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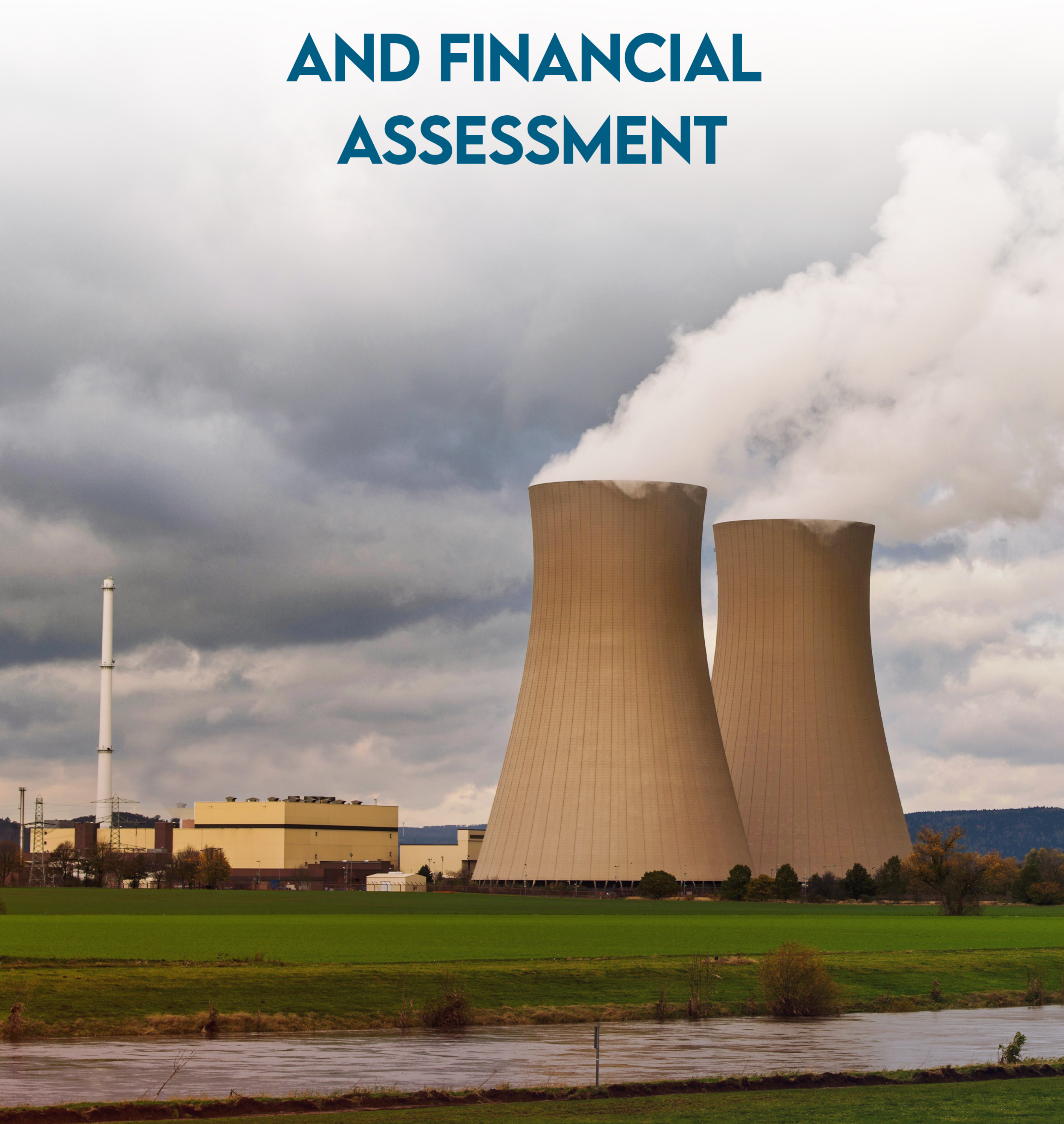
TURNING THAR COAL INTO GAS
A TECHNICAL ECONOMIC AND FINANCIAL ASSESSMENT



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Foreword

Coal gasification and coal liquefication technologies have been around since the 18th century but their success at a commercial scale without state subsidies remains doubtful even today. Their supporters argue that they reduce the use of both coal and water in energy production processes and, therefore, are relatively less harmful for the environment than the technologies that produce energy directly from coal. Their critics allege that coal gasification and coal liquefication technologies are too complex to be operated smoothly. For one, they are much costlier than other comparative technologies and often require operations and maintenance budgets way higher than those required by direct combustion of coal for power generation. Their supposed environmental benefits are also illusory because their carbon emissions are found to be quite high.

In Pakistan's case, the idea of gasifying and liquefying coal has been around since the early 2000s. In the latter part of that decade, Dr Samar Mubarakmand, a nuclear scientist, embarked on materializing that idea. A pilot project was set up in the desert region of Thar, where the bulk of Pakistan's coal is found, to gasify coal underground. Several years later, and after an expenditure of around 10 billion rupees, it was abandoned on grounds of being commercially and environmentally infeasible.

In more recent times, the idea of gasifying Thar coal has surfaced again, this time round as a means for urea fertilizer manufacturing. The technology's proponents argue that, being an agricultural country with a huge, and rapidly increasing, population to feed, Pakistan must use its vast domestic coal reserves to produce cheap fertilizer to boost agricultural productivity and ensure food security. This argument is based on the premise that other sources of manufacturing fertilizer – local natural gas and imported liquefied natural gas (LNG) – are either running out or have a price tag that local fertilizer industry cannot afford without raising its consumer prices in a big way.

Driven by these arguments, the Sindh Coal Authority engaged South African experts in 2024 to carry out a study on the technical feasibility of gasifying/liquefying Thar coal for use in a variety of applications including fertilizer manufacturing, steel making and diesel production. The study claims that Thar coal is suitable for both gasification and liquefication and may even be economical compared to its imported alternatives.

There is no denying the theoretical, even technical, feasibility of coal gasification/liquefication though its commercial viability varies from region to region, depending upon the availability of state support and the quality of technology employed. It is, indeed, clear from many examples from across the world that the use of coal gasification/liquefication has never been driven by technological, economic and environmental considerations but by other – strategic or national – factors.

Case studies from around the world illustrate that state has to intervene at every step of this technology to keep it going. For instance, China -- where gasified coal caters to 3-5 percent of the country's total natural gas consumption – uses a variety of subsidies within its synthetic natural gas (SNG) value chain to make the end products competitive with other available alternates. Chinese energy companies, which are often state-owned, receive vast amounts of capital subsidies. They also face lower barriers to entry in the market than their private sector competitors, having to spend much less money on land purchases and enjoying exclusive mining rights while setting up new projects. Chinese government also guarantees that their products are purchased so that their revenue streams do not dry up and they remain financially viable.

Research also indicates that China's coal production industry receives upwards of 2 trillion US dollars in subsidies every year. The benefits of these subsidies extend to the coal gasification/liquefication industry as well, mainly through the artificially low prices of its process inputs. Some researchers estimate that China's coal to liquids (CTL) industry received almost 2.3 billion US dollars of state support in 2022. This subsidy resulted in an almost 50 percent reduction in its coal consumption cost.

South Africa offers a similarly instructive example. Coal liquefaction technology gained traction in that country in the 1970s to preserve its energy security as it faced an international oil embargo due to its apartheid regime. Consequently, a state-owned company, Sasol, was created to convert vast local reserves of coal to diesel and other liquid fuels/petroleum products.

A 2020 study conducted by the International Institute for Sustainable Development reveals that Sasol is being kept afloat by two major forms of state subsidies: a market price support, which provides import price parity to domestic fuel production, and an exemption from the carbon tax regime on 90 percent of its emissions. In 2012-2019, Sasol received 1 billion US dollars in market price support alone. Similarly, the combined value of the carbon tax exemption and market price support it received only in 2019 is estimated to be 490 million US dollars. Despite the provision of these massive amounts of money, Sasol has often reported huge losses on its books and was forced to write-down the value of its Secunda coal to liquids facility by 1.9 billion US dollars in August 2023.

Same is the case in the United States. North Dakota coal gasification facility, the only large-scale operational coal gasification program in that country, is often presented as a commercial success story but it has had its fair share of financial troubles. It has also received regular injections of state subsidies to support its operations.

Built at a cost of 2 billion US dollars in 1980 through a federal construction loan, it produced gas at a price that could not compete with that of other fuels due to the declining oil and gas prices in the global market. The facility, therefore, ran in loss consistently till 1986. That year, the US Department of Energy stepped in and bought it at a discounted price of 1 billion US dollars. Its investors lost all their equity as a result of that deal. Later, the facility was acquired by another company that retrofitted it to produce other liquid fuels, urea/fertilizer and carbon dioxide to improve its economic feasibility.

Another facility in the United States, Kemper County coal to clean project, was eventually dismantled in 2017 after facing complexities in conversion of coal to natural gas for power generation. It also suffered cost overrun of 4 billion US dollars.

Across the border in India, much like Pakistan, coal gasification is being viewed as a means of getting maximum value out of domestic coal reserves to improve and preserve food security. India, too, is offering up to 1.1 billion US dollars in capital subsidies to the investors setting up coal gasification plants.

A common theme can, thus, be seen in all these projects: state intervention is vital to keep coal gasification/liquefication projects afloat and ensure that their end products retain market competitiveness. So, regardless of whether gasified/liquefied coal is used for energy generation or for other purposes, including fertilizer manufacturing, its commercial viability remains a strong and serious concern.

Pakistan's plans for coal gasification might face several additional problems. Given the country's low credit rating and rocky relationship with foreign investors, it is highly doubtful that it can attract private investment worth several billion dollars required to gasify Thar coal. Consequently, these plans will require the use of China's state funding (but on commercial terms, just like all the funding under the China Pakistan Economic Corridor has been) and Chinese technology even to take off the ground. If nothing else, financing on such terms will result in an increase in Pakistan's sovereign debt – heightening its already debilitating financial burden.

The gas pricing formula for these plans also leaves a lot to conjecture. The Sindh Coal Authority claims that 8 US dollars will be required to produce one million British thermal units (mmbtu) of synthetic natural gas from Thar coal. This price is subject to debate on several counts. Firstly, it cannot be cross-verified because it is based on several hidden assumptions and un-disclosed financial details. Secondly, the estimated price of 8 US dollars/ mmbtu for gasified Thar coal is certainly less than what it costs to import Liquefied Natural Gas (LNG) but Pakistan's fertilizer industry is used to consuming domestic natural gas at a much lower and highly subsidized rate. Only recently has this price been jacked up to 5 US dollars/mmbtu from 1 US dollar/mmbtu (where it had stood for several decades). This suggests that any price above 5 US dollars/mmbtu will lead to a big increase in fertilizer prices, ultimately resulting in food inflation.

Even when we are somehow willing to put aside all the economic and financial consideration mentioned above, carbon dioxide emissions from a coal gasification/liquefaction project will be too high to overlook. Evidence from other countries shows that these emissions could be significantly higher than those from other energy projects. To cite just one example, Sasol's Secunda coal liquefaction and liquid fuel manufacturing facility is the world's largest single-point emitter of carbon dioxide. It emitted over 64,000 kilotons of carbon dioxide in 2023 alone. Similarly, estimates by the Natural Resources Defense Council (NRDC), a non-profit organization based in the United States, put carbon dioxide emissions from the combustion of each gallon of liquid fuel produced from coal at 55 pounds. This is twice the amount of carbon dioxide released from the burning of conventional gasoline.

If Pakistan's coal gasification plans materialize, they will certainly worsen its carbon emissions profile, effectively derailing its climate goals and ambitions. Also, despite its desire – and also the need -- for energy independence, Pakistan does not have any financial space to offer massive subsidies that coal gasification/liquefication facilities require to keep their products – including synthetic natural gas and its derivatives – competitive.

So, in essence, whether the end product to be obtained from gasified coal is electricity or fertilizer, the problems involved in the process are so many that they require a deep and thorough analysis. This research study is only a first, and a small, step in that direction.

Admittedly, this study does not cover all the above-mentioned aspects of coal gasification/liquefication. Due to funding limitations and time constraints, it has focused only on whether producing electricity form gasified coal is cheaper and cleaner than producing electricity directly from coal and from solar panels. Its findings are unsurprising: coal gasification is highly costly and its carbon emissions are so high that they require the addition of carbon capture, utilization and storage (CCUS) technologies to become environmentally sustainable. The fact that the cost of carbon capture storage and utilization technologies is extremely high makes coal gasification plans prohibitively expensive. Pakistan's poor economic situation will make such a project even more unattainable.

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Executive Summary

Techno-Economic Assessment Study of Coal Gasification Project for Thar Coal aims to evaluate the feasibility, efficiency, and economic viability of using Thar coal for coal gasification. Thar coal, despite its vast reserves, is increasingly criticized by many policymakers, energy sector experts, and stakeholders as a false promise for indigenous energy production in Pakistan due to its severe environmental impact, health risks, economic uncertainty, and misalignment with global energy trends. Premise on that, this study focuses on assessing the technical aspects of coal gasification processes, their environmental impact, and the economic considerations for implementing these projects at an industrial scale. The primary objective is to determine the technical feasibility, environmental impact, and economic viability of converting Thar coal into synthetic gas (syngas), which can be used for power generation.

The study includes a detailed analysis of the characteristics of Thar coal, focusing on its suitability for gasification. Gasification technology having an entrained-flow gasifier is evaluated based on its ability to handle the specific properties of Thar coal. The technical assessment includes modeling the gasification process, optimizing operational parameters, sensitivity analysis, evaluating the efficiency of syngas production, and analyzing the power generation. Environmental considerations are a key component of the assessment, with a focus on reducing emissions, particularly carbon dioxide and managing by-products such as ash and slag.

The study also includes an economic analysis of coal gasification, detailing the capital investment, operational costs, and potential revenue streams from the production of syngas and its derivatives. A sensitivity analysis is conducted to evaluate the impact of fluctuations in coal prices, syngas demand, and regulatory changes on the project's profitability. Our findings suggest that Thar coal could have been a feasible option for energy production and industrial use in Pakistan provided a case can be made for its financial viability, especially when compared to renewable energy sources and its serious environmental impacts can be mitigated.

The study, therefore, also explores the potential of solar photovoltaic (PV) power plants as a sustainable alternative to coal-based power generation. It discusses the environmental and economic benefits of PV systems, advocating for their integration into Pakistan's energy mix to enhance energy security and reduce greenhouse gas emissions. The environmental advantages of PV systems, along with their project benefits and economic feasibility, are thoroughly examined. Marginal Abatement Cost Curves (MACCs)[1] are highlighted as essential tools in environmental economics, helping to identify cost-effective strategies for reducing greenhouse gas emissions.

In conclusion, the report emphasizes that the substantial financial and environmental challenges associated with coal gasification are too important to be ignored while promoting this technology. It addresses the environmental impacts of coal power generation and coal gasification and analyzes solar power plants as a sustainable alternative – both financially and environmentally. The report, thus, advocates an approach that emphasizes on renewable energy sources to ensure a secure and sustainable energy future for Pakistan.

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[1] *A Marginal Abatement Cost Curve shows the relationship between the marginal cost (the cost of abating one additional unit of pollution, usually one ton of CO2 equivalent) and the total amount of emissions reduction that can be achieved*

Chapter: 1

Introduction

1.1. Pakistan's Energy Landscape

Pakistan's energy landscape is characterized by a diverse mix of fossil fuels, hydropower, nuclear energy, and renewable sources, reflecting the country's efforts to balance energy security, economic growth, and environmental sustainability.[1] Natural gas and oil dominate energy consumption, while coal usage is rising due to the development of the Thar Coalfield. Hydropower and nuclear energy significantly contribute to electricity generation, with renewable energy, particularly solar and wind, rapidly expanding. The sector faces energy shortages, circular debt, and infrastructural inefficiencies. To address these issues, the government focuses on diversifying energy sources, implementing comprehensive reforms, and adopting advanced technologies to ensure energy security and sustainability. As of 2024, the energy mix comprises approximately 59.4% thermal (fossil fuels), 25.4% hydro, 6.8% renewable (wind, solar, and biomass), and 8.4% nuclear.[2]. indicating a slight shift from the 2022 energy mix, as shown below.

Table 1-1 Pakistan Energy Mix for year 2022 [2].

Source	MW	Percentage
Hydro	10,752	26%
Bagasse	364	1%
Solar	600	1%
Wind	1,845	4%
Gas	3,491	8%
FO	5,169	13%
RLNG	10,087	24%
Local Coal	1,320	3%
Imported Coal	4,020	10%
Nuclear	3,620	9%
Total	41,268	100%

The country remains heavily reliant on fossil fuels, particularly natural gas and coal, which account for a significant portion of its energy generation. This reliance has considerable environmental implications, including greenhouse gas emissions and air pollution[3]. In addition to fossil fuels, Pakistan has a robust hydropower sector, with several large dams and hydroelectric power plants contributing significantly to the energy supply. Some efforts are also being made to increase the use of renewable energy sources, such as wind and solar power. Pakistan has significant potential for solar energy, given the high levels of sunlight many regions receive throughout the year. Wind power development is mainly focused along the coastal areas, where strong winds can be harnessed for electricity generation.

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[2] *https://finance.gov.pk/survey/chapter_24/14_energy.pdf*

[3] *https://www.nrdc.org/stories/fossil-fuels-dirty-facts#sec-whatis*

In theory, the government seems to promote renewable energy to improve energy security and reduce greenhouse gas emissions as it has aimed for renewables to constitute 30 percent of Pakistan's energy mix by 2030 [3]. This ambitious target is supposed to be achieved through collaborations with international partners – including the United States, Germany, and China – which can provide technical and financial assistance. This target, at least on paper, reflects Pakistan's desire to sustainably address its growing energy needs and reduce its reliance on fossil fuels.[4]

In practice, however, the government still remains fixated on using hydroelectric power and fossil fuels – rather than renewables. The draft of its latest Indicative Generation Capacity Expansion Plan (IGCEP) – which provides details of its electricity generation plans till 2034 – does not provide for any significant increase in the share of renewables in the energy mix.

1.2. Coal Power Generation

Pakistan's coal power generation infrastructure has significantly evolved in recent years to meet the country's increasing energy demands. The government heavily relies on coal to generate electricity due to its abundant coal reserves and the high cost of imported fuels. As of 2020, Pakistan's total installed coal-fired power generation capacity was around 4.2 GW (4,200 MW), accounting for 11% of the country's total installed capacity4. This capacity is predominantly concentrated in the Thar coal field in the Sindh province, where the government has implemented various coal-based power projects to harness the region's substantial coal reserves.

One of the most notable projects in the Thar coalfield is the Thar Block II power plant, which has a capacity of 660 MW and is considered the largest coal-fired power plant in the country. This project is part of the China-Pakistan Economic Corridor initiative and is expected to make a significant contribution to Pakistan's energy mix. In addition to the Thar coalfield, several other coal-based power projects are in various stages of development across the country. These include the Sahiwal Coal Power Project (1,320 MW) in Punjab province, the Port Qasim Power Plant (1,320 MW) in Karachi, and the Jamshoro Power Plant (1,320 MW) in Sindh province.

Despite the global shift away from coal, Pakistan's efforts to scale up coal power generation are increasingly concerning due to significant environmental impacts, limited access to financing, and technical issues related to coal mining and power plant operations. The government claims to have made efforts to address these challenges by implementing environmental regulations, promoting renewable energy sources, and seeking investment from international development partners. [5].

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4 https://www.enerdata.net/publications/daily-energy-news/pakistan-starts-commercial-operations-13-gw-thar-coal-power-plant.html

Table 1-2 List of coal power plants in Pakistan [5].

Power Plant	Output	Coal
China Power Hub Power Plant	1,320 MW	Imported
Port Qasim Coal Power Plant	1,320 MW	Imported Sub-bituminous
Sahiwal Coal Power Plant	1,320 MW	Imported-bituminous
Thar Block I Power Plant	1,320 MW	Local
Engro Thar Coal Power Project	660 MW	Local
Lucky Electric Power Company	660 MW	Local
Thal Nova Power Thar Limited	330 MW	Local
Thar Energy Limited (TEL)	330 MW	Local
Lakhra Coal Power Plant	150 MW	Local
Maple Leaf 40MW Power Plant	40 MW	Imported and Local
Muzaffargarh Sugar Mill Power Station	120 MW	Imported

1.3. Local and Imported Coal in Power Generation

In 2022, coal's share in Pakistan's power fuel mix was 14 percent and it is expected to rise to 16 percent by 2024 [6]. A large part of this coal was imported. In 2023, for instance, the country spent approximately $467 million on importing coal for electricity production [5].

These imports have been necessitated by the fact that the vast indigenous reserves of Thar are lignite, which has high moisture content and thus low heat value. Moreover, coal transportation out of Thar is not only a significant logistical challenge but also carries a substantial environmental impact, with associated issues such as increased emissions and habitat disruption. This situation forces power plants like Sahiwal Coal Power Plant and Port Qasim, to continue their dependence on imported coal.

The installed power generation capacity based on imported coal, therefore, stands at 4,620 megawatts which is much higher than the 3,600 megawatts that power plants based on local coal can generate. The share of imported coal in the energy mix is also projected to remain at 7 percent by 2031 due to long-term contracts with commissioned and committed power projects..

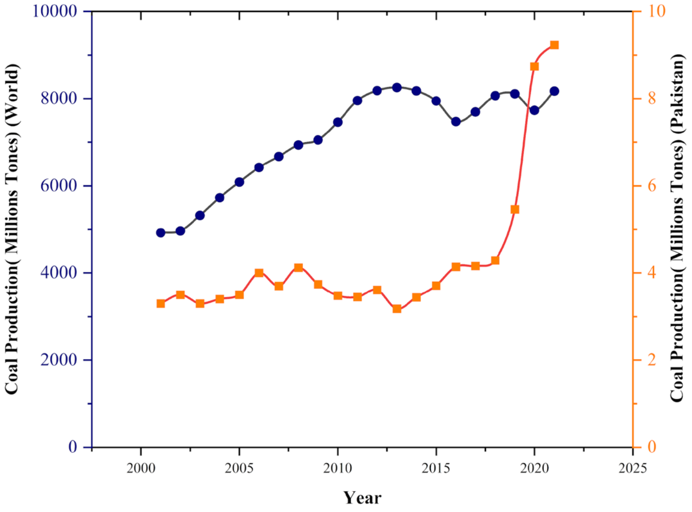
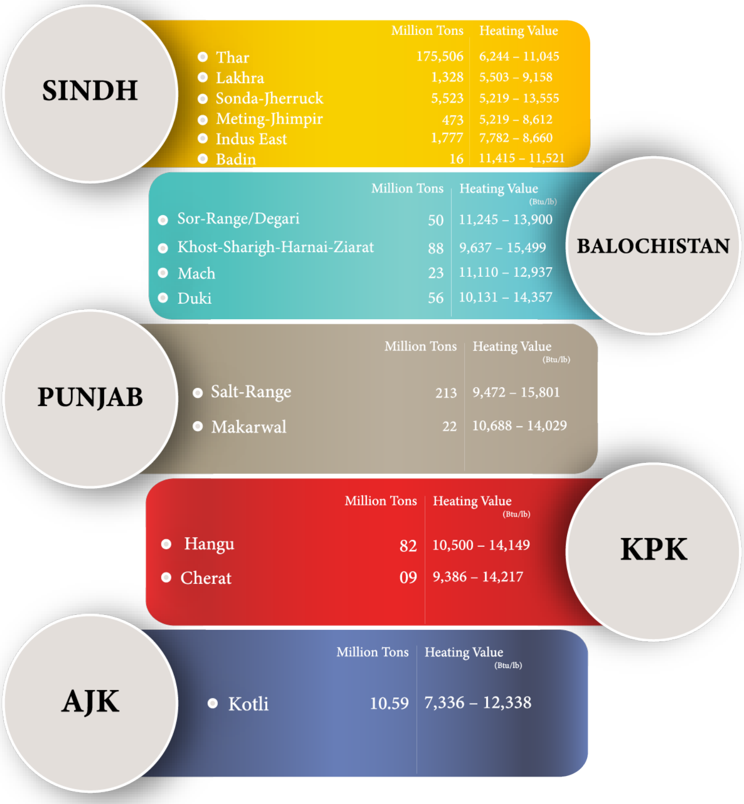


Figure 1-1 Coal Production in Pakistan [5].

