The impact of human capital, renewable energy, and economic growth on carbon emissions: A System Dynamics simulation modeling in the airline sector of South Asia

Abstract

In the implementation of sustainable development goals (SDGs), researchers have greatly focused on factors such as human capital (HC), renewable energy (RE), economic growth (EG), and environmental preservation, which influence carbon (CO_2) emissions in South Asian countries focus on (Pakistan, India, and Bangladesh). This research uses secondary data points from 1990 to 2024 from World Development Indicators to investigate variable relationships in the airline sector of Pakistan, India, and Bangladesh. The collected data was analyzed by employing two analytical methods. First, it conducts stationarity tests through the Augmented Dickey-Fuller to determine data stability. Second, the Autoregressive Distributed Lag (ARDL) model and System dynamic modeling (SD Modeling) via Python and Vensim software are used to analyze the impact of HC, RE, and EG on carbon emissions. The results reveal that both economic growth and renewable energy adoption, together with human capital investment, lead to diminished carbon emissions in South Asia. Research also demonstrates both the necessity of skilled personnel along with appropriate policy structures to achieve sustainable adoption of green technology that reduces airline sector CO_2 emissions. SD simulations determine that Pakistan, India, and Bangladesh require unified policies to integrate RE sources with enhanced education and climate management for sustainable airline growth. Thus, the work presents the systematic policy roadmap by which the governments in South Asia can operationalize SDG 7 and SDG 13 in the aviation industry by integrating clean energy transitions, institutional capacity building, and climate-consistent regulatory reforms in sustainable aviation policies.

Keywords: Human Capital; Renewable Energy; Sustainable Development Goals; Economic Growth; Low Carbon Emissions; SD Simulations Modeling

1. Introduction

Carbon dioxide (CO_2) emissions are an emerging issue for environmental sustainability (Ali, 2024) and protection, since these CO_2 emissions worsen climate change and damage the ecosystem (Kabir et al., 2023) in South Asia, especially in Pakistan, India, and Bangladesh, where fast economic development and rapid population growth occur (Sadigov, 2022). South Asian countries have experienced economic growth in the aviation industry, leading to increased carbon dioxide (CO_2) emissions from natural processes and human activities, which disturbs the atmospheric CO_2 balance (Fang et al., 2023). Airline operations produce elevated fossil fuel-powered aircraft emissions due to high transportation service requirements ((Pandey & Asif, 2022), which consume high amounts of energy and produce heightened carbon emissions (Somosi et al., 2024). The urban developments and industrial transformations generate higher aircraft-based greenhouse gas emissions (Chandio et al., 2022). Figure 1 shows that there is a drastic and steady increase in the CO_2 emissions of the aviation industry, especially in India, which underscores the increasing role of the aviation industry in the carbon intensity of the region, and the necessity of integrating renewable energy sources and intervening in climate policies. Therefore, researchers are more inclined to explore the factors that may produce elevated emissions, but sustainable management policies can mitigate this (Ozturk, 2010). The research aims to evaluate the carbon emission reduction through RE and HC development along with economic growth effects, as well as offer policy recommendations for sustainable aviation, aligning with the SDGs.

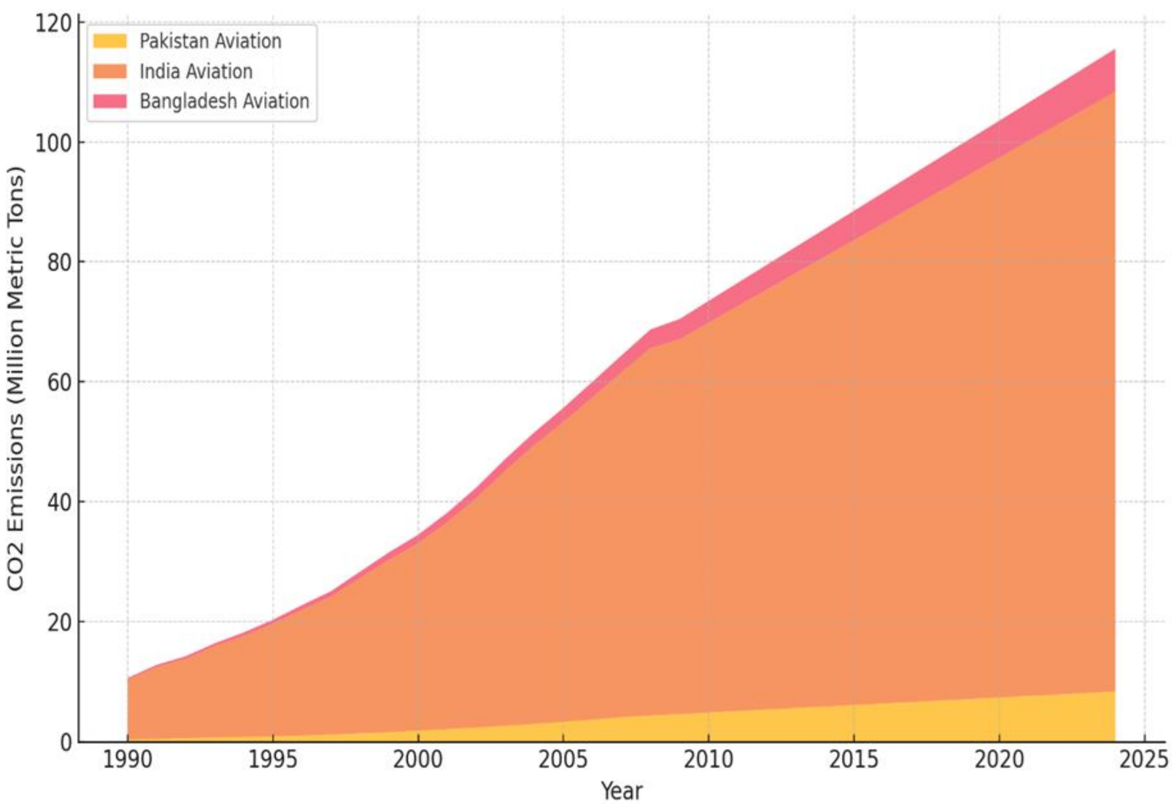

Figure 1: **Airline Sector CO_2 Emissions (Million Metric Tons), 1990–2024.**

Source: World Development Indicators (2024).

The main obstacle involves creating qualified professionals who understand sustainable aviation methods for airline operations while transitioning toward renewable power systems for environmental protection (Calvet, 2024). Fast industrial development in South Asia makes sustainability targets crucial as environmental protection remains vital (Xiuhui & Raza, 2022). Government authorities from India, Pakistan, and Bangladesh must unite to resolve their countries' energy problems due to fast economic growth and expanding airline industries in line with the SDGs goals (UN, 2015). Figure 2 reveals that the CO_2 emissions in the transport sector increase until 2000-2070 and then slowly decreases under the assumption of the policy scenario with passenger cars and heavy-duty trucks contributing the most to the total amount of emissions, followed by aviation and shipping as the major contributors in the long term, given the energy transition and the use of better technologies. By 2020, global emissions will reach their peak before experiencing a rapid decline until 2070, when all transport segments, notably passenger cars, together with heavy trucks, achieve substantial emission reductions. The 17 SDGs of the 2030 Agenda for Sustainable Development provide targeted solutions for global environmental systems, economic growth, and climate change (Somosi et al., 2024; UN, 2015). South Asian governments can collaborate to solve environmental problems originating from major industries while promoting sustainable business operations and RE practices (Østergaard et al., 2022).

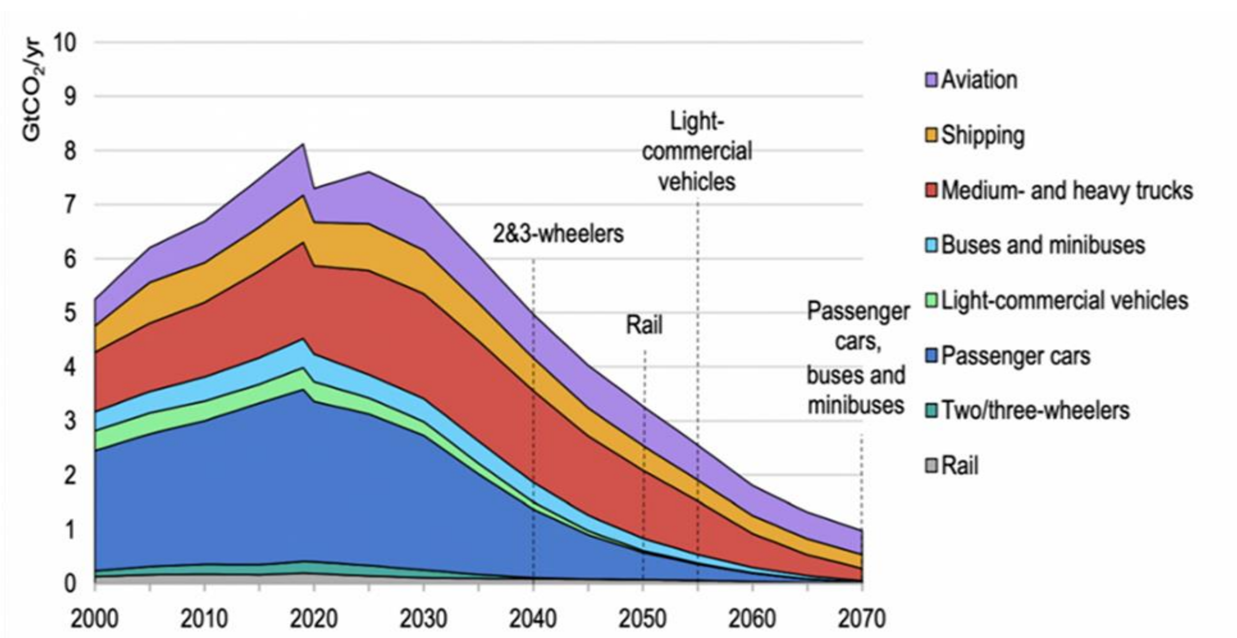

Figure 2 Global Transportation Sector CO_2 Emissions Scenario (2000–2070)

Source: International Energy Agency (2020).

