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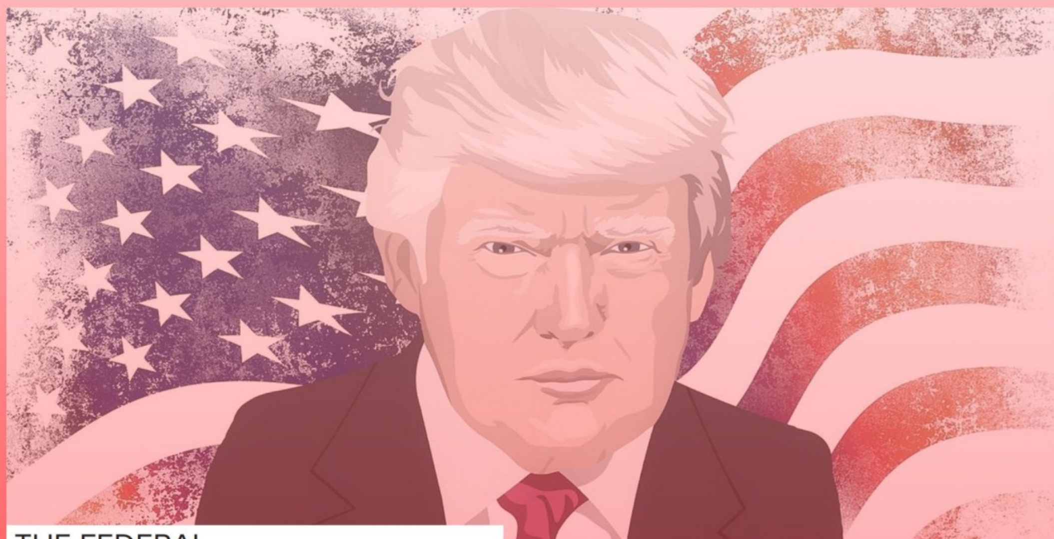

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Forecasting CO_2 Emissions from Libya's Transport Sector

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This paper presents an innovative approach to forecast carbon dioxide (CO_2) emissions from the transport sector in Libya. The method combines machine learning algorithms with historical data and future estimates. The research built a model that took into account factors such as population growth, rates of car ownership, patterns of fuel consumption and government regulations in order to provide an accurate forecast of carbon dioxide (CO_2) emissions over the next decade based on the Global Change Assessment Model (GCAM). The authors used a variety of statistical time series models to forecast future CO_2 emissions from Libya's transportation sector. These models included the exponential smoothing model (ESM) and the autoregressive integrated moving average (ARIMA). The ARIMA model outperformed the ESM model, achieving an R^2 of 0.931 and a root mean square error (RMSE) of 1.040 Mt CO_2. The results of the study found that CO_2 emissions from Libya's transport sector could increase by 27.98% and 57.99% in 2030 and 2050, respectively. The study proposed six transportation theories to reduce CO_2 emissions from Africa's and Libya's transport sectors. The identified factors encompass price systems, land use planning, eco-driving, electric automobiles, bicycle infrastructure, and telecommuting. The authors also examined the needs to reduce CO_2 emissions from Libya's transport sector in order to meet the International Energy Agency's ambitious targets for reducing CO_2 emissions from the global transport sector. These needs arise due to increasing urbanization, population growth, underinvestment in public transportation infrastructure, and the increasing incidence and severity of heat waves. Additionally, hypothetical scenarios are presented to demonstrate the importance of further reducing CO_2 emissions from these sectors to match the projections of global change assessment models.

Keywords: Paris Agreement; CO_2 emission reduction; Greenhouse gas emissions; Libya's emission reduction; Climate change; ARIMA

1. Introduction

To effectively tackle climate change and accomplish sustainable development goals in Libya, it is imperative to implement decisive measures aimed at decreasing carbon dioxide emissions in transportation systems across urban areas [1], developing towns [2], and distant villages [3]. By analyzing different policies and situations related to compliance with the Paris Agreement [4, 5], we can determine effective methods for reducing carbon emissions [6, 7] and improving sustainable transportation systems in Libya [8, 9]. This analysis can help us develop a comprehensive strategy that includes

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renewable energy sources [10], promotes public transportation [11], and encourages the adoption of electric vehicles [12]. The target of this research is to provide valuable insights into the challenges and opportunities for reducing carbon dioxide emissions in transportation networks [13] in Libya. By examining the outcomes of various policies and scenarios, we can provide evidence-based suggestions to policymakers [14, 15] and stakeholders to advance sustainable development in the nation. This study is intended to contribute to the global conversation on efforts to mitigate climate change [16] and highlight the importance of sustainable transportation in achieving emission reduction targets [17]. The target is to promote the use of cleaner and more efficient transportation options [18] in Libya, which can lead to significant environmental [19] and economic benefits for the country [20]. By analyzing data and studying different policy implementations, we can provide valuable insights into the most effective methods for reducing carbon emissions [21, 22] and promoting sustainable practices [23, 24]. This research will also facilitate the identification of potential issues and obstacles to the execution of these recommendations [25], empowering key decision-makers in the country to make more knowledgeable decisions [26]. This research serves as a strategic blueprint for future initiatives and financial investments in the transportation sector [27], guiding stakeholders towards the adoption of greener practices [28]. The target is to develop a transportation system that is environmentally friendly and extremely efficient, leading to benefits for both the economy and the environment [29]. By taking a proactive approach to reducing the impact of climate change in the transportation industry, we can work towards a more environmentally friendly future for future generations [30, 31].

The authors also discussed various transportation theories that support the reduction of CO_2 emissions from Libya's transportation sector, with the goal of achieving sustainable development objectives and reducing the continent's carbon footprint. Furthermore, authorities were recommended to prioritize expenditures in the infrastructure of public transportation [32] and promote the adoption of environmentally friendly technology in the area. The theories cover pricing mechanisms, land use planning, eco-driving, electric automobiles, bicycle infrastructure, and telecommuting. The target of these strategies is to reduce reliance on fossil fuels and promote the use of more environmentally friendly modes of transportation [33, 34]. Libya should endeavor to achieve a more ecologically sustainable future and make a significant contribution to global efforts aimed at reducing the impact of climate change by embracing these suggestions.

The transportation industry in Libya is a significant source of greenhouse gas emissions in Africa, making it a crucial obstacle to overcome in order to achieve sustainable development [35] and effectively address climate change [36]. Accurately predicting the amount of CO_2 emissions from this industry is crucial for policymakers and stakeholders to develop and implement successful plans [37] to decrease carbon footprints and encourage the use of cleaner [38] and more efficient transportation systems [39]. Accurate prediction of carbon dioxide (CO_2) emissions from Libya's transportation sector is essential for comprehending the environmental consequences of the country's fast urbanization [40], economic expansion [41,42], and the subsequent rise in vehicle ownership and usage [42, 43]. Through the application of sophisticated modeling approaches and data analysis [44], academics can offer valuable insights into prospective measures and policy interventions [45] to effectively address this urgent issue [46]. The intricate interaction of various elements that impact the release of CO_2 from Libya's transportation industry, such as the way fuel is consumed [47], developments in vehicle technology [48], and the development of infrastructure[49], highlights the significance of reliable forecasting techniques [50-52]. Through the integration of interdisciplinary methodologies and the utilization of state-of-the-art research instruments [53], scholars can produce practical insights to aid in the development of sustainable transportation strategies [54] and the achievement of carbon reduction goals in accordance with global climate agreements [55-57].

The ClimateWatch database's global change assessment model did not include carbon dioxide (CO_2) emissions from the transportation sector in Libya from 2023 to 2050. Therefore, the authors utilized a time series methodology to forecast the historical carbon dioxide (CO_2) emissions in Libya's transportation sector, covering the period from 1990 to 2022. Later on, these predictions were extended to cover the time frame from 2023 to 2050. By employing time series approaches, the authors achieved a more precise prediction of the trends and patterns in carbon dioxide (CO_2) emissions in Libya's transportation sector during the chosen timeframe. This approach was devised to address the deficiencies in prior research that overlooked the influence of transportation emissions on the total levels of carbon dioxide in Libya. In addition, the utilization of time series techniques facilitated a thorough examination of past data and predictions for the future, resulting in a stronger comprehension of the nation's carbon emissions in the transportation sector [58, 59]. The authors found that the anticipated result greatly exceeded the International Energy Agency's estimate of global CO_2 emissions in transportation by mode in the sustainable development scenario from 2022 to 2070 [60]. This study highlights the urgent need to adopt greener transportation practices in Libya to tackle the rising levels of carbon emissions. In order to attain a future that is more environmentally friendly, it is imperative to incorporate transportation emissions into future policy planning. The authors discussed several transportation theories and their practical implementations in order to address the necessary needs and strategies for reaching this purpose. A framework has been developed that advocates for the implementation of more efficient public transportation networks in order to reduce reliance on private vehicles. Furthermore, the research suggests dedicating resources to enhance the infrastructure for alternative modes of transportation [61, 62], such as cycling and walking [63], with the aim of substantially mitigating carbon emissions in Libya. In addition, the authors emphasized the importance of integrating sustainable urban design techniques to promote the growth of cities that are more favorable for walking and biking [64, 65]. By encouraging the use of active transportation and reducing dependence on cars, Libya has the capacity to significantly reduce its carbon emissions and improve air quality for its citizens [66-70]. The adoption of sustainable transportation alternatives can lead to various health benefits [71-74], such as increased physical activity [31, 75-77] and a reduced incidence of obesity and related diseases [73, 74, 78]. Investing in these projects can result in a favorable outcome for both the environment and public health in Libya.

2. Transportation Theories that Support the Mitigation of CO_2 Emissions from Libya's Transport Sector

2.1 The Theory of Pricing Mechanisms

The idea of pricing mechanisms proposes the adoption of policies (such as congestion pricing and carbon taxes) to encourage actions that result in reduced CO_2

emissions in Libya's transportation industry. Pricing mechanisms in transportation theory have a significant impact on consumer behavior and encourage the adoption of more environmentally friendly transportation options. Libya can efficiently decrease CO_2 emissions from its transportation sector and promote the adoption of environmentally friendly alternatives by introducing techniques like congestion pricing or carbon taxes. Implementing these pricing systems can internalize the external costs linked to carbon emissions, resulting in a more effective allocation of resources in the transportation sector. Moreover, they have the ability to encourage investment in cleaner technologies and infrastructure, ultimately leading to a more sustainable and environmentally conscious transportation system in Libya. Moreover, these pricing mechanisms have the possibility of creating income that may be redirected towards other sustainability projects within the transportation industry.

The adoption of congestion pricing or carbon taxes can have a significant impact on assisting Libya in attaining its environmental objectives and diminishing its carbon emissions. Through the implementation of these pricing mechanisms, Libya has the potential to mitigate traffic congestion and enhance air quality in metropolitan areas. This can result in improved public health and a more streamlined transportation system as a whole. Furthermore, the income derived from congestion pricing or carbon taxes might be used towards enhancing public transit infrastructure and encouraging the adoption of electric vehicles. This can additionally contribute to the reduction of greenhouse gas emissions and the promotion of a more environmentally friendly atmosphere in Libya. In general, introducing these pricing mechanisms can have positive effects on both the environment and the well-being of Libyan residents. This is a progressive measure aimed at fostering a sustainable and environmentally conscious future for the nation.

2.2 The Theory of Land Use Planning

The notion of land use planning prioritizes the design of cities and communities to minimize the necessity for extensive travel, thereby reducing carbon emissions resulting from transportation. Land use planning is essential in determining the transportation infrastructure of a nation, which has a direct influence on the levels of CO_2 emissions. Urban planners can effectively mitigate CO_2 emissions in Libya's transport sector by carefully positioning residential neighborhoods, commercial centers, and public transportation hubs. This approach reduces the necessity for long journeys and encourages the use of sustainable means of transportation. Incorporating green spaces and pedestrian-friendly features into urban planning can promote walking and cycling as alternate forms of transportation, thereby reducing dependence on carbon-intensive vehicles. Moreover, allocating funds towards sustainable energy sources for public transportation and enacting laws that encourage the adoption of electric vehicles can have a substantial impact on mitigating CO_2 emissions in Libya's transportation industry. In order to effectively tackle the carbon emissions caused by transportation systems in the country, it is essential to adopt a comprehensive approach to urban design that places a high value on sustainability and environmental conservation. By incorporating green spaces and pedestrian-friendly infrastructure into urban design, communities may establish more sustainable and healthier environments for their inhabitants. Advocating for mixed land use development can decrease the necessity for lengthy commutes and enhance the overall efficiency of the transportation system. This can result in a reduction in dependence on private automobiles and, thus, a decrease in emissions. Enforcing laws that provide incentives for using public transportation and non-motorized modes of travel can also have a substantial impact on reaching carbon neutrality in Libya's transportation industry.

2.3 The Theory of Eco-Driving

The theory of eco-driving posits that advocating for fuel-efficient driving practices, such as maintaining consistent speeds and refraining from excessive idling, can contribute to the mitigation of CO_2 emissions from vehicles in Libya. The concept of eco-driving focuses on employing driving strategies that minimize fuel consumption and emissions, including gradual acceleration and maintaining a consistent speed. By integrating eco-driving principles into transportation regulations in Libya, the nation can substantially reduce its carbon emissions and make a meaningful contribution to global initiatives aimed at mitigating climate change. This idea is in accordance with the overarching objective of sustainability in transportation, advocating for a more effective and eco-friendly approach to driving. Adopting eco-driving techniques can result in financial benefits for both individuals and organizations through the reduction of fuel usage, thereby leading to cost savings. Moreover, implementing eco-driving techniques can also prolong the durability of cars and diminish maintenance expenses, leading to supplementary financial advantages for drivers and fleet operators. Incorporating eco-driving concepts into transportation laws in Libya can have extensive beneficial effects on both the environment and the economy. Libya may further diminish its carbon footprint and decrease its reliance on fossil fuels by promoting the utilization of public transit, carpooling, and electric automobiles. Allocating resources towards the development of infrastructure for alternative modes of transportation, such as dedicated lanes for bicycles and designated pathways for pedestrians, can additionally enhance the sustainability of the transportation system within the country.

2.4 The Theory of Electric Vehicles

The theory of electric vehicles, which advocates for the utilization of low-emission cars propelled by electricity, plays a vital role in mitigating the carbon footprint of Libya's transportation industry. Electric vehicles offer a possible approach for mitigating carbon emissions in Libya's transportation sector, as they are devoid of any exhaust emissions. By integrating electric vehicles into Libya's transportation infrastructure, the country can make progress towards its environmental objectives and decrease its carbon emissions. Moreover, allocating funds towards renewable energy sources to fuel these cars can additionally bolster the sustainability of the transportation industry in the nation. The adoption of electric vehicles can also aid in mitigating air pollution and enhancing public health in Libya. It is imperative for the government to provide incentives for the adoption of electric vehicles and allocate resources to develop the required infrastructure to facilitate their broad usage. By advocating for the adoption of electric vehicles, Libya may both diminish its reliance on imported fossil fuels and enhance its energy security. Enacting regulations that promote the shift to electric transportation will have dual advantages: it will not only have a positive impact on the environment but also stimulate economic growth by generating employment opportunities and fostering technological advancements. Moreover, the act of investing in electric vehicles can assist Libya in broadening its economic base and diminishing its susceptibility to variations in worldwide oil prices. Through the adoption of sustainable mobility solutions, Libya has the potential to establish itself as a frontrunner in the area and entice investments in clean energy technologies.

2.5 The Theory of Cycling Infrastructure

The theory of cycling infrastructure proposes the construction of more bike lanes and trails to promote cycling as a means of transportation. The theory of cycling infrastructure highlights the need to establish secure and easily reachable routes for bicycles. This can lead to a reduction in the dependence on motor vehicles and, thus, a drop in carbon emissions. By integrating cycling infrastructure into transportation planning in Libya, the country may strive towards attaining its environmental objectives while simultaneously advocating for a healthier and more sustainable means of transportation for its population. The adoption of bike infrastructure can enhance public health by promoting physical activity and mitigating air pollution in metropolitan regions. Moreover, allocating resources to develop bicycle infrastructure might result in economic advantages by attracting more tourists and generating employment opportunities within the cycling sector. Integrating cycling infrastructure into transportation planning in Libya can have numerous positive effects on the environment and public health. By giving priority to sustainable modes of transportation, the country can lay the foundation for a future that is both cleaner and healthier for its population. In addition, advocating for cycling as a feasible means of transportation can effectively alleviate traffic congestion and diminish the dependence on fossil fuels, thereby fostering a more sustainable and eco-conscious society. Highlighting the significance of bicycle infrastructure can help promote a sense of community and connectivity among locals, ultimately improving the overall quality of life in Libya.

2.6 The Theory of Telecommuting

The theory of telecommuting, which advocates for working from home or remote areas to reduce the number of individuals commuting to work on a daily basis, has the potential to greatly diminish the carbon footprint of Libya's transport sector by reducing dependence on conventional transportation systems. Telecommuting is a transportation concept that provides a sustainable alternative for reducing Libya's transport sector's carbon footprint by reducing the requirement for daily travel. Enabling employees to work remotely reduces the number of vehicles on the road, leading to decreased CO_2 emissions and alleviating traffic congestion. This strategy is in line with international endeavors to address climate change and advance eco-friendly practices in the workplace. Furthermore, telecommuting can result in cost savings for both employees and businesses by minimizing gasoline usage and car maintenance expenses. Incorporating telecommuting into transportation strategies in Libya can yield favorable environmental outcomes and contribute to a more sustainable future. Additionally, remote work can enhance the equilibrium between work and personal life for employees, as it grants them greater autonomy in time management and alleviates the strain of commuting. Moreover, telecommuting has the potential to enhance productivity and boost employee happiness, resulting in a more effective and committed team.

Telecommuting can enhance firms' ability to attract and retain highly skilled individuals by providing them with flexible work arrangements. This can lead to a staff that is more diversified and skilled, ultimately benefiting the firm as a whole. Furthermore, telecommuting can mitigate the environmental impact of firms by diminishing the necessity for employees to travel to a brick-and-mortar office. This can facilitate the creation of a more environmentally friendly ecosystem and aid in the mitigation of climate change. Moreover, telecommuting can result in cost savings for both individuals and businesses by reducing expenses associated with commutes, office space, and utilities. Telecommuting provides a range of advantages for both workers and companies, including enhanced efficiency, better equilibrium between work and personal life, and a decreased environmental footprint. It is a mutually beneficial scenario that can result in a more effective and environmentally friendly approach to work in the contemporary world.

3. Forecasting CO_2 Emissions from Libya's Transport Sector

3.1 Data

The ClimateWatch database employed the Global Change Assessment Model (GCAM) to examine past patterns and forecast future emissions under different scenarios. The model considers variables such as population growth, economic progress, and energy usage to generate a thorough prediction of carbon dioxide emissions in Libya's transportation industry. The GCAM model incorporates governmental interventions and technical breakthroughs that have the potential to influence future emissions. This comprehensive approach aids in generating a more precise and intricate forecast of Libya's transportation carbon dioxide emissions. By utilizing a data-driven methodology, it becomes possible to produce more precise forecasts regarding future emissions. This, in turn, enables policymakers to make well-informed choices in order to reduce the impact of transportation on climate change. The GCAM model provides a comprehensive perspective on the various elements that impact CO_2 emissions in Libya's transportation sector by taking into account different variables. The utilization of the GCAM model allows for a thorough examination of possible approaches to decrease emissions and enhance sustainability in the transportation industry. Adopting a data-driven approach is crucial in formulating strategies that effectively tackle the difficulties posed by climate change in Libya.

3.2 Method of Forecast

To forecast Libya's transportation CO_2 emissions from 2022 to 2050, we will utilize an autoregressive integrated moving average (ARIMA) model and an exponential smoothing model (ESM). These models will examine historical data and detect patterns in order to make accurate forecasts. These models will utilize historical patterns and changes in the data to forecast future emissions. By utilizing these two models, researchers can enhance their comprehension of the elements that impact CO_2 emissions in Libya's transportation sector and make well-informed choices regarding prospective mitigation strategies. The utilization of data in this way will offer significant and meaningful information for policymakers and stakeholders that aim to tackle environmental issues in the area. The exponential smoothing model (ESM) is a widely used technique in time series analysis that predicts future values by assigning decreasing weights to prior observations in an exponential manner. The ESM is highly effective in capturing transient trends and seasonal patterns in the data, rendering it a promising instrument for forecasting transport CO_2 emissions in Libya in the forthcoming decades. By employing the ESM, policymakers and academics can make well-informed judgments about the implementation of initiatives aimed at reducing carbon emissions and mitigating environmental impacts. This forecasting methodology enables a more precise estimation of future patterns in carbon dioxide emissions connected to transportation, thus assisting in the formulation of sustainable policies for Libya's transportation industry. The autoregressive integrated moving average (ARIMA) model will also be used to find the linear relationship between past and present data points in order to make forecasts more accurate. Both models are extensively utilized in forecasting and have demonstrated their efficacy in capturing intricate patterns in time series data. To enhance the model's robustness, the authors integrates the advantages of ARIMA and ESM, leading to a more reliable and precise forecast of future emissions levels. This hybrid technique utilizes the advantages of both models to offer a more thorough examination of the data and enhance the precision of forecasts. The authors' objective is to enhance the reliability of future emissions level forecasts by integrating these two methodologies. The literature provides comprehensive information on the ARIMA model and its hybridization approach [9, 35, 38-40, 51, 52, 79, 80]. To fully understand how well this method works at predicting emissions levels, you need to know a lot about the specifics of the hybridization process, like how to choose parameters and evaluate models. Researchers wishing to use this hybrid model should consult these studies for a thorough manual on its implementation.

3.3 Performance of the Forecast

The carbon dioxide emissions from transportation in Libya exhibit a consistent and direct correlation over the period from 1990 to 2020, as illustrated in Figure 1. Based on Figure 1, the coefficient of determination (R^2) was 0.886%. This suggests that 88.6% of the variability in carbon dioxide emissions from transportation in Libya can be accounted for by the linear correlation found between 1990 and 2020. The high R^2 value indicates a robust link between the years and CO_2 emissions in the transportation sector. This association has the potential to be valuable in forecasting future patterns of carbon dioxide (CO_2) emissions from transportation in Libya. In addition, a more in-depth investigation could investigate the underlying reasons influencing this correlation and propose measures to mitigate emissions. Overall, this illustrates a persistent pattern in carbon dioxide emissions from transportation during the previous thirty years. Policymakers must take into account this correlation when developing initiatives to mitigate carbon emissions in the transportation sector. Comprehending the historical trend of carbon dioxide (CO_2) emissions in transportation can provide valuable insights for making informed decisions regarding sustainable development strategies. Policymakers in Libya can establish focused actions to reduce the environmental impact of transportation activities by acknowledging the influence of previous trends.

The graph in Figure 2 illustrates the expected results of annual transportation CO_2 emissions in Libya, using the exponential smoothing model (ESM) and ARIMA time series models. Figure 2 clearly demonstrates that the ESM model exhibited a steady and linear rise in transportation CO_2 emissions between 2022 and 2050. Conversely, the ARIMA model exhibited a more intricate and non-linear trend of transportation CO_2 emissions during the identical time frame. The ESM model is better suited for forecasting slow and consistent changes in CO_2 emissions, whereas the ARIMA model is more adept at capturing fluctuations and anomalies in the data. Both models offer useful insights into potential patterns in transportation CO_2 emissions in Libya. The selection between the ESM and ARIMA models may depend on the distinct attributes of the data and the intended level of precision in predicting emissions. In precision analysis, error parameters are the only established measures for evaluating the accuracy of the models.

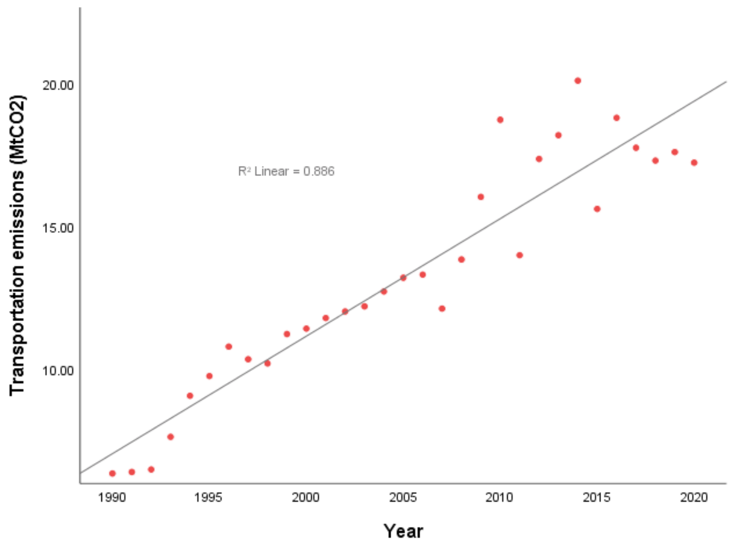

Fig. 1. Correlation between transportation emissions and year in Libya

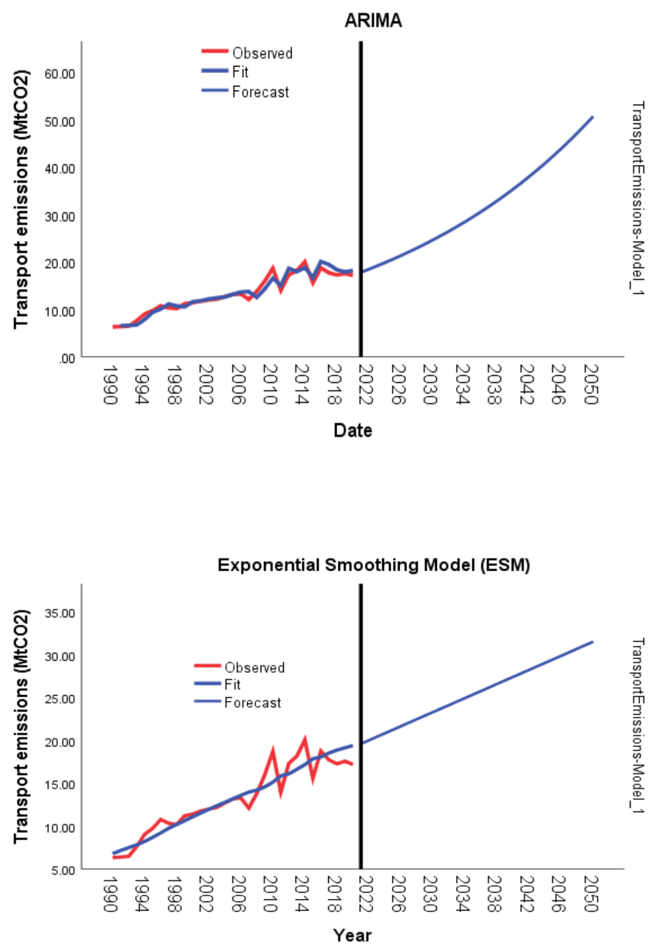

Fig. 2. Efficiency of Libya's time series models for predicting CO_2 emissions from transportation

The ARIMA model outperformed the ESM model according to the error metrics shown in Table 1, as it produced a higher R^2 value of 0.931 than the ESM model's R^2 value of 0.878, which was necessary for choosing the best fit models as shown in Table 2. The ESM model had an R^2 value of 0.878%, an RMSE value of 1.410 $MtCO_2e/yr$, a MAPE value of 7.627%, and a normalized BIC value of 0.909. The ARIMA model had a lower RMSE value of 1.040 $MtCO_2e/yr$, a MAPE value of 5.805%, and a normalized BIC value of 0.419, as shown in Table 2. In general, the ARIMA model exhibited better performance than the ESM model across several error metrics. This suggests that the ARIMA model would be better suited for accurately forecasting CO_2 emissions. In addition, the ARIMA model had a higher R^2 value of 0.931%, suggesting a superior fit to the data in comparison to the ESM model. The ARIMA model's reduced RMSE and MAPE values provide more evidence of its superior prediction ability in this particular situation.

Table 1. Details of the statistical indicators

S/N	Abbreviation	Statistical test	Expression	Ideal value
1	R^2	Coefficient of determination	$R^2 = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{ave})^2}\right]$	One
2	RMSE	Root mean square error	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}$	Zero
3	BIC	Normalized Bayesian Information Criterion	$BIC = -2log(\hat{\theta}) + KlogN$	Zero
4	MAPE	Mean absolute percentage error	$MAPE = \frac{1}{n}\sum_{i=1}^{n}\lvert O_i - P_i\rvert$	Zero

Table 2. Comparison of the performance of the ARIMA and ESM models in forecasting transport CO_2 emissions

Country	Model #	Training Model Fit statistics			
		R^2	MAPE	RMSE	BIC
Libya	ARIMA	0.931	5.805	1.040	0.419
Libya	ESM	0.878	7.627	1.410	0.909

Autoregressive integrated moving average (ARIMA) model and an exponential smoothing model (ESM)

Due to its superior performance compared to the ESM model, the ARIMA model was selected to forecast Libya's transportation CO_2 emissions. The accuracy of the ARIMA model's best fit was then compared to the documented transport CO_2 emissions in the literature. In their study, Qiao *et al.* [81] utilized a variety of machine learning models to predict carbon dioxide (CO_2) emissions specifically for the transportation industry in the United Kingdom. The machine learning models consist of Gaussin process regression (GPR), long short-term memory (LSTM) networks, gradient tree boosting with least squares (LSBoost), and random forest (RF). In this study, the ARIMA approach performed better than [81] machine learning approaches. The ARIMA model reported a lower RMSE value of 1.040 $MtCO_2e/yr$, while the LSBoost model recorded a higher value of 1.189 $MtCO_2e/yr$, the random forest (RF) model recorded 1.311 $MtCO_2e/yr$, the GPR model recorded 1.197 $MtCO_2e/yr$, and the LSTM model recorded 1.920 $MtCO_2e/yr$. The findings of this study are also found to be superior when compared to other forecast outcomes regarding transport COe emissions, which were obtained using time series and machine learning models. This comparison is evident in the publications [7, 42, 43, 82-84].

4. The Need to Reduce Libya's Transport Sector CO_2 Emissions to Meet the International Energy Agency's Drastic Projections for Global Transport Sector CO_2 Emissions Reduction

4.1 Increasing Urbanization

The urbanization trend in Libya is causing a rise in the population residing in cities, which in turn is creating a greater need for personal vehicles as people look for easy and adaptable transportation choices. The current situation is worsening the carbon dioxide emissions in Libya's transportation sector, highlighting the urgent need for the country to adopt sustainable transportation solutions in order to achieve the International Energy Agency's ambitious goals of reducing global emissions in the transport sector. According to a World Bank study, over the past ten years, urbanization in Libya has led to a 15% increase in the ownership of personal vehicles. Projections indicate that if existing regulations remain intact, there will be a 25% rise in personal automobile ownership by 2030, and this trend is anticipated to persist. It is imperative to implement sustainable transportation solutions in order to meet the increasing demand and decrease carbon dioxide emissions from the transportation industry. Addressing this issue would necessitate a thorough strategy encompassing the allocation of resources towards enhancing public transportation infrastructure, advocating for the use of electric vehicles, and fostering the use of alternate means of transportation such as cycling and walking. By promptly taking measures, Libya can strive towards attaining the objectives set by the International Energy Agency [60] and establishing a more environmentally viable future for its populace.

4.2 Growth in Population

The population growth necessitates an increased need for transportation services, which consequently leads to a greater number of automobiles on the road. As per the World Bank [85], Libya's population is expected to grow at a rate of 2.5% per year, resulting in an increased need for transportation. The anticipated population growth is expected to lead to a proportional rise in the number of vehicles on the road, hence exacerbating the emission of CO_2 from the transportation industry. In order to achieve the International Energy Agency's forecasted targets for lowering CO_2 emissions in the global transportation industry, Libya must adopt policies and strategies that specifically target the reduction of emissions from its expanding fleet of automobiles. To alleviate the environmental impact of the transportation industry in Libya, it is advisable to implement measures such as encouraging public transportation, investing in electric vehicles, and enhancing fuel economy standards. Moreover, fostering a greater understanding among the general public about the significance of adopting sustainable transportation methods can significantly contribute to the mitigation of carbon dioxide emissions originating from automobiles.

4.3 Lack of Investment in Public Transportation Infrastructure

Inadequate investment in public transit infrastructure worsens dependence on private vehicles. Based on research conducted by the World Bank [85], Libya presently has one of the lowest levels of investment in public transportation infrastructure in the area, with a mere 0.5% of its gross domestic product (GDP) committed to this sector. The absence of financial allocation has resulted in a notable increase in both the number of cars owned and their usage, which has had a substantial impact on the amount of carbon dioxide emissions produced by the transportation sector in the country. Libya must prioritize investment in public transportation infrastructure to reduce dependency on private vehicles in order to reach the International Energy Agency's target of lowering global transport sector CO_2 emissions by 60% by 2050 [60]. This would not only reduce CO_2 emissions but also enhance the accessibility and affordability of transportation for all individuals. Moreover, allocating resources to public transportation can foster economic expansion and generate employment prospects within the nation. Enhancing the public transportation system in Libya can effectively alleviate traffic congestion and enhance air quality in urban regions. This will result in a more robust and enduring ecosystem for both present and future generations.

4.4 Growth in Commercial Transportation

According to research conducted by the International Energy Agency, the transportation industry accounts for 23% of worldwide carbon dioxide (CO_2) emissions, with commercial transportation playing a substantial role in this contribution [60]. If no action is taken, the expected increase in commercial transportation will result in a 60% rise in CO_2 emissions by 2050. This emphasizes the urgent necessity for Libya to undertake policies aimed at reducing emissions in this sector. According to a World Bank [85] study, commercial transportation in Libya has increased its level of greenhouse gas emissions by 15% over the past ten years. Projections indicate that there will be an additional 25% increase in emissions by the year 2030. The economy is experiencing growth, and there is an increasing demand for products and services. This highlights the pressing requirement for specific policies and investments to decrease CO_2 emissions in the transportation industry. Enacting measures such as advocating for the use of electric vehicles, enhancing the infrastructure for public transportation, and providing incentives for fuel-efficient behaviors can effectively reduce the consequences of increasing emissions. Moreover, allocating funds towards renewable energy sources for transportation can additionally aid in diminishing carbon footprints in Libya.

4.5 The Increased Frequency and Intensity of Heatwaves

The strong association between the increasing levels of carbon dioxide (CO_2) and the more frequent heatwaves in the region highlights the pressing necessity for Libya to tackle the emissions from its transportation industry. Adopting sustainable transportation practices, such as advocating for electric vehicles and allocating resources to enhance public transportation infrastructure, is essential for achieving global emissions reduction goals and minimizing the consequences of climate change. Implementing stricter fuel economy regulations for automobiles and providing incentives for the use of alternative fuels can also play a significant role in decreasing carbon dioxide emissions in the transportation industry. Engaging in international cooperation with other nations and organizations to exchange knowledge and advanced technologies can provide additional assistance to Libya in attaining its objectives of reducing emissions. Introducing measures that give priority to the development of walking and cycling infrastructure can effectively decrease emissions and enhance air quality in metropolitan regions. The incorporation of renewable energy sources into transportation networks might additionally reduce greenhouse gas emissions and advance environmental cleanliness.

5. Scenarios that Support the Mitigation of CO_2 Emissions from Libya's Transport Sector

5.1 Implementing Fuel Efficiency Standards for Vehicles to Reduce Carbon Emissions

Enforcing fuel efficiency regulations for automobiles is an essential measure for mitigating carbon emissions from Libya's transportation industry. This program will not only aid in reducing CO_2 emissions but also make a significant contribution to the country's broader sustainability objectives and efforts to protect the environment. Libya can ensure reduced CO_2 emissions per kilometer traveled by establishing precise fuel efficiency regulations for vehicles. This will not only have a positive impact on the environment, but it will also enhance air quality and promote public health in the country.

5.2 Promoting the Use of Electric Vehicles and Expanding Charging Infrastructure across the Country

Advocating for the use of electric vehicles not only mitigates the release of greenhouse gas emissions but also diminishes reliance on fossil fuels. Increasing the availability of charging infrastructure is vital to ensuring that electric car owners have easy access to charging stations, hence promoting the adoption of greener transportation alternatives. Allocating resources towards the development of charging infrastructure might generate novel employment prospects and foster economic expansion within the renewable energy industry. By adopting electric vehicles, Libya can make substantial strides towards attaining its emissions reduction objectives and actively participating in global endeavors to battle climate change. Moreover, diminishing the dependence on fossil fuels will additionally enhance air quality and public health in Libya. Investing in electric vehicle infrastructure is consistent with the nation's dedication to sustainable growth and environmental preservation.

5.3 Encouraging the adoption of alternative fuels such as biofuels or hydrogen in the transport sector

Biofuels and hydrogen, which are alternative fuels, have the capacity to greatly diminish greenhouse gas emissions in the transportation industry, thereby aiding in the creation of a more sustainable future for Libya. By advocating for the widespread use of these more environmentally friendly energy sources, Libya can effectively decrease its carbon dioxide emissions and decrease its reliance on non-renewable energy sources, ultimately resulting in enhanced air quality and long-term energy stability. The adoption of alternative fuels can contribute to the diversification of Libya's energy sources and generate fresh economic prospects in the renewable energy industry. Furthermore, by investing in alternative fuels, Libya can effectively fulfill its international obligations to decrease carbon emissions and address the issue of climate change. By adopting these more environmentally friendly energy sources, Libya can establish itself as a prominent participant in sustainable transportation practices and serve as a model for other nations to emulate.

5.4 Implementing Policies to Incentivize Carpooling and Ride-Sharing Services

Enforcing measures to encourage carpooling and ride-sharing services can effectively diminish the number of individual vehicles on the road, resulting in a decline in carbon emissions. By advocating for these sustainable modes of transportation, Libya can strive towards attaining its environmental objectives and establishing a transportation sector that is more effective and environmentally conscious. In addition, allocating resources to provide infrastructure that facilitates carpooling and ride-sharing, such as dedicated lanes or parking areas, might further incentivize individuals to opt for these alternatives instead of driving alone. This can also mitigate traffic congestion and decrease the overall carbon footprint of the transportation sector in Libya. The government can encourage a transition to more environmentally friendly forms of transportation by providing incentives and enhancing infrastructure.

5.5 Introducing Congestion Pricing to Reduce Traffic Congestion and Emissions in Urban Areas

Congestion pricing is imposing a charge on motorists for utilizing particular roadways or accessing specified areas during periods of high demand. This approach can effectively alleviate traffic congestion by incentivizing the use of alternate transportation modes and encouraging travelers to adjust their travel schedules. By applying this strategy in metropolitan areas of Libya, it is possible to not only reduce CO_2 emissions from the transport sector but also enhance air quality, resulting in a healthier and more sustainable environment for residents. Furthermore, congestion pricing can also yield income that can be reinvested in enhancing public transportation infrastructure, providing further motivation for the use of environmentally friendly modes of transportation. Implementing this comprehensive strategy can lead to a substantial decrease in greenhouse gas emissions and provide a more streamlined and eco-friendly transportation system in Libya.

5.6 Implementing Stricter Vehicle Emission Standards and Regular Inspections to Ensure Compliance

Enforcing more stringent vehicle emission regulations and conducting frequent inspections are essential measures for decreasing the carbon footprint of Libya's transportation industry. By implementing these steps, the nation can effectively reduce detrimental emissions, enhance air quality, and make a valuable contribution to global endeavors in addressing climate change. Moreover, the adoption of these standards might also result in technological and infrastructural progress within Libya's transportation sector. This will not only have a positive impact on the environment but also generate prospects for economic expansion and advancement in the nation.

5.7 Encouraging Telecommuting and Flexible Work Arrangements to Reduce the Need for Daily Commuting

Promoting telecommuting and flexible work arrangements can substantially diminish the number of vehicles on the road, resulting in a decline in greenhouse gas emissions from transportation. This strategy not only aids in reducing CO_2 emissions but also fosters a more balanced work-life equilibrium for employees, thereby enhancing productivity and job contentment. By minimizing the necessity for daily travel to work, employees can save on time and expenses related to transportation while also making a positive impact on the environment by lowering pollution. Moreover, the implementation of telecommuting and flexible work arrangements can effectively mitigate traffic congestion and enhance the overall air quality in urban regions. In general, advocating for telecommuting and flexible work arrangements can provide favourable outcomes for both the environment and the well-being of employees. It is an enduring solution that has advantageous effects for both humans and the planet over an extended period of time.

6. Study's Insights and Concluding Remarks

The global change assessment model of the ClimateWatch database did not incorporate CO_2 emissions from the transportation sector in Libya. Hence, the authors employed a time series methodology to forecast the past Libyan carbon dioxide (CO_2) emissions in the transportation industry, spanning from 1990 to 2022. Subsequently, these forecasts were extrapolated to encompass the period from 2023 to 2050. Using the time series approach, the authors were able to obtain a more accurate estimation of the trends and patterns in CO_2 emissions in Libya's transportation sector throughout the specified time period. The authors effectively rectified the shortcomings of the global change assessment model and conducted a comprehensive analysis of Libya's carbon emissions in the transportation sector through the utilization of this method. The achieved results include a comprehensive comprehension of the historical patterns in CO_2 emissions in Libya's transportation sector, precise forecasts for future emissions until 2050, and valuable insights into potential strategies for mitigating carbon emissions in the country.

