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Carbon footprint analysis of fossil power plants in Bangladesh: measuring the impact of CO_2 and greenhouse gas emissions

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Abstract
Greenhouse gas (GHG) emissions have increased substantially due to industrialization and the rapid growth in energy demand in Bangladesh. The aim of this study is to conduct a comprehensive carbon footprint analysis of fossil power plants in Bangladesh, focusing on the impact of GHG emissions. We evaluate the carbon footprint of fossil power plants based on their power generation capacity, fuel type, specific emission rates, and global warming potential (GWp) for various GHGs. The emission factor approach has been used in conjunction with the International Panel on Climate Change (IPCC) methodology. Findings of the study indicate that fossil power plants in Bangladesh contribute significantly to the country's overall carbon footprint, with CO_2 and other GHG emissions being the primary drivers. Furthermore, we evaluate Bangladesh's GHG emissions in comparison with neighbouring countries to determine its position. In terms of greenhouse gas emissions from fossil-based power plants, we find that Bangladesh has relatively low emissions compared to its neighbours and developing countries in Asia. Nevertheless, Bangladesh has witnessed a significant increase in coal-fired power generation in recent years, which has emerged as a significant contributor to emissions. Following an analysis of GHG emissions from fossil fuel power plants, we recommend adopting advanced technologies such as carbon capture and storage (CCS) with improved energy efficiency systems and integrating renewable energy sources into the power generation mix. We conclude our analysis by highlighting the importance of transitioning to cleaner, sustainable energy sources to reduce future carbon emissions.

Highlights

1. Conducting an in-depth assessment of the carbon footprint generated by fossil power plants in Bangladesh.
2. Utilizing comprehensive data and analysis techniques to quantify the extent of carbon emissions.
3. Identifying and analyzing the major sources of carbon emissions within the energy sector of Bangladesh.
4. Conducting a comparative study to understand Bangladesh's position in relation to neighboring countries regarding greenhouse gas (GHG) and local air pollutants (LAPs) emissions.
5. Offering insights and recommendations on reducing carbon emissions from the energy sector in Bangladesh.

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Keywords Greenhouse gas · Fossil fuel · Power plant · Climate change · Renewable energy

1 Introduction

The issue of carbon footprint analysis has garnered significant attention in the past few decades due to the increasing concern over climate change as well as its adverse effects on our surroundings. One of the biggest contributors to carbon footprint, fossil power plants, have come under fire for their important role in increasing global warming [1]. The purpose of this study is to undertake a complete carbon footprint analysis of fossil power plants in Bangladesh, with a focus on evaluating the impact of greenhouse gas (GHG) and local air pollutants (LAPs) emissions. Bangladesh, a developing country with a fast expanding population and rising energy consumption, is highly reliant on fossil fuel-based power generation [2]. The generation of electricity in the country is mostly centered on coal-fired power plants and natural gas-fired power plants, both of which produce significant amounts of carbon dioxide (CO_2) and other GHG as well as LAP into the environment. These emissions not only contribute to global warming, but they also endanger the local population's health [3].

In the capital city of Bangladesh, the annual mean concentration of particulate matter (PM) linked to fossil fuel combustion surpasses the World Health Organization's recommended levels. The estimated annual average PM concentration was around 77.1 µg per cubic meter (µg/m^3), significantly exceeding the WHO guideline of 10 µg/m^3 [4]. Additionally, urban areas experience consistently rising levels of nitrogen dioxide (NO_2) due to fossil fuel combustion, with annual average NO_2 concentrations exceeding permissible limits. For example, NO_2 concentrations reach approximately 40 parts per billion (ppb), surpassing WHO guidelines and contributing to respiratory issues and other health concerns. However, the generation of GHG and LAP leads to significant challenges associated with climate change, with elevated sea levels presenting a notable risk to low-lying coastal regions in Bangladesh. Projections anticipate a potential sea-level rise of 0.3 to 0.9 m [5], exposing coastal communities to severe inundation. Additionally, Bangladesh witnesses an increased frequency and intensity of extreme weather events, including cyclones and floods, impacting crucial sectors like infrastructure, agriculture, and societal resilience. Changes in climate patterns contribute to more frequent heatwaves, affecting essential areas such as agriculture, water resources, and public health. Temperature records point to a clear upward trend. These alterations in precipitation patterns and extreme events pose a threat to crop yields, endangering food security in Bangladesh.

Hence, understanding the carbon footprint of fossil power plants is critical for developing successful climate change mitigation measures and transitioning to greener energy sources [6]. This study intends to give useful insights into the environmental effect of these power plants by estimating the quantity of GHG and LAP produced by them. The aim of our study is to meticulously pinpoint the main challenges to mitigating carbon emissions. This is achieved through a comprehensive and comparative assessment of the carbon footprint of fossil power plants in Bangladesh. Specifically, our analysis centers on highlighting the significant dependence on fossil fuels for energy production, functioning as a principal contributor to GHG and LAP emissions. By explicitly addressing this issue, our study intends to play a pivotal role in steering towards a more sustainable and environmentally friendly energy landscape. Ultimately, this will increase awareness about the environmental effect of fossil fuel power plants by taking proactive steps to reduce the damage caused by these emissions. The research undertaken in our study furnishes invaluable statistics and evidence that can bolster policy-making decisions and help initiate transformative actions. Underlining the critical significance of shifting to cleaner, sustainable, and renewable energy sources, we stress the imperative of diminishing carbon emissions derived from fossil fuel power plants. Employing a straightforward analysis of carbon footprint, our aim is to foster a future that is ecologically balanced and sustainable. The study's objectives are outlined below:

- To assess the carbon footprint of fossil power plants in Bangladesh.
- To identify the major sources of carbon emissions from the energy sector in Bangladesh and suggest policy recommendations for reducing carbon emissions.
- Examine Bangladesh's position in relation to its neighbors by comparing their carbon footprint.
- To encourage the transition to cleaner and renewable energy sources.
- To provide valuable insights and recommendations for reducing carbon emissions from the energy sector.

To assemble a comprehensive estimation, our data collection strategy involves acquiring detailed information from diverse fossil fuel power plants across Bangladesh. Key parameters, including fuel consumption, electricity generation capacity as outlined in Table 2, and emission coefficients provided in Table 3, contribute to the richness of our dataset. This comprehensive dataset serves as the basis for calculating aggregate emissions, encompassing not only greenhouse gases such as CO_2 but also air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_X). Air pollutants is linked to local air pollutants (LAPs). In contrast, greenhouse gases are known for their role in the greenhouse effect, resulting in global warming and climate change. NO_X and SO_2 are primarily air pollutants that contribute to environmental degradation, acid rain, smog formation, and health issues. They can indirectly contribute to the greenhouse effect by reacting in the atmosphere to form greenhouse gases thus affecting climate change. Despite being primarily air pollutants, their indirect impact on the greenhouse effect is significant. While greenhouse gases contribute to long-term global climate patterns, local air pollutants have more immediate and localized environmental and health impacts, affecting specific regions and communities. Therefore, measuring greenhouse gases and local air pollutants is crucial for accurately analyzing carbon footprint, as both contribute to environmental degradation and climate change. To enhance the study, we conduct a robust evaluation of the overall carbon intensity of each power plant, comparing emissions against their electricity generation output. Furthermore, our study will explore practical measures to effectively reduce carbon footprints within these power plants.

The manuscript is thoughtfully organized into five sections, each examining distinct facets of the study at hand. Commencing with section two, a thorough exploration of pertinent literature is presented, serving as a solid bedrock for the existing research. Advancing to section three, an intricately detailed methodology is expounded upon, encompassing both the study's background and the materials and methods employed. Continuing on to section four, an exhaustive analysis of the results is meticulously explicated, followed by a comprehensive discussion that shines a light on the findings and explores technological strategies for managing and alleviating greenhouse gas emissions. In section five, the study culminates with a succinct yet impactful conclusion, wherein key discoveries are succinctly encapsulated and accompanied by insightful recommendations for future endeavors.

2 Related works

The energy industry stands as a major player in the realm of global carbon emissions, making significant contributions that have spawned grave environmental ramifications, including but not limited to climate change, glacial melt, and the unsettling rise of sea levels [7]. Regrettably, Bangladesh finds itself heavily reliant on fossil fuel power plants to satiate its energy demands, resulting in a substantial carbon footprint. In light of these circumstances, the nation has admirably vowed to slash its carbon emissions by 5% come the year 2030. By way of closely scrutinizing the available literature, this study aspires to unravel the key challenges tethered to the objectives of the study at hand.

A recent [8] provides a comprehensive analysis of the greenhouse gas emissions produced by fossil fuel power stations in Bangladesh. The authors effectively shed light on the substantial role played by fossil fuel power plants in the context of global warming and climate change. They employed a variety of data collection methods, such as field surveys and measurements, to establish a deep understanding of the emissions stemming from fossil fuel power stations and utilized HOMER simulation to measure GHG emission. The study's outcomes unveil alarming levels of greenhouse gas emissions emanating from fossil fuel power stations in Bangladesh. Offering an in-depth analysis of each emission source, the authors discern the principal contributors and quantify their environmental impact. They put forward a range of strategies encompassing technological advancements, policy modifications, and the integration of renewable energy sources. Another research [9] provides an in-deep analysis of the factors contributing to the growth of energy-related CO_2 emissions in Bangladesh. The authors present a clear and comprehensive overview of the challenges confronted by the country, encompassing its rapidly escalating energy demands and the subsequent surge in CO_2 emissions. This contextual information serves as a foundation for the subsequent analysis. To delve into the factors propelling CO_2 emissions, the authors employ the Logarithmic Mean Divisia Index (LMDI) decomposition method, enabling a meticulous examination of the driving forces at play. The study's findings shed illuminating insights on the noteworthy factors that influence CO_2 emissions within the nation. The authors emphasize the substantial impacts of population growth, energy intensity, and changes in the fuel mix. Another analysis [10] provides significant information on the country's future energy choices and their environmental effects. The authors begin by emphasizing Bangladesh's urgent need to reduce CO_2 missions and the critical role of the electricity sector in attaining this aim. The essay establishes a solid basis by explaining the relevance of shifting to low-carbon technology and the possible co-benefits of such a shift. One of the study's significant characteristics is its extensive research of the various CO_2 emission reduction options available in Bangladesh's power industry using MARKAL modeling. The authors extensively investigate a variety of solutions, including renewable energy sources, energy efficiency improvements. The study involves a detailed examination of the obstacles and limits that may occur during the deployment of various technological alternatives. The authors acknowledge the need of thoughtfully considering details such as cost-effectiveness, infrastructural specifications for selecting the most appropriate technology for reducing CO_2 emissions. They [11] investigates the intricate dynamics between energy consumption, CO_2 emissions, and economic growth in Bangladesh. The authors commence by discussing the significance of understanding the causal relationships between energy use, CO_2 emissions, and economic growth. They point out the importance of exploring these connections to develop effective policies and strategies that can promote sustainable economic development while managing environmental concerns. The authors provide a solid framework for investigating the causal linkages among the variables in question by applying econometric approaches such as the Vector Autoregressive (VAR) model and the Granger causality test. The authors present several noteworthy observations. For example, the authors discover a bidirectional link between energy consumption and CO_2 emissions, implying that changes in energy consumption can affect CO_2 emissions, while changes in CO_2 emissions can likewise influence energy consumption. Based on their study findings, the authors present relevant policy recommendations. They emphasize the necessity of implementing energy conservation measures, developing renewable energy sources, and adopting energy-efficient technology in order to ensure long-term economic growth while minimizing environmental repercussions.

