organic-rich shales
5. Basalt formations

Coalbed seams could be abandoned due to many reasons including unmineable, inadequate technology, and government policies. However, this geological formation shows great potential to storage great amounts of CO_2 depending upon the depth and rank of coal. There needs comprehensive study including pilot tests to evaluate the exact potential of coalbed to store CO_2.

Thar Coalfield–Pakistan Largest Potential Sequestration Site

Thar coalfield reserves account for 175 billion tons over a single geological area, as shown in **Figure 5** and **Table 2** in Appendix I. The coal reflects a high volatile rank of lignite B type. Tharcoal offers the largest site of CO_2 storage in the country. Coal shows potential sites for geological storage in a way that it has a greater affinity towards CO_2. Due to this, there are lower or no chances of leakage to the atmosphere even at lower depths, if coal remains undisturbed after CO_2 storage.

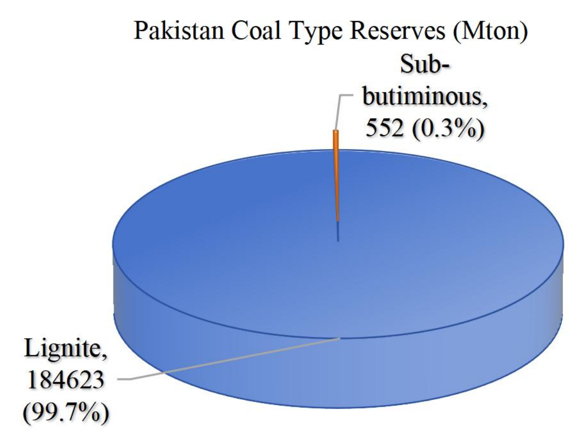

Figure 5—Coal type reserves in Pakistan (Data Collection Survey on Thar Coal Field in Pakistan: Final Report. 2013).

Although lower-rank coals show less CO_2 adsorption capacity as compared to higher ranks (Li et al. 2022), coal seams present a great amount of CO_2 that can be stored in large available areas. **Figure 5** shows dark coal (high rank) shows better adsorption capacity than brown coal (low rank). Coal micro pores contain around 98% of CO_2 as an adsorbed phase, whereas the rest exists as free gas in cleats (Perera et al. 2012). Hence, this stable storage phenomenon neglects the idea of back migration.

The CO_2, after reaching the coal seam layer, occupies the spaces around cleats and adorbs onto to coal surface. This action of CO_2 displaces any gas residing previously in cleats (Li et al. 2022). The cleats provide the means of CO_2 flow in the extended section of the seam.

The Tharcoal field, comprising several blocks and having different properties, shows variations in carbon storage potential depending upon the characteristics of a block, as shown in **Figure 6**. After an initial assessment of data and properties, blocks show storage potential for CO_2 correspondingly. It is pertinent that all blocks cannot be assigned for storage, however, blocks showing greater potential could be allocated for the purpose. Similarly, considering whole Thar coal reserves as not feasible for mining smaller parts or sections could be dedicated to mitigating the environment.

