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ENVIRONMENTAL SUSTAINABILITY AND CLEANER PRODUCTION TECHNOLOGIES WITH ADVANCED ECONOMETRIC METHODS

Environmental, technological, and economic analysis of supercritical coal-fired power system

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Abstract

Developing countries primarily rely on fossil-based energy sources to meet their energy demands. The use of fossil fuels has several adverse environmental repercussions that damage the biosphere both directly and indirectly. Among fossil fuels, coal brings about the heaviest environmental externalities, yet its abundance makes its use widespread, particular in countries having significant power generation deficits, such as Pakistan. This study presents an environmental, technological, and economic analysis of a supercritical coal-based power unit located in Pakistan and used for electricity generation. For environmental assessment, the CML-1A baseline method in OpenLCA software was used, and eight midpoint impact indicators were selected. The functional unit chosen was 1 MWh of generated electricity. The results indicated that the category of ozone layer depletion has the least impact, whereas global warming potential has the highest impact score. Except for photochemical oxidation and human toxicity, the plant operational stage dominated most of the selected impact categories. The current paper also reveals that the removal efficiency of CO_2 and other pollutants is higher in supercritical compared to subcritical plants. Moreover, the economic feasibility of supercritical plant is compared with chemical looping combustion (CLC)-based supercritical coal-fired power plant, and results shows that CLC-based coal-fired power plant is a more competitive and environmentally friendly option. The utilization of a scientific cleaner energy-management system in real-time, as exemplified in this study, may facilitate the development of a optimal policy framework that encourages for the adoption of cleaner coal power generation in developing countries, ultimately resulting in improved energy sustainability. Furthermore, this paper also presents some policy implications which could be helpful for policymakers, researchers, and industrialists to improve the sustainability of energy in emerging economies.

Keywords Life cycle assessment · Environmental sustainability · Global warming · Economic feasibility · Energy policies

Introduction

The growth of the world population and economic development brings about significant increases in energy demand. Fossil fuels are still the world's primary energy source, but an increase in their use is not sustainable, due to the significant environmental impacts that follow (Mufutau Opeyemi 2021). Among fossil fuels, coal, despite bringing about a heavy environmental burden, accounts for around 30% of worldwide primary energy generation with a particularly strong role in Asia, mainly due to significant local resources (H. H. Shah et al. 2023a, b; Amin and Shah 2022; Zhou et al. 2022). On the other hand, the use of coal brings about serious environmental impacts, not only in the form of high emissions of greenhouse gases (GHG) but also in the form

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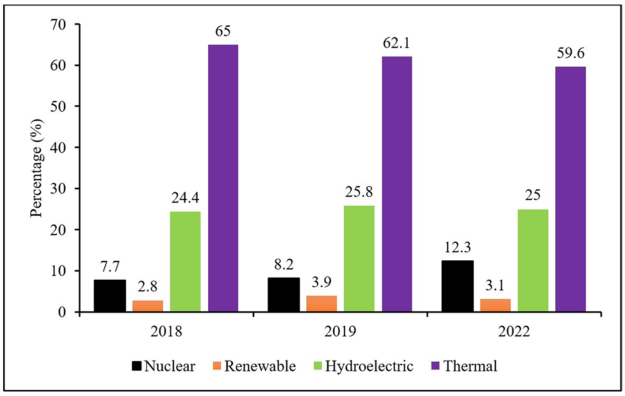


Fig. 1 Electricity generation sources in Pakistan (Pakistan, 2019)

of the emission of a vast plethora of pollutants, such as SO_2, NOx, and Hg (J. Wang et al. 2018). This said, the full transition towards renewable energy sources (RES) is still far from being completed, because of several challenges that have to be solved (Mulenga and Siziya 2019).

Among Asian countries, Pakistan has several peculiarities. First, it significantly depends on imported fossil fuels (Fig. 1), despite having significant hydroelectric and nuclear production (Valasai et al. 2017). Second, it is a developing economy, with strong growth rates for both energy consumption and energy generation (Fig. 2). Third, the growth of its power generation sector has historically lagged behind electricity consumption, with the result of a serious shortage in generation capacity, which has been estimated at around 8000 MW, and this has had a strong negative impact on the economic growth of the country (Finance Division, Government of Pakistan, n.d.; Tao et al. 2022).

Despite domestic reserves of oil and natural gas being quite limited, and their exhaustion is expected between 2025 and 2030, in recent times, very significant reserves of low-sulfur, low-ash lignite have been discovered in the Tharparkar (Thar) desert, in the southern province of Sindh (Abbas, Malik Naseem, 2015; Lohana, Kush, et al. 2021). While the exact amount of these reserves is not clear yet, with some estimates putting it at 186 billion tonnes (an amount that would make Pakistan the sixth-largest owner of coal reserves in the world), coal discovery in Tharparkar has attracted interest from both domestic and international (mainly Chinese) developers in setting up coal-fired facilities in Pakistan.

Numerous coal-related projects have been initiated, including Sahiwal's 1320 MWel coal-fired plant in Punjab province, Hubco's 320 MWel Coal Power Project in Balochistan, and Thar Engro's 660 MWel Coal Power Project in Sindh. Pakistan's coal, oil, and natural gas reserves are listed, together with their respective production rates, in Table 1.

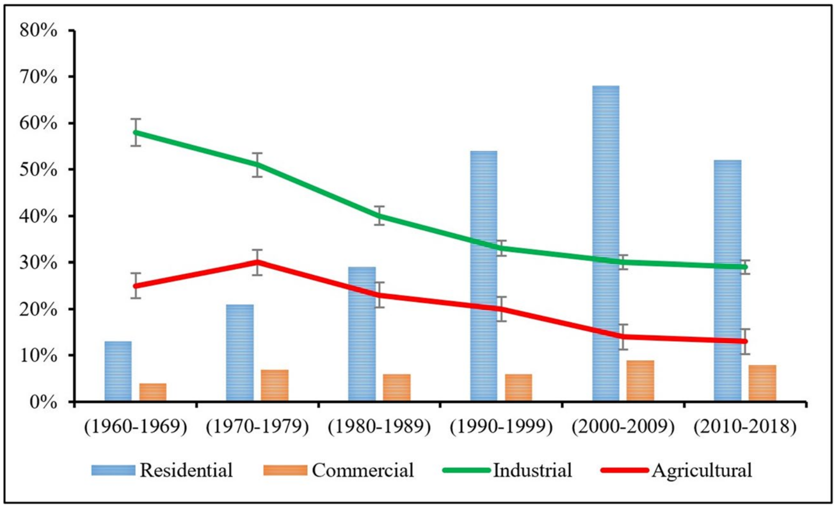
Table 1 Fossil fuel production and reserves in Pakistan (Valasai et al. 2017)

Fossil fuel	Production	Reserves	Reserves/ production ratio
Oil	4.2 MTOE/year	49.7 MTOE/year	~ 12 years
Natural gas	30.9 MTOE/year	411.6 MTOE/year	~ 13 years
Coal	1.5 MTOE/year	7775 MTOE/year	> 5000 years

MTOE: Million tonnes of oil equivalent

Another feature of Pakistan is its extreme vulnerability to climate change, with frequent extreme heatwaves which periodically exact a heavy toll on the more fragile segment of the population and a strong susceptibility to disastrous floods. While climate change is an inherently global phenomenon, which can only be mitigated by actions taken

Fig. 2 Consumption of energy in Pakistan by each sector (K.R. Abbasi et al. 2021)



at a global scale with the greatest responsibility falling on the countries which have the largest per capita GHG emission factors, these aspects have made the country very much keen to introduce policy actions focused on mitigating GHG emissions from high emissions sectors like the energy and fertilizer industry.

Recognizing the threat posed by climate change, Pakistan has initiated a series of policy actions aimed at addressing both the causes and consequences of environmental changes. These policies include investing in renewable energy projects, enhancing water conservation measures, and implementing stricter environmental regulations. For instance, the government has supported the shift towards cleaner energy sources by backing solar and wind projects alongside traditional hydroelectric power.

Also, Pakistan's updated Nationally Determined Contributions (NDC) is an ambitious program, according to which the country aims at reducing its GHG emissions by 50% by 2030, and this by increasing the fraction of primary energy deriving from RES up to 60%, and the fraction of electric vehicles to 30%.

Additionally, the Pakistan Climate Change Act was established to govern the planning and execution of projects designed to mitigate climate change impacts and to ensure that sustainable development considerations are integrated across all levels of government planning and decision-making.

Due to the reasons now briefly described, there is a long debate taking place in Pakistan about phasing out coal-fired power plants and replacing them with RES-based power plants, thus, not only reducing GHG emissions but also the number of pollutants released into the atmosphere (Dolter and Rivers 2018).

A useful tool for quantitatively evaluating the impact of any given process is life cycle assessment (LCA) (M.Amin, E.Chung, 2022; Amin, Shah, Iqbal, et al., 2022). Due to this, LCA has been proven beneficial in developing useful suggestions for the selection of a process from a variety of alternatives (Pehnt and Henkel 2009; Lelek et al. 2016; Amin et al. 2022a, b). There have been some attempts at assessing the coal-fired power production environmental implications by using the life cycle approach and other techniques. For instance, Castelo Branco et al. (2013) performed the LCA of a coal-fired power plant with and without carbon capture and storage (CCS), located in Brazil. Schreiber et al. (2009) evaluated the environmental impacts of coal-fired power plants in Germany with amine-based carbon capture.

