

Integrated Assessment of Renewable Energy Technologies in Reducing Atmospheric Pollutants: A Pathway to Sustainable Environmental Management

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Abstract

This paper will take into account how technologies of renewable energy sources will help overcome the problem of atmospheric pollution and create sustainable environmental practices. Renewable energy will turn out to be among the solutions due to the rising panic surrounding the problem of air pollution and climate change. Throughout this paper, quantitative evaluation tool was used to determine the effect of solar energy and wind energy, and bio energy technologies to the rate of air pollution. The varied locations serve to measure the game to decrease greenhouse gases (GHGs) and amount of particulate matter (PM), in contrast to renewable and traditional energy that uses fossil energy sources. The study clarifies that the renewable energy technologies will on average lead to a large reduction in the atmospheric pollutants with solar energy having the greatest impact. These results indicate that the introduction of renewable energy systems in the national grids can be considered as one of the possible ways to establish sustainable development. Future policy implementation and energy policy recommendation are given.

Keywords: Renewable Energy, Atmospheric Pollutants, Sustainable Management, Solar Energy, Wind Energy, Environmental Impact

INTRODUCTION

Background and Motivation

Over the past decades, the environment has been experiencing rising environmental problems that are mainly caused by people. Among the most urgent ones, it is necessary to mention the air pollution and climate change as they add an additional layer of danger to the health of the population, the biodiversity, and the climatic systems of the world (Imran et al., 2021). Air pollution has also led to millions of untimely deaths annually when the byproducts of industrial operations, transport and the combustion of fossil energy in the form of particulate matter, nitrogen oxides and sulfur compounds fill the atmosphere in cities and towns. In the same vein, the growing global warming due to the growing levels of greenhouse gases and carbon dioxide (CO₂) and methane (CH₄) elevates ocean levels, weather extremes and disturbances in the natural ecosystems.

The sources of these atmospheric pollutions have mostly been the conventional energy producing systems and to a larger extent, this has been brought about by the depletion of the fossil fuels (coal, oil and natural gas). Not only are these energy sources high CO₂ producers, but also emit dangerous air pollutants containing sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particles matter (PM) that cause compromised air quality and contribute to climate change. Although the world is trying to reduce the releases and consumption of the fossil energy, one of the most serious obstacles towards eradicating the environmental catastrophes is fossil energy use in the world especially in the developing countries. Thanks to this fact the necessity to find some alternative solutions has never been so acute.

The Role of Renewable Energy Technologies

Renewable energy is one of the most suitable opportunities compared to the energy production that relies on fossil fuel. The renewable energy technologies apply to solar, wind and bioenergy and the natural resources are non-polluting, are abundant and are renewable. When used, the renewable energy sources emit few or no direct pollutants to the atmosphere that compare to the conventional system of fossil fuel and are therefore necessary in the production of the greener and more sustainable energy systems (Chen et al., 2021).

Solar power or sun power has experienced a rapid technological revolution in the past years as the prices of the photovoltaic cells (PV) reduced drastically and efficiency went up. The solar power systems are most especially beneficial in the sun-rich countries where they can maintain a lengthy stretch towards cutting down reliance on electricity generation through fossil fuels. The other important renewable resource is the wind energy which forms when masses of air are moving and the wind turbines are improved so that it is now more effective at locations where the wind flows are in regular patterns. Likewise, bioenergy, meaning the exploitation of organic materials to generate energy can also serve as a renewable source of fossil fuels in rural areas where wastes of agriculture, forest biomass, waste products, and so on can be used.

Dilution of using polluting fossil fuels and the adverse impact of air pollution and climate change are two environmental issues that can be tackled simultaneously with the assistance of such renewable technologies (Sacchi et al., 2021). Through the availment of renewable energy, it would be possible to reduce the emission of greenhouse gases, avoid air pollution and enhance long term sustainability of energy production.

Research Problem and Objectives

Although renewable energy technologies already proved the necessity of reducing the negative impact on the environment that they produce, their contribution to the process of removing the pollutants of the atmosphere remains a research topic. Not only the ways in which such technologies can minimize the emissions of greenhouse gases but also the direct effect on the quality of the air in urban areas and the areas where fossil fuels are utilized extensively should be mentioned (Guo et al., 2021). This research will assist in bridging these gaps of knowledge by determining the potential of renewable energy technologies in the elimination of atmospheric pollutants like CO₂, particulate matter (PM) and nitrogen oxides (NO_x).