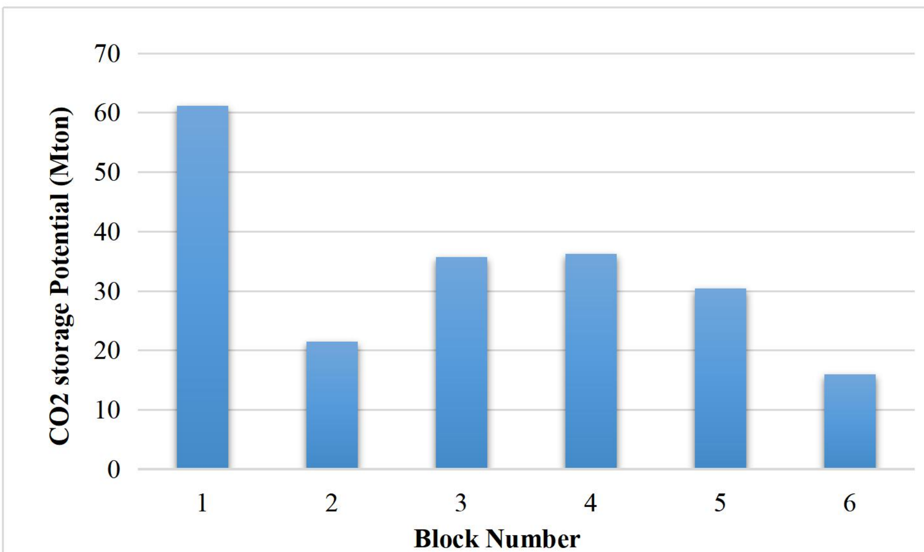

Figure 6—Block wise CO_2 storage potential in Thar Coalfield (Zahid 2017).

Analogy among Coalfields

Since no detailed studies have been carried out on carbon storage in the Thar coalfield, an analogy using given data from the world's numerous fields is drawn to estimate possibilities. The data analogy focuses on Thar coalfields along with other potential coalfields in Pakistan for CO_2 storage. However, due to the largest reserves, Thar coal is highlighted in this paper. The available data on properties relevant to carbon storage are discussed in **Table 3**.

Effect of Ash Content. CO_2 sequestration potential decreases with increasing ash content. The adsorption content is also one of the important parameters in deciding the pore volume of coal. Higher ash content reduces the adsorption capacity of methane, which leaves a significant part of methane present in cleats. This presence of methane restricts the addition of any phase onto the coal surface. Due to this reason, only a small amount of CO_2 can fill up the space available in cleats of coal. The ash content of Tharcoal resembles with North Dakota coals, shown in **Figure 7**.

Table 3—Analogy among Pakistan's largest coalfields with world's CBM coalfields.

Country	Pakistan (Harpalani and Schraufnagel 1990)			India (Prabu and Mallick 2005)	China (Yu et al. 2007)	Australia (Victorian brown coals) (Bachu et al. 2005)			Japan (Yamaguchi et al. 2005)	United States (Hares 1928)
Project	Thar coalfield	Lakhra	Sondha-jerruk	Rajastan	Northeast	Otway	Gippsland	Murray	Ishikari	North Dakota (Lignite)
Ash Content, %	2.90-11.50	4.30-49.00	2.70-52.00	15.5	11.62	4	4.4	10.8	3.62	9
Moisture content, %	29.60-55.50	9.70-38.10	9.00-48.00	41.5	35	44	51.7	56	0.87	32.17
Fixed Carbon, %	14.20-34.00	9.80-38.20	8.90-58.80	19	52.04	66	66.7	61	N/A	65.6
Depth, m	120-200	80-450	1-85	450 (avg.)	N/A	N/A	N/A	N/A	890 (avg.)	335
Estimated CO_2 storage , $MtCO_2$	200.7	N/A	N/A	0.552	2862.92	N/A	N/A	N/A	480	10.3