In contrast to the various approaches employed in previous studies investigating carbon emissions from power plants in Bangladesh, in this study we introduce a novel approach by focusing exclusively on fossil power plants using the emission factor approach. This deliberate choice is based on the method's proven effectiveness, efficiency in data processing, and adaptability to different emission sources, distinguishing it from alternative methods. The decision aligns seamlessly with our overarching objective of the study, which is to provide a comprehensive and detailed estimate of GHG alongside LAP emissions. The simplicity of the method facilitates longitudinal comparisons, while its consistency with measured data ensures accuracy. Notably, our nuanced consideration extends beyond alignment with study objectives, and it prioritizes adherence to globally accepted standards, emphasizing the need for precise but realistic emissions estimates. This unique application of the emission factor approach underscores our commitment to advancing both methodological and practical utility in carbon footprint emissions assessment. Considering the above aspects, we offer our subsequent contributions:

- Quantification of the greenhouse gas and local air pollutant emissions and their equivalent CO_2 (CO_2e) emissions from fossil fuel power plants.
- Establishing a correlation between GHG as well as LAP emissions from different technology-based coal power plants, such as ultra-super-critical and super-critical.
- Providing a comparative analysis of GHG and LAP emissions from Bangladesh in relation to other developing countries and least developed countries in Asia, highlighting Bangladesh's position.
- Emphasizing on technological advancements and necessary measures to mitigate emission levels.

3 Methodology

The systematic framework illustrated in Fig. 1 delineates a sequential procedure for evaluating the carbon footprint of fossil fuel power facilities. This approach directs our gathering of data, investigation, and evaluation of outcomes, allowing us to comprehend the extent of carbon footprint emissions and devise focused initiatives for reducing emissions and promoting sustainability. The initial phase entails delineating the extent and goals of the analysis, thereafter, acquiring data pertaining to fossil power plants in Bangladesh, encompassing their quantity, geographical distribution, capacity, and fuel categories. This material forms the basis for later investigations. In the subsequent phase, the emphasis is placed on gathering accurate data pertaining to the geographical positions, capacities, and fuel categories of power plants. Afterwards, the procedure entails computing greenhouse gas such as carbon dioxide (CO_2) emissions and air pollutants (such as sulfur dioxide, nitrogen oxides etc.) emissions individually. Subsequently, an assessment is conducted to determine the carbon footprint and the associated amount of CO_2 emissions produced by the fossil fuel power plants in Bangladesh. This analysis offers a thorough understanding of the environmental consequences.

Furthermore, an evaluation is conducted to determine the individual impact of each fuel type on the total emissions of carbon dioxide equivalent (CO_2e) from power plants. This assessment aims to identify potential areas for enhancement. Ultimately, a comprehensive evaluation is conducted to analyze the environmental impact of fossil-fuel power plants and find potential areas for improvement by considering the complete carbon footprint of all greenhouse gas and local air

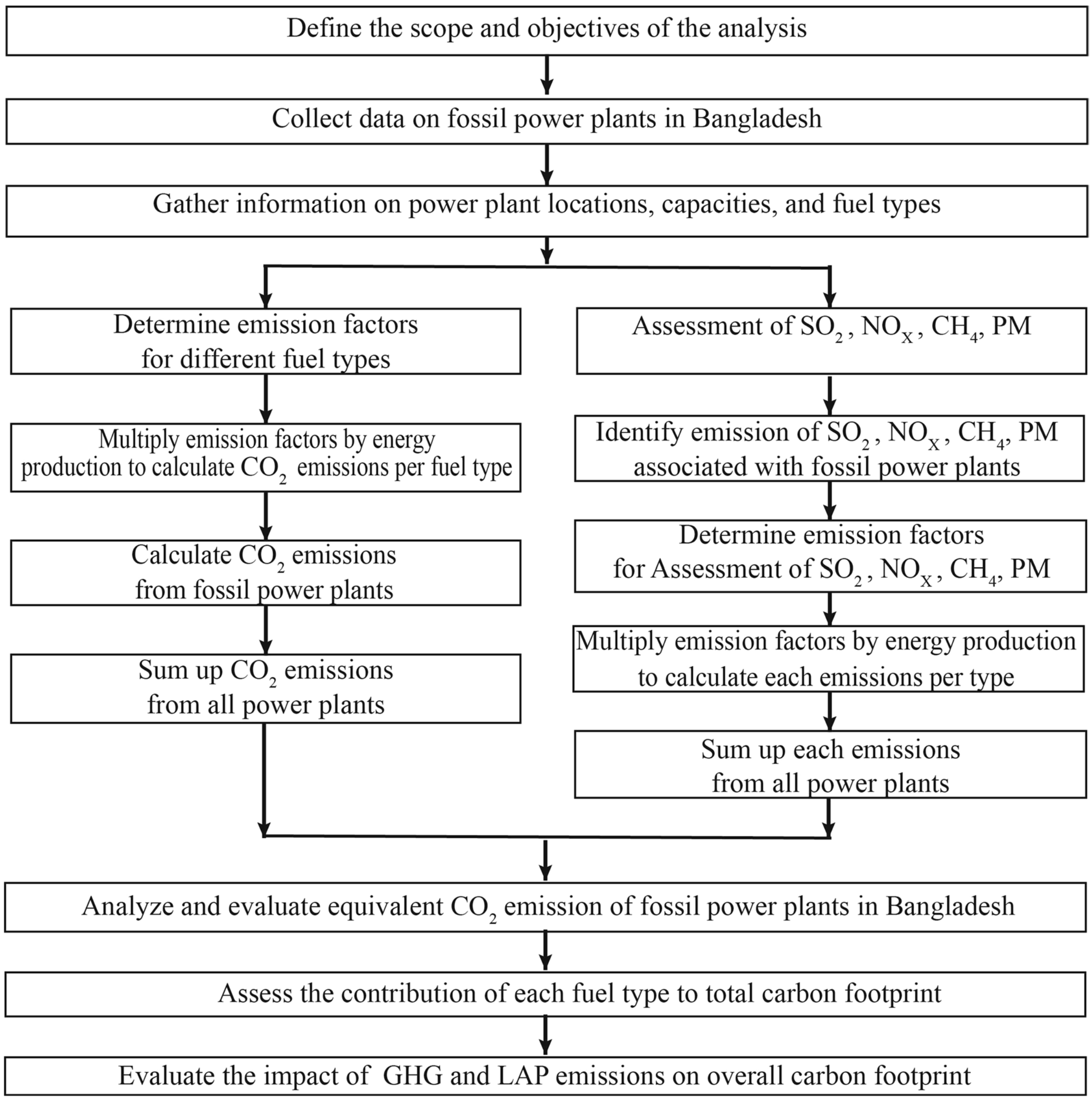


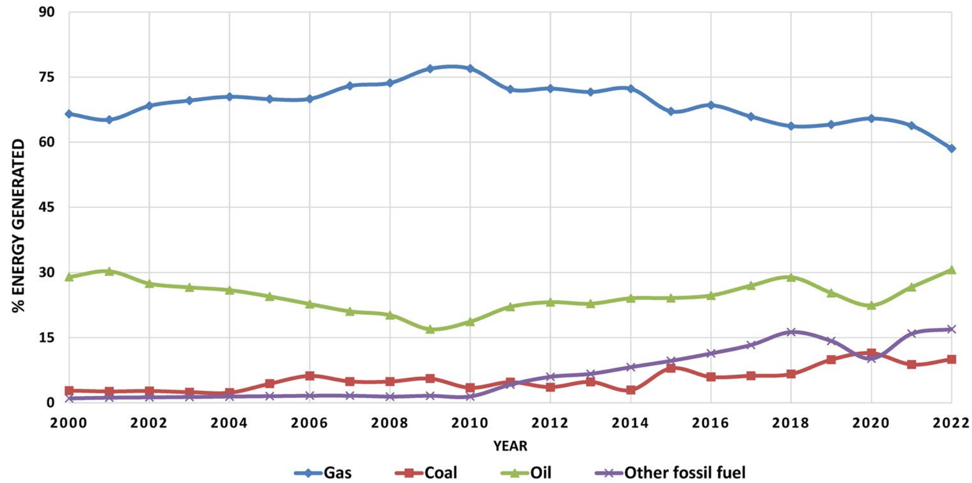
Fig. 1 Flowchart of the study

pollutant emissions. Our technique consists of two unique components: the initial component offers a comprehensive background that establishes the framework for the inquiry, while the subsequent component delves into the technical aspects, elucidating the materials and equations employed in the computational procedure.

3.1 Background of the study

Bangladesh's energy demands are primarily reliant on fossil fuels, mainly natural gas and coal. Bangladesh has limited indigenous reserves of gas [12], and it is becoming increasingly reliant on imports to fulfil its rising energy demand [13]. This reliance on fossil fuels has various consequences for the energy industry and the economy as a whole. Figure 2 depicts Bangladesh's reliance on fossil fuels based on statistics provided by the Bangladesh power development board (BDB) [14]. Based on Fig. 2, the percentage share of energy generated from gas has shown relative stability over the years in Bangladesh. Gas has maintained its position as the primary energy source, consistently contributing to over 60% of energy generation. It accounted for 66.55% in 2000 and slightly decreased to 58.57% in 2022. On the other hand, the percentage share of energy generated from coal has exhibited a fluctuating pattern. Starting at a mere 2.82% in 2000, it reached a peak of 11.45% in 2020 before gradually decreasing to 10.02% in 2022. This indicates a varying reliance on coal as an energy source. Over the years, there has been a decline in the percentage share of energy generated from oil.

Fig. 2 Bangladesh's fossil fuel-based energy landscape



In 2000, oil accounted for 29.01% of energy generation, but by 2021, it had decreased to 22.47%. This suggests a shift away from oil towards other energy sources in Bangladesh. Specific details about all coal-fired power plant are presented in Table 1.