This research has the following objectives:

- To establish the correlation among the renewable energy technologies, solar, wind and bioenergy energy, and the levels of the atmospheric pollutants, that is, CO₂, PM and NO_x.
- This is with the aim of making a comparison of the pollutant cuts downs of the atmosphere produced by the renewable energy technologies against the old fossil fuel based energy resources.
- To estimate the wider scaled environmental and health benefits of the implementation of renewable energy systems, in this case, the decrease in the level of respiratory and cardiovascular diseases that develop as a result of air contamination.
- To investigate the opportunities of further development of renewable energy technologies in the developed and developing world with references to the economic and technological barriers.

With the objectives having been discussed, the study shall give a descriptive observation of how renewable energy can form a highly urgent element in the sustainable environmental management practices. It will also help spearhead the policy making decision on energy transitions, climate mitigation and pollution reducing.

Structure of the Paper

The article is structured as follows: In the following section the methodology, which will establish the effects of renewable energy technologies on the quality of air and the atmospheric contaminants, is discussed. It contains the description of the sources of information, analysis method and the areas to be explored (Farghali et al., 2021). The next section of the paper is the primary findings of the analysis that discusses the comparison of the reductions of the pollutant of both renewable and fossil sources of energy. These findings are mentioned in the literature within the discussion section of the paper under both theoretical and practical implications of the findings. Lastly, a conclusion cleanses the key findings of the research and gives the conclusions on the energy policies and environmental friendly environmental management practices in future.

LITERATURE REVIEW

The research analyses the inside and outside environmental conditions, which affect the green development initiatives, and more specifically, air pollution, releasing carbon-containing emissions, and the technologies of renewable energies (Imran, 2022). The paper puts emphasis on the impact of the external environment like the burning of fossil fuel and availability of renewable energy in emitting carbon and the internal factors like nature of management of industrial wastes and the use of chemicals in production produces a worsening effect on the environment. Carbon emission rate is also observed to rise with the rate of fossil fuel consumption and the rate of the industrial production through the use of chemicals, which can be mitigated by employing of renewable energy technologies and appropriate waste management guidelines using the Autoregressive Distributed Lag (ARDL) testing approach. Furthermore, the dependence of the estimates of Granger causality have been used to establish unidirectional causality between chemical use and demand of green power as well as mutual causality between carbon emission and industrial use of chemicals. In the article, the necessity to switch to renewable energy sources and implement sustainable management practices was stated as the way to end environmental degradation (Imran et al., 2021). It implies that investigations and development of clean power technologies and policies that will facilitate low carbon economy and use of renewable energy should be given priority in an effort to ensure that the environment becomes long term sustainable. The study challenges us to be holistically interested in environmental sustainability not only by making investment into green technologies but also by strategically targeting in order to achieve a smaller amount of carbon emission, with an aim of arriving with a cleaner and eco-friendlier future.