The figure 3 indicates the share of total carbon footprint of tourism by sector with transport being the major contributor 49%, goods, food and beverage coming next at 12% and 10% respectively, with agriculture and services occupying the remaining 8% as well as other sources without any exception, indicating the important contribution of transportation to other tourism-related activities. The airline sector must deploy RE solutions and develop HC skills to lower carbon emissions(Wang et al., 2023) and achieve the SDGs (UN, 2015). Modern technology within the Indian aviation sector enables the use of sustainable aviation fuels, together with energy-efficient operational methods (Zhou et al., 2022). The government of Pakistan has introduced substantial goals concerning RE development until 2030 (Akram et al., 2021).

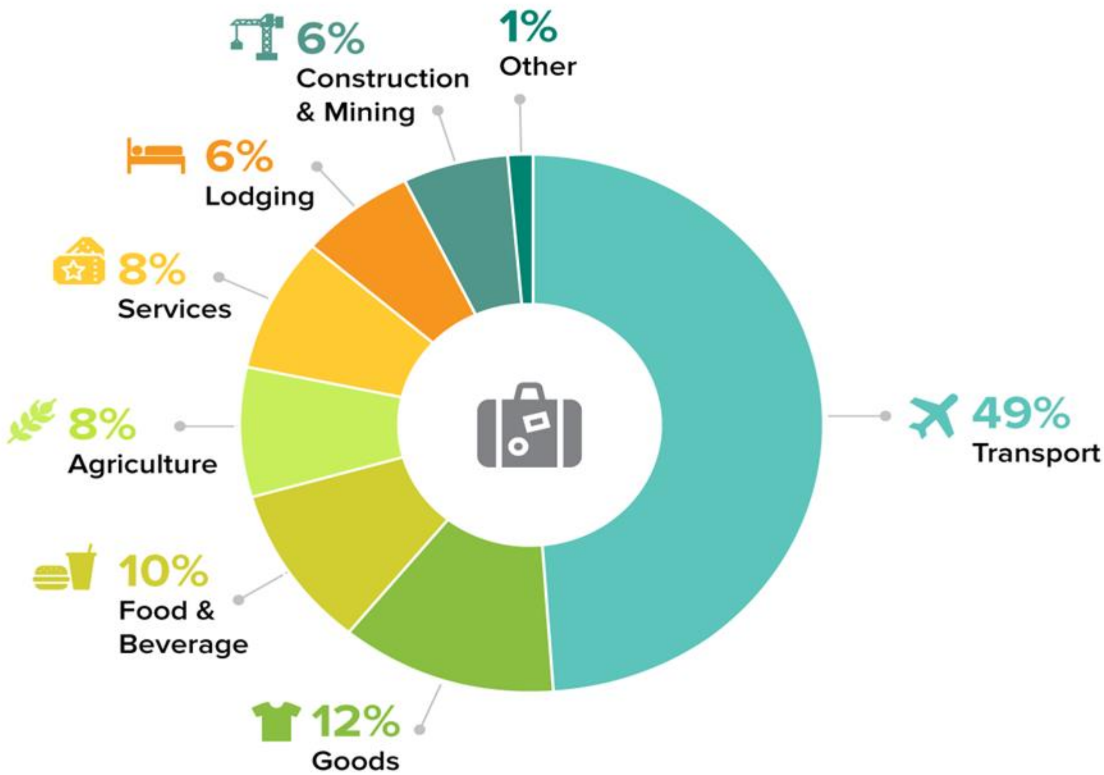

Figure 2 Carbon Footprint of Global Tourism

Source: Nature Climate Change (2018)

The aviation sector of Bangladesh explores various RE solutions to design sustainable emission reduction strategies (Mentel et al., 2022; Shabani, 2024; Wang et al., 2023). Industrial programs must be implemented because they provide solutions to achieve SDG targets while fighting carbon emissions. This research explored the effect of HC investment with RE implementation through EG trends and population developments on CO_2 emissions in the airline industry in Pakistan, India, and Bangladesh. The research aims to explore these factors to provide insights into alternative CO_2 emissions reduction methods for the airline industry of these countries, which prioritize sustainability. South Asian policymakers can develop research-driven methods to boost sustainability and foster economic expansion in airline operations. Over the past thirty-four years, India has achieved the greatest emission growth rate, although Pakistan, together with Bangladesh, maintains smaller but rising emission levels. Figure 3 showed CO_2 emission statistics (in million metric tons), for Pakistan, India, and Bangladesh from 1990 until 2024.

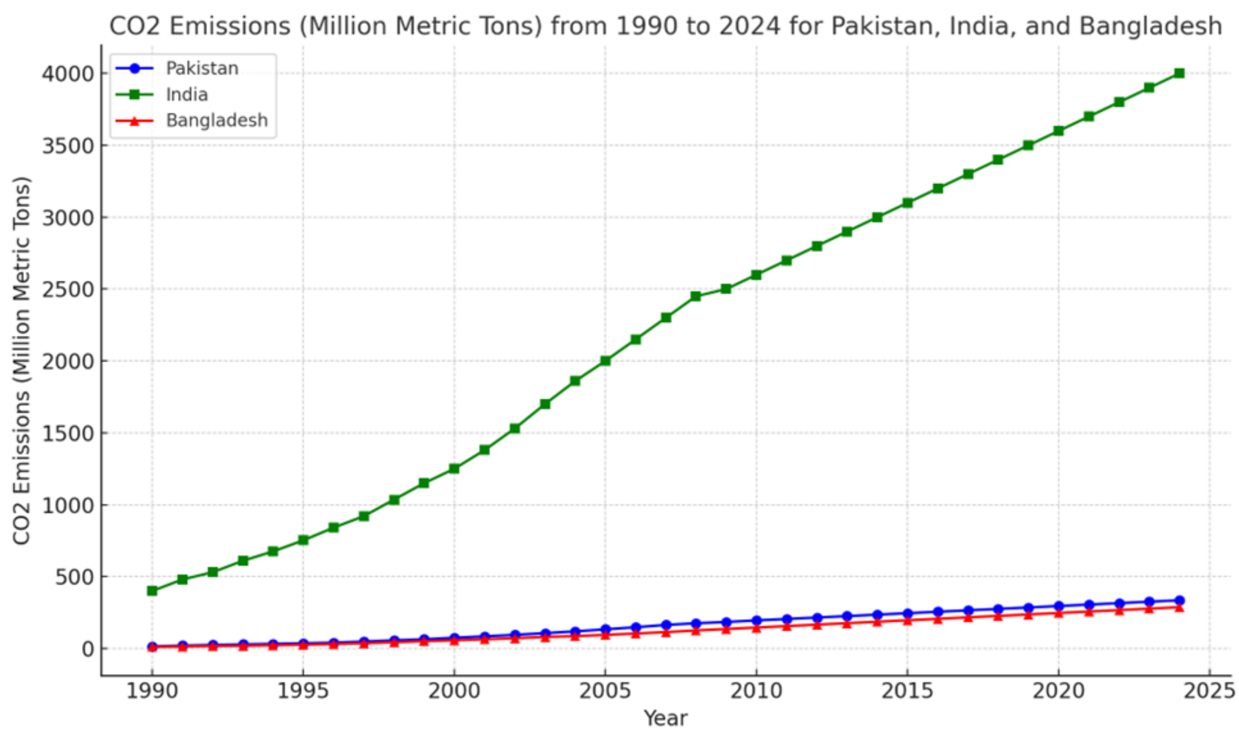

Figure 3 CO_2 emissions (in million metric tons) from 1990 to 2024 for Pakistan, India, and Bangladesh.

The study contributes to the literature by combining SD modeling and ARDL analysis with the aim of multitasking the synergies between HC and RE adoption and EG on CO_2 emissions in the South Asian airline industry. The results offer direct instructions to the policymakers and it is critical that the sustainable development of aviation requires investment in human capital and renewable energy. The study allows showing how the airline industry can both develop the economy and protect the environment by encouraging the use of renewable energy (SDG 7:

Affordable and Clean Energy) and minimizing carbon emissions (SDG 13: Climate Action). The policymakers in South Asia can employ these findings to develop research-based policies that would promote sustainability and economic growth in aviation business.