With a specific focus on GHG emissions, Steinmann et al. (2014) used Monte Carlo simulation in the life cycle of coal-fueled power production to differentiate variability from uncertainty. Koornneef et al. (2008) performed the LCAs of three pulverized coal-fired power plants by using a "cradle to grave" approach, without taking into account CCS. Similarly, Singh et al., (2016) carried out the environmental assessment of Indian coal-fired power plants with and without NOx, CO_2, and SO_2 emission controls.

This study utilizes the LCA approach to evaluate the environmental impacts associated with the functionality of a coal-fired power generation facility in Pakistan, as presently explained in the context. The power plant considered in this study is located in the south of Pakistan and has a capacity of 1320 MW. Eight environmental impact categories were considered for this aim: (1) global warming potential, (2) eutrophication, (3) abiotic depletion potential, (4) photochemical oxidation, (5) acidification, (6) ozone layer depletion, (7) human toxicity, and (8) terrestrial ecotoxicity.

This paper also compares the economic efficacy of a supercritical plant with that of a supercritical coal-fired power plant that utilizes chemical looping combustion (CLC) technology. Moreover, the authors also present some considerations on energy policies that could hopefully be beneficial for policymakers, researchers, and industrialists.

Methodology

Power plant narrative

The power plant addressed in this study is the first supercritical coal-fired facility in Pakistan's southern region and the second overall in the country. It operates with a significant generation capacity of 1.32 GWel and a gross efficiency rate of 42.21%, constructed at an estimated cost of $ 2.085 billion. The coal power station has two supercritical units (each 660 MWel), each consisting of a steam turbine, a boiler, and an electric generator. An air pre-heater of rotary type regenerative tri-sector is a feature of the single reheat, once-through boiler. Sub-bituminous coal, which is used to power the boiler, is supplied by cargo ships from Australia, Botswana, South Africa, and Indonesia. The coal is unloaded at a dock which is constructed at the plant site.

Combustion of coal produces heat, which is converted by the supercritical boiler into high-pressure steam and is released to the turbine. The steam turbine, which is driven by the steam, produces electrical energy, while the exhaust steam is discharged to the condenser. Heaters receive the extracted steam from the turbine's various sections. The turbine's mechanical energy is converted into electrical energy by the generator, which is coupled directly to the turbine shaft. The power plant's exceptional thermal sustainability is due to the noticeable variance in temperature between the high-pressure, low-temperature fluid discharged from the compressor, and the low-pressure, high-temperature fluid discharged from the turbine. The efficiency of the power plant exhibits a direct correlation with the inlet turbine

Table 2 Power plant key parameters

Parameter	Specification
Project	1320 MW (2 × 660 MW) supercritical coal-fired power plant
Primary input energy	Sub-bituminous coal
Cost	$ 2.085 billion
Technology	Supercritical
Nominal power	1320 MW (2 × 660 MW)
Rate of coal consumption	95–100 kg/s
Net output power	1200–1250 MW
Power plant net efficiency	42.21%
Annual load	6722 h
Cycle efficiency	52.01%
Thermal efficiency of the boiler	94.16%
Turbine inlet pressure	32 MPa
Turbine inlet temperature	600 °C
The rotational speed of a turbine	3000 rpm
The rotational speed of the main compressor	3000 rpm
Inlet pressure of the main compressor	7.7 MPa
The inlet temperature of the main compressor	32 °C

pressure and temperature, while an inverse correlation with the primary compressor inlet temperature.

The coal-fired power facility also includes a channel and a jetty where coal is unloaded and transported via belt conveyor to the plant coal yard. At the coal yard, the settling of coal is done using a bucket-wheel stacker reclaimer. The coal is then fed into the coal boiler bunker after being filtered and crushed. The annual consumption of coal in the power plant is approximately between 4.66 and 5. 20 million tonnes (Mt). Table 2 shows the power plant's key operational parameters.

The table shows that the plant has a high nominal power output of 1320 MW and a net power output ranging between 1200 and 1250 MW. This substantial production capability signifies the plant's role in enhancing Pakistan's energy security. Given the country's previous struggles with severe power shortages, such optimal production rates are critical. The power plant helps stabilize the national grid and reduces dependence on imported energy, thus providing a more reliable and continuous power supply.

The table also indicates a high coal consumption rate (95–100 kg/s) which highlights the importance of Pakistan's significant coal reserves. With recent discoveries increasing these reserves significantly, such as the Thar coal field in Sindh, Pakistan, has the potential to utilize these domestic resources to support its energy needs. Utilizing local coal reserves not only enhances energy security but also helps in controlling energy prices and reducing foreign currency expenditure on energy imports.

The operational efficiency of the plant, reflected through high boiler and cycle efficiencies (94.16 and 52.01%, respectively), indicates advanced technology deployment aimed at minimizing energy wastage and reducing emissions per unit of electricity generated. This aspect is crucial for developing future environmental policies as it demonstrates the potential to balance energy production with environmental sustainability through technological advancements.

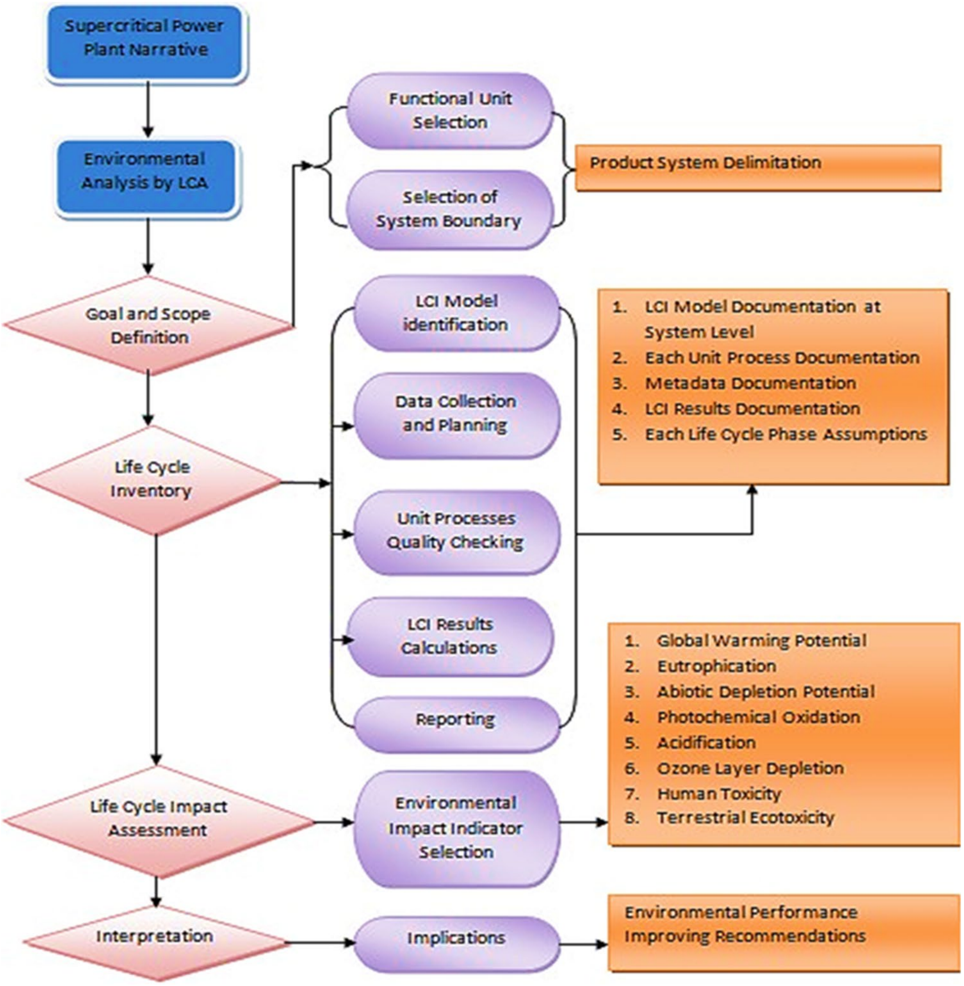
LCA methodology

To evaluate the overall comprehensive environmental implications of a process or a product, the LCA approach is employed throughout its life cycle and is sometimes characterized as a "cradle-to-grave" assessment (Šenitková and Bednárová, 2015). The framework of LCA, per ISO 14040 regulation, consists of four stages: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) results interpretation (Shah H. H. et al., 2024; Shah H. H. et al., 2023). The LCA approach employed in this study is presented in Fig. 3.

Goal and scope

The main objective of the present LCA analysis is to conduct an environmental evaluation of a coal-based power plant situated in Pakistan, which serves as a source of energy generation. The purpose is to assess and ascertain the corresponding environmental accountabilities, to propose suitable measures that promote ecologically sound energy

Fig. 3 LCA methodological framework



production, enhance efficacy, and encourage sustainable energy consumption. A life cycle "gate to gate" environmental approach is employed in this study.

Functional unit and system boundaries

For environmental analysis investigation, the functional unit selected is 1 MWh of generated electricity by the power plant. In any LCA study, the selection of functional units is very important, since it acts as a standardized benchmark for characterizing and identifying the functional and physical properties of the product (B. Guince, 2018). Figure 4 depicts the present LCA system framework. The local transportation of coal to the project site from the seaport by truck is included in the system boundaries. The activities related to coal mining are not included in this analysis due to a lack of data availability. All the processes involved in the production of electricity either by combined heat and power (CHP) or by the supercritical process are included.

Inventory analysis (LCI)

The analysis and acquisition of LCI data involve significant measures of measuring and defining the material inputs and outputs, energy consumption, and emissions within the system boundaries, which also involves the characterization of these elements. LCI of supercritical coal-based power systems for electricity production is depicted in Table 3. The primary data used for the assessment is provided by the power plant facility. The ecoinvent database is used for secondary data where the availability of primary data was not possible. The collected data was entered into OpenLCA 1.10.3 software.