The depletion of Bangladesh's natural gas reserves is one of the country's significant challenges. Bangladesh has been extracting natural gas for many decades, causing reserves to decline. This has produced a supply–demand mismatch, resulting in frequent power outages and a higher dependence on expensive imported liquefied natural gas (LNG) [22]. Another difficulty is the unfavorable ecological impacts connected with generating energy from fossil fuels. Coal and natural gas burning create greenhouse gases as well as air pollutant, which contribute to an increase in carbon footprint as well as global warming. In Table 1, USC refers for ultra-supercritical and SC stands for super-critical technology for coal power plants. When compared to supercritical technology, ultra-supercritical technology offers superior efficiency [23] and possibly lower CO_2 emissions per unit of electricity produced [24]. When compared to SC technology, USC technology is often more effective in reducing air pollutant emissions. Through the use of contemporary combustion technology incorporating enhanced control systems, USC plants may achieve reduced levels of pollutants that entail nitrogen oxides (NO_X), sulphur dioxide (SO_2), and even particle matter (PM). The rationale for the relevance of power plant location in relation to carbon emissions can be established. These locations play a key role in determining the efficacy and ecological ramifications of power generating. Interpretation of the relevance of specific power plant locations to carbon emissions seems to be complex but efficient. Proximity to coal reserves plays a crucial role in diminishing emissions of greenhouse gases and local air pollutants emissions. Power facilities situated in close proximity to coal reserves, such as the Barapukuria coal-fired power station in Dudhipur, Dinajpur and the Rampal coal-fired power plant in Rampal, Khulna, utilize advantages in terms of lower transportation costs and reduced emissions related to coal transportation. This greatly adds to the decrease in carbon emissions, making these places strategically beneficial. Furthermore, the strategic placement of power plants near densely populated areas, such as thermal power station in Patuakhali facilitates the effective dissemination of electricity. By minimizing transmission losses and their corresponding emissions, these power plants exhibit a high level of environmental friendliness. In addition, power plants situated in coastal regions, such as the Matarbari Coal Power Plant in Maheshkhali, Cox's Bazar, and the Barisal Coal Power Plant in Barguna, Barisal, support the utilization of imported coal and allow for the development of coastal infrastructure. Efficient coal handling enhances operational efficiency and has the potential to reduce emissions, making coastal areas an advantageous alternative for locating power plants. Furthermore, the close proximity of power plants to industrial areas, such as the Banshkhali Coal Power Plant in Banshkhali, Chittagong, and the Barishal Coal Power Plant in Barguna, Barisal, enables a direct delivery of electricity to industrial users. This minimizes energy wastage during transmission and enhances energy efficiency, perhaps resulting in a favorable effect on greenhouse gas emissions. The construction of the Barisal Coal Power Plant at Barguna in Barisal demonstrates a forward-thinking approach to meeting future energy demands in the region, as seen by the implementation of strategic planning for future development. This strategic plan has the capacity to diminish the necessity for long-distance power transmission and its accompanying emissions, rendering it a significant factor in determining the suitability of power plant locations with regards to carbon footprint emissions. The combined influence of these factors impacts both the efficiency of power generation and its environmental consequences, underscoring the significance of thoughtful deliberation regarding the placement of power plants in sustainable energy planning.

Table 1 Coal power plant in Bangladesh

Name	Location	Unit	Capacity MW	Coal type	Technology	Status
Banshkhali 1320 MW Coal Power Plant [15]	Banshkhali,Chittagong	2	1320	Sub-bituminous	USC	Active
Barapukuria Coal Power Plant [16]	Dudhipur, Dinajpur	3	525	Bituminous	SC	Active
Barishal 350 MW Coal Power Plant [17]	Barguna, Barisal,	1	350	Sub-bituminous	SC	Construction (1st Phase)
Matarbari 1200 MW Coal Power Plant [18]	Maheshkh-ali Cox's Bazar	2	1200	Sub-bituminous	USC	Active
Patuakhali 1320 MW Coal-fired Thermal Power Plant [19]	Dhankhali, Patuakhali	2	1320	Sub-bituminous	USC	Construction
Payra 1320 MW Thermal Power Plant [20]	Modhupara, Patuakhali	2	1320	Sub-bituminous	USC	Active
Rampal Coal-fired Power Station [21]	Rampal, Khulna	2	1320	Sub-bituminous	USC	Active

Table 2 Emission factors for different GHGs and LAPs in coal and gas fired power plants

GHGs and LAPs	Emission factor, g per KWh				Source
	Simple Cycle Gas Turbine Power Plants	Natural gas power plant	Coal power plant (super critical)	Coal power plant (Ultra-super critical)	
CO_2	550 [31]	450–550	1020.129, 1050 [31]	800–900, 740 [31]	EIA[32], EEA[33], IEA [31]
NO_X	10–25, 0.15	< 5, 0.55 [31]	0.771107	0.05–0.15	EIA [32], IEA [31]
SO_2	0.01–0.05	< 0.01	5.8967	0.1–0.3	EIA [32]
PM	0.01–0.05	< 0.01		0.01–0.05	EIA [32]
CH_4	-	0.1–4.5	0.0001	-	EIA [32]
N_2O	-	0.07	0.3–1.5	-	EIA [32], EEA [33]

Table 3 Global warming potential values for GHGs and LAPs [6]

GHG/LAP	Lifetime in Atmosphere	GW_P valve
CO_2	Centuries	1
CH_4	12 years	28–36
N_2O	114 years	265–298
SF_6	3200 years	228,000

Indeed, these power plants produces significant amounts of GHG and local air pollutant effluents, which have a notable impact on the carbon footprint.

3.2 Materials and method

In this study, we employ widely accepted guidelines developed by the Intergovernmental Panel on Climate Change (IPCC) to ensure the accuracy and consistency of the analysis. IPCC guideline is a collection of procedures implemented by the IPCC for estimating the emission of carbon footprint [25] and plays a significant role in the global effort to address climate change by providing a consistent and scientifically grounded methodology for measuring and reporting GHG and LAP emissions [26]. Applying the IPCC criteria, we deliver a robust and standardized approach to measuring GHG and LAP emissions that includes not only CO_2 but also other gases that are responsible for climate change. This enables a thorough evaluation of carbon footprints, and full knowledge of the environmental effects of fossil power plants. The data is collected from the power system master plans of Bangladesh, the Bangladesh Bureau of Statistics, and the International Energy Agency. carbon footprint in terms of equivalent CO_2 of the fossil power plants is estimated using Eq. 1.

$$Carbon\ Footprint = Electricity\ Generation\ Capacity \times EF \times Operational\ Hours \times GW_P \tag{1}$$

Here, EF represents emission factor in $gperKWh$. Global Warming Potential is abbreviated as GW_p. GW_p is the potential of a GHG or LAP to trap heat in the atmosphere, which is defined as a factor relative to carbon dioxide. Table 2 shows the emission factors for major sources of atmospheric pollutants including GHG and LAP in respect to coal and gas fueled power plants. Table 3 also shows the GW_P values associated with each gas contributing to the greenhouse effect and local air pollutants. Power plant's capacity factor is the ratio of the actual energy generated by the plant over a given time period to its highest feasible output if it were running at full capacity throughout the same time period. In other words, it measures how effectively a power plant is used. The capacity factor depends on several factors such as:

- Type of fuel used,
- Design and age of the power plant,
- Maintenance and repair schedules,
- Weather conditions, and
- Demand for electricity.

The specific factors, according to the IPCC guidelines, of each individual power plant have been considered in this study to prevent biased and generalized results. The coal-fired power plants have a capacity factor of around 54 to 59.8% [27]. Gas turbine of combine cycle power plants typically have a capacity factor ranging from 48.2% to 57.7 [27]. Factors such as the flexibility of gas turbines, fuel costs, and grid demand can influence this range. Combined cycle power plants, which use both gas turbines and steam turbines, generally have higher capacity factors compared to single-cycle gas turbine plants. Addressing the suitability of gas turbine power plants in Bangladesh [28], our study applied a capacity factor of 57.7% based on the specific specifications determined for the country.

Both GHG and LAP emissions have been determined using the emission factor method. Emission factors, referred to as coefficients that connect the quantity of pollution created to a certain activity or fuel usage, are used in this technique. The emission factor method is a credible approach for assessing these power plants' carbon footprints, taking into consideration aspects that involve consumption of fuel and energy output [29]. To estimate total emissions from a single source, the emission factors are multiplied by the rate of activity and other important characteristics such as emission reduction efficiency [30]. Equation 2 represents the general equation for estimating emissions.

$$E = A \times EF \times (1 - \frac{ER}{100}) \tag{2}$$

where E represents emissions, A represents activity rate and ER represents overall emission reduction efficiency. The amount of greenhouse gases such as CO_2 emitted into the atmosphere when fossil fuels are burned to create energy is referred to as the level of greenhouse gas emissions from fuel combustion. Emissions are commonly quantified in mass per unit of energy generated, such as grams of CO_2 per kilowatt-hour (gCO_2/kWh). The level of emissions is determined by various factors, including the kind and grade of fuel used, the efficiency of the combustion process, and the technology utilized to generate the energy. Equation 3 may be used to compute the emission factor based on fuel consumption and net power output from fossil power plants.

$$EF = \frac{\sum_{i,m} FC_{i,m} \times NCV_{i,m} \times EF_{CO2,i}}{\sum_{m} EG_m} \tag{3}$$

where, $FC_{i,m}$ is the fossil fuel consumed by "m" power generation plant during ith year; NCV is the calorific valve of the fossil fuel; $EF_{CO2,i}$ is the emission factor of CO_2 for particular fuel; EG_m is the total amount of electricity generated by m power plant. To streamline the calculation process, we utilize the emission factor values provided in Table 2. For fossil power plant, the specific equation for calculating equilibrium CO_2 emissions would be dependent on the scope and boundaries of the assessment as well as data availability. The emissions factor and global warming potential for each source of emissions from the power plant can be used to calculate the carbon footprint.

In Table 2, the acronym EIA stands for the Energy Information Administration, while the acronym IEA refers to the International Energy Agency. Another organization mentioned is the European Environment Agency, which is denoted as EEA.