The carbon dioxide emissions from transportation in Libya have a consistent and direct correlation between 1990 and 2020, with a coefficient of determination (R2) of 0.886%. This indicates a robust link between the years and CO_2 emissions in the transportation sector, which could be valuable in forecasting future patterns of CO_2 emissions in Libya. Policymakers must consider this correlation when developing initiatives to mitigate carbon emissions in the transportation sector. Understanding the historical trend of carbon dioxide emissions in transportation can provide valuable insights for making informed decisions regarding sustainable development strategies.

The exponential smoothing model (ESM) and ARIMA time series models were used to predict annual transportation CO_2 emissions in Libya. The ESM model showed a steady and linear rise in transportation CO_2 emissions between 2022 and 2050, while the ARIMA model exhibited a more intricate and non-linear trend. Both models offer useful insights into potential patterns in transportation CO_2 emissions in Libya. The selection between the ESM and ARIMA models may depend on the distinct attributes of the data and the intended level of precision in predicting emissions.

The ARIMA model outperformed the ESM model according to error metrics, producing a higher R^2 value of 0.931 than the ESM model's R^2 value of 0.878. This suggests that the ARIMA model would be better suited for accurately forecasting CO_2 emissions. In general, the ARIMA model exhibited better performance than the ESM model across several error metrics, suggesting that it would be better suited for accurately forecasting CO_2 emissions. The ARIMA model was selected to forecast Libya's transportation CO_2 emissions due to its superior performance compared to the ESM model. In their study, Qiao *et al*. [81] utilized various machine learning models to predict carbon dioxide emissions specifically for the transportation industry in the United Kingdom. The ARIMA approach performed better than Qiao *et al*.'s [81] machine learning approaches, with the ARIMA model reporting a lower RMSE value of 1.040 $MtCO_2e/yr$, while the LSBoost model recorded a higher value of 1.189 $MtCO_2e/yr$, the random forest model recorded 1.311 $MtCO_2e/yr$, the GPR model recorded 1.197

$MtCO_2e$/yr, and the LSTM model recorded 1.920 $MtCO_2e$/yr. This comparison is evident in publications [7, 42, 43, 82-84].

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Evaluating the Impact of Renewable Energy Integration on Air Quality: A Study of Pollutant Reduction in an Urban city of Calabar

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The characterization of air quality parameters was carried out in the coastal city of Calabar with the aim of reducing air pollutants in the atmosphere. Both mobile and stationary measurements were obtained. Mobile data were used for estimating air quality index and creating air quality map. The results show that the average concentration of ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2) and nitrogen Oxides (NO_x) was 0.34, 4.52, 0.53 and 0.96 ppm, respectively. The air quality index determined for each station showed that 82% of the stations were classified as “marginally polluted,” 14% were classified as “good,” and the remaining 4% were classified as “unhealthy” according to the U.S. air quality standards. Correlation analysis showed that wind speed had the highest correlation with SO_2, R = -0.72, while temperature had a high correlation with ozone, R = -0.68. The 2016 polar plots show that CO sources are located in the south and southeast, NO_x sources are located in the south and southwest, SO_2 sources are located in the southwest, and O_3 sources are located in the southeast. The 2017 polar plots show that CO sources are located in the northeast, NO_x sources are located in the northwest, SO_2 sources are located in the northeast, and O_3 sources are located in the southwest.

Keywords: Carbon monoxide; Ozone; Atmosphere; Air quality; Good

Introduction

One of the most important environmental problems facing the world today is air pollution. Due to its harmful effects, including decreased quality of life and altered characteristics of the biosphere, governments and international organizations are forced to invest financial and human resources to improve air quality in order to protect the biosphere [1]. The accelerated pace of urban construction and the resulting urbanization process have put tremendous pressure on the atmosphere. Air pollution is one of the results of this process, causing health concerns, especially fine particulate matter ($PM_{2.5}$) [2]. $PM_{2.5}$ is the specific material that has an aerodynamic diameter of smaller than 2.5 µm and is harmful to human health in addition to reducing air visibility. Fine particulate matter ($PM_{2.5}$) affects more people than any other pollutant, and it is repeatedly associated with mortality and morbidity from respiratory and cardiovascular diseases. Over the past decade, epidemiological data have linked $PM_{2.5}$ to a host of other health

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problems, including neurological diseases (such as stroke, dementia, Alzheimer's disease, autism, and Parkinson's disease), perinatal outcomes (such as premature birth and low birth weight), and cardio-metabolic diseases (such as diabetes, hypertension, and metabolic syndrome) [3].

One of the main challenges in addressing air pollution and its impact on air quality is the lack of adequate monitoring stations, especially in developing countries. Many developed countries have established comprehensive air quality monitoring networks that can accurately measure and report pollutant concentrations. However, this is not the case in many developing countries where monitoring infrastructure and resources are limited [4]. Air pollution levels depend largely on emission sources and meteorological conditions. If regional atmospheric emissions are relatively stable over a period of time, meteorological conditions may be the determining factor in the occurrence of air pollution [5]. The local and synoptic weather conditions that are in effect at the moment are crucial. Determining the relationships between air quality and meteorology is essential and can assist policymakers in creating environmental policies that will enhance people's quality of life [1]. Several authors have studied on the impact of meteorology on particulate matter [6]. Their research results conducted in South Korea showed that the generation, movement, and deposition of air pollutants were significantly influenced by meteorological factors. PM_{10} levels peaked in April, while $PM_{2.5}$ levels peaked in January. Both were at their lowest in July. Among them, the $PM_{2.5}$ concentration was highest in winter, followed by spring, autumn and summer; the PM_{10} concentration was highest in spring, followed by winter, autumn and summer. Particulate Matter (PM) concentration was negatively correlated with temperature, relative humidity and precipitation. Air quality was inversely correlated with wind speed, while PM was positively correlated with the zonal wind component and negatively correlated with the vertical wind component.

Rahaman *et al.* [7] carried out a research in Ankara, Turkey. The results showed that climate (temperature, humidity, air pressure, rainfall, etc.) and environmental factors (particulate matter, CO, NO and NO_x in the air) had an impact on the number of patients admitted to hospital for pneumonia. The impacts of air pollution on human health include cancer and tuberculosis [8].

The aim of this research is to characterize the air quality parameters in Calabar, a city in the Niger Delta, Nigeria. This research addresses the composition of air pollution through extensive air quality monitoring in the Calabar region of Nigeria. This is intended to be achieved by monitoring gaseous pollutants over a period of twenty-four (24) months. The objectives of this study include:

1. to develop of an air quality map for Calabar.
2. to establish any relationship between pollutants and meteorological parameters.
3. to trace the source and sink of these pollutants.
4. to establish the best air quality forecasting model.
5. to determine air quality trend.
6. to determine air quality health impact and risk assessment.

Methodology

Materials and Methods

The gas components were measured using an Aeroqual series 500- ENV gas analyzer (Gas-Sensing, Inwood, IA, USA) with gas sensor heads of Aeroqual SO_2 (0-10 ppm, model 1905152-006), Aeroqual O_3 (0-10 ppm, model 1407150-003), Aeroqual CO (0-100 ppm, model 0807155-004), and Aeroqual NO_2 (0-1 ppm model, 2906150-003). Met One Instruments Aerocet 531S Mass Monitor/Particle Counter (Grants Pass, OR, USA) was used to measuring particulate matter (PM 2.5 and PM 10).

To operate the Aeroqual gas analyzer, each gas head is inserted on the top of the main gas analyzer and then takes three minutes to warm up. After a three-minute warm-up period, the values for the specific gas measured at the specific investigation location are displayed on the gas analyzer. The values are displayed in units of part per billion (ppb), part per million (ppm) or $\mu g/m^3$ depending on the settings. For this project, the values of the gases are presented in ppb or in ppm. These measurements were taken from site to site throughout the project. The coordinates and elevation of the different stations were obtained using Garmin Etrex 20 GPS. The map of the study location is shown in Figure 1.

Fig. 1. Map of study location

Finally, a compass was used in determining the direction of the wind at all the locations of the project. This is a project sponsored by the Tertiary Education Trust Fund (TETFUND). Therefore, the equipment was procured using funds provided by the Fund. Study locations are shown on Table 1. The equipment shown in Figure 2 were used to obtain air quality data. Meteorological parameters at different locations of interest were measured using an Extech 45170 4-in-1 Environmental Meter (Teledyne FLIR, Wilsonville, OR, USA). The device does not require preheating. It measures different parameters such as wind speed, relative humidity, air temperature and lux and shows the values on a display.

The data for this study are divided into two parts. The first part is from a mobile Aeroqual handheld device and the second part is from a stationary AQM65 device located at the Geoenvironmental Station of the University of Calabar. The data from the mobile devices were obtained at specific time intervals and on specific dates. The data were collected on 23/05/2015, 06/06/2016, 20/06/2016, 04/07/2016, 18/07/2016, 1/08/2016, 15/08/2016 and 29/08/2016. On the other hand, the AQM65 stationary device was programmed by the company to record data at minute intervals. The machine could also be re-programmed to record data at hourly intervals. For the purpose of this study, data were acquired at minute intervals. The data from both devices were presented as monthly means. The pollutant data obtained from the mobile devices in this research were: Nitrogen dioxide (NO_2), Ozone (O_3), Carbon monoxide (CO), Sulfur dioxide (SO_2), Carbon dioxide (CO_2), The pollutant data obtained from the stationary AQM65 machine were: Nitrogen oxides (NO_x) which is a combination of Nitrogen oxide (NO) and Nitrogen dioxide (NO_2), Ozone (O_3), Carbon monoxide (CO) and sulfur dioxide (SO_2). The meteorological parameters obtained for the research were: wind speed (WS), wind direction (WD), temperature (TEMP) and relative humidity (RH). Table 1 shows all the selected locations for this study. AQ1 to AQ50 are the selected locations. Each selected site was given a unique identifier to simplify the research process. The table consists of the sample point, latitude, longitude and elevation of the selected locations.

Visualizations were done using R programming language and tableau software. The correlation analysis was done using R programming language. Trend analysis is done using the Mann-Kendall trend test. The openair package in R has also been used.

Table 1. Study locations

S/N	SAMPLE POINT	LOCATIONS	LATITUDE	LONGITUDE	ELEVATION (m)
1	AQ1	CRUTECH GATE ROUND ABOUT	4°55’53.1’’	8°19’42.0’’	26
2	AQ2	NEW AIRPORT BY ESSIEN ST.	4°55’37.1’’	8°19’25.5’’	18
3	AQ3	ABITU BY POULTRY FARM	4°55’26.4’’	8°19’19.7’’	15
4	AQ4	ANATIGHA BY THE APOSTOLIC CHURCH	4°55’04.2’’	8°19’16.0’’	14
5	AQ5	IBESIKPO BY IMAN PRISON	4°55’47.8’’	8°18’43.1’’	16
6	AQ6	AMBO MARKET ROUND ABOUT	4°56’15.2’’	8°19’0.2’’	43
7	AQ7	EYO ITA BY EDIBE EDIBE	4°56’39.0’’	8°18’46.4’’	40
8	AQ8	HENSHAW TOWN BY CHAMBLY CALABAR RD.	4°57’02.3’’	8°18’59.9’’	43
9	AQ9	WHITE HOUSE BY CHAMBLY	4°57’07.4’’	8°19’13.5’’	39
10	AQ10	MAYNE AVENUE BY WHITE HOUSE	4°56’30.9’’	8°19’18.3’’	33
11	AQ11	INYANG BY AFOKANG	4°56’14.0’’	8°19’15.9’’	34

12	AQ12	YELLOW DUKE BY EKPOABASI	4°56'10.2''	8°19'32.0''	30
13	AQ13	YELLOW DUKE BY MBUSAHA	4°56'08.5''	8°19'44.5''	28
14	AQ14	ATAMUNU BY MOUNT ZION	4°56'23.5''	8°19'44.5''	22
15	AQ15	MOUNT ZION BY OROK OROK	4°56'38.8''	8°20'19.6''	44
16	AQ16	UWANSE END OF STREET	4°56'17.3''	8°20'26.8''	26
17	AQ17	MAYNE AVENUE BY GOLDIE	4°57'02.8''	8°19'58.6''	48
18	AQ18	MAYNE AVENUE BY ADAM DUKE	4°56'49.2''	8°19'45.9''	33
19	AQ19	TARGET BY PALM STREET	4°47'10.4''	8°19'21.6''	52
20	AQ20	GOLDIE BY TARGET	4°57'17.8''	8°19'40.8''	31
21	AQ21	UNICAL MAIN STATION POINT	4°57'07.78''	8° 20' 51''	62
22	AQ22	MARY SLESSOR ROUND ABOUT	4°58'35.46''	8°19'57.15''	65.45
23	AQ23	IKA IKA OKUWA MARKET	4°58'35.46''	8°20'26.28''	83
24	AQ24	EFIO ETTE ROUND ABOUT	4°59'36.89''	8°20'42.28''	74.2
25	AQ25	IKOT EFA BY NDIDEN ISO PARLIAMENTARY	5°00'12.88''	8°20'44.90''	84
26	AQ26	GOOD LUCK JOHNATHAN BY PASS OVERHEAD BRIDGE	5° 01'13.77''	8°15'57.87''	56
27	AQ27	DESTINATION CROSS RIVER ROUND ABOUT BY BASIN AUTHORITY	5°02'43.35''	8°21'26.58''	93
28	AQ28	ARMY JUNCTION BY WELCOME TO CALABAR	5° 02'04.36''	8°28'01.06''	102
29	AQ29	SPC JUNCTION BY EPZ JUNCTION	5°01'13.55''	8°20'00.43''	95
30	AQ30	EPZ TANK FARM	5°01'08.1''	8°19'20''	53
31	AQ31	NNPC TANK FARM	5°01'01.12'	8°19'29.3''	61
32	AQ32	ISHIE TOWN BY JOHNSON/ISHIE MARKET	4°59'51.4''	8°20'20.2''	71
33	AQ33	ESSIEN TOWN JUNCTON BY HIGHWAY	4°59'22.08''	8°19'59.57''	69
34	AQ34	MARINA RESORT	4°57'55.4''	8°19'05.5''	20
35	AQ35	NEW SECRETERIATE CALABAR	4°58'51.23''	8°19'53.96''	65
36	AQ36	IBB BY STADIUM TRAFFIC LIGHT	5°49'70.9''	8°20'54.76''	69
37	AQ37	ATAKPA POLICE STATION BY TRAFFIC LIGHT	4°57'34.0''	8°19'17.7''	54
38	AQ38	IBB ROUND ABOUT BY RABANA	4°57'46.93''	8°20'10.41''	71
39	AQ39	AIR PORT BY POLICE STATION	4°57'56.9''	8°20'59.6''	52

40	AQ40	IBB BY ATIMBO ROUND ABOUT, CALABAR	4°58’22.4’’	8°20’10.41’’	71
41	AQ41	AKPABUYO BY BIG QUA RIVER	4°56’53.0’’	8°23’46.2’’	18
42	AQ42	AKPABUYO LOCAL GOVERNMENT HQ.	4°52’58.8’’	8°28’50.4’’	53
43	AQ43	MCC BY GOOD LUCK BY PASS	4°00’35.76’’	8°22’00.53’’	31
44	AQ44	UNICEM FACTORY SITE	5°04’05.9’’	8°30’44.9’’	28
45	AQ45	LEMNA DUMP SITE	5°01’59.7’’	8°21’54.8’’	27
46	AQ46	8 MILES BY AGRO FEED	4°03’22.4’’	8°21’16.6’’	70
47	AQ47	TINAPA JUNCTION	5°04’09.6’’	8°20’59.9’’	65
48	AQ48	TINAPA BUSSINESS RESORT	5°02’54.3’’	8°18’58.8’’	31
49	AQ49	RUBER ESTATE HIGHWAY	5°05’59.3’’	8°20’36.3’’	57
50	AQ50	ODUKPANI JUNCTION	5°09’19.00’’	8°20’45.7’’	31

Fig. 2. AQM65 equipment and Aeroqual had held equipment

The Mann-Kendall Z-statistic

$$Z_{mk} = \frac{S-1}{\sqrt{VAR(S)}} \; if \; S > 0 \qquad \text{Eq. 1}$$

$$Z_{mk} = 0 \text{ if } S = 0 \qquad \text{Eq. 2}$$

$$Z_{mk} = \frac{S+1}{\sqrt{VAR(S)}} \; if \; S < 0 \qquad \text{Eq. 3}$$

where $VAR(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{p-1}^{g} t_p(t_p - 1)(2t_p + 5)$ Eq. 4

The Mann-Kendall test has been used to analyze trends across different fields. For example, it was used to analyze the variations of ambient temperature [9], long-term trend and seasonality detection of the observed flow in Yangtze River [10], and air quality trends [11].

Sen's Slope Estimator

If a time series has a linear trend, a simple nonparametric approach devised by Sen can be used to estimate the true slope (change per unit time). As a result, the linear model f (t) can be written as:

$$f(t) = Qt + B \qquad \text{Eq. 5}$$

where Q denotes the slope and B denotes the constant.

The slopes of all data pairs are calculated to produce an estimate of the slope Q:

$$Q_i = \frac{X_j - X_k}{j-k}, i = 1, 2 \dots N, j > k \qquad \text{Eq. 6}$$

The Sen's estimator is used to rank the N values of Q_i from the smallest to the largest:

$$Q = \begin{cases} Q_{\frac{n+1}{2}} \ if\ N\ is\ odd \\ \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right) if\ N\ is\ even \end{cases} \qquad \text{Eq. 7}$$

The sign of Q indicates whether the data is trending upward or downward, and the number indicates how steep the trend is [12].

Calculating Air Quality Index (AQI)

Let's say there are n air quality parameters P_i (i= 1, 2, 3...n) that must be considered when computing the AQI. Let V_i be the observed values of the i^{th} parameter in ambient air, and V_{si} denotes the suggested standard value for this parameter. Then

$$Q_i = 100 * \frac{V_i}{V_{si}} \qquad \text{Eq. 8}$$

gives the quality rating Q_i for this attribute. If Q_i is greater than 100, the given parameter is inside the prescribed range. On the other hand, if $Q_i > 100$, it means that the i^{th} parameter exceeds the prescribed standard and that the ambient air is unsafe for humans to breathe. Because all of the indicators are believed to be of equal importance, only the unweighted air quality indices are calculated.

$$\text{GM} = (Q_i) * \frac{1}{n} \qquad \text{Eq. 9}$$

$$\text{AQI} = \text{Antilog}\ \left(\frac{\sum logQ_i}{n}\right) \qquad \text{Eq. 10}$$

The Ambient AQI can be calculated using Eqs. 9 and 10.

AQI based on the Individual Pollutants and Categorization of AQI

Equation 11 was used to determine the AQI for the four contaminants. This equation is used to calculate the AQI for a location based on the measured concentrations of specific pollutants. The AQI calculated based on pollutants is I_p, while C_p is the pollutant concentration rounded to the nearest decimal place. BPHi is a breakpoint that is larger than or equal to the pollutants' rounded concentration. BPLo is the breakpoint that is less than or equal to the pollutant C_p's rounded concentration. The AQI value that corresponds to BPHi is IHi. The AQI value that correlates to BPLo is ILo. The calculated value was based on the measured concentrations of the four contaminants. AQI is categorized based on Table 2. The Air Quality Index (AQI) was developed using breakpoints given by the United States Environmental Protection Agency (USEPA) in

2006. To illustrate the AQI for each position, the average of the AQI for each point was determined as:

$$Ip = \frac{IHi - ILo}{BPHi - BPLo}(Cp - BPLo) + Lo \quad 11$$

where IP is the pollutant P index, and C_p denotes the pollutant P's rounded concentration.

TABLE 2. AQI Categorization Table

Category	AQI	Description of Ambient Air
I	0-50	Good
II	51-100	Marginally polluted
III	101- 200	Unhealthy
IV	201-300	Very unhealthy
V	>300	Hazardous

Results and Discussion

Concentration of Pollutants

The average concentration of pollutants is presented in Table 3. A quick inspection of the Table shows that the highest concentration of ozone (O_3) was obtained in December with a concentration of 0.031 ppm, which is lower than the World Health Organization standard annual average value of 0.1 ppm. The lowest concentration value was obtained in March with a concentration value of 0.01 ppm. The high ozone concentration in December may be because ozone concentration increases with increasing solar radiation, and December is the peak of the dry season in Calabar, accompanied by strong solar radiation.

The highest concentration of carbon monoxide (CO) was obtained in August with a concentration of 9.876 ppm which is higher than the Nigerian national standard annual average value of 4.05 ppm. The lowest concentration value was obtained in March with a concentration value of 1.141 ppm. August is the peak of the rainy season in Nigeria. During this period, many people tend to stay indoors. This prompts the use of gasoline generators to keep them occupied. More private cars also ply the roads during this period. This could explain the slightly higher CO concentrations during this period.

The highest concentration of sulfur dioxide (SO_2) was obtained in August with a concentration of 0.017 ppm which is lower than the Nigerian national standard annual average value of 0.08 ppm. The lowest concentration value was obtained in February and march with a concentration value of 0.01 ppm. It could also be observed that there is no marked difference in the average concentration of SO_2 from January to December. The highest concentration of Nitrogen Oxides (NO_x) was obtained in October with a concentration of 0.005 ppm which is lower than the Nigerian national standard annual average value of 0.08 ppm. NO_x concentrations were lower from March to August, ranging from 0.02 to 0.013 ppm.

Figure 3 shows a correlogram of pollutants with the meteorological parameters used for this study. It can be seen from the figure that the correlation coefficient between CO and temperature is the highest, R = -0.81, and the correlation coefficient with ozone is the lowest, R = 0.11. This shows that temperature had an effect on CO of about 81% compared to other variables, albeit in a negative manner. SO_2 had the lowest correlation coefficient R of 0.36 with ozone. O_3 had the highest correlation coefficient R = -0.43 with temperature, while it had the lowest correlation coefficient R = 0.11 with CO. NO_x had the highest correlation coefficient R = -0.67 with CO, while it had the lowest correlation coefficient R = 0.17 with wind speed. This shows that NO_x had about 67% impact on CO compared with the other variables though negatively. The correlation coefficients presented in the correlogram of Figure 3 do not vividly reflect the monthly relationship between this pollutant and meteorological conditions.

Table 3. Monthly average concentration of pollutants

Month	O_3 (ppm)	CO (ppm)	SO_2 (ppm)	NO_x (ppm)	WS (m/s)	TEMP (^oC)	RH
Jan.	0.013	1.218	0.008	0.004	0.695	30.237	66.445
Feb.	0.014	3.01	0.01	0.004	0.746	30.609	68.539
Mar.	0.01	1.141	0.01	0.003	0.762	30.071	73.073
Apr.	0.015	5.141	0.014	0.002	0.696	29.376	77.403
May.	0.02	5.643	0.016	0.003	0.637	29.02	77.712
Jun.	0.027	5.78	0.014	0.002	0.628	28.197	80.959
Jul.	0.014	5.831	0.02	0.002	0.583	27.666	83.312
Aug.	0.015	9.876	0.017	0.002	0.6	27.781	82.754
Sep.	0.022	7	0.015	0.003	0.612	28.512	80.173
Oct.	0.022	2.776	0.015	0.005	0.641	29.159	76.303
Nov.	0.027	2.993	0.015	0.004	0.593	29.117	79.162
Dec.	0.031	3.812	0.016	0.004	0.61	29.656	73.894

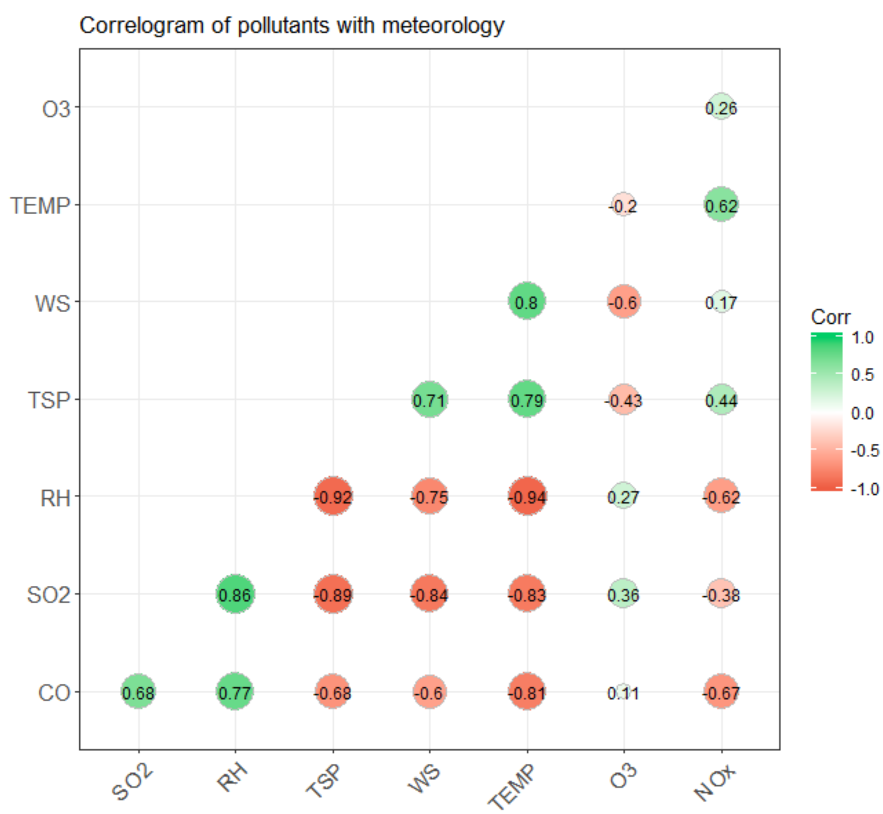

Fig. 3. Correlogram of pollutants with meteorology

Air Quality Index

The AQI values for the city of Calabar were obtained using data recorded by the mobile Aeroqual gas modules. Table 4 shows AQI breakpoints, while Tables 5 and 6 show AQI standards. In these tables, the following pollutants are represented: particulate matter with diameter less or equal to 2.5 micrometer per meter square (PM2.5), particulate matter with diameter less or equal to 10 micrometer per meter square (PM10), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ammonia (NH_3) and total suspended particulate matter (TSP). NIL in Table 4 means that no standard was available for that contaminant at the time of publication. Table 7 shows the AQI for the fifty (50) locations selected for this research. A close examination of Table 7 reveals that 82% of the stations were categorized as “marginally polluted”, which belong to the group (51-100). It can also be seen that 14% of the stations were categorized as “Good”, while the remaining 4% of the stations were categorized as “unhealthy”. An air quality map has been developed based on this Table and is presented in Figure 4. This air quality map was developed based on the AQI values. Based on this map, the stations with the green dots represent the stations categorized as “good”, those with light green colored dot are categorized as “marginally polluted”, the stations with the red colored dots represent the “unhealthy category”, and the dark green dotted stations are categorized as “critical”. According to the results of this research, it can be concluded that the city of Calabar is marginally polluted with average AQI values between 51 – 100. AQI values were also obtained based on the data obtained from the stationary AQM65 machine stationed at the University of Calabar main station. The AQI valued obtained are presented in Table 8. It’s found that these AQI values were all categorized as “marginally polluted” throughout the period of study. The difference between the values obtained from the mobile equipment and that obtained from the stationary equipment could be due to the fact that the mobile equipment were held close to the ground during data taking, while the stationary AQM65 stationary equipment is mounted at an elevation of 10 m. Figure 5 shows a plot of AQI as it varies throughout the period of study. The highest AQI was recorded in December 2015 and the lowest in March 2017.

Table 4. Breakpoint for different pollutants

O_3 (ppm) 8-hour	O_3 (ppm) 1-hour	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)	CO (ppm)	SO_2 (ppm)	NO_2 (ppm)	AQI	Category
0.000–0.064	-	0.0 – 15.4	0 – 54	0.0 – 4.4	0.00 – 0.034	(^{2})	0 -50	Good

NOTE: $N0_2$ has no short-term NAAQS and can generate an AQI only above a value of 200.

Table 5. National air quality standards

POLLUTANTS	TIME WEIGHTED AVERAGE	CONCENTRATION IN ANBIENT AIR (G/M^3)	CONCENTRATION IN ANBIENT AIR (ppm)
PM2.5	ANNUAL	300 $\mu g/m^3$	0.128
	24HRS	500 $\mu g/m^3$	0.213
PM10	ANNUAL	120 $\mu g/m^3$	0.05
	24HRS	150 $\mu g/m^3$	0.06
SO_2	ANNUAL	80 $\mu g/m^3$	0.03
	24HRS	120 $\mu g/m^3$	0.05
NO_2	ANNUAL	80 $\mu g/m^3$	0.03
	24HRS	120 $\mu g/m^3$	0.05
CO	ANNUAL	5.0 mg/m^3	4.5

	24HRS	10.0 mg/m^3	9.0
NH_3	ANNUAL	0.2 mg/m^3	0.18
	24HRS	0.6 mg/m^3	0.54
TSP		250 $\mu g/m^3$	0.11

Table 6. World Health Organization (WHO) standards

POLLUTANTS	TIME WEIGHTED AVERAGE	CONCENTRATION IN ANBIENT AIR (G/M^3)	CONCENTRATION IN ANBIENT AIR (ppm)
PM2.5	ANNUAL	10$\mu g/m^3$	0.004ppm
	24HRS	25 $\mu g/m^3$	0.011ppm
PM10	ANNUAL	20 $\mu g/m^3$	0.009ppm
	24HRS	50 $\mu g/m^3$	0.021ppm
SO_2	10 MINUTE	500 $\mu g/m^3$	0.213ppm
	24HRS	20 $\mu g/m^3$	0.009ppm
NO_2	ANNUAL	40 $\mu g/m^3$	0.017ppm
	1HOUR	200 $\mu g/m^3$	0.085ppm
O_3	ANNUAL	NIL	NIL
	8HRS	100 $\mu g/m^3$	0.042
NH_3	ANNUAL	NIL	NIL
	24HRS	NIL	NIL
CO	NIL	NIL	NIL

Table 7. Air quality Index for different locations

SITE NO	DATE OF SAMPLES	SAMPLING STATIONS	AQI	AIR QUAITY CATEGORY
AQ1	23/05/2016 - 19/12/2016	CRUTECH GATE ROUND ABOUT	74.13	MARGINALLY POLLUTED
AQ2	23/05/2016 - 19/12/2016	NEW AIRPORT BY ESSIEN ST.	62.70	MARGINALLY POLLUTED
AQ3	23/05/2016 - 19/12/2016	ABITU BY POULTRY FARM	52.80	MARGINALLY POLLUTED
AQ4	23/05/2016 - 19/12/2016	ANATIGHA BY THE APOSTOLIC CHURCH	79.13	MARGINALLY POLLUTED
AQ5	23/05/2016 - 19/12/2016	IBESIKPO BY IMAN PRISON	51.9	MARGINALLY POLLUTED
AQ6	23/05/2016 - 19/12/2016	AMBO MARKET ROUND ABOUT	59.60	MARGINALLY POLLUTED
AQ7	23/05/2016 - 19/12/2016	EYO ITA BY EDIBE EDIBE	64.57	MARGINALLY POLLUTED
AQ8	23/05/2016 - 19/12/2016	HENSHAW TOWN BY CHAMBLY CALABAR RD.	47.20	GOOD
AQ9	23/05/2016 - 19/12/2016	WHITE HOUSE BY CHAMBLY	48.80	GOOD
AQ10	23/05/2016 - 19/12/2016	MAYNE AVENUE BY WHITE HOUSE	58.88	MARGINALLY POLLUTED

AQ11	23/05/2016 - 19/12/2016	INYANG BY AFOKANG	114.8	UNHEALTHY
AQ12	23/05/2016 - 19/12/2016	YELLOW DUKE BY EKPOABASI	54.95	MARGINALLY POLLUTED
AQ13	23/05/2016 - 19/12/2016	YELLOW DUKE BY MBUSAHA	49.89	GOOD
AQ14	24/05/2016 - 19/12/2016	ATAMUNU BY MOUNT ZION	59.43	MARGINALLY POLLUTED
AQ15	24/05/2016 - 19/12/2016	MOUNT ZION BY OROK OROK	74.13	MARGINALLY POLLUTED
AQ16	24/05/2016 - 19/12/2016	UWANSE END OF STREET	74.50	MARGINALLY POLLUTED
AQ17	24/05/2016 - 19/12/2016	MAYNE AVENUE BY GOLDIE	70.79	MARGINALLY POLLUTED
AQ18	24/05/2016 - 19/12/2016	MAYNE AVENUE BY ADAM DUKE	58.88	MARGINALLY POLLUTED
AQ19	24/05/2016 - 19/12/2016	TARGET BY PALM STREET	72.44	MARGINALLY POLLUTED
AQ20	24/05/2016 - 19/12/2016	GOLDIE BY TARGET	45.92	GOOD
AQ21	24/05/2016 - 19/12/2016	UNICAL MAIN STATION POINT	51.05	MARGINALLY POLLUTED
AQ22	24/05/2016 - 19/12/2016	MARY SLESSOR ROUND ABOUT	66.07	MARGINALLY POLLUTED
AQ23	24/05/2016 - 19/12/2016	IKA IKA OKUWA MARKET	67.61	MARGINALLY POLLUTED
AQ24	24/05/2016 - 19/12/2016	EFIO ETTE ROUND ABOUT	66.07	MARGINALLY POLLUTED
AQ25	24/05/2016 - 19/12/2016	IKOT EFA BY NDIDEN ISO PARLIAMENTARY	57.54	MARGINALLY POLLUTED
AQ26	24/05/2016 - 20/12/2016	GOODLUCK JOHNATHAN BY PASS OVERHEAD BRIDGE	57.54	MARGINALLY POLLUTED
AQ27	24/05/2016 - 20/12/2016	DESTINATION CROSS RIVER ROUND ABOUT BY BASIN AUTHORITY	66.07	MARGINALLY POLLUTED
AQ28	24/05/2016 - 20/12/2016	ARMY JUNCTION BY WELCOME TO CALABAR	53.70	MARGINALLY POLLUTED
AQ29	25/05/2016 - 20/12/2016	SPC JUNCTION BY EPZ JUNCTION	63.10	MARGINALLY POLLUTED

AQ30	25/05/2016 - 21/12/2016	EPZ TANK FARM	51.29	MARGINALLY POLLUTED
AQ31	25/05/2016 - 21/12/2016	NNPC TANK FARM	67.61	MARGINALLY POLLUTED
AQ32	25/05/2016 - 21/12/2016	ISHIE TOWN BY JOHNSON/ISHIE MARKET	61.66	MARGINALLY POLLUTED
AQ33	25/05/2016 - 21/12/2016	ESSIEN TOWN JUNCTON BY HIGHWAY	58.88	MARGINALLY POLLUTED
AQ34	25/05/2016 - 21/12/2016	MARINA RESORT	44.66	GOOD
AQ35	25/05/2016 - 21/12/2016	NEW SECRETERIATE CALABAR	51.29	MARGINALLY POLLUTED
AQ36	25/05/2016 - 21/12/2016	IBB BY STADIUM TRAFFIC LIGHT	89.13	MARGINALLY POLLUTED
AQ37	25/05/2016 - 21/12/2016	ATAKPA POLICE STATION BY TRAFFIC LIGHT	75.86	MARGINALLY POLLUTED
AQ38	25/05/2016 - 21/12/2016	IBB ROUND ABOUT BY RABANA	83.18	MARGINALLY POLLUTED
AQ39	26/05/2016 - 21/12/2016	AIR PORT BY POLICE STATION	66.10	MARGINALLY POLLUTED
AQ40	26/05/2016 - 21/12/2016	IBB BY ATIMBO ROUND ABOUT, CALABAR	79.43	MARGINALLY
AQ41	26/05/2016 - 21/12/2016	IBB BY ATIMBO ROUND ABOUT, CALABAR	72.44	MARGINALLY POLLUTED
AQ42	26/05/2016 - 21/12/2016	AKPABUYO LOCAL GOVERNMENT HQ.	51.29	MARGINALLY POLLUTED
AQ43	26/05/2016 - 21/12/2016	MCC BY GOOD LUCK BY PASS	67.60	MARGINALLY POLLUTED
AQ44	26/05/2016 - 21/12/2016	UNICEM FACTORY SITE	81.28	MARGINALLY POLLUTED
AQ45	26/05/2016 - 21/12/2016	LEMNA DUMP SITE	50.20	GOOD
AQ46	27/05/2016 - 21/12/2016	8 MILES BY AGRO FEED	72.44	MARGINALLY POLLUTED
AQ47	27/05/2016 - 21/12/2016	TINAPA JUNCTION	70.79	MARGINALLY POLLUTED
AQ48	27/05/2016 - 21/12/2016	TINAPA BUSSINESS RESORT	48.75	GOOD

AQ49	27/05/2016 - 21/12/2016	RUBER ESTATE HIGHWAY	60.07	MARGINALLY POLLUTED
AQ50	27/05/2016 - 21/12/2016	ODUKPANI JUNCTION	105.68	UNHEALTHY

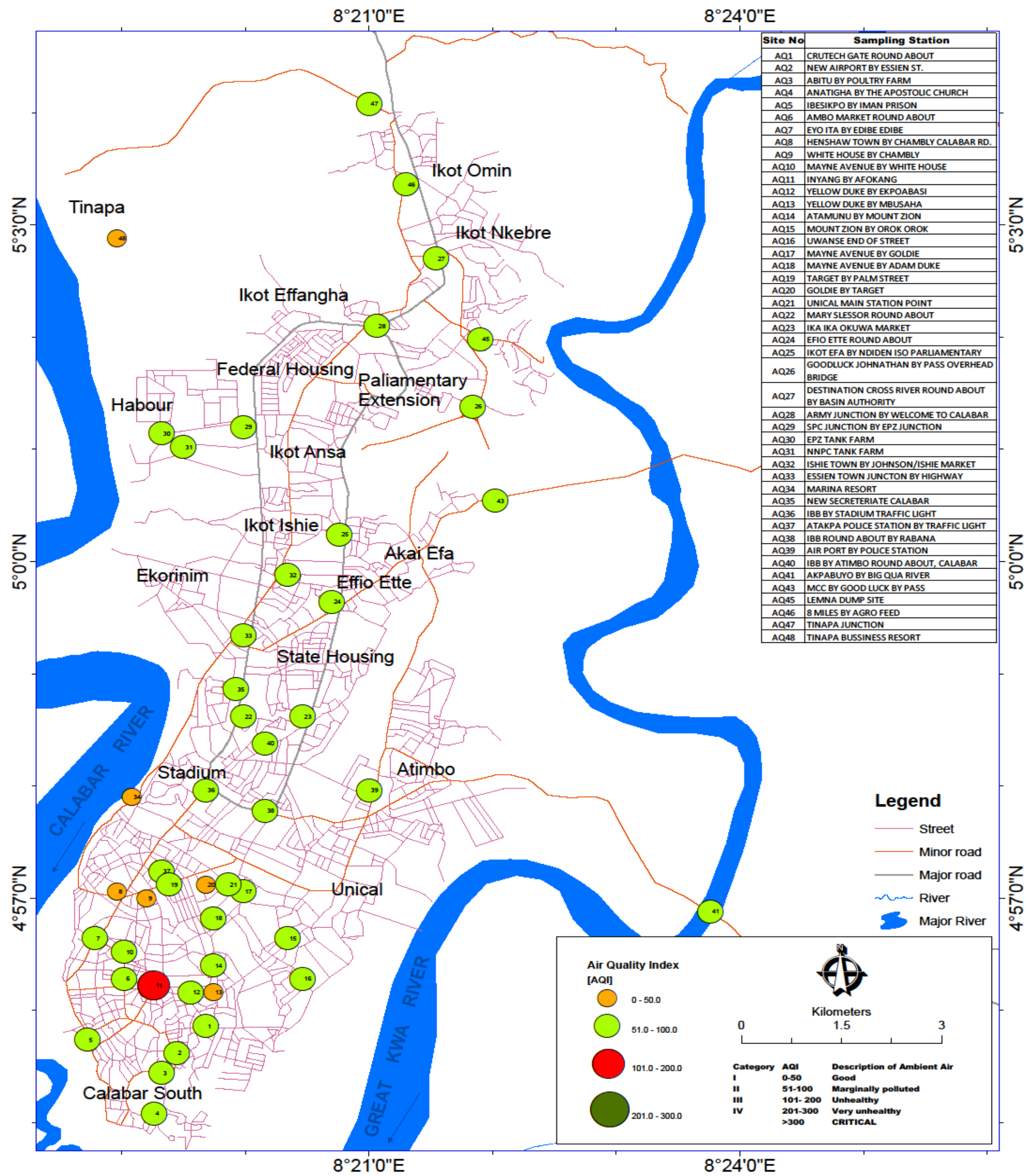

Fig. 4. Air quality map for Calabar

Correlation Analysis

Table 8 shows the correlation between AQI values and pollutants. It can be seen that AQI has the highest correlation of R = 0.93 with NO_x. This shows that NO_x has the greatest impact on AQI, while CO has the lowest impact with R = -0.12. Table 9 shows the coefficient of determination R^2 between the AQI and pollutants. The coefficient of determination between TSP and AQI is presented as the highest R^2 = 0.873. This shows that 87.3% variation of AQI in the location can be explained by the concentration of TSP in ambient air. The lowest value of $R^2 = 0.014$ was between AQI and CO. This also tells us that only 1.4% variation of AQI can be attributed to the concentration of CO.