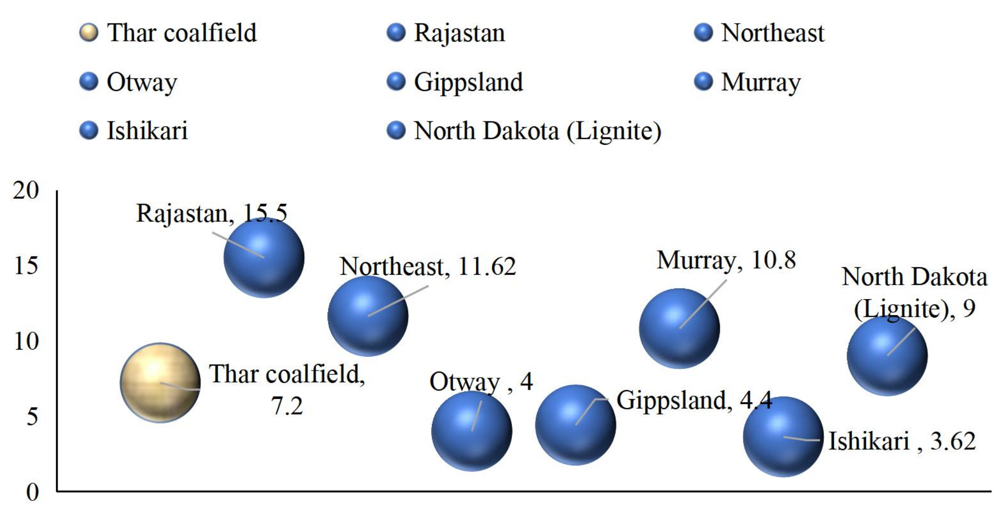

Figure 7—Ash content of different coalfields.

Effect of Moisture Content. The higher moisture content of coal decreases carbon storage potential. This is due to the presence of water restricting the entrance of CO_2 within cleats. Also, the CO_2 flow rate decreases, with increasing injection pressure, due to the swelling of cleat structures (Zhang et al. 2023). The data of different coalfields shows that higher moisture coal has a lower volume for CO_2 sequestration. Lignite coals of North Dakota show a similarity of moisture content with Thar coals, shown in **Figure 8**. North Dakota field (USA) presents lower storage, which corresponds to lower carbon storage in the Thar coalfield.

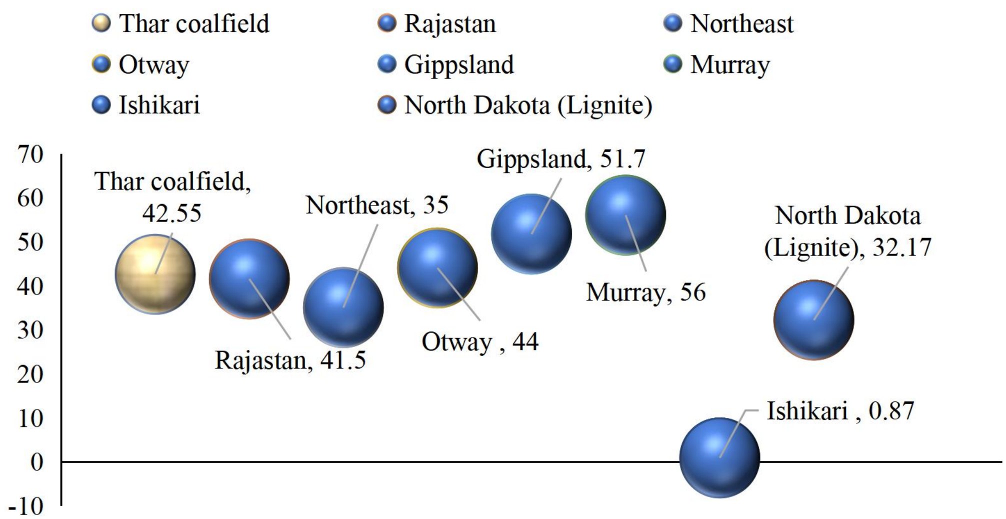

Figure 8—Moisture content of different coalfields.

Effect of Carbon Content. Carbon content is related to the rank of coal. The higher-rank coals show more CO_2 storage potential than that of lower rank (Li et al. 2022). The data in **Table 2** shows higher carbon ensures greater carbon sequestration. **Figure 9** shows Rajasthan coalfield carbon content provides better similarity than the others in Table 2.