Impact assessment

For impact assessment, the CML-1A baseline method in OpenLCA 1.10.3 software is used. CML is one of the most widely used approach for environmental impact assessment. CML modeling for impact assessment enables to reduce the uncertainties and also allows the assessment more

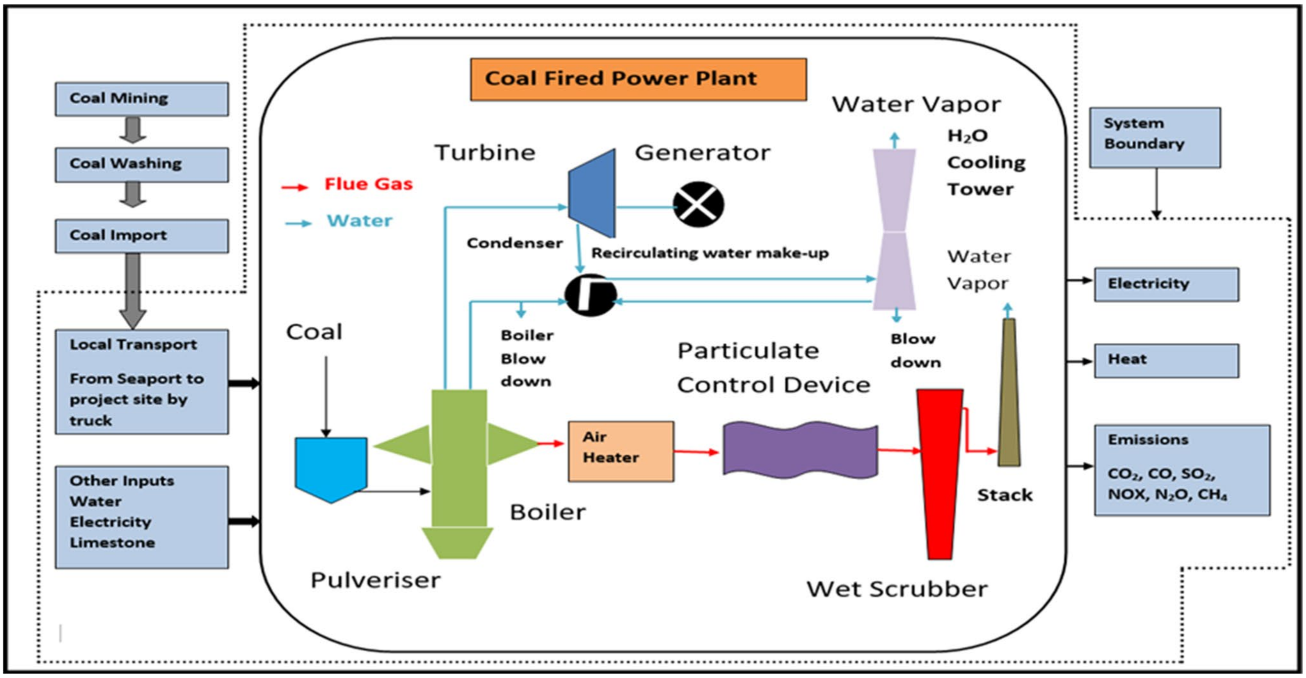


Fig. 4 Process flow, LCA boundary, and the power plant key energy production process

Table 3 Power plant LCI data as per 1 MWh of the functional unit

Parameters	Unit	Process stages	
		Coal and material transport	Power generation
Inputs from Technosphere			
Diesel	kg	2.50	
Coal	kg	-	380.45
Water	kg	-	3360.0
Limestone	kg	-	5.00
Electricity	kWh	-	51.87
Outputs (air emissions)			
CO_2	kg	91.52	552.0
CH_4	kg	0.46	0.03
CO	kg	0.031	0.051
NOx	kg	0.15	0.45
SO_2	kg	0.34	0.81
H_2O	kg	0.45	0.51
TSP	kg	9.85	0.15
GD	kg	-	0.03
Boiler ash	kg	-	76.00

TSP: total suspended particles, *GD:* gypsum desulfurization

transparently at the cause-effect chain early stages (Hernandez et al. 2017). The environmental impact indicators selected in this method are global warming potential (GWP), eutrophication (EU), abiotic depletion potential (ADP), photochemical oxidation (PO), acidification potential (AP), ozone layer depletion (ODP), human toxicity (HT), and terrestrial ecotoxicity (TE).

The CML-IA baseline method, developed by the Institute of Environmental Sciences (CML) at Leiden University, is a widely utilized approach in environmental impact assessments. This method systematically evaluates and quantifies the environmental impacts of products and processes throughout their entire life cycle—from raw material extraction and manufacturing to usage and disposal. Employing specific impact categories and characterization factors, the CML-IA baseline method translates LCI data into indicators of potential environmental impacts. Characterized by its focus on midpoint impact categories, the method provides detailed insights into various environmental consequences. This enables decision-makers to understand the direct effects of emissions and resource use, thus supporting the development of focused and effective environmental improvement strategies.

Economic analysis

The present study compares the economic viability of a conventional supercritical coal-based power plant with that of a supercritical coal-based power plant that utilizes CLC technology. The aim of the economic analysis is to compare the financial viability and cost-effectiveness of conventional supercritical coal-based power plants with those employing CLC technology. The comparison seeks to quantify cost differentials, assess economic benefits, and identify potential

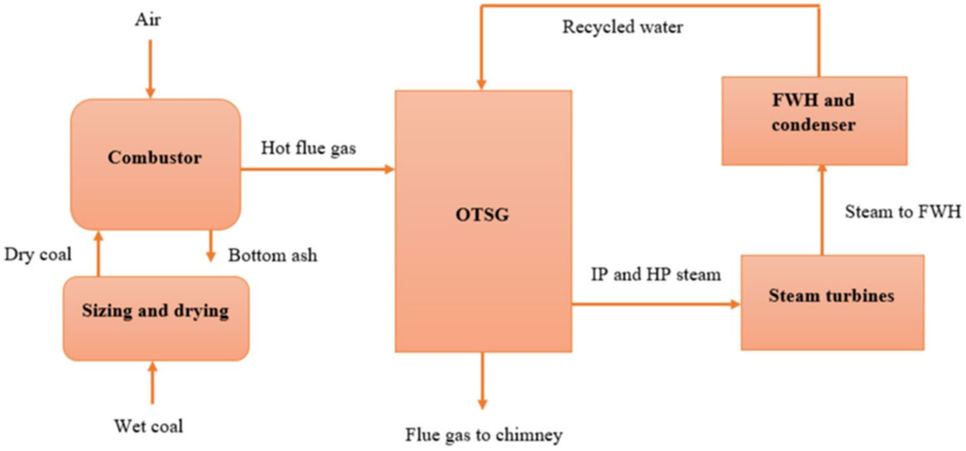


Fig. 5 Flow diagram of the conventional supercritical coal-fired power plant without CO_2 capture

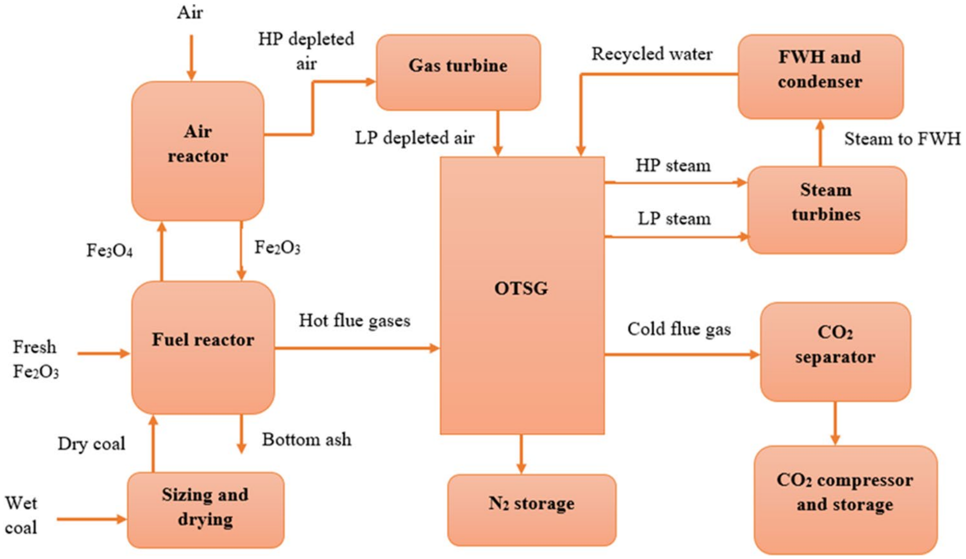


Fig. 6 Flow diagram of CLC-based coal-fired power plant

financial incentives or drawbacks associated with adopting advanced carbon capture technologies in coal-fired power generation. This analysis highlights the economic advantages and potential cost benefits of adopting CLC technology, which could significantly reduce operational costs and environmental impact. Such information is essential for Pakistan as it aims to balance economic growth with sustainable energy practices, especially given its substantial coal reserves and increasing energy needs.

To evaluate the economic performance of these two technologies, the analysis will consider a range of factors such as specific capital cost, levelized cost of electricity (LCOE), CO_2 avoided cost, and overall levelized cost of electricity ($LCOE_{overall}$). Below is a concise summary of supercritical conventional and chemical looping combustion-based coal-fired power plants.

Conventional supercritical coal-fired power system

The power plant's key parameters consist of a steam supercritical boiler installed in Pakistan by China Pakistan Economic Corridor (CPEC) Authority is presented in Table 2. A detailed description of the power plant is discussed in above section. Figure 5 shows the schematic representation of a conventional supercritical power plant without CCS.