2. Literature Review

The airline sector of South Asia is the essential economic force in Pakistan, India, and Bangladesh, facilitating transportation and economic development (Hakim & Merkert, 2016). The industry produces major emissions, recently becoming a central subject of climate change and global warming discussions (IATA, 2020; Koçak et al., 2020). The tourist arrival in these countries produces greater emissions (Koçak et al., 2020; Selvanathan et al., 2021; Sharif et al., 2017). The industry contribution to climate change continues to raise concerns in the context of SDG Goal 13 (UN, 2015). Thus, identifying sources of carbon emissions and developing effective management strategies to combat CO_2 emission is important (Wong et al., 2024). The airline industry's carbon emissions are driven by three fundamental factors: HC investment, RE adoption, and economic growth (Mentel et al., 2022). Identifying interrelationships between these factors enables the development of sustainable plans that incorporate emission reduction methods (Mentel et al., 2022).

HC investment is essential for forming the workforce in the airline industry (Liu et al., 2021). HC develops innovative solutions, improves operational efficiency, and immediately adapts environmental technologies to their professional skills (Talib et al., 2025; Twum et al., 2021). The workforce needs both knowledge and initiative to implement sustainable procedures in aviation. Research demonstrates that combining educational initiatives with training approaches generates productive aircraft control systems that utilize smart fuel systems and achieve increased routing and quality maintenance delivery (Pourdehnad & Smith, 2012). Energy efficiency training is crucial (Kafle et al., 2024). It enhances fuel efficiency and reduces carbon pollution levels, but the rapid growth in the South Asian airline industry creates substantial environmental challenges (Wang et al., 2024). However, HC investment provides a solution for implementing carbon-reducing technologies and operational deployment strategies (Hasan et al., 2021).

The airline industry requires RE conversion to decrease carbon emissions. Today's airline industry strives to adopt renewable power sources, including biofuels and solar power, because these renewable options offer higher sustainability than conventional fossil fuels in aviation applications

(Pereira & da Silva Ferreira, 2021). Various research studies describe biofuels as an effective method to decrease carbon pollution in airline operations (Ambrosio et al., 2025; Khujamberdiev & Cho, 2024). The International Air Transport Association (IATA) has revealed that the proper production of biofuels can minimize airline industry carbon emissions by 80% (IATA, 2020). Commercial airline testing is conducted in the aviation sectors of South Asian countries such as India and Sri Lanka to estimate biofuels. The limited adoption of RE in airline operations is mainly due to high production costs, insufficient infrastructure support, and technical advancement needed to replace existing jet fuel standards. RE options face a substantial economic challenge, although scholars identify them as a potential solution for emission reduction in the future (Sarma et al., 2022).

EG patterns related to energy usage and carbon emissions have been investigated in the South Asian countries of India and Pakistan (Ahmed et al., 2022). Research demonstrates that EG increases emissions, but countries develop carbon-free EG using emission reduction technology and environmental policies during certain periods(R Alaganthiran & Anaba, 2022; Rigas & Kounetas, 2024). The Indian airline sector invests substantially in sustainable technologies such as hybrid-electric aircraft prototypes and carbon capture technologies, as economic development is aligned with government support for environmental initiatives (Thummala & Hiremath, 2022). The aviation sector in Bangladesh shows both rapid emission growth and new biofuel adoption initiatives for RE systems to reduce future air pollution(Rahman et al., 2024).

Researchers have established that economic growth positively correlates with carbon emission levels by employing the Environmental Kuznets Curve (EKC) (Barra et al., 2025; Caporin et al., 2024; Odei et al., 2025). EG increases CO_2 emissions until a certain level is reached, at which point implementing new sustainable technology decreases air pollution (Chen & Wang, 2025). South Asian airline sector emissions show an upward trend due to increased travel demand by regional EG. EG generates funding for eco-friendly infrastructure development that prevents higher CO_2 emissions (Rahman et al., 2020). The new investments in electric aircraft technology and airport facilities with energy-saving capabilities increased the Indian airline's emissions (Jha & Kumar, 2020). The main obstacle to achieving sustainable growth is striking an equilibrium between all three factors: policy incentives, market-based mechanisms, and technological innovation to link EG with sustainability goals (Dorri & Shahini, 2024; Iglesias-Casal et al., 2025).

Different countries in the region have adopted emissions trading systems, carbon pricing measures, and strict fuel efficiency standards as either proposed or official initiatives(Massetti & Tavoni, 2012). Indian electricity power operates under carbon trading, and authorities are considering expanding this system to regulate emissions from other industrial sectors, including airlines. Implementing sustainable solutions faces obstacles, such as significant capital investments, technological development, and appropriate sustainability regulations. Efforts to build RE policies should eliminate biofuel barriers by eliminating fossil fuel incentives and establishing biofuel production and distribution systems (Ganguly et al., 2022).

The interactions between HC investments for power generation and EG regarding the CO_2 rates of South Asian commercial flights. HC investment, RE adoption, and sustainable EG can cause major emission reductions, yet significant efforts must be applied to overcome existing barriers(Shabani, 2024). South Asian government officials must promote technological progress by developing policies that allow RE integration while establishing economic programs that address climate objectives. Strategic integration among these dimensions allows the South Asian airline sector to achieve the SDGs by reducing CO_2 emissions. Studies from various South Asian areas have examined the association between EG and CO_2 emissions. (M. B. Khan et al., 2022; Vidyarthi, 2014). EG produced carbon emissions before the establishment of clean technology, demonstrating the ability to reduce emissions in economies permanently. South Asian countries may implement appropriate policies to weaken the connection between EG and greenhouse gas CO_2 emissions in the airline industry. The study indicates that policymakers should establish environmental growth policies to support sustainable development (Amin et al., 2022).

Researchers are dedicated to exploring the effect of RE adoption in the airline sector. The study reviewed two South Asian airline using RE methods, namely biofuel systems and photovoltaic aircraft, but focused on emission reduction (Jaiswal et al., 2022). The findings revealed that biofuels cost more than fossil fuels but should be used due to their positive environmental effects. The researchers forecast that substantial technological development of solar-powered aircraft will lead to commercial applications during the next decade. This study reinforced governmental support and appropriate legislation's ability to empower airline transition toward RE as public-private approaches align with global efforts in achieving SDG 13.

The airline industry needs specialized HC expertise to decrease pollution from airline operations. Singh et al. (2021) argued that training initiatives shaped the fuel efficiency of Indian airlines. Designing and implementing workforce training programs enabled airlines to drop their fuel expenses by 15-20% compared to those that did not conduct these programs. Ongoing sustainability-oriented programs, such as education and training, reduce CO_2 emissions. Recent studies have extensively analyzed policy programs that enable the airline industry to minimize emission levels. All emission sources in the South Asian aviation sector are subject to the region's numerous emission regulations. The regulatory frameworks for air travel between India and Pakistan are evolving. Both countries have implemented a new generation of carbon tax laws to reduce emissions; however, the effectiveness of these measures is hindered by insufficient monitoring and reporting mechanisms. Governments must combine robust institutional systems with open and consistent policy enforcement in order to establish industrial accountability (Sharma & Gupta, 2021).

Indira Gandhi International Airport in Delhi employs energy-efficient systems, waste reduction practices, and green building certification programs. Patel et al. (2023) found that sustainability initiatives help airports to reach two strategic objectives: lowering emissions from airport operations and supporting the industry-wide adoption of comparable practices. Sustainability requires cohesive rules that integrate the various segments of the airline industry to operate as a singular system. The economic initiatives and sustainable practices reduce CO_2 emissions. Indian airline companies can achieve up to 40 percent carbon emission reduction by implementing RE solutions, fleet upgrades, and operational optimization programs (Sharma et al., 2022). Coordinated action among the energy, transportation, and policy sectors is essential for emission reduction.

The SDGs necessitate the collaboration of stakeholders, such as government agencies, airline companies, and the active participation of the public through strategic partnerships for substantial emissions reduction (ICAO, 2019). Researchers should focus on three primary objectives: the development of new policy frameworks, the enhancement of emission factor measurement models, and the establishment of a sustainable aviation sector through the evaluation of alternative fuel options. The airline sectors of Pakistan and Bangladesh are still in the early phases of biofuel adoption, as previous experiments have been unable to overcome high operational costs and insufficient infrastructure (ICAO, 2019).

3. Methodology

Theoretical Framework.

The Environmental Kuznets Curve (EKC) has been used as the theoretical background of investigation on the relationship between economic growth (EG) and carbon emissions in the airline sector in South Asia. The EKC hypothesis states that emissions grow at the beginning of economic growth because of the growing energy use, industrialization, and aviation (Barra et al., 2025; Caporin et al., 2024; Odei et al., 2025). The aviation industry during this phase is marked by fleet growth, an increased number of passengers and reliance on fossil fuels which increase CO_2 emissions. Nonetheless, with the development of the economies, structural change, and technological advances, and increased cleaner production and energy-efficiency, emissions will also decrease (Chen & Wang, 2025). Such a shift is the reason why the trend in India is rising and the trends in Pakistan and Bangladesh are rising gradually.

In the aviation industry, human capital (HC) and renewable energy (RE) are key processes that enable the downward turning point of the EKC. Human capital improves the sector ability to embrace fuel efficiency technologies, flight operations, and maintenance system as well as introducing sustainable aviation fuels. An efficient Labor force will help the airlines to incorporate renewable energy sources including biofuels and solar fuelled airport functions, which will decrease the intensity of carbon (Talib et al., 2025; Twum et al., 2021). At the same time, the use of renewable energy is a direct replacement of fossil fuel, which undermines the beneficial relationship between the growth of the economy and emissions. Therefore, HC is an organizational catalyse, and RE is the technological conduit within which emission reduction takes place.