1.4. Pakistan Coal Reserves

The coal reserves in Pakistan hold significant importance in the nation's industrial and energy landscape. With abundant coal reserves, particularly in the Sindh province, Pakistan has been focusing on utilizing this Indigenous resource to enhance energy security and reduce reliance on imported fuels [7]. The overall coal reserves in Pakistan are shown in Figure 1-2 as follows.



SINDH

	Million Tons	Heating Value
Thar	175,506	6,244 – 11,045
Lakhra	1,328	5,503 – 9,158
Sonda-Jherruck	5,523	5,219 – 13,555
Meting-Jhimpir	473	5,219 – 8,612
Indus East	1,777	7,782 – 8,660
Badin	16	11,415 – 11,521

BALOCHISTAN

	Million Tons	Heating Value (Btu/lb)
Sor-Range/Degari	50	11,245 – 13,900
Khost-Sharigh-Harnai-Ziarat	88	9,637 – 15,499
Mach	23	11,110 – 12,937
Duki	56	10,131 – 14,357

PUNJAB

	Million Tons	Heating Value (Btu/lb)
Salt-Range	213	9,472 – 15,801
Makarwal	22	10,688 – 14,029

KPK

	Million Tons	Heating Value (Btu/lb)
Hangu	82	10,500 – 14,149
Cherat	09	9,386 – 14,217

AJK

	Million Tons	Heating Value (Btu/lb)
Kotli	10.59	7,336 – 12,338

Figure 1-2 Pakistan Coal Reserves [8].

The development of Thar coal is often promoted as a major milestone in Pakistan's energy sector, focused on mining and using lignite coal reserves from Thar Coalfield Block I for electricity production [9]. The government argues that this initiative is crucial for diversifying Pakistan's energy mix and reducing reliance on costly imported fuels. They also assert that the Thar coal industry is essential for the growth of key sectors like steel and cement, claiming that local coal could lower production costs [10] . However, these claims overlook significant concerns. The use of lignite coal brings severe environmental challenges, including water and air pollution, and the need for effective mitigation measures to address these issues. The purported benefits for energy security and economic development [11] must be weighed against the substantial environmental and financial costs, which cast doubt on the overall value of expanding coal use.

1.5. Thar Coal Reserves

Sindh province, particularly the Thar Desert, hosts the largest coal reserves in Pakistan, which are estimated to be among the largest untapped coal reserves globally. These reserves have become a crucial component of Pakistan's energy generation mix, with several coal-fired power projects operational or under development [12]. These projects aim to enhance energy security, reduce dependence on imported fuels, and provide affordable electricity to meet the growing demand.

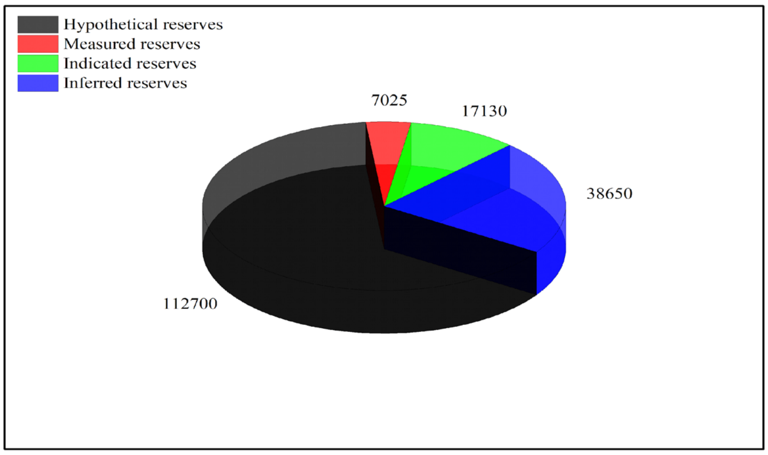


Figure 1-3 Thar Coal Reserves (million tons) [8].

According to exploration and drilling works conducted by GSP and USAID, the Thar coalfield boasts 175,506 million tons of coal reserves, covering an area of 9,100 square kilometers. Open-pit mining has been suggested by various studies, including those by J.T. Boyd (1994), RWE Germany (2002), and Shenhua China (2004). The total area of the coalfield is divided into 12 blocks, with several blocks already under investment agreements with international and local companies.

1.6. Technical Specifications of Thar Coal

The technical specifications of Thar coal are notable, with coal seams ranging in thickness from 12 to 21 meters, found at depths of 170 meters under an average depth of 80 meters of sand. The coal is found in the Bara formation of the Paleocene-Eocene age, with developed coal seams ranging in thickness from 0.20 to 22.81 meters. The cumulative coal seam thickness ranges from 0.2 to 36 meters, and the coal color varies from brown to brownish black. Thar coal is generally classified as Lignite B to Lignite A, with varying moisture, ash, volatile matter, sulfur content, and heating values. After testifying numerous sets of samples, the coal quality can be seen in the table below.

Table 1-3 Thar Coal Qualities [13]

Block	Area (km2)	Total reserves (billion tons)	Moisture (%)	Ash (%)	Volatile Matter (%)	Sulfur (%)	Heating Value (Btu/lb.)	Fixed Carbon (%)
I	122.0	3.56	43.13	6.53	30.11	0.92	6,398	20.11
II	79.6	2.24	47.89	7.37	25.15	1.12	5,008	19.68
III-A	99.5	2.00	45.41	6.14	28.51	1.12	6,268	19.56
111-B	76.8	1.45	47.72	9.30	25.49	1.15	4,808	16.79
IV	82.0	2.47	43.24	6.56	29.04	1.20	5,971	21.13
V	63.5	1.39	46.82	8.92	30.24	1.20	5,682	13.26
VI	66.0	1.65	46.80	5.89	29.34	0.90	5,727	16.60
VII	100.0	2.17	48.27	8.03	25.30	1.16	5,440	25.30
VIII	100.0	3.03	49.57	7.78	24.32	1.44	5,302	18.10
IX	100.0	2.86	48.60	5.92	29.03	0.96	5,561	15.73
X	100.0	2.87	48.99	6.35	30.79	1.17	4,840	13.54
XI	101.0	1.61	49.97	8.07	24.16	1.61	5,228	17.26
XII	100.0	2.34	50.82	5.71	25.00	1.11	5,459	17.26

1.7. Current Projects on Thar Coal

Four projects, comprising a total of six units, are operational based on Thar coal, with a combined power output of 3,450 MW. These projects utilize various technologies, such as Circulating Fluidized Beds and Pulverized Coal Boilers, and all use local Thar Coal. The detailed tabular description is given below.

Power Plant	Operator	Output	Unit	Source	Method	Technology	Operation Condition	Location	Merit Order
Thar Block I Power Plant	Shanghai Electric Power Company Limited	1,320 MW	2 (660 MWe)	Thar Coal	Combustion	Circulating Fluidized Bed	Subcritical	Thar Block I	2
Thal Nova Power Thar Limited	HUBCO	330 MW	1	Thar Coal	Combustion	Circulating Fluidized Bed	Subcritical	Thar Block - II	3
Engro Thar Coal Power Project	Engro Power Gen Thar	660 MW	2 (330 MWe)	Thar Coal	Combustion	Circulating Fluidized Bed	Subcritical	Thar Block - II	4
Thar Energy Limited (TEL)	HUBCO Power	330 MW	1	Thar Coal	Combustion	Circulating Fluidized Bed	Subcritical	Thar Block - II	5

Table 1-4 Specification of Coal Power Plants based on Thar Resources [14], [15]

1.8. Tariff of Local and Imported Coal

The National Electric Power Regulatory Authority releases documents annually estimating the actual cost of electricity generation from various sources. These tariffs include the complete value chain of the sector, including generation, transmission, distribution, market operation, and supply, determined through a regulated framework. The National Electric Power Regulatory Authority also defines the merit order under section 2(I)(x) of the National Electric Power Regulatory Authority Licensing (Generation) Rules 2000.

Table 1-5 Merit Order of Power Plants [16]

Plant Groups	Fuel Type	Fuel Cost Rs. /kWh	Variable O&M Cost Rs. /kWh	Specific Cost Rs. /kWh	Status In Last Merit Order (2 May, 2024)
Thar Coal Block-I	Coal	4.3369	1.19470	5.5316	2
Thall NOVA	Coal	4.2962	1.3205	5.6167	3
Engro Power Thar	Coal	4.2965	1.3205	5.617	4
Thar Energy Limited	Coal	4.2965	1.32050	5.617	5
China Power HUB Gen CO	Coal	13.1682	0.7062	13.8744	15
Port Qasim	Coal	13.9751	0.3845	14.3596	19
Lucky Electric Power Company	Coal	14.0621	0.6901	14.7522	17
Sahiwal Power	Coal	24.2757	0.38	24.6557	25

1.9. Government Strategic Approach to Utilizing Thar Coal Reserves

The Sindh government has developed a "Coal to Gas and Coal to Liquids Policy" that aims at exploiting Thar's coal reserves to meet Pakistan's energy demands and encourage economic growth[5]. It seeks to convert coal into synthetic gas – supposedly at a cost lower than that of both imported gas and imported coal. The policy emphasizes the promotion of diverse project models, like private sector initiatives, public-private partnerships and public sector initiatives with the possibility for future private investments. The policy also encourages partnership between local engineering businesses and foreign firms to enhance technology transfer and capacity creation, thereby indigenizing Pakistan's energy sector. Financing for the projects under this policy will be procured through a combination of equity and debt, with minimum equity requirements ranging from 20 per cent to 30 percent.

1.10. South African report on thar coal quality

To find out if the quality and environmental impacts of Thar coal suited coal gasification projects, the Sindh government sent its samples for Fischer assay testing in South Africa for testing. The South African laboratory is reported to have found that Thar coal's ash content averages around 18 percent which makes it suitable for gasification. The tests are also reported to show that Thar coal can yield more than 20 per cent tar which can be turned into liquid fuels. Another important finding of these tests reportedly suggest that ash flow tem-

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[5] *Pakistan urged to tap indigenous coal*

peratures of Thar coal range from 1320°C to 1340°C which are well-suited for its usage in high-temperature operations [6], including its conversion to gas.

This study aims at looking at these test results by carrying out its own techno-economic assessment of Thar coal's gasification. To do so, it uses integrated gasification combined cycle (IGCC) technology that combines coal gasification with a gas turbine and a steam turbine to generate electricity. The study aims at analyzing the following aspects of coal gasification:

i) Comparison of direct combustion of coal and Integrated gasification combined cycle (IGCC) for a 300 MW power plant

ii) impacts of both coal power technologies on the precarious water resources of Thar region in Sindh province of Pakistan. It covers the drinking water crisis, biodiversity losses and livelihood disruptions caused by dewatering of coal mines and dumping of effluent water discharged from mining and power generation processes

iii) Economics assessment including the capital cost, total electricity generated cost and cost per kWh

iv) Emissions production and mitigation strategies and (v) Alternative solutions.

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[6] *Thar coal: S. African lab results quite encouraging: DG SCA*

Chapter: 2

Coal Gasification

2.1. Background

Coal gasification is a thermochemical process that converts coal into a mixture of gasses, mainly carbon monoxide and hydrogen, that can be used as a fuel for power generation or a chemical feedstock for producing synthetic fuels, chemicals, and fertilizers [17]. Coal gasification involves heating coal in the presence of controlled oxygen or steam, and sometimes a catalyst such as limestone or dolomite, to break down the complex hydrocarbons in coal into simpler molecules [18]. The resulting gas mixture, called syngas or producer gas, can be cleaned and processed to remove impurities such as sulfur, mercury, and carbon dioxide [19]. Coal gasification can reduce greenhouse gas emissions and increase energy efficiency compared to conventional coal combustion, which produces mainly carbon dioxide and water as byproducts.

The historical background of coal gasification shows how this process has been influenced by various factors, such as scientific discoveries, economic needs, environmental concerns, and social preferences [17]. The first experiments with coal gasification were conducted by Jean Tardin in France and John Clayton in England in the 17th century, who discovered that coal could produce flammable gas when heated in a closed vessel [18]. The first industrial-scale coal gasification plant was built in London in 1812, by the Gas Light and Coke Company, and soon coal gas became widely used for domestic and industrial purposes, such as street lighting, cooking, and heating. Coal gasification also played a role in the development of the steel industry, as it provided a cheap source of fuel for blast furnaces [19]. The invention of the hot blast process by James Beaumont Neilson in 1828 increased the efficiency of coal gasification and reduced the consumption of coke. However, coal gasification declined in popularity after the discovery of natural gas and petroleum in the late 19th and early 20th centuries, as they were cleaner and more efficient sources of energy [20]. Coal gasification experienced a revival in the second half of the 20th century, as it offered a way to utilize low-grade coal and reduce greenhouse gas emissions. Coal gasification is being gradually phased out today in countries, such as China and India, where coal is abundant but also highly subsidized. Coal gasification is a historical and technological process that has evolved over time and has both advantages and disadvantages for different applications and contexts.

2.2. Process description of coal gasification

The basic principle of coal gasification is to react coal with a controlled amount of oxygen and/or steam to produce syngas. The reaction can be represented by the following equations:

$$C + O_2 \rightarrow CO_2 \ (combustion)$$

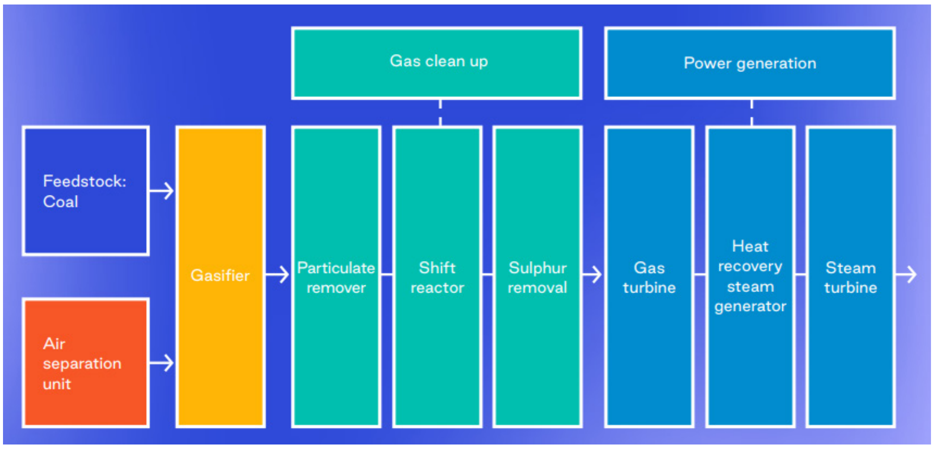
$$C + 1/2O_2 \rightarrow CO \ (partial\ combustion)$$

$$C + H_2O \rightarrow CO + H_2 \ (water - gas\ reaction)$$

$$C + CO_2 \rightarrow 2CO \ (boudouard\ reaction)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \ (water - gas\ shift\ reaction)$$

There are different types of gasifiers that use different configurations and operating conditions to achieve coal gasification. Some of the common types are fixed beds, fluidized beds, entrained flow, and moving bed gasifiers [21]. The choice of gasifier depends on various factors, such as coal properties, syngas quality requirements, scale of operation, and cost. Coal gasification is not a new technology. It was historically used to produce coal gas for heating and lighting before the advent of natural gas [22]. However, coal gasification has gained renewed interest in recent years due to the increasing demand for clean and efficient energy sources and the abundant availability of coal worldwide. Coal gasification can also enable the production of hydrogen from coal, which can be used for various applications such as ammonia synthesis, fuel cells, or hydrogen economy [23]. A coal gasification process schematic is shown in Figure 2-2, which shows the conversion of coal into syngas that is utilized to generate electricity after cleaning up the raw syngas.



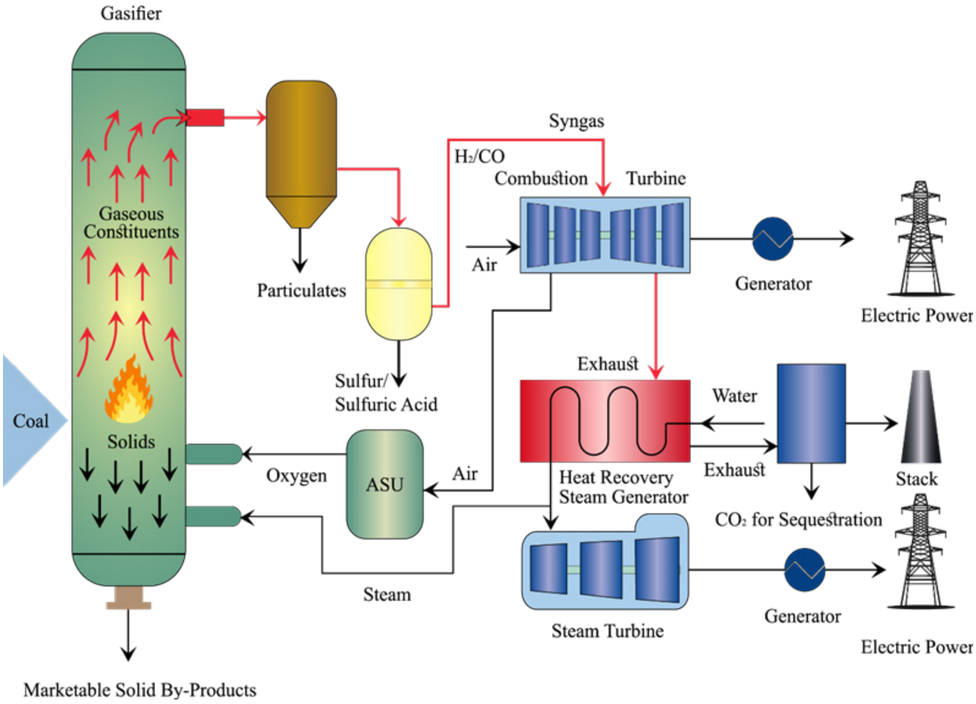


Figure 2-1 Schematic of Coal Gasification Process [25]

2.3. Coal Gasification Technologies

There are different types of coal gasification technologies based on the reactor design, coal feedstock, gasifying agent, and operating conditions. Some of the common types are:

1. **Entrained flow gasifiers**, in which pulverized coal particles and gases flow concurrently at high speed. This type of gasifier can achieve high temperatures (1200 to 1600°C) and pressures (2 to 8 MPa), resulting in high syngas production and efficiency [24]. However, it also requires high-quality coal feedstock and produces large amounts of slag and tar.

2. **Fluidized bed gasifiers**, in which coal particles are suspended in the gas flow; coal feed particles are mixed with the particles undergoing gasification. This type of gasifier can operate at lower temperatures (800 to 1000°C) and pressures (1 to 2 MPa), allowing for more flexibility in coal feedstock and gasifying agent [26]. It also produces less slag and tar than entrained flow gasifiers.

3. **Moving bed (also called fixed bed) gasifiers**, in which gases flow relatively slowly upward through the bed of coal feed. This type of gasifier can operate at low temperatures (500 to 800°C) and pressures (0.1 to 0.5 MPa), making it suitable for low-rank coals and biomass feedstocks [26]. It also produces high-quality syngas with low tar content. However, it has lower syngas production and efficiency than other types of gasifiers, and it is prone to clogging and agglomeration problems [27].

4. **Molten bed gasifiers**, in which coal particles are immersed in a molten salt bath that acts as a heat transfer medium and a catalyst. This type of gasifier can achieve high temperatures (1000 to 1400°C) and pressures (1 to 5 MPa), resulting in high syngas production and efficiency [28]. It also produces less slag and tar than entrained flow gasifiers, and it can handle various types of coal feedstocks. However, it requires high maintenance and operational costs due to the corrosive nature of the molten salt.

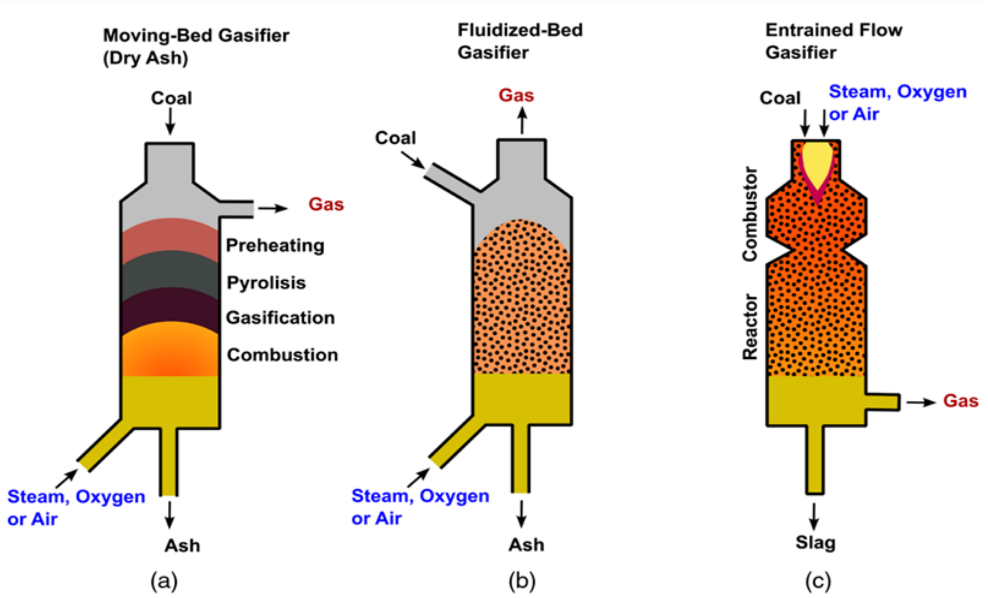


Figure 2-2 Major configurations for coal gasifiers: (a) moving-bed gasifier (dry ash); (b) fluidized-bed gasifier; (c) entrained flow gasifier [29]

2.4. Advantages and Disadvantages of Coal Gasification

Coal gasification is a process that transforms coal into synthetic gas, which has various applications, such as hydrogen production, electricity generation, and chemical synthesis [30]. Coal gasification has some pros and cons compared to other ways of using coal.