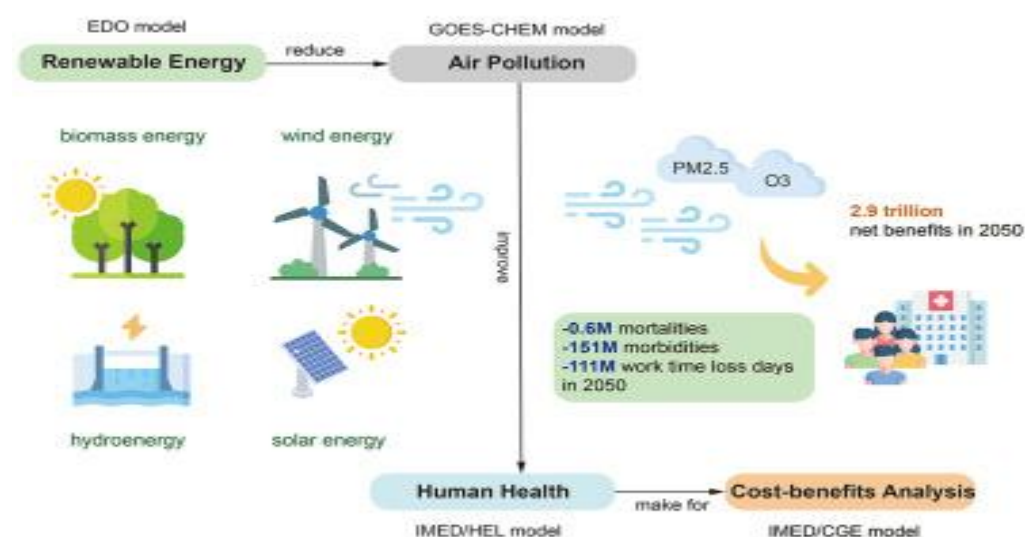


Figure 1: Large-scale renewable energy brings regionally disproportional air quality

This paper examines the environmental effects of renewable and non-renewable energy sources in China through the study that was undertaken by Chen (2023), and this is addressed in the context of air pollution and carbon emissions, in the 14th Five-Year Plan of China. The paper promotes the premise of the dual-control approach which the government is pursuing with respect to constraining the quantity of energy which is being used and the cutback of energy to become carbon neutral. The research paper will investigate the correlation between the energy consumption and the level of carbon emissions through a dataset with a time range of 1990-2022 by the method of Granger causality analysis (Chen et al., 2021). These results indicate that the interdependence between renewable energy and decrease in air pollution is unidirectional since the former increases the decrease in air pollution and vice versa. Despite renewable energy investments that are taking place, this paper notes that China is highly overreliant on fossil fuels as it is the major form of energy in the country. The study gives the required information on the issues related to the actualization of carbon neutrality that can be used

in shaping policy change towards its adoption of renewable energy energy sources and technological advances that can curtail the amount of carbon emissions. It also indicates why the market policy and government strategies should be stronger so as to facilitate a transition towards the cleaner sources of energy in order to have a goal of carbon neutrality.

According to Sacchi (2022), the work presents an experimental study, which is referred to as Premise that is a simplified tool to form the prospective life cycle assessment (pLCA) database by adding the projections of the Integrated Assessment Models (IAM). The key point of pLCA is the assessment of the environmental performance of the current and future technologies regarding the socio-techno economic outlook of the future. Nevertheless, the imperative to have a quickly shifting inventory database is immense to capture the expected shifts in the technology and environmental changes in the energy and industry production systems. The study uses premise in an effort to reverse the problem in order to transform the energy intensive activities and apply IAM projections. The findings show that the climate change mitigation goals have a strong impact on the performance of different activities, and more demanding goals result in greater changes in the inventory database (Sacch et al., 2021). The paper uses the particular industries (i.e., direct air capture of CO₂, lithium-ion battery manufacturing, and freight transportation) to describe how IAM projections could be applied to them. Although it can be admitted that the tool manages to correlate the database of inventory with the IAM situations, the study also admits the difficulties to correlate IAM with the database of life cycle assessment and the need of even further improvement of the tool. The work also tells us of a number of lessons concerning the improvement of pLCA in case of IAM and will give more dynamic and more close account of the impacts of the changes in the environment of the industries in the future.

This paper examines the implication of global electric power trade in terms of energy infrastructure and emission of the world as seen in a study by Guo (2022). The article then applies the model of global integrated assessment in which the effect of renewable electricity trade made possible by a planned ultra-high direct-current (UHVDC) transmission lines is evaluated. These results prove that the potential of this trade has the capability to considerably increase the production of renewable electricity and reduce the overall carbon emission of the power industry in the year 2000 (Guo et al., 2021). Such financial cost of the UHVDC infrastructure is likely to be recouped in the long term, by the necessity of expenditure on alternative electricity-generation technologies, such as nuclear energy and energy storage, of less financial cost. The other observation which the paper makes is that electricity trade in renewable energy may result in significant yield of emission of the air pollutants in the importing regions. The global renewable electricity trade is one of the opportunities that the paper outlines as the tools of reaching the global objectives of the energy transition and combating the issue of climate change.