Economic growth will supply the financial means that will be used to invest in cleaner infrastructure, research and development, and regulatory reform. In conjunction with HC development and integration of renewable energy, the economic growth can be shifted to sustainable aviation development as opposed to carbon-intensive growth. Thus, the EKC structure of the current paper is expanded past the conventional EG-emissions nexus to include HC and RE as structural factors contributing to the accelerated transition to the falling stage of the same.

Pakistan, India and Bangladesh policymakers can employ this longer EKC view and develop policies that will strike a balance between aviation growth and environmental sustainability. The integration of renewable energy is in line with SDG 7 (Affordable and Clean Energy), whereas reducing emissions is in line with SDG 13 (Climate Action). In order to make the aviation industry start on a path to low-carbon development, strategic investment in workforce skills, the development, and utilization of green aviation technology, and the development of renewable energy infrastructure is necessary. This combined approach can offer the conceptual reasoning and functional guidance on sustainable aviation change in South Asia.

3.1 Method

This research aims to evaluate the impact of HC, RE, EG, and CPI on the CO_2 emissions in the airline industry of South Asian countries such as Pakistan, India, and Bangladesh, specifically examining their connection to SDGs. The intricate relation between HC and emissions led us to adopt exploratory research first to understand how various factors affect the CO_2 emissions in the airline sector of these countries (Akram et al., 2025). Researchers used secondary data from 1990 to 2024, obtained from World Development Indicators, to perform the analysis. Data variables in the research included educational achievement statistics, workforce health indicators, skills development measurements, and airline carbon emissions from the three countries. Secondary data is an integral component in uncovering important indications of proposed factors on the CO_2 emission of Pakistan, India, and Bangladesh to enhance understanding about factors behind South Asia's airline industries' carbon emissions and develop recommendations to reduce their environmental impact in line with the SDG 7 and SDG 13.

A proxy on national climate governance and regulatory effectiveness is added to the Climate Policy Index (CPI). The CPI is designed as a composite index of the performance of a country in climate mitigation policies, promoting renewable energy, undertaking commitments of reducing its emissions, implementing regulations about energy efficiency, and implementation mechanisms. The index is normalized on a percentage scale to make it comparable across countries and time. Within the framework of the aviation industry, CPI reflects the policy environment on airline emissions, such as carbon taxation policies, sustainable aviation fuel (SAF) promotion policies, emissions reporting policies, regulatory compliance policies and the alignment with international standards such as ICAO and the Paris Agreement. In this way, CPI will indicate the institutional capability and strength of regulations that affect the practice of decarbonization of the aviation-related industry.

SD Simulations are performed through Python and Vensim software (Coyle, 1997), establishing relationships of HC, EG, and CPI with airline industry CO_2 emissions. A mathematical formula has been developed to present this relationship between variables. Equation 1 represents the research proposed model.

$$\text{Airline Carbon Emission}_t = \alpha_0 + \gamma_1 \cdot \text{HC}_t + \gamma_2 \cdot \text{REGen}_t + \gamma_3 \cdot \text{REon}_t + \gamma_4 \cdot \text{EconGrowth}_t + \gamma_5 \cdot \text{PopGrowth}_t + \gamma_6 \cdot \text{ClimatePolicy}_t + \epsilon_t \text{ ------------------------------------}(1)$$

The dependent variable represents airline sector CO_2 emission levels named Carbon Emission_t at time t. The independent variables include HC_t, which quantifies the skills, education, and health of the population, RE Generation (REGen_t) and RE Consumption (REon_t), which reflects the extent of RE production and its use, Economic Growth (EconGrowth_t), which captures the rate of economic expansion, Population Growth (Pop Growth_t), which accounts for changes in demographic size, and Climate Change Policy Index (ClimatePolicy_t), which measures the effectiveness of policies aimed at reducing emissions. ε_t represents the error term, accounting for unobserved factors that could affect emissions.

In outlining the meaning of CPI and its applicability in the aviation industry, the model incorporates institutional and regulative aspects into the analytical system through which the contribution of climate governance in mitigating the association between economic growth and carbon emissions in the airline industry in South Asia can be better assessed.

The proposed model examines the connections between carbon emissions and four primary variables. The coefficient γ_1 shows that HC affects emissions yet produces opposing results by boosting manufacturing activity and enabling more efficient use of resources through better technology implementation. Greater utilization of RE sources as both generator (γ_2) and consumer (γ_3) should yield negative effects on carbon emissions because it reduces fossil fuel dependence. The total contribution of EG usually increases carbon emissions because expanding industrial facilities, combined with infrastructure, build up energy requirements and carbon-heavy production methods. The population growth rate (γ_5) should positively affect emissions because expanded human numbers will increase resource usage, particularly in the energy and transport sectors, creating higher emissions. Stronger climate policies incorporated through Climate Policy (γ_6) demonstrate a direct negative impact on carbon emissions in the airline industry.

This equation reveals an essential understanding of the effects of different variables on emissions through their coefficients. The pollution reduction effectiveness of the airline industry regarding clean energy technologies can be measured by observing substantial negative values of RE consumption. Rapid industrialization and urbanization in these regions create rising emissions rates when analyzed through positive coefficient measurements for EG. The research method is powerful for analyzing CO_2 emission patterns between economic variables, demographic factors, and policy decisions affecting the South Asian airline sectors. The analytical results will evaluate current policy performance and create plans for SDG 7, and SDG 13. By pursuing this method, we aim to reveal the relationship points between HC development, RE adoption, EG, and effective climate policy targeting emissions while advancing sustainable development in these developing countries.

This research uses the change in CO_2 emissions from one period to another as our main output, which CO_{2t} represents. These essential elements for analyzing carbon emissions include HC, renewable power generation, renewable use rates, EG patterns, population growth, and international climate change controls. The model uses time-lagged variables and dynamic effects to explain both temporary movement and lasting adjustments of spatial data. The main relationship between CO_2 emission changes and various factors is Equation 2.

$$\Delta CO_t^2 = \alpha_0 + \sum_{i=1}^{n} \delta_i \Delta CO_{t-i}^2 + \sum_{j=1}^{n} \delta_j \Delta HCI_{t-j} + \sum_{k=1}^{n} \delta_k \Delta REGen_{t-k} + \sum_{l=1}^{n} \delta_l \Delta RECon_{t-l} + \sum_{m=1}^{n} \delta_m \Delta EconGrowth_{t-m} + \sum_{n=1}^{n} \delta_n \Delta PopGrowth_{t-n} + \sum_{o=1}^{n} \delta_o \Delta ClimatePolicy_{t-o} + \varphi_1 CO_{t-1}^2 + \varphi_2 HCI_{t-1} + \varphi_3 REGen_{t-1} + \varphi_4 RECon_{t-1} + \varphi_5 EconGrowth_{t-1} + \varphi_6 PopGrowth_{t-1} + \varphi_7 ClimatePolicy_{t-1} + \epsilon_t \text{ --------------------------------(2)}$$

The dependent variable ΔCO_{2t} displays the total emission changes during one specific timeframe. The variable shows exactly how CO_2 emissions develop during movements in the other independent factors. The formula features delayed inputs because changes from each independent variable today influence emissions alongside their historical effects. The past change in emission levels at period ΔCO_{2t}-1 affects total emission measurements today. The δ_1 term indicates how earlier shifts in CO_2 emissions impact new emissions today. When past emissions rise, they remain active in determining today's emission levels, which shows that changes in emissions take a set path forward. The results of δ_2 through δ_7 explain the temporary influence of HC development, RE sector progress, and population dynamics on the RE-related changes in CO_2 emissions. An unfriendly δ_3 value shows that higher RE use lowers CO_2 emissions, proving that cleaner energy decreases industry emissions.

The current positions of seven variables affect CO_2 emissions through time-based analysis. The first relationship term, φ1, measures how earlier CO_2 emissions connect to future emissions. This lets us determine if rising emissions continue expanding or naturally decrease towards better sustainability. The effect of population growth in recent years on long-term CO_2 emissions appears in φ_6 of the $PopGrowth_t$-1 parameter. A positive value of this coefficient highlights that an increasing population brings about greater emissions resulting from extra energy and transportation use. The error term (ε_t) combines all unknown factors that affect CO_2 emissions, including hidden technological shifts and unexpected occurrences. Essentially, the error term describes all unaccounted factors affecting emissions that the model cannot capture.

3.2 Error Correction Model

The system uses an Error Correction Model (ECM) to explore how CO_2 emissions react in both short-term and long-term situations. ECM helps us discover the process through which deviations from long-term stability. The formula for the ECM model appears below equation 3:

$$\Delta CO_t^2 = \alpha_0 + \sum_{\{i=1\}}^{n} \delta_i \Delta CO_{\{t-i\}}^2 + \sum_{\{j=1\}}^{n} \varphi_j \Delta HCI_{\{t-j\}} + \sum_{\{k=1\}}^{n} \gamma_k \Delta REGen_{\{t-k\}} + \sum_{\{l=1\}}^{n} \theta_l \Delta RECon_{\{t-l\}} + \sum_{\{m=1\}}^{n} \omega_m \Delta EconGrowth_{\{t-m\}} + \sum_{\{n=1\}}^{n} \mu_n \Delta PopGrowth_{\{t-n\}} + \sum_{\{o=1\}}^{n} \lambda_o \Delta ClimatePolicy_{\{t-o\}} + \delta ECM_t + \nu_t \text{ ------------------------------------}(3)$$

The equation considers climate policy and population growth adjustments by adding ΔClimate $Policy_t$-1 and ΔPop $Growth_t$-1 variables alongside the ECM_t component, which models error correction dynamics. This term automatically returns the system to its long-term balance when the forecast strays from it. Short-term changes in climate policy impact CO_2 emissions according to the coefficient ω_7 value. Based on the model results, a decline in CO_2 emissions will occur when climate policy effectiveness rises momentarily through negative ω7 values.