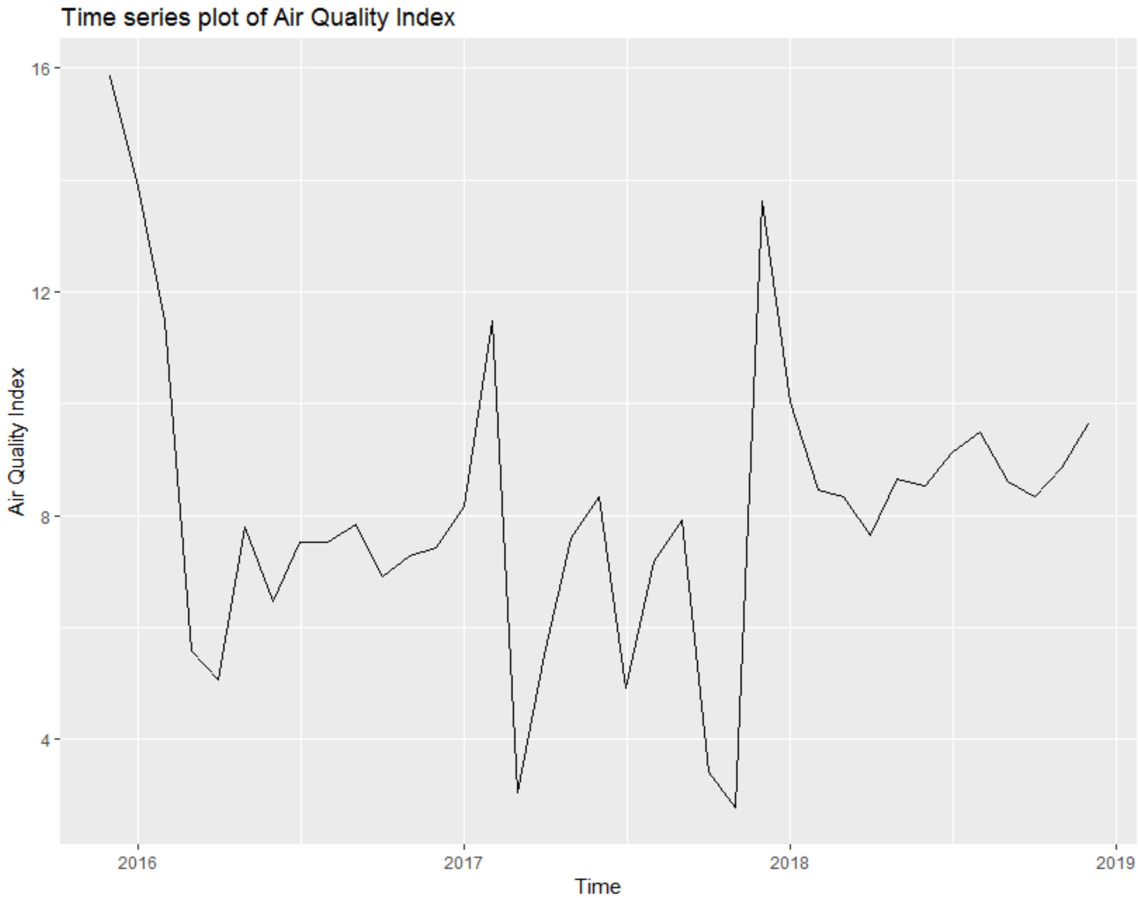

Fig. 5. Seasonal variation of AQI for Calabar

Table 8. Correlation coefficient for pollutants

	O_3	SO_2	CO	NO_x	AQI	WS	TEMP	RH
O_3	1							
SO_2	0.01	1						
CO	0.45	0.50	1					
NOx	0.38	-0.45	-0.36	1				
AQI	0.46	-0.33	-0.12	0.93	1			
WS	-0.28	-0.72	-0.42	0.50	0.48	1		
TEMP	-0.68	-0.06	-0.31	0.06	0.14	0.47	1	
RH	-0.08	0.34	0.35	-0.86	-0.87	-0.64	-0.52	1

Table 9. Correlation coefficient between AQI and pollutants

Correlation	R^2
AQI with O_3	0.211
AQI with CO	0.014
AQI with SO_2	0.108
AQI with NO_x	0.858
AQI with TSP	0.873
AQI with wind speed	0.235
AQI with Temperature	0.018
AQI with Relative humidity	0.766

R^2 = 0.094 is the coefficient of determination between AQI and H_2S. This means that the effect of H_2S is responsible for 9.4% of the variation in the Air Quality index over the study period. R^2 = 0.211 is the coefficient of determination between AQI and O_3. This means that the effect of O_3 is responsible for 21% of the variation in the Air Quality index across the research period. R^2 = 0.014 is the coefficient of determination between AQI and CO. This means that CO is responsible for 1.4% of the change in the Air Quality index across the study period. R^2 = 0.108 is the coefficient of determination between AQI and SO_2. This means that the effect of SO_2 accounts for 10.8% of the variation in the Air Quality index across the research period. R^2 = 0.858 is the coefficient of determination between AQI and NO_x. This means that the effect of NO_x is responsible for 85.8% of the variation in the Air Quality index over the study period. R^2 = 0.873 is the coefficient of determination between AQI and TSP. This means that the effect of TSP is responsible for 87.3% of the change in the Air Quality index across the study period. R^2 = 0.235 is the coefficient of determination between AQI and wind speed. This means that the effect of wind speed is responsible for 23.5% of the variation in the Air Quality index over the study period. R^2 = 0.018 is the coefficient of determination between AQI and Temperature. This means that the effect of temperature accounts for 1.8% of the change in the Air Quality index across the research period. R^2 = 0.766 is the coefficient of determination between AQI and relative humidity. This means that the effect of relative humidity is responsible for 76.6% of the variation in the Air Quality index over the study period.

Bipolar Plots

Figure 6 shows wind rose plot for 2016 that characterize the speed and direction of winds at a location. When multiple monitoring stations are available, the wind speed dependence of a source can reveal important details about the source type and characteristics. In 2016, when easterly and southeasterly wind speeds increased, there were signs that CO_2 concentrations increased, as shown in Figure 7. For various wind speeds, there was also evidence of origin from the SSE. In 2016, there was evidence of an increase in NO_x concentrations with increasing wind speeds from the south and southwest, as seen in Figure 8. In 2016, when the easterly and southwesterly wind speeds increased, SO_2 concentration showed signs of increasing, as seen in Figure 9. For various wind speeds, there is additional evidence that the wind source is located in the southwest. In 2016, there is evidence that O_3 concentrations increase when wind speed increases from the southeast, as seen in Figure 10. For a variety of wind speeds, there is additional evidence of a source to the southeast.

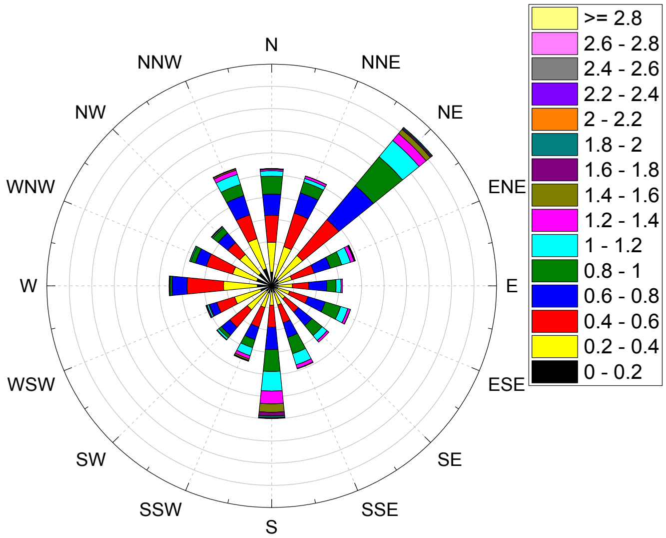

Fig. 6. Wind rose diagram for mean wind direction for year 2016

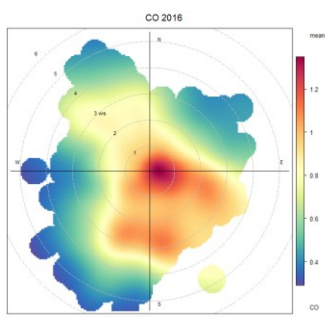

Fig. 7. Polar graph for CO in 2016

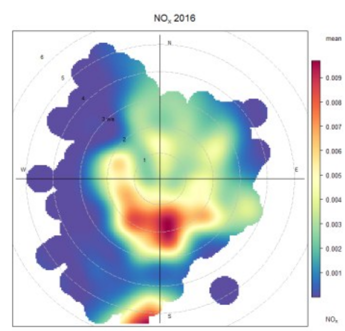

Fig. 8. Polar graph for NO_x 2016

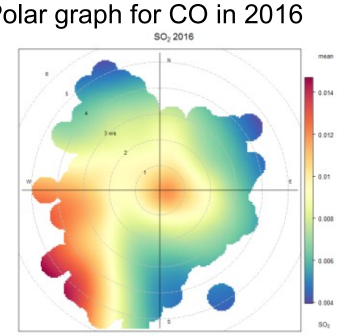

Fig. 9. Polar graph for SO_2 2016

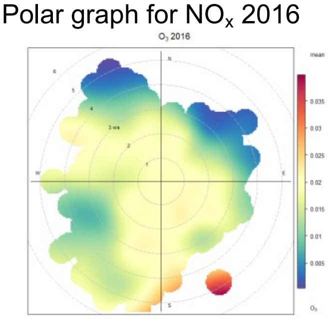

Fig. 10. Polar plot ozone 2016

Figure 11 shows wind rose plot for 2017. When multiple monitoring stations are available, the wind speed dependence of a source can reveal important details about the source type and characteristics. In 2017, there was indications of increasing CO concentrations when wind speed increased from the east and south-east, as seen in Figure 12. For a variety of wind speeds, there was also evidence that the source is located in the SSE. In 2017, there was evidence of increasing NO_x concentrations as wind speed increased from the south and south-west, as seen in Figure 13. In 2017, there were indications of increasing SO_2 concentrations when wind speed increased from the east and south-west, as seen in Figure 14. For a variety of wind speeds, there is additional evidence of a source to the southwest. In 2017, there was evidence of increasing O_3 concentrations when the wind speed increased from the south-east, as seen in Figure 15. For a variety of wind speeds, there is additional evidence of a source to the southeast.

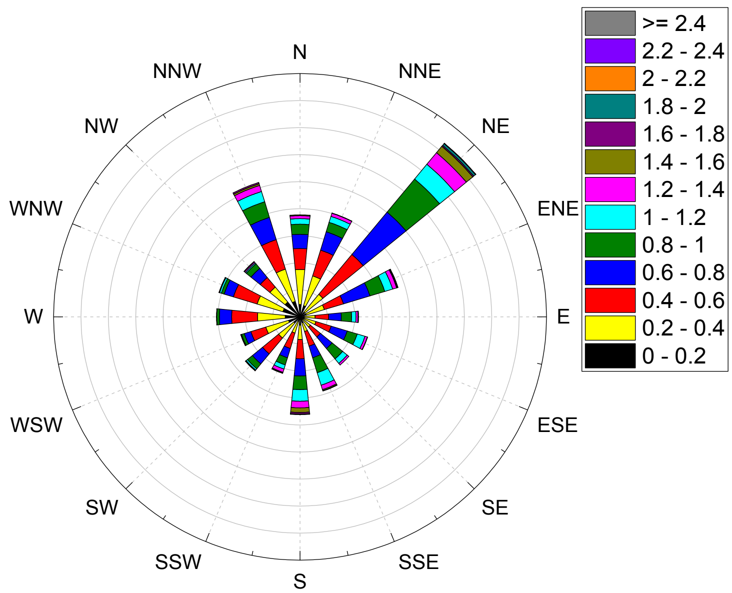

Fig. 11. Wind rose diagram for mean wind direction for year 2017

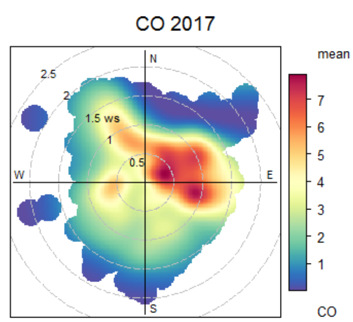

Fig. 12. Polar plot of CO for 2017

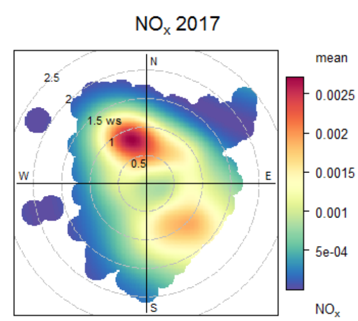

Fig. 13. Polar plot of NO_x for 2017

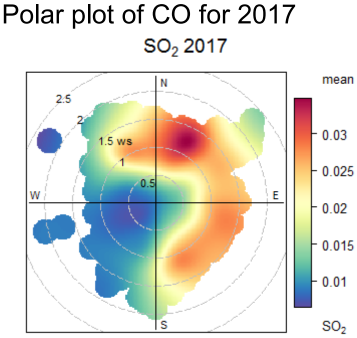

Fig. 14. Polar plot of SO_2 for 2017

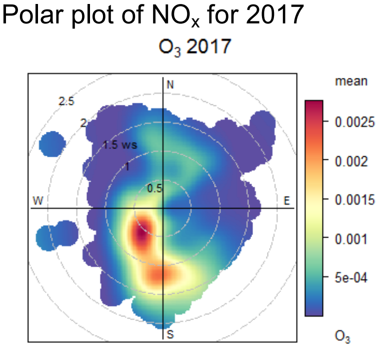

Fig. 15. Polar plot of O_3 for 2017

Time Variation of Pollutants

Figure 16 shows a time variation plot of CO for the year of 2016. The graph shows that over a 24-hour day in 2016, CO concentrations were higher during the first 12 hours of the day but steadily decreased over the remaining 12 hours of the day. Starting in June, CO concentrations have been rising steadily. From the weekly analysis, CO concentrations increased sharply on Fridays and dropped sharply on weekends.

Figure 17 shows a time variation plot of NO_x for the year of 2016. The graph shows that over the 24-hour period in 2016, NO_x concentrations increased steadily throughout the 24 hours. NO_x concentration increases steadily from August onwards. In the analysis of weekdays, a sharp increase in NOx concentration was observed on Wednesdays, a sharp drop in concentration in the middle of the week and a slight increase during weekends.

Figure 18 shows a time variation plot of SO_2 for the year of 2016. The graph shows that in the 24-hour day of 2016, there was a steady increase in SO_2 concentration throughout the 24-hour day. However, during the last 6 hours of the day, the concentrations decreased. The concentration of SO_2 increased steadily since August. For the weekday analysis, there was a sharp increase in SO_2 concentration on Wednesdays and Fridays, a sharp drop in concentration on Thursdays and a sharp decrease during the weekends.

Figure 19 shows a time variation plot of O_3 for the year of 2016. The plot shows that in the 24-hour day of the year of 2016, there was a steady increase of O_3 concentration throughout the 24 hours of the day. However, during the last 6 hours of the day, the concentrations decreased. The concentration of O_3 increased steadily since May. For the weekday analysis, there was a sharp increase in O_3 concentration on Thursdays and Saturdays, a sharp drop in concentration on Fridays and a sharp decrease during the weekends.

Figure 20 shows a time variation plot of CO for the year of 2017. The plot shows that in the 24-hour day within the year of 2017, there was a steady increase of CO concentration throughout the 24 hours of the day. However, there was a drop-in concentration during the last 6 hours of the day. The concentration of CO increased steadily since August. For the weekday analysis, there was a sharp increase in CO concentration on Thursdays and Saturdays, a sharp drop in concentration on Fridays and a sharp decrease during the weekends.

Figure 21 shows a time variation plot of NO_x for the year of 2017. The graph shows that in 2017, NO_x concentrations rose sharply during 12 hours of the day over a 24-hour period. The concentration of NO_x increased sharply in the month of July. For the weekday analysis, there was a sharp increase in NO_x concentration on Wednesdays and a sharp drop in concentration towards the weekends.

Figure 22 shows a time variation plot of SO_2 for the year of 2017. The plot shows that in the 24-hour day of 2017, there was a steady increase of SO_2 concentration throughout the next 12 hours of the day. However, there was a drop-in concentration during the last 6 hours of the day. There was a sharp increase in concentration of SO_2 in the month of May. For the weekday analysis, there was a sharp increase in SO_2 concentration on Tuesdays and a sharp drop in concentration towards the weekends.

Figure 23 shows a time variation plot of O_3 for the year of 2017. The plot shows that in the 24-hour day of 2017, there was a steady increase of O_3 concentration during the first 12 hours of the day. However, there was a slight increase in the concentration during the last 6 hours of the day. The concentration of O_3 increased steadily since March.

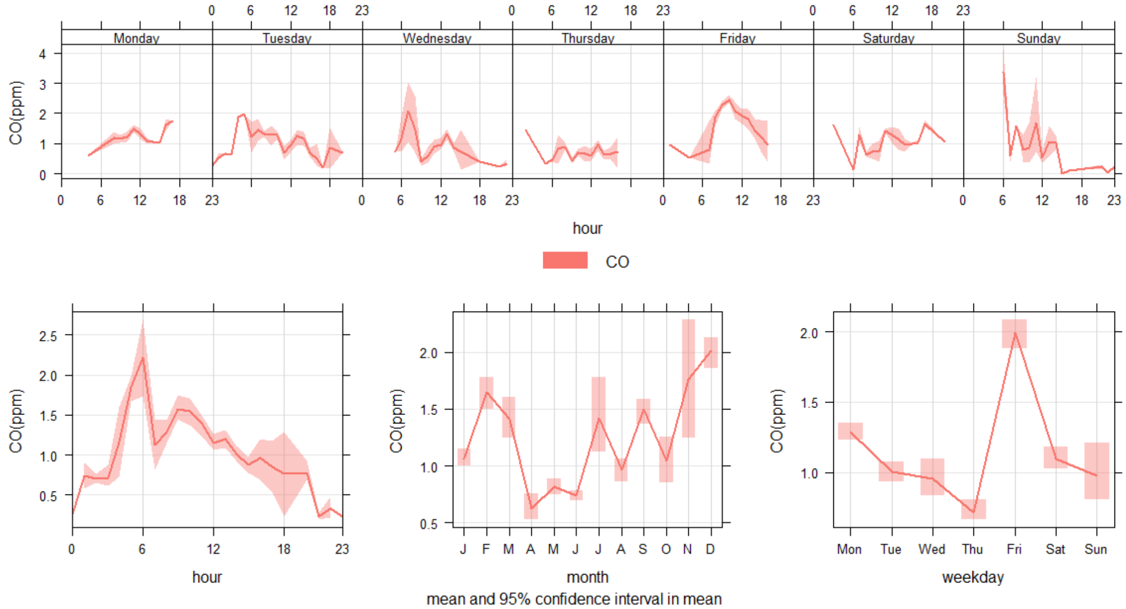

Fig. 16. Time variation of CO for 2016

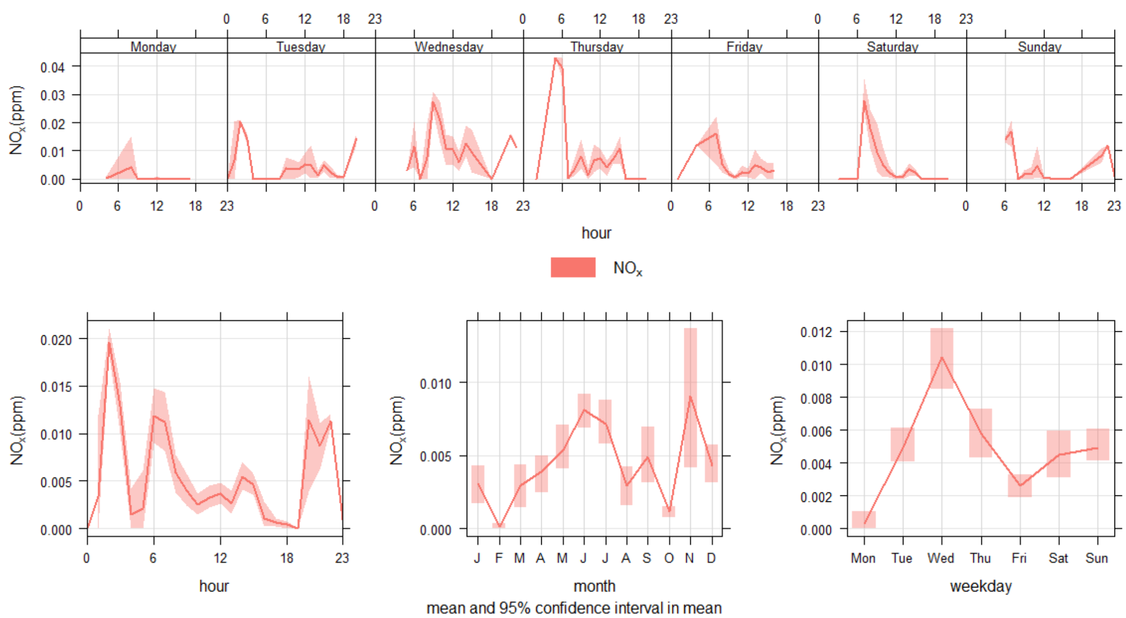

Fig. 17. Time variation of NO_x for 2016

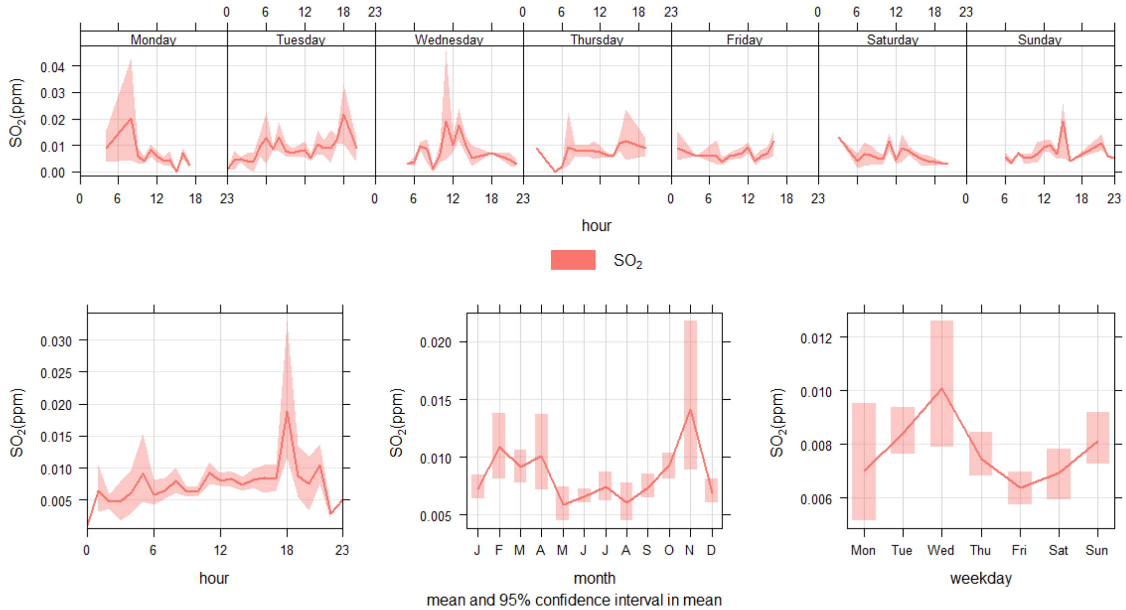

Fig. 18. Time variation of SO_2 for 2016

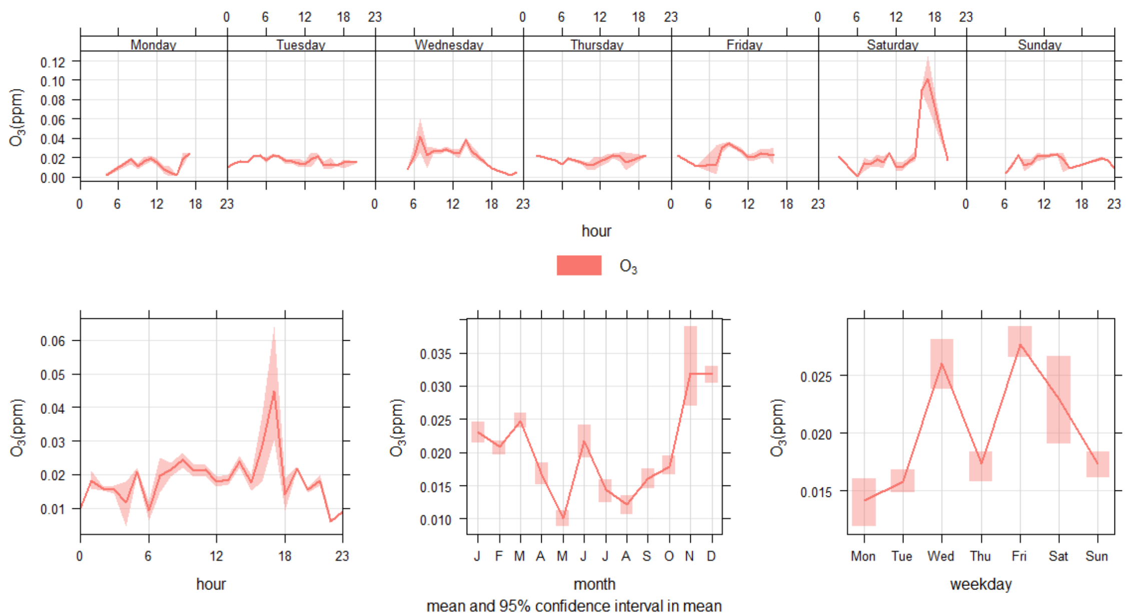

Fig. 19. Time variation of O_3 for 2016

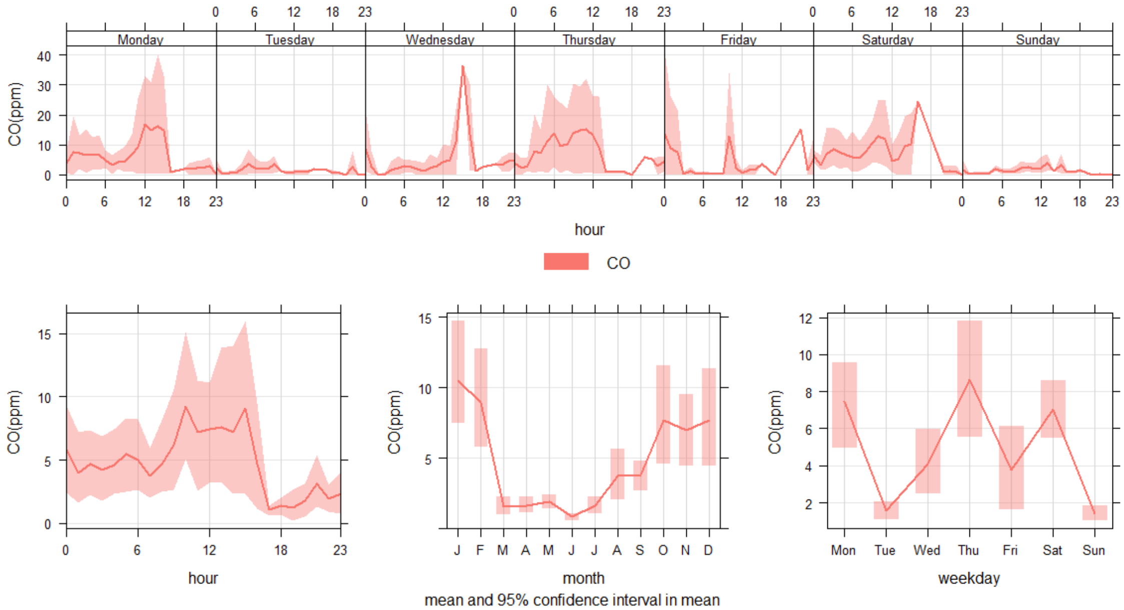

Fig. 20. Time variation of CO for 2017

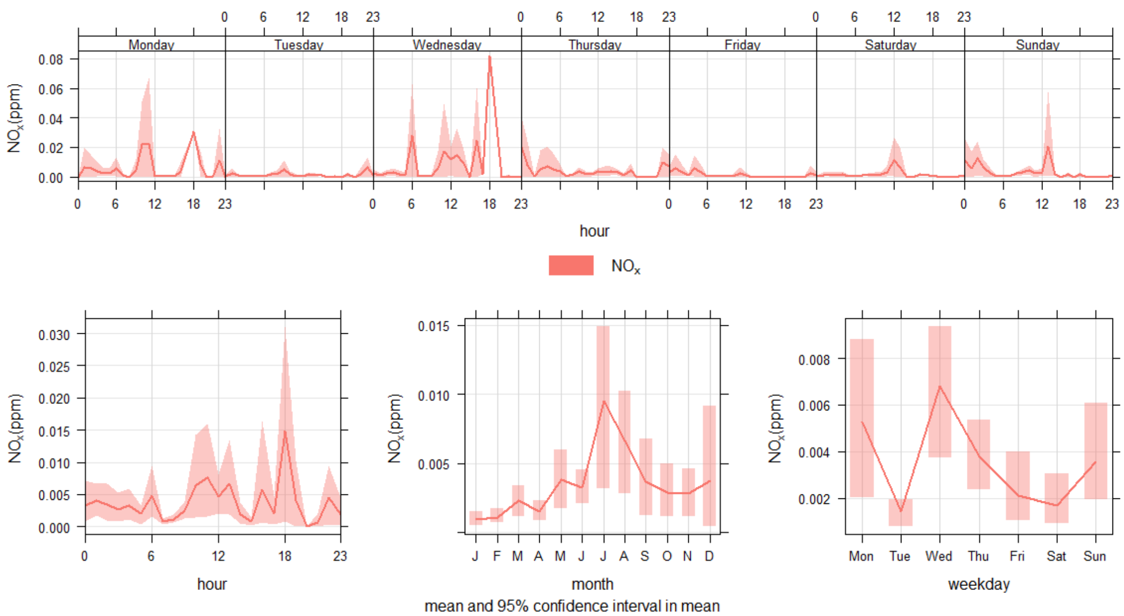

Fig. 21. Time variation of NO_x for 2017

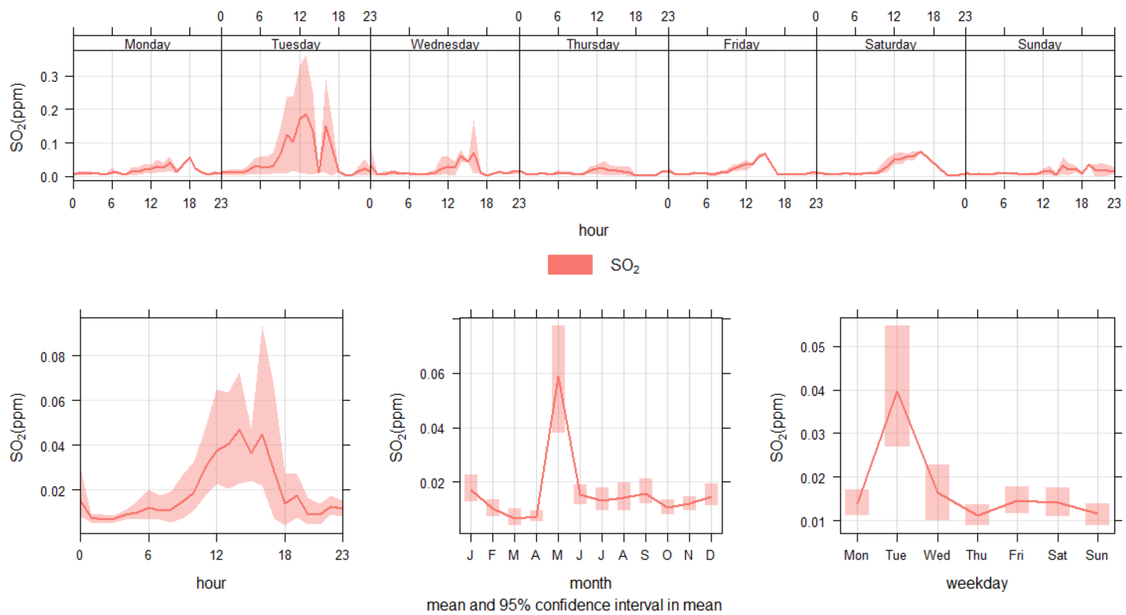

Fig. 22. Time variation of SO_2 for 2017

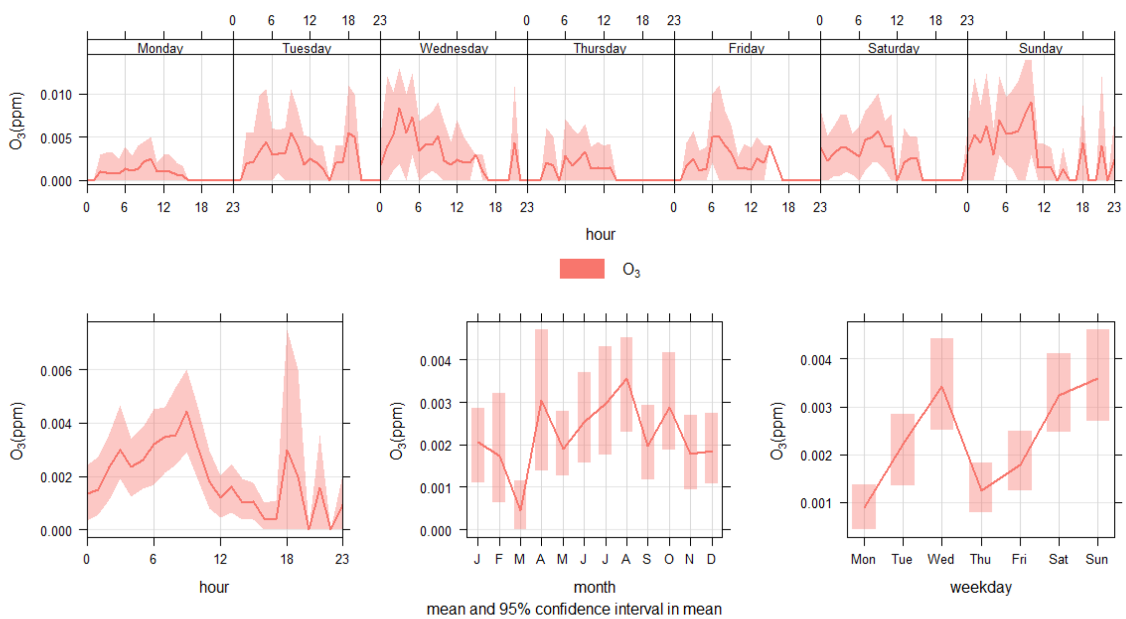

Fig. 23. Time variation of O3 for 2017

Trend Analysis

Table 10 shows the Mann-Kendall trend analysis parameters representing the air quality index analysis, including: Z-value, Mann-Kendall statistic (S), probability value (p-value), and tau (τ) for 2016. It can be seen that there were "no trend" recorded for O_3 and NO_x. This is because the p-value is greater than the set alpha value of 0.05, so we concluded that there was no trend. Since there is no trend, the positive z-scores become insignificant, as well as the positive tau values. For SO_2, and CO, the p-value is less than the set alpha value of 0.05, hence we concluded that there was a trend. Positive z-scores, along with positive tau values, indicated an upward trend.

Table 11 shows the Mann-Kendall trend analysis parameters including the Z-value, the Mann-Kendall statistic (S), the probability value (p-value), and the tau (τ) for the year of 2017. It can be seen that there were "no trend" recorded for CO, SO_2, NO_x and O_3.

Table 12 shows the Mann-Kendall trend analysis parameters which include the Z-value, the Mann-Kendall statistic (S), the probability value (p-value), and the tau (τ) for the combined period of study. From this Table, it can be seen that there were "no trend" recorded for O_3, NO_x and CO. For SO_2, the p-value is less than the set alpha value of 0.05, hence we concluded that there was a trend. The positive z-value as well as the positive tau value for CO and NO_x show that the trend was an increasing trend. The smaller value of Sen's slope indicates a smaller increase.

Table 10. Mann-Kendall trend test parameters for 2016

Pollutant	Z-value	Sen's slope	p-value	tau(τ)	Trend
O_3	0.702	0.177	0.483	0.167	No Trend
NO_x	0.071	0.000	0.944	0.030	No Trend
CO	2.126	1.161	0.034	0.485	Increasing Trend
SO_2	2.072	0.863	0.038	0.470	Increasing Trend

Table 11. Mann-Kendall trend test parameters for 2017

Pollutant	Z-value	Sen's slope	p-value	tau(τ)	Trend
O_3	1.519	2.042	0.129	0.348	No Trend
NO_x	0.139	0.000	0.890	0.045	No Trend
CO	0.962	12.940	0.336	0.227	No Trend
SO_2	0.630	0.694	0.529	0.151	No Trend

Table 12. Mann-Kendall trend test parameters for 2016-2017

Pollutant	Z-value	Sen's slope	p-value	tau(τ)	Trend
O_3	-0.342	0.000	0.733	0.041	No Trend
NO_x	0.253	0.000	0.800	0.003	No Trend
CO	3.584	1.317	3.385	0.413	No Trend
SO_2	2.838	0.410	0.004	0.326	Increasing Trend

SUMMARY AND CONCLUSIONS

Summary

The characterization of air quality parameters has been carried out for the coastal city of Calabar. The data for this work were obtained in two parts. The first part which was used for the development of an air quality map based on AQI calculation was obtained via mobile hand held aeroqual gas sensors. The second part was obtained via the stationary AQM65 machine stationed at the University of Calabar. The data obtained covered a period of twenty-four (24) months. The results show that the average concentration of ozone (O_3) was 0.34ppm which is higher than the World Health Organization standard annual average value of 0.04ppm. The least concentration value was obtained in March with concentration value of 0.01ppm. The average concentration of carbon monoxide (CO) was 4.52ppm which is higher than the Nigerian national standard annual average value of 4.05ppm. The average concentration of Sulfur dioxide (SO_2) was 0.53ppm which is greater than the World health Organization (WHO) standard of 0.008ppm 24hr mean and 0.213ppm 10 minutes mean. It is also greater than the Nigerian national standard annual average value of 0.08ppm. It was also observed that there is no marked difference in the average concentration of SO2 from January to December. The average concentration of Nitrogen Oxides (NO_x) was 0.06ppm which again is greater than the WHO standard of 0.02ppm but less than 0.09ppm 1hr mean. It is also less than the Nigerian national standard annual average value of 0.08ppm. The concentration of NO_x was low in months of March to August with concentration ranging from 0.02 to 0.013ppm.

It has been discovered that the highest concentration of ozone (O3) was obtained in December with concentration of 0.031ppm which is lower than the World Health Organization standard annual average value of 0.1ppm. The least concentration value was obtained in March with concentration value of 0.01ppm. This high concentration in December could be due to the fact that ozone concentration increases with increase solar radiation, hence December is the peak of dry season in Nigeria which comes with intense solar radiation. The highest concentration of carbon monoxide (CO) was obtained in August with concentration of 9.876ppm which is higher than the Nigerian national standard annual average value of 4.05ppm. the least concentration value was obtained in march with concentration value of 1.141ppm. August is the peak of rainy season in Nigeria. During this period, many people tend to stay indoors. This prompts the use of gasoline generators to keep them occupied. More personal cars also ply the roads during this period. This can explain the slightly high concentration of CO during this period. The highest concentration of sulfur dioxide (SO_2) was obtained in August with concentration of 0.017ppm which is lower than the Nigerian national standard annual average value of 0.08ppm. The least concentration value was obtained in February and march with concentration value of 0.01ppm.