Chemical looping combustion (CLC)-based supercritical coal-fired power system

Figure 6 presents a generalized schematic diagram of a coal-fired power plant based on CLC configuration, featuring several key components such as a CLC reactor, drying and sizing unit, once-through steam generator (OTSG), gas and steam turbine unit, CO_2 storage and compressor unit, and condenser and feed water heater (FWH) unit. To illustrate the CLC integration, Fig. 7 depicts the process flow

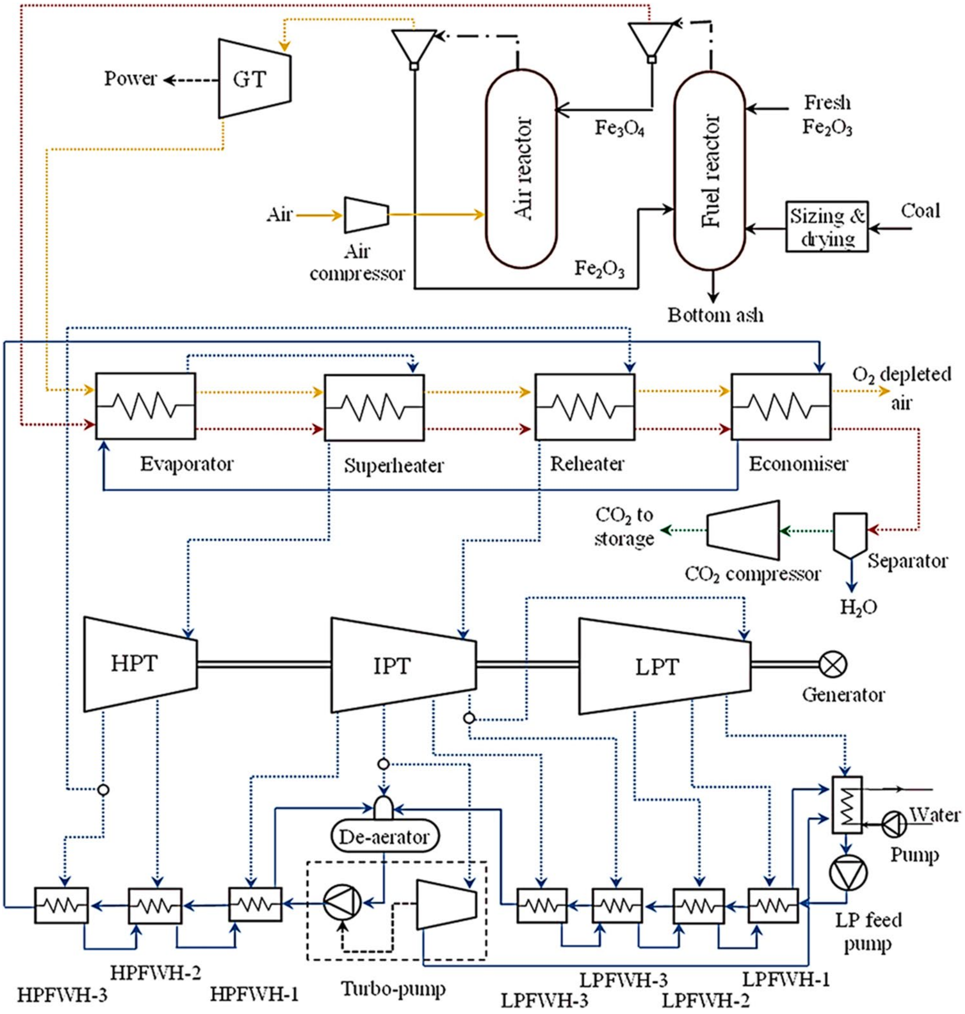


Fig. 7 Schematic representation of supercritical CLC-based coal-fired power plant. Indicators: steam (--------), water (———), Flue gas (------), solid–gas mixture (— · — ·), solid (———), deplete air (-------), and CO$_2$ (------)

diagram of supercritical coal-fired power plant, respectively. The power plant has the same FWH configurations and steam parameters as a conventional power plant but uses air and fuel reactors instead of combustors. Additionally, the compressor unit and CO$_2$ capture are integrated into the flowsheet of the CLC plant.

After processing through the sizing and drying unit, the pulverized coal is combined with an oxygen carrier (OC), containing 30% aluminum oxide and 70% iron oxide, by mass. The mixture is then conveyed to the adiabatic fuel reactor for coal combustion. The reduced OC, in the form of magnetite (Fe$_3$O$_4$), from the fuel reactor is conveyed to the isothermal air reactor, where it undergoes oxidation in the presence of pressurized air. The resultant high temperature and pressure gas is directed to the gas turbine and subsequently to the Once-Through Steam Generator (OTSG) unit for the recovery of heat. The flue gas, comprising CO$_2$ and H$_2$O, is utilized in the OTSG unit for heat recovery from the fuel reactor. Based on the power plant's energy demands, supercritical steam is produced in the OTSG unit, which is then utilized by the steam turbines to generate electricity. The flue gas, containing steam and CO$_2$, exits the OTSG unit and is conveyed to a condenser for steam condensation. This CO$_2$ is then compressed and stored for further use.

Parameters

The present study estimates and compares the operation and maintenance (O&M) as well as capital cost of the plants under consideration. An economic assessment is conducted utilizing the techno-economic analysis guidelines of the National Energy Technology Laboratory (NETL) for thermal power plants (Zoelle et al. 2015). This evaluation approach involves various stages, including estimating the overall capital cost, which takes into account equipment and installation costs, as well as the

Table 4 Economic analysis assumptions

Parameters	Value	Unit	Reference
Fixed cost	1.0	%	(Hanak and Manovic 2017)
Variable cost	2.0	%	(Hanak and Manovic 2017)
Cost of raw iron oxide	94	\$/t	(U.S. Geological Survey 2021)
Carbon tax	0	€/tCO_2	(Hanak and Manovic 2017)
Cost of raw aluminum oxide	3,100	\$/t	(Aluminum Prices Can't Keep Up With Energy Costs, Driving Wave of Closures. Wsj. https://www.Wsj.Com/Articles/Aluminum-Prices-Cant-Keep-up-with-Energy-Costs-Driving-Wave-of-Closures-11643547605, 2023)
Coal price	154	\$/t	(National Electric Power Regulatory Authority, Pakistan. https://nepra.org.pk/Tariff/Generation%20IPPs%20Coal.Php, 2023)
Cost of CO_2 transport and storage	10.0	€/tCO_2	(Hanak and Manovic 2017)
Expected lifetime	25	Years	(Mishra et al. 2019)
The social cost of carbon	1.05	\$/tCO_2	(Tol 2019)
Capacity factor	80	%	(Hanak and Manovic 2017)
Interest rate of project	8.80	%	(Hanak and Manovic 2017)

determination of both variable and fixed O&M costs (Zoelle et al. 2015).

This study employs the capacity ratio exponent approach to determine the equipment capital cost based on present values. To estimate the equipment/plant cost, Eq. (1) provides the correlation for cost estimation. Assuming a given capacity (whether it be plant size, energy, or mass flow rate), denoted as q1, the corresponding equipment cost is represented as C1. In that case, the equipment cost for a different capacity q2 denoted as C2 can be calculated as follows:

$$C_2 = C_1(q_2/q_1)^n \tag{1}$$

where n is the scaling factor and its value is depending on the particular type of plant/equipment being considered.

Moreover, the present-day equipment cost is calculated using the Chemical Engineering Plant Cost Index (CEPCI) for previous and current years to establish the original cost (refer to Eq. (2)). The scaling factors and CEPCI used in the calculation are obtained from existing literature (Zoelle et al. 2015).

$$\text{Present cost} = \text{original cost} \times \left(\frac{\text{CEPCI at present}}{\text{CEPCI at the time of original cost}}\right) \tag{2}$$

The current study utilizes the purchasing power parity index (PPPI) to calculate the exchange rate between two countries. This index represents the ratio of currencies based on their respective purchasing powers. The formula for computing cost conversion between two countries is provided by Eq. (3). Detailed information regarding the Power Capital Costs Index (PCCI) and PPPI for various countries can be found in published literature (Adams et al. 2017).

$$C_{\text{country}} = C_{\text{known country}} \times \left(\frac{\text{PCCI for current year}}{\text{PCCI for original year}}\right) \times \text{PPPI}_{\text{year}} \tag{3}$$

The current investigation includes the fixed and variable costs related to O&M, which are expressed as a proportion of the plant's total capital cost shown in Table 4. To evaluate the economic feasibility of the conventional supercritical coal-fired power plant, a comparison is conducted with a supercritical CLC-based plant. This comparison is based on the metrics of LCOE and the cost of avoided CO_2 emissions, which are determined by utilizing Eq. (4) and Eq. (5), respectively (Hanak and Manovic 2017).

$$\text{LCOE} = \frac{\text{TCR} \times \text{FCF} + \text{FOM}}{W_{\text{net}} \times \text{CF} \times 8760} + \text{VOM} + \frac{\text{SFC}}{n_{\text{th}}} \tag{4}$$

$$\text{CO}_2\text{avioded cost} = \frac{\text{LCOE}_{\text{capture}} - \text{LCOE}_{\text{non capture}}}{E_{\text{CO2 non capture}} - E_{\text{CO2 capture}}} \tag{5}$$

The correlation described by Eq. (4) establishes a connection between the thermodynamic performance parameters of the plant, including net power output (W_{net}), capacity factor (CF), net specific CO_2 emissions, energy efficiency (nth), and the economic performance parameters, which include total capital requirement (TCR), specific fuel cost (SFC), variable O&M costs (VOM), fixed O&M costs (FOM), and fixed charge factor (FCF). These economic parameters are assessed by considering the project interest rate and the plant's lifespan. The variable ECO_2 in Eq. (5) denotes the specific rate of CO_2 emission in tons of CO_2/MW_{el}h, which can be determined by using Eq. (6) (Surywanshi et al. 2022).