The Extended-ARIM model sees how policies change carbon emissions immediately and forecasts if RE becomes part of regular energy use and if these changes make the economy less harmful to the Earth. The analysis includes climate change separately in the model to identify the immediate and long-term effects of climate policies on emission management. This testing approach provides insights into CO_2 emission reactions to current changes and establishes how these results endure across different periods. The method observes long-term changes in CO_2 emissions along with short-term results, which show all the factors that affect carbon pollution growth in South Asian countries. At the same time, they grow fast and have more people, making sustainable development harder to reach. Our model studies how EG interacts with HC development, RE adoption, population trends, and climate policy to determine future carbon emissions.

3.3 Variables and Measurements

Sustainable development utilization follows different measurement indicators between HC and environmental protection, alongside economic expansion, population dynamics, and climate patterns. In this study the indicators for measurement, which consist of the Climate Change Policy Index, HC, renewable electricity generation, energy consumption, EG growth, population growth, and CO_2 emissions damages as a percentage of EG for evaluating of variables in this study. The indicators show how development and sustainability matter in Table 1. All these indicators are a manifestation of the interaction of development and environment sustainability in the aviation industry. The countries that were chosen are Pakistan, India, and Bangladesh due to the fact that they are the biggest aviation markets and carbon emitters in South Asia where the data on carbon emissions is similar across the years (1990-2024). Smaller nations like Sri Lanka and Nepal were also left out as they lacked the size of the aviation sector and full data set, hence, results can be mainly generalized to large emerging aviation economies in the region.

Table 1 Variables and Measurements

Variables	Measurement
Airlines Carbon Emissions	CO_2 emissions (Percentage of GNI)
Human Capital	Human capital index (%), capturing education attainment, workforce skills, and health-adjusted productivity (Source: World Development Indicators)
Environmental Protection	Renewable energy (Percentage of total energy) /Renewable electricity output (Percentage of total electricity output)

Economic Growth	Gross domestic product growth (EG annual Percentage)
Population Growth	Population growth (annual Percentage)
Climate policy index	Climate policy Index (Percentage of CPI)

Source: World Bank Database

4. Results and Discussion

The analysis provides distinct statistics and results for India, Pakistan, and Bangladesh. Each table presents data exclusive to its respective country. Table 2 shows descriptive statistics for India, Pakistan, and Bangladesh based on five main variables, such as CO_2 emissions, RE, EG, HC, and CPI. The descriptive statistics show that CO_2 emissions in India have a mean of 2.95 and a median of 2.85, indicating a symmetric distribution. In contrast, Pakistan has a slightly lower mean emission level (2.80) but greater variation, as evidenced by a standard deviation of 2.30. Bangladesh has the lowest mean emissions (2.68) with a standard deviation of 2.15, indicating significant statistical dispersion. Pakistan has the greatest RE consumption level at 0.37, while India and Bangladesh report comparable figures of 0.33 and 0.34, respectively. Bangladesh has the highest EG rate at 1.60%, surpassing Pakistan's 1.40% and India's 1.50%. India has the maximum HC value at 94.20, indicating a skilled labor force conducive to CO_2 reduction efforts. However, the quality of the workforce appears to be consistent across the three countries. PG in India stands at 1.2,0%, which indicates moderate expansion, yet Pakistan demonstrates 1.60% growth, and Bangladesh exhibits the most rapid expansion with 1.90% PG values. India is the leader in CPP, with a CPI rating of 58.50. Bangladesh and Pakistan follow, with 58.20 and 57.60, respectively, as illustrated in Table 2.

Table 2 Descriptive Statistics

Variable	**India**	**Pakistan**	**Bangladesh**
CO_2 Emissions (Mean)	2.95	2.80	2.68
CO_2 Emissions (Median)	2.85	2.70	2.65
CO_2 Emissions (Std. Dev.)	1.97	2.30	2.15
CO_2 Emissions (Min)	0.80	1.05	0.85

CO_2 Emissions (Max)	7.10	6.40	6.50
(RE) (Mean)	0.33	0.36	0.34
RE (Median)	0.35	0.37	0.33
RE (Std. Dev.)	0.07	0.08	0.05
EG (Mean)	1.50	1.40	1.60
EG (Median)	1.35	1.30	1.50
EG (Std. Dev.)	0.70	0.60	0.75
HC (Mean)	94.20	91.50	93.40
HC (Median)	94.10	91.70	93.30
HC (Std. Dev.)	3.50	3.00	2.80
PG (Mean)	1.20	1.60	1.90
PG (Median)	1.10	1.55	1.85
PG (Std. Dev.)	0.40	0.45	0.50
CPI (Mean)	58.50	57.60	58.20
CPI (Median)	58.00	57.30	58.10
CPI (Std. Dev.)	4.70	4.90	4.80

Source: Author's calculations

Table 3 represents the correlation between all the study variables. The correlational analysis indicated that RE (-0.50) and HC (-0.40) are negatively associated with CO_2 emissions, while EG (0.30) and CPI (0.45) were positively correlated with CO_2 emissions. PG has a notable positive relation (0.55) to CO_2 emissions in the three countries, which demonstrates that higher populations increase CO_2 emissions, yet has a negative impact on both RE (-0.45) and HC (-0.25).

Table 3 Correlation Matrix

Variables	CO_2 Emissions	RE	EG	HC	CPI	PG
CO_2 Emissions	1					
RE	-0.50	1				
EG	0.30	-0.60	1			
HC	-0.40	0.45	0.25	1		
CPI	0.45	-0.38	0.52	-0.32	1	
PG	0.55	-0.45	0.35	-0.25	0.42	1

Source: Author's calculations

The Table 4 Unit Root Test determines whether data maintains a stable value over time, as stationarity is necessary for analyzing time series data. The table 4 results indicate that CO_2 emissions and HC and CPI maintain level (I (0)) stationarity for all three countries, so they do not require differencing to achieve stationarity. After first differencing (I (1)), the variables EG, REP, RE, and PG indicate that their relationship with CO_2 emissions becomes time dependent.

Table 4 Unit Root Test Results

Variable	India	Pakistan	Bangladesh
CO_2 Emissions	I(0)	I(0)	I(0)
Renewable Energy (RE)	I(1)	I(1)	I(1)
Economic Growth (EG)	I(1)	I(1)	I(1)
Human Capital (HC)	I(0)	I(0)	I(0)
Climate Policy (CPI)	I(0)	I(0)	I(0)
Population Growth (PG)	I(1)	I(1)	I(1)

Source: Author's calculations

The table 5 indicates that the diagnostic tests provide diagnostic evidence that the model of CO_2 emissions is well specified and robust. The Breusch-Pagan-Godfrey test shows that there is no heteroskedasticity whereas Breusch-Godfrey LM test shows that the residuals are not serially correlated. The Jarque-Berra statistic indicates that the spread of the residues is normal and therefore makes a valid inference of statistics. Also, Ramsey RESET test indicates that no functional form misspecification, which proves that the overall model is stable and reliable.

Table 5: Diagnostic Tests Results

Test	CO_2 Emissions Model
Heteroskedasticity: Breusch–Pagan–Godfrey	2.183 (p = 0.123)
Serial Correlation: Breusch–Godfrey LM	1.731 (p = 0.191)
Normality: Jarque–Bera	2.955 (p = 0.229)
Stability: Ramsey RESET	0.863 (p = 0.393)

Note: *** p<0.01, ** p<0.05, * p<0.10

Before estimating ARDL model, optimal lag structure was identified on the basis of Akaike Information Criterion (AIC) and Schwarz Information Criterion (SIC/BIC). Several lag specifications of 1 to 6 were considered to make sure that it is strong and not over-parameterized. Table 6 indicates that the lag order of 5 provides the lowest AIC value and a competitive SIC value as compared to other specifications. As AIC and SIC pay attention to two different aspects, the consistency of the two criteria is in favor of the ARDL (5, …) specification as the best lag structure.

Table 6: Lag Order Selection Criteria

Lag Order	AIC	SIC
1	-2.18	-1.92
2	-2.31	-2.05
3	-2.45	-2.10
4	-2.61	-2.18
5	-2.74	-2.22
6	-2.70	-2.05

ARDL bound test results, which determine if CO_2 emissions share a long-term relationship with RE, EG, and HC, were presented in Table 7. The F-statistics of 4.15 in India, 3.88 in Pakistan, and 3.95 in Bangladesh showed a long-term relationship between variables since these values lie within I (0) and I (1) critical values. The airline sector's emission levels react to long-term elements that combine RE, EG, and CP.