It could also be observed that there is no marked difference in the average concentration if SO_2 from January to December. The highest concentration of Nitrogen Oxides (NO_x) was obtained in October with concentration of 0.005ppm which is lower than the Nigerian national standard annual average value of 0.08ppm. The concentration of NO_x was low in months of March to August with concentration ranging from 0.02 to 0.013ppm. Considering the effect of meteorology on the pollutants, CO had the highest correlation coefficient R = -0.81 with temperature while it had the least correlation coefficient R = 0.11 with ozone. This shows that temperature had about 81% impact on CO compared with the other variables though negatively. SO2 had the highest correlation coefficient R = -0.89 with TSP while it had the least correlation coefficient R = 0.36 with ozone. This shows that SO_2 had about 89% impact on TSP compared with the other variables though negatively. As the concentration of TSP increased in the atmosphere, the concentration of SO_2 decreased. O_3 had the highest correlation coefficient R = -0.43 with temperature while it had the least correlation coefficient R = 0.11 with CO. This shows that O_3 had about 43% impact on TSP compared with the other variables though negatively. NOx had the highest correlation coefficient R = -0.67 with CO while it had the least correlation coefficient R = 0.17 with wind speed. This shows that NO_x had about 67% impact on CO compared with the other variables though negatively. TSP had the highest correlation coefficient R = -0.92 with relative humidity while it had the least correlation coefficient R = -0.43 with ozone. This shows that relative humidity had about

92% impact on TSP compared with the other variables though negatively. The air quality map developed reveals that 82% of the stations were categorized as “marginally polluted”, which falls with the group (51-100). Also 14% of the stations were categorized as “Good”, while the remaining 4% of the stations were categorized as “unhealthy”. From the stationary data, AQI has the highest correlation of R = 0.93 with NOx. This shows that NOx has the greatest impact on AQI while CO has the least impact with R = -0.12. Ratio analysis shows mobile sources are contributing to CO and SO_2 concentration in the city of Calabar compared to point sources. This work will also provide scientist with a tested model which is the DWT-ARIMA model which has outperformed the ARIMA model in the forecasting of air quality in the city of Calabar. For the year 2016, there were Increasing trends for SO_2, CO. There were no trends recorded for NOx and O_3. This is because the p-value is greater than the set al. pha value of 0.05 hence we conclude that there is no trend. The positive z-value as well as the positive tau value becomes insignificant since there is no trend. For the year 2017, there are no trends recorded for CO, SO_2, NO_x and O_3.

Conclusions

The following conclusions have been drawn from this research work:

1. A comprehensive air quality study has been carried out for Calabar, Nigeria. There has not been such a study in Calabar prior to this study.
2. An air quality map has been developed for Calabar. This map will give policy makers the insight on the air quality situation in Calabar and its environs. It will als help them come up with method to improve air quality in the affected areas.
3 That due to the importance of this research, monitoring of Air Quality should be done comprehensively throughout the country by placing monitoring equipment at strategic positions.
4 Further research should be done on transboundary air pollution to ascertain all the possible sources of transboundary pollution.
5 Catalytic converters should be inserted at the exhaust pipe of motor vehicles to reduce pollution.
6 Biofuels should be adopted in Nigeria as an alternative to fossil fuels.
7 Bicycles should be adopted as means of transportation in Nigeria.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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A Promising Path toward a Net-Zero Clean Energy Future in Africa and Southeast Asia

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This paper explores strategies for a rapid transition to net-zero energy in Africa and Southeast Asia through renewable energy sources. The study analyzes the current energy landscape and challenges faced by these regions, focusing on opportunities for economic development based on renewable energy generation, specifically solar PV and wind energy. The results show that an increase in renewable energy generation in Southeast Asia resulted in a comparable rise in renewable energy supply, electricity generation, and overall energy supply between 2021 and 2022. In Africa, an increase in renewable energy generation from 201-210 TWh demanded an increase in renewable energy supply, electricity generation, and overall energy supply between 2021 and 2022. Southeast Asia exceeded Africa in terms of solar PV generation in both years, with a share of 38-45 TWh, while Africa achieved a lesser proportion of 14-16 TWh in solar PV generation in the historical scenario. The same incremental trend was observed in both the stated policy scenario and the announced pledged scenario for both Africa and Southeast Asia in 2030 and 2050. According to the analysis, Africa produced a higher fraction of total wind energy production at 23–25 TWh, compared to Southeast Asia, which reported 9–14 TWh under the historical scenario between 2021 and 2022. However, according to the announced pledged scenario, Southeast Asia is predicted to outperform Africa in wind energy output between 2030 and 2050. However, by 2050, Southeast Asia is forecast to vastly outperform Africa in terms of wind energy output, with a staggering record of 1207 TWh compared to Africa's estimated 593 TWh. The authors propose five potential solutions to the challenges of renewable energy supply in Africa and Southeast Asia, based on the International Energy Agency's forecast between 2030 and 2050. These include exploring solar energy advancements, floating turbines, wave energy converters, ocean thermal energy conversion systems, energy storage and thermal energy solutions, and IoT integration for energy efficiency enhancement. The authors emphasize the need for long-term solutions and suggest policy implications for sustainable scenarios that encourage environmentally sound behaviors, drive economic growth, and promote social development. These scenarios include integrated resource planning, market liberalization, government incentives, and capacity-building.

Keywords: Renewable energy; Sustainable development; Decarbonization; Energy transition; Cutting-edge strategies; Net-zero transition

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Introduction

The global imperative to achieve a net-zero clean energy future is of utmost urgency, and this transformative shift is equally critical for Africa and Southeast Asia. These regions, like the rest of the world, face the daunting challenge of transitioning to sustainable energy systems in order to mitigate climate change and ensure a prosperous future for their populations [1]. These regions possess an abundance of natural resources [2], including solar, wind, geothermal, and hydroelectric power, which makes them highly promising for the development of renewable energy sources. By harnessing these resources effectively, these areas can establish themselves as leaders in sustainable energy production and contribute significantly to reducing carbon emissions. Given the unique economic challenges faced by regions like Africa [3] and Southeast Asia, it is imperative that they embrace forward-thinking and pioneering approaches to swiftly achieve a net-zero energy future [4]. By harnessing cutting-edge strategies, these regions can effectively address their energy needs [5] while simultaneously mitigating the adverse effects of climate change [6]. Such innovative solutions will not only ensure sustainable development but also pave the way for economic growth [7] and improved quality of life for their populations [8]. These strategies should prioritize the utilization of sustainable energy sources [9] to effectively address the escalating energy requirements [10] in these regions. By leveraging renewable energy sources, we can efficiently cater to increasing energy demands [11] while ensuring environmental preservation [12] and long-term viability [13].

Our objective is to leverage the outcomes derived from data analysis to foster knowledge exchange among these regions, thereby enabling them to make well-informed decisions and successfully attain their renewable energy objectives. By harnessing the power of data analysis, we aim to empower these regions with the necessary insights and expertise required to drive their renewable energy ambitions forward. Through data analysis, we can identify patterns and trends in renewable energy usage, allowing us to develop targeted strategies and solutions for each region's unique challenges. By sharing this knowledge and expertise, we can create a collaborative environment where regions can learn from each other's successes and failures, accelerating the global transition towards sustainable energy sources.

To analyze the complex relationship between energy demand and macroeconomics in Africa and Southeast Asia, we used the following data: population (millions), share of urbanization (urbanization percentage), total consumption (EJ), total CO_2 emission (MtCO2), oil production (Mb/d), oil demand (Mb/d), natural gas production (bcm), natural gas demand (bcm), coal production (Mtce), and coal demand (Mtce). These data points allowed us to assess the correlation between energy demand and various economic indicators in Africa and Southeast Asia. By examining the population, urbanization rate, total consumption, CO_2 emissions, oil production and demand, natural gas production and demand, as well as coal production and demand, we gained valuable insights into the intricate interplay between energy needs and macroeconomic factors in these regions. This comprehensive analysis will provide a foundation for understanding the dynamics of energy demand and its impact on economic development in Africa and Southeast Asia. Additionally, it will help identify potential regions for investment and policy interventions to promote sustainable energy solutions and address the challenges of energy access and climate change in these regions. By considering the socio-economic context and specific energy requirements of each region, this analysis aims to inform decision-makers and stakeholders on strategies that can foster inclusive growth and mitigate environmental risks in Africa and Southeast Asia.

Our research delves into the energy transformation landscapes of Africa and Southeast Asia, enabling us to pioneer revolutionary solutions for the energy industry in these regions. By analyzing and understanding the unique challenges and opportunities presented by these landscapes, we strive to implement game-changing ideas that will revolutionize the energy sector in both Africa and Southeast Asia. This research segment aims to explore diverse avenues for securing international funding, strategically directed towards catalyzing sustainable energy transitions in different regions of Southeast Asia. We believe that securing international funding is crucial for driving sustainable energy transitions in Southeast Asia. By exploring diverse avenues, such as partnerships with global financial institutions and engaging with private investors, we aim to leverage the necessary resources to implement our game-changing ideas. Our goal is to not only address the unique challenges faced by these regions but also create a ripple effect that will transform the energy sector across Africa and Southeast Asia.

By analyzing the data on total energy supply, renewable energy supply, electricity generation, solar PV generation, and wind generation in Africa and Southeast Asia, we can gain valuable insights into the current state of renewable energy generation in these regions. This information will enable us to identify trends, patterns, and potential challenges that may arise in achieving their renewable energy goals. Ultimately, our goal is to share this knowledge with these nations to empower them to make informed decisions that will drive sustainable development and help them achieve their renewable energy targets. By analyzing the data on solar PV and wind generation, we can also identify the areas with untapped potential for renewable energy in Africa and Southeast Asia. This will help us prioritize investments [14] and resources in these regions, maximizing their capacity for clean energy production [15] and reducing reliance on fossil fuels [16]. Understanding the challenges faced by these regions in implementing renewable energy projects will allow us to provide targeted support and solutions to overcome barriers and accelerate their transition towards a greener future [17].

In this section, our investigation aimed to identify the most viable and sustainable solutions for renewable energy supply in Africa and Southeast Asia. By exploring advancements in solar energy, such as perovskite solar cells and solar paint, as well as other innovative technologies like floating turbines and airborne systems, wave energy converters, ocean thermal energy conversion systems, flow batteries, hydrogen storage, thermal energy solutions, and the potential of IOT integration for energy efficiency enhancement, we sought to determine the most promising prospects and next steps for these regions. These technologies offer unique advantages and solutions to the energy challenges faced by Africa and Southeast Asia. Perovskite solar cells and solar paint provide cost-effective and efficient ways to harness solar energy, while floating turbines and airborne systems tap into the vast potential of wind energy. Wave energy converters, ocean thermal energy conversion systems, flow batteries, hydrogen storage, thermal energy solutions, and IOT integration offer diverse options for sustainable energy generation and storage. By embracing these innovations, these regions can not only increase their energy independence but also reduce their carbon footprint [18] and contribute to global efforts to combat climate change [18]. Furthermore, the adoption of these technologies can stimulate economic growth and create job opportunities in the renewable energy sector [19], promoting a sustainable and prosperous future for Asia [20].

We undertook an extensive exploration of various sustainable solutions to investigate the policy implications for renewable energy supply in Africa and Southeast Asia. Our approach involved initiating four distinct scenarios, each targeting a specific aspect. These scenarios encompassed integrated resource planning, market liberalization, government incentives, and capacity building, enabling us to comprehensively assess the potential impacts and opportunities for renewable energy in these regions. Through integrated resource planning, we analyzed the optimal allocation of renewable energy resources in Africa and Southeast Asia, taking into account factors such as geographical suitability and energy demand. Market liberalization allowed us to evaluate the potential for increased competition and private sector investment in renewable energy markets. Additionally, government incentives were examined to understand how policy support can encourage the adoption of renewable energy technologies. Lastly, capacity-building initiatives were explored to assess the readiness of local communities and institutions to embrace renewable energy solutions. Overall, our study provides a comprehensive analysis of the factors influencing the growth and adoption of renewable energy technologies. It highlights the importance of a multi-faceted approach that combines market dynamics, government policies, and community engagement to accelerate the transition towards a sustainable energy future. The findings from our study can serve as a valuable resource for policymakers [21], investors [22], and stakeholders interested in promoting renewable energy development [23] and achieving climate change mitigation goals [24].

Exploring the Intricate Relationship between Energy Demand and Macro-Economics in Africa and South Asia

Exploring the intricate relationship between energy demand and macro-economics in Africa and Southeast Asia reveals a complex web of factors that shape the energy landscape in these regions. As these economies continue to grow, the demand for energy is skyrocketing, presenting both challenges and opportunities for sustainable development. Understanding the dynamics between energy demand and macro-economic indicators is crucial for devising effective policies [25] and strategies to meet rising energy needs [26] while ensuring economic stability [27] and environmental sustainability [28]. Factors such as population growth [29], urbanization [30], and industrialization [31] play a significant role in driving the energy demand in Africa and Southeast Asia. The availability and accessibility of energy resources [1], technological advancements [20], and government policies [32] also influence the energy landscape [33] in these regions. Therefore, a comprehensive analysis of these interrelated factors is essential for developing a holistic approach towards sustainable energy development [16] in Africa and Southeast Asia.

According to the United Nations, the population of Southeast Asia is projected to reach approximately 700 million by 2030 and could further increase to nearly 760 million by 2050 [34]. This rapid population growth will undoubtedly have significant implications for energy demand in the region. As the population expands, so does the need for electricity, transportation, and other energy-intensive services [35]. The International Energy Agency [36] estimates that Southeast Asia's energy demand will grow by almost 60% between 2019 and 2040, making it one of the fastest-growing regions in the world. This surge in energy demand poses challenges for governments and policymakers to ensure a reliable and sustainable energy supply. Meeting this increasing demand will require significant investments in infrastructure, renewable energy sources, and energy efficiency measures to reduce reliance on fossil fuels and mitigate the environmental impact.

According to the United Nations, Africa's population is projected to reach 2.5 billion by 2050, almost doubling its current population [34]. This rapid growth is expected to have significant implications for energy demand on the continent. The International Energy Agency estimates that Africa's energy demand will grow by 60% between 2019 and 2040 [16]. Meeting this growing energy demand sustainably will require a comprehensive approach that includes not only increasing energy production but also implementing policies and initiatives to promote energy conservation and efficiency [36]. These figures highlight the urgent need for sustainable and accessible energy solutions [37] to meet the growing demands of Africa's population and economy [38]. It is essential to prioritize the development of clean and affordable energy infrastructure [39] that can provide reliable power to both urban and rural areas [40].

According to a report by the United Nations, Africa's urban population is projected to nearly triple by 2050, reaching 1.34 billion people [34]. This rapid urbanization will significantly impact energy demand on the continent [41]. For instance, a study conducted by the International Energy Agency estimates that Africa's urban areas will account for 56% of the continent's total energy consumption by 2040 [34]. The increasing urbanization in Africa will lead to a rise in energy demand due to various factors such as increased population density, economic growth, and improved living standards. As more people migrate to cities in search of better opportunities, the demand for energy-intensive activities like transportation [42], housing [25, 43], and industrial production will increase [44]. The growing middle class in urban areas will also contribute to higher energy consumption as they adopt modern lifestyles and consumer habits [41]. These factors highlight the urgent need for Africa to invest in sustainable and renewable energy sources to meet the rising energy demands of its urban population [45]. The datasets obtained from Table 1 were used to compare the population assumptions of Africa and Southeast Asia in relation to energy demand and macroeconomic impacts using the compound annual growth rate within 2000–2022, 2022–2030, and 2022–2050, as well as the projected timescale in millions ranging from 2022–2050. Africa and Southeast Asia showed a continuous drop under the compound annual growth rate scenario. Africa surpassed Southeast Asia by 2.6% between 2000 and 2022, whereas Southeast Asia contributed 1.2%. These findings suggest that Africa's population growth rate has been higher than that of Southeast Asia during the specified time period. However, it is important to note that population growth rates can vary significantly within different regions and countries within Africa and Southeast Asia. Additionally, other factors, such as economic development and government policies [46], may also play a role in determining energy demand and macroeconomic impacts in these regions [47] as shown in Table 1. For example, countries with higher levels of industrialization and urbanization may have higher energy demands compared to countries that are more rural and agricultural [48]. Government policies promoting renewable energy sources can also influence energy demand and macroeconomic impacts in both Africa [49] and Southeast Asia. Therefore, it is crucial to consider these factors when analyzing the relationship between population growth, energy demand, and macroeconomic impacts in these regions.

Systematic and best evidence reviews have a methods section. This section enables motivated researches to repeat the review. Narrative reviews do not have a methods section but should include some information about applied methods at the end of the introduction.

Regarding the compound average annual growth rate of the population by region, Africa contributed 2.3% from 2022 to 2030, and Southeast Asia contributed 0.8% as presented in Table 1. The growth rates reflect diverse population patterns throughout areas, with Africa exhibiting more population increase than Southeast Asia. Fertility rates, death rates, and migration patterns significantly influence population dynamics. However, Southeast Asia is expected to contribute 2.0% between 2022 and 2050, whereas the Southeast contributed 0.5%. In 2022, Africa had a population of 1425 million, while Southeast Asia had a population of 679 million. However, by 2030, Africa had substantially surpassed Southeast Asia, with a population of 1708 million compared to 739 million in Southeast Asia. Africa had the most people in 2050, with a total population of 2482 million, while Southeast Asia had 787 million. It is impossible to overlook the effects of this prospective population growth in Africa and Southeast Asia on energy demand, especially with regard to infrastructure development and energy consumption [50]. With a significantly larger population, Africa's energy demand is expected to rise exponentially, putting pressure on its already strained resources and necessitating the need for extensive investment in energy infrastructure. Similarly, Southeast Asia's growing population will also require substantial energy resources to meet their increasing needs, highlighting the urgency for sustainable and efficient energy solutions in the region.

The data extracted from Table 1 serves as a crucial foundation for examining the correlation between urbanization rates and the percentage of population in Africa and Southeast Asia, particularly concerning energy consumption and its macroeconomic consequences. This analysis encompasses both the historical period (2022) and future projections (2030 and 2050), providing valuable insights into the anticipated trends in these regions [51]. Table 1 presents compelling evidence of the sustained growth in urbanization across the regions from 2030 to 2050. The data depicted in the Table 1 unequivocally demonstrates the progressive increase in urbanization trends over the specified period. However, Southeast Asia's urbanization rate clearly exceeded Africa's in 2022, 2030, and 2050, with aggregate percents of 52%, 56%, and 66%, respectively, compared to Africa, which delivered 44%, 48%, and 59% in 2022, 2030, and 2050, respectively. In terms of urbanization, Southeast Asia outpaced Africa significantly in 2022, 2030, and 2050. The urbanization rates for Southeast Asia during these years stood at 52%, 56%, and 66%, respectively, whereas Africa recorded lower percentages of 44%, 48%, and 59% for the same periods. This divergence highlights the remarkable progress made by Southeast Asian countries in transforming their urban landscapes. However, the effects of urban growth on energy demand in this region are of increasing concern. Rapid urbanization often leads to a surge in energy consumption as cities require more resources to power infrastructure, transportation, and residential areas [52]. As Southeast Asia continues to urbanize at a faster pace than Africa, it is crucial for policymakers and stakeholders to address the potential challenges associated with meeting the growing energy demands in a sustainable and efficient manner. This includes investing in renewable energy sources, implementing energy-efficient technologies, and promoting sustainable urban planning [53] practices to mitigate the environmental impact of urban growth [54]. The rapid urbanization of Southeast Asia has led to an increased demand for energy, particularly in the transportation and housing sectors. This surge in energy consumption poses challenges for the region's sustainability goals and calls for innovative solutions to ensure efficient and clean energy sources are utilized. The strain on infrastructure and resources due to urban growth must be carefully managed to avoid potential environmental and social consequences [55].

According to a recent study by the International Energy Agency [34], Southeast Asia is projected to witness a significant urbanization trend in the coming decades. The report estimates that by 2050, around 70% of the region's population will be living in urban areas, compared to the current 50%. This rapid urbanization is expected to have profound implications for energy demand. As cities expand and populations increase, there will be a surge in energy consumption for various purposes, such as transportation, housing, and industrial activities. The International Energy Agency [16] highlights that urban areas consume approximately 78% of the world's energy and are responsible for around 60% of global greenhouse gas emissions [16]. As Southeast Asia undergoes this urbanization trend, there will be a pressing need to address the energy consumption and environmental impact of cities in order to ensure sustainable development in the region. Efforts to promote energy efficiency [56], renewable energy sources [57], and smart city technologies will be crucial in mitigating the potential negative effects of rapid urbanization on energy demand and climate change [58].

The potential industrialization of Southeast Asia is projected to have a significant impact on energy demand in the region [59]. According to a report by the International Energy Agency [60, 61], Southeast Asia's energy demand is expected to increase by 80% between 2017 and 2040, making it one of the fastest-growing regions in terms of energy consumption. This surge in energy demand can be attributed to the rapid growth of industries such as manufacturing, construction, and transportation [62], which are key drivers of economic development in the region. For instance, countries like Vietnam and Indonesia have been attracting foreign investments in various industries such as manufacturing, electronics, and automotive [60]. This surge in industrial activities will undoubtedly lead to a substantial rise in energy demand across Southeast Asia. As these industries continue to expand and modernize, the need for energy-efficient technologies and renewable energy sources becomes crucial in order to meet the growing energy demand sustainably [63].

The potential industrialization of Africa is a topic of great interest and has the potential to significantly impact energy demand in the continent. According to a report by the United Nations Industrial Development Organization summit with IEA, IRENA, and World Bank, Africa's industrial sector has been growing steadily, with manufacturing output increasing by 3.5% annually between 2005 and 2015[64]. According to a report by the International Energy Agency [64], Africa's industrialization is projected to significantly impact its energy demand in the coming years. The report states that by 2040, Africa's industrial sector could account for nearly half of the continent's total energy consumption, highlighting the potential for rapid growth and development. This growth is expected to continue, driven by factors such as population growth, urbanization, and rising consumer demand [65]. These factors are expected to lead to an increase in the manufacturing and construction sectors, further driving up energy demand.

Africa is continent rich in diverse energy resources, with vast potential for both conventional and renewable sources. According to the International Energy Agency [64], Africa holds approximately 7% of global proven oil reserves and 7.5% of global natural gas reserves. The continent boasts significant coal reserves, particularly in South Africa [66]. Africa has abundant renewable energy resources, including solar, wind, hydro, and geothermal. For instance, the African continent receives an average of 325 days of sunshine per year [66, 67], making it a prime location for solar energy production [68]. It is estimated that Africa has the potential to generate over 10 terawatts of solar power, which is more than enough to meet the continent's energy needs [69]. Africa's wind resources are also substantial [70], with the potential to generate over 1,000 gigawatts of wind power [71]. The IEA estimates that Africa has the potential to generate more than 10 terawatts of solar power, which is more than the continent's current energy needs [64]. Africa's hydroelectric potential is estimated to be around 1,750 gigawatts, making it one of the largest untapped sources of renewable energy in the world year [72]. These renewable energy sources have the potential to not only provide clean and sustainable energy for Africa but also contribute to global efforts to combat climate change [73,74].

Southeast Asia is blessed with abundant energy resources, both conventional and renewable. According to the International Energy Agency [64], the region possesses significant oil and natural gas reserves, with proven oil reserves estimated at around 4.7 billion barrels and natural gas reserves of approximately 97 trillion cubic feet. Southeast Asia also possesses significant fossil fuel reserves [75]. The region is known for its substantial natural gas reserves, with countries like Indonesia and Malaysia being major producers and exporters [76, 77]. Southeast Asia has substantial coal reserves, with countries like Indonesia and Vietnam being among the top coal producers in the world. These fossil fuel reserves provide an alternative energy source for the region, ensuring a diverse energy mix and contributing to its potential availability and accessibility. Southeast Asia has a diverse range of renewable energy sources such as solar, wind, hydro, and biomass. According to a report by the International Renewable Energy Agency [16], the region has abundant renewable energy sources such as solar, wind, hydro, and biomass. For instance, solar energy potential in Southeast Asia is estimated to be around 442 GW by 2030. The accessibility of these energy resources varies across countries in the region. For instance, Indonesia has a significant potential for geothermal energy due to its location on the Pacific Ring of Fire, while countries like Vietnam and Thailand have favorable conditions for wind and solar energy generation [78]. The development and utilization of these renewable energy sources in Southeast Asia can not only reduce reliance on fossil fuels but also contribute to economic growth and job creation in the region [79].

Southeast Asia has witnessed significant technological advancements in various sectors, including renewable energy and smart grid systems. According to a report by the International Renewable Energy Agency [16], the region's renewable energy capacity is expected to increase by 230% by 2030, with solar and wind power leading the way. According to a report by the International Renewable Energy Agency [16], renewable energy capacity in Southeast Asia is expected to more than double by 2030. This growth can be attributed to the region's abundant renewable resources, such as solar and wind power. These advancements in clean energy technologies are likely to have a profound impact on the region's energy demand [80]. The implementation of advanced digital technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), can further enhance the efficiency and effectiveness of renewable energy systems in Southeast Asia [79]. By leveraging AI and IoT, renewable energy infrastructure can be better optimized, allowing for real-time monitoring and control of energy generation and consumption [79]. This not only improves the reliability and stability of the grid but also enables smarter energy management [81], ultimately reducing costs [77] and carbon emissions [82].

Africa has witnessed remarkable technological advancements in recent years, with a significant impact on energy demand. According to a report by the International Energy Agency [16], Africa's electricity demand is projected to double by 2040, growing at an annual rate of 4.5%. This surge in energy demand can be attributed to the increasing population, urbanization, and economic growth across the continent. Advancements in renewable energy technologies have the potential to revolutionize Africa's energy landscape [83]. For instance, the falling costs of solar photovoltaic (PV) panels [84] and the abundance of sunlight in many African countries present a great opportunity for widespread adoption of solar energy [85]. The IEA [18] estimates that by 2040, solar PV capacity in Africa could reach 320 gigawatts, which is equivalent to the total installed capacity of the continent's current power generation. This significant growth in solar energy can not only help meet rising energy demand but also reduce reliance on fossil fuels, mitigate climate change impacts, and improve energy access for remote and underserved communities [86]. The deployment of innovative storage technologies such as battery systems can ensure a stable and reliable power supply, even during periods of low sunlight or high demand.

Southeast Asia is expected to witness a significant increase in energy demand in the coming years due to its rapid economic growth and population expansion. To address this growing demand, governments in the region are likely to implement various policies aimed at diversifying their energy mix, promoting renewable energy sources, and enhancing energy efficiency. For instance, countries like Thailand and Indonesia have already set ambitious targets for renewable energy deployment. Thailand aims to generate 30% of its total energy from renewable sources by 2036, while Indonesia has set a target of reaching 23% renewable energy in its energy mix by 2025 [18]. These targets demonstrate the commitment of these countries to transition towards a more sustainable and environmentally friendly energy sector. Additionally, both Thailand and Indonesia have also introduced incentives and subsidies to attract investments in renewable energy projects, further accelerating the adoption of clean energy technologies in the region.

Africa is experiencing rapid economic growth and urbanization, leading to an increased demand for energy. To meet this growing demand, governments in Africa are implementing various policies to ensure a sustainable and reliable energy supply [87]. For instance, several countries are investing in renewable energy sources such as solar and wind power [88]. According to a report by the International Renewable Energy Agency [16], Africa has the potential to generate 310 gigawatts of renewable energy by 2030, which could significantly reduce its reliance on fossil fuels and contribute to a greener and more environmentally friendly energy sector. For instance, in South Africa, the government has implemented a Renewable Energy Independent Power Producer Procurement Program (REIPPPP) to encourage private investment in renewable energy projects [89]. This program has already attracted significant investments and has helped diversify the country's energy mix [90], reducing its dependence on coal-fired power plants [91]. South Africa has also set a target to install 8,400 megawatts of solar and wind capacity by 2030, further demonstrating its commitment to transitioning towards a sustainable energy future [92].

Table 2 presents an overview of energy consumption, CO_2 emissions, and fossil fuel trends in Africa and Southeast Asia spanning historical, stated policy, and declared promise scenarios from 2010 to 2050. The IEA research [93] distinguishes between historical scenarios, which examine the evolution of energy consumption and CO_2 emissions, and stated policy scenarios, which delineate the present trajectory based on existing legislation and pledges. The announced pledge scenario forecasts possible future results contingent upon nations fulfilling their commitments to decrease emissions and shift to greener energy alternatives. Africa's total final energy consumption increases consistently, reaching 42.8 EJ in the historical scenario by 2050, but declines to 33.3 EJ under declared promises, underscoring the influence of stringent climate pledges. In the historical scenario, Southeast Asia's consumption reaches a maximum of 33.8 EJ by 2050, while it declines to 27 EJ with the implementation of committed climate initiatives. CO_2 emissions in Africa show a decline from 1,991 Mt CO_2 in 2050 (historical) to 1,171 Mt CO_2 (pledges), reflecting substantial decarbonization initiatives. In Southeast Asia, emissions may significantly decrease under commitments, from 2,530 Mt CO_2 in 2050 to 982 Mt CO_2. Oil and coal output diminishes in both areas across all scenarios, particularly in the stated promises scenario, indicating worldwide transitions toward renewable energy sources. This underscores the increasing impetus toward realizing climate objectives, whereby the move to cleaner energy sources is crucial, bolstered by changes in energy consumption habits and a decrease in reliance on fossil fuels.

Table 1. Population assumptions by region

Region	Compound average annual growth rate			Population (million)			Urbanization (share of population)		
	2000-2022	2022-2030	2022-2050	2022	2030	2050	2022	2030	2050
Africa	2.6%	2.3%	2.0%	1,425	1,708	2,482	44%	48%	59%
Southeast Asia	1.2%	0.8%	0.5%	679	723	787	51%	56%	66%

Source: World Energy Outlook 2023 by International Energy Agency, certified under CC BY-NC-SA 2.0 [93].

Table 2. Renewable Energy Generation and Its Impact on Total Energy Supply and Electricity Generation in Africa and Southeast Asia

Region	Parameter	Historical scenario			Stated policies scenario		Announced Pledges scenario	
		2010	2021	2022	2030	2050	2030	2050
Africa	Total final consumption (EJ)	20.7	25.4	25.9	29.7	42.8	25.3	33.3
Southeast Asia	Total final consumption (EJ)	16.1	19.2	19.8	24.7	33.8	23.0	27.0
Africa	Total CO_2 emissions* (Mt CO_2)	1168	1364	1385	1468	1991	1328	1171
Southeast Asia	Total CO_2 emissions* (Mt CO_2)	1163	1690	1733	2047	2530	1836	982
Africa	Oil production (mb/d)	10.2	7.4	7.1	6.0	5.7	5.5	2.9
Southeast Asia	Oil production (mb/d)	2.6	1.9	1.8	1.3	0.8	1.3	0.4
Africa	Oil demand (mb/d)	3.3	3.8	4.0	4.7	7.7	4.5	5.4
Southeast Asia	Oil demand (mb/d)	4.0	4.6	4.8	6.0	6.9	5.5	3.6

Africa	Natural gas production (bcm)	203	265	262	283	360	266	240
Southeast Asia	Natural gas production (bcm)	216	195	189	166	117	147	77
Africa	Natural gas demand (bcm)	106	174	170	202	277	182	182
Southeast Asia	Natural gas demand (bcm)	150	162	158	191	254	171	122
Africa	Coal production (Mtce)	210	196	202	173	155	151	44
Southeast Asia	Coal production (Mtce)	318	489	539	449	458	409	207
Africa	Coal demand (Mtce)	155	147	146	130	110	109	27
Southeast Asia	Coal demand (Mtce)	122	260	269	327	427	291	163

Source: World Energy Outlook 2023: International Energy Agency, certified under CC BY-NC-SA 2.0 [93].

Unveiling Promising Prospects and Next Steps in Renewable Energy in Africa and Southeast Asia

Leveraging the immense potential of renewable energy sources, the study delves into the prospects and next steps for developing a sustainable energy supply in Africa and Southeast Asia. By examining the current landscape and identifying key challenges, this research aims to shed light on the promising opportunities that lie ahead in these regions. Through a comprehensive analysis of policies, technologies, and investment strategies, we seek to pave the way for a greener future while fostering economic growth and social development [94]. This section thoroughly examines diverse strategies and explores various avenues to drive the development of a sustainable energy supply in Africa and Southeast Asia. By delving into these multifaceted approaches, we can identify promising prospects and outline the necessary next steps for achieving long-term sustainability in both regions. These approaches include promoting renewable energy sources such as solar and wind power, implementing energy efficiency measures, and encouraging the adoption of clean technologies. Partnerships with international organizations and private sector entities can play a crucial role in mobilizing resources and expertise to support the implementation of these strategies.

Explore the Potential of Solar Energy Advancements, such as Perovskite Solar Cells or Solar Paint

Through the exploration of cutting-edge solar energy technologies such as perovskite solar cells and solar paint, our goal is to unleash a world of untapped potential in Africa and Southeast Asia. This ambitious initiative not only lays the foundation for a sustainable future but also provides a sneak peek into the promising opportunities and future actions required to fulfill the renewable energy needs of these regions. This innovative approach will contribute to economic growth, job creation, and improved living standards in these areas. By harnessing the power of perovskite solar cells and solar paint, we can revolutionize the energy landscape in Africa and Southeast Asia. These technologies have the potential to provide affordable and reliable electricity to remote and underserved communities, enabling them to leapfrog traditional energy infrastructure and accelerate their development. Moreover, the deployment of these innovative solutions will also reduce greenhouse gas emissions, mitigating the impacts of climate change and ensuring a cleaner and healthier environment for future generations.

Currently, African countries have yet to fully harness the untapped potential of solar energy advancements, including perovskite solar cells and solar paint. By incorporating these innovative technologies into their energy infrastructure, African nations can unlock a sustainable and efficient source of power, paving the way for a brighter and greener future. According to a report by the International Renewable Energy Agency [16], Africa has the potential to generate more than 10 terawatts of solar power, which is more than enough to meet the continent's current energy needs. However, only a small fraction of this potential has been tapped into so far. For instance, in 2019, solar energy accounted for only 2% of Africa's total electricity generation [18]. By fully embracing and investing in solar energy advancements, Africa could significantly reduce its reliance on fossil fuels and improve energy access for its population.

IRENA's report highlights Africa's immense potential in solar power generation, estimating it to exceed the current total installed electricity capacity of the entire continent by over 1,000 GW[95]. This ground-breaking revelation opens up unprecedented opportunities for Africa to revolutionize its energy sector and become a continental leader in renewable energy production. Similarly, Southeast Asia has abundant solar resources, with countries like Thailand and Vietnam having high solar irradiation levels. Implementing these advanced solar technologies could significantly increase the renewable energy capacity in these regions and help meet their growing energy demands. Investing in renewable energy infrastructure will attract foreign investments and create job opportunities in the region. This will not only boost the economy but also contribute to the overall sustainable development goals of these countries.

Beyond Traditional Wind Farms: Exploring the Potential of Floating Turbines and Airborne Systems

Unleashing the untapped potential of renewable energy sources, our ground-breaking research delves into the uncharted territory of floating turbines and airborne systems in Africa and Southeast Asia. By transcending the limitations of traditional wind farms, we aim to revolutionize the renewable energy landscape with cutting-edge technologies that harness the power of wind in unconventional ways. Through this pioneering approach, we strive to unlock vast opportunities for sustainable development and propel these regions towards a greener future. By utilizing floating turbines and airborne systems, we can tap into previously untapped wind resources over bodies of water and in remote areas [96]. This not only maximizes the potential for renewable energy generation but also reduces the impact on land use and local ecosystems. With our innovative solutions, we envision a future where clean and abundant wind energy becomes a catalyst for economic growth and environmental preservation in Africa and Southeast Asia.

Only a small portion of Africa's potential for renewable energy has been realized, according to research published by the International Renewable Energy Agency [18]. The report states that Africa has the potential to generate 1,000 GW of wind energy alone, with floating turbines and airborne systems being a promising solution for harnessing this untapped potential [18]. However, as of now, there are limited installations of floating turbines or airborne systems in African countries [18]. This indicates a significant opportunity for African countries to further develop their renewable energy sector and maximize their untapped potential. Implementing floating turbines and airborne systems could not only contribute to reducing carbon emissions but also create job opportunities and improve energy access in remote areas.

Southeast Asian nations have only used a small portion of their potential when it comes to floating turbines and aerial systems, according to a report published by the International Renewable Energy Agency [18]. The report states that as of now, less than 1% of the region's total energy capacity comes from these sources. They also revealed that there is significant untapped potential for renewable energy in the region, including floating turbines and airborne systems. due to the abundance of coastal areas and strong wind resources. The study estimates that if fully harnessed, Southeast Asia could generate over 800 gigawatts of electricity from floating turbines alone, greatly reducing reliance on fossil fuels and mitigating climate change impacts. Additionally, the adoption of airborne systems such as solar-powered drones could further contribute to the region's renewable energy goals by harnessing solar energy in remote and inaccessible areas.

Diving into the Potential of Wave Energy Converters and Ocean Thermal Energy Conversion Systems as Promising Renewable Technologies

Exploring the untapped potential of Wave Energy Converters (WECs) and Ocean Thermal Energy Conversion (OTEC) systems presents an exciting opportunity to harness the vast energy resources offered by our oceans. These cutting-edge renewable technologies have shown great promise in their ability to provide sustainable and clean energy solutions for a greener future. Exploring the untapped potential of wave energy converters and ocean thermal energy conversion systems in Africa and Southeast Asia can revolutionize the renewable energy landscape. By harnessing the power of ocean waves and temperature gradients, these innovative technologies offer a sustainable solution to meet the growing energy demands of these regions, while reducing carbon emissions and promoting a greener future.

Currently, African countries have yet to tap into the vast potential of wave energy converters and ocean thermal energy conversion systems, despite their promising nature as innovative renewable technologies. However, by embracing these cutting-edge solutions, African nations can unlock a sustainable future powered by the abundant energy resources available in their coastal regions. According to a report by the International Renewable Energy Agency (IRENA), only a small fraction of Africa's vast wave energy potential has been tapped, with less than 1% of the estimated 39,000 MW capacity being utilized [95]. These statistics underscore the untapped potential of Africa's ocean energy resources. Harnessing wave and ocean thermal energy could significantly contribute to the continent's energy mix, reducing reliance on fossil fuels and promoting sustainable development. However, further investment in research, technology development, and supportive policies is needed to unlock this untapped potential and accelerate the deployment of ocean energy projects in Africa.

Wave energy converters and ocean thermal energy conversion systems only contribute a small portion of Southeast Asia's total energy production, according to a report by the International Renewable Energy Agency [95]. The report states that as of 2020, less than 1% of the region's renewable energy capacity is derived from these technologies[95]. This indicates a significant untapped potential for Southeast Asian countries to further explore and invest in these promising renewable technologies, which can help diversify their energy mix and reduce their dependence on fossil fuels. By harnessing the power of waves and ocean thermal gradients, Southeast Asian countries can not only contribute to global efforts to combat climate change but also create new job opportunities and stimulate economic growth in the region. Additionally, investing in these technologies can enhance energy security by reducing reliance on imported fuels and mitigating the impact of fluctuating fuel prices.

Unveiling the Future of Energy Storage: Exploring Flow Batteries, Hydrogen Storage, and Thermal Energy Solutions

Presenting a forward-thinking perspective on energy storage, this section aims to delve into the potential of cutting-edge technologies such as flow batteries, hydrogen storage, and thermal energy solutions in Africa and Southeast Asia. These advanced energy storage technologies have the potential to address the intermittent nature of renewable energy sources and ensure a stable and reliable power supply. By implementing these solutions, Africa and Southeast Asia can further enhance their renewable energy production capabilities and pave the way for a sustainable future. The International Renewable Energy Agency [95] found that only 8% of Africa's total energy consumption is derived from renewable sources, underscoring the region's unrealized potential for cutting-edge technologies. These statistics demonstrate the significant room for growth and innovation in harnessing these cutting-edge technologies in Africa's energy sector. By investing in and adopting advanced technologies, Africa has the opportunity to not only increase its renewable energy capacity but also drive economic growth and create sustainable development. It is crucial for governments, organizations, and investors to recognize the immense potential of these technologies and work towards implementing them on a larger scale to meet the continent's growing energy demands while reducing its carbon footprint.

A report published by the International Renewable Energy Agency [95] states that only 17 percent of Africa's energy is derived from renewable sources, suggesting a large unmet market for cutting-edge technologies. They also found that the adoption of innovative energy storage solutions like flow batteries and hydrogen storage systems remains limited in Southeast Asia, with less than 5% of installed capacity being attributed to these technologies. These statistics highlight the need for increased investment and implementation of advanced energy storage technologies in Southeast Asia to tap into the untapped potential of renewable energy sources. By investing in and implementing these technologies, Southeast Asian countries can not only reduce their dependence on fossil fuels but also contribute to global efforts to mitigate climate change. The adoption of advanced energy storage solutions can provide a more reliable and stable grid infrastructure, ensuring a consistent and uninterrupted supply of clean energy to meet the region's growing electricity demand.

Exploring the Potential of IoT Integration for Energy Efficiency Enhancement

Unleashing the untapped potential of IoT integration holds immense promise for revolutionizing energy efficiency in Africa and Southeast Asian countries. By seamlessly integrating IoT technologies into existing energy systems, we can unlock unprecedented opportunities to optimize resource consumption, reduce waste, and foster sustainable development in these regions. This integration can enable real-time monitoring and control of energy usage, allowing for efficient allocation of resources and the identification of areas for improvement. IoT integration can also facilitate the implementation of smart grids, enabling better management and distribution of electricity, ultimately leading to increased reliability and affordability for consumers.