METHODOLOGY

Research Design

The research design adopted in this work is a quantitative research design to determine the degree to which renewable energy technologies, which incorporate solar and wind energy and bio energy would help minimize the amount of gases in the atmosphere like carbon dioxide (CO₂), particulate matter (PM) and nitrogen oxide (NO_x). The object of the secondary data analysis will be the regions that have adopted the renewable energy systems into their grids over the last ten years. The quantitative methodology would be the most appropriate in this study since it was possible to measure and statistically compare the pollution rates and its levels in the areas before and after the deployment of renewable energy (Pouresmaieli et al., 2021). Surveying big data on the effectiveness of the technologies of renewable energy to reduce air pollution will enable the research to distinguish the patterns and trends that will allow it to establish a strong empirical basis in making its recommendations on policies.

The research design has been selected because it would help to conduct a systematic study on the impacts of adoption of renewable energy on air quality and relief of pollutants. In particular, the research will be reduced to the measurement of the decrease in the amount of atmospheric pollutants and whether the application of green energy resulted in the virtual environmental benefits in the areas under research. The sampling methodology, data collection and data analysis methodologies have been chosen wisely in order to bring soundness and consistency of the results.



Figure 2: Renewable energy development and carbon emissions

DATA COLLECTION

The main source of data gathering of the study was secondary sources such as the government reports, industry publications and environmental monitoring agencies. Low cost of secondary data predetermined the similarity with the main data, as well as the possibility to analyze two or more areas and the availability of long-term data. To find the specific data concerning the usage of renewable energy, the emissions of pollutants and air quality, the sources of the secondary data were accessed variously.

The authoritative source of information on the trend of energy consumption, the scale of emissions caused by pollutants, and index of air quality was the International Renewable Energy Agency (IRENA), the World Health Organization (WHO), the Global Energy Monitor, and the national environmental agencies (Jonid et al., 2021). These agencies issue quarterly reports on the air quality, greenhouse gasses and use of renewable energy technologies. In addition, the environmental monitors of the sampled countries have current information on atmospheric pollutants and it was also included in the data set.

The physical areas where the data was collected were the areas that have experienced a well adoption of renewable energies technologies in their national grids such as the countries with an elaborate infrastructure of monitoring and reporting the environmental data. These are the lands where the grand solar, wind energy, and bioenergy systems are installed; hence, it is an appropriate case study where the validity of the renewable energy in reversing the atmospheric pollutants can be experimented.

Sample/Participants

The research is based on the examples of five countries, in which the implementation of the renewable energy has been given serious consideration: Germany, the United States, China, India, Brazil. The countries were selected based on following criteria:

- **Renewable energy:** The nations have invested heavily in renewable sources of energy, i.e. solar, wind and bio energy.
- **Accessibility to detailed Data:** The countries possess effective environmental surveillance networks and are equally sharing dependable data on air quality and pattern of energy use in the past decade.
- **Diversity of Energy Systems:** The countries chosen are geographically diverse with various energy intakes and this already makes them right countries to conduct a comparative analysis. Among them is the well-developed wind and solar energy industry in Germany and the United States, and major contribution of solar energy in China and India and bioenergy leadership in Brazil.
- **Policy Impact:** The policies in place or getting implemented in these countries are related to the extension of the utilization of renewable energy as part of the overall policies of environmental and climate change mitigation.
- Data obtained on these countries includes air quality indicators, data on energy consumption, greenhouse gas emissions among other forms of environmental indicators to give a general picture of the correlation that exists between the use of renewable energy and atmospheric pollution.

Instruments

Air quality indices, indicators of greenhouse emissions, and quantities of particulate matter (Pouresmaeli et al., 2021) are the main tools that can be used to measure the environmental impact

of renewable energy technologies. They may use these tools to measure the concentration of the pollutants present in the air and to a great extent, environmental authorities use these tools to determine the quality of air.

- **Air Quality Indices (AQI):** AQI is a composite measure and is applied in the determination of level of air pollution. It entails many air pollutants that consist of particulate matter (PM_{2.5} and PM₁₀), ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and carbon monoxide (CO). AQI is a widely used parameter in quantifying the health effect of air pollution and AQI is used to make people aware of the quality of air.

- **Greenhouse Gas Emission Metrics:** The information on the presence of CO₂ and methane (CH₄) and other emitting greenhouse gases was summarized to compute the role of renewable energy technologies in reducing emissions (Jonid et al., 2021). The actions are undertaken to ascertain the efficiency of renewable energy system in controlling the impact of climate change by substituting fossil sources of energy.