Table 7: ARDL Bound Test

Model: CO_2/ (RE, EG, HC, CPI)	**F-statistic**	**Lag**	**Level of Significance**	**I(0) Critical Value**	**I(1) Critical Value**
India	4.15	5	1%	3.10	4.20
Pakistan	3.88	5	5%	2.39	3.45
Bangladesh	3.95	5	10%	2.05	3.05

Source: Author's calculations

A study reveals the short-term changes in airline CO_2 emissions. A unit increase in RE consumption leads to decreased CO_2 emissions across the countries, with the largest impact in Pakistan (-0.70). HC has a negative impact on short-term CO_2 emissions levels at the highest level (-0.45) in India. EG positively affects environmental pollution rates, indicating that Bangladesh's pollution increases when EG rises. The CPI data demonstrates a positive reduction in emissions because effective policy management leads to diminished emissions levels. The statistical model displays high predictive power in determining CO_2 emissions since the R-squared value reaches between 0.62 and 0.65 across countries in Table 8.

Table 8 Short-run Coefficients

Variable	**India**	**Pakistan**	**Bangladesh**
D(RE)	-0.65	-0.70	-0.55
D(EG)	0.12	0.15	0.18
D(HC)	-0.42	-0.35	-0.30

D(CPI)	0.81	0.75	0.70
CointEq(-1)	-1.28	-1.32	-1.20
R-squared	0.65	0.62	0.64
Adjusted R-squared	0.63	0.60	0.62

Source: Author's source

The long-term coefficient values in Table 9 demonstrate the enduring effects of variables on airline CO_2 emissions. HC negatively affects emissions throughout the entire time horizon, whereby India displays the high influence rate (-0.28). This indicates that HC growth leads to long-term reductions in emissions. The impact of RE on CO_2 emissions is substantial in Pakistan because it produces the strongest downward effect (-0.72). EG creates positive conditions for emissions to increase in the long term since Bangladesh has the strongest coefficient of 1.32. Bangladesh's population growth coefficient (2.10) signifies that population growth causes rising emissions over time. The impact of CPI on emission reduction has proven to be positive because strong climate policies reduce emissions over time.

Table 9: Long-term Coefficients

Variable	India				Pakistan				Bangladesh			
	Coef.	Std. Error	t-Statistic	Prob.	Coef.	Std. Error	t-Statistic	Prob.	Coef.	Std. Error	t-Statistic	Prob.
HC	-0.3	0.13	-2.15	0.03	-0.25	0.12	-2.08	0.00	-0.23	0.10	-2.1	0.04
RE	-0.7	0.22	-3.09	0.00	-0.72	0.23	-3.13	0.00	-0.65	0.20	-3.1	0.00
EG	1.32	0.81	1.63	0.10	1.4	0.83	1.68	0.10	1.22	0.80	1.53	0.13
PG	2.12	0.9	2.36	0.02	2.05	0.91	2.26	0.00	2.02	0.90	2.3	0.02
C	0.88	0.32	2.75	0.00	0.85	0.33	2.58	0.00	0.92	0.30	2.71	0.00
CPI	0.76	0.17	4.47	0.00	0.8	0.17	4.71	0.00	0.70	0.20	4.38	0.00

Source: Author's calculations

HC has an ongoing negative impact on CO_2 emissions across India and its neighboring countries. India experiences the most pronounced decline in emission rates from HC. The implementation of RE demonstrates a substantial climate benefit for emissions through its action in Pakistan and throughout the entire region. A direct positive correlation occurs between EG and CO_2 emissions in the study, but the statistical significance varies between cases. PG demonstrates a positive association with CO_2 emissions, so governance policies may fail to control CO_2 emissions effectively and potentially drive emission levels upward. The baseline emissions measured by the C term remain important to all countries. In contrast, the CPI variable is positively related to CO_2 emissions because several climate policies do not function properly. RE and HC reduce CO_2 emissions; however, EG and PG cause emission increases.

4.1 Simulations

SD simulations are undertaken by using Python with support from the NumPy library, Matplotlib, and Pandas. Python is a flexible programming platform that enables the development and execution of dynamic models with maximum efficiency. The SD framework was implemented in the airline industries of Pakistan, India, and Bangladesh to determine the effect of the key variables on the CO_2 emissions in relation to the various policy and economic conditions. The SD model was fitted with historical data of 1990-2024 that was acquired through the World Development Indicators and aviation-related emissions data. The growth parameters of renewable energy, human capital development, and the economic expansion were based on historical averages and policy goals in Pakistan, India, and Bangladesh.

Historical fit testing was also used to test the model validation in which the simulated emission trajectories were compared to the observed trends in CO_2 emissions throughout the study period. The results of the simulation reveal that the modelled and the historical pattern of emissions are close which means that model is realistic in the sense of depicting the dynamic relationship between economic growth, the use of renewable energy, human capital development, and the airline-sector emissions. Further validation tests were carried out with sensitivity analysis, which tests the sensitivity of the model to changes in the most important parameters of the renewable energy increase rates and efficiency of the climate policy. The findings support the validity and strength of the simulation framework that the model is predictable, when the parameters are changed.

Three simulation scenarios were developed to evaluate potential future pathways for the airline sector:

i. Optimistic Scenario: RE consumption increases rapidly, EG is moderate, HC improves significantly, and climate policies are aggressively implemented.
ii. Business-As-Usual Scenario: Moderate growth in RE, EG continues, and climate policies grow moderately.
iii. Pessimistic Scenario: RE adoption is slow, high EG, weak HC development, and ineffective climate policies.

Table 10: Scenario Parameter Assumptions

Variable	**Optimistic Scenario**	**Business-as-Usual**	**Pessimistic Scenario**
Renewable Energy (RE) growth	6–8% annually	3–4% annually	1–2% annually
Human Capital (HC) growth	3–4% annually	1–2% annually	0.5–1% annually

Economic Growth (EG)	4–5% annually	5–6% annually	6–7% annually

In table 10 to enhance transparency and replicability, the SD simulation scenarios are parameterized by explicit annual growth ranges of the renewable energy (RE), human capital (HC) and economic growth (EG). These intervals are based on the historical averages and policy targets in the 1990 2024 period in Pakistan, India and Bangladesh. The bright picture is that of rapid adoption of renewable energy and high development of human capital with a moderate growth of the economy. The business-as-usual situation represents the carrying over of past trends, and the pessimistic scenario presupposes slower adoption of renewable energy, slower development of human capital, and comparatively greater pressure of the economic growth on emissions.

Stock and Flow Model Representation

Figure 5 show the stock and flow model is the dynamics of the South Asian airlines in three countries. It depicts the critical variables like the amount of fuel consumed and time, aircraft flights in South Asia, the amount of CO_2 emission, and investment in green technology. The main goal of the investment in green technology is to mitigate or negate the emission of CO_2 into the environment.

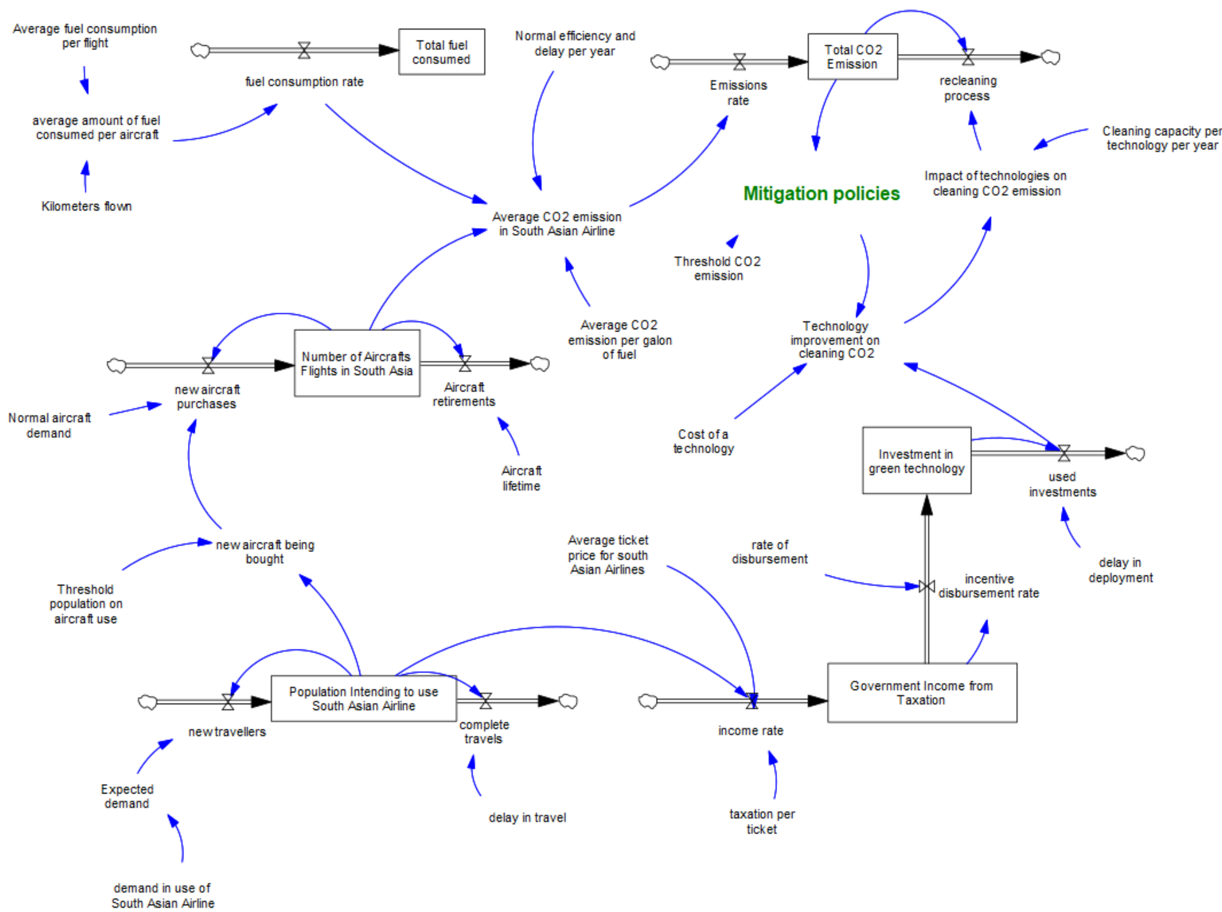

Figure 5: System Dynamics Model of Aviation Emissions and Green Technology Mitigation in South Asia