Some of the pros of coal gasification are:

- It can utilize low-quality coal or coal waste as feedstock, which reduces the demand for mining and transporting coal.
- It can generate a cleaner and more flexible fuel than burning coal directly, which lowers the emissions of sulfur dioxide, nitrogen oxides, particulate matter, and mercury.
- It can facilitate carbon capture and storage technologies, which cut down greenhouse gas emissions by capturing and storing carbon dioxide from syngas.
- Some of the cons of coal gasification are:
- It is more complicated and costly than burning coal directly, requiring high temperature and pressure conditions and advanced equipment.
- It uses more energy and water than burning coal directly, which decreases the overall efficiency and increases the environmental impact.
- It still releases considerable amounts of carbon dioxide and other pollutants, such as tar, ash, slag, and trace metals, which need to be treated and disposed of properly.

2.5. International Coal Gasification Projects

Coal gasification projects have been implemented globally, showcasing various technologies and applications. One notable example is the Kemper County Energy Facility in Mississippi, USA. Owned by Mississippi Power, it aimed to integrate carbon capture and storage technologies using the Transport Integrated Gasification process. However, the project faced challenges such as cost overruns and technical difficulties, leading to a transition to natural gas. The Wabash River Coal Gasification Plant in Indiana, USA, operated by Duke Energy, demonstrated the Wabash River IGCC technology. It successfully converted high-sulfur coal into synthetic gas for electricity generation, serving as an early example of commercial-scale coal gasification. The Kingsnorth Power Station in Kent, UK, featured the Clean Coal Technology Program, including a coal gasification demonstration project utilizing the Shell Coal Gasification Process. However, changes in energy policies and economic considerations resulted in the discontinuation of the project. In China, the Dongying Coal Chemical Industry Base in Shandong province serves as a major hub for coal gasification and chemical production. It incorporates multiple projects utilizing various gasification technologies such as entrained flow and fluidized bed gasifiers. These projects contribute to power generation, chemical manufacturing, and other industrial applications. Another noteworthy project is FutureGen 2.0 in Illinois, USA, which aimed to construct a nearly emission-free coal-fired power plant. It planned to employ the oxy-combustion process to generate a concentrated stream of CO_2 for capture and storage in underground formations. However, funding challenges halted the project's progress. These coal gasification projects exemplify the advancements and challenges associated with this technology. They showcase the diverse applications of coal gasification, including electricity generation, synthetic fuel production, and chemical manufacturing. While some projects have encountered difficulties, they continue to drive innovation and research towards more efficient and environmentally friendly coal gasification processes. Over time, coal prices have fluctuated due to a variety of reasons, including supply and demand dynamics, movements in the energy market, environmental restrictions, and geopolitical developments. The fluctuating nature of coal prices has historically been a result of shifting market circumstances. As countries adopt policies for sustainable energy, this change may eventually have an influence on coal pricing. Table 2.2 provides a summary of various Integrated Gasification Combined Cycle (IGCC) plants demonstrated globally for both power generation and fuel conversion.

Table 2-2 Power Plants, A comparison of Different Countries [31] [32]

Country **Parameters**	**USA**	**USA**	**South Africa**	**China**	**USA**	**USA**	**USA**
Plant Name	Tampa Electric Integrated Gasification Combined Cycle (IGCC) Plant	Wabash River Coal Gasification Repowering Project	Sasol Secunda Synfuels Operations	Huaneng Yuhuan Coal Gasification	Hydrogen Energy California (HECA)	Great Plains Synfuels Plant	Kemper County Energy Facility (formerly known as Kemper Project)
Plant Location	Polk County, Florida, USA	West Terre Haute, Indiana, USA	Secunda, South Africa	Zhejiang Province, China	Kern County, California, USA	Beulah, North Dakota, USA	Kemper County, Mississippi, USA
Plant Capacity (MW)	260	262	11000 bpd	4110	300	145 million cu.ft/day	582
Feedstock	Bituminous Coal	Coal	Coal	Coal	75% sub-bituminous Coal+25% petroleum coke	Lignite coal	Lignite Coal
Technology	Entrained flow gasifier	Louisiana Gasification Technology	Circulating fluidized bed gasifier	Entrained flow gasifier	Oxygen blown gasifier	14 Lurgi Mark IV gasifiers.	Transport integrated gasification
Operation Year	1996	1995	1955	2006	2017	1984	2015
Efficiency (%)	83.5	77	50	90	90	75	79
CO2 Capture	No	Yes	No	No	Yes	No	Yes
Investment Cost (million USD)	303	438	132	-	408	2000	6100
Plant Status	Operational	Operational	Operational	Operational	Operational	Operational	Demolished in 2021

2.6. Canceled IGCC Plants

The performance and economic viability of gasifier units are critical determinants of the commercial success of Integrated Gasification Combined Cycle plants. Despite their potential benefits, gasifiers have often been central to numerous project failures. This report delves into the intricacies of gasifier design, integration challenges, economic considerations, and case studies of high-profile Integrated Gasification Combined Cycle projects, offering insights into the complexities and risks associated with this technology. Integrated Gasification Combined Cycle technology holds promise for efficient and cleaner coal utilization. However, the success of Integrated Gasification Combined Cycle plants heavily relies on the performance of gasifier units. While gasifiers are often referred to as single units, they encompass multiple design parameters that require meticulous customization [33]. This report explores the factors that contribute to the technical and economic challenges of gasifiers in Integrated Gasification Combined Cycle plants and examines the reasons behind the failures of several high-profile projects. Each gasifier must be uniquely designed based on various factors: Technology Type, including fixed bed gasifiers, moving bed gasifiers, and circulating fluidized bed gasifiers; Coal Feeding Conditions, with choices between slurry feed or dry feed significantly impacting the design; and Oxidizing Agent, where the use of air-blown or oxygen-blown systems dictates different design requirements. These design considerations necessitate a high level of customization for each Integrated Gasification Combined Cycle plant, making the gasifier unit a complex component tailored to specific project needs. Integrated Gasification Combined Cycle plants require seamless integration and synchronization across multiple subsystems to achieve high efficiency and smooth operations. Effective operation relies on tight coordination between gasification, power generation, and emission control subsystems. Poor integration can lead to increased maintenance, reduced availability, and degraded reliability. The need for high synchronization levels makes Integrated Gasification Combined Cycle plants more challenging to design and operate compared to conventional coal plants. Integrated Gasification Combined Cycle plants demand substantial initial investments and long lead times for design and synchronization before achieving stable operations. These factors contribute to the economic risks associated with Integrated Gasification Combined Cycle projects. The technical complexity of Integrated Gasification Combined Cycle plants often leads to significant budget overruns due to repeated modifications during design and construction phases and increased complexity from integration issues and unforeseen technical challenges. These cost overruns have been a major factor in the failure of several Integrated Gasification Combined Cycle projects. Several high-profile Integrated Gasification Combined Cycle projects have faced significant challenges and were ultimately suspended or failed due to these complexities. The Kemper Integrated Gasification Combined Cycle project encountered substantial cost overruns and technical issues, leading to its suspension. The FutureGen project in the United States was suspended due to unmanageable and escalating costs. ZeroGen in Australia faced similar cost and technical challenges, resulting in its suspension. The Taean Integrated Gasification Combined Cycle project in South Korea encountered scaling challenges that led to a loss of momentum and eventual suspension. In the early 2000s, numerous coal-gasification projects were proposed in the United States. Out of 25 proposed projects, only Edwardsport and Kemper County were completed. These projects, however, were completed at significantly higher costs and without incorporating the initially planned carbon capture technologies. Most projects were suspended due to high costs, long project lead times, and technological difficulties. The development of Integrated Gasification Combined Cycle technology highlights the complex balance between innovation and practical implementation. The need for customized gasifier design and seamless integration across subsystems presents significant challenges. Economic risks, driven by high capital costs and potential cost overruns, further complicate the commercialization of Integrated Gasification Combined Cycle plants. These factors underscore the importance of thorough risk assessment and strategic planning in the early stages of Integrated Gasification Combined Cycle project development. The substantial technical and economic challenges associated with gasifier design and system integration have led to the suspension of many projects and significant cost overruns for those completed. A critical evaluation of these factors is essential when considering investments in Integrated Gasification Combined Cycle technology. Future advancements may mitigate some of these challenges, but lessons from past failures highlight the need for careful planning and robust engineering solutions. Developing standardized protocols for gasifier design to reduce customization costs and complexity, implementing comprehensive project management frameworks that emphasize integration across subsystems from the outset, establishing robust risk mitigation strategies to address potential cost overruns and technical challenges early in the project lifecycle, and investing in continuous research and development to improve gasifier technologies and integration methods, reducing the likelihood of future failures are essential steps [34].

Table 2-3 Canceled IGCC Projects [34]

Canceled IGCC projects	Canceled year	Country	Size (MW)	Technology
Ashtabula IGCC	2006	US	830	IGCC
Polk Power Station Unit 6	2007	US	630	IGCC
Southern Illinois Clean Energy Center	2007	US	600	IGCC
PacifiCorp Sweetwater Project	2007	US	450	IGCC
Stanton Energy Center	2007	US	285	IGCC
Nueces IGCC Plant	2007	US	600	IGCC
Bowle IGCC	2007	US	600	IGCC
Huntley Generating Station	2008	US	680	IGCC
Buffalo Energy Project	2008	US	1100	IGCC
Future Gen	2008	US	200	IGCC/pre-combustion capture
Kwinana Power Station	2008	Australia	500	IGCC/pre-combustion capture
Great Bend IGCC	2009	US	629	IGCC
Hebel Chaohua IGCC	2010	China	800	IGCC
Goldenbergwerk IGCC	2010	Germany	450	IGCC/pre-combustion capture
Mesaba Energy Project	2011	US	603	IGCC
ZeroGen	2011	Australia	500	IGCC/pre-combustion capture
Magnum IGCC	2011	Netherlands	1311	IGCC
Mountaineer IGCC	2011	US	629	IGCC/pre-combustion capture
Taylorville Energy Center	2013	US	770	IGCC/co-production
Lianyungang IGCC	2014	China	1300	IGCC/pre-combustion capture
Teesside IGCC	2015	United Kingdom	850	IGCC/pre-combustion capture
Texas Clean Energy Project	2017	US	400	IGCC/pre-combustion capture
North Killingholme IGCC	2017	United Kingdom	470	IGCC/pre-combustion capture

2.7. Pakistan Underground Coal Gasification

In 2010, the Pakistani government allocated a substantial budget of Rs 8.8 billion for the Thar Underground Coal Gasification (UCG) pilot project, intending to build a 100MW power plant using this technology. While the project was presented as an innovative solution, offering significant economic and environmental benefits by converting coal into product gas directly within the coal seam, the reality is far less promising. Underground Coal Gasification, despite its claims of reducing costs and limiting environmental impact, comes with its own set of risks and uncertainties. The process involves injecting oxidants into non-mined coal seams to gasify the coal underground, which, in theory, avoids surface disruptions caused by traditional mining. However, this technology has a history of failures and environmental concerns globally, including groundwater contamination, subsidence, and uncontrolled gas releases. The 2002-2003 screening study by Ergo Exergy Technologies, Inc., suggested the potential for a 1,200MW power plant in Thar Block III, with reserves that could last for 30 years. Yet, this optimistic outlook ignores the long-term environmental damage and the unproven nature of UCG technology in Pakistan's context. Rather than delivering sustainable power and economic growth, the Thar UCG project risks becoming another costly experiment with severe ecological consequences.

However, the initiative quickly faced considerable challenges, including funding concerns, technological difficulties, and regulatory delays. Despite the initial budget, the project struggled to secure steady funding, leading to delays and increased costs. Technical issues, such as well collapses and equipment failures, further hampered progress, highlighting the inherent risks associated with Underground Coal Gasification technology. Injecting oxidants into coal seams can lead to unpredictable underground reactions, making the process difficult to control effectively. Environmental concerns also emerged as a major issue, particularly groundwater contamination. Underground Coal Gasification can release toxic compounds like benzene and toluene into the water supply, posing severe risks to human health and the environment. Thar, already experiencing water scarcity, cannot afford further deterioration of its water resources. Additionally, the risk of underground fires and explosions adds another layer of danger, potentially leading to uncontrollable disasters. These environmental risks are especially alarming given Thar's ecological sensitivity, with any adverse impact having long-lasting consequences [35].

In summary, the Thar Underground Coal Gasification project, despite its innovative concept and potential benefits, has been hindered by significant funding, technical, environmental, and transparency challenges. These issues highlight the complexity and risks associated with Underground Coal Gasification technology and raise serious doubts about its viability as a sustainable energy solution for Pakistan [36], [37].

Chapter: 3

Modeling of Direct Combustion and Integrated Gasification Combined Cycle Power Plant

3.1. Introduction

The project aimed to simulate both direct combustion and Integrated Gasification Combined Cycle plants. Aspen Plus, a widely utilized simulation software in process industries for tasks such as energy and materials balance, economic analysis, emissions analysis, and optimization, was employed for this purpose. This chapter provides detailed descriptions of the simulated models for both the direct combustion of coal and the Integrated Gasification Combined Cycle plant.

3.2. Direct Coal Combustion

In the Aspen model representing the direct combustion of coal and turbine operation for electricity generation, several components are involved, all working together within a single unit, typically referred to as a boiler; Figure 3-1 Shows Block Diagram of the Aspen Model while Figure 3-2 show the Actual model of the direct combustion unit. The Yield Reactor converts coal into its main components, such as Carbon, Hydrogen, Nitrogen, Sulphur, Oxygen, and produces some water as a byproduct, while the output from the Yield Reactor undergoes combustion in the Gibbs Reactor to produce the desired product gas, known as Syngas. This gas is a key intermediate in the process. After the gas is produced in the Gibbs Reactor, the Gas Splitter divides it into separate lines to prevent overload when passing through equipment with lower capacity. The Heat Exchanger plays a crucial role in the process by using the hot gases (Syngas) to heat up water and generate steam, which then powers a turbine to produce electricity. The cold gases resulting from the heat exchange exit into the environment. Overall, these components work in tandem within the boiler to efficiently convert the energy contained in coal into electricity, with each component serving a specific function in the overall process.

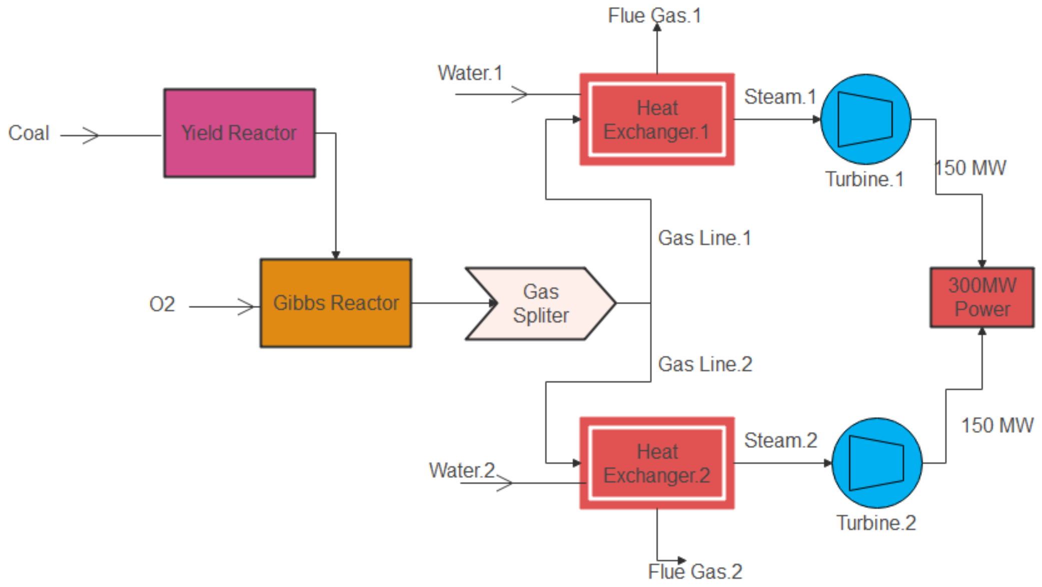


Figure 3-1 Block Diagram of Direct Coal Combustion Power Plant

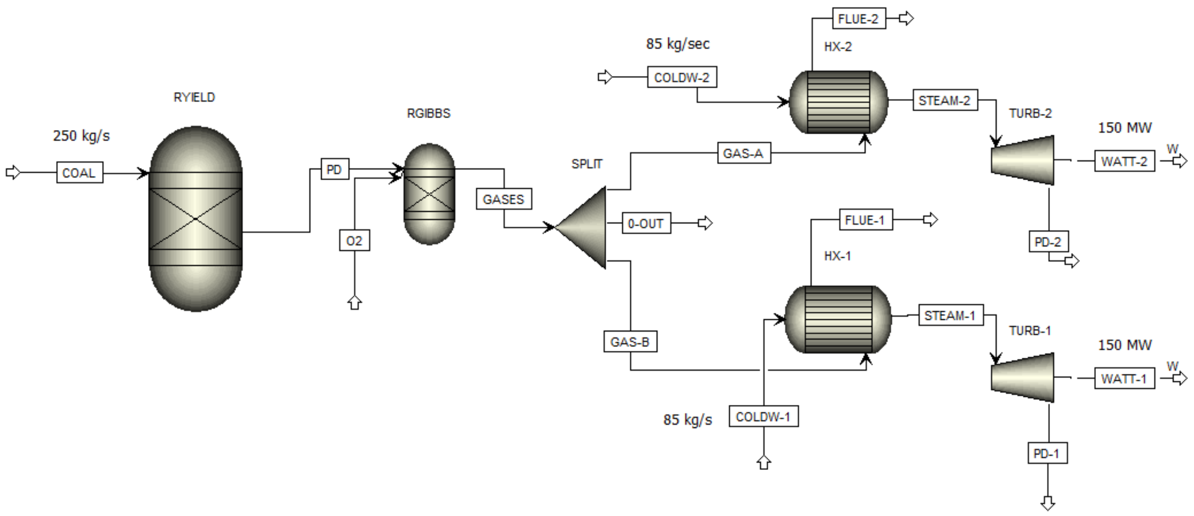


Figure 3-2 Aspen Based Process Flow Diagram of Direct Coal Combustion System

Table 3-1 Description of Abbreviations Used for Blocks in Figure 3-1

Design Name	Description
RYIELD	Represent Yield Reactor, to convert Coal into its products
PD	Represent Products of Yield Reactor
RGIBBS	Represent Gibbs Reactor which is used as a boiler
GASES	Represent Syngas which is produce during combustion of coal with oxygen
SPLT	Represent Splitter which split the main gas stream into two or more stream
GAS-A and B	Represent Syngas Gas Stream A and B
COLDW-1 and 2	Represent water which use to generate steam
HX-1 and 2	Represent Heat Exchanger 1 and 2
FLUE-1 and FLUE-2	Represent flue gases which directly went to environment
STEAM-1 and STEAM-2	Represent high temperature water steam
TURB-1 and TURB-2	Represent Steam Turbine 1 and 2
PD-1 and PD-2	Represent low temperature steam

3.3. Aspen Model of Integrated Gasification Combined Cycle

A block diagram of the Aspen-based model for the Integrated Gasification Combined Cycle plant is depicted in Figure 3.3, while Figure 3.4 illustrates the Process Flowsheet developed in Aspen. The flowsheet/model encompasses the Air Separation unit, Sizing Section of Coal, Gasifier section, Water gas shift reaction, Power section, and cleaning sections. Table 3-1 provides descriptions of some abbreviations used in Figure 3-4. The first segment of the model, referred to as the Sizing section or fuel preparation section, involves passing coal through various ball mills to reduce its size to the required dimensions. Subsequently, water is added to create a slurry for smoother flow and to prevent equipment overheating during grinding. Once converted into slurry, the coal undergoes modification in the change block, which adjusts properties such as temperature, pressure, composition, and flow rates of the stream. The slurry then proceeds to undergo stoichiometric reactions in the NCCHNG block for initial reaction. In the second section, the Air separation unit converts air into its pure components, nitrogen and oxygen, which are utilized in subsequent gasification processes. The separated nitrogen is directed through a Splitter, dividing it into different streams for use in subsequent sections. Moving to the third section, the Gasification process involves reacting the fully prepared slurry from the sizing section with oxygen from the air separation unit in a controlled gasifier to produce synthetic gas, known as Syngas. In the fourth section (cleaning), the produced syngas undergoes cleaning to remove impurity gases like Hydrogen Sulfide, resulting in a clean syngas primarily composed of carbon monoxide and hydrogen. Finally, in the fifth section (power), the generated hot syngas is directed through various gas turbines to produce electricity.

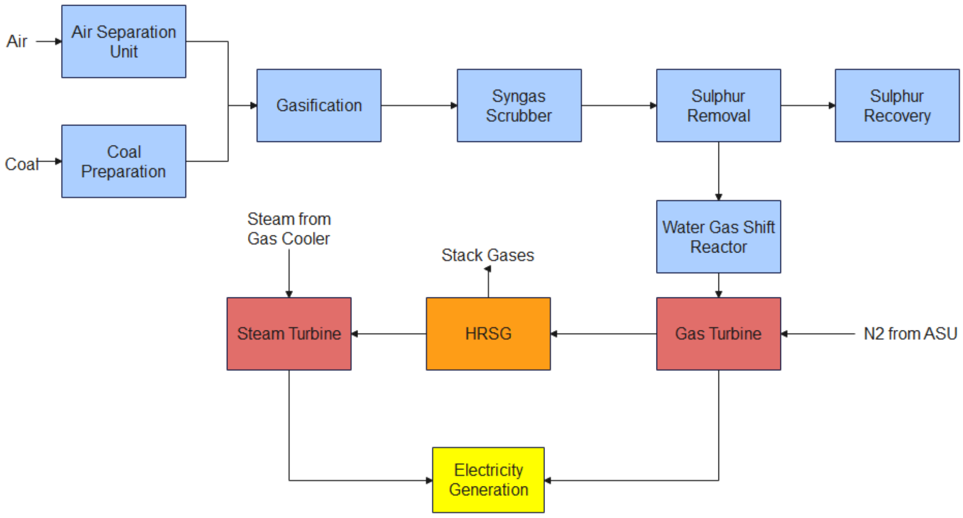


Figure 3-3 Block Diagram of Integrated Gasification Combined Cycle

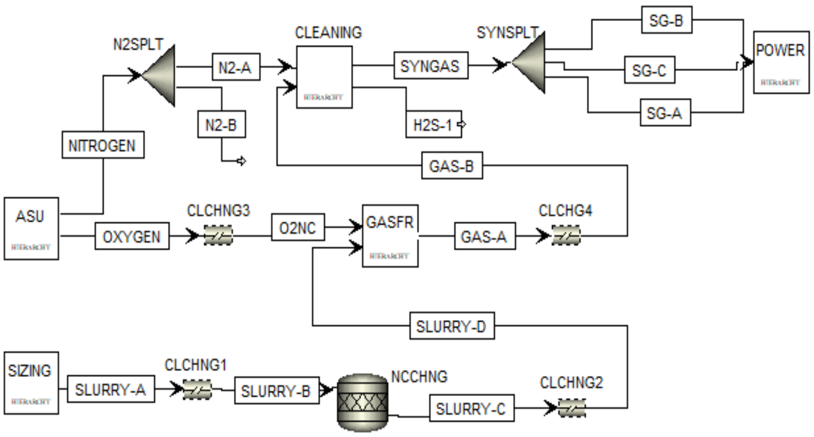


Figure 3-4 Aspen Based Process Flow Diagram of Integrated Gasification Combined Cycle

Table 3-2 Description of Abbreviations Used for Blocks in Figure 3-4

Name	Description
CLCHNG	It represents a Change block used to change the specifications of a stream within a process simulation.
NCCHNG	Stoichiometric Reactor is used to convert coal from its native "naturally occurring" (NCPSD) form to a "non-coal" (NC) form.
N2SPLT	Nitrogen gas splitter
SYNSPLT	Syngas Splitter
ASU	Air Separation Unit
SIZING	Show the Sizing Section
SLURRY	Shows the fully prepared slurry of Coal and water before entering to Gasifier
SG A, B ,C	Represent Syngas A stream, B stream, C Stream
GASFR	The Gasifier Hierarchy
SG	Stand for Syngas

Chapter: 4

Power Generation

4.1. Thar Coal Characterization

A comprehensive field survey was conducted at the Thar Coal Fields in Block II, Tharparkar District, Sindh Province, Pakistan, to collect and assess the quality and potential of coal and groundwater contamination. The primary objectives of the survey were to collect representative coal samples and groundwater samples for subsequent laboratory analysis. Rigorous adherence to established protocols and engineering best practices was maintained throughout the study.