Choosing emission factor approach aligned with the focus of our study, including efficiency, simplicity, and scalability in the context of large-scale studies and policy evaluations. Although this method speeds up the analysis, it is essential to recognize its potential for oversimplification and generalization, such as biases as well as uncertainties. This pragmatic choice prioritizes operational feasibility. To work around these problems, we have used specific plant data, such as emission factors for natural gas power plants, simple cycle gas turbine power plants, supercritical coal power plants, and ultra-supercritical coal power plants, which can be seen in Table 2. This data was gathered by analyzing at the plant specifications in Table 1. In contrast, the comprehensive nature of life cycle assessment (LCA) provides deeper insights but requires extensive resources, making it more suitable for detailed assessments. By consciously choosing the emission factor approach, we balance practicality with transparency, recognize its limitations, and contribute to a nuanced understanding of emissions in the context of fossil power plants in Bangladesh. Moreover, in this study, we have employed several data sources to scrutinize power plant operations in Bangladesh. These resources include annual reports, journals, and reliable associations such as the European Environment Agency and the Energy Information Administration. The dataset includes information such as location, unit, capacity in MW, coal type, technology, and condition. The resources contained therein are up-to-date, ensuring their relevance to the current state of power plant operations in Bangladesh. Greenhouse gas emission factors are corroborated by multiple sources, such as the US Energy Information Administration and the European Environment Agency. The incorporation of a wide range of sources and precise data enhances

Table 4 GHG/LAP emissions Comparison between coal- and gas-fired power plants

GHG/LAP	Coal Fired Power Plant				Gas Fired Power Plant	
	Super critical (SC)		Ultra super critical (USC)			
	Emission Kilo tons	Emission per unit energy, ton/ MWh	Emission Kilo tons	Emission per unit energy, ton/ MWh	Emission, **Kilo tons**	Emission per unit energy, ton/ MWh
CO_2	5231.36	5978.67	27,330.87	4217.73	26,730.6	2266.65
NO_X	29.3788	33.57	11.6914	1.80	0.594013	0.050
SO_2	3.83633	4.38	3.689712	0.57	32.67074	2.770
PM	2.49113	2.85	1.844856	0.28	0.594013	0.050

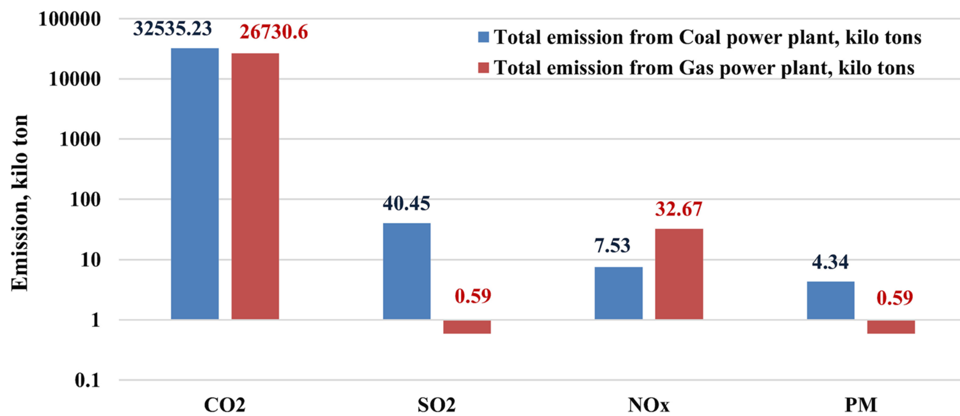


Fig. 3 Emission from coal and gas-based power plant

the reliability of our approach and mitigates its limitations. The selection of data sources is rationalized based on their varied and dependable nature.

4 Results and discussion

To facilitate clear understanding of our analysis we have divided our findings and analysis into 2 parts. Initially, we present our calculations and results covering several aspects, including comparative emissions of coal and gas-fired power plants, equivalent CO_2 emissions, and annual CO_2e emissions. Taking this further, we conclude with a comparative analysis that draws attention to the diversity between our findings and other nations and participates in a broader conversation based on our observations.

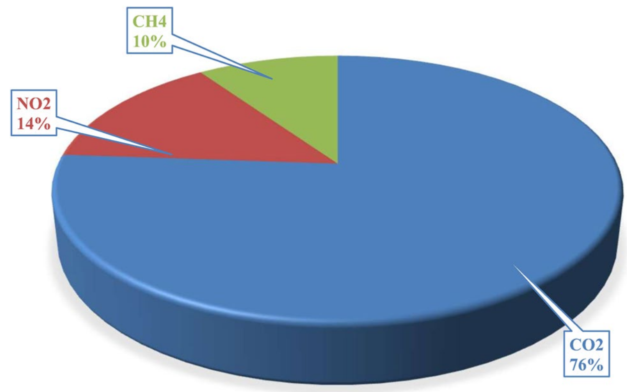
4.1 Result

Table 4 and Fig. 3 compares the emissions from different types of coal-fired power plants including super critical, ultra-supercritical and gas-fired power plants. In Table 4, it is evident that coal-fired power plants emit higher amounts of CO_2 compared to gas-fired power plants. This is expected, as coal is a carbon-intensive fuel. This highlights the advantage of using gas-fired power plants in reducing overall CO_2 emissions. Additionally, it is worth noting from finding that the USC Coal-fired power plants have the lowest CO_2 emission per unit of energy among all others. NO_x emissions are known to cause air pollution and contribute to respiratory issues. Table 4 illustrates that coal-fired power plants emit higher levels of NO_x compared to gas-fired power plants. Moreover, the emission rates of NO_x per unit of energy are significantly lower for gas-fired power plants. If we compare SC and USC technology-based coal power plant, USC configuration emits much lower emission. Coal-fired power plants emit higher levels of SO_2 compared to gas-fired power plants, particularly the SC configuration. However, it is important to note that the gas-fired power plants have lower emission rates of SO_2 per unit of energy compared coal power plants. Lastly, for particulate matter (PM) emissions, both types of coal-fired power plants have higher emissions compared to gas-fired power plant. However, ultra-supercritical coal-fired power plant has lower PM emissions compared to supercritical coal-fired power plant. This highlights the benefit of utilizing

Table 5 Equivalent CO_2 emissions of different gas from coal and gas fired power plant

Power Plant	Emission in million kg CO_2 equivalent of		
	CO_2	NO_2	CH_4
Coal fired Power Plant	32,535.2313	9988.229745	0.11726224
Gas fired Power Plant	26,730.60345	1101.894876	7484.56897
Total	59,265.83475	11,090.12462	7484.68623

Fig. 4 Percentage share CO_2 equivalent of different GHG



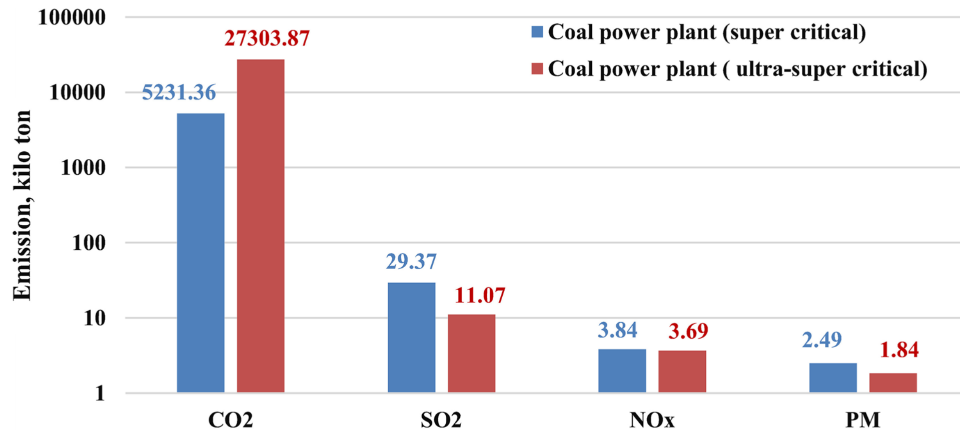
gas-fired power plants for reducing PM emissions and enhancing air quality. Table 4 underscores the environmental advantages of gas-fired power plants and adverse impact of coal power plants. Gas-fired power plants demonstrate lower greenhouse gas emissions and air pollutants per unit of energy compared to coal-fired power plants. Utilizing advanced technologies such as ultra-supercritical in coal power plants can reduce the emission level of gases, which causes global warming significantly.

Table 5 and Fig. 4 show the equivalent CO_2 emissions of different greenhouse gases and air pollutants from power plants. The warming potential of each gas in relation to CO_2 is taken into consideration by measuring the emissions in CO_2 equivalent (CO_2e). CO_2 is the primary greenhouse gas emitted by both types of power plants, but other gases like NO_2 and CH_4 also contribute to their environmental impact. We notice that compared to gas-fired power plants, coal-fired power plants release greater CO_2 and NO_2. However, the gas-fired power plant has higher CH_4 emissions (7,484.56897 million kg) compared to the coal-fired power plant (0.11726224 million kg) in terms of total emission. Gas-fired power plants primarily burn natural gas, which is primarily composed of methane (CH_4). Methane is an extremely potent greenhouse gas with a greater potential to cause global warming than CO_2. Emission rate of CH_4 is corporately higher in gas power plant than coal power plant. Emission values from Table 5 signify the adverse impact coal-fired than gas-fired power plants. This is a significant concern for Bangladesh that is becoming heavily rely on coal for electricity generation. The emissions of nitrogen oxides are also noteworthy as they are responsible for pollutants in the air and have negative effects on human health, particularly among coal-fired power stations as mentioned in Table 4.

Figure 5 shows emissions from coal power plants in Bangladesh. It indicates that the ultra-super critical coal power plant emits significantly more CO_2 compared to the super-critical coal power plant in terms of total CO_2 emission. Super-critical coal power plant emits a higher amount of SO_2 compared to the ultra-super critical coal power plant. This is because ultra-super-critical technology includes advanced pollution control systems. Both types of coal power plants emit relatively similar levels of NO_X. Super-critical coal power plant emits a higher amount of PM compared to the ultra-super-critical coal power plant. It's important to note that ultra-super-critical technology is more efficient and can generate more power output with the same amount of fuel compared to super-critical technology. Therefore, the emissions per unit of energy generated is lower for the ultra-super-critical plant. Moreover, USC power plants account 88% of power from coal-based power plant than SC coal power plant. Figure 5 highlights the need to consider the trade-offs between emissions and efficiency when evaluating the environmental impact of different technical technologies.

Trends in CO_2e emissions by different power source in Bangladesh is represented by Fig. 6. We observe an overall increasing trend in CO_2e emissions from gas power plants in Fig. 6a. This indicates a significant growth in the use of gas for power generation over the years. From 2008 to 2020, the emissions from coal power plants in Bangladesh showed a fluctuating trend. There was an increase in emissions between 2016 and 2019 followed by a significant decline in 2020.