Table 5 Quantified impact values as per 1 MWh functional unit of generated electricity for the selected impact categories

Impact category	Coal transport	Electricity production	Total impact score	Unit
Global warming potential	200	651	851	kg CO_2 eq
Eutrophication	0.108	0.121	0.229	kg PO_4 eq
Abiotic depletion potential	0.0170	0.153	0.170	kg Sb eq
Photochemical oxidation	2.97×10^{-3}	1.33×10^{-3}	4.30×10^{-3}	kg C_2H_4 eq
Acidification	0.0663	1.31	1.37	kg SO_2 eq
Ozone layer depletion	1.50×10^{-9}	7.10×10^{-8}	7.25×10^{-8}	kg CFC-11 eq
Human toxicity	2.84	0.341	3.18	kg 1,4 DCB eq
Terrestrial ecotoxicity	0.134	3.10	3.23	kg 1,4 DCB eq

$$E_{\mathrm{CO2}} = \frac{\left(m_{\mathrm{CO2\ emit}}\right)}{\left(W_{\mathrm{net}}\right)} \tag{6}$$

where mCO_2 (in kg/s) is the net emitted CO_2 into the atmosphere.

Carbon dioxide emissions are widely acknowledged as a key driver of climate change, with devastating impacts, including, extreme weather events such as destructive storms and flooding, disrupted agricultural productivity, sea levels rising, and other severe consequences. These outcomes can impose substantial financial burdens on individuals, corporations, and governments, manifesting as increased costs of food, healthcare, property damage, and other expenses. To gauge the economic cost of these effects, the social cost of carbon (SCC) serves as a metric for assessing the resulting total damages from the CO_2 emission (1 ton) into the atmosphere (Rahil et al. 2019). The literature presents various estimates of the SCC, and there exists a divergence in the predictive methods employed to determine SCC (Zhen et al. 2018). Tol (2019) calculated the SCC for nearly every country by incorporating climate model forecasts, empirical estimations of climate-induced economic damage, and socio-economic projections. This study conducts an economic evaluation utilizing the national SCC for Pakistan, as reported by Tol (2019) which estimates \$1.05 per tonne of carbon emitted. Using this as a representative study case, the cost of damages resulting from CO_2 emissions by the coal-fired power plant ($EcCO_2$) is determined by multiplying the specific rate of CO_2 emissions (ECO_2) with the SCC, as illustrated in Eq. (7) (Rahil et al. 2019):

$$E_{C_{\mathrm{CO2}}} = E_{\mathrm{CO2}} \times \mathrm{SCC} \tag{7}$$

This study defines the $\mathrm{LCOE}_{\mathrm{overall}}$ as follows, incorporating SCC:

$$\mathrm{LCOE}_{\mathrm{overall}} = \mathrm{LCOE} + E_{C_{\mathrm{CO2}}} \tag{8}$$

Results and discussions

Analysis of environmental impacts

Coal-fired power plants based on supercritical technology have been developed as a means to improve efficiency and reduce the environmental impacts of traditional coal-fired power plants. However, the environmental impact analysis of such power plants indicates that they still have significant negative effects on the environment. The GHG emissions, such as CO_2, are lower than those from traditional coal-fired power plants per unit of electricity generated. Nonetheless, the absolute levels remain high, contributing significantly to climate change. Additionally, emissions of nitrogen oxides, sulfur dioxide, and particulate matter can cause smog and respiratory problems. The large amounts of water required for cooling purposes can strain local water resources, and the effluent from the plant can impact the quality of nearby water bodies. Overall, supercritical coal-fired power plants are an improvement over traditional coal-fired power plants; careful management and implementation of advanced emissions control technologies are necessary to minimize their environmental impacts.

For the eight impact categories that were considered, impact scores are calculated and shown in Table 5. Transportation of materials and plant operation for power generation are the two process stages that each contribute a certain percentage to the selected midpoint impact indicators shown in Fig. 8. The utilization of Ecoinvent data v2.0 results in identical characterization factors for both high and low-population density, thereby neglecting any potential differences in the environmental impact assessment between these two settings. In this section, modeling results are discussed further and compared with existing literature. The results derived from the comprehensive modeling of environmental impacts, utilizing a life cycle approach, hold significant implications and establish a factual basis for assessing the sustainability of various coal-fired power generation systems in developing countries where energy scarcity is a prevailing issue.

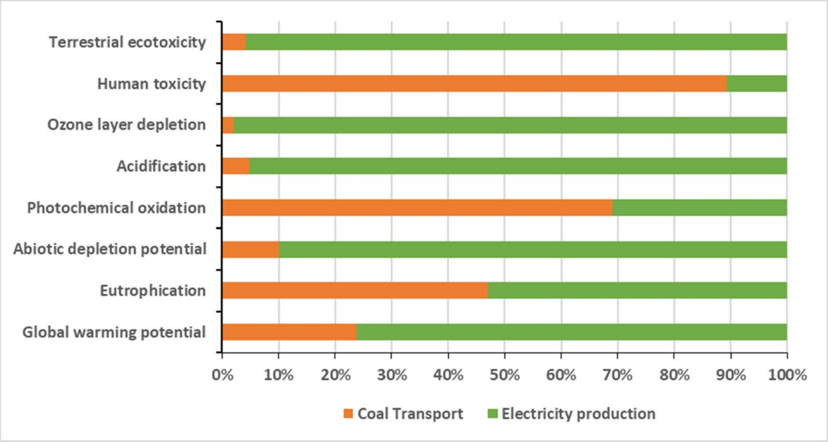


Fig. 8 Power plant two stages relative contributions in the selected eight impact categories for power generation

Global warming potential (GWP)

For the power plant under consideration, the GWP of the power plant being examined is estimated at 851 kg$_{\text{CO2 eq}}$ (as shown in Table 5). When compared to the other chosen impact categories, the GWP category has the highest percentage. Power generation accounts for 77% of the plant's operation, with the remaining 23% being attributable to materials and coal transportation (as illustrated in Fig. 8). Improving efficiency is a potential strategy for reducing GHG emissions from current coal power plants. According to a previous investigation of a pulverized coal-fired plant, a 1% increase in net output efficiency led to a 3% reduction in CO_2 emissions (N. Wang et al. 2019a, b; Y. Wang et al. 2019a, b).

Liang et al. (2013) conducted an LCA of various coal-based power systems in China. The outcomes showed that the ultra-supercritical and combined-integrated gasification cycle had the least impact, while the impact score of the supercritical and subcritical method was 762 and 890 kg$_{\text{CO2 eq}}$, respectively. CCS is a useful technique to reduce the GHG emissions caused by widespread fossil fuels use. The total CO_2 emissions from coal power plants can be significantly reduced by CCS technologies; however, greater CO_2 levels are produced due to the additional energy that CCS requires. Petrescu et al. (2017) investigated the LCA of pulverized supercritical coal power plants with and without CCS systems. The results showed a higher impact score (970 kg$_{\text{CO2 eq}}$ without CCS), while for power plant employing the CCS system, they found a value of eq 402 kg$_{\text{CO2 eq}}$. Asante-Okyere et al. (2016) also carried out an LCA study of a coal power plant based on supercritical technology located in China with and without CCS. The results showed that the supercritical process with a CCS system has a lower impact score (276 276 kg$_{\text{CO2 eq}}$) than the supercritical process without a CCS system (19.61 kg$_{\text{CO2 eq}}$), which shows a 71% reduction in GHG emissions due to the adoption of CCS.

Eutrophication

Eutrophication (EP) is usually caused in coal mining, transportation, and the production of power stages. The effect is usually large during the coal mining process due to emissions of living wastewater, leaching water, and coal gangue. Table 5 indicates a EP of 0.229 kg$_{\text{PO4 eq}}$ per MWh of generated electricity by the power plant under consideration. The EP environmental impact category relates to nitrogen or phosphorous compounds (e.g., nitrogen, nitrogen oxides, ammonia, nitrates, and phosphate).

Wang et al. (2018) carried out an LCA study of coal-fired power generation in China. Chemical oxygen demand (COD) had the highest rate of emissions that contributed to EP (67.4%). Related studies also have shown that COD contributed to EP is more than 50% across the entire life cycle of coal-fired power production, with coal combustion being the key factor in COD EP impact. Regarding EP, Asante-Okyere et al. (2016) found values of 0.675 kg$_{\text{PO4 eq}}$ (supercritical without CCS) and 272 kg$_{\text{PO4 eq}}$ (supercritical with CCS), indicating an increase of 22% and 303% for freshwater and marine EP respectively, due to CCS. In contrast, it is clear that CCS, which utilized more coal, would result in significant phosphate or phosphor leaching into water bodies through activities such as ash disposal, coal mining, and reclaimer waste disposal. Therefore, contributing to CCS recording a higher freshwater EP value, treatment measures of EP included engineering and biological measures, aquatic animal treatment, chemical methods, and comprehensive and ecological prevention. Aquatic animal treatment and biological measures were the most widely used techniques for minimizing EP water pollution. Furthermore, controlling inputs of exogenous nutrients can also efficiently decrease EP at the source (Sherwood and Qualls 2001).