The Thar Coal Fields in Sindh Province, Pakistan, hold significant importance as a potential energy resource. As part of an engineering study, a field survey was undertaken to gather critical data on the region's coal composition and groundwater characteristics. Two distinct coal samples were collected and labeled as Thar Coalfield Block II-1 and Thar Coalfield Block II-2, respectively, to capture variations in coal composition: **(1)** A representative surface coal sample was gathered from accessible coal outcrops within the study area. This sample was obtained following standard geological sampling practices. **(2)** An in-depth coal sample was collected from a subsurface location, reflecting the coal deposits at a significant depth. All collected samples were carefully labeled, documented, and preserved to maintain sample integrity during transportation to the laboratory. Proper sample containers and preservation techniques were employed to prevent contamination or alteration of the samples. The collected samples underwent rigorous laboratory analysis. As shown in Table, the coal samples were subjected to proximate and ultimate analysis to determine properties such as moisture content, ash content, fixed carbon, volatile matter, and calorific value. Data on the moisture content, ash content, volatile matter, and gross calorific value of coal samples Thar Coalfield Block II-1 and 2 were vitally essential and were obtained through the proximate analysis. These factors are crucial in determining the quality of coal and its applicability for different uses. We shall examine the results of the values collected in this debate. As it significantly affects several elements of coal consumption and combustion processes, moisture content is crucial in the proximate analysis of coal samples. In this discussion, we will look at the moisture content results for coal samples Thar Coalfield Block II-1 (5.4%) and Thar Coalfield Block II -2 (6.0%) and their ramifications. The term "moisture content in coal" refers to the total amount of water in the coal, including surface moisture and inherent moisture within the coal matrix. This factor is crucial because it directly affects the coal's energy content and combustion characteristics. When coal is utilized as a fuel, high moisture content can have several adverse effects. Coal's calorific value (heating value) decreases as moisture content increases on a mass basis. The energy available for heating is reduced since combustion with water uses energy to evaporate the water. The effectiveness of combustion can be lowered by the presence of moisture in coal. Higher temperatures are required to drive out the moisture before the carbon content can be effectively burned. As a result, combustion processes may use more fuel and have worse thermal efficiency.

Table 4-1 Specifications of Sample Obtained from Thar Coalfield Block II

Sample	Moisture (%)	Ash (%)	Volatile Matter	Fixed Carbon	Gross Calorific Value	
	%	%	%	%	Kcal/kg	Btu/lb
Thar Coalfield Block II-1	5.4	6.2	52.4	36.0	6,647	11,957
Thar Coalfield Block II-2	6	4.8	56.1	33.0	6,332	11,390

More significant emissions of pollutants, including carbon dioxide, sulfur dioxide, and nitrogen oxides during burning, may result from coal with a greater moisture content. This is because vaporizing the moisture requires more energy than usual, which might change the chemistry of combustion. High moisture content can make handling and shipping coal more difficult logistically. Wet coal is more likely to burn spontaneously, resulting in problems like coal pile fires. Moreover, the extra weight of the water drives up the shipping cost. The proximate analysis of coal samples uses ash content as a critical metric since it gives essential details about the mineral matter in coal. In this discussion, we will examine the ash content values for coal samples Thar Coalfield Block II-1 (6.2%) and Thar Coalfield Block II-2 (4.8%) and their importance in determining coal quality. As seen in Thar Coalfield Block II-2 (4.8%), less ash often indicates improved combustion efficiency. This is because coal with reduced ash content has more combustible carbon in its bulk, increasing the coal's calorific value and improving energy generation efficiency during burning. During combustion, reduced emissions of particulate matter and other pollutants, such as sulfur dioxide, are linked to lower ash content. This has implications for concerns about air quality and environmental compliance. Ash deposition and slagging in furnaces and boilers can rise with higher ash concentration, such as the 6.2% in Thar Coalfield Block II-1. This calls for more regular upkeep and cleaning, slows operations, and raises expenses. The ash content measurements made for coal samples Thar Coalfield Block II-1 and Thar Coalfield Block II-2 reveal variations in each sample's capacity for combustion, environmental effect, and applicability. While Thar Coalfield Block II-1's greater ash concentration may necessitate further processing or specific uses, Thar Coalfield Block II-2's lower ash content is often helpful for energy generation and environmental considerations. Proper coal characterization, including ash content, is crucial to maximize coal usage and reduce operational and ecological difficulties. The amount of coal that may be driven out as gas or vapor when heated in a controlled atmosphere is called volatile matter in coal. Variations in the volatile matter between Thar Coalfield Block II-1 and Thar Coalfield Block II -2 suggest different combustion characteristics. Thar Coalfield Block II-2 has a greater volatile matter concentration (56.1%), implying that it is more reactive and ignitable. This can be helpful in activities like power generation or industrial ones where quick combustion is necessary. Due to its lower volatile matter concentration (52.4%), Thar Coalfield Block II-1 could be more appropriate for industrial situations where regulated combustion and less flame propagation are sought. The part of stable and non-volatile coal is known as fixed carbon. The observed variances in fixed carbon content between Thar Coalfield Block II-1 and Thar Coalfield Block II-2 show the changes in the coal's carbon-rich percentage. The percentage of fixed carbon in Thar Coalfield Block II-1 is more significant, at 36%, which often results in a higher gross calorific value (explained below). This implies that Thar Coalfield Block II-1 could have more energy per unit of mass. Due to its lower fixed carbon content (33.1%), Thar Coalfield Block II-2 could have a slightly lower mass-based energy content than Thar Coalfield Block II-1. The gross calorific value indicates the total energy released per unit mass of coal upon complete burning. It is a crucial factor in determining how much energy coal can produce. Compared to Thar Coalfield Block II-2, Thar Coalfield Block II -1 has a more excellent gross calorific value of 6647 Kcal/kg, meaning it has more energy per unit mass. This increased energy content may be beneficial in situations where heat generation and energy efficiency are important. Thar Coalfield Block II-2, although having a somewhat lower gross calorific value of 6332 kcal/kg, may nevertheless be appropriate for situations where reaching the maximum energy content is less crucial than ensuring quick combustion and ignition. The distinctions between Thar Coalfield Block II-1 and Thar Coalfield Block II-2 in terms of volatile matter, fixed carbon, and gross calorific value highlight the significance of coal characterization when choosing the best coal type for a particular application. Each form of coal has benefits and could be more appropriate for industrial processes or combustion systems. According to proximate analysis, the combustion behavior and energy content of coal samples Thar Coalfield Block II-1 and Thar Coalfield Block II-2 vary. These coals should be chosen depending on the needs of the intended use, considering elements like ignition characteristics, combustion efficiency, and energy content. Proper coal type selection is crucial for maximizing efficiency and reducing environmental effects.

4.2. Coal Consumption

The graphs below provide a comparative analysis of coal consumption in the Direct Combustion systems and the Integrated Gasification Combined Cycle. The Direct Combustion system utilizes a significantly higher amount of coal than the Integrated Gasification Combined Cycle system. This discrepancy arises from the different operational mechanisms of the two systems.

More coal is required to produce a substantial volume of flue gases in the Direct Combustion system. These flue gases are essential for converting more water into steam, which drives the turbines and generates power. This process inherently demands a higher coal input to achieve the necessary thermal energy for steam production.

On the other hand, the Integrated Gasification Combined Cycle system employs a more advanced and efficient method of coal utilization. By gasifying the coal, the Integrated Gasification Combined Cycle system converts it into a synthesis gas (syngas), which can be cleaned of impurities before combustion. This syngas is then used to fuel gas turbines, with the resultant waste heat being used to produce steam for additional power generation via a steam turbine. This dual-cycle approach enhances the overall efficiency of the power generation process and significantly reduces the amount of coal required.

To illustrate this with specific figures, the Direct Combustion system utilizes approximately 250 kilograms of coal per second to generate 300 megawatts of electrical power (MWe). The Integrated Gasification Combined Cycle system requires 34 kilograms of coal per second to produce the same energy. However, higher upfront costs, and the significant environmental risks associated with carbon emissions and water consumption do raise concerns about the long-term sustainability of coal gasification as a truly viable solution for cleaner energy generation.

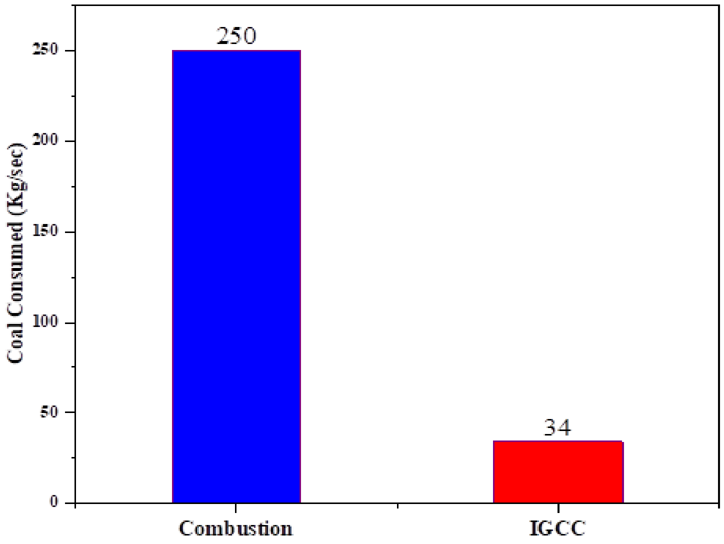


Figure 4-1 Comparison of coal amount consumption in Both Integrated Gasification Combined Cycle and Direct Combustion

4.3. Power Generation

The Integrated Gasification Combined Cycle system utilizes a diverse range of feedstocks such as coal, petroleum coke, and biomass. This versatility makes it a unique technology for electricity generation.

Below, tables 4-3 represent the amount of fixed carbon and how the amount of fixed carbon affects the power generation in both Integrated Gasification Combined Cycle and Direct Combustion.

Process	Fixed Carbon (%)	Power (MWe)
Combustion	36	300
IGCC	36	316

Table 4-2 Power Generation

This system produces electricity through a combination of gas and steam turbines. Specifically, the designed system generates 252 megawatts (MWe) of power using gas turbines and an additional 64 (Mwe) through a steam turbine, culminating in a total capacity of 316 megawatts of electrical output (MWe).

Chapter: 5

Emissions from Power Plants and its Impact on the Environment

Pakistan ranks as the second most polluted country globally, following Bangladesh, based on population-weighted Particulate Matter 2.5 concentration, according to the 2023 World Air Quality Report by IQAir[7]. In 2023, two of the 15 most polluted cities were in Pakistan, with an average Particulate Matter $_{2.5}$ concentration of 73.7 μg/m^3 – 14 times higher than the World Health Organization guideline of 5 μg/m^3 [8]. High pollution levels make air pollution the leading environmental risk factor for mortality in Pakistan, responsible for over 256,000 deaths in 2021[9]. The Status of Global Air report (Health Effects Institute, 2019) estimates a reduction in life expectancy at birth due to air pollution exposure in Pakistan by 2 years and 8 months.

Major sources of air pollution globally include the burning of fossil fuels in the transportation sector and energy production/industries, biomass burning for cooking/heating, agricultural biomass burning, dust/pollution emissions from construction, and municipal waste burning. Improvement in air quality has been observed in regions that reduced harmful emissions and shifted towards cleaner energy sources, such as the United States, European Union, and China. India has also implemented stricter emission standards and formulated a national clean air action plan to reduce pollution levels. Contrarily, Pakistan is increasing its fossil fuel capacity with new coal-based power plants, exacerbating pollution problems. This issue is critical given the lack of stringent emission standards for coal-based power plants, unlike those in the European Union, United States, China, and India. As of 2024, Pakistan has significantly expanded its coal-fired power generation capacity. The country currently has an installed capacity of 6,600 MW from various coal-fired power plants. This includes 3,300 MW from five power plants using Thar coal and an additional 3,960 MW from plants using imported coal[10]. A power plant can affect the environment through both its construction and operation, with impacts that can be either temporary or permanent. The plant and its auxiliary components such as water intakes and discharge, coal delivery and storage systems, new transmission lines, and waste disposal sites occupy space, utilize water resources, and often emit pollutants. Fossil fuel-fired and biomass-fired plants burn fuels to produce hot air or steam to spin turbines and generate electricity, creating exhaust gases and other by-products, including air pollutants. Operating coal-fired power plants emit these pollutants into the atmosphere, necessitating pollution control equipment to reduce emissions and mitigate their environmental impact.

Table 5.1: Major Air Pollutants

Major Air Pollutants from Coal Power Plant		
Sulfur dioxide	SO_2	tons/hr
Nitrogen oxides	NO_x	tons/hr
Carbon monoxide	CO	tons/hr
Ozone	O_3	tons/hr
Particulate matter	$PM_{2.5}$ or PM_{10}	tons/hr
Lead	Pb	tons/hr

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[7] *https://www.iqair.com/world-most-polluted-countries*

[8] *https://thefridaytimes.com/19-Mar-2024/pakistan-is-world-s-second-most-polluted-country-for-2023*

[9] *https://www.stateofglobalair.org/hap*

[10] *https://thediplomat.com/2023/09/pakistans-energy-crossroads-coal-dependency-the-climate-crisis-and-a-quest-for-sustainability/*

5.1. Global Climate

The planet's ability to retain solar heat is dependent on concentrations of "greenhouse gases" that are in the atmosphere. Greenhouse gases are gases in the atmosphere that trap heat, like greenhouse glass, and help keep the planet warm enough for life to survive. The three main greenhouse gases influenced by human activities are carbon dioxide, methane, and nitrous oxide. Power plants fueled by fossil fuels like coal produce large amounts of carbon dioxide. Since the beginning of the industrial revolution when large-scale consumption of fossil fuels began, atmospheric concentrations of carbon dioxide have increased over 30 percent. About half of that increase has occurred since 1970, and the rate of increase has grown since 2000. Scientists believe that increases in Greenhouse gases concentrations have contributed to additional warming of the planet, and continued increases in concentrations are expected to cause further warming and a variety of global climate changes soon. Increasing amounts of carbon dioxide and other greenhouse gases in the atmosphere appear to be having substantial impacts on the environment and human health in a variety of places on the planet already. These impacts could include rising sea levels, melting of glaciers and polar ice caps, altered ocean currents, climate alteration, and wider ranges of insect-borne diseases of humans and crops. To reduce these impacts carbon capture and storage is essential to address when dealing with coal-fired thermal power plants (Figure 5-1).

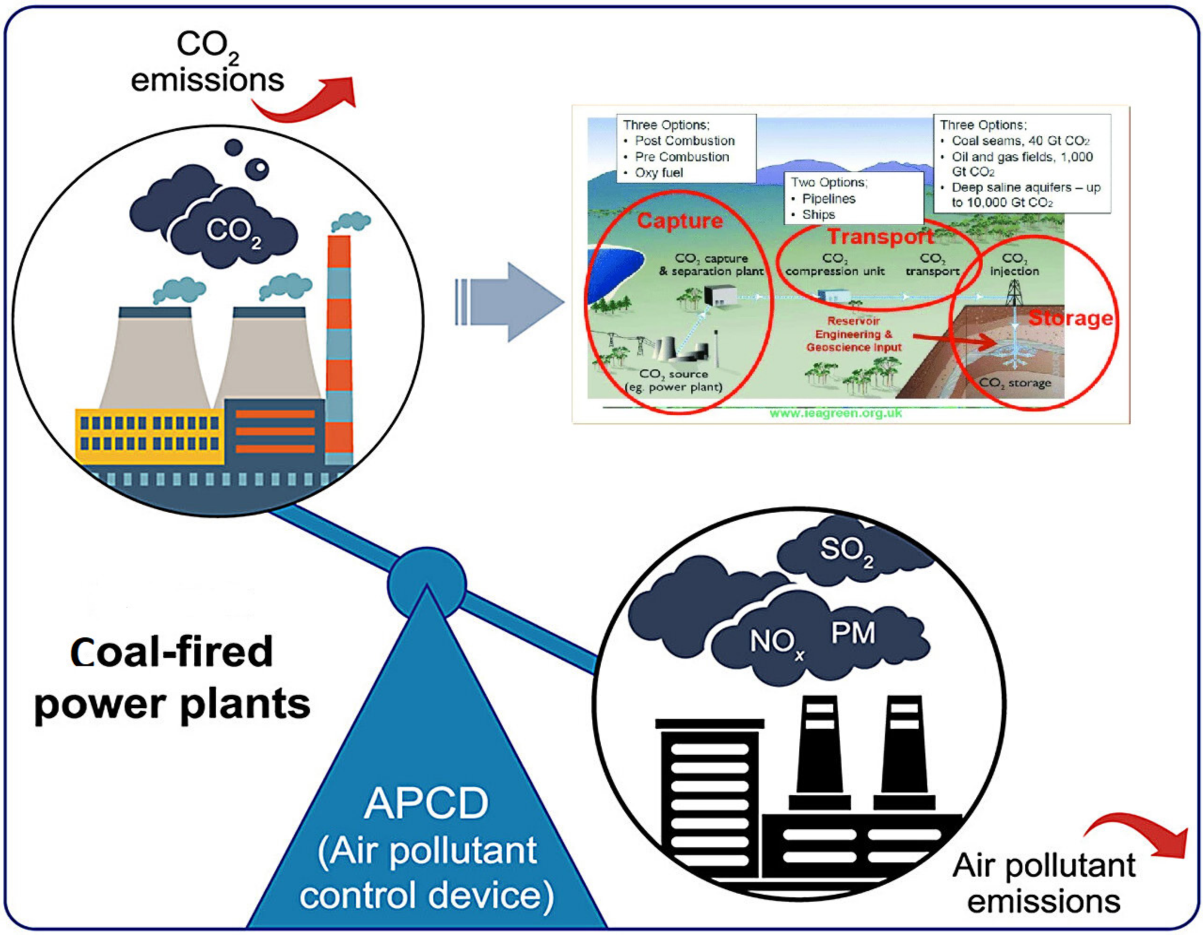

Figure 5.1: Major emissions from coal-fired power plants and mitigation technologies [38]

The Intergovernmental Panel on Climate Change proposed reducing greenhouse gases emissions. Either by capturing carbon dioxide at the exhaust stack and depositing it in underground geologic formations or planting forests to take it up carbon dioxide. However, it is not likely that enough trees could be planted to significantly reduce greenhouse gases levels in the atmosphere, indeed not in time to avoid climate change. A third way to reduce greenhouse gases emissions would be to reduce fossil fuel-fired power plant generation with increased industrial, commercial, and residential energy efficiency (or conservation) and by generation of electricity using renewable resources such as wind power, solar power, or possibly short-term closed-loop biomass power plant systems. With conservation and renewable resources for energy, methods are also being researched, looking for ways to extract carbon dioxide from the atmosphere.

5.2. Major Pollutants from Coal Power Plant

Many types of coal contain varying amounts of sulfur, which, when burned, combine with oxygen to form sulfur dioxide. Sulfur dioxide has been a cause of acid precipitation, commonly known as “acid rain,” which can damage vegetation and acidify lakes. Species vulnerable to acidic conditions have trouble reproducing and, in some cases, die. To reduce sulfur dioxide emissions from thermal power plants, several strategies and technologies can be implemented, such as Flue Gas Desulfurization, also known as scrubbers, which can remove sulfur dioxide from exhaust flue gases by using chemical reactions with a sorbent, typically lime or limestone. Fluidized Bed Combustion can burn fuel in a bed of solid particles, such as limestone, which reacts with sulfur to form solid calcium sulfate, thus removing sulfur dioxide before escaping into the atmosphere.

Nitrogen oxides and volatile organic compounds are components of ozone formation. Ozone is a principal component of smog and can result in respiratory health and other environmental effects. Particulate matter 10 includes dust and smaller particles with a maximum particle diameter of 10 microns. It takes 1,000 microns to equal 1 millimeter. In addition to PM_{10} emission standards, there are federal standards for Particulate $matter_{2.5}$, tiny particles with a diameter less than 2.5 microns. Small particulates have been known to cause severe respiratory problems because they can penetrate deeper into the lungs than larger particulates. A more significant concern is the nitrogen oxides and Sulfur dioxide emissions from power plants that burn coal or natural gas. These compounds are part of a complex chemical reaction in the atmosphere that creates nitrate- and sulfate-based fine particulates.

5.3. Emissions

Environmental Impact Assessment reports for Block II, Thar Energy Limited, and Block VI power stations reveal significant emissions. These projects utilize Circulating Fluidized Bed and subcritical pulverized coal boilers, and their emissions data have been generalized across similar projects. Emissions were calculated by the Centre for Research on Energy and Clean Air, assuming the plants operate at 7,000 full-load hours per year. For plants without Environmental Impact Assessments, emissions were estimated using data from similar plants, scaled by capacity.

The findings indicate substantial mercury emissions, particularly for Block VI, where actual emissions are estimated to be 200 times higher than reported, due to underestimation of mercury capture by fly ash controls, which typically capture only about 20% of mercury. This presents a significant environmental and public health concern. Additionally, the EIA report from ***Thar Energy Limited*** indicates that particulate matter levels exceed Sindh Environmental Quality Standards and IFC guidelines, with similar issues likely for other plants in the cluster were anticipated. High emissions of nitrogen oxides and sulfur dioxide from these plants contribute to poor air quality and pose health risks, including respiratory issues and acid rain.

Dust emissions from the lignite mines, calculated using European Monitoring and Evaluation Program factors, are also significant. These calculations were based on coal consumption estimates, which are generally lower than production volumes, indicating potential underestimation of actual dust levels. The combined emissions from power plants and associated lignite mines in the Thar region significantly contribute to air pollution, affecting over 100,000 residents. The projected impacts include high levels of particulate matter $_{10}$, nitrogen oxides, sulfur dioxide and mercury, posing severe health and environmental risks.