Fig. 5 Emissions from USC and SC Coal power plants in Bangladesh



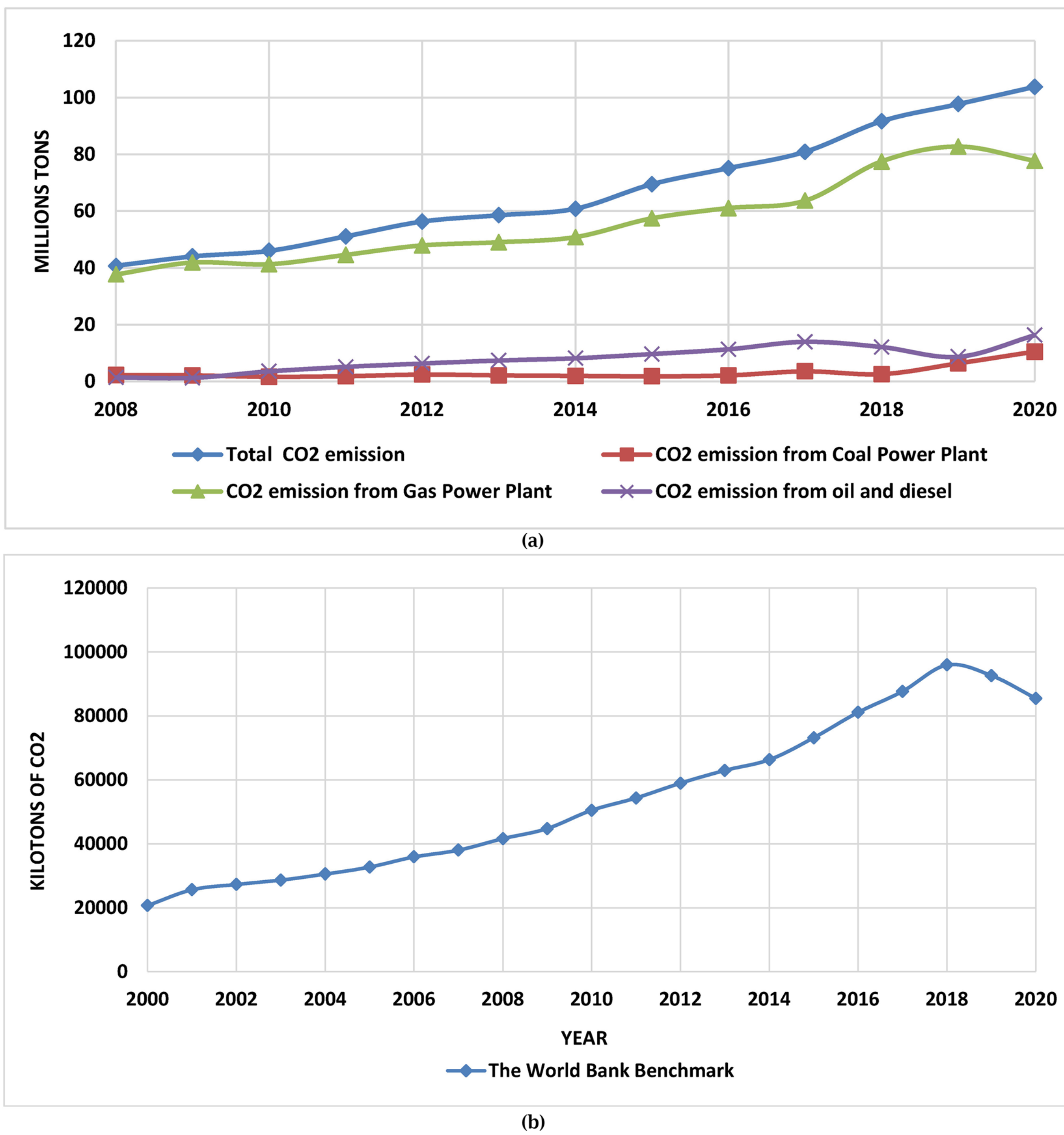


Fig. 6 Annual CO_2e Emissions from Different Power Plants in Bangladesh: **a** Plant specific emissions, **b** General historical emission from fossil fuel-based power plant

But overall emission from coal increase gradually since 2018. The fluctuations suggest variations in coal consumption and power generation patterns in the country. Figure 6a shows a substantial increase in CO_2e emissions from oil-based power plants in Bangladesh. This indicates a significant reliance on oil-based power generation, which is known to have higher carbon emissions compared to other forms of energy production. Figure 6b illustrates a well-defined historical sequence of CO_2 emissions over a period of twenty years, facilitating a comprehensive analysis of emission trends over time utilizing the World Bank benchmark. Between 2000 and 2020, there has been a steady upward trend in the levels of CO_2 emissions, with occasional fluctuations in the pace of growth. Reviewing emissions during this period shows a notable and steady increase, with growth rates especially picking up after 2010. Investigating emissions yields valuable consideration about the environmental consequences of CO_2 emissions. The continuous increase in emissions indicates a growing influence on the environment and climate change, which is consistent with the overall pattern of rising levels of carbon dioxide observed in Fig. 6a. By comparing this historical pattern of emissions in the analysis with Fig. 6a, a thorough perspective of the scenario is provided. Carbon dioxide (CO_2) emission predictions from 2000 to 2020 enhance our understanding of the environmental repercussions. Significantly, and Fig. 6b exhibit identical observation patterns, highlighting the importance and uniformity of utilizing the emission factor technique. The consistent rise in CO_2 emissions seen during this time, along with occasional fluctuations in the rate of increase, emphasizes the significance of our empirical approach in capturing these intricacies. This comparison highlights the effectiveness of the emission factor approach. This method demonstrates its worth in establishing the relationship between emission patterns and wider environmental repercussions. By offering a broad perspective, it facilitates an in-depth analysis of historical emission trend, providing valuable insights on the effectiveness of current policies and programs designed to reduce CO_2 emissions and tackle climate change. Nevertheless, it is crucial to recognize the constraints of the emission factor method. This method oversimplifies the complexities of estimating emissions to some extent by focusing on average features that may not adequately represent different sources of emissions in certain circumstances. Furthermore, there have been issues regarding the variability of the data and the method's limited scope. Although the emission factor technique is effective in providing a detailed and complete view of CO_2 emissions across time, it is important to acknowledge its limits. An inclusive approach that integrates several approaches and considers wider environmental issues is crucial for a more precise and comprehensive evaluation of emission trends and their consequences. Having a sophisticated comprehension of this matter is of the utmost importance for developing efficient strategies and policies to reduce the consequences of CO_2 emissions on the environment and climate.

Within the complex terrain of Bangladesh's energy sector, the fluctuating patterns of greenhouse gas and air pollutant emissions originating from power plants that rely on fossil fuels provide valuable insights into changing patterns and awareness of environmental issues. Carbon footprint is related to phases such as conversion, combustion, and conversion within the fossil fuel-based plant. Emissions from these phases must be considered when assessing the total footprint. Figure 7 reveals significant trends in the transmission and combustion processes, providing explanations for the decisions made about fuel usage and their subsequent effects on carbon footprints. Regarding transmission phase, the emissions

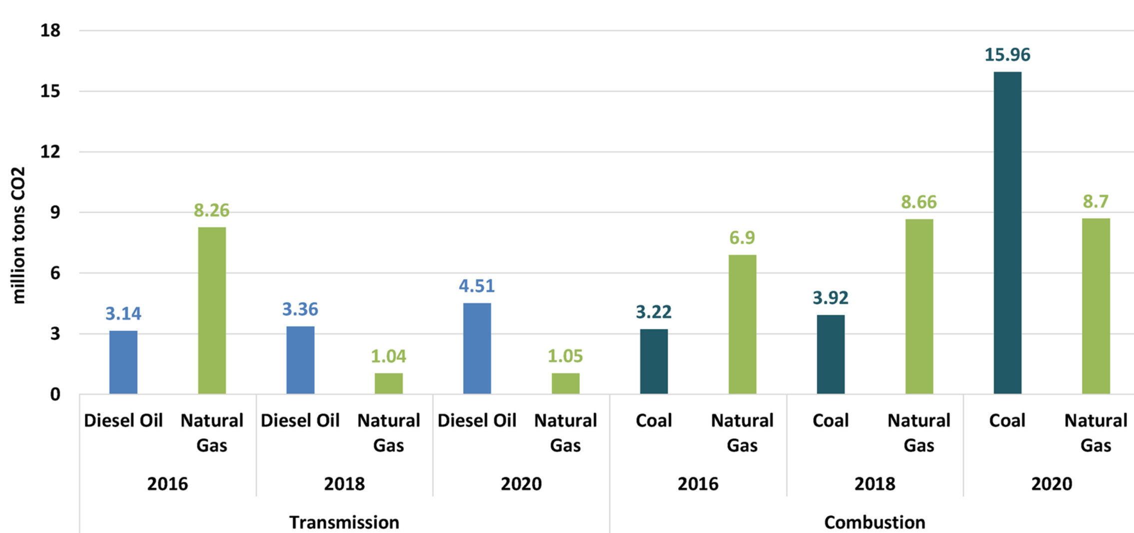


Fig.7 Fossil fuel-based CO_2 emission patterns in transmission and combustion processes

associated with the use of diesel oil have shown a consistent increase, going up from 3.14 million tons of CO_2 in 2016 to 4.51 million tons in 2020. This rise demonstrates an escalating dependence on diesel oil for the transmission of power. In contrast, the emissions resulting from natural gas have significantly decreased, dropping from 8.26 million tons in 2016 to 1.05 million tons in 2020. This significant decline indicates a transition towards electricity generation that relies on coal. However, examining emissions connected to combustion phase reveals fascinating patterns. The emissions from burning coal, which resulted in the release of 3.22 million tons of CO_2 in 2016, saw a further rise to 3.92 million tons in 2018, followed by a substantial rise to 15.96 million tons in 2020. This indicates a possible transition towards power generation that relies on coal, highlighting the necessity of implementing measures to decrease carbon emissions and address the environmental consequences of electricity generating. In contrast, the emissions from the burning of natural gas have stayed rather consistent over the years, experiencing a slight decline from 6.9 million tons in 2016 to 8.7 million tons in 2020. The constant stability shown here may suggest a continual and reliable input of natural gas into the energy combination, potentially due to its comparatively lower carbon intensity in comparison to other fossil fuels.

Moreover, fuel consumption and operational efficiency, as well as maintenance, greatly affect the carbon footprint of fossil fuel-based power plants. Increased conversion efficiency results in decreased fuel requirements for a given energy production, particularly in power plants that rely on fossil fuels. Traditional utility-scale power plants typically achieve net conversion efficiencies ranging from 30 to 35%. This means that approximately one-third of the energy derived from fuel sources like coal, diesel, and natural gas is successfully converted into electricity. Advanced combined-cycle power plants can attain efficiencies of 40%, resulting in additional reductions in fuel demands and carbon footprint emissions per unit of electricity generated. Off-grid power generators typically exhibit poorer efficiency, underscoring the significance of both plant scale and technology. Cogeneration plants, which are specifically engineered to generate both electricity and process heat, achieve conversion efficiencies that can reach up to 80 percent. This high efficiency improves the conversion of fuel into useful energy and helps to decrease carbon emissions. Maximizing plant efficiency is a crucial approach to reducing environmental effects and improving the sustainability of electricity generation from fossil fuels.

Table 6 shows the annual emissions of CO_2, SO_2, and NO_X from both gas and coal power plants in Bangladesh from 2008 to 2020. These emissions contribute to air pollution and have significant environmental impacts. Table 6 highlights the significant CO_2 emissions from both gas and coal power plants, which contribute significantly to Bangladesh's carbon footprint. Both gas and coal power plants have shown an upward trend in CO_2 emissions over the years. SO_2 and NO_X emissions from both gas and coal power plants have generally increased similar with CO_2. The emission of SO_2 and NO_X from power plants is associated with air pollutant issues such as smog, acid rain, and respiratory problems and indirectly contribute greenhouse gas effect. There are some observations from Table 6, which are listed below:

1. CO_2 emissions from gas power plants increased from 14,226,613.33 tons in 2008 to 29,347,495.83 tons in 2020, on the other hand, CO_2 emissions from coal power plants increased from 1,234,540.826 tons in 2008 to 5,780,493.484 tons in 2020.