Abiotic depletion potential (ADP)

In Table 3, it is shown that the resources used to produce coal-fired electricity mostly consist of coal, water, electricity, limestone, and diesel fuel, with a total contribution of 0.170 $kg_{Sb\ eq}$ to the category of abiotic resource depletion impact (Table 5). The stage of coal transport contributes just 10%, whereas the stage of plant operations consumes 90% of these resources (Fig. 8). The production of coal-fired electricity is primarily dominated by water usage, followed by coal resource consumption.

A comparative LCA was carried out by Liang et al. (2013) by comparing four different pulverized coal power generating technologies; integrated gasification combined cycle (IGCC), sub, super, and ultra-supercritical. The findings demonstrated that IGCC has a high contribution for ADP (0.118 $kg_{Sb\ eq}$), while super-critical technology has a smaller contribution (0.0127 $kg_{Sb\ eq}$). On the other hand, sub-critical and ultra-supercritical give 1.51×10^{-10} $kg_{Sb\ eq}$, and 0.120 $kg_{Sb\ eq}$ contributions for ADP, respectively. Water consumption during the coal mining process is often very high, indicating that a lot of water is used throughout the entire coal-fired power production life cycle, from coal mining through power generation. Coal resource consumption is second to water consumption in the entire life cycle of coal-fired production. This was also concluded by Wang et al. (2018) under the LCA category of resource consumption for a Chinese coal-fired power generation that the impact score of water had the highest proportion followed by coal having percentage contributions of 53.9% and 16.1%. As a result, electricity production in coal-fired power plants requires a lot of water, hence water use needs to be optimized and rigorously monitored using route balance water testing. The consumption of coal also needs to be reduced. As the combustion of coal is usually done in the boiler, enhancing the parameters like maintaining boiler quality as well as sealing performance and heat transfer effects can improve the efficiency of the coal combustion (S. Shah and Adhyaru 2011).

Photochemical oxidation (PO)

The emission of nitrogen molecules and their oxides frequently results in PO. The total impact score of PO is 4.30×10^{-3} $kg_{C2H4\ eq}$ (Table 5). The material and coal transportation stage dominates the PO impact category with a total contribution of 68%. Methane (CH_4) contributes more to PO compared to carbon monoxide (CO). The combined effect of PO on transportation and power generation stages is shown in Fig. 8.

Koornneef et al. (2008) conducted LCA of a pulverized coal power plant by assessing three cases: (1) sub-critical pulverized coal-fired power generation, (2) power generation using pulverized coal in ultra-supercritical technology, and (3) a state-of-the-art coal-fired power plant with CCS using monoethanolamine for post-combustion CO_2 capture. The results showed the total impact score of PO in case 1 was 9.06×10^{-5} $kg_{C2H4\ eq}$, while for cases 2 and 3, the total impact score was 5.13×10^{-5} $kg_{C2H4\ eq}$ and 6.69×10^{-5} $kg_{C2H4\ eq}$ (including coal mining stages). The comparison between cases 1, 2, and 3 demonstrates a reduction of 43 and 28%, respectively. This is mainly caused by the increased removal of SO_2 in the CO_2 capture and flue gas desulfurization processes. While conducting the LCA study of coal-fired power generation in China, Wang et al. (2018) also concluded that the major contributor to PO was CO with a 78.5% contribution rate, followed by CH_4 (21.5%). Therefore, measures must be done to limit the CO emissions to reduce the PO environmental impact. Some measures such as increasing combustion air quality in the boiler and making modifications to ventilation and distribution of coal can reduce CO emissions. Moreover, large-scale ammonia selective catalytic reduction (SCR-NH3) and wet limestone-gypsum flue gas desulfurization (WFGD-Ca) procedures have been developed for the purification of flue gas in coal-fired power plants.

Acidification potential (AP)

Table 5 shows an AP of 1.37 $kg_{SO2\ eq}$ per MWh of energy produced by the chosen power plant. NO_2 and SO_2 are the major contributors of AP, while the impact category is preliminarily dominated by the plant operation stage (95%) as shown in Fig. 8. The power project utilizes an electrostatic precipitator (ESP) to eliminate SOx from the flue gas before it enters a flue gas desulfurized (FGD) that is based on limestone-gypsum. The flue gas flow proceeds from the absorber bottom to its top, while the limestone slurry is continually sprayed to achieve the maximum possible flue gas contact. This method effectively removes SO_2 (90%), generating gypsum as a by-product.

Liang et al. (2013) calculated an AP of 1.32 $kg_{SO2\ eq}$ of supercritical coal power in China. In their study, the AP impact category is dominated by the power generation stage having contributed more than 80%. In another study, Rewlay-ngoen et al. (2014) estimated AP of 1.26×10^{-3} $kg_{SO2\ eq}$ for a supercritical coal-fired power in Thailand. The AP is mostly due to by plant operation stage; therefore, to limit the emissions of SO_2, coal desulfurization technology must be employed for the efficient sulfur removal from raw coal during the power production stage. Moreover, by employing sophisticated coal combustion technologies, like liquid coal technology, the emissions of NOx and SO_2 can also be decreased from the process of coal combustion.

Ozone layer depletion (ODP)

The category of ODP is usually caused as a result of two basic organic halogenated compounds, di-chlorotetrafluoroethane, and tri-chlorofluoromethane. The total impact score of this category is 7.25×10^{-8} $kg_{CFC\text{-}11\ eq}$ (Table 5). The contribution of the transportation stage is much lower (2%). As depicted in Fig. 8, the plant operational stage has maximum shares which is about 98%. The cooling fluid utilized in electricity generators contains $C_2Cl_2F_4$ and CCl_3F compounds, and small amounts of these substances are released into the atmosphere as a result of fugitive emissions.

Asante-Okyere et al. (2016) performed the LCA of a supercritical coal power plant located in China with and without CCS by using mono-ethanolamine (MEA) as absorption capture. The total impact score with CCS was 8.70×10^{-11} $kg_{CFC\text{-}11\ eq}$, while without CSS, the score was 1.38×10^{-10} $kg_{CFC\text{-}11\ eq}$. The use of CCS technology lowers ionizing radiation and ozone depletion potentials. Ammonia use during the reduction of NOx causes relatively higher ODP, as well as ionization radiation. Organic and radioactive substances are excused into the environment by the waste tailings from the production of ammonia. Liang et al. (2013) also reported the ODP category with a total impact score of 9.77×10^{-8} $kg_{CFC\text{-}11\ eq}$ by comparing various coal-fired power plant technologies. The contribution of coal transportation was 5.13×10^{-8}, while the power generation stage contributed 4.64×10^{-8} $kg_{CFC\text{-}11\ eq}$, which is quite similar to the present study. The primary cause of ODP emissions is electricity. However, compared to other energy generation technologies (uranium, lignite, and gas), which each contribute a very small amount, hydropower generation generates no ODP at all (Sharaai et al. 2010).

Human toxicity (HT)

Table 5 presented that the total net contribution by both processes to HT is 3.18 $kg_{1,4DCB\ eq}$. Out of which plant operations stage contributes only 12% and 88% contribution is by the coal and material transport (Fig. 8). This demonstrated that this category's overall contribution is lower, due to the number of preventative measures implemented by the plant authorities such as FGD and ESPs system installation with 95% and 99% efficiencies, respectively. Smoke and dust particles can be efficiently trapped by ESPs, and around 90% of SO_2 can be removed from the flue gases using FGD. Moreover, the facility is equipped with low NOx burners that have effectively maintained NOx emissions well below the mandated thresholds.

Xiao et al. (2011) studied the emission ratio life cycle in all phases of coal power generation technologies in China. The findings showed that the emission ratio of supercritical power plants without FDG was high which is 48 for particulate matter, 90 for NOx, and 98 for SO_2. While the emission ratio of supercritical + FGD was low which is 44 for smoke, 87 for NOx, and 61 for SO_2. This shows that in comparison to typical supercritical coal power plants, supercritical + FGD technology offered substantially lower emissions for particulate matter, NOx, and SO_2, for coal transportation and power generation stages. In a similar study, Wang et al. (2018) investigated HT under the category of health hazard. The contribution rate of SO_2 was significant (88.9%) followed by NOx (10.7%) and CO (0.4%). Thus, the suspended particle generation such as dust and smoke during the coal transportation process is attributed to having the maximum contribution potential.

Terrestrial ecotoxicity (TE)

For 1 MWh functional unit generated electricity, the total impact contribution for the category of TE is 3.23 $kg_{1,4\ DCB\ eq}$, as shown in Table 5. Coal and material transport only account for a 4% contribution. The majority of the impact under this category is related to the plant operation stage which is 96% (Fig. 8). Under this category, the main contributor is the generation of solid waste such as coal gangue, boiler ash, desulfurization gypsum, peat, and garbage.

Due to the numerous mitigation and control measures implemented at the plant by the Environmental Protection Authority directive, the overall impact attributed to this category is low. A conventional ash yard has been built with a 1.5 m deep clay layer for seepage control, a dam slope, and polyethylene geo-membrane underneath the fields to create an artificial barrier with a $<1.00\times10^{-7}$ cm/s permeability coefficient. A submerged scraper conveyor filled with water is currently employed to gather the bottom ash generated beneath the furnace. The ash is subsequently dewatered and transferred to each boiler's slag silo, which has an effective volume of 80 m^3. Fly ash, which can be utilized partially or fully substitute in other processes as raw material, is produced by coal power plants (55%) as their secondary product (Akhtar et al. 2019). The process of coal combustion produced a significant boiler ash amount in the plant operation stage. This was concluded by Wang et al. (2018) by performing a LCA study of coal-fired power plant for electricity generation. Boiler ash had a significant contribution of 87.0% followed by coal gangue having contribution 12.9%. The contributions of living garbage, desulfurization gypsum, and peat were lower (<0.1%).