With IoT integration, real-time data collection and analysis can enable better monitoring and management of energy usage. This can lead to the implementation of targeted strategies such as demand response programs and predictive maintenance, ultimately driving significant cost savings and environmental benefits. IoT integration can empower local communities by providing access to affordable and reliable energy services, paving the way for economic growth and improved quality of life.

A study conducted by the international energy agency found that the adoption of Internet of Things (IoT) integration for energy efficiency enhancement in African countries is still relatively low, with only a few pilot projects implemented so far [15]. These figures highlight the untapped potential for IoT integration in African countries to improve energy efficiency. The low adoption rate may be attributed to various factors, such as limited infrastructure, a lack of awareness, and financial constraints. However, with the right support and investment, there is a significant opportunity for African countries to harness the benefits of IoT integration and make substantial progress in energy efficiency. By leveraging IoT technology, African countries can optimize energy consumption, reduce waste, and enhance overall productivity. For instance, smart grid systems can enable real-time monitoring and control of energy usage, allowing for more efficient distribution and allocation of resources. IoT-enabled devices can provide valuable data insights that can inform policy decisions and drive sustainable development in the energy sector. With concerted efforts and strategic partnerships, African countries have the potential to transform their energy landscapes and pave the way for a greener future.

Southeast Asia has barely scratched the surface of its IoT integration potential for improving energy efficiency, according to a report published by the International Renewable Energy Agency (IRENA). The report states that as of now, the region has only achieved around 20% of its full potential in this area [17]. This indicates a significant untapped opportunity for Southeast Asian countries to further enhance their energy efficiency and reduce their carbon footprint through the integration of IoT technologies. By fully harnessing this potential, Southeast Asian countries can optimize their energy consumption, improve operational efficiency, and contribute to global sustainability efforts. The integration of IoT technologies can enable real-time monitoring and control of energy systems, allowing for more precise and targeted energy management strategies. IoT-enabled devices can provide valuable data insights that can inform decision-making processes and drive continuous improvement in energy efficiency practices. By embracing IoT integration in energy efficiency enhancement, Southeast Asian countries can not only reduce their carbon footprint but also unlock economic benefits by optimizing resource allocation and minimizing energy waste. This can lead to cost savings for businesses and households, as well as create new job opportunities in the renewable energy sector. IoT integration can also enhance grid reliability and resilience, ensuring a more stable and sustainable energy supply for the region.

Sustainable Solutions: Exploring Policy Implications for Renewable Energy in Africa and Southeast Asia

As we delve into the critical issue of renewable energy supply in Africa and Southeast Asia, it is imperative to consider sustainable solutions that can address the pressing challenges at hand. By exploring the policy implications surrounding this matter, we can pave the way for innovative approaches that not only promote environmentally-friendly practices but also drive economic growth and social development in these regions. By adopting an innovative approach, we aim to identify practical strategies that can drive the transition towards a greener and more resilient future for these continents. These strategies can include: 1) The Integrated Resource Planning scenario focuses on optimizing the mix of renewable energy sources to meet the energy demand while considering environmental and social factors. 2) The Market Liberalization scenario explores the potential benefits of opening up the renewable energy market to private sector participation, fostering competition and innovation. 3) The Government Incentives scenario examines the role of policy incentives, such as tax breaks and subsidies, in promoting the adoption of renewable energy technologies in Africa and Southeast Asia. These incentives can help attract investment and drive the growth of the renewable energy sector. 4) The Capacity Building scenario highlights the importance of investing in human capital and building technical expertise to support the development and deployment of renewable energy projects. This includes training programs, knowledge sharing platforms, and partnerships with international organizations to enhance local capabilities and foster innovation in renewable energy technologies. By investing in capacity building, countries in Africa and Southeast Asia can develop a skilled workforce that is equipped to handle the complexities of renewable energy projects. These initiatives can create job opportunities and contribute to economic growth in the region, further incentivizing the adoption of renewable energy sources.

The Integrated Resource Planning Scenario

This scenario aims to develop a comprehensive strategy that maximizes the utilization of renewable energy sources, taking into account the unique environmental and social contexts of Africa and Southeast Asian countries. By integrating various factors such as resource availability, technological advancements, and policy frameworks, the Integrated Resource Planning scenario seeks to create a sustainable energy landscape that promotes economic growth and minimizes environmental impact in these regions. As the global energy landscape continues to evolve, it is crucial to adopt forward-thinking strategies that prioritize sustainability and address the unique challenges faced by Africa and Southeast Asian countries [52]. The Integrated Resource Planning scenario offers a comprehensive approach that not only emphasizes the optimization of renewable energy sources but also takes into account crucial environmental and social factors such as carbon emissions [97, 98], land use [99], and community engagement. By harnessing this innovative framework, these regions can pave the way towards a greener future while simultaneously promoting economic growth and social well-being [100]. This approach recognizes the unique needs and challenges of each country, allowing for tailored solutions that address specific energy demands and local contexts. The Integrated Resource Planning scenario encourages collaboration and knowledge sharing among countries, fostering a collective effort to tackle common issues and accelerate sustainable development in the region. By adopting this approach, Africa and Southeast Asian countries can prioritize renewable energy sources and implement policies that support their development and deployment. This not only reduces greenhouse gas emissions and mitigates climate change but also creates new job opportunities and improves access to clean and affordable energy for all citizens [101]. Promoting renewable energy sources can also enhance energy security and reduce dependence on fossil fuels, which are often imported at high costs. Investing in renewable energy technologies can spur innovation and drive economic growth, as it opens up new markets and attracts foreign investments in the region.

Investigating long-term policy implications, such as the Integrated Resource Planning scenario for renewable energy supply in Africa, is crucial for understanding the potential benefits and challenges of transitioning to renewable energy sources. According to a report by the International Renewable Energy Agency [95], Africa has the potential to generate 310 gigawatts of renewable energy by 2030, which could meet almost two-thirds of the continent's electricity demand. However, achieving this potential requires careful planning and implementation of policies that promote investment in renewable energy infrastructure, address regulatory barriers, and ensure a just transition for affected communities. It is crucial for understanding the potential benefits and challenges of transitioning to renewable energy sources. According to a report by the International Renewable Energy Agency [95], Africa has the potential to generate 310 gigawatts of renewable energy by 2030, which could meet almost two-thirds of the continent's electricity demand. However, achieving this potential requires careful planning and implementation of policies that promote investment in renewable energy infrastructure [102], address regulatory barriers, and ensure a just transition for affected communities [103]. It is important to prioritize access to affordable and reliable energy for all Africans, especially those in remote and underserved areas. This can be achieved through innovative financing mechanisms, such as public-private partnerships and microfinance initiatives, that enable the deployment of renewable energy technologies in off-grid communities. Fostering regional cooperation and knowledge sharing among African countries can help accelerate the adoption of renewable energy solutions and create a sustainable energy future for the continent [104].

One possible way to investigate the long-term policy implications of the Integrated Resource Planning scenario for renewable energy supply in Southeast Asia is by conducting a comprehensive cost-benefit analysis. This analysis would involve quantifying the potential economic, social, and environmental benefits of transitioning to renewable energy sources in the region. Additionally, it would be crucial to consider the potential challenges and barriers that may arise during the implementation of such policies, such as technological limitations, infrastructure requirements, and political considerations. By incorporating these factors into the analysis, policymakers can make informed decisions about the feasibility and long-term sustainability of transitioning to renewable energy sources [51, 105]. Moreover, stakeholders can better understand the potential trade-offs and opportunities associated with this transition, allowing for effective planning and resource allocation [105]. One example of investigating long-term policy implications for renewable energy supply in Southeast Asia is the study conducted by the International Renewable Energy Agency (IRENA). According to their analysis, implementing an integrated resource planning scenario could lead to a significant increase in renewable energy capacity in the region, reaching up to 1,725 GW by 2050 [95]. This would not only help reduce greenhouse gas emissions but also contribute to energy security and economic growth in Southeast Asia. Furthermore, such a scenario would also create job opportunities and promote technological innovation in the renewable energy sector. It could also enhance energy independence for countries in the region, reducing their reliance on imported fossil fuels and mitigating the risks associated with fluctuating global oil prices. Additionally, the transition to renewable energy sources would improve air quality and public health by reducing pollution from traditional fossil fuel power plants.

The Market Liberalization Scenario

The Market Liberalization scenario explores the potential benefits of opening up the renewable energy market to private sector participation, fostering competition and innovation. This scenario delves into the potential advantages of allowing private sector involvement in the renewable energy market, thereby stimulating competition and fostering innovation in countries across Africa and Southeast Asia. By embracing market liberalization, these regions can unlock the untapped potential of their renewable energy sectors, attract investments, and drive sustainable development. Private sector involvement in the renewable energy market can bring in expertise, technology, and capital that may not be readily available within the public sector. This collaboration can lead to increased efficiency in the production and distribution of renewable energy, ultimately benefiting both the economy and the environment. By creating a competitive market, private sector participation can drive down costs and make renewable energy more accessible to a larger population, accelerating the transition towards a greener future. Private sector involvement can also foster innovation and research in renewable energy technologies. Companies often have the resources and incentives to invest in research and development, leading to the discovery of new and more efficient ways to harness renewable energy sources. This continuous advancement can further drive down costs and improve the overall sustainability of renewable energy solutions in countries across Africa and Southeast Asia. Private sector involvement can also contribute to the creation of job opportunities in the renewable energy sector. By investing in renewable energy projects, companies can create a demand for skilled workers, leading to job growth and economic development in these regions. The involvement of private sector players can help establish partnerships with local communities and governments, ensuring a more holistic and inclusive approach towards achieving a greener future.

To investigate the long-term policy implications of market liberalization for renewable energy supply in Southeast Asia, we will analyze relevant data and research findings. This will include examining the current market trends, evaluating the potential economic benefits, and assessing the environmental impact of such a scenario. We will review existing studies and reports from reputable sources like the International Renewable Energy Agency (IRENA) and the World Bank to ensure a comprehensive analysis of this topic. According to IRENA [95], Southeast Asia has immense untapped potential for renewable energy, particularly solar and wind power. Their report highlights the region's favorable climate conditions and vast land availability, which can support the development of large-scale renewable energy projects. Moreover, the World Bank emphasizes the importance of policy reforms and investment incentives to attract private sector participation and accelerate the deployment of renewable energy technologies in Southeast Asia. These insights will provide valuable context for our analysis of the liberalization of renewable energy supply in the region.

For instance, the Philippines has implemented feed-in tariffs and tax incentives to encourage investment in renewable energy, resulting in a significant increase in installed capacity. Thailand has set a target to achieve 30% of its energy from renewable sources by 2037 and has introduced a net metering program to incentivize households and businesses to generate their own renewable energy [95]. For example, Philippines has implemented various policy reforms and incentives to attract private sector investment in renewable energy. These include feed-in tariffs, tax incentives, and streamlined permitting processes. As a result, the country has seen significant growth in its renewable energy sector, with an increasing number of solar and wind projects being developed. Neighboring countries such as Thailand and Vietnam have also introduced similar measures to encourage private sector participation in renewable energy development. For example, we can look at how policy reforms and investment incentives have been implemented in countries like Philippine, Thailand, and Vietnam, which have seen significant growth in their renewable energy sectors, and replicate them in other Southeast Asian countries and beyond. We can also explore the potential challenges and opportunities that may arise from the liberalization of renewable energy supply, such as the need for grid infrastructure upgrades and the potential for increased competition among renewable energy developers. These examples highlight the potential impact of policy reforms and investment incentives on driving the growth of renewable energy in Southeast Asia.

To investigate long-term policy implications, we are examining the market liberalization scenario for renewable energy supply in Africa. According to a report by the International Renewable Energy Agency (IRENA), the potential for renewable energy in Africa is vast, with estimates suggesting that it could meet nearly a quarter of the continent's energy needs by 2030 [95]. They also projects that market liberalization in the renewable energy sector could attract significant private investments, leading to increased job opportunities and economic growth in Africa. For example, the study highlights those countries like Kenya and South Africa have already made significant progress in attracting private investments in renewable energy projects, resulting in the creation of thousands of jobs and boosting their economies. The report emphasizes that harnessing Africa's renewable energy potential can also contribute to reducing greenhouse gas emissions and mitigating the impacts of climate change on the continent. This is particularly important for countries in Africa that have abundant renewable energy resources but lack the necessary infrastructure and financing to fully exploit them. By opening up the market and encouraging private sector participation, African countries can tap into their renewable energy potential and create a sustainable and resilient energy system for the future.

The Government Incentives Scenario

The Government Incentives scenario explores how policy incentives, including tax breaks and subsidies, can drive the widespread adoption of renewable energy technologies in Africa and Southeast Asia. By incentivizing the use of clean energy sources, governments aim to accelerate the transformation of the energy landscape in these regions, paving the way for a sustainable and environmentally friendly future. These incentives play a crucial role in attracting investment and stimulating the growth of the renewable energy sector in Africa and Southeast Asia. By offering financial advantages and favorable policies, they create a conducive environment for investors to channel their resources into renewable energy projects, ultimately driving sustainable development in these regions. This can lead to increased funding for research and development as well as the construction of new renewable energy projects. These incentives can also create job opportunities in the renewable energy sector, contributing to economic growth and sustainability in Africa and Southeast Asia. The growth of the renewable energy sector can also have positive environmental impacts. By reducing their reliance on fossil fuels, countries can decrease their carbon emissions and mitigate the effects of climate change. This transition to renewable energy sources can also promote energy independence and security as countries become less dependent on imported fossil fuels.

In order to thoroughly explore the long-term policy implications of the government incentive scenario for renewable energy supply in Africa and Southeast Asia, a comprehensive analysis of various factors is necessary. This includes examining the potential economic benefits, environmental impacts, and social implications associated with such policies. It is crucial to consider the existing literature and studies on similar initiatives implemented in other regions to draw insightful comparisons and draw evidence-based conclusions. By incorporating figures and citations from reputable sources, this investigation aims to provide a robust understanding of the potential outcomes and consequences of the proposed policies.

To investigate long-term policy implications, it is crucial to consider the government incentive scenario for renewable energy supply in Africa. According to a report by the International Renewable Energy Agency (IRENA), government incentives play a vital role in promoting renewable energy adoption and achieving sustainable development goals in Africa [95]. These incentives can include financial support, tax breaks, feed-in tariffs, and regulatory frameworks that encourage investment in renewable energy projects. By analysing the effectiveness of such incentives and their impact on renewable energy deployment, we can better understand the factors that drive the growth of renewable energy in Africa. For instance, a study conducted by Nwokolo et al. [106] found that countries in Africa that offered strong financial incentives for renewable energy projects experienced a significant increase in their renewable energy capacity. The study also highlighted the importance of supportive policies and regulations in creating an enabling environment for renewable energy deployment in Africa. This analysis can help policymakers and stakeholders identify areas where further incentives or improvements in existing ones are needed to accelerate the transition to clean and sustainable energy sources.

For instance, a study conducted by the International Renewable Energy Agency (IRENA) found that countries in Southeast Asia that implemented feed-in tariffs experienced a significant increase in renewable energy capacity [17]. The study also highlighted the importance of long-term contracts and stable policy frameworks in attracting investment and driving renewable energy deployment in the region. IRENA report also showed that financial incentives such as tax breaks and subsidies have played a crucial role in promoting renewable energy projects in Southeast Asia, leading to rapid growth in the sector. The report emphasized that these incentives have not only attracted domestic investors but also encouraged foreign investment in renewable energy projects. The IRENA report suggested that governments should continue to provide financial support and create a favourable regulatory environment to ensure the sustained growth of renewable energy in Southeast Asia.

The Capacity Building Scenario

The capacity-building scenario emphasizes the critical role of investing in human capital and cultivating technical expertise to facilitate the growth and implementation of renewable energy initiatives. This approach underscores the significance of equipping individuals with the necessary skills and knowledge to drive the advancement and successful execution of sustainable energy projects in Africa and Southeast Asia. By providing individuals with the tools and resources to develop their expertise, capacity-building initiatives can empower local communities to take ownership of renewable energy projects and contribute to their long-term sustainability. Fostering collaboration and knowledge sharing among stakeholders can further enhance the effectiveness of capacity-building efforts, creating a network of skilled professionals dedicated to driving the transition towards clean energy in Africa and Southeast Asia. This network can also facilitate the exchange of best practices and lessons learned, enabling local communities to overcome common challenges and accelerate the adoption of renewable energy solutions. Capacity-building initiatives can support the development of innovative technologies and business models that are tailored to the specific needs and conditions of these regions, ensuring long-term success and scalability. Partnerships with local governments and organizations can help secure funding and policy support for clean energy projects. By engaging with stakeholders at all levels, this network can foster a holistic approach to sustainable development and create a thriving ecosystem for clean energy innovation in Africa and Southeast Asia. Partnerships with international organizations and governments can provide financial and technical assistance to help African and Southeast Asian countries build the necessary infrastructure for clean energy. Promoting public awareness and education about the benefits of renewable energy can encourage widespread acceptance and support for these initiatives in African and Southeast Asian countries, which can also leverage their abundant natural resources, such as solar and wind energy, to drive the transition towards clean energy. By investing in research and development, they can further enhance their technological capabilities and become leaders in the renewable energy sector. Fostering collaboration between local entrepreneurs and international clean energy companies can facilitate knowledge transfer and accelerate the deployment of sustainable solutions in these regions.

The capacity-building scenario for renewable energy supply in Southeast Asia has significant long-term policy implications. According to a report by the International Renewable Energy Agency (IRENA), if the region invests in renewable energy infrastructure and enhances its capacity, it could achieve a 35% share of renewable energy in its total final energy consumption by 2030 [17]. They equally stated that if the region invests in enhancing its renewable energy capacity, it could achieve a 23% reduction in carbon emissions by 2030 compared to business-as-usual scenarios. This would not only contribute to reducing greenhouse gas emissions and combating climate change but also enhance energy security and create job opportunities in the region. Investing in renewable energy could lead to a decrease in reliance on fossil fuels, reducing the region's vulnerability to price fluctuations and geopolitical tensions associated with traditional energy sources. The growth of the renewable energy sector would create a demand for skilled workers, stimulating job creation and economic growth within the region.

According to a report by the International Renewable Energy Agency [17], implementing a capacity-building scenario for renewable energy supply in Africa could lead to significant long-term policy implications. The report highlights that by 2030, such efforts could result in a 42% increase in Africa's total renewable energy capacity, creating around 4.4 million jobs and reducing carbon emissions by approximately 310 megatons per year. The report highlights that by 2030, renewable energy could provide up to 67% of Africa's total power generation, creating numerous socio-economic benefits and driving sustainable development. These figures demonstrate the immense potential for sustainable development and economic growth that can be achieved through the expansion of renewable energy in Africa. This scenario would not only help meet the continent's growing energy demands but also reduce greenhouse gas emissions, improve energy access, and enhance energy security. It would attract investments, stimulate job creation, and foster technological innovation in the renewable energy sector. The transition to renewable energy sources would also reduce reliance on fossil fuels, mitigating the negative environmental impacts associated with their extraction and combustion. The increased use of renewable energy could contribute to Africa's efforts to achieve its climate change commitments under international agreements like the Paris Agreement.

Insights and Concluding Remarks

The analysis reveals that Africa emerged as a frontrunner in renewable energy generation, surpassing Southeast Asia by a significant margin. With an impressive output of 23–25 TWh, Africa's contribution to the total renewable energy generation was far greater than Southeast Asia's reported 9–14 TWh during the historical scenario spanning 2021 and 2022. This indicates that Africa has made a more significant contribution to overall renewable energy production compared to Southeast Asia during the specified time period. Nevertheless, based on the projected trajectory, Southeast Asia is anticipated to surpass Africa in wind energy production from 2030 to 2050, aligning with the announced pledged scenario. This prediction highlights the region's potential for substantial growth and underscores its commitment to renewable energy development. In terms of wind energy production, Southeast Asia's current output stands at 128 TWh, which is relatively lower than Africa's estimated 593 TWh. However, future projections paint a different picture. By 2050, Southeast Asia is poised to witness exponential growth in wind energy generation, reaching an astonishing record of 1207 TWh, surpassing Africa's estimated output by a significant margin. This forecast highlights Southeast Asia's potential to become a global leader in wind energy production and contribute significantly to the global renewable energy market. With favorable geographical conditions and a growing focus on sustainable development, Southeast Asia is expected to attract substantial investments in wind energy infrastructure and technology. This growth in wind energy production not only promises to reduce carbon emissions but also presents opportunities for job creation and economic growth in the region.

The authors shed light on five potential avenues for further exploration and action concerning the influence of economic factors on energy demand. These insights are particularly relevant in light of the projected surge in human population and urbanization across Africa and Southeast Asia, as forecasted by the International Energy Agency for the period between 2030 and 2050. These include investigating the potential of solar energy advancements such as perovkite solar cells or solar paint, investigating the potential of floating turbines and airborne systems, investigating the potential of wave energy converters and ocean thermal energy conversion systems as promising renewable technologies, investigating the future of energy storage and thermal energy solutions, and finally investigating the potential of IoT integration for energy efficiency enhancement.

In order to address the crucial challenges surrounding renewable energy supply in Africa and Southeast Asia, it is imperative to explore forward-thinking strategies that can offer sustainable and lasting solutions. By thoroughly analyzing the underlying issues at hand, we can pave the way for transformative initiatives that will effectively tackle these pressing concerns in the long run. Through a comprehensive examination of the policy implications surrounding this matter, the authors successfully devised novel and sustainable scenarios. These scenarios not only foster environmentally responsible behaviours but also stimulate economic growth and propel social development within the regions. By exploring the policy implications, the authors have effectively crafted innovative solutions that address both environmental concerns and socio-economic progress. These regions encompass a range of scenarios, each contributing to their own professional and innovative approach. These include the integrated resource planning scenario, which optimizes resource allocation; the market liberalization scenario that fosters competition and efficiency; the government incentives scenario that encourages sustainable practices; and the capacity-building scenario that enhances knowledge and skills within the industry. These scenarios are designed to address various challenges and opportunities in the energy sector. For example, the integrated resource planning scenario helps ensure that resources are allocated efficiently and effectively, minimizing waste and maximizing output. Similarly, the market liberalization scenario promotes competition among energy providers, leading to improved efficiency and lower costs for consumers. Additionally, the government incentives scenario incentivizes businesses to adopt sustainable practices by offering financial rewards or tax benefits. Lastly, the capacity-building scenario focuses on developing the knowledge and skills of professionals in the energy sector, allowing them to better manage and optimize energy resources. This scenario includes training programs, workshops, and educational initiatives that equip professionals with the necessary tools to make informed decisions and implement sustainable practices. By investing in capacity-building, the energy sector can ensure a competent workforce that can navigate the complexities of the industry and drive innovation for a greener future.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Climate Risks and Economic Consequences of Rising Global CO_2 Emissions in Aviation, Shipping, and Heavy-Duty Transport

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This study examines methods to lessen the environmental consequences of global CO_2 emissions from the hard-to-abate transport sector. The paper analyzed historical and projected trends in global CO_2 emissions from the hard-to-abate transport industry under two scenarios: the stated policy scenario (STEPS) and the announced pledged scenario (APS). The study covered the historical period from 2010 to 2022 and projected emissions up to 2050. The analysis revealed that the compound annual growth rate (CAAGR) of STEP exceeded that of APS in 2030 and 2050 for challenging emissions from heavy- duty vehicles, aircraft, and shipping when compared to the baseline year of 2022. The aviation industry has a higher CAAGR of 5.3% and 2.5% for 2030 and 2050, respectively, compared to heavy-duty vehicles at 1.6% and 0.9% for 2030 and 2050, respectively, and shipping at 0.7% and 0.9% for 2030 and 2050, respectively, under STEPS. Under the APS scenario, shipping showed a negative CAAGR of -0.8% and -2.8% for 2030 and 2050, respectively, and 0.4% and -1.8% for 2030 and 2050, respectively, for heavy-duty trucks. In comparison, the aviation industry had CAAGRs of 4.5% and 0.8% for 2030 and 2050, respectively. The data shows that the aviation industry is expected to see a far greater CAAGR in emissions than heavy-duty vehicles and shipping in both STEPS and APS scenarios. Targeted efforts are necessary to mitigate the environmental effects of air travel in the upcoming decades. The paper also examined 56 publicly traded international transportation companies and their corresponding carbon emission targets. Only seven companies, or 12.5%, have established goals for reducing emissions from 2023 to 2050; 10 companies, accounting for 17.9%, have committed to achieving carbon neutrality by 2040 to 2060; five corporations, representing 8.9%, have set targets for reducing emission intensity from 2025 to 2034; and 34 global corporations, making up 60.7%, have committed to achieving net zero emissions between 2040 and 2050. Despite some progress in setting emission reduction targets in the air travel industry, many companies still need to set carbon footprint reduction goals.

Keywords: Heavy-duty trucks; Aviation industry; Shipping industry; Transport infrastructure; CO_2 emission; Net zero targets

1. Introduction

The worldwide transportation industry is responsible for roughly 25% of energy-related carbon dioxide (CO_2) emissions, making it one of the most significant contributors to climate change [1]. Within this sector, "hard-to-abate" businesses such as

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aviation, shipping, and long-haul transportation face substantial challenges in decreasing CO_2 emissions due to their reliance on energy-dense fuels and the inherent difficulties of shifting to low-carbon alternatives [2]. As the world transitions to a low-carbon future, reducing emissions from these businesses is important to meeting global climate goals [3]. Hard-to-abate businesses are distinguished by their reliance on fossil fuels [4], significant capital investment in long-lived assets [5], and a scarcity of commercially viable alternatives [6]. For instance, kerosene-based jet fuels, which provide a high energy density necessary for long-haul flights, are significantly utilized in the aviation industry [7]. In a similar vein, heavy fuel oils are necessary for the propulsion of huge vessels over long distances in marine commerce [8], which accounts for 90% of all global commodities transit [9]. Long-haul transportation encounters difficulties implementing electrification because of battery weight and range constraints [10], particularly in areas with wide geographic landscapes [11]. It will become more urgent to discover scalable solutions since these sectors are predicted to increase over the next few decades [12].

Recent technological improvements and policy developments provide a glimmer of hope for decarbonizing these industries [13]. Sustainable aviation fuels (SAFs), for example, offer a promising future for the aviation sector. SAFs can be produced from biomass, waste, or synthetic processes such as power-to-liquid technology [14]. Airlines like United Airlines and British Airways began implementing SAFs into commercial flights in 2022 [15, 16], but expanding manufacturing and lowering prices remain difficult problems [16].

Innovative technologies that promise to drastically cut emissions, such as ammonia and hydrogen-based fuels [17, 18], are also being investigated by the shipping sector [17]. A bridge to zero-emission marine transportation may be provided by the investments made in ammonia-powered ships by companies like Maersk and NYK Line [19]. Furthermore, as complementary options, the electrification of short-sea ships [20] and the development of wind-assisted propulsion technologies are being tested [21]. Technological advances in hydrogen fuel cells and batteries are opening up new possibilities for heavy-duty road transport [22]. Diesel trucks may eventually be replaced with zero-emission vehicles thanks to the development of high-performance [23], long-range hydrogen-powered vehicles like the Nikola One and the Hyundai Xcient Fuel Cell [24]. Even though it is still in its infancy, Tesla's semi-electric truck heralds a paradigm shift in the direction of electrifying freight transportation [25].

Advancements in these sectors are also being fuelled by creative policies [26]. By 2050, the "Fit for 55" program from the European Union intends to cut transportation emissions by 90% via a combination of fuel requirements [27], carbon price, and infrastructure improvements [28]. While the International Civil Aviation Organization (ICAO) approved the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to stabilize aviation emissions at 2020 levels, the International Maritime Organization (IMO) has set aims to halve shipping emissions by 2050 [29]. Scaling solutions is still a major difficulty despite these efforts, mostly because of their high prices [30], poor acceptance rates [31], and gaps in technological maturity [32]. Governments, businesses, and academic institutions must work together to speed innovation and large-scale implementation [33].

The initial part of this article discusses the many variables influencing CO_2 emissions in the transportation sector, including developments in vehicle design and alternative fuel sources, government regulations supporting sustainable mobility, and consumer preferences for environmentally friendly forms of transport. It is essential to take all these factors into account when creating thorough strategies to reduce carbon emissions in the transportation sector. To achieve a more sustainable and eco-friendly transportation system, we might address technical, regulatory, and behavioral elements. Obstacles to reducing CO_2 emissions in the transport sector include limitations in infrastructure for electric vehicles [34] and public transit, economic barriers to implementing sustainable transport solutions [35], globalization [35], and increasing demand for freight transportation [36]. Recognizing the interdependence of these challenges is crucial, requiring comprehensive solutions that consider many stakeholders and their interests [37]. Collaboration between governments, businesses, and communities is essential for overcoming obstacles and achieving substantial advancements in developing an eco-friendlier transportation sector [38].

The section includes case studies on successful CO_2 emission reduction measures, such as the European Union's emission reduction targets for the transport industry. The case studies provide valuable insights into potential approaches and solutions for reducing CO_2 emissions in the transportation sector. Stakeholders may learn how to manage the complexities of transitioning to a more sustainable transportation system by examining these successful examples [39]. The section also includes an analysis of historical and projected trends in global transportation CO_2 emissions. It examines the assessment of the necessity for further measures considering the challenging trends in worldwide transportation-related CO_2 emissions. In this part, the author examined publicly listed global transportation businesses and their associated carbon emissions goals. This analysis provides valuable insights into the progress being made towards reducing carbon emissions in the transportation sector. By studying these examples, stakeholders can gain a better understanding of effective strategies for achieving sustainability goals in this industry.

2. Critical Elements Impacting the Global Landscape's CO_2 Emissions from Transport Sector

2.1 Factors Influencing CO_2 Emissions in the Transport Sector

2.1.1 Technological Advancements in Vehicle Design and Alternative Fuel Sources

Technological advancements in vehicle design, such as the development of electric and hybrid vehicles, have the potential to significantly reduce CO_2 emissions in the transport sector [40]. For example, the use of lightweight materials and aerodynamic designs can improve fuel efficiency and decrease carbon emissions [41]. The adoption of alternative fuel sources like biofuels and hydrogen can further contribute to lowering greenhouse gas emissions and promoting sustainability in transportation [42]. These advancements are crucial in addressing the environmental impact of the transport sector [43] and moving towards a more eco-friendly future. The shift towards alternative fuel sources like biofuels, hydrogen, and electricity can further reduce the environmental impact of transportation on a global scale [44]. These alternative fuel sources offer a cleaner and more sustainable option for powering vehicles [45, 46], ultimately leading to lower CO_2 emissions [47]. The development of infrastructure to support these alternative fuel sources is essential for their widespread adoption. Ultimately, these efforts will play a significant role in reducing our dependence on fossil fuels and mitigating the effects of climate change.

According to a study by the International Energy Agency [48], the adoption of EVs alone could lead to a 30% reduction in CO_2 emissions from road transport by 2030 globally. The IEA also stated that these advancements have the potential to cut CO_2 emissions from road transport by up to 70% by 2050 [48]. This highlights the importance of transitioning to alternative fuel sources and embracing technological innovations in the transportation industry to combat climate change. It is crucial for governments and industries to continue investing in sustainable transportation solutions to achieve significant reductions in CO_2 emissions. The development of alternative fuel sources like biofuels and hydrogen fuel cells is also playing a crucial role in decarbonizing the transportation sector and mitigating its environmental impact [49]. According to a study by the International Energy Agency [28], transitioning to alternative fuel sources could reduce global CO_2 emissions from transportation by up to 30% by 2050 globally. This highlights the urgent need for widespread adoption of sustainable transportation technologies to address the growing threat of climate change.

According to a study by the International Energy Agency, these advancements have led to a 23% decrease in CO_2 emissions from light-duty vehicles in the United States between 2005 and 2018 [28]. They also predicted that the adoption of EVs alone could reduce CO_2 emissions by up to 50% by 2050 in the United States of America [50, 51]. The adoption of alternative fuel sources like biofuels and hydrogen fuel cells has further helped in lowering carbon emissions from transportation [52]. These advancements have not only reduced emissions but have also improved air quality and public health [53]. As the world continues to shift towards sustainable transportation options, further reductions in CO_2 emissions are expected in the coming years [54]. Overall, the ongoing efforts to promote sustainable transportation are crucial to combating climate change [55] and creating a healthier environment for future generations [56, 57]. It is important for governments, industries, and individuals to continue investing in and adopting these cleaner technologies to achieve long-term environmental benefits.

According to a study by the International Energy Agency, these advancements have led to a 33% decrease in CO_2 emissions from new vehicles between 2005 and 2015 in China [58]. The adoption of alternative fuel sources like biodiesel and natural gas has further helped reduce emissions by providing cleaner energy options for transportation in China [59]. These alternative fuel sources have also played a role in diversifying the energy mix in the transport sector, reducing reliance on traditional fossil fuels in China [60]. These advancements and shifts towards cleaner energy sources have been instrumental in lowering CO_2 emissions from transportation in China [61]. According to a study by the International Energy Agency, these advancements have helped reduce CO_2 emissions from passenger cars by 12% between 2005 and 2015 in Japan [58]. They also projected that the adoption of EVs alone could lead to a 40% reduction in CO_2 emissions by 2050 in Japan. The adoption of alternative fuel sources like electric vehicles and hydrogen fuel cells has further decreased emissions, with electric vehicles alone accounting for a 2% reduction in CO_2 emissions from passenger cars during the same period in Japan. The adoption of alternative fuel sources like hydrogen fuel cells has further reduced emissions [62], with Japan being a leader in this technology with over 100 hydrogen refueling stations nationwide.

According to a study by the International Energy Agency, these advancements have led to a 2% decrease in CO_2 emissions from transportation in Canada from 2018 to 2019 [51, 63]. These alternative fuel sources are considered more environmentally friendly compared to traditional gasoline and diesel, leading to a decrease in overall carbon emissions in Canada. As Canada continues to invest in sustainable transportation solutions, the reduction in CO_2 emissions is expected to further improve in the coming years [64].

The adoption of alternative fuel sources like electric and hydrogen-powered vehicles has further contributed to lowering emissions in the transport sector Germany [64]. According to a study by the German Environment Agency, these advancements have helped decrease CO_2 emissions from transportation by 3% between 2010 and 2018 in Germany [65]. According to a study by the International Energy Agency, these advancements have led to a 19% decrease in CO_2 emissions from passenger cars in Germany between 2010 and 2018 [28]. The study also found that the increase in public transportation usage and cycling infrastructure has played a role in reducing emissions. These efforts have been successful in making significant progress towards achieving environmental goals in the transportation sector.

Vehicle design advances in technology have helped decrease CO_2 emissions in transportation. EV registrations had an 185.9% growth from 2019 to 2020, as reported by the United Kingdom Department for Transport, demonstrating the positive effect of these improvements in reducing emissions [66]. The UK Department for Transport data indicates a 130% growth in registered ultra-low emission vehicles (ULEVs) from 2018 to 2020 [67], signaling a trend towards more environmentally friendly transportation choices. A study conducted by the UK Department for Transport found that emissions from road transport dropped by 3.3% from 2018 to 2019 as a result of the use of cleaner technology [68]. Alternative fuel sources, such as biofuels and hydrogen fuel cells, have contributed to reducing carbon emissions from automobiles in the UK. These developments in emission reduction are essential for addressing climate change and enhancing air quality. The increasing prevalence of ULEVs and the use of cleaner technology are beneficial advancements for a more sustainable transportation industry [69]. Enforcing tougher emissions laws and offering incentives for electric vehicles have significantly contributed to lowering carbon emissions from road transport [70]. These endeavors are crucial for achieving environmental goals and establishing a more sustainable future for transportation.

2.1.2 Government Policies and Regulations Promoting Sustainable Transportation

Government policies and regulations promoting sustainable transportation, such as fuel efficiency standards and incentives for electric vehicles, have been shown to significantly reduce CO_2 emissions in the transport sector. According to a study by the International Energy Agency, these policies have led to a 3% decrease in global transport emissions between 2019 and 2020 [28]. The IEA also projected that these measures have the potential to cut global transport emissions by up to 70% by 2050. A study by the International Energy Agency found that implementing stricter vehicle emission standards could lead to a 25% reduction in CO_2 emissions from the transport sector by 2050 [50]. Research from the World Resources Institute has found that countries with strong sustainable transportation policies have seen greater reductions in CO_2 emissions compared to those with weaker regulations. Investments in public transportation infrastructure have been proven to decrease reliance on individual car usage, further contributing to lower emissions.

For example, the government's promotion of electric vehicles has led to a significant increase in their market share, with sales reaching 41,359 units in 2020, up from just 2,545 units in 2013 in Taiwan [28]. The implementation of stricter emissions standards for vehicles has also played a crucial role in lowering overall CO_2 emissions from transportation activities. According to a study by Chen *et al.* [71], government policies such as promoting electric vehicles and improving public transportation infrastructure have led to a 15% decrease in CO_2 emissions from the transport sector since 2015. The implementation of fuel efficiency standards for vehicles has also contributed to reducing carbon emissions by 10% in the same period. Initiatives like the promotion of electric vehicles and public transportation have contributed to a significant reduction in carbon emissions, aligning with Taiwan's goal of achieving carbon neutrality by 2050 [27].

According to data from the European Environment Agency [48], France saw a 3.5% reduction in CO_2 emissions from transport between 2018 and 2019 due to these measures. Initiatives such as subsidizing electric vehicles and expanding public transportation options have further contributed to this positive trend. These efforts align with France's commitment to reducing its carbon footprint and meeting climate goals set by the European Union. As a result, France has become a prominent player in promoting sustainable transportation practices and reducing CO_2 emissions in the transport sector.

A study by the International Energy Agency found that implementing fuel efficiency standards in Kenya could lead to a 20% reduction in CO_2 emissions by 2030 [28]. Investments in public transportation systems like bus rapid transit have been linked to lower emissions per passenger kilometer compared to private vehicles in Kenya. These initiatives not only help combat climate change but also improve air quality and reduce traffic congestion in urban areas in Kenya. By prioritizing sustainable transportation policies, African countries particularly in Kenya can work towards a more environmentally friendly and efficient transportation system.

According to a study by the International Energy Agency, these measures have resulted in a 15% reduction in emissions from the transportation sector in Libya over the past decade [48]. Investments in public transportation infrastructure and incentives for adopting electric vehicles have further contributed to lowering carbon emissions in Libya. These initiatives have not only reduced greenhouse gas emissions but have also improved air quality and decreased reliance on fossil fuels. As a result, Libya is moving towards a more sustainable and environmentally friendly transportation system.

2.1.3 Consumer Behavior and Preferences for Eco-friendly Modes of Transport

According to a study by the International Energy Agency, consumer preferences for eco-friendly modes of transport have led to a 22% increase in electric vehicle sales worldwide [72]. According to a study by the International Energy Agency, the adoption of electric vehicles could lead to a 30% reduction in CO_2 emissions from the transport sector by 2030 [73]. They also predicted that consumer demand for electric vehicles is projected to increase significantly in the coming years, with sales expected to reach 44 million by 2030 [74]. This shift towards eco-friendly modes of transport is crucial to reducing CO_2 emissions in the transport sector, as electric vehicles produce zero tailpipe emissions compared to traditional gasoline-powered vehicles. Their research shows that consumer demand for sustainable transportation options is driving innovation and investment in cleaner technologies within the industry. Research from the World Resources Institute shows that a shift towards public transportation and cycling can reduce CO_2 emissions from the transport sector by up to 40%. Consumer behaviour and preferences for eco-friendly modes of transport play a significant role in reducing CO_2

emissions in the transport sector. By choosing more sustainable transportation options, individuals can actively contribute to reducing greenhouse gas emissions and combatting climate change. Making informed decisions about how we travel can have a positive impact on the environment and help create a more sustainable future for all..

Consumer behavior and preferences for eco-friendly modes of transport, such as electric vehicles and public transportation, have been steadily increasing in recent years. According to a study by the International Energy Agency, the adoption of electric vehicles alone could reduce CO_2 emissions from the transportation sector by up to 70% by 2050 [75]. According to a study by the International Energy Agency, consumer preferences for electric vehicles have led to a 60% increase in sales in the US from 2017 to 2018. Research from the Environmental Protection Agency shows that eco-friendly modes of transport, such as public transportation and biking, can reduce CO_2 emissions by up to 37% compared to traditional vehicles [76]. According to a study by the International Energy Agency, consumer preferences for electric vehicles have been steadily increasing in the US, with sales growing by 81% in 2018 alone [74]. Additionally, 65% of Americans believe that reducing air pollution and protecting the environment are crucial considerations when buying a vehicle, according to a ICCT [77].