Table 6 Annual emission inventory of gas and coal power plants in Bangladesh

Year	Emission from gas power plant in tons			Emission from coal power plant in tons		
	CO_2	SO_2	NO_X	CO_2	SO_2	NO_X
2008	14,226,613.33	258.67	14,226.61	1,234,540.826	6901.67	915.911
2009	15,818,354.39	287.61	15,818.35	1,194,948.193	6680.32	886.53
2010	15,610,692.99	283.83	15,610.69	903,647.8062	5051.82	670.42
2011	16,851,832.37	306.39	16,851.83	1,024,291.011	5726.27	759.92
2012	18,105,962.19	329.19	18,105.96	1,336,266.027	7470.36	991.38
2013	18,526,182.95	336.84	18,526.18	1,172,101.655	6552.60	869.58
2014	19,212,492.92	349.32	19,212.49	1,082,815.537	6053.45	803.34
2015	21,716,643.2	394.85	21,716.64	978,634.0478	5471.03	726.05
2016	23,071,123.34	419.47	23,071.12	1,166,751.572	6522.69	865.61
2017	24,057,687.56	437.41	24,057.69	1,958,718.118	10,950.16	1453.1
2018	29,287,746.66	532.50	29,287.75	1,420,478.455	7941.15	1053.86
2019	31,262,970.07	568.42	31,262.97	3,491,255.963	19,517.78	2590.18
2020	29,347,495.83	533.59	29,347.49	5,780,493.484	32,315.71	4288.58

2. SO_2 emissions from gas power plants in Bangladesh ranged from 258.67 tons in 2008 to 533.59 tons in 2020. Similarly, SO_2 emissions from coal power plants ranged from 6,901.67 tons in 2008 to 32,315.71 tons in 2020.
3. NO_X emissions from gas power plants in Bangladesh varied from 14,226.61 tons in 2008 to 29,347.49 tons in 2020 where NO_X emissions from coal power plants ranged from 915.911 tons in 2008 to 4288.58 tons in 2020.

In the following section, we analyze our findings by comparing them to international benchmarks in terms of per capita emissions, employing statistics from the World Bank, exploring Kuznets relations, and considering comparable Asian nations. It is important to note that gas power plants provide a considerable contribution to the production of electricity in Bangladesh, whereas coal power plants only make up 10% to 15% of the total. However, both coal-fired and gas-fired power plants exhibit comparable GHG emissions alongside local air pollutants in terms of emissions per unit of energy produced, notwithstanding the differences in their contributions. Surprisingly, coal-fired power plants produce a significant quantity of different greenhouse gases and local air pollutants per unit of energy produced. From here, it seems that gas-fired power plants are more ecologically benign than coal-fired ones. In contrast, renewable energy generates significantly fewer emissions than coal-fired and gas-fired power plants. Figure 8 provides a comparison of GHG and LAP emission level expressed in grams of CO_2 per unit energy and produced by various energy sources, distinguishing between conventional fossil fuels and environmentally friendly, renewable alternatives.

Coal, as a fossil fuel, has the highest levels of emissions, highlighting its significant environmental impact. While natural gas is cleaner than coal, it still makes a considerable contribution to carbon emissions. Conversely, renewable and sustainable energy sources exhibit their advantages for the environment. Nuclear power stands out as a trailblazer, boasting a very low emission level of 12 gCO_2/kWh. While nuclear energy is not classified as a renewable energy source, it does generate carbon emissions at a far lower rate compared to conventional fossil fuels. Traditional renewable energy sources release much reduced amounts of carbon emissions. However, wind energy closely trails nuclear energy at an equivalent level. The emission level of solar power is 42.3 gCO_2/kWh. Hydropower and biomass have emission levels ranging from 23 gCO_2/kWh to 230 gCO_2/kWh, respectively. Geothermal also emits considerable low emission but it is not suitable in context of Bangladesh. This emphasizes the necessity of shifting towards low-emission and renewable energy alternatives in order to alleviate climate change and establish a more sustainable energy framework.

4.2 Discussion

An analysis of the estimated per capita GHG emission with World Bank [34] offers valuable insights into the trajectory of GHG emissions over time. This comparison is especially pertinent within the framework of GHG emissions originating from power plants fueled by fossil fuels, employing the emission factor methodology. The per capita GHG emissions from fossil fuel-based power plants in Bangladesh, as shown in Fig. 9, demonstrate a noticeable trend of progressive growth during the indicated time period. The trend indicates an increase in per capita GHG emissions, revealing that, on average, emissions have been steadily rising. The pattern shows gradual expansion, with notable changes in specific years. The increase in per capita GHG emissions from fossil fuel-based power plants is associated with factors such as

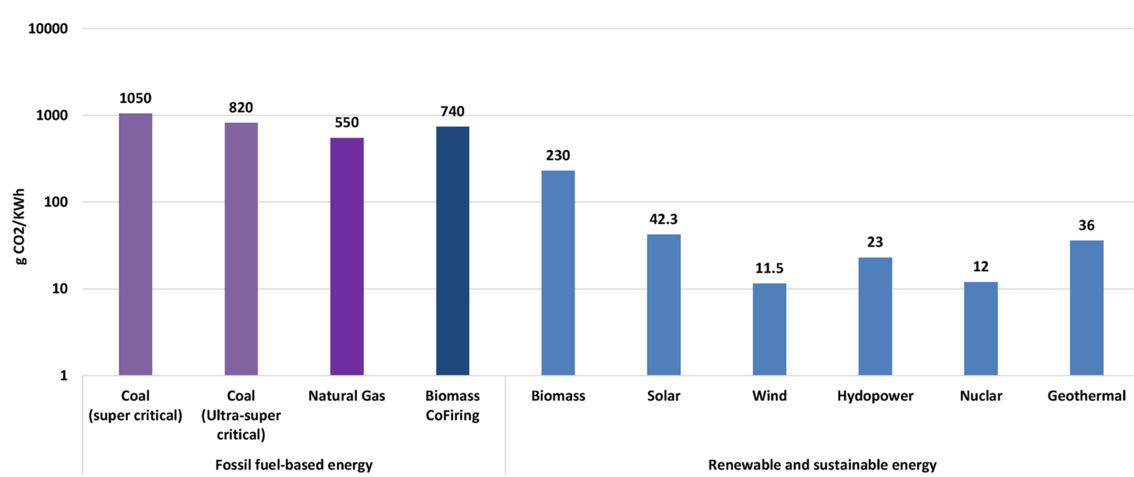


Fig. 8 Comparative emission levels of multiple energy sources

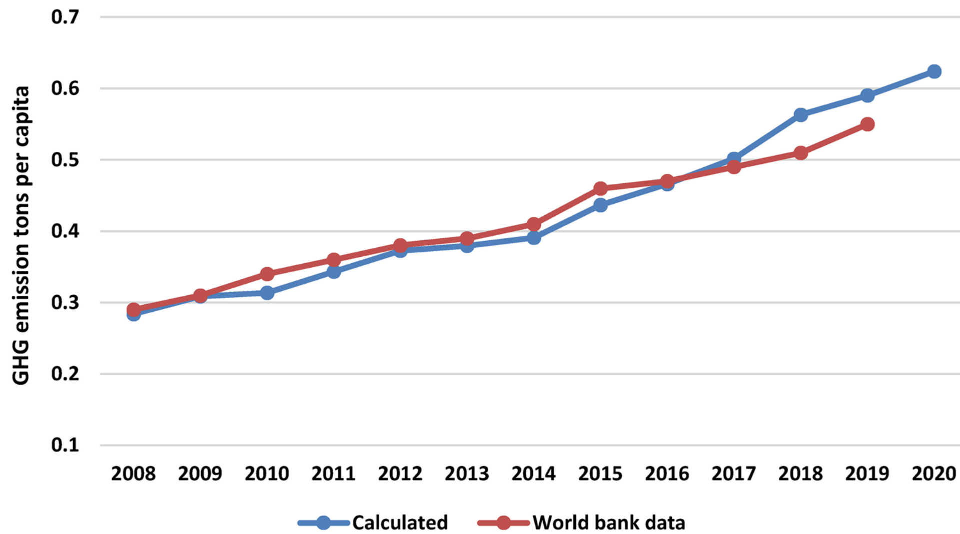


Fig. 9 Per capita emission of GHGs

rapid economic growth, population growth, and potential delay in adopting greener technology. Furthermore, the growing need for energy, along with a dependence on conventional energy sources, ultimately contributes to this pattern. Furthermore, the efficacy of policies, difficulties in infrastructure, and external influences all contribute to the direction of emissions. The estimated per capita GHG emissions, and the data from the World Bank [34] both indicate a steady rise in emissions over time. The computed figures exhibit a high degree of consistency with the World Bank statistics, suggesting a reliable estimation of GHG emissions per capita. The maintenance of this consistency is crucial in order to comprehend the environmental consequences of power plants that rely on fossil fuels, as well as their contribution to overall GHG emissions. The noteworthy aspect of this consistency is the utilization of the emission factor method, which entails the multiplication of the activity level, such as energy production, with the emission factor related to each specific type of fuel. This is especially significant when evaluating GHG emissions from power plants that rely on fossil fuels, as the type of energy source used is crucial.

However, the effect on the environment can be effectively comprehended by establishing a correlation between per capita GHG emissions and per capita income, as depicted in Fig. 10. In this scenario, the Kuznets relationship proves to be a highly efficient tool. The Kuznets relation is a theoretical framework that posits a correlation between environmental degradation and economic progress [35]. According to this concept, during the early stages of industrialization and economic expansion, there is a tendency for environmental degradation to worsen in a country. Nevertheless, with the ongoing progress of the economy and the subsequent increase in per capita income, environmental degradation

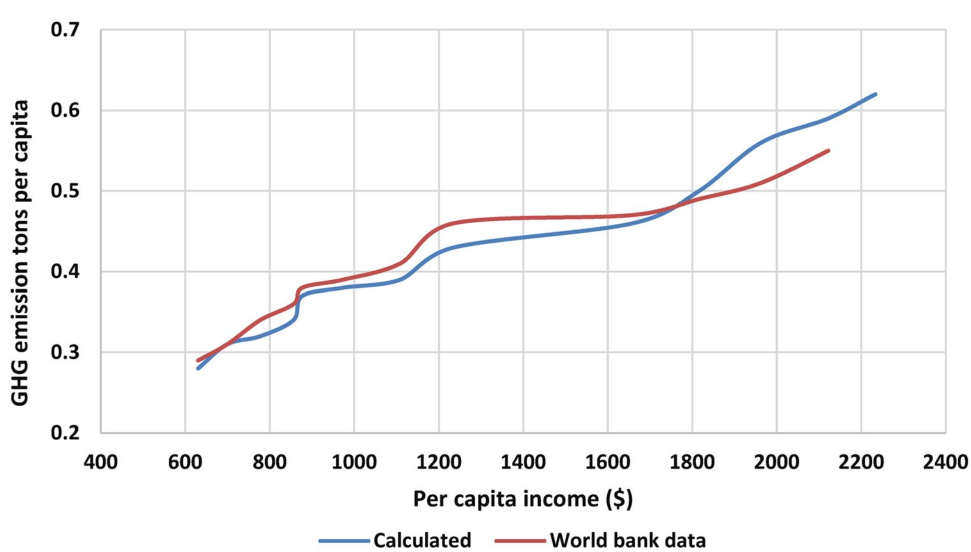


Fig. 10 Implications of greenhouse gas emissions on the per capita income

gradually diminishes. Upon analyzing Fig. 10, we observe direct relation between per capita GHG emissions and per capita income. During the period from 2008 to 2012, there was a positive correlation between per capita income and emissions, indicating that as per capita income increased, so did emissions. This corresponds to the upward trend of the Kuznets relationship, indicating a period of growing environmental effects during the process of economic growth. Nevertheless, throughout the period from 2013 to 2020, there was a noticeable stabilization or even a slight decline in per capita emissions, primarily due to a significant rise in per capita income. This suggests a possible pivotal moment in the Kuznets theory, where the ecological consequences start to decrease as the economy advances. Kuznets relationship in Fig. 10 demonstrates a distinct and quantifiable positive correlation between per capita income and calculated GHG emissions per capita. This connection highlights the importance of implementing regulations that encourage ways to separate economic expansion from its negative effects on the environment. This entails a purposeful transition towards more environmentally friendly energy sources, emphasizing improving the effectiveness of energy usage and the adoption of sustainable methods in the power-producing industry.