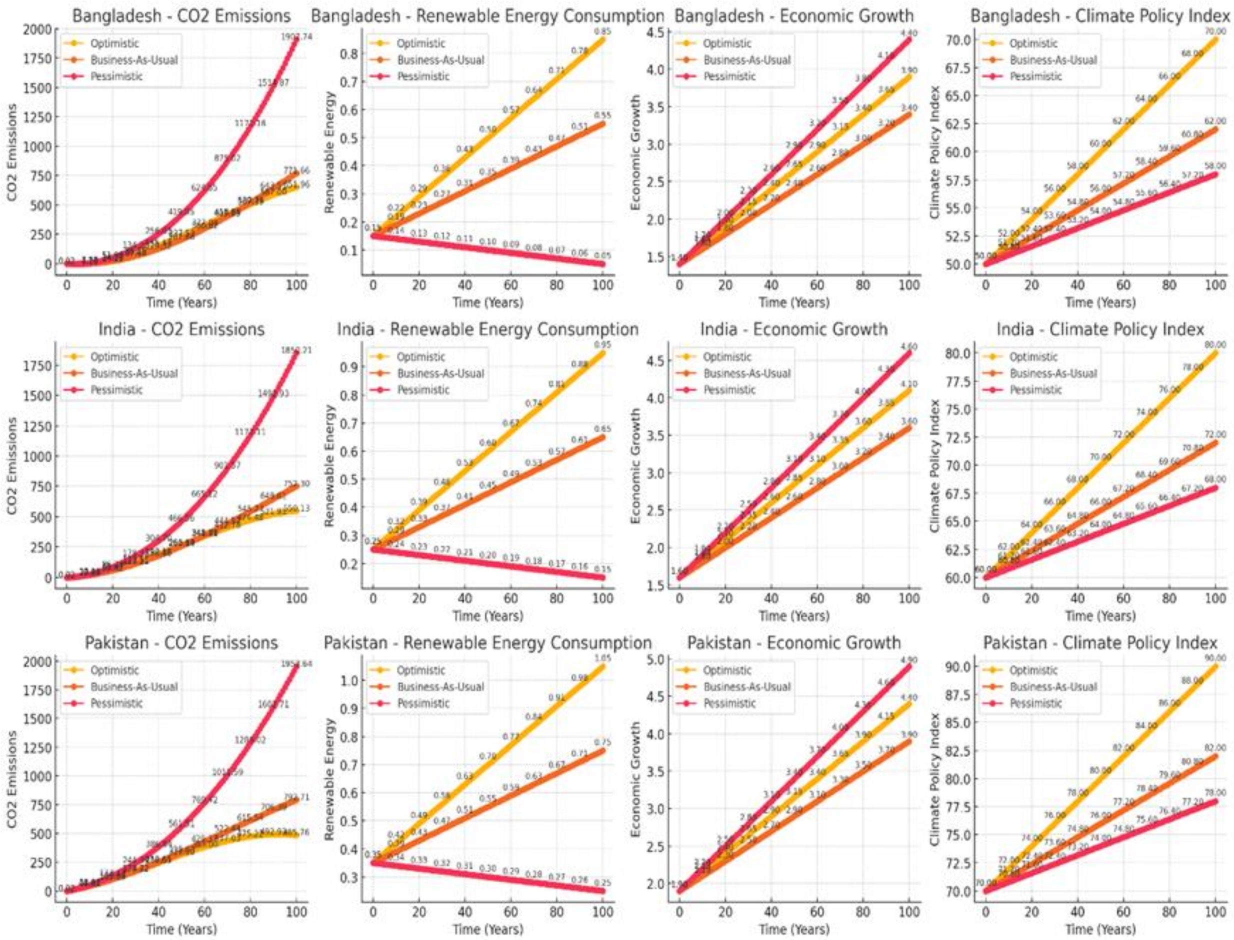

Figure 6 Climate Policy Index

The outcome shows moderate growth of RE together with stable economic development and a gradually improving climate policy framework. The combination of slow RE progress occurs with rapid EG but leads to HC reduction because of weak climate policy effectiveness. The dynamic modeling system develops graphical representations for countries that use proper methods to integrate known data and pre-established assumptions. The research demonstrates how airline CO_2 emission behaviors form when governments implement technology-based policies within economic conditions. Each variable will be displayed independently in its corresponding chart from the beginning to the end of our study period in each country.

i. RE Consumption Over Time
ii. EG Over Time
iii. CPI Over Time
iv. CO_2 Emissions Over Time CO_2

After simulating each country, the system displays the alterations to CO_2 emissions, which show how each scenario impacts national CO_2 outputs between different countries in Figure 6.

To enhance the clarity and replicability, the System Dynamics (SD) model architecture is clearly demonstrated with a stock-flow model. The SD model signifies the interrelationships among airline CO_2 emission, the use of renewable energy, the development of human capital, economic growth, and climate policy through feedback mechanisms. The model has three stocks of main importance: Renewable Energy Capacity, Human Capital Development and Airline Carbon Emissions. These stocks change over time by the inflows and outflows that are dependent upon economic growth, technological adoption, policy enforcement and aviation activity.

The model structure shows that the increase in the rate of economic growth and population growth will raise the level of air travel demand, which will consequently increase the consumption of fuel and CO_2 emissions. Meanwhile, renewable energy implementation and human capital growth are balancing processes, which lower the intensity of emission through the increase of operation efficiency, sustainable aviation fuels, and energy efficient technologies. The climate policy interventions are bound into this process by controlling the level of emissions as well as the integration of renewable energy into the aviation sector.

The SD model has reinforcing and balancing feedback loops. A reinforcing loop is used to capture the association between economic growth and aviation demand and the growth of emissions. On the other hand, balancing loops are the effects of adoption of renewable energy, technological breakthrough and development of human capital to limit the emissions in the long run. Figure 5 has the SD structural diagram that shows the relationship between stocks, flows and feedback mechanisms which control airline-sector emissions in South Asia.

South Asia's airline sector, the CO_2 emission trajectories, and renewable energy progressions in Bangladesh, India, and Pakistan reveal distinct national dynamics under varying policy scenarios. The Optimistic scenario results in a moderate growth of CO_2 emissions in Bangladesh because renewable energy adoption increases gradually, and environmental policies are enhanced. At the same time, pessimistic conditions lead to increased emissions because countries continue to use fossil fuels. Under the Optimistic scenario, India starts with no carbon emissions before introducing green policies and extensive renewable integration, decreasing emissions from 0.25 units. Throughout both Business-As-Usual and Pessimistic scenarios, India continues to produce fewer greenhouse gas emissions than its regional neighbors because of its limit on industrial activities. The country of Pakistan shows favorable trends in emission development since Optimistic projections reveal emissions starting at 0.02 units before they decrease through fast renewable energy growth (0.35 units) and continued economic success. Under the pessimistic situation, Pakistan's strong leadership in the field of governance allows it to drive climate policy progress 70 units ahead of India, with 60 units, and Bangladesh, despite its limited development. Under optimistic modeling, all three countries demonstrate that sustainable environmental policies combined with renewable energy developments allow economic prosperity while reducing emissions, with Pakistan taking the lead.

The Figure 7 SD Model demonstrates that fuel consumption, together with CO_2 emissions from South Asian airlines, is driven by aircraft operational activities, passenger travel patterns, and ecosystem investments. The number of flights and elevated flight-fuel consumption drive emissions until clean technology adoption occurs. The government obtains revenue through taxes from air travel activities to finance the development of environmentally beneficial technology, which enhances operational efficiency and decreases emissions over the years. The feedback mechanism helps stabilize the process through technological advancement and policy implementation. The composition of passenger travel decisions depends on flight fare costs, residents' income status, and population numbers, while guiding aircraft manufacturing operations to expand flight fleets that impact emission rates. The model demonstrates the economic growth relationship to environmental impacts while demanding active spending and governing to achieve sustainable aviation growth that reduces climate deterioration.