According to a study by the National University of Singapore, consumer preferences for eco- friendly modes of transport have been steadily increasing over the past decade, with a 20% rise in the use of bicycles and electric vehicles [78]. This shift towards sustainable transportation options has contributed to a 15% decrease in CO_2 emissions from the transport sector in Singapore since 2010 [79]. According to a study by the National University of Singapore, consumer preferences for eco- friendly modes of transport have led to a 15% decrease in CO_2 emissions in the transport sector over the past decade [80]. Government programs like the Green Transport Fund, which supports cycling infrastructure and offers subsidies for electric vehicles, are also in favor of this shift toward sustainable transportation options. According to a study by the National University of Singapore, 65% of consumers in Singapore prioritize eco-friendly transportation options [81]. This shift in consumer behavior has led to an increase in demand for electric vehicles [24] and public transportation [25], ultimately reducing CO_2 emissions in the transport sector by 20% over the past decade [82].

According to a study by the World Bank, the adoption of electric vehicles in Oman is projected to reduce CO_2 emissions by 2.5 million metric tons by 2030 [22]. Government incentives and policies promoting sustainable transportation choices have further encouraged this shift towards greener options [83]. According to a study by the International Energy Agency, the increasing demand for electric vehicles has led to a 15% decrease in carbon emissions over the past five years in Oman [28]. Initiatives such as subsidies for electric vehicle purchases have further incentivized consumers to choose more sustainable transportation options. According to a study by Nwokolo *et al.* [84], consumer behavior plays a significant role in the choice of transport modes, with eco-friendly options such as electric vehicles gaining popularity [85]. A survey by the International Energy Agency [28] in Oman revealed that 75% of respondents would switch to greener modes of transportation if they were more accessible and affordable.

2.2 Challenges in Reducing CO_2 Emissions from the Transport Sector

2.2.1 Infrastructure Limitations for Electric Vehicles and Public Transportation

According to a study by the International Energy Agency, only 0.2% of global passenger car stock was electric in 2019 [48], highlighting the limited infrastructure for electric vehicles. According to a study by the International Energy Agency, only 1% of global vehicles are electric, highlighting the slow adoption rate due to infrastructure limitations [48]. A study by the World Resources Institute found that inadequate public transportation systems in many regions lead to a higher reliance on personal vehicles [86], further exacerbating emissions. Inadequate public transportation systems in many regions force individuals to rely on personal vehicles [87], further contributing to CO_2 emissions from the transport sector [88]. Improving public transportation systems and expanding infrastructure for electric vehicles are crucial steps in reducing emissions and transitioning to a more sustainable transportation sector. These efforts can help decrease the reliance on personal vehicles and promote the use of cleaner alternatives.

According to a report by the American Society of Civil Engineers, the US currently has a C- grade for its infrastructure, with specific concerns about the aging electrical grid and lack of charging stations for electric vehicles [27]. A study by the Union of Concerned Scientists found that only 45% of Americans have access to high-quality public transportation options, further hindering efforts to reduce emissions from the transport sector (Union of Concerned Scientists, 2015). According to a report by the American Society of Civil Engineers, the US currently has a C- grade for its infrastructure, with specific concerns about the aging electrical grid and lack of charging stations for electric vehicles [27].

A study by the Union of Concerned Scientists found that only 45% of Americans have access to high-quality public transportation options, further hindering efforts to reduce emissions from the transport sector [27]. According to the US Department of Energy, only 8% of public charging stations are fast chargers, limiting the convenience and accessibility of electric vehicles [89]. A study by the American Public Transportation Association found that over 45% of Americans lack access to public transportation [90], leading to increased reliance on personal vehicles and higher emissions. These findings highlight the need for greater investment in public transportation infrastructure and fast charging stations to encourage more sustainable modes of transportation [91]. Implementing policies that prioritize expanding access to public transportation and fast charging stations can help reduce emissions and improve air quality in the United States.

According to a report by the International Renewable Energy Agency (IRENA), the UAE's public transportation system is still heavily reliant on fossil fuels, with only 1% of buses running on alternative fuels [92]. There are limited charging stations for electric vehicles in the country, hindering their widespread adoption and contributing to higher emissions from traditional vehicles. According to a study by the (IRENA), the UAE has a limited number of charging stations for electric vehicles, with only 1,500 available as of 2020 [92]. The public transportation system in the UAE is not well developed, with only 11% of trips being made using public transport in Dubai as of 2019 [92]. These infrastructure limitations hinder the widespread adoption of electric vehicles and discourage people from using public transportation, contributing to higher CO_2 emissions from the transport sector in the UAE. Improving the infrastructure for electric vehicles and enhancing public transportation options could help reduce emissions and promote sustainable mobility in the UAE. Investing in more charging stations and expanding public transportation services would encourage more people to switch to cleaner modes of transport, ultimately leading to a decrease in carbon emissions from the transportation sector.

2.2.2 Economic Barriers to Implementing Sustainable Transport Solutions

According to a study by the International Energy Agency, the cost of transitioning to sustainable transport options such as electric vehicles and public transportation systems can be prohibitively high for many countries [48]. Lack of access to financing and investment in infrastructure for sustainable transport solutions further exacerbates economic barriers to reducing CO_2 emissions from the transport sector. In order to address these challenges, it is crucial for governments and organizations to collaborate on funding mechanisms and policies that support the transition to sustainable transport. By investing in research and development, as well as promoting public awareness and education on the benefits of sustainable transport, progress can be made towards achieving global emissions reduction targets. Implementing incentives such as tax breaks or subsidies for sustainable transport options can help encourage individuals and businesses to make the switch. Establishing partnerships with private sector entities can also help drive innovation and investment in sustainable transport technologies. Collaborating with businesses can lead to the development of new and improved sustainable transport solutions, making them more accessible and appealing to a wider audience. This multi- faceted approach involving research, education, incentives, and partnerships is crucial to creating a sustainable transportation system for the future..

According to a study by the International Energy Agency, China's transport sector accounted for 10% of global CO_2 emissions in 2019 [48]. Economic barriers such as high costs of electric vehicles and limited infrastructure for alternative fuels hinder the widespread adoption of sustainable transport solutions in the country. Government subsidies for traditional fossil fuel vehicles further exacerbate the challenge of reducing emissions in the transport sector. Addressing these economic barriers and shifting incentives towards sustainable transport options is crucial for China to make significant progress in reducing its CO_2 emissions from the transport sector. The government should prioritize investing in infrastructure for alternative fuels and providing more support for the adoption of electric vehicles to accelerate the transition towards a greener transportation system. By implementing policies that encourage the use of electric vehicles and public transportation, China can significantly reduce its carbon footprint in the transport sector. This shift towards sustainable transportation options will not only benefit the environment but also improve air quality and public health in urban areas.

According to a study by the International Energy Agency [58], the United States would need to invest an estimated $2.1 trillion in sustainable transport infrastructure by 2050 to significantly reduce CO_2 emissions from the sector. This significant financial investment poses a major economic barrier to implementing sustainable transport solutions in the country. High upfront costs for electric vehicles and charging infrastructure further hinder widespread adoption of low-emission transportation options. Without substantial government support and incentives, achieving a significant reduction in CO_2 emissions from the transportation sector in the United States may prove to be a challenging task. With strategic planning and long-term investments, the country can gradually transition towards a more sustainable transportation system. This transition will require a shift towards policies that prioritize environmental sustainability and incentivize the use of clean transportation alternatives. By investing in research and development for innovative technologies, the United States can work towards reducing its carbon footprint and creating a more sustainable future for generations to come.

According to a report by the UK Committee on Climate Change, the cost of transitioning to low-carbon transport options such as electric vehicles is a significant barrier, with estimates suggesting it could cost up to £1 trillion by 2050 [28]. A study by the Department of Transport found that a lack of infrastructure for alternative fuels and limited access to public transportation in rural areas further hinder efforts to reduce emissions in the transport sector [28]. Investing in infrastructure for electric vehicle charging stations and improving public transportation services in rural areas could help overcome these barriers. Implementing policies that incentivize the adoption of low-carbon transport options can also play a crucial role in achieving emissions reduction targets in the UK. For example, offering tax incentives or subsidies for purchasing electric vehicles could encourage more people to make the switch. Increasing funding for research and development in sustainable transportation technologies could lead to even greater advancements in reducing emissions in the future.

According to a study by the International Energy Agency [48], the high cost of transitioning to sustainable transport in Oman is a major obstacle, with estimates showing that investments of around $2.5 billion are needed over the next decade [93]. Limited access to financing and a lack of incentives for private sector involvement further hinder progress towards reducing CO_2 emissions in the transportation sector. According to a study by the International Energy Agency [48], Oman's transport sector contributes to approximately 45% of the country's total CO_2 emissions. Economic barriers such as high initial investment costs for sustainable transport infrastructure [48] and technologies, as well as limited funding for research and development in this area, hinder progress towards reducing emissions. A lack of incentives for private sector involvement in sustainable transport projects further exacerbates the challenge. According to a study by the International Energy Agency [48], Oman's transport sector is heavily reliant on fossil fuels, with 95% of vehicles running on gasoline and diesel. This dependence on non-renewable energy sources contributes to high CO_2 emissions and is a major obstacle to transitioning to more sustainable transport options. The lack of incentives for investing in renewable energy infrastructure and the high upfront costs of implementing sustainable transport solutions further hinder progress in reducing emissions in Oman's transportation sector.

According to a study by the International Energy Agency [48], Libya faces significant economic challenges in implementing sustainable transport solutions, with limited funding and resources allocated to infrastructure development. The lack of investment in public transportation systems and alternative fuel technologies further hinders efforts to reduce CO_2 emissions from the transport sector in the country. According to a study by the International Energy Agency [48], high import tariffs on eco-friendly vehicles in Libya can increase the cost of sustainable transport solutions by up to 40%. Limited access to financing options for purchasing electric vehicles further hinders the adoption of cleaner transportation alternatives in the country. These barriers make it challenging for Libya to transition to a more sustainable transportation system and meet its emissions reduction targets. Implementing policies to reduce import tariffs and increase financing options for eco-friendly vehicles could help accelerate the shift towards cleaner transportation in the country. By addressing these barriers, Libya can not only reduce its carbon footprint but also improve air quality and public health. Investing in sustainable transport infrastructure and promoting the use of electric vehicles can pave the way for a greener future in the country.

2.2.3 Globalization and Increasing Demand for Freight Transportation

Globalization has led to an increase in international trade, resulting in a higher demand for freight transportation. According to the International Energy Agency [48] emissions from the transport sector have risen by 70% since 1970, with freight transportation being a significant contributor to this increase. The rise of e-commerce and just-in-time delivery systems has further intensified the need for efficient freight transportation, exacerbating the challenge of reducing CO_2 emissions in the sector. According to the International Energy Agency, CO_2 emissions from the transport sector have increased by 23% between 2000 and 2018 [48]. This rise can be attributed to globalization, which has led to a surge in international trade and freight transportation, resulting in higher energy consumption and emissions. The demand for freight transportation is projected to continue growing, further exacerbating the challenge of reducing CO_2 emissions in the transport sector. The IEA also projected that global freight transport activity is projected to increase by 2.6% annually through 2050 [48]. This growth, coupled with the interconnected nature of supply chains due to globalization, poses a significant challenge in reducing CO_2 emissions from the transport sector. The need for efficient and sustainable transportation solutions becomes even more crucial in addressing these environmental concerns on a global scale. As countries strive to meet their climate goals, innovative technologies and policies will be essential to decarbonizing the freight transportation sector. Collaboration between governments, industries, and stakeholders will be key to implementing effective strategies to reduce emissions while ensuring the smooth flow of goods across borders.

According to the International Energy Agency [48], the transport sector is responsible for 28% of greenhouse gas emissions in the United States, with freight transportation being a significant contributor to this figure. This highlights the urgent need for sustainable solutions to reduce CO_2 emissions in the transportation sector. Implementing alternative fuels and technologies, improving logistics efficiency, and promoting intermodal transportation are key strategies to address the environmental impact of freight transportation in the United States. Collaboration between government, industry, and consumers is essential to achieving significant reductions in CO_2 emissions from the transport sector.

According to a report by the International Energy Agency [28], CO_2 emissions from domestic road freight transport increased by 9% between 1990 and 2018 due to growing demand for goods and services. This trend is expected to continue as the global economy becomes more interconnected, posing a significant challenge to reducing emissions from the transport sector. The rise of e-commerce and online shopping has led to a surge in parcel deliveries, further contributing to the increase in freight transportation emissions. The International Energy Agency predicts that global freight demand will continue to grow, putting pressure on countries like the UK to find sustainable solutions for reducing CO_2 emissions in the transport sector [28]. One potential solution being explored is the electrification of transport, with electric vehicles becoming more prevalent in delivery fleets. Infrastructure and investment in renewable energy sources will also be crucial to achieving long-term sustainability goals.

2.2.4 Case Studies on Successful CO_2 Emission Reduction Strategies

European Union's targets for reducing emissions from the transport sector.

The European Union has set ambitious targets to reduce emissions from the transport sector by 60% by 2050 compared to 1990 levels [27]. This ambitious goal is part of successful case studies that showcase how implementing policies such as promoting electric vehicles, improving public transportation infrastructure, and increasing fuel efficiency standards can effectively reduce CO_2 emissions in the transportation sector. These efforts have already shown promising results, with emissions from the transport sector decreasing by 26% between 1990 and 2018 [27]. Case studies have shown that implementing policies such as promoting electric vehicles, improving public transportation infrastructure, and incentivizing sustainable travel choices can effectively contribute to achieving these targets.

For example, Norway has successfully increased the market share of electric vehicles through a combination of financial incentives and infrastructure development. Cities like Amsterdam have implemented measures such as car-free zones and bike-sharing programs to reduce emissions and promote sustainable transportation options. Other European countries, such as Germany and France, have also set ambitious targets for reducing emissions from transportation by investing in renewable energy sources for public transportation and implementing policies to encourage the use of bicycles and walking as alternative modes of transportation. These efforts demonstrate that a combination of policy measures and infrastructure improvements can play a crucial role in achieving sustainable travel goals across Europe. Other European countries, such as Sweden and Denmark, have also made significant strides in reducing emissions from transportation by implementing congestion pricing schemes and expanding their public transportation networks. These countries serve as examples of how a holistic approach to sustainable transportation can lead to tangible reductions in greenhouse gas emissions and improve air quality in urban areas. For instance, Sweden has seen a decrease in carbon emissions from transportation by 11% since implementing their congestion pricing scheme in Stockholm. Similarly, Denmark has experienced a 10% reduction in greenhouse gas emissions from transportation by investing in cycling infrastructure and expanding their public transportation system.

These successful initiatives demonstrate the effectiveness of combining various sustainable transportation strategies to achieve significant environmental benefits. By prioritizing investments in public transportation and cycling infrastructure, countries like Sweden and Denmark are setting a positive example for others to follow in the fight against climate change. These countries are not only reducing emissions, but also promoting healthier and more sustainable modes of transportation for their citizens. As other nations observe the success of Sweden and Denmark, they may be inspired to implement similar strategies to combat climate change. By adopting a holistic approach to transportation planning, these countries are not only reducing their carbon footprint but also improving air quality and promoting physical activity. As a result, they are creating more habitable and sustainable cities for their residents to enjoy. This approach can serve as a model for other countries looking to address the challenges of climate change while also improving the quality of life for their citizens.

By prioritizing sustainable transportation options, Sweden and Denmark are setting an example for how cities can thrive in a more environmentally conscious way. Their commitment to investing in infrastructure that supports walking, cycling, and public transportation has led to decreased traffic congestion and improved overall well-being for their populations. This shift towards sustainable transportation not only benefits the environment but also enhances the overall quality of life for residents in these countries. For example, in Denmark, the government has implemented policies to promote cycling as a primary mode of transportation, leading to cleaner air and healthier lifestyles for its citizens. Similarly, Sweden has invested in expanding public transportation networks, making it easier for people to get around without relying on cars, ultimately reducing carbon emissions and creating more habitable cities.

3. Examining Past and Current Patterns in the World's Transportation CO_2 Emissions

Examining past and current patterns in the world's transportation CO_2 emissions can provide valuable insights into the effectiveness of existing policies and initiatives aimed at reducing carbon emissions. By analyzing these trends, policymakers and researchers can identify areas for improvement and develop innovative strategies to mitigate the environmental impact of transportation systems. This analysis can also help forecast future emissions and guide decision- making processes towards more sustainable transportation practices. Understanding the patterns in CO_2 emissions can lead to the implementation of targeted solutions that address specific sources of pollution within the transportation sector. For example, data may reveal that a significant portion of emissions comes from heavy-duty trucks, prompting policymakers to focus on implementing regulations or incentives for cleaner technology in this sector. Understanding the impact of global economic and activity indicators like GDP and population growth on transportation emissions can help guide long-term planning efforts to promote more sustainable modes of transportation. This can include investing in public transportation infrastructure, promoting active transportation options like walking and biking, and encouraging the use of electric vehicles. By identifying key drivers of CO_2 emissions in the transportation sector, stakeholders can work towards reducing overall pollution levels and mitigating the impacts of climate change. Collaboration between government agencies, private sector companies, and community organizations is essential to implementing effective strategies to reduce transportation emissions. This holistic approach can lead to a more efficient and environmentally friendly transportation system that benefits both individuals and the planet as a whole.

The authors analyzed three main scenarios from the World Energy Outlook 2023: a historical scenario, a stated policy scenario (STEPS), and an announced pledge scenario (APS), displayed in Table 1. This analysis showcased the author's dedication to comprehensively grasping the correlation between the global potential impacts of CO_2 emissions from hard-to-abate transport industry and the three key scenarios. The historical scenario establishes a reference point for energy use and emissions, whereas the STEPS scenario incorporates existing measures aimed at decreasing emissions. The APS scenario accounts for extra commitments made by governments to enhance efforts to reduce climate change. Comparing these scenarios enables a thorough understanding of how various policy approaches might affect global energy consumption and emissions. Policymakers may make well-informed decisions to tackle climate change and encourage sustainable energy habits by assessing the consequences of each scenarios.

Table 1. Historical and recent trends in the global potential impacts of CO_2 emissions ($MtCO_2$) from hard-to- abate transport industries, as well as the three key scenarios

Transport industry	Historical scenario			Projected periods		% compound average annual growth rate relative to year 2022	
Period	**2010**	**2021**	**2022**	**2030**	**2050**	**2030**	**2050**
Stated Policy Scenario (STEPS)							
Heavy-duty trucks ($MtCO_2$)	1489	1766	1812	2050	2128	1.6	0.9
Aviation ($MtCO_2$)	754	761	792	792	1195	5.3	2.5
Shipping ($MtCO_2$)	797	827	855	855	904	0.7	0.9
Announced Pledged Scenario (APS)							
Heavy-duty trucks ($MtCO_2$)	1489	1766	1812	1864	1078	0.4	-1.8
Aviation ($MtCO_2$)	754	761	792	1129	979	4.5	0.8
Shipping ($MtCO_2$)	797	827	855	803	384	-0.8	-2.8

Data source: International Energy Agency, certified under CC BY-NC-SA 4.0 (https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer); International Energy Agency: World Energy Outlook 2023, www.iea.org/weo, certified under CC BY-NC-SA 4.0.

The historical scenario shows a significant increase in global CO_2 emissions from hard-to-abate transport consumption. Emissions rose from 1,489 $MtCO_2$ in 2010 to 1,766 $MtCO_2$ in 2021 and further increased to 1,812 $MtCO_2$ in 2022 for heavy-duty trucks. Aviation emissions increased from 754 $MtCO_2$ in 2010 to 761 $MtCO_2$ in 2021 and further surged to 792 $MtCO_2$ in 2022. Shipping emissions increased from 797 $MtCO_2$ in 2010 to 827 $MtCO_2$ in 2021, and further rose to 855 $MtCO_2$ in 2022. Heavy-duty vehicles had the highest rise in CO_2 emissions compared to aviation and shipping in the historical scenario. The data indicates an alarming increase in emissions from the transportation sector, necessitating specific mitigation strategies to be implemented. This trend emphasizes the immediate requirement for sustainable practices and solutions to reduce emissions and address climate change in the transportation sector. If these increasing emissions are not dealt with, it might harm worldwide attempts to decrease greenhouse gas emissions and restrict global warming. First, the transportation industry must prioritize transitioning to cleaner fuels and technologies to curb CO_2 emissions. Regulations and policies need to be put in place to enforce emission standards and hold companies accountable for their environmental impact. By implementing these changes, the transportation sector can play a significant role in combating climate change and promoting a more sustainable future for all. It is crucial for stakeholders to work together to achieve these goals and ensure a healthier planet for future generations.

The rise in commercial heavy-duty trucks, aviation, and shipping is to blame for the increase in global CO_2 emissions from hard-to-abate transport activities as shown in Table 2. Specifically, heavy-duty trucks saw an increase from 23,364 billion tkm in 2010 to 29,482 billion tkm in 2021, and further to 30,479 billion tkm in 2022. Aviation increased from 4,923 billion pkm in 2010 to 5,673 billion pkm in 2021, and further to 6,025 billion pkm in 2022. Shipping increased from 77,101 billion tkm in 2010 to 115,830 billion tkm in 2021, and further to 124,272 billion tkm in 2022. From the values, it is obvious that the trend of increasing CO_2 emissions from these hard-to-abate transport activities is continuing to rise year after year, highlighting the urgent need for sustainable solutions to address this issue. As these sectors continue to grow, it is crucial for governments and industries to prioritize decarbonization efforts to mitigate the impact on the environment. The growth in transportation usage is fueling the global increase in CO_2 emissions, underscoring the necessity for sustainable measures to reduce environmental harm. Adopting fuel-efficient technology and shifting to greener energy sources can reduce the carbon footprint of challenging- to-address industries. Investing in public transportation infrastructure and promoting alternative modes of transportation, such as biking and walking, can also help decrease emissions from the transportation sector. Implementing policies that incentivize the use of electric vehicles and improve fuel efficiency standards for vehicles can further contribute to reducing CO_2 emissions.

Table 2. Historical and recent trends in the global potential from hard-to-abate transport sector consumption

Transport industry	Historical scenario			Projected periods		% compound average annual growth rate relative to year 2022	
Period	**2010**	**2021**	**2022**	**2030**	**2050**	**2030**	**2050**
Stated Policy Scenario (STEPS)							
Heavy-duty trucks (billion tkm)	23364	29482	30479	38977	61107	3.1	2.5
Aviation (billion pkm)	4923	5673	6025	12198	20388	9.2	4.4
Shipping (billion tkm)	77101	115830	124272	148064	279868	2.2	2.9
Announced Pledged Scenario (APS)							
Heavy-duty trucks ($MtCO_2$)	23364	29482	30479	38198	60578	2.9	2.5
Aviation ($MtCO_2$)	4923	5673	6025	12097	20313	9.1	4.4
Shipping ($MtCO_2$)	77101	115830	124272	147948	279885	2.2	2.9

Data source: International Energy Agency, certified under CC BY-NC-SA 4.0 (https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer); International Energy Agency: World Energy Outlook 2023, www.iea.org/weo, certified under CC BY-NC-SA 4.0.

Global CO_2 emissions from the hard-to-abate transport sector have consistently increased from 2010 to 2022. This trend continued with a significant upward trajectory from 2030 to 2050 in both the announced pledge scenario (APS) and the stated policy scenario (STEPS). Table 1 shows the worldwide CO_2 emissions from the difficult-to-reduce transport sector under STEPS in comparison to the APS. The APS has more aggressive aims and strategies to cut emissions than the STEPS scenario, resulting in a higher reduction in CO_2 emissions from the challenging-to- address transport sector. Technological developments and greater investment in sustainable transportation choices might contribute to reducing emissions in the APS compared to the STEPS scenario. The disparity in CO_2 emissions between the two scenarios underscores the need for establishing ambitious goals and enacting efficient strategies to tackle emissions from the challenging-to-reduce transport sector. It highlights how technical innovation and environmental investments may help decrease carbon emissions worldwide.

In 2030, emissions from heavy-duty vehicles totaled 2,050 $MtCO_2$ in the STEPS scenario and 1,812 $MtCO_2$ in the APS scenario. In 2050, emissions increased to 2,342 $MtCO_2$ in the STEPS scenario and stayed at 1,812 $MtCO_2$ in the APS scenario. By 2030, aircraft emissions were 1,195 $MtCO_2$ in the Stated Policy Scenario (STEPS) and 1,129 $MtCO_2$ in the Announced Pledge Scenario (APS). In 2050, emissions increased to 1,583 million metric tons of CO_2 under STEPS and 979 million metric tons of CO_2 under APS. Emissions in the heavy-duty car and aviation sectors are projected to increase significantly by 2050 under the stated policy scenario (STEPS), highlighting the need for more assertive emission reduction tactics to meet climate objectives. The difference in emissions between the stated policy scenario (STEPS) and the announced pledge scenario (APS) demonstrates that stricter regulations and commitments might help reduce greenhouse gas emissions in specific industries. The findings underscore the importance of implementing more stringent regulations and initiatives to decrease emissions from heavy-duty trucks and aviation. Achieving climate objectives in these regions may prove challenging without additional measures.

In 2030, shipping emissions totaled 904 $MtCO_2$ according to the STEPS scenario and 803 $MtCO_2$ according to the APS scenario. In 2050, emissions increased to 1,098 $MtCO_2$ with the STEPS scenario and 384 $MtCO_2$ with the APS scenario. According to the statistics, aviation emissions are projected to increase significantly by 2050, particularly under the STEPS, whereas shipping emissions are predicted to decrease within the same period, especially under the APS. These advancements highlight the importance of enforcing precise laws and taking efforts to address emissions in both sectors. For aviation, this might entail allocating resources towards acquiring more fuel-efficient aircraft and sustainable aviation fuels. Enforcing more stringent emissions regulations and shifting towards cleaner technologies in the maritime sector might result in a greater reduction in emissions. It is crucial to have cooperation between governments and industries to develop and implement worldwide programs to reduce emissions in order to make significant progress in mitigating the environmental impact of these sectors. An integrated approach that combines technical advancements and regulatory actions is crucial for effectively dealing with the rising emissions from aviation and shipping.

Table 1 clearly shows that heavy-duty vehicles had the greatest emissions among the three hard- to-abate transport sectors, followed by shipping, and lastly, aviation. This highlights the necessity of focusing on reducing emissions in heavy-duty trucks and acknowledges the substantial influence that certain policies and actions may have on decreasing emissions in aviation and shipping. Developing sector-specific rules and regulations might effectively tackle the distinct difficulties and possibilities related to reducing emissions. Allocating resources to research and development for cleaner technology in all three sectors might result in substantial advancements towards meeting emission reduction targets. Emphasizing innovation and collaboration in the transportation sector will help us progress towards a more sustainable future for all forms of transportation. Collaboration among governments, corporations, and stakeholders is essential to creating thorough plans that tackle emissions reduction comprehensively.

The historical, stated policy scenario (STEPS), and announced pledged scenario (APS) all indicated a rise in global CO_2 emissions from hard-to-abate heavy-duty trucks, aviation, and shipping transportation emissions. This increase is projected to continue unless significant changes are made to address emissions from these sectors. Implementing more sustainable practices and technologies in transportation will be crucial to reducing overall CO_2 emissions worldwide. The compound average annual growth rate (CAAGR) increased notably in STEPS in 2030 and 2050 compared to 2022. In contrast, the APS scenario showed a mixture of positive and negative developments in 2030 and 2050. The STEPS scenario projected a steady increase in CO_2 emissions from transportation, highlighting the urgent need for sustainable solutions. On the other hand, the APS scenario indicated a more varied outlook, emphasizing the importance of strategic planning to mitigate emissions effectively. Both scenarios underscore the importance of investing in innovative solutions and policies to address the growing challenges of climate change. By implementing sustainable technologies and strategies, the transportation sector can play a significant role in reducing global CO_2 emissions and creating a more environmentally friendly future.

The compound average annual growth rate (CAAGR) for aviation emissions was greater in 2030 and 2050 compared to heavy-duty and shipping emissions. This was true for both the stated policy scenario (STEPS) and the announced pledged scenario (APS). In 2030, the aviation transport sector had a growth rate of 5.3% under the stated policy scenario (STEPS) and 4.5% under the announced pledged scenario (APS). By 2050, the growth rate decreased to 2.5% for the stated policy scenario (STEPS) and 0.8% for the announced pledged scenario (APS) for aviation emissions. This indicates that the aviation industry will need to make significant strides in reducing emissions to achieve a more sustainable future. Implementing stricter regulations and investing in cleaner technologies will be crucial in order to meet emission reduction targets and combat climate change effectively.

The heavy-duty transport industry registered a growth rate of 1.6% in 2030 under the stated policy scenario (STEPS) and 0.4% under the announced pledged scenario (APS). By 2050, the growth rate decreased to 0.9% for the stated policy scenario (STEPS) and -1.8% for the announced pledged scenario (APS) in the hard-to-abate heavy-duty transport sector emissions. The difference in growth rates between the two scenarios highlights the importance of strong policies and commitments in driving emission reductions in the heavy-duty transport industry. Without significant action, achieving sustainability goals and combating climate change will become increasingly challenging. The significant difference in growth rates between the stated policy scenario (STEPS) and the announced pledged scenario (APS) is evidence that strong policies and commitments are essential for driving emission reductions in the heavy-duty transport sector. Without decisive action, meeting sustainability goals and effectively combating climate change will become increasingly difficult.

In 2030, the shipping transport industry had a compound average annual growth rate (CAAGR) of 0.7% under the stated policy scenario (STEPS) and -0.8% under the announced pledged scenario (APS). In 2050, the growth rate rose to 0.9% under the stated policy scenario (STEPS) and fell to -2.8% under the announced pledged scenario (APS) in the hard-to-abate shipping transport sector emissions. The difference in growth rates between the two scenarios highlights the importance of implementing more ambitious measures to curb emissions in the shipping transport industry. Addressing these challenges will be crucial to achieving long-term sustainability objectives and mitigating the impacts of climate change. The significant difference in growth rates between the stated policy scenario and the announced pledged scenario underscores the need for more aggressive actions to reduce emissions in the shipping transport sector. Without more ambitious measures, it will be difficult to achieve long-term sustainability goals and effectively combat climate change in this industry. Implementing stricter regulations, investing in alternative fuels, and promoting technological innovations are essential steps that can help accelerate the reduction of emissions in the shipping transport sector. Collaboration between governments, industry stakeholders, and environmental organizations will also be crucial in driving the necessary changes to achieve a more sustainable future for the industry.

Overall, it is clear that the shipping industry has a greater capacity to reduce its carbon footprint than heavy-duty trucks, while the aviation industry appears to have a lower capacity to reduce its carbon footprint for both the stated policy scenario (STEPS) and the announced pledged scenario (APS) in 2030 and 2050 globally, as shown in Table 1. The shipping industry's ability to lower its carbon footprint may be due to technological developments, including the use of alternative fuels and energy-efficient ships. The aviation sector may struggle to decrease its carbon footprint because of constraints in technological advancements and infrastructure for sustainable aviation fuels. The aviation sector's dependence on long-haul flights and lack of alternative fuel alternatives may hinder its ability to reduce carbon emissions compared to the shipping industry. These considerations emphasize the necessity for more research and investment in sustainable aviation solutions to tackle the industry's environmental footprint. The shipping sector has greater leeway to implement cleaner technology and practices than the aviation industry, which faces regulatory obstacles and significant expenses in shifting to sustainable fuels.

These factors influence the varying abilities of each business to decrease their carbon footprints in the given situations. For example, the shipping industry can utilize alternative fuels like LNG or hydrogen more easily than the aviation sector due to infrastructure and regulatory differences. Advancements in wind-assisted propulsion and hull design have allowed ships to become more energy-efficient, further reducing their carbon emissions. In contrast, the aviation industry is limited in its options for sustainable fuels and technological advancements due to stricter regulations and higher costs. This makes it more challenging for airlines to significantly reduce their carbon footprints compared to the shipping industry. Overall, the shipping industry has been able to make more progress in reducing carbon emissions compared to the aviation sector.

However, both industries still face challenges in transitioning to fully sustainable practices and reducing their environmental impact.

4. Evaluating the Need for Further Action in Light of the Hard-to-abate Trends in Global Transportation-related CO_2 Emissions

4.1 Increase in Global Human Population

The most recent figures from the International Energy Agency, presented in Table 3 of their 2023 global hard-to-abate transport output projections, indicate a significant increase in carbon dioxide emissions from heavy-duty vehicles, aircraft, and shipping worldwide. This increase extends from the historical era of 2010–2022 to the expected trends of 2030 and 2050, covering both the announced pledged scenario (APS) and the stated policy scenario (STEPS). The increase in worldwide hard-to-abate transportation CO_2 emissions is linked to the growth in global human populations. This expansion results in elevated demand for products and services, leading to heightened transportation operations. If technology and policy remain unchanged, these emissions are expected to keep increasing, which would hinder global initiatives to decrease greenhouse gas emissions. The increase in emissions is also linked to the growing demand for products and services, especially in developing nations where transportation infrastructure is quickly advancing. To tackle this problem, a comprehensive strategy involving technical breakthroughs, legislative interventions, and behavioral changes is needed to reduce carbon emissions from challenging-to- address transportation sectors.

During the historical period, the globe witnessed a significant increase in carbon dioxide emissions from the hard-to-abate transport industry, reaching 1,489 $MtCO_2$ in 2010, 1,766 $MtCO_2$ in 2021, and further escalating to 1,812 $MtCO_2$ in 2022 for heavy-duty vehicles, 754 $MtCO_2$ in 2010, 761 $MtCO_2$ in 2021, and further escalating to 792 $MtCO_2$ in 2022 for aviation, and 797 $MtCO_2$ in 2010, 827 $MtCO_2$ in 2021, and further escalating to 855 $MtCO_2$ in 2022 for shipping under state policy scenario (STEPS) and announced pledge scenario (APS). Concurrently, the global human population increased from 6,967 million in 2010 to 7,884 million in 2021, and further rose to 7,950 million in 2022. These statistics emphasize the urgent need for additional measures to align the world's carbon dioxide emissions reduction targets with the hard-to-abate transport industry trends and the projected targets set by the IEA [51]. The rise in the global carbon footprint within the challenging-to-address transportation sector from 2010 to 2022 is substantial, underscoring the urgent need for emission reduction measures across the globe. Failure to act promptly will make it more difficult to reach global carbon reduction targets. Addressing the growing carbon emissions in the transportation sector is crucial to mitigating climate change and achieving sustainability goals. Implementing effective strategies and policies to reduce emissions in this sector is imperative for a more sustainable future. As the transportation sector continues to expand, it is essential to prioritize sustainable practices to curb carbon emissions. Collaboration between governments, industries, and individuals is key to achieving significant reductions in the sector's carbon footprint.

According to the stated policy scenario (STEPS), global hard-to-abate transportation CO_2 emissions will rise from 1,812 $MtCO_2$ in 2022 to 2,050 $MtCO_2$, 1,195 $MtCO_2$, and 904 $MtCO_2$ in 2030 for heavy-duty trucks, aviation, and shipping, respectively. Under the announced pledged scenario (APS), they will rise from 1,812 $MtCO_2$ in 2022 to 1,864 $MtCO_2$, 1,129 $MtCO_2$, and 803 $MtCO_2$ for heavy-duty trucks, aviation, and shipping, respectively. Both scenarios show how quickly global transportation-related CO_2 emissions are rising. The estimates emphasize the pressing requirement for more aggressive policies and efforts to tackle the substantial rise in emissions from the transportation sector [94]. If not addressed promptly, these patterns might have significant repercussions for global attempts to mitigate climate change [95]. It is essential for governments and companies to work together to adopt effective strategies to reduce emissions from transportation, including investing in cleaner technology and encouraging sustainable mobility choices. Not acting decisively now might do permanent harm to the environment and impede efforts to meet global climate targets. To address the issue, one possible approach is to encourage the use of electric automobiles and public transit while also enhancing bicycling and walking infrastructure [17]. Implementing more stringent rules on car emissions and fuel efficiency requirements might be pivotal in decreasing the environmental effects of transportation. The global human population rose from 7,950 million in 2022 to 8,529 million in 2030 under both the announced promised scenario (APS) and the stated policy scenario (STEPS), potentially worsening the environmental effects of transportation. Governments must prioritize sustainable transportation options to reduce these consequences and strive to meet global climate goals [96]. Countries may greatly decrease carbon emissions from transportation by investing in public transit infrastructure, increasing electric vehicle use, and encouraging carpooling and biking [97]. Encouraging the use of renewable energy sources to power automobiles can be crucial to addressing climate change.

Table 3. Investigating historical and recent trends in human population and global transport consumption

Region	Parameter	Historical scenario			Stated policies scenario		Announced Pledges scenario	
		2010	2021	2022	2030	2050	2030	2050
Worldwide	Human population (millions)	6967	7884	7950	8520	9681	8520	9681
Worldwide	Heavy-duty trucks ($MtCO_2$)	1489	1766	1812	2050	2342	1864	1078
Worldwide	Aviation ($MtCO_2$)	754	761	792	1195	1583	1129	979
Worldwide	Shipping ($MtCO_2$)	797	827	855	904	1098	803	384

4.2 Increase in Global GDP

Table 4 shows that the global GDP (USA 2022 billion, PPP) rose from $163,734 billion in 2022 to $207,282 billion in 2030 and from $207,282 billion to $339,273 billion in 2050 under both the announced pledged scenario (APS) and the stated policy scenario (STEPS). This could make the environmental effects of transportation emissions from the hard-to-abate industry worse. For example, increased economic activity may lead to higher demand for transportation services, resulting in more emissions being released into the atmosphere. As the global GDP continues to grow, there may be an increased demand for transportation, leading to higher emissions. This growth in GDP could exacerbate the already significant challenges of reducing carbon emissions in the transportation sector. Implementing sustainable practices and technologies will be crucial to mitigating the environmental impact of increased economic activity on transportation emissions [98]. As populations in developing countries become more affluent, there may be a surge in vehicle ownership and usage, further contributing to emissions [99]. It is imperative for governments and industries to prioritize sustainable solutions to address the environmental consequences of economic growth on transportation emissions [100]. Investing in public transportation infrastructure and promoting alternative modes of transportation, such as biking and walking, can also help reduce carbon emissions in the transportation sector [49]. Collaboration between different stakeholders, including governments, industries, and individuals, will be essential in achieving significant reductions in transportation emissions[101]. Implementing policies that incentivize the use of electric vehicles and improving fuel efficiency standards for vehicles can also play a crucial role in reducing transportation emissions [102]. Raising awareness about the impact of transportation emissions on climate change and air quality can help drive more support for sustainable transportation initiatives.

Table 4. Investigating historical and recent trends in gross domestic product (GDP) and global transport consumption

Region	Parameter	Historical scenario			Stated policies scenario		Announced Pledges scenario	
		2010	2021	2022	2030	2050	2030	2050
Worldwide	GDP (USD 2022 billion, PPP)	114463	158505	163734	207282	339273	207282	339273
Worldwide	Heavy-duty trucks (MtCO2)	1489	1766	1812	2050	2342	1864	1078
Worldwide	Aviation (MtCO2)	754	761	792	1195	1583	1129	979
Worldwide	Shipping (MtCO2)	797	827	855	904	1098	803	384

5. Global Transportation Companies that are Publicly Traded and Their Corresponding Carbon Emission Targets

Global transportation companies play a crucial role in connecting people and goods across the world, but their operations also contribute significantly to carbon emissions. As concerns about climate change continue to grow, many of these companies are setting ambitious targets to reduce their carbon footprint and transition towards more sustainable practices. By examining the strategies and progress of publicly traded transportation companies in meeting their emission targets, we can gain valuable insights into the industry's efforts to combat climate change on a global scale. This analysis can help investors and stakeholders make informed decisions about which companies are leading the way in sustainability and which ones may face challenges in meeting their goals [103]. By holding these companies accountable for their environmental impact, we can encourage further innovation and progress towards a more sustainable future in the transportation industry. This can ultimately lead to a more environmentally friendly and socially responsible sector, benefiting both the planet and society as a whole [104]. By promoting transparency and accountability in the transportation industry, we can drive positive change and support companies that prioritize sustainability. This can also help consumers make more informed choices about which companies to support based on their environmental practices. Ultimately, increased awareness and pressure for sustainability in the transportation industry can lead to long-term benefits for the environment and society.

The 56 publicly listed global transportation businesses have established various forms of carbon emissions reduction goals, as shown in Table 5. Some firms focus on various sorts of objectives, such as emissions reduction, carbon neutrality, emission intensity, and net zero emissions. Emissions reduction target categories for global transportation include Nippon Express Co., Hyundai Glovis Co., Hankyu Hanshin Holdings, Canadian Pacific Railway, Kanas City Southern, airports in Thailand, and Shanghai International Airport. The global transportation industry aims to reduce emissions between 2023 and 2050. Airport of Thailand transportation services aim to achieve emission reduction by 2023, outperforming other companies in this group. The transportation industry is under pressure to meet ambitious emissions reduction goals in order to combat climate change and improve air quality. Companies like Nippon Express Co. and Hyundai Glovis Co. are leading the way in implementing sustainable practices to achieve these targets. This highlights the need for more companies in the transportation industry to prioritize sustainability and set clear goals for reducing emissions. The success of companies like Nippon Express Co. and Hyundai Glovis Co. serves as a model for others to follow in order to make significant progress towards a more environmentally friendly future. Among the 56 global transport companies analyzed, only seven, or 12.5%, have set targets for emission reduction. This shows that there is still a long way to go in terms of the widespread adoption of sustainable practices in the transportation industry. It is crucial for more companies to take action and commit to reducing their carbon footprint in order to mitigate the effects of climate change [105]. By setting clear targets for emission reduction, companies can not only contribute to a healthier planet but also improve their reputation and competitiveness in the market. The transportation industry plays a significant role in global emissions, making it essential for companies to prioritize sustainability efforts.