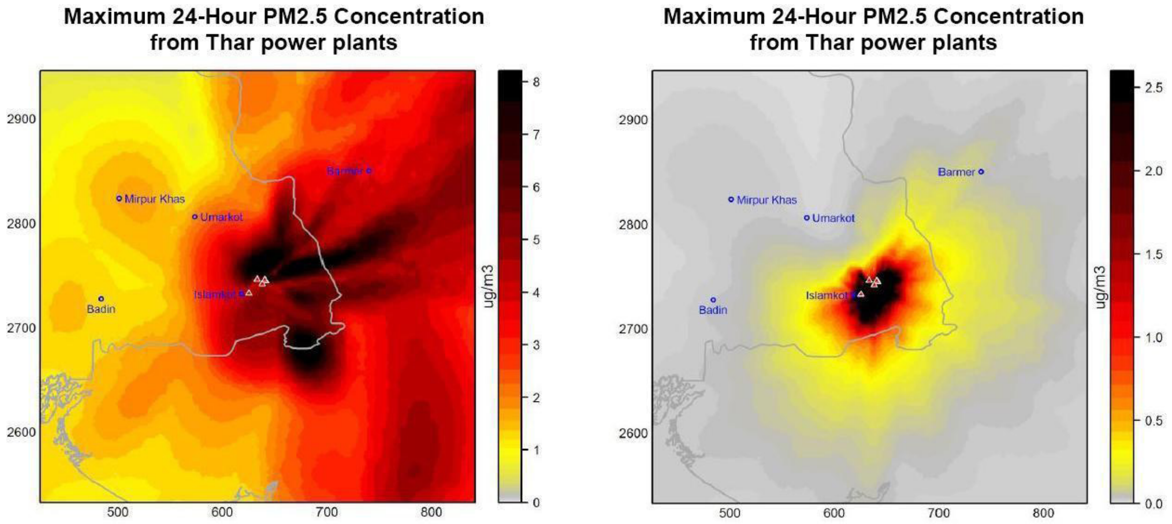

Figure 5.2: Projected contributions from the Thar power plants and mines to ambient Particulate matter $_{2.5}$ levels.

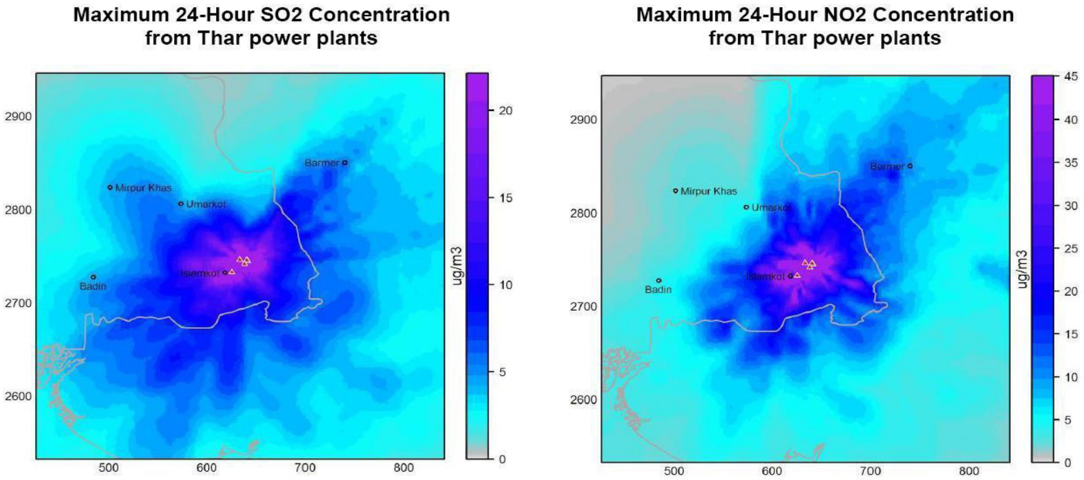

Figure 5.3: Projected contributions from the Thar power plants to ambient nitrogen oxides and sulfur dioxide levels.

5.3.1 Mercury and Heavy Metal Deposition

The Thar power plant and mining cluster are projected to emit approximately 1,400 kg of mercury and 5,000 tonnes of heavy metal-containing particulate matter (coal dust and fly ash) annually. About 22% of the emitted mercury, or approximately 320 kg per year, is expected to be deposited into land and freshwater ecosystems in the region. Mercury deposition rates as low as 125 mg/ha/year can result in unsafe levels of mercury in fish[11]. The plants are predicted to cause mercury deposition above this threshold over an area of 1,300 km² to the northeast, impacting a population of approximately 100,000 people.

While the actual mercury uptake and biomagnification depend on local chemistry, hydrology, and biology, the predicted rates are a serious concern. An urgent assessment of the impacts and measures to reduce mercury emissions is essential.

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[11] *Swain EB, Engstrom DR, Brigham ME, Henning TA & Brezonik PL 1992: Increasing Rates of Atmospheric Mercury Deposition in Midcontinental North America. Science257:784-787.*

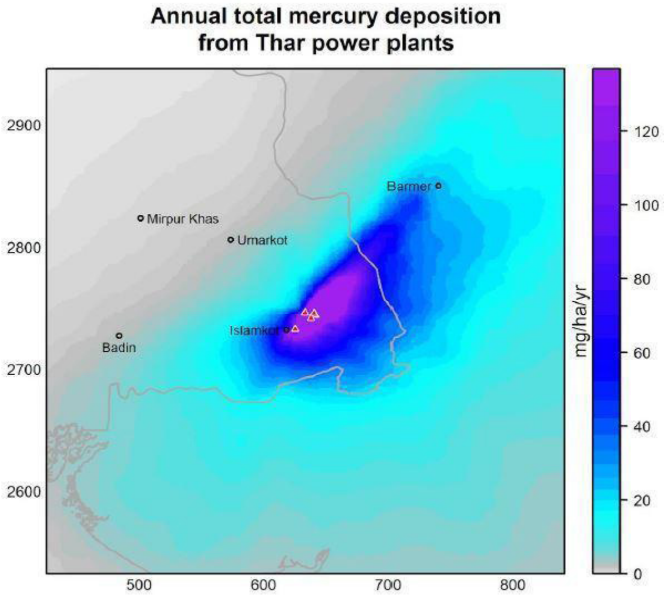

Figure 5:4 **Annual Mercury contributions from the Thar power plants**

5.4. Importance of fixed Carbon in Coal Combustion

Fixed carbon in coal combustion plays a critical role as it represents the solid, combustible residue that remains after the volatile matter in the coal is driven off. Fixed carbon reacts with oxygen during the combustion process to produce carbon dioxide and heat. This reaction occurs after the volatile matter has been released and burned, providing sustained heat over a more extended period. Fixed carbon combustion is responsible for a significant portion of the total heat generated from burning coal. This heat is essential for power generation in thermal power plants.

$$\text{Fixed Carbon (\%)} = 100\% - \text{Moisture (\%)} - \text{Volatile Matter (\%)} - \text{Ash (\%)}$$

The fixed carbon content is a critical indicator of coal quality. Higher fixed carbon content generally signifies better fuel quality with higher calorific value and more efficient combustion characteristics. Therefore, a simulation-based comparative study for a 300 MW power plant was performed to elaborate on the comparison of emissions between direct combustion and the Integrated Gasification Combined Cycle process. For both processes, fixed carbon (36%) has been considered, as observed in sample Thar Coalfield Block II-1.

5.5. Comparison of Emissions in Direct Combustion and Integrated Gasification Combined Cycle

Table 2 reflects the mass fraction and number of pollutants in kg/hr and tons/hr generated from direct combustion and Integrated Gasification Combined Cycle. The significant contaminants mentioned above are carbon dioxide, Nitrogen oxides, Sulfur dioxide, carbon monoxide, methane, and Particulate matter, while others include water, hydrogen, argon, oxygen, and chlorine. Figure 5 represents the pie chart for the emissions generated by both technologies. The Integrated Gasification Combined Cycle process exhibits a lower carbon dioxide amount compared to direct combustion. This suggests that the Integrated Gasification Combined Cycle process has the potential for lower carbon dioxide emissions, making it a more environmentally friendly option but not wholly carbon-free. Both methods produce Nitrogen oxides emissions, but the Integrated Gasification Combined Cycle process has a slightly lower amount of Nitrogen oxides, as shown in Figure 5. This could contribute to improved air quality.

The Integrated Gasification Combined Cycle process appears to have potentially lower emissions options but with significant environmental and economic challenges, such as over-direct combustion, particularly in terms of carbon dioxide emissions and Nitrogen oxides reduction. However, both processes come with their own set of challenges and considerations, and a comprehensive analysis should include factors such as cost, efficiency, and technological feasibility, which is discussed in TORs for level IV. The suitable technologies to accommodate the energy requirements instead of coal processing technologies that can be installed are renewable energy resources, e.g., solar power and wind power, bioenergy, and waste-to-energy generation.

Table 5.2: Emission Comparison of Direct Combustion and Integrated Gasification Combined Cycle

Direct Combustion				IGCC		
Components	Mass Fractions	Mass Flow (kg/hr)	Mass Flow (tons/hr)	Mass Fractions	Mass Flow (kg/hr)	Mass Flow (tons/hr)
CO2	0.1197477	181058.589	199.58	0.249768	57258.841	63.12
NOx	0.007560014	7892.65441	8.70	0.0119033	2736.51	3.02
SOx	0.023639495	24679.6326	27.20	8.56951E-05	1678.8733	1.85
PM	0.047632391	49728.2164	54.82	0.084	25748.346	28.38
CH4	0.001080264	1127.79607	1.24	3.48E-07	0.0887889	0.00
CO	0.674438668	7.04E+05	776.03	0.519622	119123.41	131.31
O2	4.46E-18	4.66E-12	0.00	0.004514675	0.004364	0.00
Cl2	0.000998906	1.04E+03	1.15	-	-	-
H2O	0.000661171	690.262276	0.76	0.2606	79897.076	6.80
H2	0.10368041	108242.348	119.32	0.02767528	6170.6659	119.32
Ar	-	-	-	0.021514383	4742.378	5.23

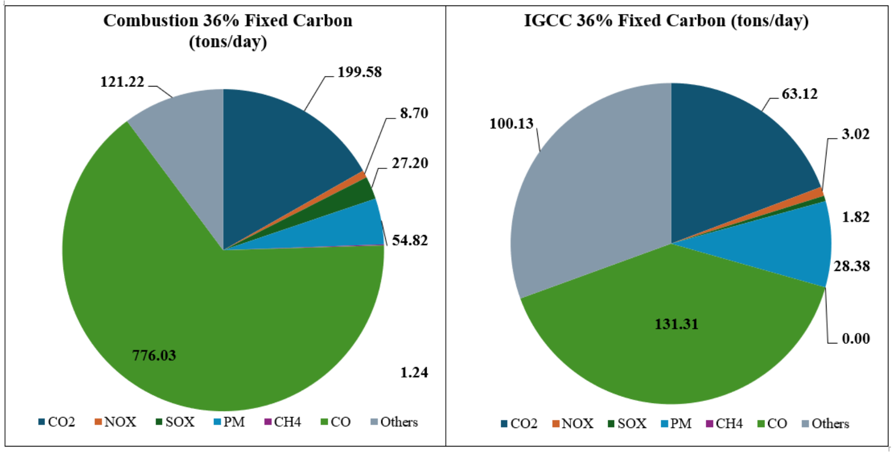

Figure 5.5: Comparison of emissions from direct combustion and Integrated Gasification Combined Cycle, (a) Direct combustion and (b) Integrated Gasification Combined Cycle

Carbon dioxide emissions from coal power plants are a major contributor to global warming. To enhance energy security, two approaches could play a vital role: implementing carbon capture and storage technologies or transitioning to renewable energy sources like solar, wind, hydropower, and geothermal, along with nuclear power. However, policy measures, technological advancements, energy efficiency improvements, and public engagement are crucial to facilitating this transition.

Chapter: 6

Water Supply and Environmental Impact

6.1. Overview

This chapter examines the water supply and environmental impacts of coal mining and coal-fired power generation in the Thar region. It highlights the challenges of water scarcity, contamination, and the broader implications for public health and environmental sustainability. The chapter provides a detailed analysis of water usage, contamination levels, health impacts, and potential mitigation strategies to address these critical issues.

Extracting energy from indigenous coal sources requires significant water use for coal mining and thermal generation. Throughout its lifecycle—from mining and processing to transportation and combustion—coal releases numerous pollutants into the air, water, and soil. This pollution begins with coal mining, which emits harmful contaminants such as methane, a potent greenhouse gas contributing to global warming, and particulate matter, which can cause premature deaths, chronic bronchitis, heart attacks, and aggravate respiratory and cardiovascular diseases. Furthermore, coal combustion at thermal power plants releases five primary air pollutants: PM, nitrogen oxides, sulfur dioxide, mercury, and carbon dioxide, compounding the environmental and health challenges faced by the Thar region.

Coal mining operations impact both surface water and groundwater. Acid mine drainage, a waste product from mining sites, carries heavy metals and toxins into streams and groundwater, making the water undrinkable. Surface mining involves removing soil and rock above coal deposits, causing deforestation, changing landscapes, and eroding natural habitats. Besides air pollution and land degradation, coal mining operations and power generation at thermal plants also adversely impact local water resources. Open-pit mining, a technique used in the Thar region, involves dewatering, which depletes the groundwater table. Highly acidic water containing heavy metals like arsenic, copper, and lead are often discharged from mining operations, contaminating nearby water bodies such as rivers, streams, lakes, and aquifers, posing severe threats to public health and local ecosystems.

After mining, coal is washed with water and chemicals to remove impurities, producing coal slurry stored in improvised ponds that can leak, spill, or fail. Coal combustion at thermal power plants leaves behind coal ash, a gray powdery substance containing concentrated amounts of toxic elements, including arsenic, lead, and mercury. Sulfur dioxide from coal combustion causes acid rain, which acidifies lakes and streams, destroying aquatic habitats and damaging forests. Mercury released from coal power plants is deposited on soil and water, transforming into methylmercury, a highly toxic form that accumulates in fish tissue.

Coal-fired power plants require vast amounts of water to create steam, which turns turbines to generate electricity. This water is typically sourced from nearby rivers, lakes, and canals. Water utilization for coal power plants significantly affects local communities that depend on these water sources for drinking, domestic use, irrigation, fishing, and other livelihoods.

The Thar Desert, where Pakistan's enormous lignite coal reserves are located, is notable for being the only desert where plants can grow. Although rich in coal and other mineral resources, Thar is a water-scarce region with no regular surface water. The primary water source is underground, with water quality ranging from saline to brackish. Most of the local population relies on dug wells, which vary in depth from 10 to 100 meters, for drinking, domestic use, and animal rearing. Donkeys, camels, and human effort pull out water from these wells. People spend three to four hours daily fetching a few liters of water in many areas. The region receives an average rainfall of 250-300 millimeters (mm), mainly during the monsoon season from mid-June to mid-August. Based on 17 years of data (2004-2020), the maximum rainfall recorded was 1,361 mm during August-September 2011 at Mithi station. The district has a tropical desert climate with deficient rain. (Figure 6-1).

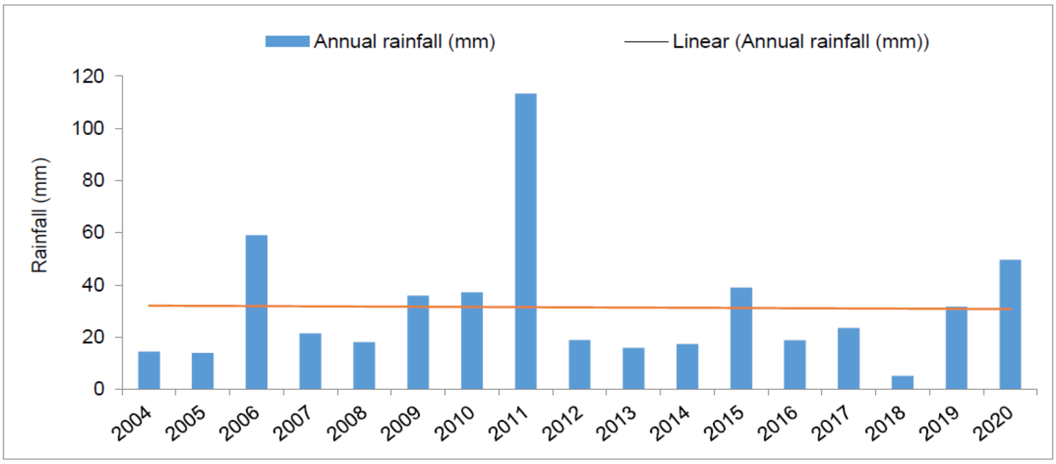

Figure 6-1 Mean Annual Rainfall at Mithi, Thar [39]

This water-scarce region of Pakistan hosts the Seventh-largest coal reserves in the world[12]. Out of the total coal reserves of 186 billion tons (bt), 176 are concentrated in a single contiguous 9,000 square kilometers in the Tharparkar district of Sindh province. Mithi, the district headquarters of Tharparkar, is located approximately 380 km east of Karachi, the provincial capital of Sindh (Figure 6-1). The 'Thar coal reserves' exceed the combined oil reserves of Saudi Arabia and Iran by 50 billion tons, with the potential to generate 100,000 megawatts (MW) of electricity for over 200 years. This vast potential underscore the significance of Thar coal in bolstering Pakistan's energy security and meeting its long-term power needs.

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[12] *LOCAL COAL FOR POWER GENERATION IN PAKISTAN*

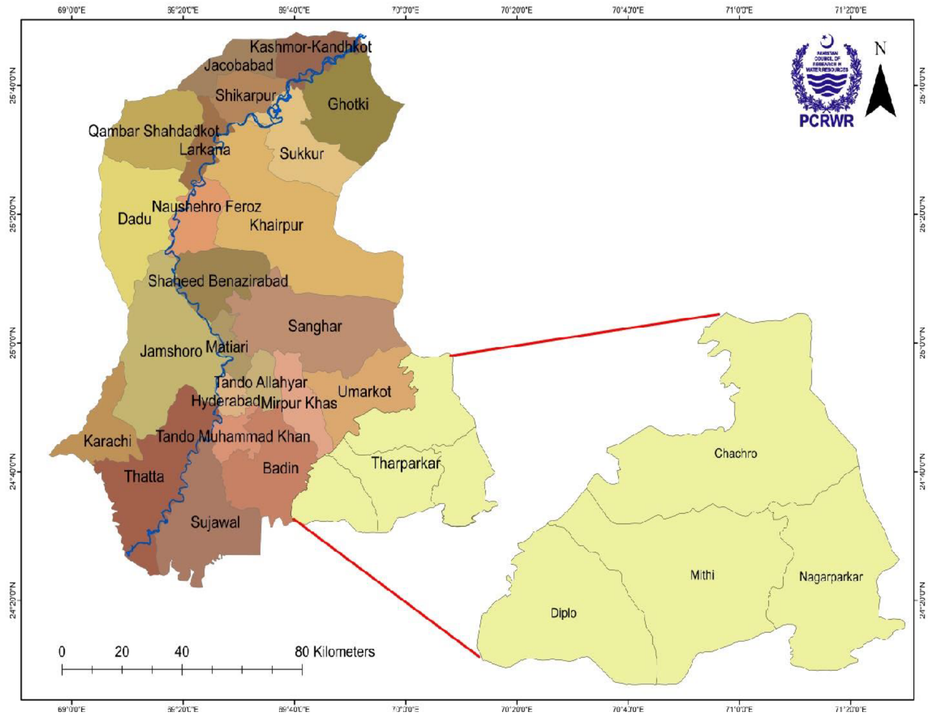


Figure 6-2 Map of Tharparkar [39]

Activities related to coal mining and power production in Thar have significantly impacted local communities. These activities include:

I. **The disposal of saline water extracted from coal mines,**

II. **The discharge of wastewater from coal mines and thermal power plants and**

III. **The infrastructure for diverting water from the Nara Canal to the Thar coalfield is being constructed.**

These actions have resulted in water depletion, increased water toxicity, a significant rise in malaria incidence, and livestock death, severely affecting the health and livelihoods of the local population.

6.2. Aquifers of Thar Coal Field

Thar coal is buried under layers of groundwater or aquifers (Figure 6-3, 6-4):

I. **The recent dune sand aquifer, located at a depth of 50m to 60m,**

II. **The sub-recent or coal seam roof aquifer, at a depth of 100m to 120m,**

III. **The Bara formation or coal seam floor aquifer, at 200m to 250m depth.**

Among these, only the top aquifer, recharged by rainwater, is deemed usable. For coal extraction, these aquifers must be drained, making dewatering of open pits an essential component of coal mining projects. Depressurization is necessary to reach coal at a depth of 150 meters, keeping the mine dry and safe. Coal companies have installed submersible sumps at the bottom of the pits to drain the groundwater. This dewatering lowers the water table, particularly in areas neighboring mining sites, causing noticeable water depletion in nearby villages.

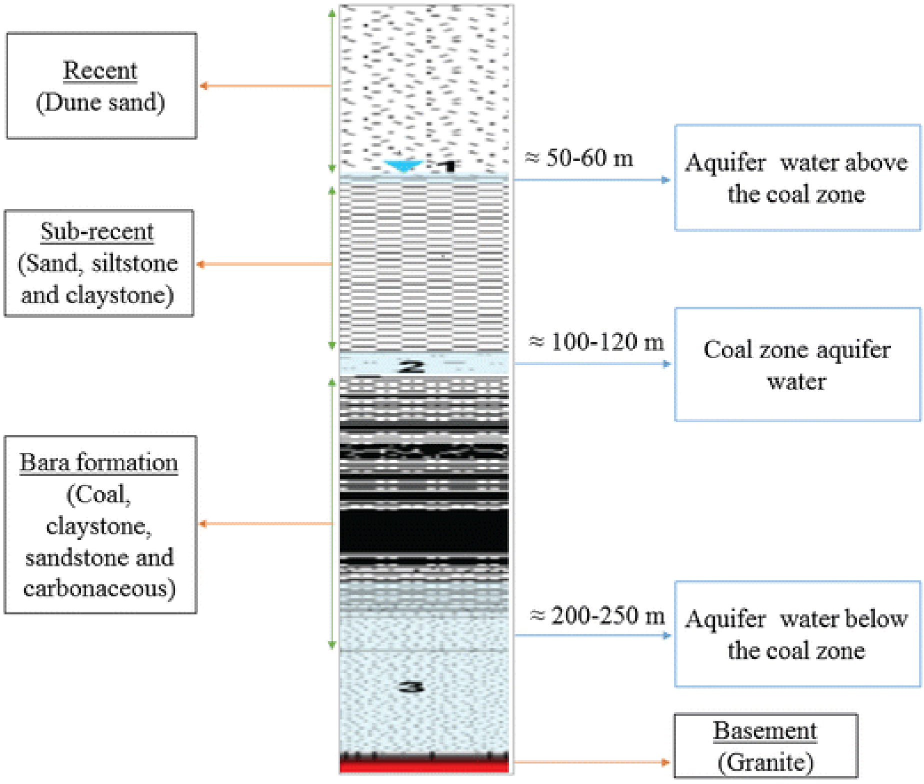


Figure 6-3 Coal Buried Under Aquifer [40]

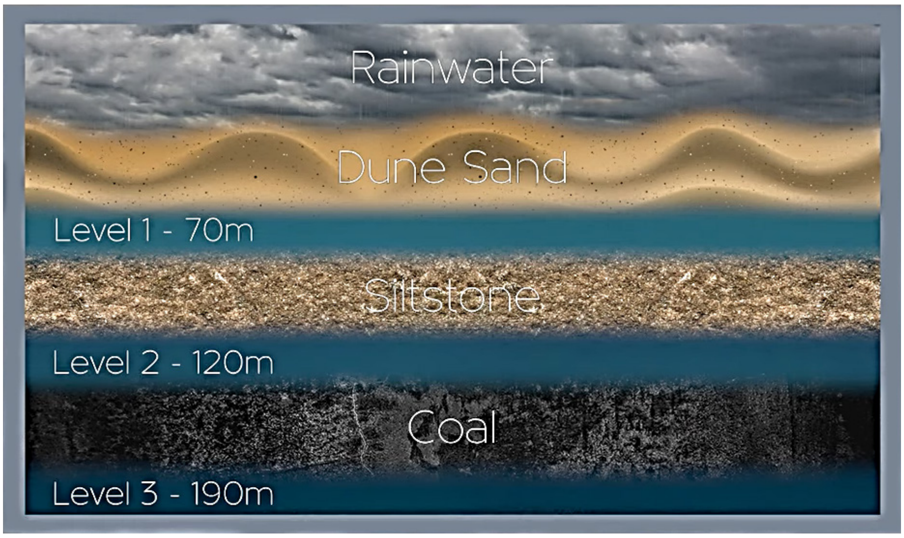


Figure 6-4 Coal Under Earth's Surface [41]

Millions of gallons of water are extracted daily from Block I and Block II mining sites to facilitate coal mining operations. Large reservoirs are necessary to manage and dispose of this flowing water. The Sindh Engro Coal Mining Company constructed the first reservoir at Gorano in 2016, covering an area of 1500 acres and located 37 kilometers from the Block II coal mining site (Figure 6-5). Effluent water from Block II is discharged near the Dukkar Shah village, while effluent from Block I is discharged near the Warvai village. These discharge practices have raised concerns among local communities about water contamination and its impact on their health and livelihoods.