Figure 7 System Dynamics Model for the Airline Sector in South Asia

The SD Model demonstrates that fuel consumption, together with CO_2 emissions from South Asian airlines, is driven by aircraft operational activities, passenger travel patterns, and ecosystem investments. The number of flights and elevated flight-fuel consumption drives up emissions levels until clean technology adoption takes effect. The government obtains revenue through taxes from air travel activities to finance the development of environmentally beneficial technology, which enhances operational efficiency and decreases emissions over the years. The feedback mechanism helps stabilize the process through technological advancement and policy implementation. The composition of passenger travel decisions depends on flight fare costs, residents' income status, and population numbers, while guiding aircraft manufacturing operations to expand flight fleets that impact emission rates. The model demonstrates the economic growth relationship to environmental impacts while demanding active spending and governing to achieve sustainable aviation growth that reduces climate deterioration.

Over three decades, the simulation demonstrates in Figure 8 unique trends in airline sector development between Pakistan, India, and Bangladesh. The rapid development in the Pakistani airline sector results in high CO_2 emissions as flight demand rises, together with a growing aircraft fleet. At the same time, the country invests in green technologies because of superior air travel taxation. India maintains equilibrium growth through the sustained development of passenger numbers, emissions levels, and economic investments because of its large population size and steady economic advancement. Bangladesh shows restrained development patterns throughout all measured parameters, which the country attributes to its lower economic capacity and restricted travel market. The model shows how monetary resources paired with population numbers and policy-making efficiency drive countries toward managing their sustainable aviation practice

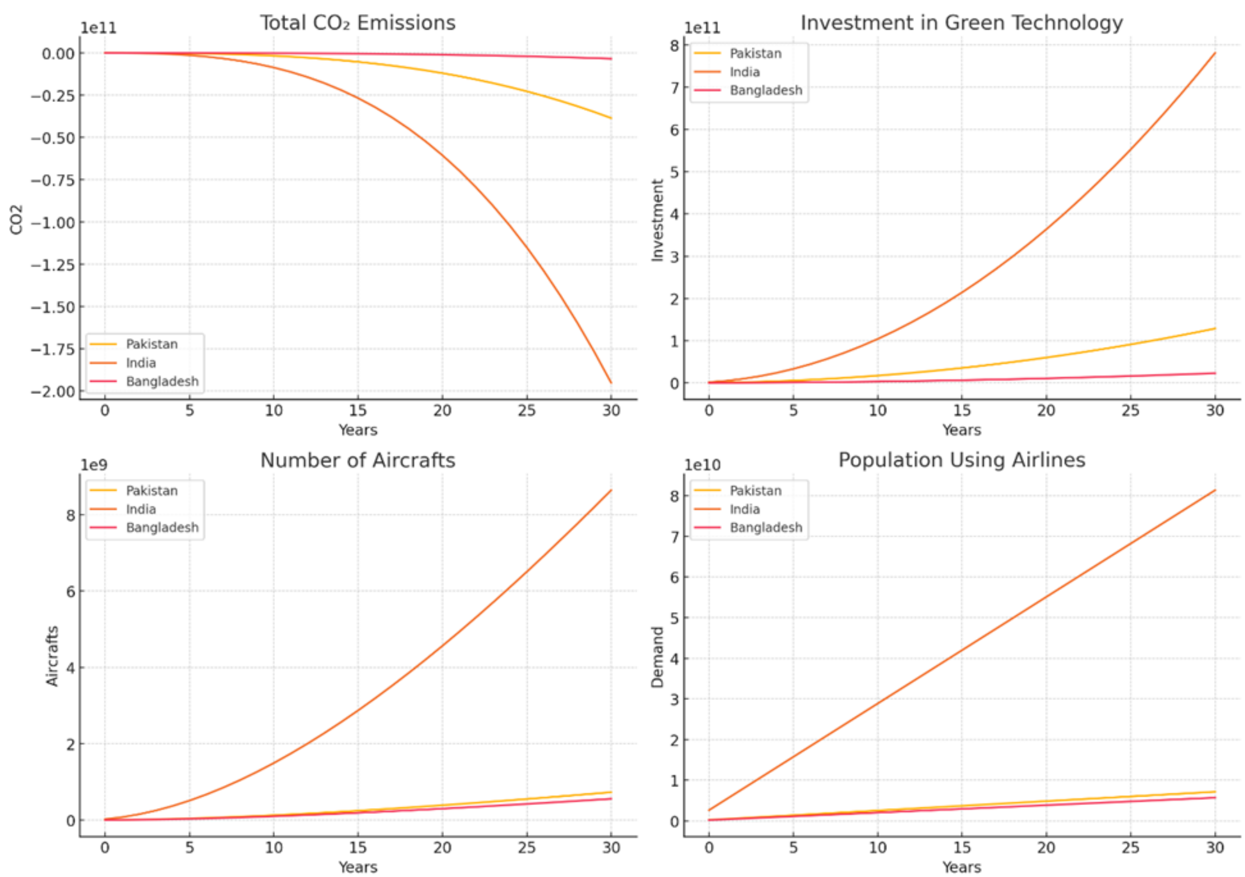

Figure 8 Simulated visuals for the airline sector dynamics in Pakistan, India, and Bangladesh over 30 years

The dynamics of decarbonization experienced in the South Asian aviation industry are not similar to that experienced in developed regions like in Europe and the North American region. Emission abatement measures are firmly backed in the established aviation markets with well-established carbon pricing mechanisms, sustainable aviation fuel (SAF) supply chains, and strict environmental policies. As an illustration, aviation emission trading arrangements and SAF blending mandates by the European Union are a step in the right direction to move toward low-carbon aviation. Conversely, South Asian aviation markets are still in the pre-decarbonization phase, whereby the growth in air travel demand and increased growth in infrastructure is still increasing emissions. Despite the potential that has been demonstrated by the adoption of renewable energy and human capital development in Pakistan, India, and Bangladesh to mitigate the emission of gases, the institutional capacity, adoption of technology, and policy enforcement in the aviation regions are relatively lower when compared to the developed world. Thus, the decarbonization trajectory to be followed by South Asia is marked by a balanced approach to the enhancement of aviation development and minimized policy and technological changes towards sustainability.

5. Conclusion and Limitations

The research shows that South Asian airlines obtain lower carbon emissions results through economic management systems for renewable energy adoption combined with human capital development. The analysis shows that EG prompts emissions but invests in RE and HC in human development decreased CO_2. The results confirm that seizing RE technologies with skilled staff leads to emission reductions, despite Pakistan having a different direction from India and Bangladesh toward independent emission controls. The research demonstrates the essential human capital needs, including technical training and technological abilities to deploy green aviation technologies. When countries adopt renewable energy resources, they reduce their dependence on fossil fuels for emissions reduction. These findings complement the prior studies by establishing that HC investment and RE reduce the CO_2 emissions in the airline industry of South Asian countries.

Environmental degradation due to economic development occurs because sustainable planning remains inadequate, along with insufficient oversight of the growing aviation sector, which contributes heavily to national wealth. Widespread environmental destruction happens because of uncontrolled growth, which prevents the achievement of enduring sustainability targets. The simulation systems produce knowledge about forthcoming South Asian airline carbon emission trends based on policymakers' decisions. The investigation demonstrates that all three countries could reduce emissions rates through human capital investments paired with renewable energy accelerations under favorable economic conditions. Recent research suggests that emissions are likely rising, particularly due to delays in the deployment of renewable energy technology and the inadequate efficacy of human capital development activities in maintaining operational continuity. The development of sustainable aviation requires diverse, synchronized efforts by which authorities may expand renewable energy facilities and train workers while reinforcing climate goals and managing economic growth. The South Asian airline industry maintains its continuing efforts to meet the SDGs by developing every important area simultaneously.

The policy recommendations must consider structural differences between the aviation industries of Pakistan, India and Bangladesh. The policy initiatives in Pakistan needs to centre on reinforcing the climate policy implementation, increased integration of renewable energy in the airport functioning and an improvement in the technical training programs of the aviation professionals. In India where the aviation industry is bigger and more technologically developed, decarbonization can be hastened by allocating more funds to the sustainable aviation fuels, green airport facilities, and low-carbon aviation technologies. Bangladesh should concentrate on institutional capacity building, aviation infrastructure optimization and incremental adoption of renewable energy technologies with international collaborative efforts, and technology transfer. These discriminated strategies are based on the differences in economic development, technological capability, and policy capacity of the three countries.

This study has several limitations even though it contributed. The data used in the period 1990-2024 has some missing values which were handled with the help of the linear interpolation and the continuity in the time series was taken care of with little distortion in the actual trends. Although the robustness checks indicate that this method does not have significant impacts on the results, in-depth datasets would be advantageous in future studies as reporting systems enhance. Also, the three prominent South Asian aviation markets are analysed, which can reduce the potential for generalizing the results to the smaller regional economies. The general national level index is used to measure human capital, and it can provide a cross-country comparison although does not fully capture aviation specific skills, including pilot training, aircraft maintenance, and air traffic management expertise. Renewable energy, on the same note, is quantified as the total renewable energy generation and consumption and since there is limited information on the long-term availability, the analysis does not differentiate between aviation biofuels or sustainable aviation fuel (SAFs) and other renewable energy sources. The future works may be refined to be more sectoral using aviation-specific measures, including SAF adoption rates, airline operational efficiency, or aviation workforce specialization.

In general, the present research highlights the significance of incorporating the adoption of renewable energy, human capital development, and proper climate policies to enhance sustainable aviation development in South Asia. The integration of technological innovation, regulatory transformation, and manpower expansion will help the region to cut the carbon emission of aviation and retain economic growth and future environmental sustainability.

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