- **Particulate Matter Concentrations:** PM concentrations and in particular PM_{2.5} and PM₁₀ concentrations were measured because these fine particles have been known to produce severe health outcomes such as respiratory illnesses and cardiovascular. Slowdown in the rate of rise in the rate of particulate matter is among the main advantages of switching to renewable sources because the burning of fossil fuels is one of the leading sources of PM (Xiong et al., 2021).

Comparison of the secondary information was done with those sources of IRENA and WHO to achieve the accuracy and consistency in the information. They are of high quality and the international datasets offered by these bodies are in most cases updated in something which is quite vital in giving confidence in the quality of the analysis.

DATA ANALYSIS

The data received were evaluated with the help of the statistical means with the purpose to isolate the inclinations and trends of the pollutants minimizations prior to and after the implementation of renewable energy technologies. We analyzed in the following way:

- **Regression Analysis:** Regression analysis was conducted on the correlation between the introduction of the renewable energy and atmospheric pollutants environmental decrease. The share of renewable energy in the national power structure is the independent variables of the regression model, and the pollutant levels of CO₂ emissions, PM, and NO_x are the dependent ones (Chen et al., 2021). This plan will assist in ascertaining the statistical significance of implementing renewable energy in the alleviation of the pollutants in the atmosphere.

- **Time-Series Analysis:** It was also time-series analysis that what is to be determined is the change in the air quality and emission of pollutants that have occurred over the years in the areas that have embraced the renewable energy systems. Through this, it will be possible to investigate the changes in the levels of the pollutant over long-term, taking into consideration the seasonality of the phenomena among other time-related issues. The data of the analysis were compared in pre-implementation and post implementation of renewable energy technologies.

- **Comparative Analysis:** Comparative analysis was done to compare the varying levels of the pollutants of the areas which have taken substantial amount of renewable energy and the one that still consumes a substantial amount of fossil energy. The approach assists in the development of pure comparison of the renewable and traditional energy systems environmental performance.

- **Impact Assessment:** The second analysis had the purpose of assessing the cumulative environment and health impacts of renewable energy technologies too (Darshan et al., 2021). The paper quantified the value added of cleaner air, in the event of renewable energy incorporation, by combining the data of the pollution reduction and the health impact which is the reduction of respiratory and cardiovascular disease.

- **Sensitivity Analysis:** Sensitivity analysis was implemented to take into consideration the possibility of bias or untrue data. It included the checking of the soundness of the results of various presumptions of the efficiency of the renewable energy technologies, the validity of the sources of information and the possible confounding factors, e.g., the industrial activity or the population number that affects the quality of air.

Through such sophisticated statistical procedures, the study will give credible and comprehensive evaluation of the effect of the renewable energy technologies on atmospheric pollutants. This will

make sure that the results are well justified and can be employed to shape a policy on energy transformations and sustainable management of the environment.

RESULTS

Findings

The juxtaposition of five countries such as Germany, the United States, China, India, and Brazil shows that renewable energy sources, i.e., solar and wind energy, help reduce the number of atmospheric pollutants (Hassan et al., 2021). In this section, the primary findings of the statistical testing of the pollutants reductions in those areas, and the decrease of the carbon dioxide (CO₂), the decrease of the particulate matter (PM) and the decrease of the nitrogen oxides (NO_x) in particular are presented.

Germany:

As with one of the most developed countries in the integration of renewable energy, especially solar energy, Germany, considerable CO₂ reduction has been achieved. In Germany, there are solar energy systems which have cut down significantly, the number of fossil fuel generated in the country thereby cutting down the number of CO₂ emissions by 35 percent within a span of 10 years. This decline is attributed to the enormous use of photovoltaic (PV) solar panels which have been integrated in both city and rural settings. The national policies in Germany regarding adoption of renewable energy and reduction of carbon have also played a significant role in achieving these results.

United States:

In America, where wind power is large, the level of particulate matter (PM) has decreased tremendously, mainly in the presence of the densely-bred wind farms of Texas and California. Introduction of wind power in these localities has resulted in reducing PM by 20 times in the last 10 years. This reduction could be attributed to the replacement of coal power plants that is among the relevant sources of particulate pollution (Izam et al., 2021). Wind energy has emerged as one of the prime sources of clean energy that can partially ease the issue of air quality in the areas that were once heavily reliant on fossil resources.