Technological comparison

Various improvements in conventional coal-based power generation technologies have been made since the development of advanced steam turbines in 1884. Because of its

Fig. 9 System configuration of subcritical (conventional) vs. supercritical boiler

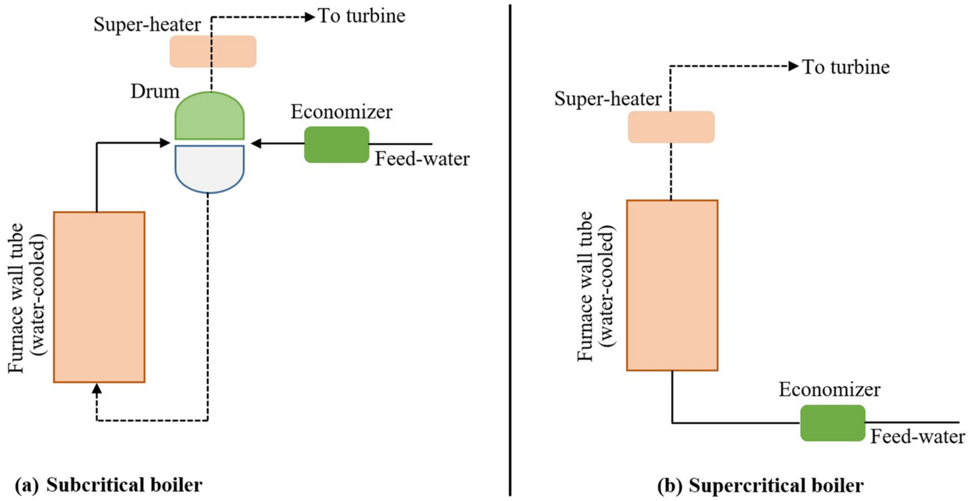
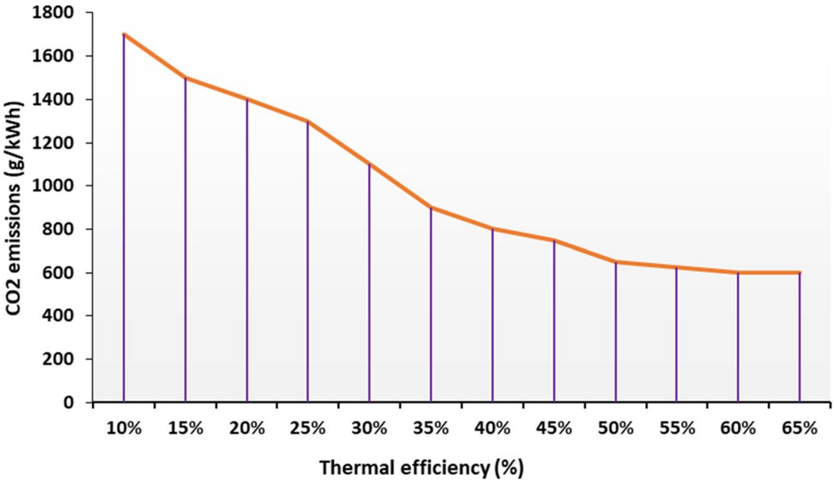


Fig. 10 Relative correspondence between plant efficiency and CO_2 emission reduction



economic and technological advantages, pulverized coal (PC) energy production is the most extensively used configuration of coal-fired plants.

The characteristic feature of a supercritical boiler is that it is drum-less, which maintains pressure and temperature to convert water inflow into a non-distinguishable liquid–gas phase. In a supercritical boiler, the generation of steam occurs under constant pressure and high temperature and the turbines are significantly operating at higher levels of Carnot cycle thermodynamic efficiency. This exterminates the requirement for a conventional drum (Fig. 9b) for boiling water storage because the water is kept in a high-temperature environment to enable uniform conversion into steam within the tubes of the boiler. The steam cycle and basic design of subcritical and supercritical technology are shown in Fig. 9.

Figure 10 depicts the relative CO_2 emissions reduction with increased power plant efficiency. A 1% improvement in thermal efficiency in PC plants results in a 2 to 3% reduction in CO_2 emissions. Beyond reducing CO_2, higher efficiency also typically leads to reductions in other pollutants like SO_2, NOx, and PM, further benefiting the environment. Moreover, reducing fuel consumption decreases operational costs over time, which can be significant given the high costs associated with coal purchasing and transport. The net energy efficiency of selected supercritical coal-based power plant is 41–43% (Table 1) which is approximately 11% higher than the thermal efficiency of typical coal power generation systems. The International Energy Agency (IEA) reported that replacing existing subcritical systems with super or ultra-supercritical units can result in a 23% reduction in CO_2 emissions (Nalbandian and IEA Coal Research. Clean Coal Centre., 2008). Moreover, an increase of 1% in net energy efficiency can mitigate 500 tons of PM, 2000 tons of SO_2 and NOx, and 2.4 Mt of CO_2 with a longer coal-based energy unit lifespan (Du et al. 2016). This shows that the efficiency of pollutant removal of subcritical power units is less than supercritical power systems (Fig. 11) (D. Cebrucean et al. 2020).

The relationship between efficiency improvement and emissions reduction in power plants is exponential, not

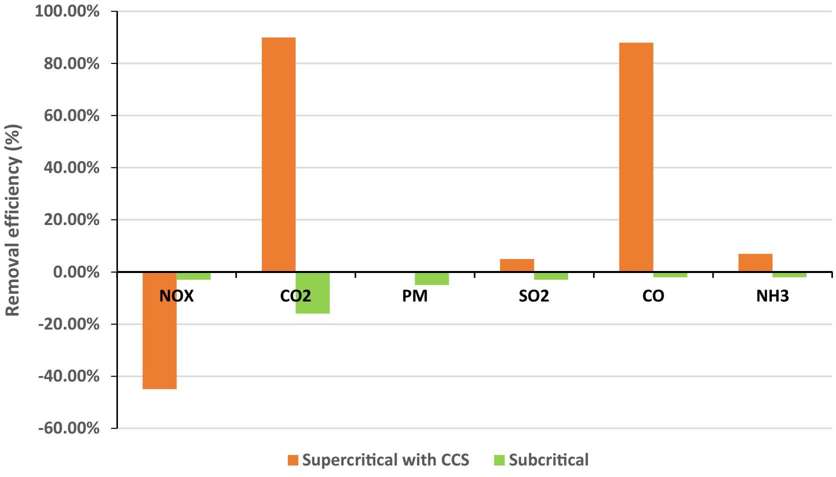


Fig. 11 Efficiency of pollutants removal of supercritical and subcritical coal-fired power systems

linear. This exponential relationship is due to the fact that each unit of coal not burned not only reduces emissions directly from the power plant but also avoids the energy use and emissions associated with mining, transporting, and processing the coal. These activities consume energy and produce emissions themselves, thus amplifying the effect of the initial efficiency gain. Furthermore, the efficiency of a power plant is largely determined by the thermodynamic cycle it uses to convert heat into electricity. Enhancements in plant efficiency typically involve operating at higher temperatures and pressures, optimizing the cycle's effectiveness. Consequently, with less energy lost to heat and other inefficiencies, the plant consumes less fuel per unit of electricity produced. Therefore, CO_2 emissions are disproportionately reduced relative to the efficiency improvement.

Economic analysis

Table 6 shows the economic performance of conventional and CLC-based coal-fired power plants operating on supercritical technology. The LCOE for the conventional coal-fired power plant is €68.92/MW_{el}h, while the LCOE for the CLC-based power plant is €93.10/MW_{el}h. This represents an increase of approximately 35.4% in LCOE for the CLC-based coal-fired power plant compared to the conventional coal-fired power plant. The higher LCOE for the CLC-based power plant is primarily due to the additional costs associated with the CLC process, such as the requirement for oxygen carriers and additional equipment.

The specific capital cost for the CLC-based coal-fired power plant is €1043.89/$kW_{el,\ gross}$, while the specific capital cost for the conventional coal-fired power plant is €1270.15/$kW_{el,\ gross}$. This represents a reduction of approximately 17.8% in specific capital cost for the CLC-based power plant compared to the conventional coal-fired power plant. The lower specific capital cost for the CLC-based power plant is primarily due to the lower cost of the oxygen carrier and the ability to reduce the size of the power plant due to the increased efficiency of the CLC process.

Table 6 Economic comparison between supercritical conventional and supercritical CLC coal-fired power plant

Variables	Units	Supercritical	
		Conventional coal-fired power plant	CLC-based coal-fired power plant
LCOE	€/MW_{el}h	68.92	93.10
Specific capital cost	€/$kW_{el,\ gross}$	1270.15	1043.89
CO_2 avoided cost	€/tCO_2	-	43.82
$LCOE_{overall}$	€/MW_{el}h	108.80	93.10

The CO_2 avoided cost for the CLC-based coal-fired power plant is €43.82/tCO_2, while there is no CO_2 avoided cost associated with the conventional coal-fired power plant. This means that the CLC-based coal-fired power plant has an advantage in terms of reducing CO_2 emissions.

When both the CO_2 avoided cost and LCOE are considered, the $LCOE_{overall}$ for the conventional coal-fired power plant is €108.80/MW_{el}h, while the $LCOE_{overall}$ for the CLC-based power plant is €93.10/MW_{el}h. This represents a reduction of approximately 16.1% in $LCOE_{overall}$ for the CLC-based coal-fired power plant compared to the conventional coal-fired power plant. The lower $LCOE_{overall}$ for the CLC-based power plant is primarily due to the advantage of reducing CO_2 emissions. This indicates that the CLC-based coal-fired power plant is a more competitive and environmentally friendly option.