We compare annual CO_2 emissions from fossil fuel-based power plants of Bangladesh with some Asian countries in Fig. 11a. CO_2 emission data for the comparison is sourced from the World Bank dataset [36] and we focused solely on emissions from fossil fuel-based power plants. Other emission sources and the overall carbon footprint of the countries are not accounted for in this analysis. The calculated value of CO_2 emissions in Bangladesh is 97,723 kilotons, whereas the World Bank statistics shows a value of 90,740 kilotons during 2019. This indicates that the calculated value is slightly higher than the World Bank data. This is due to the variation of factors mentioned in the result section. When compared to neighboring countries e.g., India and Pakistan, Bangladesh has relatively lower CO_2 emissions. India has large amount of emission due to its large population and energy demand. Vietnam and Philippines have higher CO_2 emissions compared to Bangladesh due to rapid industrialization [37] and heavy reliance on coal power to

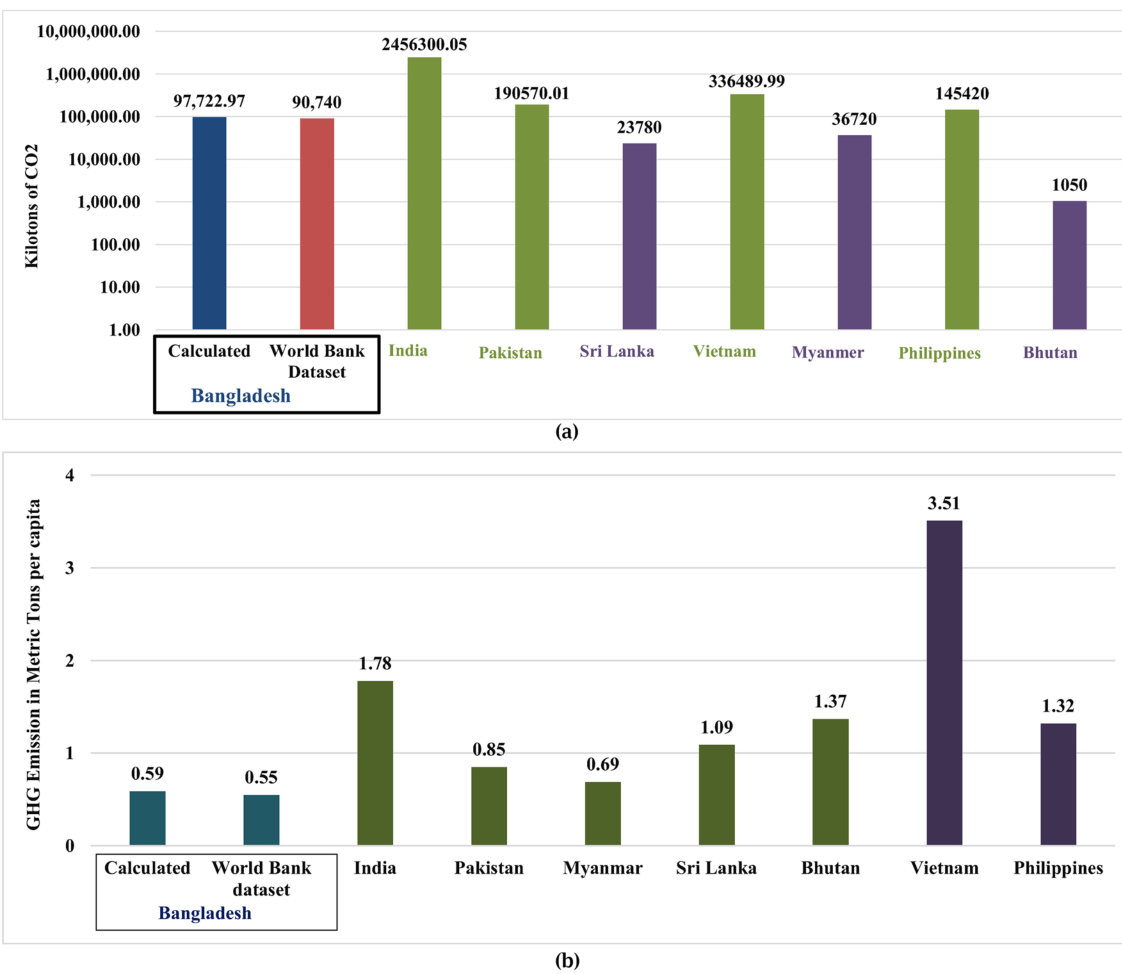


Fig. 11 Comparison of from fossil fuel-based power plants in country-wise carbon footprints **a** annual CO_2 emissions **b** emission per capita

meet higher energy demand. Bhutan and Sri Lanka have lower emission than Bangladesh. Sri Lanka has smaller population and has a mix of energy sources [38] and Bhutan focuses on renewable energy particularly hydropower [39].

We observe from Fig. 11b that Bangladesh has the lowest GHG emissions among the neighbor countries, with a rate of 0.59 metric tons per capita. This implies that, on average, fossil fuel-based power plant in Bangladesh produces considerably less carbon emissions compared to the other countries. India, on the other hand, stands out as the highest emitter, with a rate of 1.78 metric tons per capita. Pakistan and Myanmar fall in the middle of the range, with GHG emission rates of 0.85 and 0.69 metric tons per capita respectively. Sri Lanka, Bhutan, and the Philippines have GHG emission rates of 1.09, 1.37, and 1.32 metric tons per capita respectively. Although these countries have higher emissions compared to Bangladesh. Vietnam, with the highest GHG emission rate of 3.51 metric tons per capita, presents a significant challenge in terms of carbon reduction. It is crucial for all countries to prioritize initiatives aimed at reducing GHG emissions in order to combat climate change and achieve sustainable development.

Although there are slight differences in comparison of the calculated emissions with the World Bank benchmark [34, 36] this is attributed to the method employed. The inequalities in GHG emission estimates between the emission factor approach and the World Bank methodology arise from their divergent methods. The emission factor approach streamlines computations by utilizing specific emission factor coefficients, potentially disregarding sector-specific intricacies and regional disparities. The emphasis on CO_2 emissions may overlook a thorough evaluation of many contaminants. However, the World Bank utilizes a thorough approach to evaluate GHG emissions associated with its broad range of energy sector initiatives. The assessment covers the complete energy supply cycle, encompassing the extraction of fuel and its utilization by customers. The World Bank methodology used equations derived from IPCC guidelines to transform projected fuel consumption effects into estimates of GHG emissions. Essential inputs consist of project-specific information regarding fuel consumption, carbon intensity, energy value, emission rates, and the efficiency of fuel conversion technology. The strategy specifically focuses on mitigating CO_2 emissions, as World Bank initiatives often have minimal effects on methane and nitrous oxide. Due to the escalating emission of greenhouse gases from fossil fuel-based power plants, there are significant adverse impacts on the environment, public health, and climate. CO_2, the primary greenhouse gas released by these power plants, plays a substantial role in global warming and climate change. This leads to an increase in the frequency and intensity of extreme weather events, a rise in sea levels, and disturbances in ecosystems. Excessive emissions of CO_2, CH_4 result in the greenhouse effect, which entails the retention of heat in the Earth's atmosphere and subsequent increase in temperature. In addition, the release of gases, such as sulphur dioxide (SO_2) and nitrous oxide (N_2O) as air pollutants, through the burning of fossil fuels can worsen the greenhouse effect, hence amplifying the consequences of climate change. Furthermore, these emissions are a significant factor in the occurrence of air pollution, which in turn results in respiratory ailments and various health complications among the neighboring people. Furthermore, the emission of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) from these power plants can result in the formation of acid rain, causing detrimental effects on aquatic ecosystems, flora, and infrastructural corrosion. Considering the adverse effect of greenhouse gases from fossil fuel-based power plants strategies as well as policy and regulations should need to be taken. Considering the significant consequences resulting from the release of greenhouse gases by power plants that utilize fossil fuels, it is crucial to promptly implement thorough strategies, as well as strong legislation and regulations. It is imperative to implement strategies that not only reduce emissions but also lay the foundation for a sustainable and resilient future, giving priority to both environmental and public health concerns. In this study, we examine the emissions of air pollutants (such as NO_x, SO_2) from power plants that use coal and natural gas as fuel sources. Coal-fired plants are recognized for emitting greater amounts of air pollutants compared to gas-fired plants. However, gas-fired plants have fewer emissions per unit of energy generated. Utilizing sophisticated technology, such as ultra-supercritical coal-fired facilities, has demonstrated potential for substantially decreasing emissions of air pollutants. Gas-fired power plants have a significant advantage in reducing the release of air pollutants, thereby improving air quality. Implementing gas-fired power plants is a viable approach to reducing air pollution emissions and tackling environmental issues related to energy production. Furthermore, it is essential to acknowledge that both the release of air pollutants and the emission of greenhouse gas (specifically CO_2) are significant environmental issues associated with power generation, with differences observed between coal-fired and gas-fired facilities. Emissions of air pollutants from coal-fired power plants worsen air pollution, leading to respiratory problems and other health concerns. However, greenhouse gas emissions specifically, have a substantial influence on global warming and climate change, affecting ecosystems and weather patterns. A thorough understanding of these emissions and their origins is critical for formulating comprehensive approaches to reduce environmental consequences and encourage sustainable energy practices. In the following section, we have discussed how GHG and LAP emissions can be reduced effectively by strategies and policies.