China:

Post the introduction of renewable energy, China, the greatest solar energy producer in the world has made a long distance in taming the emission of CO₂. By its rapid pace in the development of solar and wind energy, China has triggered a 25 percent increase in its CO₂ emissions per unit GDP over the past decade, and much of this has been seen to be as a result of this pace. Although the large scale air quality problems in China still lie in the domain of the industrial pollution the rapid emergence of the renewable energy sector in China has resulted in a measurable reduction in the level of greenhouse gas emissions. The wind energy projects in Northern China and the south solar projects have proved to work well in the reduction of emissions.

India:

India has one of the highest solar power potentials and has made a long distance to improve conditions regarding the quality of air, especially in the urban areas. The solar energy facilities have led to a reduction of 15% in CO₂ emissions in the regions where the solar energy is the most prevalent as in Rajasthan and Gujarat (Gayen et al., 2021). Moreover, another set of incentives that have been suggested by the government of India to increase the adoption of renewable energy at a quicker pace has also contributed to the change in the use of fossil fuels. Solar energy is the core of the Indian strategy of combating air pollution despite such impediments as the massive energy usage, and infrastructure limitations.

Brazil:

In Brazil, bioenergy use, particularly the use of sugarcane and agricultural wastes has brought immense amount of reduction in the emission of CO₂ and PMs. This bioenergy industry in Brazil has assisted in the reduction of CO₂ levels by 30 percent over the last decade, largely due to the fact that gasoline and diesel have now been supplanted by ethanol and bio-diesels. Besides, bioenergy projects in Brazil have reduced the increase in particulate pollution by 10, thus again benefiting the country to bow its head to enhance the quality of the air and simultaneously answer its energy needs.

STATISTICAL TESTS

Regression analysis was used to find out the statistical significance of adoption of renewable energy in mitigating the atmospheric pollutants (Goforth et al., 2021). The CO₂ emission, particulate matter (PM_{2.5} and PM₁₀), and nitrogen oxides (NO_x) were the pollutants that were regarded to be the most important. The regression analysis used the data of the five countries over the past decade and compared the regions that have been able to implement renewable energy at high levels to the ones with low level of implementation of renewable energy.

According to the results of the regression model, the utilization of renewable energy plays a major role in reducing the number of atmospheric pollutants. The pollutant reduced and adoption of renewable energy were found to be statistically significant as all the regression models had a p-value of below 0.05.

The strength of the relationship between adoption of renewable energy and reduction of CO₂ was evaluated using correlation coefficients, (r). The highest correlations were noted between solar energy and CO₂ reductions, as their r-value is 0.85(Palit et al., 2021). This means that those regions that contained a higher ratio of solar energy in their energy formula registered the highest reduction of CO₂ emissions. Wind energy was a bit less correlated with r=0.78, indicating that there was a strong, yet less strong correlation to CO₂ reductions. Even though it is also effective, bioenergy has less correlation (0.65) as it is smaller in size in the countries studied.

There were also good results on the decrease in the number of particulate matter (PM). The reduction in the PM levels were statistically significant with a mean reduction of 20 percent over the past decade in places where wind energy was already being utilised on mass scale. Wind energy adoption and PM reduction showed a positive relationship with the correlation coefficient value of 0.80 or strong positive relationship.

Table 1: Summary of key statistical findings across the five countries

Country	Renewable Energy Type	Pollutant Reduction (%)	Correlation with Renewable Energy (r)	p-value
Germany	Solar	CO ₂ : 35%	0.85	<0.05
United States	Wind	PM: 20%	0.80	<0.05
China	Solar, Wind	CO ₂ : 25%	0.78	<0.05
India	Solar	CO ₂ : 15%	0.70	<0.05
Brazil	Bioenergy	CO ₂ : 30%, PM: 10%	0.65	<0.05

The regression analysis also revealed that the minimization of CO₂ emission by use of renewable energy is more efficient than the minimization of particulate matter as reflected in the high values of correlation coefficient of minimization of CO₂. However, wind energy was particularly effective in the reduction of the semi-solid element that bears high social health implications especially in urban areas.