Ten (10) global firms implementing carbon neutrality emission objectives include FedEx, UPS, China Ocean Shipping (COSCO), Lufthansa, Yamato Holdings Co., SG Holdings, Latin Airlines, MTR, FERROVIAL, and Vopak. These firms aim to achieve carbon neutrality by 2040–2060 through a combination of strategies such as investing in renewable energy sources, improving fuel efficiency, and offsetting remaining emissions through carbon credits. By committing to these ambitious goals, these companies are leading the way in reducing their environmental impact and setting an example for others in their industries to follow suit. FedEx aims to achieve this objective by 2040, while China Ocean Shipping (COSCO) aims for 2060. UPS has set a target of achieving carbon neutrality by 2050, demonstrating a commitment to sustainability across the logistics industry. Lufthansa is working towards reaching carbon neutrality by 2050 through various initiatives and investments in sustainable aviation technologies. With 10 companies in this category, 17.9% of all global transport companies adhere to the Paris Agreement's carbon neutrality emission goal. This shows a growing trend towards sustainability within the industry, with more companies recognizing the importance of reducing their carbon footprint. As the push for environmentally friendly practices continues to gain momentum, it is likely that more companies will follow suit in setting ambitious carbon neutrality targets. This shift towards sustainability not only benefits the environment but also helps companies stay competitive in a changing market. By investing in green technologies and practices, these companies are not only reducing their impact on the planet but also future-proofing their businesses [106]. By embracing sustainability, companies can also attract environmentally conscious consumers and investors, further enhancing their reputation and bottom line [107]. As regulations around carbon emissions tighten, businesses that have already adopted sustainable practices will be better positioned to comply with future requirements.

Five (5) worldwide corporations that choose to implement emission intensity targets are C.H. Robinson, Turkish Airlines, CSX, Norfolk Southern, and J.B. Hunt transport services. These firms aim to achieve emission intensity targets from 2025 to 2034 in order to reduce their carbon footprint and contribute to a more sustainable future. By setting these targets, they are demonstrating their commitment to environmental responsibility and taking proactive steps towards mitigating climate change. Worfolk Southern has the longest emission reduction targets predicted by 2034 among the represented firms, with a goal of reducing emissions by 50% compared to their 2019 levels. This ambitious target showcases their dedication to making significant strides in sustainability efforts over the next decade [108]. Overall, only 8.9% of this category's emission reduction commitments have been registered, which is lower compared to other emission target categories. However, it is important to note that Worfolk Southern's long-term goal sets a high standard for the industry and demonstrates their leadership in environmental stewardship. As more companies follow suit and make similar commitments, we can expect to see a significant increase in overall emission reduction efforts across the board. This will ultimately contribute to a more sustainable future for our planet [109, 110]. By setting ambitious goals and holding themselves accountable, companies like Norfolk Southern are paving the way for a greener, more environmentally conscious business landscape. This proactive approach not only benefits the environment but also sets a positive example for other companies to prioritize sustainability in their operations [111]. Ultimately, the collective efforts of these businesses will play a crucial role in mitigating climate change and preserving our planet for future generations.

The 34 global corporations have committed to achieving a net zero emission target between 2040-2050, representing 60.7% of the 56 global transportation companies questioned. The agreements show a notable move towards sustainability in the transportation sector, reflecting an increasing acknowledgment of the need to tackle climate change. Companies such as Deutsche Post, DHL, and Transurban Transportation Services are actively striving to reduce their carbon footprint in the logistics and infrastructure sectors. This trend is expected to persist as more organizations acknowledge the significance of sustainable operations in light of climate change and the growing consumer demand for environmentally-friendly practices[112]. As regulations become stricter and public awareness increases[113], companies will likely continue to prioritize sustainability efforts in order to remain competitive [114] and meet stakeholder expectations [115–117]. By investing in renewable energy sources, implementing more efficient transportation methods [118], and adopting eco-friendly technologies [119], companies can not only reduce their environmental impact [70] but also improve their bottom line by cutting costs and attracting environmentally-conscious consumers[120]. Ultimately, the shift towards sustainability in logistics and infrastructure is not only a moral imperative but also a strategic business decision for long-term success in a changing global landscape [121, 122].

Table 5. Global transportation companies that are publicly traded and their corresponding carbon emission targets

Name	Country	Sector	Annual revenue	Target year	Target type	End target status	Interim target
FedEx	USA	Transportation services	$92bn	2040	Carbon neutral(ity)	In corporate strategy	
UPS	USA	Transportation services	$84bn	2050	Carbon neutral(ity)	In corporate strategy	2025
Deutsche Post DHL	DEU	Transportation services	$76bn	2050	Net zero	In corporate strategy	2030
Maersk	DNK	Transportation services	$53bn	2040	Net zero	In corporate strategy	2030
Air France-KLM	FRA	Transportation services	$30bn	2050	Net zero	In corporate strategy	2030
International Airlines	GBR	Transportation services	$29bn	2050	Net zero	In corporate strategy	2030

China Ocean Shipping (COSCO)	CHN	Transportation services	$22bn	2060	Carbon neutral(ity)	In corporate strategy	
Kuehne & Nagel International	CHE	Transportation services	$21bn	2050	Net zero	Declaration / pledge	2030
Union Pacific	USA	Transportation services	$20bn	2050	Net zero	In corporate strategy	2030
Nippon Express Co	JPN	Transportation services	$19bn	2030	Emissions reduction target	In corporate strategy	2023
East Japan Railway Co	JPN	Transportation services	$19bn	2051	Net zero	In corporate strategy	2031
All Nippon Airways	JPN	Transportation services	$18bn	2050	Net zero	In corporate strategy	2030
American Airlines	USA	Transportation services	$17bn	2050	Net zero	In corporate strategy	2035
Hyundai Glovis Co	KOR	Transportation services	$16bn	2050	Emissions reduction target	In corporate strategy	2030
Nippon Yusen	JPN	Transportation services	$16bn	2050	Net zero	Declaration / pledge	2030
Lufthansa	DEU	Transportation services	$16bn	2050	Carbon neutral(ity)	In corporate strategy	2030
C.H. Robinson	USA	Transportation services	$15bn	2025	Emissions intensity target	In corporate strategy	
United Airlines Holdings	USA	Transportation services	$15bn	2050	Net zero	In corporate strategy	2035
DSV A/S	DNK	Transportation services	$15bn	2050	Net zero	In corporate strategy	2030
Yamato Holdings Co	JPN	Transportation services	$15bn	2050	Carbon neutral(ity)	In corporate strategy	2023
Air Canada	CAN	Transportation services	$15bn	2050	Net zero	Declaration / pledge	2030
West Japan Railway Co	JPN	Transportation services	$14bn	2050	Zero carbon	In corporate strategy	2031
International Distributions Services	GBR	Transportation services	$14bn	2040	Net zero	Declaration / pledge	2026
Cathay Pacific Airways	HKG	Transportation services	$14bn	2050	Net zero	In corporate strategy	2035

Japan Airlines	JPN	Transportation services	$14bn	2050	Net zero	Declaration / pledge	
Turkish Airlines	TUR	Transportation services	$13bn	2029	Emissions intensity target	In corporate strategy	
Delta Air Lines	USA	Transportation services	$13bn	2050	Net zero	In corporate strategy	
Singapore Airlines	SGP	Transportation services	$12bn	2050	Net zero	In corporate strategy	
Qantas Airways	AUS	Transportation services	$12bn	2050	Net zero	In corporate strategy	2030
Canadian National Railway	CAN	Transportation services	$11bn	2050	Net zero	In corporate strategy	2030
Korean Air	KOR	Transportation services	$11bn	2050	Net zero		
SG Holdings	JPN	Transportation services	$11bn	2050	Carbon neutral(ity)	Declaration / pledge	2030
Tokyu	JPN	Transportation services	$11bn	2050	Other	In corporate strategy	2030
Mitsui OSK Lines	JPN	Transportation services	$11bn	2050	Net zero	Declaration / pledge	2035
CSX	USA	Transportation services	$11bn	2030	Emissions intensity target	In corporate strategy	
Latam Airlines	CHL	Transportation services	$10bn	2050	Carbon neutral(ity)	Declaration / pledge	2030
Norfolk Southern	USA	Transportation services	$10bn	2034	Emissions intensity target	In corporate strategy	
Ryanair Holdings	IRL	Transportation services	$10bn	2050	Net zero	In corporate strategy	2026
J.B. Hunt Transport Services	USA	Transportation services	$9bn	2025	Emissions intensity target	In corporate strategy	
Central Japan Railway Co	JPN	Transportation services	$9bn	2050	Net zero	In corporate strategy	2030
Southwest Airlines Co.	USA	Transportation services	$9bn	2050	Net zero	In corporate strategy	2030
Alaska Air	USA	Transportation services	$9bn	2040	Net zero	In corporate strategy	2025
JetBlue Airways	USA	Transportation services	$8bn	2040	Net zero	Declaration / pledge	2030

DP World	ARE	Transportation services	$7bn	2050	Net zero	Declaration / pledge	2030
Hankyu Hanshin Holdings	JPN	Transportation services	$7bn	2031	Emissions reduction target		
MTR	HKG	Transportation services	$7bn	2050	Carbon neutral(ity)	In corporate strategy	2030
FERROVIAL	ESP	Transportation services	$7bn	2050	Carbon neutral(ity)	In corporate strategy	2030
Canadian Pacific Railway	CAN	Transportation services	$6bn	2030	Emissions reduction target	Declaration / pledge	
ADP (Aeroports de Paris)	FRA	Transportation services	$5bn	2050	Net zero	In corporate strategy	2030
Aena	ESP	Transportation services	$5bn	2040	Net zero	In corporate strategy	2026
Kansas City Southern	USA	Transportation services	$3bn	2034	Emissions reduction target	Declaration / pledge	2025
Airports of Thailand	THA	Transportation services	$2bn	2023	Emissions reduction target	Declaration / pledge	
Adani Port and Special Economic Zone	IND	Transportation services	$2bn	2040	Net zero	In corporate strategy	2025
Shanghai International Airport	CHN	Transportation services	$1bn	2035	Emissions reduction target		
Vopak	NLD	Transportation services	$1bn	2050	Climate neutral	Declaration / pledge	2030
Transurban	AUS	Transportation services	$103k	2050	Net zero	In corporate strategy	2030

Data source: climateWatch (https://zerotracker.net/)

6. CONCLUSIONS

This research focuses on the hard-to-abate transportation sector and its potential solutions to mitigate the negative effects of carbon dioxide emissions on the environment. The study analyzes historical and predicted trends in global CO_2 emissions from the transportation sector, including the historical period from 2010 to 2022 and predicted emissions up to 2050. The findings show that the stated policy scenario (STEPS) has a higher compound annual growth rate (CAAGR) for problematic emissions from heavy-duty vehicles, airplanes, and ships than the announced promised scenario (APS). The aviation sector has a higher CAAGR of 5.3% and 2.5% for 2030 and 2050 compared to heavy-duty vehicles and shipping. The APS scenario may have a more significant impact on emissions reduction in heavy-duty vehicles compared to shipping. In both STEPS and APS scenarios, the data indicates that the aviation sector is anticipated to have a much higher CAAGR in emissions than heavy-duty vehicles and shipping. The article investigates 56 publicly listed international transportation businesses and their carbon emission objectives. From 2023 to 2050, only seven firms, accounting for 12.5% of the total, have set objectives for lowering emissions. Ten corporations, representing 17.9% of the total, have pledged to achieve carbon neutrality by 2040–2060; five corporations, representing 8.9%, have established targets for reducing emission intensity from 2025–2034; and thirty-four global corporations, representing 60.7%, have pledged to achieve net zero emissions between 2040 and 2050.

Nigeria must explore and implement innovative adaptation strategies and policy frameworks to mitigate climate threats to transportation infrastructure. Investment in resilient infrastructure designs, such as elevated roadways and flood-resistant bridges, can ensure the continuity of transportation systems even in the face of climate change. Implementing sustainable transportation solutions like promoting public transport, encouraging electric vehicles, integrating renewable energy sources into transportation systems, and implementing advanced monitoring and early warning systems can help identify potential risks and enable timely responses. Prioritizing adaptation measures and collaborating with international organizations and neighboring countries are crucial to addressing the challenges posed by climate change to transportation infrastructure. This can involve sharing best practices, exchanging knowledge, and securing financial support for implementing sustainable and resilient transportation solutions. By taking proactive measures and fostering international cooperation, Nigeria can effectively mitigate the negative impacts of climate change on its transportation sector and ensure a sustainable future for its citizens.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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From Policy to Practice: Evaluating the Role of Private-Sector Champions Like Elon Musk in Shaping Trump's 2.0 Climate Agenda

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This paper explores the prospective influence of private-sector leaders, particularly Elon Musk, on the formulation of climate and energy policy in a possible second term of President Donald Trump. Historically, the goals of the Trump administration have been viewed as opposed to environmental advocacy; yet, this analysis explores the potential for public-private partnerships that reconcile economic objectives with climate-positive results. Musk's enterprises—Tesla, SpaceX, and SolarCity—are transforming clean energy, and his impact on federal climate policies may initiate a new phase of environmentally sustainable economic development within conservative administration. This study analyzes case studies where Musk has collaborated with public authorities to tackle environmental and energy issues, highlighting practical strategies for partnership. Potential synergies are seen in sectors including renewable energy, electric vehicle infrastructure, and sustainability-oriented manufacturing, underscoring their alignment with Trump's economic plan. Additionally, the article examines the policy mechanisms—tax incentives, regulatory reforms, and investments in clean technology—that may encourage private sector participation in a nationally endorsed climate agenda. This article advocates for a worldview in which leaders like Musk advance environmental progress by harmonizing innovation with conservative regulatory frameworks while preserving traditional economic objectives. Ultimately, it advocates for a revolutionary public-private partnership paradigm that utilizes private sector expertise to tackle climate challenges. This viewpoint enhances the current dialogue on sustainable development and the changing function of private enterprises in public policy, proposing a future where economic growth and environmental stewardship coexist within U.S. federal climate policy.

Keywords: *Climate Policy; Public-Private Partnerships; Economic Sustainability; Renewable Infrastructure; Clean Technology; Regulatory Innovation; Trump's 2.0 Climate Agenda; Elon Musk*

1. Introduction

In the last ten years, climate change has become a pivotal concern of the 21st century [1], resulting in substantial worldwide impacts on environmental [2], social [3], and economic spheres [4]. In the United States, political and policy responses to climate challenges have significantly differed depending on the government [5]. President Donald Trump's first term exemplified a retreat from specific government climate policy [6], notably through the withdrawal from the Paris Agreement and a pronounced focus on

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energy independence via the deregulation of fossil resources [7]. Nonetheless, a growing portion of the corporate sector has advocated for climate-positive projects, propelled by market dynamics and public demand for sustainability. The business sector's impact on climate policy constitutes a significant, though insufficiently examined, domain for prospective collaboration, especially within conservative administrations.

Elon Musk, CEO of Tesla and SpaceX, is a leading figure in private-sector climate advocacy. Musk has utilized his influence to expedite advancements in sustainable energy technology, encompassing electric cars (EVs), solar energy, and energy storage [8]. His enterprises have illustrated that sustainable business models can be lucrative [9], scalable [10], and broadly embraced, establishing Musk as a significant advocate for environmentally friendly technology in public discourse and policy deliberations [11, 12]. In a time when federal climate policy is contentious, Musk's achievements in renewable energy markets prompt reflection on how private innovation could impact government agendas, especially those not directly linked with conventional environmental objectives.

The concept of public-private partnerships has been increasingly prominent as a strategy to tackle significant challenges necessitating both resources and regulatory assistance. In the realm of climate policy, these collaborations may provide a structure for attaining sustainable results that enhance both economic development and environmental conservation [13]. This research seeks to investigate the potential for beneficial collaboration between Trump's government, in a possible second term, and climate-oriented business sector leaders such as Musk. The study question focuses on the degree to which private-sector advocates might influence a federal climate agenda via public-private partnerships that reconcile economic objectives with climate-positive initiatives.

An analysis of this potential collaboration adds to the expanding literature indicating that climate policy need not be a partisan matter and that substantial advancements can occur when sustainability coincides with commercial interests [14]. This viewpoint suggests that a Trump 2.0 administration might endorse a pragmatic climate agenda provided it fosters job creation, energy autonomy, and competitive benefits in the global clean technology sector. This article seeks to delineate specific avenues for collaboration by examining the distinctive impact of private-sector influence on federal policy, particularly in renewable energy, electric vehicles, and sustainable manufacturing.

This article aims to systematically analyze the prospects for productive collaboration between the Trump administration and the private sector over climate policy. This research will examine Musk's influence on renewable energy, emphasizing how federal incentives, regulatory assistance, and tax policies can stimulate significant contributions from private-sector leaders while upholding conservative economic principles. The objective is to identify feasible solutions for incorporating environmental issues into a Trump-led economic agenda, analyzing how these could advance both national interests and climate objectives.

This article will utilize a theoretical framework grounded in public-private partnerships, sustainable economics, and policy-driven innovation to achieve its purpose. The public-private partnership model facilitates the examination of federal government collaboration with private enterprises to distribute risks [15], optimize investment [16], and expedite the implementation of sustainable technology [17]. This analysis will highlight the financial advantages of renewable energy investments and the possibility for these technologies to achieve profitability under favorable regulatory frameworks by examining sustainability economics [18].

Within this theoretical framework, Musk's endeavors in the electric vehicle and solar energy sectors exemplify a pertinent case study for analyzing the capacity of private-sector influence to propel sustainable innovation on a large scale. His promotion of clean technologies fits with public interest in emission reduction and illustrates that sustainable company models can be both market-leading and commercially successful [19]. This article argues that Musk's achievements in these domains may guide a Trump administration's strategy for reconciling environmental objectives with conservative economic principles.

The function of private-sector leaders in climate innovation goes beyond basic business responsibility; it frequently entails altering public perception and impacting policy dialogues. Musk's influence is notably evident in the transportation and energy sectors, where his enterprises have implemented groundbreaking solutions like Tesla's electric automobiles and SolarCity's solar installations. This study will analyze these contributions to underscore the capacity of private sector leaders to influence federal agendas in alignment with public sentiment and governmental goals.

Musk's alliances with state and municipal governments establish a basis for envisioning such relationships at the federal level. Tesla's engagement with California's electricity system exemplifies how private enterprises can tackle public sector energy issues. This case study and similar examples demonstrate that Musk's collaboration with governmental bodies has produced favorable environmental results, indicating that federal alliances could have even more significant effects.

This report will offer specific collaborative models for public-private partnerships that correspond with Trump's economic agenda. These encompass the expansion of renewable energy programs, the development of a robust electric vehicle infrastructure, and the promotion of sustainable manufacturing methods that create employment opportunities. This article will analyze different policy instruments, including tax credits, direct subsidies, and research grants, to see which strategies could incentivize private-sector participation in a climate-oriented agenda.

This research fundamentally examines hypothetical policy synergies. Trump's economic agenda focuses on job creation, sustaining energy independence, and diminishing regulatory constraints. This article will examine the potential intersections between these aims and Musk's climate advocacy, yielding mutually advantageous results. Increased investment in renewable energy initiatives could coincide with Trump's job creation plan, while electric vehicles provide a means to achieve energy independence by diminishing dependence on imported oil.

The U.S. government possesses many policy instruments to promote public-private partnerships in climate innovation, and this study will delineate these processes. This study will evaluate how the Trump administration could facilitate sustainable technology development by examining potential modifications to tax incentives, subsidies, and regulatory frameworks. This analysis will evaluate the fiscal and political viability of these proposals within a conservative framework.

Private-sector leaders such as Musk contribute economic advantages that can bolster both local and national economies. The green energy sector demonstrates significant potential for sustained growth and stability in job generation. This study will analyze how federal policy might facilitate such results by harmonizing tax rules, trade advantages, and labor incentives with the objectives of private sector climate proponents.

In addition to economic effects, sustainability initiatives driven by the private sector provide social and environmental co-benefits. Enhanced air quality, fewer emissions, and better public health outcomes are among the possible benefits of climate-positive economic development [20]. This article will examine how these social advantages could enhance federal collaboration with private-sector leaders.

Nonetheless, the challenges to such alliances must also be recognized. Ideological and operational obstacles may hinder federal endorsement of private-sector-driven sustainability efforts, particularly within conservative paradigms. This article will analyze these problems, exploring potential mitigation through strategic involvement, openness, and accountability measures [21].

Critical viewpoints on public-private partnerships emphasize issues related to regulatory capture, conflicts of interest, and the privatization of public assets. This presentation will address these counterarguments, offering a balanced perspective that acknowledges potential hazards while underscoring the necessity for ethical oversight and regulatory protections.

This research seeks to illustrate that bipartisan cooperation on climate matters is achievable when common objectives are highlighted. This study contends that a second Trump administration may implement climate policies appealing to both conservative and progressive stakeholders by concentrating on intersections between economic growth and environmental sustainability.

The possibility of a Trump 2.0 administration supporting a public-private partnership-driven climate agenda is a notable development in sustainable policy. This article contributes to the discussion on climate change by examining how government policy could evolve to integrate private-sector innovations while maintaining economic growth.

The research offers insights for policymakers seeking to promote collaborative strategies for addressing environmental concerns. This article analyzes Musk's influence on clean technology and recommends a paradigm for future federal-private cooperation that promotes sustainable growth within a conservative framework.

This study contends that climate action aligns with conservative economic principles and may be enhanced through private sector innovation. This study examines the potential partnership between a Trump-led administration and figures such as Elon Musk, offering a strategy for advancing climate progress in the U.S. It illustrates that environmental stewardship and commercial interests can coexist together.

2. Theoretical Frameworks for Public-Private Partnerships, Sustainability Economics, and Policy-Driven Innovation

The convergence of private-sector innovation and public policy has gained significance in tackling intricate global issues such as climate change. As governments endeavor to formulate sustainable environmental policies, private-sector leaders may assume a crucial role in influencing the trajectory of global environmental strategies. This theoretical section examines essential frameworks that elucidate how public-private partnerships (PPPs), sustainability economics, and policy-driven innovation can be leveraged to promote climate action, particularly within the U.S. context, especially during a potential second term of the Trump administration. These frameworks offer the analytical instruments required to assess the possible synergies between the public and private sectors in furthering a climate agenda.

2.1 Public-Private Partnerships (PPPs): A Collaborative Model for Climate Innovation

Public-private partnerships (PPPs) have historically been advocated as a strategy to secure reciprocal advantages for the government and private entities, particularly in sectors necessitating significant investment, long-term planning, and innovation. The fundamental concept of PPPs is that the public and private sectors contribute unique, complementary advantages. The government supplies regulatory frameworks, public confidence, and the capacity to influence extensive policy, whereas the private sector delivers technological proficiency, financial assets, and market efficacy [22]. In the realm of climate change, public-private partnerships (PPPs) can utilize the knowledge and capital of private enterprises such as Tesla, SpaceX, and other innovators to expedite the implementation of green technology, including renewable energy, electric vehicles, and sustainable infrastructure.

To comprehend how PPPs could influence Trump's climate agenda in a second term, it is crucial to examine the processes of these alliances. Theoretical frameworks of public-private partnerships highlight the mutual sharing of risk and profit, wherein both entities contribute to the innovation and infrastructure necessary for attaining sustainability objectives. Trump's economic model renders this partnership framework especially appealing since it facilitates the equilibrium of economic expansion and environmental care. Public-private partnerships (PPPs) provide a systematic method for enhancing climate innovations through tax incentives, deregulation, and investment in renewable energy, all while adhering to an economically conservative framework.

2.1.1 Types of Public-Private Collaborations in Climate Policy

Diverse kinds of public-private partnerships (PPPs) can be tailored to the climate sector, each offering distinct benefits. This encompasses joint ventures, wherein the government and private sector co-invest in projects; contractual agreements, wherein private companies render services in return for remuneration from public funds; and regulatory partnerships, wherein the government and private entities cooperate to fulfill regulatory standards. Since Trump secured a second term, the government might promote the extensive use of clean technologies by rewarding cooperation through advantageous policies, including tax incentives for green technology companies [23], infrastructural investment, and regulatory assistance.

2.2 Sustainability Economics: Integrating Environmental Objectives with Economic Development

Sustainability economics provides a theoretical framework for comprehending the economic consequences of sustainable development. This methodology amalgamates environmental health with enduring economic sustainability, underscoring that sustainable economic advancement must not jeopardize the environment [24]. The fundamental principle of sustainability economics is the recognition that unmitigated environmental deterioration will eventually jeopardize economic stability [25]. Within the framework of a potential second Trump administration, sustainability economics can reconcile environmental objectives with economic imperatives, indicating that both can be realized through innovation, investment, and market-oriented solutions [26]. Green

Growth and Innovation in Sustainability Economics Green growth is a fundamental principle of sustainability economics, denoting the generation of economic possibilities that mitigate environmental damage while fostering new employment and industries [27]. Musk's enterprises, especially Tesla, exemplify green growth by integrating technology innovation with an emphasis on renewable energy and sustainable transportation. From an economic standpoint, green growth posits that significant investments in renewable energy infrastructure, energy storage, and electric vehicles would not only alleviate climate change but also generate considerable economic value, especially in job creation and technical advancement [28]. These principles correspond with Trump's economic emphasis on promoting job creation, energy autonomy, and innovation-centric sectors.

2.2.1 Environmental Capital and Economic Returns

A fundamental element of sustainable economics is the notion of environmental capital, which denotes natural resources that yield economic value, including clean air, water, and renewable energy. Within the context of sustainability economics, private-sector inventions such as Tesla's electric automobiles and SolarCity's solar panels can be regarded as investments in environmental capital. These technologies facilitate the reduction of carbon emissions while simultaneously yielding economic benefits through energy savings and the establishment of new market sectors. By synchronizing private-sector innovations with federal policies, the Trump administration may leverage the notion of environmental capital, guaranteeing that green investments yield both economic and ecological benefits.

2.2.2 The Impact of Technological Innovation on Sustainability Economics

A fundamental principle of sustainability economics is that technological innovation is crucial for surmounting the obstacles to sustainable development [29]. Innovative technologies in energy generation, storage, and efficiency can offer scalable solutions to environmental issues while remaining commercially feasible. Musk's contributions to the advancement of electric vehicles and solar power systems exemplify this form of innovation. Public-private partnerships (PPPs) facilitate the incorporation of technical breakthroughs into national climate initiatives, promoting innovation while maintaining robust and competitive economic growth. Within this approach, technological innovation serves not as a threat to economic interests, but as a crucial catalyst for future prosperity and sustainability [30].

2.3 Policy-Driven Innovation: Frameworks for Facilitating Private Sector Leadership

Policy-driven innovation (PDI) is a conceptual framework that examines how government policies might foster innovation in the private sector [30]. This approach underscores that the government's role extends beyond regulation to actively promoting innovation that coincides with public objectives, including sustainability [31]. Government actions, including subsidies, tax incentives, research and development funds, and market-oriented regulations, can foster conditions that encourage private enterprises to innovate and expand sustainable technologies [32]. Musk's capacity to expand Tesla and SolarCity was partly attributable to federal initiatives such as electric vehicle tax credits and subsidies for renewable energy installations.

A fundamental aspect of policy-driven innovation is the government's facilitative role in establishing the policy framework that fosters innovation [33]. The private sector predominantly propels technical advancement, although government measures might either expedite or obstruct the rate of innovation. Government mandates, including renewable energy standards and electric vehicle quotas, might compel private enterprises to devise inventive solutions that fulfill these objectives. In contrast, policies that diminish market barriers and establish clear, long-term objectives can ensure that private firms remain incentivized to invest in sustainable technologies.

Policy mechanisms that facilitate sustainability-oriented innovation are essential in guiding private-sector initiatives. These instruments may encompass market-based mechanisms (including carbon pricing, emissions trading systems, and renewable energy subsidies) [34], regulatory frameworks (such as emissions standards or mandates for renewable energy utilization) [35], and financial incentives (like tax breaks or grants for the advancement of green technology) [36]. This article examines the integration of such instruments into Trump's economic strategy, promoting private-sector innovation in accordance with the administration's emphasis on job creation and economic growth.

In addition to formal policy instruments, institutional factors significantly contribute to the promotion of innovation. This encompasses the formation of regulatory bodies that promote green technologies, public research institutes that partner with the commercial sector, and the establishment of public-private innovation centers. Entities such as the U.S. Department of Energy’s Loan Programs Office, which has facilitated renewable energy businesses, can exemplify future endeavors. This methodology will be utilized to evaluate how Trump's administration might establish institutional frameworks that motivate private enterprises to spearhead sustainable innovation.

A crucial element of policy-driven innovation is the creation of novel business models that harmonize financial objectives with sustainability aims [37]. This encompasses circular economy models, wherein corporations develop products with end-of-life reuse or recycling considerations, and shared-value models, where companies generate benefit for both society and shareholders through sustainable practices. Tesla's capacity to merge substantial profitability with sustainability goals exemplifies how enterprises can attain both environmental and economic success. This article will examine the potential integration of these models into the climate policies of a second-term Trump administration.

The concluding element is comprehending how market forces can be utilized to promote sustainability. Consumers, investors, and corporations are progressively emphasizing environmental sustainability, hence generating market demand for eco-friendly products and services. By harnessing these market dynamics, private-sector leaders like Musk can not only spearhead innovation but also influence overarching market trends. Governments may significantly influence by formulating laws that bolster consumer demand for sustainable products and incentivize private enterprises to fulfill this demand.

Political economy offers a framework for comprehending the interplay between governmental policies, private-sector interests, and market results. The political economy framework will analyze how economic ideologies, institutional structures, and political interests influence the formulation of climate policies. This analysis will examine how Trump's administration might align conservative economic ideals with the increasing demand for climate action through strategic policy decisions.

Notwithstanding the potential of PPPs, there are intrinsic obstacles that require resolution. Obstacles to effective collaboration encompass ideological disparities, regulatory ambiguities, and the possibility of corporate interests superseding public welfare. This article will examine how these issues may be alleviated through transparent governance frameworks, explicit legislation, and proactive stakeholder involvement. By implementing this approach, PPPs can be designed to optimize their capacity for promoting climate objectives while mitigating potential hazards.

A concluding theoretical concern is the significance of transparency and accountability in guaranteeing that policy-driven innovation fulfills its commitments. This encompasses systems for assessing the effects of climate policy, assuring compliance of private-sector partners with sustainability objectives, and holding both governmental and corporate entities accountable for their conduct [38]. This article will suggest policy frameworks that guarantee openness and accountability in public-private partnerships, thereby enhancing their legitimacy and promoting public support for sustainability efforts.

This article will examine how these frameworks can be implemented in the climate agenda of a second-term Trump administration. The objective is to discern implementable methods that utilize public-private partnerships, sustainable economics, and policy-oriented innovation to advance green growth and climate initiatives. This section's theoretical frameworks establish the basis for comprehending how climate action can be realized through partnership between the public and private sectors. Through the integration of sustainability economics, innovation policy, and efficient governance models, a Trump-led administration might establish a precedent for the compatibility of conservative governance with climate-positive measures. The future of climate action in the U.S. hinges on reconciling political ideology with the imperative for sustainable development. By adopting the theoretical frameworks outlined in this section, Trump's second-term government may significantly facilitate private-sector innovation while achieving national climate objectives.

3. Shifting Landscape: Climate and Energy Policy in Trump's Second Term

The developing interplay among climate policy, energy policy, and private sector innovation will be a crucial concern in the second term of a Trump administration. Trump's initial term was characterized by pessimism regarding climate change efforts and a focus on conventional energy sectors; however, a subsequent term may witness a transition toward more pragmatic, market-oriented strategies for climate action. This study examines prospective policy possibilities based on public-private partnerships (PPPs), sustainable economics, and innovation driven by policy. We examine how Trump might use private-sector strategies to combat climate change while sustaining economic growth and upholding conservative values. By analyzing legislative deficiencies and requirements, we pinpoint opportunities for private-sector leaders, such as those spearheaded by Elon Musk, to address critical gaps and advance a more sustainable and resilient future.

3.1 Potential Policy Directions

3.1.1 Shifts Toward Pragmatic Environmental Policies

In a second term, President Trump is expected to maintain his dedication to deregulation while increasingly acknowledging the significance of climate action. Although his administration has prioritized minimizing government action in the energy sector, climate and energy policy may progress towards more pragmatic solutions that facilitate private-sector participation without compromising conservative economic principles.

A viable policy option might involve a transition to market-driven climate solutions that leverage the private sector's capabilities to combat climate change while promoting economic growth. This may entail reduced direct government interference, favoring the encouragement of innovation and the advancement of sustainable energy technology via tax credits, subsidies, and selective deregulation [39]. Eliminating regulatory obstacles would allow the government to facilitate faster innovation and the scaling of technology such as electric vehicles (EVs), energy storage systems, and renewable energy solutions [40].

Trump's economic policy has historically prioritized the private sector, especially in significant industries like oil and gas, but his government may increasingly need to adopt renewable energy solutions to attract a wider electorate. This can be accomplished through public-private partnerships that reconcile economic development with the necessity of climate action. The energy shift is in progress, and by integrating market-oriented solutions, Trump can uphold his economic program while addressing the increasing public demand for sustainability.

3.1.2 Leveraging Tax Policy and Market-Based Approaches

A highly successful method to promote private-sector engagement in climate change is the smart use of tax policy. During a second term, Trump may contemplate augmenting tax incentives for clean energy projects, like renewable energy production tax credits (PTCs) or investment tax credits (ITCs). These regulations may be modified to guarantee that corporations possess substantial financial incentives to expand technology that facilitates carbon reduction [41].

For example, offering tax incentives or direct subsidies for the advancement of energy storage technologies, which facilitate the integration of intermittent renewable energy sources into the grid, could promote innovation while safeguarding energy security. Likewise, tax incentives for electric vehicles and the requisite infrastructure, including EV charging stations, might expedite the shift to clean transportation [42]. These proposals will promote private-sector leadership in climate change, circumventing stringent government regulations and harmonizing with Trump's inclination towards deregulation.

Additionally, market-oriented solutions like carbon pricing or a carbon tax might be implemented to accurately represent the full cost of carbon emissions. An effectively structured carbon pricing scheme would enable the market to determine the most efficient strategies for emission reduction, while private enterprises may innovate and implement technology that diminishes carbon footprints, yielding financial returns. This approach prioritizes rewarding innovation over requiring certain technology, perhaps reconciling environmental sustainability with conservative economic ideals.

3.1.3 Pragmatic Collaboration with the Private Sector

The Trump administration may additionally adopt increased public-private partnerships (PPPs) to promote innovation and address climate change. Public-private partnerships enable private enterprises to spearhead the advancement and execution of innovations, while the government helps through incentives, regulatory frameworks, and infrastructure development. This strategy may coincide with Trump's business-oriented initiatives, guaranteeing that private-sector innovation is utilized for climate objectives.

A potential paradigm for collaboration involves federal collaborations with clean technology companies that concentrate on the extensive implementation of renewable energy infrastructure. These collaborations may encompass investments in solar and wind energy initiatives, utilizing private sector capital and innovation to fulfill national energy requirements. Moreover, private enterprises may partner with the federal government to innovate technology for carbon capture and storage (CCS) or enhance energy efficiency in industrial sectors, promoting sustainability without excessive governmental interference.

Specific federal incentives might increase the participation of companies like Tesla and NextEra Energy, which are currently making significant investments in renewable energy and energy storage technologies. These companies may collaborate with federal authorities to implement technology that would bolster grid resilience, diminish emissions, and improve energy security. Such alliances could yield pragmatic and efficacious climate solutions while also fostering economic growth through the attraction of private investment.

3.2 Policy Gaps and Needs

The material and methods section contains information about data sources (*e.g.* bibliographic databases), search terms and search strategies, selection criteria (inclusion/exclusion of studies), the number of studies screened, the number of studies included, and statistical methods of meta analysis.

3.1 Potential Policy Directions

3.2.1 Recognizing Deficiencies in Federal Climate and Energy Policy

Notwithstanding the increasing recognition of the necessity for climate action, numerous deficiencies persist in the federal government's climate and energy policies that private-sector innovation may rectify. A major deficiency exists in energy storage technology. Although renewable energy sources like wind and solar electricity are plentiful, their sporadic nature poses obstacles for system integration. The absence of extensive energy storage technologies constrains the capacity to completely shift to renewable energy, particularly during peak demand or periods of low supply.

Private enterprises, particularly within the technology and energy industries, possess the capability to innovate in this domain. Nonetheless, in the absence of suitable policy support, such as specific tax incentives or grants, these technologies may fail to attain the scale required to revolutionize the energy sector. A second-term Trump administration may address this gap by delivering explicit market signals to encourage private enterprises to invest in energy storage and other grid-enhancing technology.

A significant deficiency exists in the inadequate infrastructure for electric cars (EVs). Despite considerable advancements in the EV market, the absence of a comprehensive national charging infrastructure continues to impede widespread adoption. The federal government might collaborate with private enterprises to construct essential infrastructure, offering grants or tax incentives to facilitate the construction of EV chargers in underserved regions.

Private-sector leaders such as Tesla have significantly contributed to the advancement of electric vehicle technology and infrastructure. The proliferation of charging stations and other critical infrastructure necessitates cooperation between federal agencies and private enterprises. The government can facilitate the expansion of electric vehicle infrastructure through public-private partnerships, enabling private enterprises to foster innovation in this sector.

3.2.2 Market-Driven Climate Action: Addressing Rising Public Demand for Sustainability

The rising public demand for sustainability presents a distinctive opportunity for the corporate sector to spearhead the advancement of climate solutions. Consumers across all industries are increasingly emphasizing sustainability, hence boosting the demand for products and services that reduce environmental impact. In this environment, private enterprises have the capacity to address customer demands while concurrently aligning their operations with climate objectives.

Private-sector entities can address this demand by investing in green technology, including renewable energy systems, carbon capture technologies, and energy-efficient products [43]. Moreover, enterprises are progressively acknowledging that tackling climate change can improve their profitability by creating new markets, lowering expenses, and alleviating risks. This alteration in the private sector's strategy toward climate action signifies significant potential for a Trump administration to promote collaboration and utilize market dynamics.

Moreover, consumer preferences are compelling corporations to implement more sustainable business models by integrating environmental, social, and governance (ESG) factors into their operations. By motivating enterprises to fulfill these new standards via legislative frameworks that promote sustainability and innovation, the government may guarantee that market-driven initiatives correspond with national climate objectives. Such measures could facilitate the advancement of sustainable industries and employment, guaranteeing that the transition to a green economy is inclusive and advantageous to the wider populace.

A second Trump administration may synchronize its economic objectives with the necessity of tackling climate change via innovative and pragmatic policies. By adopting public-private partnerships and utilizing market-driven climate solutions, the administration may assist private-sector entities, such as Musk's firms, in spearheading the development of the technologies and infrastructure essential for a sustainable future. Tax incentives, deregulation, and targeted funding may establish a robust climate innovation ecosystem that harmonizes economic growth with environmental stewardship. Recognizing and rectifying policy deficiencies in sectors such as energy storage, electric vehicle infrastructure, and renewable energy implementation will be essential for progressing climate objectives. The increasing public demand for sustainability and the emergence of private-sector leaders in green technologies provide the government with an opportunity to leverage market forces while achieving environmental goals.

A second-term Trump administration may facilitate significant advancements in climate action by implementing policies that promote innovation and collaboration between the public and private sectors, demonstrating that sustainability and economic growth are compatible.

4. Public-Private Partnerships, Sustainability Economics, and Policy-Driven Innovation: The Role of Elon Musk in Climate Action

The increasing imperative to tackle climate change necessitates innovative and scalable solutions that reconcile environmental sustainability with economic prosperity. Public-private partnerships (PPPs), especially in domains like clean energy, electric vehicles, and aerospace, present advantageous avenues for stimulating climate action. This study examines how Elon Musk, as a climate innovator, has utilized his companies—Tesla, SolarCity, and SpaceX—to promote sustainable solutions, harmonizing private profit motives with public climate objectives. Through an analysis of Musk's contributions to clean energy and his partnerships with government entities, we evaluate the potential of public-private partnerships (PPPs) to expedite the transition to a low-carbon economy, while assessing the feasibility of these models under a second-term Trump administration.