The difference in the LCOE between the two plants indicates a crucial trade-off. The higher LCOE of the CLC-based plant compared to the conventional plant highlights the premium paid for advanced technology that significantly

Table 7 Sensitivity of total plant cost and LCOE to uncertain cost variables for the CLC plant

Cost item	Cost, €/MW$_{el}$h	%varying	Effect on total plant cost	Effect on LCOE
CLC equipment	1,695,600	± 20	± 8.5%	± 2.02%
CO_2 removal and compression	234,900	± 20	± 1.3%	Negligible effect
Price of electricity	225	± 20	-	± 9.5%

The cost is calculated based on present currency exchange rates

reduces environmental impact. While the initial and operational costs for CLC technology are higher, the long-term benefits of reduced CO_2 emissions contribute not only to meeting environmental regulatory compliance but also to potential economic benefits through mechanisms like carbon credits. The challenge here is to balance these higher costs with the environmental benefits in a way that they become appealing to investors and stakeholders who are traditionally cost-sensitive.

The lower specific capital cost for the CLC-based plant, despite its higher LCOE, suggests that the technology, while expensive to operate, does not require as much capital to set up. This could be due to advancements in technology that reduce the complexity or scale of equipment needed. However, the operational efficiency and maintenance costs likely drive up the LCOE, pointing to areas where further technological innovations or operational optimizations could be focused. Reducing these operational costs could drastically improve the economic competitiveness of CLC plants.

The specific metric of CO_2 avoided cost for the CLC-based plant highlights its role in environmental sustainability. This figure quantifies the cost-effectiveness of the plant's ability to mitigate carbon emissions compared to traditional coal-fired power plants. In regions or countries with carbon pricing mechanisms, these costs could potentially be offset by government subsidies or through the sale of carbon credits. This not only helps in recovering some of the higher operational costs but also incentivizes further investments into cleaner technologies.

The economic and environmental frameworks within which these plants operate are heavily influenced by national and international policies on emissions and renewable energy targets. Policies such as carbon pricing, renewable energy incentives, and stricter emissions standards could tilt the balance in favor of technologies like CLC. For instance, if carbon tax increases or if there are substantial subsidies for low-carbon technologies, the overall economic metrics of CLC technology would become more favorable.

In summary, while the CLC-based power plants currently exhibit higher costs in terms of LCOE, their lower specific capital costs and significant environmental benefits present a compelling case for their adoption, particularly in a future shaped by stringent environmental regulations and carbon pricing mechanisms. The ongoing development and optimization of such technologies are vital, not only for making them economically viable but also for ensuring their scalability and adaptability to various operational environments and market conditions.

Sensitivity analysis

Sensitivity analysis was performed to evaluate the impact of certain key variables, such as the cost of CLC equipment and the price of electricity, on the LCOE of a CLC plant. Table 7 outlines how different cost items influence the total plant cost and LCOE. When the cost of CLC equipment was varied by ± 20%, the effect on total plant cost was noticeable, showing an 8.5% variation. However, this change had a negligible impact on LCOE. Conversely, the price of electricity, set at €225/MW$_{el}$h, when varied by ± 20%, led to a significant 9.5% shift in LCOE. This substantial variation highlights the greater sensitivity of LCOE to electricity pricing compared to the cost of CLC equipment. The minimum impact of these cost factors on LCOE, aside from electricity pricing, provides a optimal level of confidence in the estimates for total plant cost and LCOE, indicating a stable financial outlook for the plant under varying economic conditions.

Policy implications

It is reasonable to propose that in Pakistan, government should drive the adoption of clean coal technology via public administration mechanisms. Several strategies have been suggested as potential policies, including the following.

Enhance the legal framework to enforce the utilization of clean coal

Empirical evidence suggests that the development of clean coal technology is generally stimulated by environmental regulations and policy initiatives in different nations. Notably, in the USA, the Clean Air Act and, in the European Union, air pollution control policies require the implementation of rigorous, time-bound environmental control measures, and violations can result in severe penalties, including criminal sanctions (Kuklinska et al. 2015).

While other countries rely on environmental policies to promote clean coal development, Pakistan predominantly employs technical policies for this purpose. Pakistan should review and amend applicable regulations and environmental policies. This may involve imposing more rigorous emission standards on coal-reliant industries, levying charges on total emissions, penalizing excessive emissions that go beyond regulations, establishing a trading system for emissions, and collecting environmental taxes.

Design incentives for clean coal technology utilization through tax preferences and financial subsidies

Sufficient financial support is an indispensable element in facilitating the successful implementation of clean coal technology. As an illustration, the American clean coal program has been contributed with a total investment of 7.14 billion USD, of which roughly 35% is derived from government sources (Lu et al. 2008). To begin with, Pakistan should slowly but steadily augment government funding to provide adequate financial backing for the clean coal sector and classify it as a top-priority development area to synchronize economic and industrial structures. At the same time, the integration of the clean coal industry into the long-term development strategy for the national economy and society must be guaranteed.

Secondly, it is important to create investment policies that attract companies and encourage the adoption of eco-friendly coal technologies. A powerful strategy is to offer incentives such as tax breaks and low-interest loans for incorporating advanced technologies, which will increase companies' interest in adopting these methods (Zhang et al. 2022). As the cost of clean coal technologies can be high, it is crucial to establish reliable and stable sources of capital to create a favorable investment climate. The government can help by developing mechanisms to improve financial channels for corporations to facilitate the development of such technologies. For instance, a clean coal development fund or multi-tier finance system could help reduce the investment threshold for smaller businesses.

Implement coal utilization life-cycle management practices

The comprehensive life cycle of coal exploitation and utilization involves multiple stages encompassing not only the coal industry itself but also downstream sectors such as chemical, building materials, metallurgical, and power industries. The disruption of any stage in the chain can lead to significant environmental impacts (N. Wang et al. 2019a, b). Improper planning and management practices in coal mining and processing can impose a considerable burden on environmental resources, such as water, air, and land (De Valck et al. 2021) Therefore, it is imperative to expand the scope of clean coal initiatives to cover the entire life cycle of coal utilization, instead of limiting the focus to individual processes. The adoption of environmentally responsible management practices throughout the complete life cycle can enhance environmental sustainability (Burchart-Korol et al. 2016). However, current research in Pakistan on this matter is insufficient, and practical implementation of life cycle management is still lacking. It is essential to prioritize the improvement of comprehensive coal utilization efficiency throughout the whole life cycle for the future of coal usage in Pakistan. Pakistan can initiate demonstration projects that serve as case studies for the comprehensive life cycle management of coal in regions abundant in coal resources. These initiatives can expedite the establishment of fundamental practices, data, and experience, which can subsequently facilitate the formulation of more appropriate policies in the future.

Conclusion and recommendations

Conclusion

This study presents a comprehensive LCA and environmental impact analysis of a supercritical coal-fired power plant in Pakistan, without the implementation of CCS technology. Results indicate that ODP is the least affected category (7.25×10^{-8} $\mathrm{kg}_{\mathrm{CFC\text{-}11\ eq}}$), whereas GWP has the highest impact score (851 $\mathrm{kg}_{\mathrm{CO2eq}}$). The operational stage of the power plant dominates in most impact categories, except for PO and HT. Emissions from the plant, including boiler ash, SO_2, CO, and TSP, have the greatest potential for ecological impacts. Furthermore, an economic analysis of the conventional and CLC-based coal-fired power plants under supercritical conditions reveals that the CLC-based plant has a lower specific capital cost and $\mathrm{LCOE}_{\mathrm{overall}}$ compared to the conventional plant. However, the CLC-based plant has a higher LCOE, indicating that its higher cost could be a barrier to adoption. The LCOE for a CLC plant is significantly sensitive to the electricity price and total plant cost. A variation of ± 20% in the price of electricity results in a 9.5% change in LCOE. Therefore, it is recommended to enhance the legal framework for enforcing clean coal use, design incentives for clean coal technology adoption, and implement coal utilization life-cycle management practices in Pakistan. These measures would not only accelerate clean coal development but also improve environmental sustainability while aligning economic and industrial structures.

Future work

The role of coal as an energy source maintained its significance in developing countries especially in Pakistan because of its low cost, stability of supply, and wide availability. However, compared to other fuels, CO_2 emissions from coal is high. The main problem preventing the development of coal-fired power facilities is their environmental impacts. In Pakistan, most of the previously installed conventional coal-based power units are causing huge environmental damage because they are operating on conventional technologies. The power plant under consideration in this study which is equipped with modern supercritical technology may prove to be a benchmark for future advancements in Pakistan's sustainable coal-fired energy production. This analysis can act as a stepping stone for further enhancing the environmental and technological viability of coal-based systems for generating energy by employing CCS, ultra-supercritical, advanced ultra-supercritical, and renewable technologies. However, economic costs related to these technologies are the barrier to this development. Following are the way forward and a few recommendations:

1) The most widely used approach for optimizing the efficiency of power plants is co-firing. Coal co-firing with bagasse and biomass for the generation of electricity can be another cleaner and viable alternative because Pakistan is an agricultural state and produce these feedstocks in sufficient amount.
2) Although Pakistan's coal reserves are approximately 186 billion tonnes, their high sulfur content is the primary challenge. By implementing the process of coal washing, this problem can be rectified which can enhance the properties of coal by significantly lowering the sulfur as well as ash content. When employed in plant facilities, this modified coal can ensure economic and environmental benefits while replacing imported coal.
3) In Pakistan, imported coal is used in most of the power plants; therefore, converting these power plants into biomass co-firing not only increase the efficiency of power plant but also decrease dependence on fossil fuel and 11–25% CO_2 emissions.

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Data availability Data will be made available upon request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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