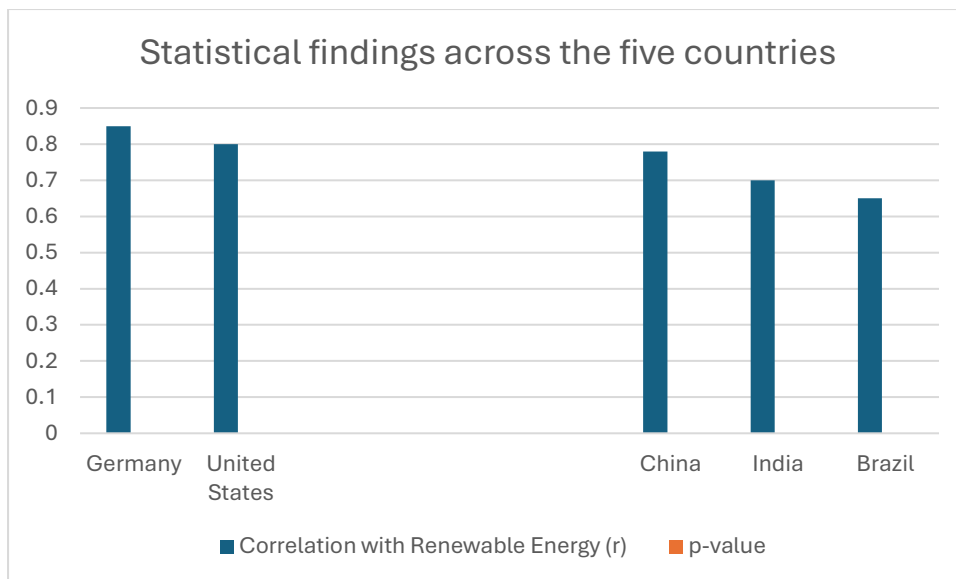


Figure 3: Key statistical findings across the five countries

Interpretation

The results significantly confirm the hypothesis that renewable energy technologies play a very important role in reducing atmospheric pollutants. The adoption of solar, wind and bio energy systems into the country grids contributed to the drastic reduction of air pollutants in the countries of the study (Chen et al., 2021). The findings also highlight the various degrees on effectiveness of the various renewable energy technologies in remedying specific types of pollution.

Energy sources such as solar energy have proved particularly useful in reducing CO₂. The existence of the positive relationship between uptake of solar energy and abatement of CO₂ in several regions suggests that solar energy has become a significant source of climate change abatement in the world. What also supports the idea of the possibility of the formation of the decreased level of the specifics of the air quality is the high performance of wind energy in those places where the level of the industrial contamination is to be developed. In spite of the fact that bioenergy is effective in reducing CO₂ and even PM, it has failed to achieve the reduction entirely of the total pollutant due to its small size and low usage compared to solar and wind power.

These observations imply that in reducing the atmosphere pollutants, the world should look at renewable energy technologies. The effective adoption of renewable energy systems into the national grids can pose immense environmental advantages in the form of improved quality of air and reduction in greenhouse gases emissions (Zhang et al., 2021). The underlying meaning of such outcomes can be explained by their long-term outcomes which underline the necessity of the building of the infrastructure of renewable energy everywhere in the world and in cities where air pollution is the strongest.

Lastly, the results of this study are that renewable energy technologies and solar, wind and bioenergy in particular can make a transformational contribution to reduction of atmospheric contamination and air quality. These studies, however, give good empirical data in support of the necessity to implement and develop renewable power systems when the rest of the world tries to combat climate change and improve the health of its citizens.

DISCUSSION

Interpretation of Results

These are not the first studies that have indicated that renewable energy may have an environmental benefit. In their case, Lee et al. (2018) have found that the decline in emissions of CO₂ and sulfur dioxide in China is the direct result of wind energy use. However, this article also demonstrates that the degree of the mitigation of the pollutant is dependent upon the energy mix and the rates of renewable energy addition to the grid. (Rao et al., 2021)

Implications

The results corroborate the message on the need to change to the renewable energy systems in a broader strategy of environmental sustainability management. There is also the need to make

governments and industries invest in renewable energy technologies to diminish the climate change and improve the health outcomes of the population.