Figure 6-5 Mining Site Distance [41]

The expansion of mining operations necessitates the construction of additional reservoirs in the Thar coalfield, as the Gorano reservoir alone cannot accommodate the increasing volume of wastewater. This surge in wastewater has significantly impacted both the quality and quantity of groundwater in Thar, leading to land degradation and posing severe threats to animals and livestock. Water samples from nine locations near Block II (Figure 6-6) were recently tested at the USPCAS-W laboratory of Mehran University of Engineering and Technology, Jamshoro (Figure 6-7). As detailed in Table 6-1, the results confirmed significant water contamination. Contaminants such as lead, mercury, and arsenic were found at levels far exceeding acceptable standards. Five reverse osmosis plants are currently operating in Gorano village to mitigate these issues.

Figure 6-6 Water Sample Collection Sites [41]

Table 6-1 Water Contamination Levels in Thar Coal Block 2 (Highlighted rows represent the WHO standards, and others represent Sindh Standards) [41]

Water Sample	Khario Ghulam Shah Village	Village Jamun Samno Well	Amra Well Ehitra	Pare So Tar Water Tank	Megho Jo Tar Pipeline	Megho Jo Tar Water Tank
Pb (Lead)	610% Higher	750% Higher	690% Higher	290% Higher	3200% Higher	1400% Higher
	42% Higher	50% Higher	58% Higher	N/A	560% Higher	200% Higher
Hg (Mercury)	5900% Highest	1800% Higher	4600% Higher	18,900% Higher	9400% Higher	9300% Higher
	5900% Higher	1800% Higher	4600% Higher	18,900% Higher	9400% Higher	9300% Higher
As (Arsenic)	N/A	160% Higher	150% Highest	N/A	150% Higher	150% Higher
	N/A	N/A	N/A	N/A	N/A	N/A
Se (Selenium)	N/A	N/A	500% Higher	N/A	1900% Higher	620% Higher
	N/A	N/A	500% Higher	N/A	1900% Higher	620% Higher
Cr (Chromium)	N/A	N/A	N/A	N/A	N/A	36% Higher
	N/A	N/A	N/A	N/A	N/A	36% Higher

6.3. Source of Water for Thar Coal Power Plant

A thermal power plant converts fuel into heat energy, which is then transformed into electricity using a steam turbine. This process requires substantial amounts of freshwater to produce steam. The primary water sources for the Thar coal power plant are the Left Bank Outfall Drain and underground water extracted during coal mining operations. This underground water, initially saline, is treated for use in the power plant. For the operation of a 660 MW power plant, approximately 17 cusecs (about 481 liters) of water per day are required. During mining, around 25 cusecs of saline water are extracted daily. After treatment and accounting for losses, 17 cusecs of usable water remain, sufficient for the plant's needs [41].

6.4. Water Informatics of Thar Coal Block II

In this study, to assess the hydrogeological conditions around the coal fields, three groundwater samples were collected from strategically selected locations: Aban Jothar (AJS-1), Bithra (BS-2), and Jeando Dars (JDS-3). The locations of these samples are as follows:

Water Samples	Collected Location
AJS-1	6km from mine and 2km from power plant
BS-2	4km from mine and 1km from power plant
JDS-3	1.5km from mine and 1km from power plant

All samples were meticulously labeled, documented, and preserved to maintain their integrity during transportation to the laboratory. Appropriate sample containers and preservation techniques were used to prevent contamination or alteration. Various physical and chemical properties, including pH, salinity, total dissolved solids, resistance, conductivity, and turbidity, were measured and are tabulated in Table 6-2. These measurements are crucial for understanding the potential impact of mining activities on local water resources and developing strategies to mitigate any adverse effects.

Table 6-2 Properties of Collected Samples

Sample	pH	Salinity (PSU)	TDS (mg/L)	Resistance (Ω)	Conductivity (Simens)	Turbidity (ntu)
AJS-1	7.74	3.03	2.780	180	5.570	0.05
BS-2	8.08	5.14	4.570	110	9.115	0.22
JDS-3	7.78	1.59	1.508	329	3.041	1.30

pH is crucial in chemical reactions, industrial operations, and aquatic ecosystems. The pH readings in this study fall within the generally neutral range, indicating that the water is neither too acidic nor very alkaline. However, the slightly alkaline nature of BS-2 could influence its suitability for specific industrial uses and aquatic environments. Salinity levels significantly impact marine life and determine the water's appropriateness for various applications. The highest salinity level was found in Bithra-2 (5.14 PSU), possibly due to different water sources or geographic regions. Such variations must be considered when evaluating water for specific uses.

Total Dissolved Solids measurements reflect the amount of dissolved substances in the water, including minerals and salts. The higher total dissolved solids level in Bithra-2 (4.570 ppm) indicates a more significant presence of dissolved components, which can influence the water's suitability for irrigation or drinking. Electrical conductivity, measured through water resistance, helps determine the ion concentration in the water. Higher resistance values, like in JDS-3 (329), imply lower conductivity. Conversely, the more excellent conductivity in Bithra-2 (9.115 Siemens) suggests a higher ion concentration, potentially affecting the water's corrosiveness and impact on aquatic life.

Turbidity measures water clarity and the presence of suspended particles. The different turbidity values across the samples (AJS-1: 0.05 NTU, BS-2: 0.22 NTU, and JDS-3: 1.30 NTU) indicate varying levels of particulate matter. As AJS-1 (0.05 NTU) shows, lower turbidity suggests more transparent water, which is preferable for applications like water treatment.

6.5. Water Requirement for Integrated Gasification Combined Cycle and Direct Combustion

Considering the critical relationship between power generation and water, it is essential to understand the water-related impacts associated with deploying advanced emerging technologies like Integrated Gasification Combined Cycle. Water consumption is a significant factor in the feasibility and sustainability of these technologies. Table 6-3 illustrates water consumption for various power generation platforms with and without carbon dioxide capture. Adding carbon dioxide capture and compression increases water consumption by 50% to 90%. This increase results from reduced plant efficiency (Figure 6-7) and the additional cooling water and process water requirements associated with carbon dioxide capture and compression. Understanding these impacts is crucial for planning and managing water resources in regions where water scarcity is a concern.

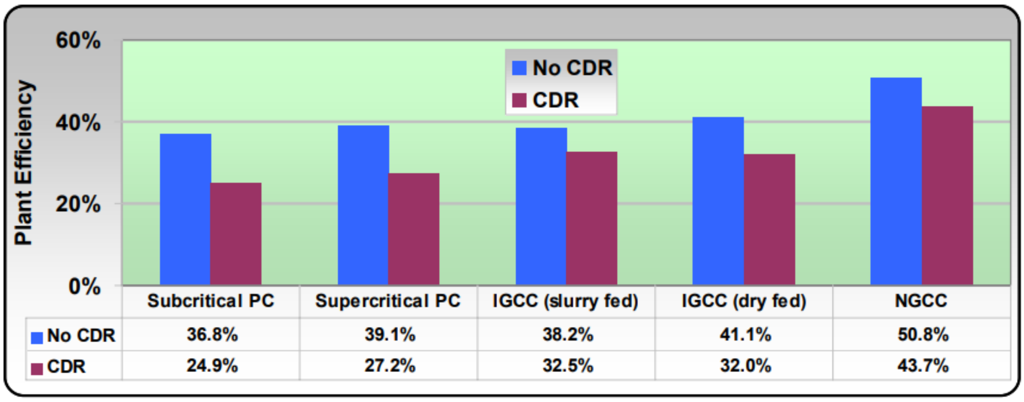


Figure 6-7 Comparison of Net Plant Efficiencies with and without Carbon Dioxide Recovery

Many advanced power platforms use less water and experience a lower increase in water demand with the incorporation of carbon dioxide capture equipment compared to current technologies. In this context, “consumption” refers to the water that needs to be replenished to account for both evaporation in the cooling tower and a relatively small amount used in unit operations within the generation process. The percentage change in water demand with the addition of carbon dioxide capture varies between cooling duty and overall water consumption because cooling duty does not include processed water requirements. While advanced technologies like IGCC may be somewhat more water-efficient than traditional power generation methods, their environmental and financial impacts remain significant and far less favorable compared to available renewable energy alternatives.

Table 6-3 Water Consumption for Thermoelectric Power Plants [42], [43]

Water Consumption (gallons per MWh)			
Technologies	Without CO_2 Capture	With CO_2 capture	% Change with CO_2 capture
Subcritical Pulverized Coal	520	990	+90%
Supercritical Pulverized Coal	450	840	+90%
IGCC, slurry-fed	310	450	+50%

6.6. Water Usage in Thermoelectric Plants (Direct Combustion)

The water-related impacts of fossil fuel thermoelectric power plants depend on two main factors: (1) the cooling and process water needs and (2) the system used to provide the cooling water. Thermoelectric power plants primarily use water to cool and condense the steam that drives the turbines. This cooling process is essential for the efficient operation of the plant. Additionally, smaller quantities of water are used for processing steam make-up and other water-intensive processes. Understanding these water needs is crucial for evaluating the overall environmental impact of thermoelectric power generation. Effective management of water resources is vital, especially in regions facing water scarcity, to ensure sustainable and environmentally responsible power production.

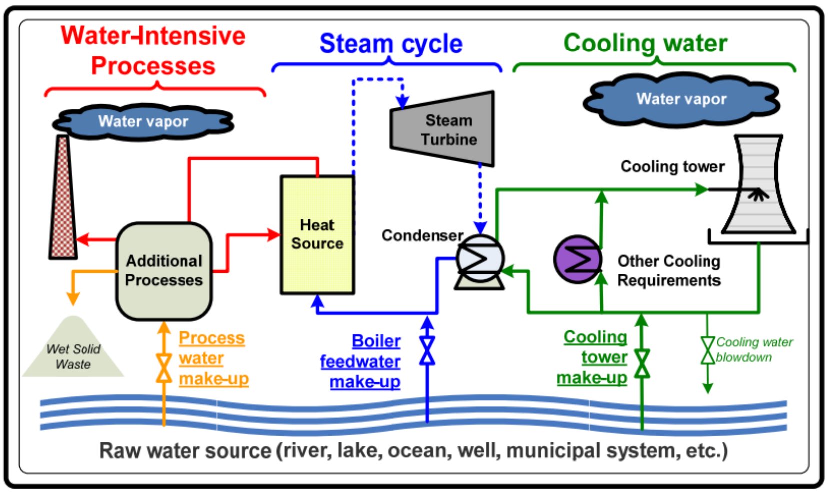


Figure 6- 8 Water Flow Schematic for Power Plants [43]

Approximately 43% of existing thermoelectric power plant generating capacity employs a once-through cooling water system. In this system, water is drawn from a natural water body, used to condense steam, and then returned to a higher temperature. This process, while simple, can contribute to thermal pollution of the water body. To mitigate this, more recent once-through cooling systems have incorporated cooling towers that lower the temperature of the discharged water, reducing its thermal impact on the environment.

Further reductions in water withdrawal can be achieved with recirculating systems. In these systems, most water is cooled in evaporative cooling towers and reused, with only a tiny amount discharged and replaced. This significantly decreases the total water usage compared to once-through systems.

An even more significant reduction in water use is possible with dry cooling systems, which are especially beneficial for arid regions. These systems utilize closed-loop air cooling, eliminating water losses due to evaporation and making them highly efficient in water-scarce areas. Adopting these advanced cooling systems is crucial for minimizing the environmental footprint of thermoelectric power plants.

6.7. Water Usage in Integrated Gasification Combined Cycle Plants

An Integrated Gasification Combined Cycle power plant has a significantly lower water profile than subcritical or supercritical pulverized coal plants, as shown in Figure 9. This is primarily because the gas turbine requires minimal cooling water and produces approximately 60% of the plant's total electrical output. The hot exhaust gas from the gas turbine passes through a heat recovery steam generator to drive a steam cycle. It is noteworthy that an IGCC's steam cycle operates at a lower pressure (1800 PSIG) compared to subcritical (2400 PSIG) and supercritical (3500 PSIG) PC plants. Consequently, an Integrated Gasification Combined Cycle plant consumes more water per MWh produced from the steam turbine than a PC plant.

In addition to the cooling water used for the steam condenser, an Integrated Gasification Combined Cycle plant has several other cooling requirements. In the air separation unit, cooling water is needed to cool compressed air before it enters the cryogenic air separation unit cold box. In the acid gas removal unit, hydrogen sulfide is removed through absorption by a chemical or physical solvent that must be regenerated using heat. Cooling water is primarily used in the regenerator tower condenser to cool the regenerated solvent. Finally, a small amount of cooling water is required for compressor intercoolers in the tail gas treating unit. Integrated Gasification Combined Cycle plants also have water make-up requirements related to the gasification process itself. In the gasifier, coal, oxygen, and steam react to produce a combustible gas called syngas. This complex process, though more efficient in water usage than traditional PC plants, still necessitates careful water management to optimize efficiency and minimize environmental impact.

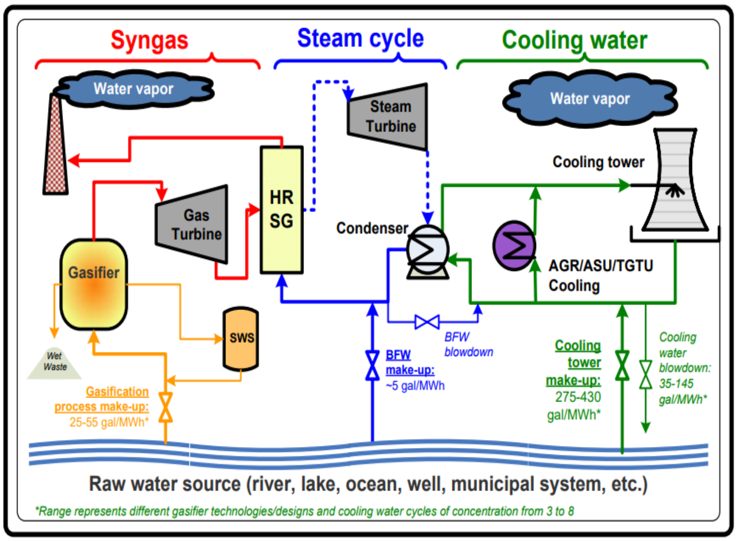


Figure 6-9 Water Flow Schematic for an Integrated Gasification Combined Cycle Plant Utilizing a Wet Cooling Tower [43]

Table 6-4 Comparison of Water Consumption for Integrated Gasification Combined Cycle and Direct Combustion

System	Start-up Demineralized Water (kg/sec)	Makeup Demineralized Water (kg/sec)	River Water (kg/sec)	Total flow rate (kg/sec)	Total flow rate (tons/day)	Total flow rate (m3/hr)	Total flow rate (Gallons/day)	Total flow rate (cusecs)
Combustion	170	34	34.72	238.72	22736	947	6 006 216	11
IGCC	52	10.4	20	82.4	7848	327	2 073 222	4

Figure 6-10 Comparison of water consumption for Integrated Gasification Combined Cycle and direct combustion

Figure 6-10 shows that the Integrated Gasification Combined Cycle system demonstrates significantly higher water efficiency than the direct combustion system. It utilizes approximately one-tenth of the water consumed by the combustion process for the same power output. This efficiency can be attributed to the advanced and more efficient water management systems employed in Integrated Gasification Combined Cycle technology. High water consumption can strain local water resources, particularly in water scarcity regions. However, adding carbon dioxide capture and compression increases water consumption by 50% to 90%, which must be considered when evaluating the overall water efficiency of these systems.

6.8. Health Issues Faced by Local Communities Due to Water Pollution and Scarcity

Coal combustion at thermal power plants produces coal ash, a grey powder-like substance containing concentrated amounts of toxic elements such as arsenic, lead, and mercury. Exposure to coal ash significantly increases the risk of cancer, cardiovascular diseases, neurological disorders, reproductive problems, and other serious public health issues. Additionally, sulfur dioxide emissions from coal combustion contribute to acid rain, which acidifies lakes and streams, destroying aquatic habitats and damaging forests and plants. Mercury released from coal power plants is deposited on soil and in water, where it transforms chemically into methylmercury, a highly toxic form that accumulates in fish tissue (Figure 6-11). Managing coal ash and emissions is crucial to mitigate these severe health and environmental impacts and ensure the safety and well-being of affected communities.

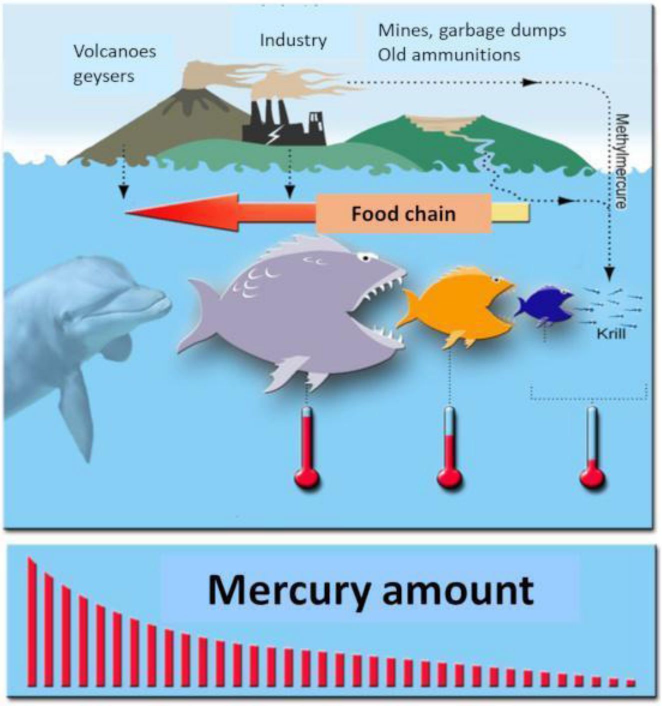


Figure 6-11 Mercury accumulation in fish tissue due to coal power plants [43]

The water allocation for coal power plants significantly impacts local communities, who rely on these water sources for drinking, domestic use, irrigation, fishing, and other livelihood activities. The coal rush in Tharparkar district has uprooted thousands of families from their ancestral homes and native lands, exacerbating the Thari people's water challenges. Key activities related to coal mining and power production such as the disposal of saline water extracted from coal mines, the discharge of wastewater from coal mines and thermal power plants, and the construction of infrastructure for diverting water from the Nara Canal to the Thar coalfield have had profound effects on communities across Thar. These consequences include water depletion, increased toxicity, a significant rise in malaria incidence, and poisoned and dying livestock (Figure 6-12). The depletion of vital water resources and the contamination of remaining supplies pose severe health risks and undermine the livelihoods of the affected communities, highlighting the urgent need for sustainable water management practices.

Figure 6-12 A camel died after drinking poisoned water in Thar Coalfield Block I. [44]

The sweet water of dug wells near wastewater reservoirs is becoming toxic, and incidents of malarial fever are increasing in the villages around these reservoirs. The water levels of the dug wells are depleting in villages neighboring coal mining sites, and the number of animals dying after drinking wastewater from coal mines and power plants is rising. The following section details the suffering of local communities due to effluent water being released from coal mines and coal-fired power plants in Tharparkar.

With the increasing volume of effluent water in the Thar coalfield, companies have been dumping wastewater in an arbitrary, irresponsible, and dangerous manner. Tilwaiyo, Warwai (Thar Coalfield Block I), Jaman Samoon, and Bitra (Thar Coalfield Block II) are the most affected. Over the past several months, herds of livestock, including camels, cows, sheep, and goats, have died after drinking wastewater released in these villages. The wastewater has also created breeding grounds for mosquitoes, leading to an endemic case of malaria in the area. Before the introduction of wastewater ponds, mosquito infestation was unknown in the locality. In October 2021, Sino Sindh Resource Limited began dumping wastewater into the grazing land of two neighboring villages of Thar Coalfield Block I, namely Tilwaiyo and Warwai. This has resulted in the contamination of a dug well of sweet water in Tilwaiyo village, rendering it toxic.

Figure 6-13 Dumping of Wastewater in the grazing land [44]

The impact of these activities is severe, posing a significant threat to the health and livelihoods of the local communities while also undermining the sustainability of the environment in the region. Effective management and regulation of wastewater disposal are crucial to mitigate these adverse effects and protect the well-being of the Tharparkar communities.

Around 250 families and 500 livestock relied on a well, which took the local community four to five months to dig for Rs. 700,000. Over the past three months, this well has become unusable. Additionally, at least fifty camels and a significant number of sheep and goats have died after drinking the toxic water in Tilwaiyo and Warvai villages. In Thar Coalfield Block II, the Sindh Engro Coal Mining Company (SECMC) has been discharging wastewater from the coal power plant into Jaman Samoon and Bitra villages for over a year. In the past year, approximately 300 sheep and goats and 50 cows have died after drinking the toxic water in these villages (Figure 6-14).

The severity of these impacts highlights the urgent need for effective wastewater management and regulation. Without proper measures, the health and sustainability of the environment and local communities will continue to deteriorate, underscoring the importance of promptly and efficiently addressing these challenges.

Figure 6-14 Goat died after drinking the toxic water in Thar. [45]

Chapter: 7

Economics

7.1. Economic Analysis

The economic viability of the Integrated Gasification Combined Cycle system, particularly for the Thar coal gasification project, is crucial for determining its feasibility. This chapter provides a detailed analysis of the various cost components associated with Integrated Gasification Combined Cycle, including capital, operating, and utility costs. Additionally, it examines the costs associated with integrating Carbon Capture and Storage technology. By comparing these costs with those of traditional coal-fired power plants and other energy generation technologies, this chapter offers a comprehensive understanding of the economic implications and potential benefits of adopting Integrated Gasification Combined Cycle technology for Pakistan's energy sector. Furthermore, Marginal Abatement Cost Curves are introduced to evaluate the cost-effectiveness of different emission reduction measures, helping to identify the most efficient strategies for reducing greenhouse gas emissions.