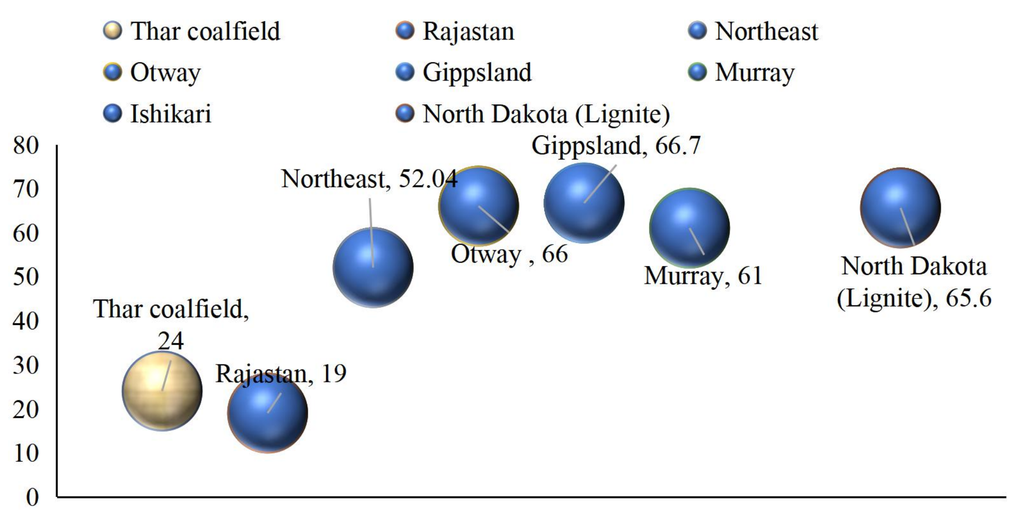

Figure 9—Carbon content of different coalfields.

Critical Analysis

Pakistan, being among the most affected countries by global warming, has to take initiatives towards minimizing emissions of GHG to let its inhabitants survive. The country's fragile economy does not allow lower its GDP and development for the sake of emissions. Carbon sequestration in coalbeds provides a way forward and a win-win position for the cause. The CO_2 occupies the space and displaces methane gas from coalbeds hence making it enhanced coal bed methane (ECBM) recovery. Methane recovery depends upon the properties of coal and eventually offsets the cost of CO_2 storage. **Figure 10** illustrates the process of CO_2 injection and CH_4 (methane) production from coal seams.

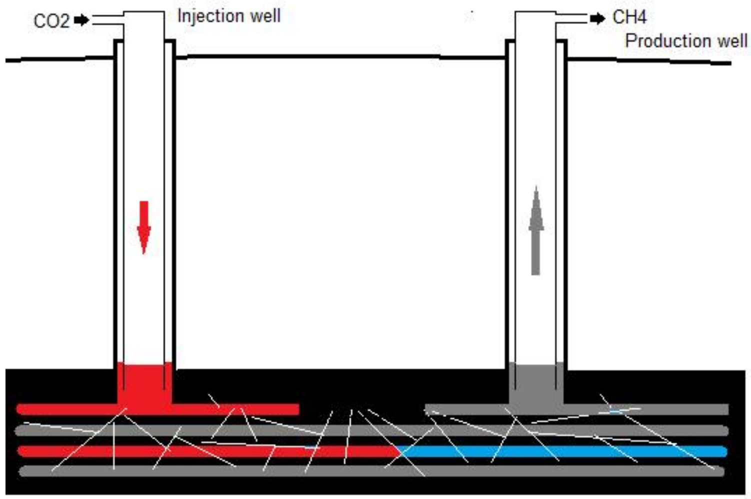

Figure 10—Vertical well showing CO_2-ECBM recovery.

The uncertain and unpredictable nature of climate change poses an added challenge to policymakers who are tuned to make decisions based on historical and known denominators. The climate change challenge that we are facing could be turned into a new opportunity based on cleaner technology and a low-carbon economy. The country needs to start planning for its long-term implementation.

For reliable calculation of storage capacity following methodology may be employed:

1. Calculate the coal mass available for CO_2 storage for each field.
2. Based on experimental investigation, calculate the average CO_2 mass storage per tonne. Many coalbeds at different depths should be studied for this. To obtain the best possible storage mass of CO_2.

Conclusions and Recommendations

Increasing emissions are part of the progress of developing countries. The emissions associated with coal consumption can be prevented from damaging the environment. Since many coal power plants were built near coalfields, this significantly reduces the cost of transporting CO_2 for storage. Also, the carbon storage process in coalbeds depends upon several factors, including coal mass, coal permeability, gas desorption, and adsorption. The properties of Thar coalfield provided similarities as Rajasthan and North Dakota coalfields. The features of these two projects could help in the practical implementation of carbon storage in Thar coals.