4.2.1 Strategies to reduce fossil fuel based carbon footprint

While the GHG and LAP emissions are currently lower compared to neighboring countries, but special consideration must be given to reducing these emissions. It is worth noting that the number of coal-fired power plants and the electricity generated from coal are increasing at a significant rate. This upward trend implies a subsequent increase in generation of GHG alongside LAP. Therefore, taking proactive measures to address the carbon footprint from fossil power plants becomes imperative. To effectively control carbon footprint, we propose the implementation of the following measures, which have proven to be highly efficient in addressing this issue:

1. Improvements of energy efficiency and emission reduction efficiency.
2. Utilizing carbon capture and storage (CCS).
3. Fuel switching.
4. Improvements of maintenance and operations.
5. Implementing policy and regulation.
6. Transition to renewable energy sources.

Additionally, a significant reduction in total emission levels can be accomplished by improving emission reduction efficiency. According to Eq. 2, this tactical move lays the way for a more formidable and effective approach to address environmental issues. There is a linear relationship between air pollutant emission and emission reduction efficiency. We observe that higher levels of efficiency results in a greater decrease in emissions, whereas lower levels of efficiency have a negative impact on the effectiveness of emissions reduction in Fig. 12. By lowering CO_2 emissions, CCS technology may offer a viable remedy for combating climate change [40]. It permits coal power plants to keep running while reducing their negative effects on the environment. There are various processes involved in implementing CCS in coal power facilities [41]. First, different methods, such as absorption or adsorption, are used to absorb the carbon dioxide released during the burning of coal. The collected CO_2 is then moved to an appropriate storage location through pipelines or by transporting it as liquid. CO_2 is then permanently stored by being injected far below into geological formations like depleted oil and gas reserves or saline aquifers.

An important role may be played by switching to renewable energy, which not only delivers clean and sustainable energy but also aids in reducing carbon footprint. In the context of Bangladesh, fuel switching refers to the process of shifting from conventional fossil fuels to more environmentally friendly alternatives, including natural gas and renewable energy sources. Considering increasing demand for energy, Bangladesh has the potential to lessen its reliance on imported fossil fuels, such as LNG, oil, and coal, by intensifying domestic gas exploration and fostering the use of renewable energy throughout the country. This approach not only decreases susceptibility to external disruptions in global fossil fuel markets but also strengthens domestic energy stability. Improving the maintenance and operations of fossil fuel power facilities can offer a vital chance to reduce carbon footprint. Fossil fuel-based power plants are able to significantly decrease their carbon footprint by applying advanced technology and best practices, such as optimizing

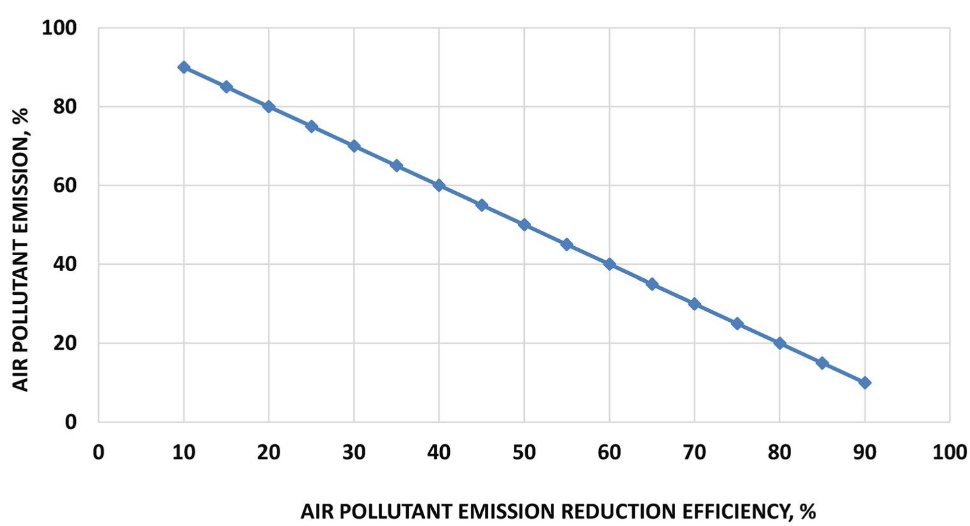


Fig. 12 Relationship between air pollutant emission and emission reduction efficiency

combustion processes, lowering fugitive emissions, and enhancing overall operating efficiency. Additionally, making investments in contemporary monitoring and control systems, together with embracing cleaner fuel alternatives, might additionally assist in the reduction of emissions. Furthermore, performing routine maintenance and implementing upgrades on aged infrastructure can improve energy efficiency, resulting in a decrease in GHG as well as LAP emissions per unit of electricity produced. By implementing these improvements, Bangladesh may effectively reduce its impact on climate change while simultaneously enhancing air quality and public health. This can contribute to the development of a more sustainable and environmentally aware energy sector for the nation's future. Embracing renewable energy sources is essential to decreasing carbon footprint. Bangladesh possesses the capacity to diminish its dependence on fossil fuels and adopt sustainable energy options, primarily centered on solar, wind, and hydroelectric electricity. This transformation not only cuts carbon emissions but also improves energy security and resilience in response to climate change. By allocating resources towards the development of renewable energy infrastructure and advocating for clean energy initiatives, we can pave the path for a more environmentally friendly and sustainable future, thus ensuring a cleaner environment.

4.2.2 Policy and regulations to mitigate carbon footprint

The carbon footprint of Bangladesh has been a matter of great concern. Furthermore, the anticipated coal power plants are forecast to release over 100 million metric tons of CO_2 by 2030, indicating a significant rise in the potential for generating power from coal. Although Bangladesh is one of the countries with the lowest levels of carbon emissions worldwide, it has committed to a significant reduction of 22% by 2030. This reduction amounts to 89.47 million metric tons of CO_2 and will be achieved through various measures. These include the implementation of more renewable energy projects, the adoption of advanced technology for power generation, and the reduction of emissions from sectors such as transport, agriculture, and waste management. Bangladesh's commitment demonstrates its active involvement in global efforts to reduce carbon footprint and its promotion of renewable energy, energy efficiency, and conservation. Bangladesh prioritizes sustainable development through efforts such as the Bangladesh Climate Change Strategy and Action Plan (BCCSAP). Additionally, it advocates for the implementation of renewable energy initiatives, the adoption of energy-efficient practices, and the establishment of afforestation programs. Bangladesh is dedicated to adhering to global accords such as the Paris Agreement, making efforts to curtail greenhouse gas emissions, and preparing for the consequences of climate change. With a comprehensive and multi-sectoral approach, Bangladesh intends to create a low-carbon and climate-resilient economy by incorporating climate considerations into its development strategies. At the 28th meeting of the Conference of the Parties (COP), Bangladesh underscored the significance of using a scientific methodology to tackle the climate change challenge, and stresses the importance of making difficult choices regarding fossil fuels, guided by scientific data, in order to restrict the rise in global temperatures to the critical threshold of 1.5 °C. Bangladesh seeks to form partnerships with nations that have similar goals in order to enhance the draft and effectively increase the climate adaptation fund by twofold. Furthermore, it promotes the importance of political dedication to decrease worldwide carbon emissions, with a specific emphasis on the leadership responsibility of industrialized nations. Moreover, Bangladesh is actively making preparations to secure cash from the damages fund, showcasing its dedication to tackling climate concerns. The overarching objective is to attain a significant and fair accord that benefits all nations. In addition, Bangladesh must decrease emissions from areas such as transportation, agriculture, and waste management. The country needs to seek international investment in green energy to achieve a significant reduction in emissions and promote environmental sustainability. Bangladesh has the potential to mitigate carbon emissions from fossil fuel-powered plants by allocating resources towards the adoption of renewable energy alternatives, including solar, wind, and hydroelectric power. Implementing stringent emissions regulations and providing incentives for the adoption of clean technologies can also have a pivotal impact. Utilizing carbon pricing systems, advocating for energy efficiency, and fostering the implementation of carbon capture and storage (CCS) technology are efficacious measures. Moreover, improving the public transportation system and advocating for the use of electric vehicles can effectively reduce carbon emissions. In addition, promoting reforestation and afforestation activities can effectively counterbalance carbon emissions. These strategies can cumulatively lead to substantial decreases in Bangladesh's carbon emissions from power plants that rely on fossil fuels.

5 Conclusion

Carbon footprint analysis of fossil power plants in Bangladesh has clearly demonstrated the significant environmental impact of greenhouse gas and local air pollutant effluents emissions. After analyzing the greenhouse gas emissions and comparing them with those of neighboring countries, it becomes essential to highlight the immediate requirement for comprehensive actions to decrease carbon emissions and address the negative impacts of climate change within the country. Despite the fact that the GHG and LAP emission rates are relatively lower than those of its neighboring country, India, and Pakistan, it is still imperative to take proactive measures to address this pressing issue. The findings of the study can be summarized as follows:

1. Fossil power plants in Bangladesh contribute significantly to GHG and LAP emissions.
2. Implementation of gas-fired power plants is seen as a viable approach to reducing air pollution emissions and addressing environmental concerns related to energy production.
3. Improving energy efficiency in power plants such as USC is also essential for reducing carbon footprint. Implementing energy-saving measures and technologies can optimize energy usage and decrease emissions.
4. The study emphasizes the urgent need for transitioning to cleaner and more sustainable energy sources in Bangladesh to mitigate the environmental and health risks associated with fossil fuel combustion.

According to our findings from the analysis, coal power plants in Bangladesh are a significant source of carbon emissions, which not only hasten global warming but also present considerable threats to the environment and human health. It is clear that these emissions have negative impacts on ecosystems and biodiversity as well as wide-ranging effects such as rising temperatures and a rise in the frequency of extreme weather events. Bangladesh must make the switch to more sustainable and clean energy sources in order to handle these issues. The adoption of renewable energy technology, increased energy efficiency, and efficient laws and regulations are only a few of the many aspects of this shift that are required. To encourage the reduction of carbon emissions, it is also necessary to design and implement regulatory frameworks and regulations.

The evaluation of Bangladesh's fossil fuel power station's carbon footprint sheds light on the urgency of taking action to reduce not only GHG emissions but also LAP emissions. The study can play a pivotal role in energy policy development, technology investment, infrastructure planning, and public governance. The study highlights the necessity of investigating strategies geared towards improving the energy efficiency of fossil power plants. It also emphasizes the critical role of developing long-term strategies to address carbon emissions within the power sector. Moreover, exploring the integration of renewable energy sources into the power generation mix emerges as a vital avenue for further inquiry.

Author contributions Related works, Methodology, Results and Discussion: Shaon Md Tariqur Rahman. Introduction, Overview of Methodology and Results and paper Formatting: Antor Mahamudul Hashan. Related works and Conclusion: Md Mahabubur Rahman Sharon. Worked on reverse manuscript: Shekhor Saha.

Data availability Data sets generated during the current study in order to calculate the emissions of greenhouse gases are available from the corresponding author upon reasonable request. The emission factors and global warming potential values for greenhouse gas data are available from the Journal of Data, Statistics, and Useful Numbers for Environmental Sustainability at:https://doi.org/10.1016/B978-0–12-822958–3.00004–2. Data for the comparison of annual CO_2 emissions and emissions per capita for different countries are available in the World Bank dataset at https://datatopics.worldbank.org/world-development-indicators/themes/environment.html.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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