7.2. Coal Gasification Power Plant Cost Component

The economic analysis for coal gasification power plant cost includes,

7.2.1 Capital Cost

Capital cost encompasses all expenses required for the initial setup of the coal gasification power plant. This includes:

- **Land Acquisition:** Costs associated with purchasing the land for the power plant.
- **Buildings and Infrastructure:** Construction costs for facilities and infrastructure.
- **Machinery and Equipment:** Procurement of all necessary machinery and equipment.
- **Other Long-Term Assets:** Additional expenses for setting up long-term operational assets.

7.2.2 Equipment Cost

This covers acquiring all equipment required for coal gasification, including gasifiers, turbines, and ancillary systems.

7.2.3 Installation Cost

The installation cost includes the expenses for:

- **Purchasing and Transporting Machinery**: Costs associated with logistics and transportation of heavy machinery.
- **Installing Equipment**: Labor and material costs for setting up the equipment on-site.

7.2.4 Materials Cost

Materials cost represents the annual expenses incurred for purchasing raw materials necessary for production. The cost of coal is a significant component of the Thar coal gasification project.

7.2.5 Utilities Cost

Utility cost encompasses expenses for:

- **Electricity:** Powering essential equipment and machinery.
- **Refrigerants:** Propane and Freon 12 are used for cooling applications in the gasification system.

7.2.6 Operating Cost

Operating costs include all expenses related to running and maintaining the plant annually, such as:

- **Labor Costs:** Wages and benefits for the workforce.
- **Maintenance Costs:** Routine and non-routine maintenance.
- **Insurance and Other Operational Expenses:** Various recurring costs to ensure smooth operations.

7.3. Local Prices of Materials

The cost of materials is a crucial factor in the overall economic analysis of a coal gasification power plant. Local prices can vary significantly based on geographical location, availability of resources, and market conditions. For example, the local price of Thar Coal Block II is $30.40 per ton [46].

7.4. Economics for Integrated Gasification Combined Cycle

To calculate the estimated unit cost per kWh, the financial aspects considered include Non-EPC costs, capital development, working capital, sales tax, land acquisition, project development costs, O&M mobilization, testing and commissioning, insurance during construction, SINOSURE fees, financing fees, and interest during construction of a coal-based power project at Gwadar, Balochistan, with a capacity of 2 x 150 MW (Gross) [47]. The auxiliary charges include water, ash disposal, and limestone expenses, as outlined in the Upfront Thar Coal Tariff for Thar Coal Block-I Power Generation Company (Pvt.) Ltd [48] Table 7-1 provides an estimated cost breakdown for an Integrated Gasification Combined Cycle power plant, with capital costs and finance charges taken from NEPRA reports.

Table 7-1 Overall Summary of Economics for Integrated Gasification Combined Cycle , [50]

Energy Generation		
Power	MWe	300
Annual Energy Generation	kWh	2,233,800,000
Annual Energy Generation	MWh	2,233,800
Capital Cost		
Equipment Cost	$	183,938,900.00
Installation Cost	$	194,468,900.00
Non-EPC	$	5,770,000.00
CD, WH, and Sales Tax	$	10,870,000.00
Land	$	5,770,000.00
Project Development Cost	$	10,500,000.00
O&M Mobilization	$	3,210,000.00
Testing and Commissioning	$	2,740,000.00
Insurance during Construction	$	2,410,000.00
Total	$	419,677,800.00
Finance Charges		
SINOSURE Fee	$	3,440,000.00
Financing Fee and Charges	$	5,790,000.00
Interest during Construction	$	28,570,000.00
Total	$	37,800,000.00
Operating Cost		
Raw Material Cost	$	41,808,200.00
Utility Cost	$	87,944,400.00
Maintenance Cost	$	23,411,100.00
Labour Cost	$	20,153,400.00
Total	$	173,317,100.00
Auxiliary Charges		
Water Charges	PKR/kWh	0.5071
Ash Disposal	PKR/kWh	0.2200
Limestone	PKR/kWh	0.0900
Total	PKR/kWh	0.8171
Unit Charges		
IGCC	PKR/kWh	36.00
Project Cost		
Project Cost	$	457,477,800.00
Project Cost	PKR	130,381,173,000.00
Project Cost in Million	M $	457.48

Project Cost in Billion	B $	0.5
Project Cost/MW in Million	M $/MW	1.52
Project Life	years	30

7.5. Economics for Coal Gasification Power Plant with Carbon Capture

Carbon capture and storage systems are designed to absorb and permanently store carbon emissions, typically in geological formations such as saline aquifers. Carbon Capture and Storage can capture carbon at the emission point or directly from the air. The primary approaches for capturing emissions at the source include pre-combustion, post-combustion, and oxy-fuel capture technologies:

- **Post-Combustion Capture:** This technique, primarily used in power plants, employs amine-based solvents to remove carbon dioxide from exhaust gases following fuel combustion. It is the most mature carbon capture technology used in the steel industry.

- **Pre-Combustion Capture:** This involves gasifying fuel to produce syngas, from which carbon dioxide is captured before combustion. This method is mainly in the testing stage for power applications and is often integrated with Integrated Gasification Combined Cycle configurations.

- **Oxy-Fuel Capture:** This technique burns fuel in an oxygen-rich environment, resulting in a concentrated carbon dioxide stream that is more easily captured.

- **Direct Air Capture (DAC):** This process captures carbon dioxide directly from the atmosphere using liquid or solid sorbent devices. It is a relatively new approach that is gaining attention because it can potentially reduce atmospheric carbon dioxide levels.

Implementing Carbon Capture and Storage with Integrated Gasification Combined Cycle technology presents significant challenges due to high capital costs, which can hinder its competitiveness with other power plant technologies. While conventional pulverized coal plants currently offer the lowest price for electricity generation, Integrated Gasification Combined Cycle's potential lies in its ability to be retrofitted with existing power plants, potentially reducing its high initial costs. The integration of Carbon Capture and Storage is crucial for reducing carbon emissions, but it also increases the price. The operating cost for Carbon Capture and Storage associated with Integrated Gasification Combined Cycle is estimated to be between $10-20 per ton of CO_2.

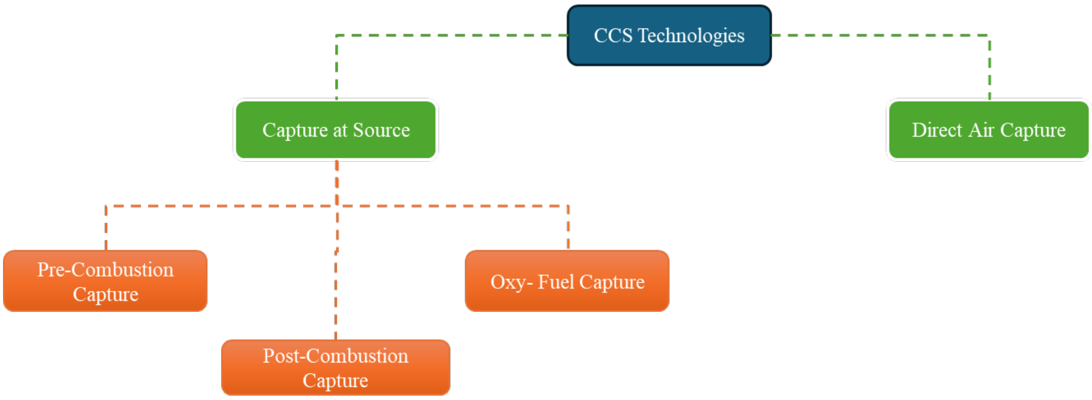


Figure 7-1 Carbon Capture technologies [34].

Implementing Integrated Gasification Combined Cycle technology faces significant challenges due to its high capital costs, which hinder its competitiveness with other power plant technologies. Conventional pulverized coal plants currently offer the lowest price for electricity generation. However, Integrated Gasification Combined Cycle has the advantage of potentially being retrofitted into existing power plants, which could help mitigate its high initial costs. Despite this, high costs remain the primary obstacle, compounded by uncertain carbon regulations. Nevertheless, integrating Carbon Capture and Storage with Integrated Gasification Combined Cycle is crucial for reducing carbon emissions and meeting environmental standards.

To calculate the estimated unit cost per kWh, several financial aspects are considered, including Non-EPC costs, capital development, working capital, sales tax, land acquisition, project development costs, O&M mobilization, testing and commissioning, insurance during construction, SINOSURE fees, financing fees, and interest during construction of a coal-based power project at Gwadar, Balochistan, with a capacity of 2 x 150 MW (Gross) [48]. The auxiliary charges include water, ash disposal, and limestone expenses, as outlined in the Upfront Thar Coal Tariff for Thar Coal Block-I Power Generation Company (Pvt.) Ltd [48].

Around 30% of captured carbon dioxide is retained, with the majority used in enhanced oil recovery to increase well pressure and flow rates. The Boundary Dam project in Canada is the only operational Carbon Capture and Storage-equipped coal plant, costing over $1.2 billion. [34]. The operating cost for Carbon Capture and Storage associated with Integrated Gasification Combined Cycle ranges from $10 to $20 per ton of carbon dioxide [49].

Table 7-2 Integrated Gasification Combined Cycle with Carbon Capture

Energy Generation		
Power	MWe	300
Annual Energy Generation	kWh	2,233,800,000
Annual Energy Generation	MWh	2,233,800
Capital Cost		
Equipment Cost	$	183,938,900.00
Carbon Capture Equipment	$	3,200,000,000.00
Installation Cost	$	194,468,900.00
Non-EPC	$	5,770,000.00
CD, WH, and Sales Tax	$	10,870,000.00
Land	$	5,770,000.00
Project Development Cost	$	10,500,000.00
O&M Mobilization	$	3,210,000.00
Testing and Commissioning	$	2,740,000.00
Insurance during Construction	$	2,410,000.00
Total	$	3,619,677,800.00
Finance Charges		
SINOSURE Fee	$	3,440,000.00
Financing Fee and Charges	$	5,790,000.00
Interest during Construction	$	28,570,000.00
Total	$	37,800,000.00

Operating Cost		
Raw Material Cost	$	41,808,200.00
Utility Cost	$	87,944,400.00
Maintenance Cost	$	23,411,100.00
Labour Cost	$	20,153,400.00
Carbon Capture	$	8,293,968.00
Total	$	181,611,068.00
Auxiliary Charges		
Water Charges	PKR/kWh	1.0142
Ash Disposal	PKR/kWh	0.2200
Limestone	PKR/kWh	0.0900
Total	PKR/kWh	1.3242
Unit Charges		
IGCC with CCS	PKR/kWh	178
Project Cost		
Project Cost	$	3,657,477,800.00
Project Cost	PKR	1,042,381,173,000.00
Project Cost in Million	M $	3657.48
Project Cost in Billion	B $	3.7
Project Cost/MW in Million	M $/MW	12.2
Project Life	years	30

7.6. Tariff for Integrated Gasification Combined Cycle and Integrated Gasification Combined Cycle with Carbon Capture

The Integrated Gasification Combined Cycle technology converts coal into synthetic gas in a gasifier and uses this syngas to power a combined cycle power plant. To capture and store the carbon dioxide emissions produced during this process, Integrated Gasification Combined Cycle with Carbon Capture and Storage incorporates additional technology. This section compares the capital expenses, operating and maintenance costs, and the impact of carbon capture on overall efficiency and costs for both systems.

The comparative analysis shows that Integrated Gasification Combined Cycle with Carbon Capture and Storage is significantly more costly (178 PKR/kWh) than a simple Integrated Gasification Combined Cycle power plant (36 PKR/kWh). The higher costs associated with Integrated Gasification Combined Cycle with Carbon Capture and Storage are due to the additional capital expenditures and operating costs required for the carbon capture technology. This demonstrates the economic challenge of implementing Carbon Capture and Storage despite its environmental benefits.

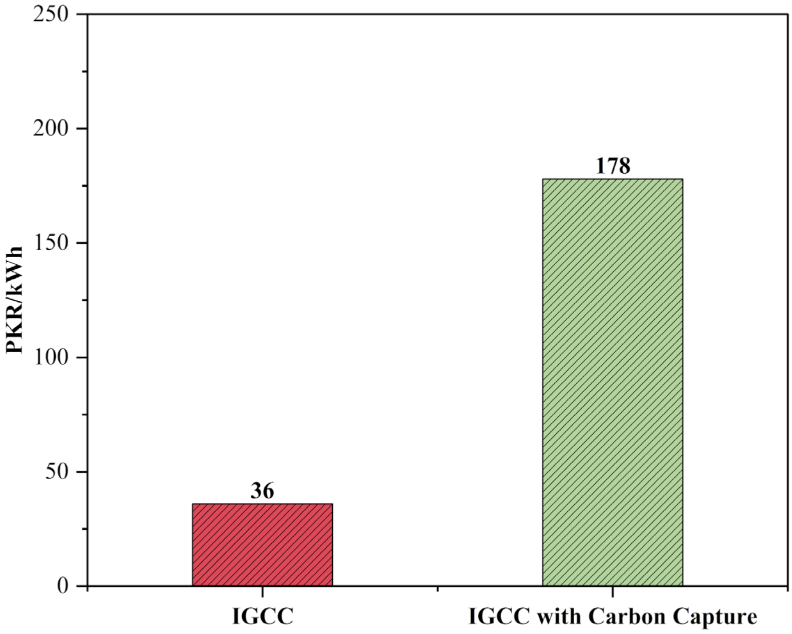


Figure 7-2 Cost comparison of Integrated Gasification Combined Cycle and Integrated Gasification Combined Cycle with Carbon Capture

7.7. Comparison of Integrated Gasification Combined Cycle and Integrated Gasification Combined Cycle integrated with CCS with other Operational Coal Power Plant

Table 7-3 Comparison of Cost PKR/kWh

Plant Groups	Merit Order	Cost PKR/kWh
Thar Block I Power Plant	2	5.53160
Thal Nova Power Thar Limited	3	5.61670
Engro Thar Coal Power Project	4	5.61700
Thar Energy Limited (TEL)	5	5.61700
China Power Hub Power Plant	15	13.87440
Lucky Electric Power Company	17	14.75220
Port Qasim Coal Power Plant	19	14.35960
Sahiwal Coal Power Plant	25	24.65570
IGCC	-	36.00000
IGCC with Carbon Capture	-	178.00000

7.8. MACC curves

Marginal Abatement Cost Curves are essential tools in environmental economics that aid policymakers and businesses in making cost-effective decisions to reduce greenhouse gas emissions. These curves graphically display the cost and efficiency of various emission reduction measures, helping to allocate resources optimally. Marginal Abatement Cost Curves illustrate the relationship between the cost of reducing emissions and the quantity reduced, showing that not all reductions have the same price. By ranking strategies from least to most expensive, Marginal Abatement Cost Curves allow decision-makers to prioritize actions that provide the most significant environmental benefit at the lowest cost. Additionally, Marginal Abatement Cost Curves highlight the abatement potential, indicating the maximum emissions reduction achievable at a specific price. This is vital for setting realistic emission targets and crafting effective climate policies. Businesses can leverage Marginal Abatement Cost Curves to find cost-efficient ways to lower their carbon footprint, while governments can design carbon pricing and regulations that promote emission reductions with minimal economic impact.

7.8.1 Methodology

The Marginal Abatement Cost Curves can be calculated using the following formula:

$$Marginal\ Abatement\ Cost\ (\$/tCO_2e) = \frac{Net\ Present\ Value\ (\$)}{Total\ CO_2\ emissions\ abated\ over\ the\ life\ of\ the\ project}$$

Where,

$$Net\ Present\ Value\ (NPV) = \frac{Total\ project\ costs - Total\ project\ savings}{(1 + discount\ rate) project\ lifetime}$$

Net Present Value adjusted for the time value of money, measures a project's overall worth using a 10% discount rate in this study. When project expenses exceed savings, the Net Present Value is negative, indicating a net cost. Conversely, when savings surpass expenses, the Net Present Value is positive, signaling a return on investment. To determine the Marginal Abatement Cost we multiply the Net Present Value by -1. A hostile Marginal Abatement Cost denotes economically feasible initiatives that yield cost savings, while an optimistic Marginal Abatement Cost represents an actual cost per tonne of carbon dioxide abated. A hostile Marginal Abatement Cost ($/t carbon dioxide) signifies emissions reduction and financial benefits, whereas an optimistic Marginal Abatement Cost ($/t carbon dioxide) indicates emissions reduction without financial gains.

It is important to note that the data used for Marginal Abatement Cost Curves in this analysis are primarily obtained from older literature, and certain assumptions have been made due to the lack of more recent data. Additionally, the data can vary significantly depending on the specific technology being analyzed. This context should be considered when interpreting the results and making decisions based on the Marginal Abatement Cost Curves.

7.8.2 Marginal Abatement Cost Curves for Identification of Cost-effective Technologies

The Figure 7-3 below illustrates the marginal abatement costs for various thermal power plant technologies in addition to integrated renewable energy production. Notably, biomass co-firing and energy efficiency improvements in power plants stand out, each offering a cost saving of approximately $20.45 per ton of carbon dioxide reduction. These options are economically attractive and provide significant monetary benefits while achieving substantial environmental impact. Over 20 years, biomass co-firing plants of 1000 MW can reduce carbon dioxide emissions by 40 million tons, and energy efficiency improvements can achieve a reduction of 20 million tons. While other technologies may achieve more significant overall carbon dioxide reductions, they are less favorable from a cost-effectiveness perspective compared to these two options.

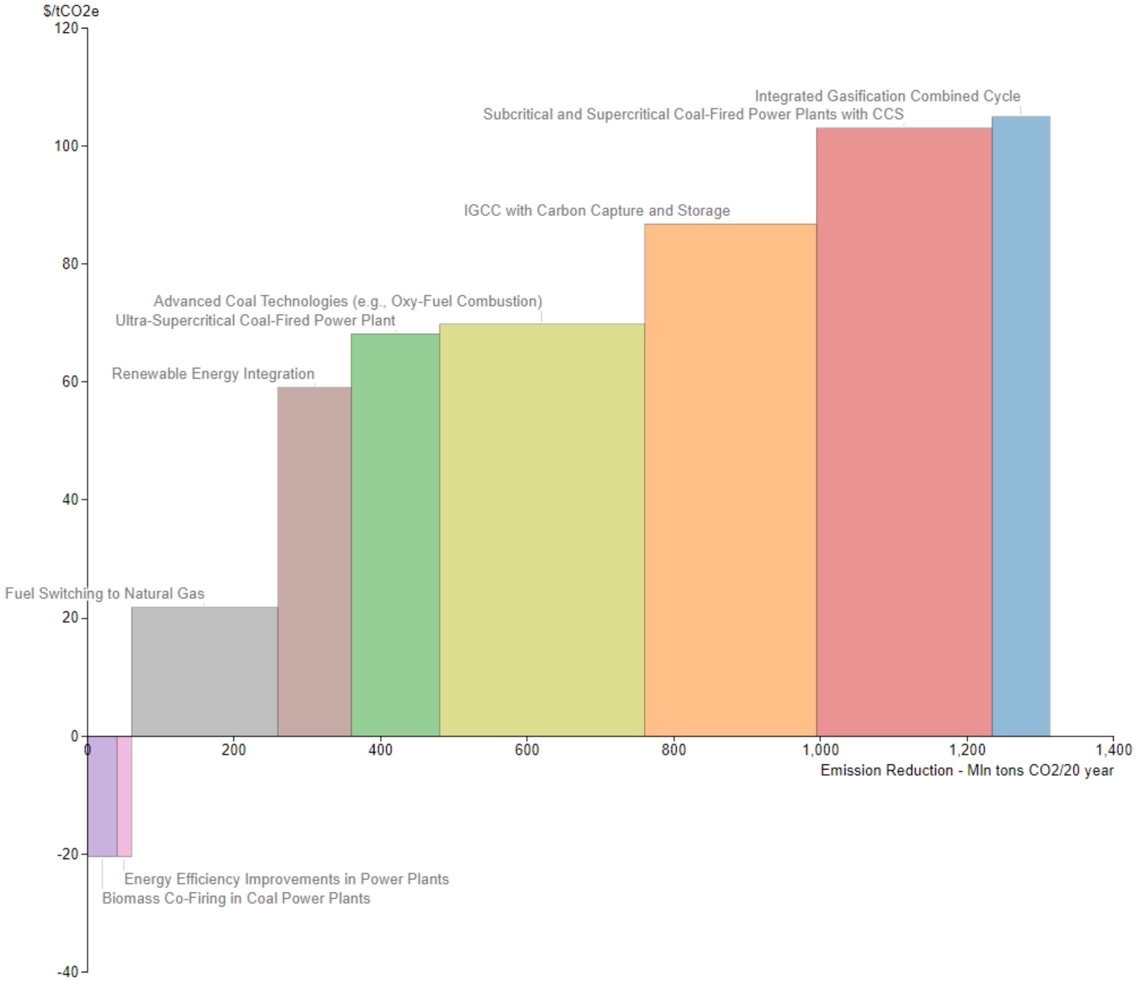


Figure 7-3 Marginal Abatement Cost Curves for various coal combustion technologies for power generation

Chapter: 8

PV Power Plants as a Sustainable Alternative

8.1. Introduction

Thar Block-II, a vast desert region located in the southern province of Sindh, Pakistan, holds immense potential for energy generation. This region boasts the country's largest coal reserves, estimated at around 175 billion tons. However, the current exploration of this potential through gasification projects raises significant environmental concerns. Gasification, a process that converts coal or other carbonaceous materials into synthetic gas, to fulfill energy demands but the process comes at a cost to the environment and the local communities. The gasification process releases harmful pollutants like nitrogen oxides, sulfur oxides, and particulate matter into the air. These pollutants contribute to respiratory illnesses, impacting the health and well-being of residents in Thar Block-II. Furthermore, gasification plants require large amounts of water for cooling and gas cleaning, potentially straining already scarce water resources in the arid region. The environmental impact does not stop there. Gasification plants also contribute to greenhouse gas emissions, accelerating climate change and its associated detrimental effects like extreme weather events. The local communities in Thar Block-II bear the brunt of these environmental consequences. Increased air and water pollution can lead to a rise in respiratory problems, waterborne illnesses, and other health issues. Additionally, gasification projects can disrupt existing ecosystems and displace local communities, impacting their livelihoods and cultural heritage. Considering these environmental and social concerns, deploying a 300MW solar photovoltaic power plant in Thar Block-II emerges as a sustainable alternative. Solar photovoltaic offers a clean and environmentally friendly solution for energy generation. It produces electricity without harmful emissions, reduces reliance on fossil fuels and their associated pollution, and minimizes water usage. Thar's Block-II vast desert landscape, coupled with its high solar radiation levels, makes it an ideal location for a large-scale solar photovoltaic plant. This shift towards solar energy promises not only environmental benefits but also opens doors for sustainable development in the region. The deployment of a solar photovoltaic plant can create new job opportunities, promote energy security, and contribute to a cleaner and healthier future for Thar Block-II.

8.2. Solar PV Plant

Solar Technologies are being utilized globally to meet the energy demand, not only offsetting the conventional power generation techniques as well as significantly reducing the carbon footprint of the energy. Solar photovoltaic Technology has specifically been on the forefront of this shift from conventional energy production technologies with contribution of around 4.5% globally, followed by the wind and hydro technologies. Pakistan has a solar power potential of around 40GW, enough to meet the country's current and future energy demand. Moreover, solar photovoltaic technology provides the option to the domestic electricity consumer to become a prosumer, which no other renewable technology offers. In the case of the Thar Power Project, the deployment of Solar photovoltaic power plants provides significant economic and environmental advantages against traditional gasification methods being used in Thar Block-II. These advantages translate into significant benefits for the project and the surrounding region.