The concept of clean coal technology should be implemented keeping a view of a low-carbon economy. Besides of passive strategies of planting trees, Pakistan should take aggressive steps to reduce up to 20% of projected GHG emissions by 2030, as ratified under the Paris agreement. Current technologies need to cater according to conditions to apply lignite coals of Thar coalfields. However, the following challenges are coming across, which delay or prevent practical applications,

1. Lack of knowledge of coal seam permeability before CO_2 sequestration.
2. Extensive laboratory tests are to be carried out for samples of lignite (Thar coalfield) for calculation of adsorption, and desorption at different depths.
3. Post-CO_2 storage risk assessment studies, economic optimization studies, project-screening models, etc. are to be carried out.

The following sequence was proposed for maximum sequestration in given coalbeds.

1. Water production stage: producing water will leave space for other fluids to adsorb onto coal.
2. Gas production stage: Unloading of water allows gas to flow towards the wellbore. This gas production will increase empty spaces in the cleat/pores of coalbeds.
3. CO_2 injection: After the creation of empty spaces due to gas flow, more spaces are held in pores/cleats for CO_2 storage.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

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Osama Ajaz is working under the capacity of Petroleum Engineer with Landmark Resources Pakistan (Pvt) Limited. He holds B.E and M.S. in Petroleum Engineering. His research areas include drilling engineering, artificial lifting methods, enhanced oil & gas recovery, and engineering aspects of carbon storage.

Saleem Qadir Tunio is serving as Assistant Professor at faculty of Engineering, Cyprus International University. He obtained his B.E in Petroleum and Natural Gas from Mehran University of Engineering and Technology, M.S in Petroleum Engineering from The University of Adelaide, Australia, and holds Ph.D.in Petroleum Engineering from Universiti Teknologi Petronas (UTP), Malaysia. He has expertise in the areas of unconventional hydrocarbons and enhanced hydrocarbons recovery.

Jahangeer Zafar is working under the capacity of Petroleum Engineer with United Energy Pakistan Limited. He holds B.E and M.S. in Petroleum Engineering. His research areas include production engineering, well testing, and enhanced oil & gas recovery.

Appendix I

Table 2—Coal reserves in Pakistan (Data Collection Survey on Thar Coal Field in Pakistan: Final Report. 2013)

Province	Location	Quantity (Million Tones)	Type	Moisture content (%)	Ash Content (%)	Heating Value (Btu/lb)	Fixed Carbon (%)
Sindh	Thar	175,506	Lignite B-A	29.60-55.50	2.90-11.50	10723-11353 (dry basis)	14.20-34.00
	Lakhra	1328	Lignite -A	9.70-38.10	4.30-49.00	5503-9158	9.80-38.20
	Sondha-Jherruch	5523		9.00-48.00	2.70-52.00	5219-13555	8.90-58.80
	Meting-Jhimpir	473	Lignite	Data not available			
	Indus East	1777					
	Badin	16					
Total	**184,623**						
Baluchistan	Sor-range/Degari	50	Sub-bituminous	3.90-18.90	4.9-17.20	11245-13900	41.00-50.80
	Khost/Harnai/Ziarat	88		1.70-11.20	9.30-34.00	9637-15499	25.50-43.80
	Mach	23		7.10-12.00	9.60-20.30	11110-12937	32.40-41.50
	Duki	56		3.50-11.50	5.00-38.00	10131-14164	28.00-42.00
Total	**217**						
Punjab	Salt-range	213	Sub-bituminous	3.20-10.80	12.30-44.20	9472-15801	25.70-44.80
	Makarwal	22		2.80-6.00	6.40-30.80	10688-14029	34.90-44.90
Total	**235**						
KPK	Cherat	9	Sub-bituminous	0.10-7.10	5.30-43.30	9386-14217	21.80-76.90
	Hungu	82					
Total	**91**						
AJK	kotli	9	Sub-bituminous	0.20-6.00	3.30-50.00	7336-12338	26.30-69.50
Total	**9**						
Total Pakistan		**185,175**					