4.1 Profile of Elon Musk as a Climate Innovator

4.1.1 Musk's Vision for a Sustainable Future

Elon Musk's contributions to combating climate change have transformed entire industries. He transformed the electric vehicle (EV) market through Tesla, demonstrating that high-performance automobiles can be both appealing and environmentally sustainable. SolarCity, co-founded by Musk, sought to establish solar energy as a feasible substitute for conventional fossil fuels. SpaceX, while largely concentrating on aerospace, incorporates sustainability by developing reusable rockets, thereby diminishing the environmental impact of space exploration. Musk's comprehensive vision unifies these many initiatives under the shared topic of sustainable energy, framing them as solutions for both economic progress and the global public benefit.

Tesla's dedication to manufacturing electric vehicles, including the Model S, Model X, and Model 3, has demonstrated the scalability of renewable energy technologies. The success of these vehicles has profoundly impacted the global automobile industry, prompting other manufacturers to transition towards electric fleets. SolarCity, which merged with Tesla in 2016, has advanced the use of rooftop solar panels, illustrating the potential for decentralized and democratized renewable energy generation, thereby enabling consumers to produce their own clean energy.

4.1.2 Tesla: A Leading Example of Clean Energy Innovation

The significance of Tesla as a climate pioneer is paramount. The company's initiative to incorporate sustainable energy into the mainstream is based on a business strategy that harmonizes market success with environmental accountability. Tesla epitomizes the efficacy of private sector innovation through electric automobiles, solar panels, and energy storage systems. Musk has characterized these initiatives not as philanthropic endeavors but as commercial necessities that address the increasing demand for sustainable solutions, utilizing technical advancements to develop economically feasible alternatives to fossil fuels.

The development of the Tesla Powerwall and Powerpack energy storage solutions exemplifies this methodology. These technologies enable residences and enterprises to accumulate solar energy for utilization during times of diminished output or elevated demand, hence decreasing dependence on conventional grid power sources. Tesla is revolutionizing the energy sector by combining solar power with battery storage, thereby diminishing carbon emissions and bolstering energy security—initiatives that closely align with international climate objectives.

The establishment of Tesla's Supercharger network has significantly advanced the adoption of electric vehicles by mitigating a key obstacle to EV integration: charging infrastructure. Tesla has expedited the shift to electric vehicles by facilitating quicker and more efficient charging, exemplifying that private enterprises may spearhead the development of essential infrastructure for a sustainable future.

4.1.3 SpaceX and Environmental Considerations in Aerospace

Although SpaceX is mostly recognized for its accomplishments in space exploration, the business has also made significant progress in incorporating environmental sustainability into its operations. Musk saw SpaceX as a means to lower the expenses associated with space travel, a goal he has accomplished by creating reusable rockets. The Falcon 9 rocket may be reused numerous times, thereby considerably diminishing the environmental effect of space missions.

SpaceX's reusable rocket technology exemplifies how private sector innovation can foster more sustainable practices. Musk has advocated for a strategy that integrates economic efficiency with environmental stewardship in an industry historically characterized by elevated emissions and waste. This dedication to minimizing the environmental impact of space travel further emphasizes Musk's overarching philosophy of incorporating sustainability into technical advancement.

4.1.4 SolarCity: A Decentralized Model for Solar Energy

Musk, via SolarCity, established a business model that allows users to obtain renewable energy directly, eliminating the initial expenses usually linked to solar installation. SolarCity's strategy of leasing solar systems instead of selling them outright facilitated the adoption of solar technology by homeowners and businesses, hence accelerating the expansion of renewable energy in the U.S. market.

The amalgamation of SolarCity with Tesla's energy storage products, including the Powerwall, has established a comprehensive renewable energy ecosystem. The integration of solar panels, energy storage systems, and electric vehicles presents a unified framework for a sustainable future, allowing customers to generate, store, and utilize renewable energy while diminishing their reliance on conventional energy networks. This amalgamation of many renewable energy technology exemplifies the capacity for private-sector innovation to tackle various aspects of climate change, encompassing power generation and mobility.

4.2 Case Study Analysis: Musk's Collaborations with Public Agencies

4.2.1 Tesla and California's Energy Grid

Tesla's engagement with California's electricity system exemplifies a public-private relationship that enhances both the adoption of sustainable energy and the stability of the grid. In 2016, Tesla collaborated with Pacific Gas and Electric (PG&E) to implement large-scale battery storage systems aimed at stabilizing the grid and storing surplus renewable energy. The project, now the largest lithium-ion battery installation globally, illustrates the collaboration between the private sector and government institutions to deliver new energy solutions. Tesla's engagement with California's energy system underscores the potential of public-private collaborations to advance climate initiatives while also tackling practical issues like energy storage and grid dependability. The project garnered substantial backing from the state government, a frontrunner in advocating renewable energy legislation. This relationship illustrates how a market-driven enterprise may match state interests in carbon emission reduction with its economic ambitions, so contributing to policy goals while reaping government rewards. Furthermore, Tesla's participation in the California energy system highlights the significance of innovation clusters—geographic areas where corporations, academic institutions, and governmental bodies cooperate to advance pioneering technology. California's dedication to clean energy legislation, along with Tesla's technological proficiency, has established the state as a center for sustainable innovation, where governmental policies and business initiatives collaborate to attain common climate goals.

4.2.2 SpaceX's Environmental Considerations and Government Collaboration

While SpaceX is not predominantly a climate-oriented enterprise, its partnership with NASA and various governmental bodies illustrates how private-sector entities can facilitate sustainable practices in unforeseen domains. SpaceX's reusable rocket technology diminishes the cost of payload launches into space, so indirectly enhancing sustainability by reducing the environmental effect of space missions. SpaceX is enhancing efficiency in a traditionally resource-intensive industry by minimizing the number of rockets required for each launch and reusing components.

The collaboration between SpaceX and NASA, particularly in the Commercial Crew Program, underscores how governmental assistance may expedite technology advancements in the private sector. These agreements have facilitated progress in reusable rocket technology, allowing SpaceX to reduce the environmental impact of space exploration while simultaneously improving the economic feasibility of space-related endeavors. SpaceX's efforts to mitigate the environmental impact of space travel contribute to a comprehensive view of sustainability, exemplifying the potential of public-private cooperation to decrease global emissions across several industries.

4.3 Potential Applicability to a Trump Administration

The feasibility of public-private partnerships in climate innovation during a second-term Trump administration may be influenced by its emphasis on economic growth, deregulation, and energy independence. The Trump administration has historically supported fossil fuel businesses; nevertheless, its focus on minimizing government intervention in markets may enable private-sector entrepreneurs such as Musk to assume a more significant role in combating climate change.

4.3.1 Balancing Economic Growth and Environmental Impact

A fundamental problem for the Trump administration will be reconciling economic growth with environmental sustainability. Musk's paradigm of innovation driven by the private sector is a viable avenue for attaining this equilibrium. Musk has illustrated that sustainability can serve as a lucrative business strategy by concentrating on economically feasible clean technology. The Trump administration might adopt this strategy by promoting market-driven solutions that mitigate environmental damage while preserving economic growth. Policies that promote the advancement of renewable energy technology, electric vehicles, and energy storage may encourage private-sector investment while concurrently furthering climate objectives. The administration's emphasis on diminishing regulatory constraints may align with a dedication to sustainability if the government offers specific incentives for green technologies, such as tax reductions for renewable energy investments or infrastructure grants for electric vehicle charging stations.

4.3.2 Leveraging Tax Policy to Encourage Innovation

Tax incentives and subsidies have historically served as a crucial mechanism to promote private-sector investment in clean energy and technologies. The Trump administration may prolong or augment tax incentives for renewable energy technology, electric automobiles, and energy storage systems, fostering a more advantageous climate for companies such as Tesla to prosper. These policies would synchronize private-sector profit incentives with public climate objectives, guaranteeing reciprocal advantages for both the government and the private sector.

Additionally, the Trump administration might investigate market-oriented alternatives like carbon pricing or clean energy requirements, which would motivate firms to decrease emissions while simultaneously receiving government assistance. These regulations would enable the market to propel innovation, with firms such as Tesla at the forefront of clean technology development.

Elon Musk's contributions to clean energy and sustainability via Tesla, SolarCity, and SpaceX exemplify the transformative potential of the private sector in climate change. His methodology for climate innovation amalgamates commercial necessities with public climate objectives, exemplifying the efficacy of public-private partnerships in facilitating systemic transformation. The case studies of Tesla's engagement with California's energy system and SpaceX's partnerships with NASA highlight the capacity for private enterprises to collaborate with government entities in creating solutions that mitigate emissions and promote sustainability.

A second-term Trump administration may leverage these relationships to achieve economic development and environmental sustainability. Through the utilization of market-oriented solutions and specific policy incentives, the administration could establish a framework in which private-sector entities, such as Musk's companies, can spearhead the forthcoming era of climate innovation, thereby ensuring that economic and environmental objectives are both aligned and mutually supportive.

5. Pathways for Public-Private Partnerships in Climate Policy: A Comprehensive Framework for Collaboration and Policy Innovation

The imperative of tackling climate change has catalyzed worldwide initiatives to shift towards sustainable energy systems, focusing on using the combined capabilities of the public and private sectors. This collaboration, commonly referred to as public-private partnerships (PPPs), possesses the capacity to foster significant innovation and economic advancement in climate policy. Nevertheless, given that climate change is a very sensitive topic, particularly in U.S. politics, the effective execution of these collaborations relies on identifying synergies between governmental structures and private-sector motivations. This article examines novel kinds of public-private partnerships for climate innovation, emphasizing the structuring of these collaborations within the framework of a Trump-led administration. The article examines legislative mechanisms and incentives that could encourage private-sector leaders to engage in federal climate initiatives, promoting a harmonious balance between economic development and environmental sustainability.

5.1 Framework for Collaboration: Models of Public-Private Partnerships in Climate Innovation

5.1.1 The Potential for Symbiotic Partnerships

Central to public-private partnerships in climate policy is the possibility for mutually beneficial collaborations, wherein the government supplies the legal framework, financial incentives, and market stability, while the private sector contributes innovation, efficiency, and capital. The U.S. government, particularly under a Trump administration, must balance economic growth with environmental protection to foster beneficial partnerships. Historical instances, such as Tesla's involvement in California's electricity infrastructure and SpaceX's engagement with NASA, illustrate how public-private partnerships may foster innovation while advancing overarching policy objectives.

A viable collaborative model is the public procurement framework, in which the government serves as a principal purchaser of green technologies, thus mitigating investment risks for private enterprises. The government may, for instance, pledge to procure electric vehicles (EVs) or renewable energy solutions in bulk, so offering companies like Tesla a secure and expansive market, which subsequently drives technological progress. This strategy corresponds with the Trump administration's focus on economic expansion and employment generation, while also promoting sustainability objectives.

The research and development (R&D) partnership model is also significantly pertinent for advancing climate innovation. Federal agencies, including the Department of Energy (DOE) and the Environmental Protection Agency (EPA), may partner with private technology firms to advance next-generation energy solutions, such as carbon capture, advanced nuclear technologies, or renewable energy storage systems. In some instances, public money may facilitate early-stage research, while private sector entities invest in the commercialization and development of technology.

5.1.2 Leveraging Tax Credits and Subsidies for Clean Tech Innovation

The tax credit and subsidy framework has historically shown to be a successful mechanism for promoting innovation, especially within the renewable energy industry. During the Trump administration, initiatives like the Investment Tax Credit (ITC) and the Production Tax Credit (PTC) have offered essential incentives for corporations to engage in solar and wind energy. An ongoing extension of these tax credits or the implementation of new ones aimed at innovative technologies such as green hydrogen or improved energy storage will foster private-sector innovation. These subsidies significantly diminish the initial expenses related to the implementation of renewable energy and enhance the appeal of these technologies to investors, thereby expediting the transition to a sustainable energy system.

Furthermore, tax laws can be modified to synchronize the financial incentives of private enterprises with the overarching public objective of diminishing carbon emissions. Implementing tax incentives for companies that meet defined sustainability objectives—such as diminishing their carbon emissions or augmenting the proportion of renewable energy in their supply chain—could serve as a compelling motivation for companies to innovate and invest in cleaner technologies. Performance-based incentives would attract private sector entities, such as Musk's Tesla and other green technology firms, driven by financial gains and environmental results.

5.1.3 Exploring Trump Administration Viability in Embracing Public-Private Collaborations

The political landscape of a second-term Trump administration presents a distinctive, albeit problematic, framework for executing public-private partnerships in climate policy. The administration has frequently allied itself with fossil fuel interests and exhibited skepticism towards international climate agreements, while it has also adopted specific private-sector advances in several fields. Successful collaboration hinges on presenting climate action as an economic opportunity instead of a regulatory encumbrance.

A Trump-led administration might adopt public-private partnerships in climate innovation, particularly in advancing energy independence via clean technologies. Trump's emphasis on energy security and employment generation may coincide with private-sector initiatives in renewable energy and sustainable technologies. A vital strategy entails establishing collaborations that aim to bolster national competitiveness in the global green technology sector, concurrently diminishing reliance on foreign energy sources. A partnership between the government and private enterprises in advancing next-generation battery storage technology could enhance energy independence and sustainability objectives, yielding direct economic advantages through job creation and market dominance in burgeoning industries.

5.2 Policy Levers and Incentives: Attracting Private-Sector Participation

5.2.1 Targeted Tax Policies and Investment Incentives

One of the principal mechanisms for promoting private-sector engagement in climate policy is the establishment of specific tax policies and investment incentives. The Trump administration, recognized for its pro-business orientation, may leverage these measures to stimulate private investment in clean technologies while also promoting climate objectives. Tax credits akin to the Green New Deal, designed to incentivize corporations for adopting clean energy technologies, might be customized to align with conservative economic objectives while promoting sustainable growth.

A potential legislative proposal may include providing corporations with expedited depreciation for investments in renewable energy systems, energy-efficient technology, and electric vehicle infrastructure. This legislation will enable firms to expedite the depreciation of renewable energy systems and other clean technology, providing immediate financial advantages while fostering the long-term integration of sustainable technologies.

Moreover, novel carbon pricing mechanisms—such as a carbon tax or cap-and-trade system—may be investigated to motivate enterprises to diminish their carbon emissions while simultaneously establishing a reliable market for low-carbon technologies. Although carbon taxes have historically been contentious, conservative backing may be secured by presenting the measure as a matter of economic competitiveness. A carbon tax could yield cash that is reinvested in renewable energy initiatives or utilized to finance tax reductions in other sectors of the economy, rendering it a politically feasible alternative under a pro-business administration.

5.2.2 Private Investment in Clean Tech through Public-Private Ventures

Policymakers should stimulate private-sector investment in climate innovation by promoting public-private ventures (PPVs) that jointly invest in clean technology and infrastructure. These initiatives may be organized to mitigate financial risk for private investors by utilizing public funds for initial projects, while guaranteeing that the private sector spearheads the scaling and commercialization of technology. The government might serve as a guarantee for loans or provide co-investment possibilities in green infrastructure initiatives, such as establishing electric vehicle charging stations or renovating industrial facilities to comply with energy efficiency regulations.

Additionally, the promotion of green bonds as a legislative instrument could facilitate the allocation of private resources to ecologically sustainable initiatives. Green bonds may finance public infrastructure initiatives, like renewable energy installations, public transit networks, or energy-efficient structures [44]. These bonds would provide a reliable return on investment for private investors while directly aiding climate mitigation initiatives.

5.2.3 Regulatory Innovation: Streamlining Approvals for Green Projects

Alongside economic incentives, regulatory frameworks may be modified to accelerate the clearance process for green technology initiatives. A significant obstacle for private enterprises investing in clean technologies is the protracted permitting process necessary for new energy projects. The government might substantially expedite the market introduction of new technologies by establishing accelerated approval processes for renewable energy projects, energy storage systems, and electric vehicle infrastructure. Moreover, environmental impact evaluations for sustainable initiatives could be optimized, minimizing bureaucratic delays while guaranteeing compliance with environmental regulations. These modifications would facilitate the deployment of breakthrough technology by private enterprises, so expediting the transition to a low-carbon economy.

5.2.4 Combining Economic Growth with Environmental Impact

To attain the dual objectives of economic growth and environmental sustainability, public-private partnerships must establish a balance that facilitates technical innovation while mitigating environmental harm. Policies that foster the establishment of circular economies, including systems for recycling and resource reutilization, may serve as a significant instrument in this context. Incentives for firms to implement recycling technology or waste-to-energy systems would foster sustainability and generate economic opportunities, especially in the manufacturing and waste management sectors. Integrating sustainability criteria into tax incentives and investment regulations can facilitate the alignment of economic growth with environmental objectives. Policies can promote a market-driven approach to environmental stewardship by rewarding firms to fulfill specified sustainability requirements, like the reduction of carbon emissions, water conservation, and waste minimization.

5.3 A Path Forward for Public-Private Partnerships in Climate Policy

The viability of public-private partnerships in climate policy during a Trump presidency will hinge on reconciling economic growth with environmental sustainability. Utilizing tailored incentives, tax policies, and regulatory changes can foster an environment conducive to private-sector innovation while advancing overarching climate objectives. Both public and private entities can gain advantages, potentially expediting the transition to a low-carbon economy, improving energy security, and generating employment in burgeoning industries. As climate change poses unparalleled challenges, the private sector's role in fostering innovation will be essential. Public-private partnerships designed to foster economic growth while addressing environmental concerns can exemplify future collaborations, so aiding the global initiative to combat climate change.

6. Economic and Social Consequences of a Cooperative Climate Initiative: Sustainability Driven by the Private Sector

The cooperative climate agenda, which incorporates active involvement from the private sector in renewable energy and clean technology creation, presents a persuasive option for tackling economic and environmental issues. As countries worldwide contend with the effects of climate change, the involvement of private enterprises in promoting sustainability has gained significant prominence. This article examines the economic and social ramifications of a private-sector-driven renewable energy transition, emphasizing its effects on national and local economies, employment generation, energy security, competitiveness, public health, and environmental results [45]. It also analyzes how private-sector participation might alleviate risks associated with climate change, especially in at-risk populations.

6.1 Advantages of Sustainability Driven by the Private Sector

6.1.1 Economic Consequences of Clean Technology Innovations

The economic shift driven by developments in renewable energy and clean technology from the private sector is significant. By investing in the development and implementation of renewable energy technologies—such as solar, wind, and geothermal power—companies are diminishing the economy's dependence on fossil fuels while simultaneously fostering a resilient and varied green technology industry [46]. By doing so, they stimulate both national and local economies by promoting new industries and enhancing energy efficiency. The global market for renewable energy technology is anticipated to attain $2.15 trillion by 2025, with private enterprises leading this expansion.

Nationally, private-sector participation in clean energy can result in substantial GDP growth. This is accomplished via direct investments in infrastructure, manufacturing, research and development, and services associated with renewable energy. The effects on local economies are significantly more pronounced. The establishment of solar farms or wind turbines generates employment in construction, engineering, operations, and maintenance. The surge in job prospects generates a multiplier effect, increasing the demand for local goods and services and subsequently stimulating additional economic activity. Furthermore, local economies with a significant presence of green technology firms can use innovation clusters that enhance regional development and worldwide competitiveness.

6.1.2 Employment Generation and Labor Market Evolution

The generation of employment is among the most direct and concrete economic advantages of a clean energy revolution driven by the private sector. The renewable energy sector has emerged as one of the most rapidly expanding job industries in recent years. In the United States, employment in solar and wind energy has surged by nearly 150% since 2010, a trend anticipated to persist as more private enterprises pledge to decarbonization objectives. The new employment is often varied, encompassing skilled labor skills like electricians and engineers, as well as administrative functions in project management and policy compliance.

Furthermore, the green economy's focus on innovation fosters the development of advanced, skilled employment opportunities. The creation and production of electric vehicles (EVs), sophisticated energy storage systems, and intelligent grids necessitate expertise in disciplines such as engineering, materials science, and software development [47]. Consequently, there exists considerable opportunity for people to shift from conventional sectors—such as fossil fuel industries—to clean energy professions, promoting an inclusive economic transformation that offers workers elevated incomes and improved long-term opportunities.

6.1.3 Energy Security and Autonomy

A renewable energy market led by the private sector enhances national energy security. By transitioning from imported fossil fuels to local renewable energy sources, nations can diminish their dependence on unstable global energy markets and enhance energy autonomy. The United States' initiative to adopt renewable energy technologies reduces reliance on foreign oil and stabilizes energy costs through diversification of energy sources. Private enterprises have been essential in this shift, especially in nations where market-oriented strategies prevail in energy policy. Tesla's advancement of residential battery systems, which allow consumers and enterprises to retain surplus solar energy, exemplifies this innovation. The decentralization of energy production bolsters grid resilience, complicating the ability of external influences, such as geopolitical conflicts or market fluctuations, to destabilize national energy systems [48].

6.1.4 International Competitiveness in Sustainable Technologies

The global green technology market gives a substantial potential for nations to establish themselves as frontrunners in the burgeoning clean economy. Firms that develop in renewable energy, energy storage, electric vehicles, and green hydrogen technologies might get a competitive edge in the global market, regarding both exports and investments. By implementing laws that encourage private-sector participation, governments can establish a favorable climate for domestic enterprises to succeed in international markets. Germany has effectively positioned itself as a global leader in solar energy technology and electric vehicles by fostering private-sector research and development, providing incentives for business investment in clean technologies, and maintaining long-term policy stability. The U.S. market, featuring firms such as NextEra Energy and First Solar, has likewise gained a competitive advantage in the solar industry [49]. These market leaders are facilitating domestic economic expansion while also aiding the global shift towards a low-carbon economy.

6.2 Societal and Ecological Co-Benefits

6.2.1 Enhanced Public Health Results

Private-sector sustainability activities can produce significant social co-benefits, especially regarding public health. The extensive implementation of clean energy technology can substantially diminish air and water pollution, which are major factors in numerous health issues, including asthma, respiratory ailments, and cardiovascular disorders. The transition from fossil fuel-based energy to renewable energy directly diminishes the emissions of deleterious pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter [50]. Research indicates that health problems associated with air pollution impose annual costs of billions of dollars on economies due to healthcare expenses and diminished productivity. By adopting cleaner energy sources, the private sector can mitigate certain expenses. The swift adoption of electric vehicles (EVs) diminishes greenhouse gas emissions and alleviates traffic-related pollution, thus enhancing air quality and public health in urban environments [51]. Furthermore, enterprises that invest in clean technology contribute to fostering a better environment for at-risk groups, like children and the elderly, who are particularly exposed to health hazards associated with pollution.

6.2.2 Mitigated Environmental Deterioration

Private-sector involvement in climate initiatives also aids in mitigating environmental damage. The transition to renewable energy and sustainable practices in sectors including agriculture, forestry, and industry aids in ecosystem preservation, biodiversity protection, and the reduction of land degradation. For instance, substantial expenditures in renewable energy initiatives, such as wind farms and solar power facilities, do not produce equivalent levels of habitat devastation and water usage as fossil fuel extraction techniques like coal mining and oil drilling.

Furthermore, private enterprises can actively contribute to the preservation of natural resources by investing in sustainable practices. Agricultural companies are progressively implementing precision farming practices that diminish the necessity for pesticides and fertilizers, resulting in improved soil health and less water pollution. In the forestry sector, private enterprises that emphasize replanting and sustainable timber extraction are contributing to the reduction of deforestation and its related environmental consequences [52].

6.2.3 Climate Resilience in At-Risk Communities

Private-sector participation is essential for enhancing climate resilience in at-risk communities, which frequently suffer the most from the effects of climate change, including flooding, heatwaves, and severe weather phenomena. Private investments in sustainable infrastructure, including resilient housing, renewable energy systems, and flood protection technology, enable communities in high-risk locations to more effectively endure the impacts of climate change.

Companies that produce and implement green infrastructure solutions, like permeable paving, green roofs, and urban wetlands, enhance climate resilience in urban areas. These solutions can alleviate the urban heat island effect, minimize flooding, and enhance water conservation, directly benefiting low-income and marginalized groups most vulnerable to climate-related disasters [53]. Moreover, private enterprises investing in climate resilience initiatives inside at-risk communities may get local tax incentives, concurrently securing enduring environmental and economic advantages for these regions.

6.2.4 Reducing Risks and Improving Adaptive Capacity

The private sector can significantly assist vulnerable areas in mitigating hazards related to climate change. Private enterprises can assist vulnerable communities in preparing for and adapting to climate impacts by promoting the development and implementation of early warning systems, insurance products, and climate risk assessments. Insurance companies are progressively creating climate-risk policies that provide coverage for damages resulting from extreme weather occurrences, thereby alleviating the financial strain on at-risk areas during disasters [54].

Furthermore, commercial enterprises may invest in climate adaptation technology, including water-efficient irrigation systems, drought-resistant crops, and low-carbon cooling solutions for people vulnerable to heat exposure. These innovations not only alleviate climate impacts but also promote the long-term sustainability of vulnerable populations, thereby boosting their adaptive potential.

The economic and social ramifications of a cooperative climate agenda, propelled by private-sector innovation, provide a persuasive argument for a future where sustainability and economic growth coexist harmoniously. The renewable energy and clean technology sectors are transforming the global economy while generating new prospects for employment, energy security, and competitiveness. The private sector's engagement in combating climate change transcends environmental advantages, yielding substantial enhancements in public health, diminished environmental degradation, and increased resilience for at-risk populations.

Aligning private-sector profit motives with public climate objectives enables the private sector to act as a pivotal force in the transition to a low-carbon, sustainable economy. This synergy will guarantee that economic progress and environmental sustainability can coexist, fostering a more egalitarian and resilient global society. As countries strive to meet their climate objectives, the involvement of the private sector will be crucial in guaranteeing that the economic, social, and environmental advantages of the clean energy transition are accessible to all.

7. Challenges and Counterarguments: Navigating Barriers to Effective Public-Private Climate Collaboration

Public-private partnerships in the climate sector offer a chance for governments and the business sector to collaborate in tackling a critical global issue: climate change. The prospect of productive collaboration between a government led by a figure such as former President Donald Trump and private-sector climate advocates presents considerable inquiries regarding the ideological, regulatory, and practical obstacles that may hinder substantial action. This article analyzes the obstacles to collaboration between government entities and private-sector climate campaigners, especially those spearheaded by prominent individuals such as Elon Musk. It examines the ideological and regulatory friction points, such as conflicts of interest, political opposition, and apprehensions over regulatory capture, while critically evaluating the arguments opposing dependence on private-sector entities for fostering climate innovation [6]. The study finishes by proposing strategies to alleviate these risks and guarantee responsibility in the quest for sustainable climate solutions.

7.1 Possible Obstacles to Collaboration

7.1.1 Ideological Obstacles: Conservative Climate Skepticism

A major ideological obstacle to collaboration between a Trump-led administration and private-sector climate advocates is the Republican base's skepticism regarding climate science and governmental economic intervention. Many conservative officials perceive climate change as a politically motivated narrative rather than an immediate scientific issue. Under the Trump administration, this cynicism was evident in the departure from the Paris Agreement, the repeal of environmental regulations, and the preference for fossil fuel companies over renewable energy sources.

This ideological resistance fosters a difficult atmosphere for engagement with private-sector climate proponents, who frequently champion assertive measures against climate change, encompassing significant emissions reductions and investments in clean energy technologies. The conflict between economic expansion and deregulation versus environmental sustainability may result in a fundamental disconnection between the government and climate-oriented enterprises, especially those spearheaded by private individuals such as Musk, who advocate for green innovation.

Musk's enterprises, Tesla and SpaceX, are driven by a distinct objective to promote technology that mitigate greenhouse gas emissions and investigate sustainable energy options. Nonetheless, these private-sector activities are frequently regarded as anomalies within a government that has persistently prioritized fossil fuel interests and opposed robust environmental legislation. This ideological schism complicates the pursuit of consensus for productive collaboration, as policy inclinations for climate action conflict with political and economic doctrines that emphasize deregulation and free-market approaches.

7.1.2 Regulatory Obstacles: The Politics of Environmental Regulation

Regulatory impediments provide a substantial hindrance to public-private partnerships in climate action. The regulatory landscape in the U.S. has traditionally been influenced by divergent political philosophies. In a conservative administration, the regulatory framework for environmental safeguards typically adopts a more laissez-faire approach, aiming to reduce government intrusion in the private sector [55]. The Trump administration's initiatives to abolish regulations like the Clean Power Plan and the Waters of the United States rule were motivated by the conviction that governmental regulation inhibits innovation, economic expansion, and competitiveness.

Private-sector climate proponents generally regard regulation as an essential instrument to guarantee that the market functions in a manner conducive to sustainability. Numerous renewable energy enterprises depend on environmental regulations and governmental incentives to foster innovation and facilitate market uptake. The federal Investment Tax Credit (ITC) and Production Tax Credit (PTC) have been instrumental in the growth of the renewable energy sector by offering financial incentives to enterprises investing in solar and wind technology. Such legislative frameworks are crucial for attracting investment and fostering the advancement of clean energy infrastructure.

A Trump-led administration will likely prioritize the repeal of such incentives to promote energy independence and alleviate regulatory constraints on fossil fuel industry. This regulatory framework may constrain the capacity of private-sector entities to develop and broaden their renewable energy initiatives. In the absence of supportive regulation, companies like as Tesla and others in the renewable energy sector may find it challenging to compete with subsidized fossil fuel industries, hindering collaboration between the public and private sectors.

7.1.3 Operational Obstacles: Conflicts of Interest and Regulatory Capture

In addition to ideological and regulatory issues, practical obstacles to effective collaboration stem from apprehensions regarding conflicts of interest and regulatory capture. A primary issue in partnerships between government and the private sector is the risk of private corporations exerting excessive influence over regulatory procedures, resulting in outcomes that favor corporate interests over the general welfare. Elon Musk's enterprises have prompted apprehensions regarding the consolidation of political and economic authority among a select group of technology billionaires, leading to inquiries about the possibility of regulatory capture.

Regulatory capture transpires when commercial interests, by lobbying or other means of persuasion, exert control over the regulatory authorities designated to supervise them. The involvement of the private sector in climate innovation poses a specific risk, since it allows huge firms to influence climate legislation in a manner that favors their economic interests over overarching environmental objectives. The Trump administration, known for its pro-business stance, increases the likelihood of regulatory capture by prominent private-sector entities. Such dynamics can erode public confidence in the regulatory framework and diminish the efficacy of climate policy.

Musk’s promotion of diminished government intervention and deregulation in the energy sector, although frequently congruent with the free-market tenets of the conservative agenda, may provoke apprehensions regarding whether his companies, including Tesla, are attempting to sway regulatory decisions that favor their own commercial interests over the wider climate agenda. The potential for conflicts of interest may undermine public confidence in the efficacy of public-private partnerships, especially in sectors where climate change is perceived as an urgent matter necessitating prompt action.

7.2 Contrasting Arguments and Analytical Viewpoints

7.2.1 Evaluating the Effectiveness of Dependence on Private-Sector Climate Innovation

Despite the optimistic prospects of private-sector innovation in climate initiatives, some critical viewpoints challenge the effectiveness of depending on private enterprises, including those spearheaded by Elon Musk, to facilitate the shift towards a sustainable, low-carbon economy. A primary criticism is that private-sector entities are fundamentally driven by profit maximization, potentially undermining the long-term objectives of climate mitigation and environmental preservation. Critics contend that corporations such as Tesla, despite promoting green technologies, may not consistently put environmental consequences over profit and may exploit government incentives or subsidies for their own advantage.

Moreover, several critics argue that dependence on a limited number of private-sector entities for climate innovation could result in a concentration of power among a few businesses, thereby constraining competition and hindering the extensive innovation required to tackle the intricacies of climate change. Should the government depend excessively on enterprises like as Musk's for climate solutions, there exists a risk that large entities may monopolize the market, adversely affecting smaller, nascent competitors that could provide alternative options. Furthermore, insufficient regulatory control may result in private corporations establishing their own regulations, thereby jeopardizing the wider public interest.

There is a fear that private-sector solutions, especially in the technology industry, may lack inclusivity and equity. For instance, whereas electric vehicles and renewable energy technologies may be extensively utilized in affluent areas, their implementation in lower-income or developing countries may be hindered by financial constraints or inadequate infrastructure. Critics contend that an emphasis on advanced, market-oriented solutions may neglect the requirements of marginalized groups and exacerbate disparities in access to clean energy and the allocation of climate effects.

7.2.2 Addressing the Critique: Harmonizing Private Innovation with Public Regulation

In addressing these critiques, it is crucial to recognize that although private-sector figures like as Musk can significantly influence climate innovation, their efforts must be supported by stringent governmental monitoring to guarantee alignment with the overarching climate agenda. A viable solution to these issues is the creation of explicit, open regulatory frameworks that impose rigorous environmental standards on private enterprises and guarantee their accountability for environmental impacts.

Government rules may mandate that private enterprises achieve designated carbon reduction targets, comply with equitable labor standards, and guarantee that their inventions serve the broader societal good. Governments can take steps to guarantee that public financing or incentives for private enterprises are allocated to projects that yield quantifiable and equitable environmental results, rather than merely enhancing corporate profits.

Furthermore, public-private partnerships can be designed to foster competition and collaboration instead of the concentration of power. Governments can promote collaboration among various stakeholders, from small startups to huge enterprises, through targeted funding, cooperative research programs, and technology-sharing agreements, rather than permitting a single company to monopolize a certain industry. This strategy can promote innovation across diverse industries, mitigate market monopolies, and guarantee that climate solutions are available to a broader spectrum of communities.

7.2.3 Guaranteeing Accountability and Transparency

To alleviate the risks of regulatory capture and conflicts of interest, governments must emphasize transparency and accountability in public-private partnerships. This may entail the creation of autonomous oversight entities to evaluate the efficacy of climate policy, guaranteeing that private enterprises fulfill their environmental obligations, and promoting public engagement in decision-making procedures. Furthermore, explicit criteria for managing conflicts of interest should be established, mandating private enterprises to report their lobbying activities and impact on regulatory procedures.

Governments may conduct regular evaluations of climate policies and the involvement of private-sector entities, ensuring their alignment with the changing requirements of society and the environment. These evaluations can be organized to foster constant discussion between the public and private sectors, facilitating required revisions to laws and regulations to uphold accountability and promote continual advancement.

The obstacles and counterarguments to public-private partnership in the climate sector, especially under a Trump-led administration and involving private-sector figures such as Elon Musk, are intricate and varied. Although ideological, regulatory, and practical obstacles may hinder collaboration, they are not insuperable. By confronting these difficulties directly and employing tactics for openness, accountability, and widespread innovation, it is feasible to guarantee that private-sector contributions to climate action are both effective and equitable. An equitable strategy that promotes collaboration while safeguarding the public interest will be essential for realizing the complete potential of public-private partnerships in combating climate change.

8. Conclusion: Unlocking the Potential for Public-Private Partnerships in Climate Action under a Second-Term Trump Administration

8.1 Summary of Key Findings

This investigation has examined the capacity of public-private partnerships (PPPs) to facilitate significant advancements in climate action, especially inside the framework of a second-term Trump administration and its association with private-sector innovators like Elon Musk. The findings suggest a substantial chance for a mutually beneficial collaboration between private-sector leaders and a Trump-led administration, contingent upon addressing various ideological, regulatory, and operational hurdles.

The initial important conclusion underscores the pivotal importance of private-sector innovation in progressing climate solutions. Entities such as Tesla and SpaceX have exemplified that private organizations can lead in the advancement of clean technology, encompassing electric automobiles and renewable energy innovations. This innovative capacity offers a favorable opportunity for a Trump administration dedicated to economic expansion and minimizing governmental interference in the market. By leveraging private-sector expertise and resources, the government might attain significant advancements in its climate agenda without implementing extensive regulatory frameworks that may encounter political resistance.

Nevertheless, ideological disparities, especially climate denial among the conservative base, together with regulatory obstacles, surfaced as substantial impediments to collaboration. The Trump administration's emphasis on energy independence via fossil fuels and its opposition to stringent climate laws hinder the alignment of the government's climate agenda with private-sector climate proponents. Deregulation and a free-market approach to energy may resonate with conservative principles, although they present a challenge to the substantial government-driven incentives and policies that numerous clean tech companies depend on to foster innovation.

This study identifies several places where collaboration could flourish in overcoming these obstacles. Targeted incentives for private enterprises investing in renewable energy and clean technology, including tax credits, grants, and loan guarantees, could foster a climate conducive to economic growth and environmental advancement. These market-oriented solutions can be articulated to resonate with conservative economic ideas while concurrently facilitating the transition to a more sustainable economy.

Furthermore, the analysis highlights the significance of transparency and accountability in public-private partnerships (PPPs). Concerns regarding conflicts of interest and regulatory capture, especially involving prominent private individuals such as Musk, must be meticulously addressed to guarantee that climate policies do not unduly favor private enterprises to the detriment of public interests. The report proposes the establishment of independent supervision mechanisms and mandates that private enterprises adhere to rigorous environmental standards in exchange for public incentives.

8.2 Implications for Future Policy

The conclusions derived from this analysis provide crucial direction for future policymaking regarding public-private partnerships in environmental and energy matters. Policymakers under a second-term Trump administration, or any subsequent government, can utilize these insights to cultivate an atmosphere conducive to public-private partnerships that line with national climate objectives while promoting economic growth and innovation.

A vital policy conclusion is the necessity for adaptable regulatory frameworks that enable private enterprises to develop while guaranteeing their actions benefit the public interest. Policymakers must to devise specific incentives that foster clean technology while guaranteeing equity and transparency in their distribution. Tax credits, research and development subsidies, and energy storage incentives exemplify governmental instruments that can stimulate innovation without incurring the regulatory encumbrances that many enterprises consider onerous.

Another issue is the necessity to confront political polarization regarding climate change. Although reconciling entrenched ideological divides may prove challenging, there exists a distinct opportunity to redefine the climate discourse in economic terms that resonate with conservative principles. Promoting the economic growth potential of the green economy, particularly regarding job creation, energy security, and worldwide competitiveness, may serve as an effective method to obtain bipartisan support for climate action.

Moreover, the results emphasize the necessity of establishing accountability in public-private partnerships. The effectiveness of any collaboration will hinge on public trust in government climate policies. To cultivate confidence, policies must have procedures for independent review, public engagement in decision-making, and transparent reporting on advancements towards environmental and economic objectives.

8.3 Final Remarks and Calls for Further Research

This analysis provides a thorough examination of the possibilities for public-private partnerships in climate action; nevertheless, numerous areas require additional inquiry to enhance our understanding of how to optimize these collaborations. A possible avenue for future research is the analysis of longitudinal case studies of successful public-private climate initiatives. Prolonged research may yield significant insights into the efficacy of various partnership models, elucidating what is effective and what is not over time. These studies may concentrate on particular sectors, such as renewable energy or electric vehicles, and assess the effects of public-private collaboration on technological innovation, economic results, and environmental performance.

A further avenue for future research is a comprehensive examination of how changing political attitudes towards environmental innovation influence the business sector's propensity to invest in sustainability efforts. Specifically, comprehending how alterations in political authority—whether via a second-term Trump administration or a subsequent administration—impact the dynamics of public-private collaboration may yield significant insights into how governments can establish stable and predictable policy frameworks for climate investments. This research may examine how varying political circumstances influence the motivations of private enterprises to participate in climate innovation, as well as how these companies adapt to evolving regulatory environments.

Additional research is required to examine the social and equity ramifications of public-private partnerships in climate change. Although clean technology and renewable energy solutions provide considerable environmental advantages, there are apprehensions regarding their accessibility for low-income populations and emerging countries. Future research may investigate the structuring of public-private partnerships to guarantee that marginalized communities are not excluded in the shift to a low-carbon economy. Research may concentrate on reconciling the economic advantages of climate innovation with the necessity for inclusive and equitable results.

Furthermore, investigating the ways to avert regulatory capture in public-private partnerships is crucial. This study addresses concerns that conflicts of interest and the excessive influence of private firms in the regulatory process may compromise the efficacy of climate policy. Future study may explore the design of regulatory frameworks aimed at mitigating these risks, ensuring that private-sector entities stay accountable to the public interest while advancing their climate innovation initiatives.

Ultimately, investigating the prospects for international collaboration between governments and private-sector innovators may yield significant insights into how global partnerships might expedite climate action. This article concentrated on the U.S. environment, although there exists considerable potential for the amplification of private-sector-led climate initiatives via international collaboration, especially in nations with ambitious climate objectives. Research may investigate the influence of multinational corporations and the methods by which governments globally might foster favorable conditions for international cooperation on climate solutions.

8.4 Conclusion

The capacity for public-private partnerships to effect significant advancements in combating climate change is considerable, although it is accompanied with hurdles. Within a second-term Trump administration, the convergence of conservative economic principles with private-sector climate innovation presents a distinctive chance for advancement, contingent upon the resolution of significant barriers—ideological, regulatory, and practical. Policymakers are essential in cultivating an atmosphere that promotes private-sector innovation while guaranteeing accountability, transparency, and equal results. This analysis provides insights that can inform future policy to maximize the efficacy of public-private partnerships in combating climate change.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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