8.3. Environmental Advantages

Clean Energy Generation: Solar photovoltaic plants produce electricity without any harmful emissions, unlike gasification plants which release air pollutants and contribute to greenhouse gases. This translates to cleaner air and a reduced impact on climate change, fostering a healthier environment for the local communities.

Water Conservation: Solar photovoltaic has minimal water requirements compared to gasification, which utilizes significant water for cooling and gas cleaning. This is particularly crucial in Thar Block-II's arid climate, where water scarcity is a major concern. The project will help conserve this precious resource.

Minimal Land Disruption: Solar photovoltaic farms can be installed on barren land, minimizing disruption to existing ecosystems. Unlike gasification plants which require significant land for construction and operation, solar offers a more sustainable land-use option for Thar Block-II desert landscape.

8.4. Project Benefits

Reduced Operational Costs: Compared to gasification, solar photovoltaic boasts lower operation and maintenance costs in the long run. This translates to cost savings for the project, making it a more financially sustainable endeavor.

Energy Security and Independence: Thar Block-II can achieve greater energy security and independence by harnessing its own abundant solar resources. This reduces reliance on external fuel sources and price fluctuations.

Job Creation and Economic Development: The construction and maintenance of a solar photovoltaic plant can create new job opportunities in Thar Block-II, boosting the local economy and contributing to the region's development.

8.5. Additional Advantages:

Scalability: Solar photovoltaic plants can be easily scaled up or down based on future energy demands, offering greater flexibility for the project.

Low Noise Pollution: Solar photovoltaic plants operate quietly, minimizing noise pollution in the area compared to the industrial noise generated by gasification plants.

By implementing a 300MW solar photovoltaic plant, the Thar Block-II project can achieve its energy generation goals while promoting environmental sustainability, economic development, and a healthier future for the local communities.

8.6. Techno-Economic Feasibility

A 300MW Solar PV Plant was designed for the Thar Block-II on the state-of-the-art renewable energy analysis software System Advisory Model developed by NREL (National Renewable Energy Laboratory). The analysis included the choice of panels, inverters readily available in the market with current economic and financial policy consideration of Pakistan. The details of the panels and the inverters selected for the design are presented in Table 8-1 and 8-2, respectively.

Table 8-1 Panel Details LONGI Mono C-Si 555W

Parameter	Value
Model/Technology	LONGI Green Energy/Mono-c-Si
Rated Power	555
Nominal Efficiency	22.30%
Maximum Power (Pmp)	555.29 (Pdc)
Max Power Voltage (Vmp)	42.1 (Vdc)
Max Power Current (Imp)	13.2 (Adc)
Temperature Coeffecients (Power)	-2.08

Table 8-2 Inverter Details Huawei SUN2000-100KTL

Parameter	**Value**
Model	Huawei Technologies SUN2000-100KTL
Number of MPPT	1
Maximum AC Power	100000 (Wac)
Maximum DC Power	101448 (Wdc)
Minimum MPPT DC Voltage	880 (Vdc)
Maximum MPPT DC Voltage	1200 (Vdc)
Power use during Operation	180 (Wdc)

8.7. Photovoltaic System Designing

The photovoltaic Array designing process includes the configuration and matching of photovoltaic Module voltage with the inverter MPPT ranges, followed by the Solar photovoltaic Module structure angles and its orientation towards the sun. The design parameters are presented in Table 8-3.

Table 8-3 Design Parameters for 300MW Solar PV Power Plant

Parameter	Value
Number of Modules	540,270
Number of Strings	20,010
Number of Inverters	2500
DC to AC Ratio	1.2
Modules per String	27
Name Plate DC Capacity	300,011 kWdc
Total AC Capacity	250,000 kWac
Total Module Area	1345272 m^2
Total Land Area Requirement	1,108.79 acres
Tilt	25.35 (Latitude)
Azimuth	180 (South Facing)
GCR	0.3

8.8. Financial Parameters and Economic Considerations

The financial parameters utilized in the economic evaluation of the proposed system include the rates of electricity, debt fraction, interest rate alongside the loan term rates. Moreover, economic considerations like the current currency inflation rate are also utilized. The details of the economic and financial considerations used in the analysis are presented below in Table 8-4. The electricity rates and the debt fractions are utilized for similar sized solar projects implemented recently in Pakistan.

Table 8-4 Economic and Financial Parameters for 300MW Solar photovoltaic Power Plant

Parameter	Value
Inflation Rate	2.50%
Discount Rate	**6.40%**
Debt Fraction	75%
Loan Term	**12 years**
Loan Rate	12% (Avg. LIBOR & KIBOR)
Electricity Selling Rate	**0.025 ($/kWh)**

8.9. Techno-Economic Analysis

The techno-economic analysis for the proposed photovoltaic plant was done utilizing the state-of-the-art clean energy feasibility software System Advisory Model. An in-depth hourly resolution data was utilized for the analysis with hourly time domain analysis for achieving higher analysis reliability. The total capital cost for the system is calculated at $80,582,672. A breakdown of initial cost is provided in Table 8-5. The summary of the analysis is presented in Table 8-6.

Table 8-5 Breakdown of Total Initial Cost of the Project

Parameter	Value
Module	$39,001,480
Inverter	**$20,000,000**
Allied Cost	$30,001,139
Contingency (2%)	**$1,580,052**
Operating Cost	$0.2/kW/yr
Insurance Rate	1% of total Initial Cost
Total Initial Cost	**$90,782,672**

Table 8-6 Economic and Technical Summary of the Power Plant

Metric	Value
Annual AC Energy (Year 1)	512,629,440kWh
DC Capacity Factor	19.50%
Energy Yield	1709kWh/kW
Performance Ratio	0.76
LCOE	2.41¢/kWh
Payback Time	7.2 years
Net Present Value	$31,472,140
Capital Cost	$90,782,672
Equity	$20,695,668
Debt	$68,087,008

A total annual generation of 512,629,440kWh is calculated for the 300 MW solar PV power plant at Thar Block-II. A DC Capacity Factor of 19.5% is calculated for the power plant, generating electricity at the LCOE of 2.41¢/kWh. The system is highly feasible with a positive NPV and a considerable payback time of 7.2 years.

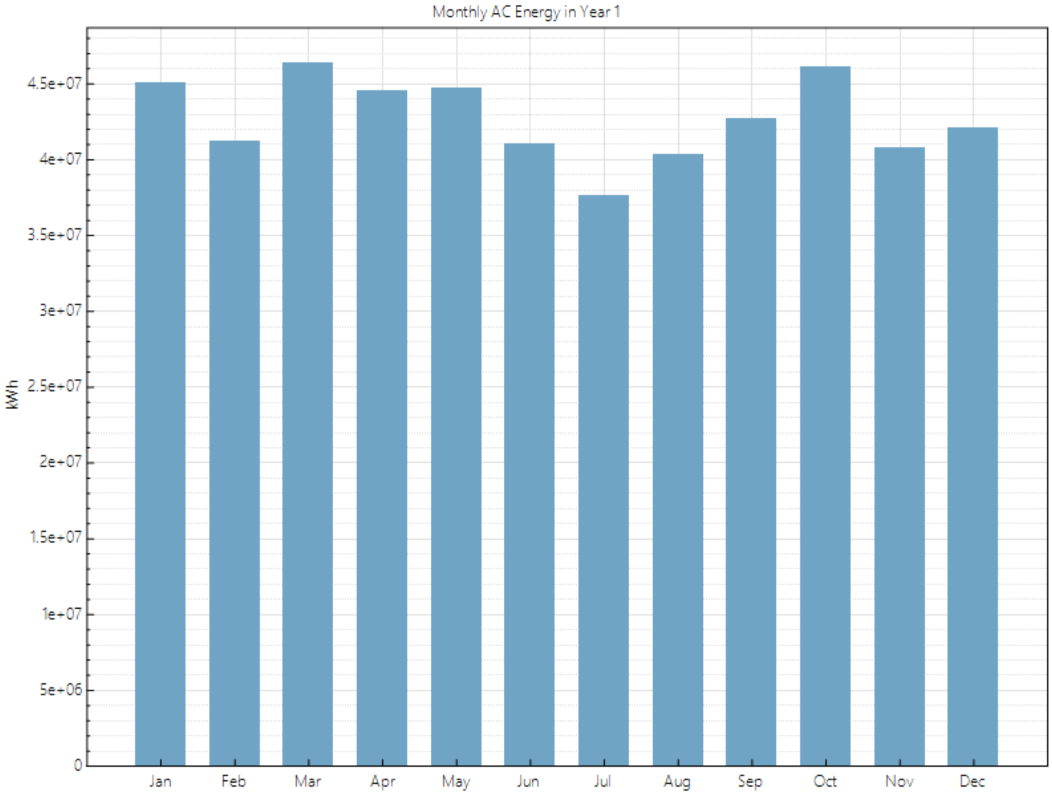


Figure 8.1: Monthly AC energy generation (Year1)

The Power plant will be providing energy year-round to the grid as shown in figure 8.1. The power plant would be injecting constant power to the grid during sunlight hours with monthly variability of less than 10%.

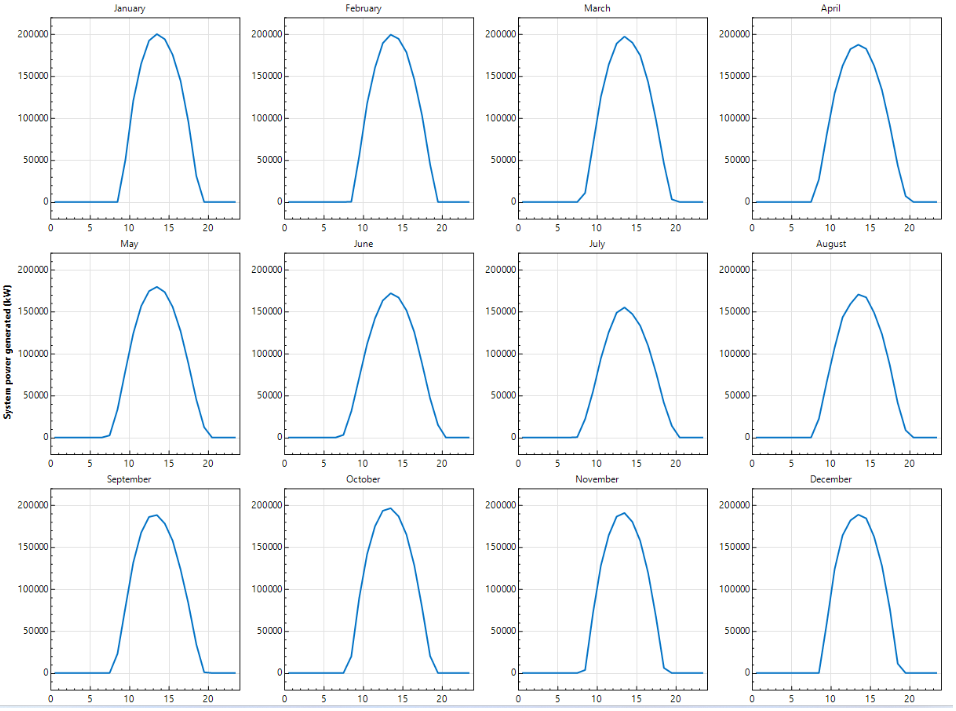
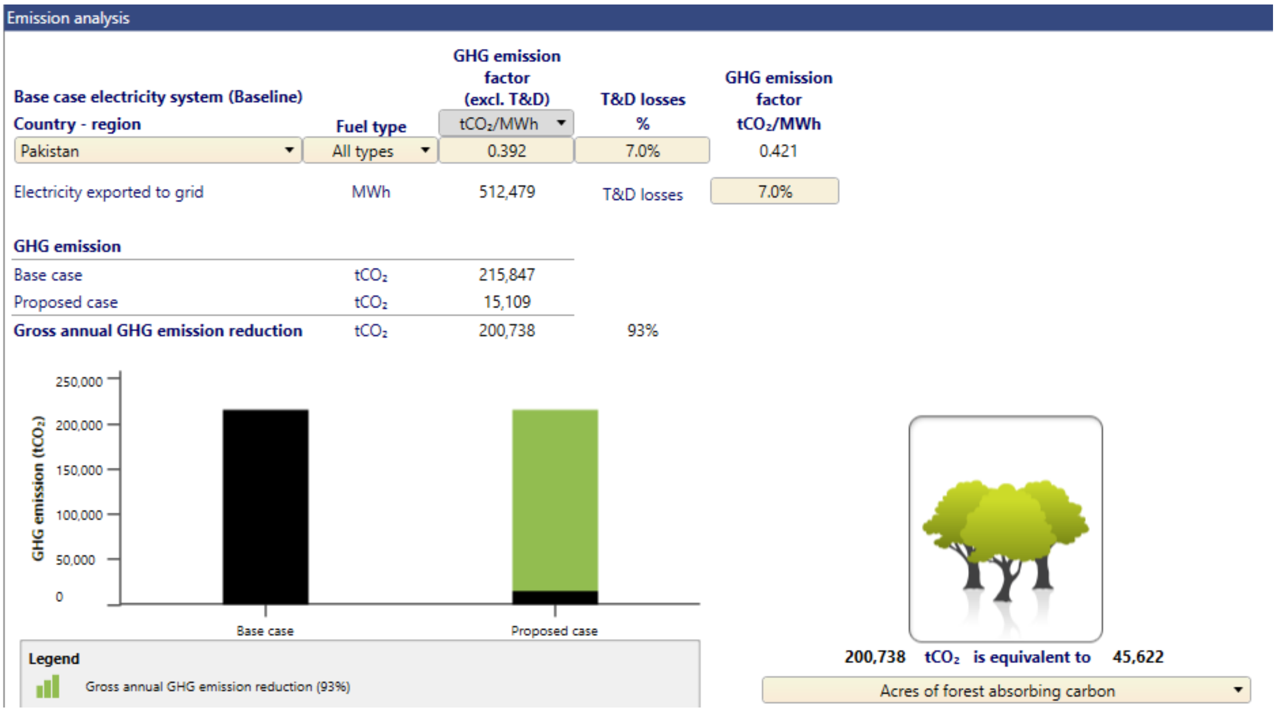


Figure 8.2: Monthly Generation dispatch to the grid from 300MW power plant

Figure 8.2 illustrates the monthly system power generation of a solar plant, showcasing its optimized dispatch to align with the peak daytime load hours of the National Grid. The plots, organized by month, reveal a consistent pattern of maximum power generation occurring during the midday hours, coinciding with the periods of highest electricity demand. This strategic dispatch ensures that the solar plant's output is effectively utilized to meet the grid's needs, contributing to a more efficient and sustainable energy supply.

8.10. Environmental Implications

Solar photovoltaic Technology provides clean energy generation with no operational greenhouse gasses emission. Implementation of 300MW Solar photovoltaic Power Plant at Thar Block-II will provide a significant reduction in the greenhouse gasses emission in comparison to all other fuel types including coal, gas and other thermal power plant technologies. Pakistan has a greenhouse gasses emission factor of 0.392 tCO_2/MWh. A total greenhouse gas reduction of around 200,738 tCO_2 is calculated for the 300MW Solar PV power plant. The total greenhouse gasses emission from the Power Plant is around 15,809 tCO_2, in comparison to the conventional thermal power plant technologies of the same size producing around 215,847 tCO_2. A gross reduction of 93% in the greenhouse gasses emission is achievable by implementation of Solar photovoltaic Power Plant, which is equal to 45,622 acres of forest absorbing carbon. This will not only reduce greenhouse gasses emission but as well as enhance the local air quality and provide a clean environment for the local community with access to clean and green energy. The details of the emission analysis are presented below in Figure 8.3.



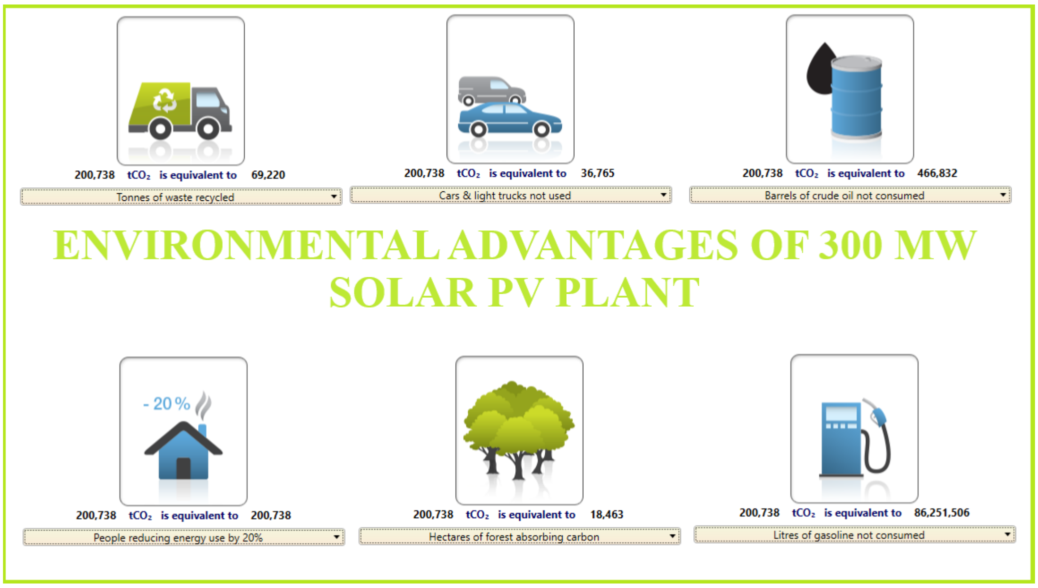
Emission analysis

Base case electricity system (Baseline) Country - region	Fuel type	GHG emission factor (excl. T&D) tCO_2/MWh	T&D losses %	GHG emission factor tCO_2/MWh
Pakistan	All types	0.392	7.0%	0.421
Electricity exported to grid	MWh	512,479	T&D losses	7.0%

GHG emission			
Base case	tCO_2	215,847	
Proposed case	tCO_2	15,109	
Gross annual GHG emission reduction	tCO_2	200,738	93%

200,738 tCO_2 is equivalent to 45,622
Acres of forest absorbing carbon

Figure 8-3 Emission analysis for the 300MW Solar PV Power Plant



200,738 tCO_2 is equivalent to 69,220
Tonnes of waste recycled

200,738 tCO_2 is equivalent to 36,765
Cars & light trucks not used

200,738 tCO_2 is equivalent to 466,832
Barrels of crude oil not consumed

200,738 tCO_2 is equivalent to 200,738
People reducing energy use by 20%

200,738 tCO_2 is equivalent to 18,463
Hectares of forest absorbing carbon

200,738 tCO_2 is equivalent to 86,251,506
Litres of gasoline not consumed

Figure 8-4 Environmental advantages of 300MW Solar PV Plant

Figure 8.4 presents the relative environmental advantages of implementing the 300MW Solar PV Plant. The total amount of GHG reduction is equivalent to 69,220 Tonnes of waste recycled, or 466,832 Barrels of Crude oil not used by the vehicles. Additionally, such macro adaptation of renewable technology is equivalent to 200,738 people reducing energy use by 20% or 18,463 hectares of forest absorbing carbon. These macro level renewable adaptations result in significantly reducing the carbon footprint of the country as well as its fuel mix.

Chapter: 9

Conclusion

In 2022, Pakistan's energy mix heavily relied on fossil fuels, comprising 59 percent thermal, 25 percent hydro, 7 percent renewable, and 9 percent nuclear power. The country possessed a coal-fired power generation capacity of approximately 5,620 MW. Major projects like Thar Coalfield Block I, Thar Coalfield Block II, Sahiwal coal power project and Port Qasim power project have faced enormous environmental and financial challenges. The Thar region harbored vast coal reserves estimated at 175 billion tons spread over 9,100 km². Even though local coal is cheaper, logistical challenges remain significant, and reliance on imported coal is both costly and unsustainable, with expenses reaching $467 million in 2023. This underscores the drawbacks of continuing to depend on coal as an energy source.

On paper, coal gasification promises enhanced efficiency and reduced emissions compared to traditional direct coal combustion. It employs various gasifier types like entrained flow, fluidized bed, moving bed, and molten bed gasifiers. However, in reality it has numerous drawbacks including heightened complexity and costs, escalated energy and water consumption, and the emission of pollutants requiring appropriate treatment and disposal. The Thar Underground Coal Gasification project encountered significant obstacles, such as financial limitations, technical challenges, and environmental concerns, which ultimately led to its discontinuation and highlighted the difficulties of adopting this technology.

This study explores the Integrated Gasification Combined Cycle technology and compares it with the direct combustion system by developing models in Aspen Plus. The findings reveal Direct combustion systems consumed more coal compared to Integrated Gasification Combined Cycle systems due to higher steam production requirements. An integrated gasification combined cycle (IGCC) system, generating 316 MW of power, promised superior efficiency and flexibility in feedstock utilization. The direct combustion power plants primarily utilize water for steam condensation and turbine driving, with minor usage for process steam makeup and other water-intensive operations. The water profile of an Integrated Gasification Combined Cycle power plant was notably lower than that of direct combustion plants, as the gas turbine generated approximately 60 percent of the total electrical output. For a 300 MW power plant, direct combustion required 11 cusecs of water, while Integrated Gasification Combined Cycle required 4 cusecs of water without carbon capture and storage. The fixed carbon content in thar coal significantly influenced the total heat generated from combustion. Higher fixed carbon content typically indicates superior fuel quality with higher calorific value and more efficient combustion properties. The Integrated Gasification Combined Cycle process demonstrated a lower carbon dioxide concentration (63 tons/day) compared to direct combustion (199 tons/day). The estimated cost for Integrated Gasification Combined Cycle is 36 PKR/kWh with an initial investment of 457 million dollars.

On the other hand, the 300MW solar photovoltaic power plant illustrated that despite an initial investment of 91 million dollars, the proposed solar PV plant exhibited a positive net present value and a rapid payback period of only 7.2 years. Furthermore, the calculated Levelized Cost of Energy of 2.41 ¢/kWh (7 to 8 PKR) significantly undercut other available power generation technologies, establishing solar photovoltaic power plants as a highly competitive solution. Beyond economic advantages, the proposed solar photovoltaic power plant promised substantial environmental benefits. It was anticipated to achieve a noteworthy reduction of approximately 200,738 tonnes of carbon dioxide emissions annually, constituting a 93% decrease compared to existing gasification technology. This substantial reduction would significantly contribute to climate change mitigation and diminish the country's overall carbon footprint. Additionally, solar PV power plants promised undeniable environmental benefits, including significant reductions in greenhouse gas emissions and improved local air quality. Implementation of this project could foster a cleaner, healthier environment and contribute to a more sustainable energy future for Pakistan. This solar plant also preserves the aesthetic of the Thar coal area, promotes agri voltaics culture, and protects the environment of the Thar region. Moreover, the positive environmental impact extended to potential improvements in local air quality and public health. By transitioning away from emission-intensive gasification methods, the project could foster cleaner air, consequently enhancing health outcomes for neighboring communities.

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