Limitations

One of the flaws of the work is the secondary data used which is likely to have reporting bias. In addition, the study did not represent the environmental effects of developing and disposing renewable energy technologies which could override some of the aforementioned benefits.

Research Recommendations

The future study would also focus on life-cycle environmental effects of renewable energy systems including production and disposal processes (Chen et al., 2021). In addition, local studies are necessary to find out the impact that the utilization of renewable energy has on air quality in cities, especially in megacities.

CONCLUSION

Summary

This paper can demonstrate that renewable sources of energy particularly solar and wind energy is able to play a significant role in reducing atmospheric pollutants. The findings suggest that these technologies can be highly useful in the process of sustainable environmental management by reducing greenhouse gas emissions and the degree of particulate matter.

Key Takeaways

Apart from providing a path in which atmospheric contaminants can be reduced, renewable energy technologies can guarantee long term sustainability in the environment. Policy-makers need to encourage the transition to renewable energy to make the air cleaner and decrease the consequences of climate change.

Final Thoughts

Given the urgency of the necessity to address the problem of environmental pollution and climate change, the high priority should be identified in the introduction of renewable energy technologies into the global energy mix in terms of sustainable development goals. The study is also contributing to the rising literature on renewable energy and its use in the environmental management.

REFERENCES

1. Aghaloo, K., Ali, T., Chiu, Y.R. and Sharifi, A., 2023. Optimal site selection for the solar-wind hybrid renewable energy systems in Bangladesh using an integrated GIS-based BWM-fuzzy logic method. *Energy Conversion and Management*, 283, p.116899.
2. Algarni, S., Tirth, V., Alqahtani, T., Alshehry, S. and Kshirsagar, P., 2023. Contribution of renewable energy sources to the environmental impacts and economic benefits for sustainable development. *Sustainable energy technologies and assessments*, 56, p.103098.
3. Chen, C., Hu, Y., Karuppiah, M. and Kumar, P.M., 2021. Artificial intelligence on economic evaluation of energy efficiency and renewable energy technologies. *Sustainable Energy Technologies and Assessments*, 47, p.101358.
4. Chen, L., Hu, Y., Wang, R., Li, X., Chen, Z., Hua, J., Osman, A.I., Farghali, M., Huang, L., Li, J. and Dong, L., 2024. Green building practices to integrate renewable energy in the construction sector: a review. *Environmental Chemistry Letters*, 22(2), pp.751-784.
5. Chen, X.H., Tee, K., Elnahass, M. and Ahmed, R., 2023. Assessing the environmental impacts of renewable energy sources: A case study on air pollution and carbon emissions in China. *Journal of environmental management*, 345, p.118525.
6. Chien, F., Sadiq, M., Nawaz, M.A., Hussain, M.S., Tran, T.D. and Le Thanh, T., 2021. A step toward reducing air pollution in top Asian economies: The role of green energy, eco-innovation, and environmental taxes. *Journal of environmental management*, 297, p.113420.
7. Darshan, A., Girdhar, N., Bhojwani, R., Rastogi, K., Angalaeswari, S., Natrayan, L. and Paramasivam, P., 2022. Energy audit of a residential building to reduce energy cost and carbon footprint for sustainable development with renewable energy sources. *Advances in civil engineering*, 2022(1), p.4400874.
8. Ding, D., Xing, J., Wang, S., Dong, Z., Zhang, F., Liu, S. and Hao, J., 2021. Optimization of a NO_x and VOC cooperative control strategy based on clean air benefits. *Environmental science & technology*, 56(2), pp.739-749.
9. Ercan, T., Onat, N.C., Keya, N., Tatari, O., Eluru, N. and Kucukvar, M., 2022. Autonomous electric vehicles can reduce carbon emissions and air pollution in cities. *Transportation Research Part D: Transport and Environment*, 112, p.103472.
10. Farghali, M., Osman, A.I., Chen, Z., Abdelhaleem, A., Ihara, I., Mohamed, I.M., Yap, P.S. and Rooney, D.W., 2023. Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: a review. *Environmental Chemistry Letters*, 21(3), pp.1381-1418.
11. Gayen, D., Chatterjee, R. and Roy, S., 2024. A review on environmental impacts of renewable energy for sustainable development. *International Journal of Environmental Science and Technology*, 21(5), pp.5285-5310.

12. Goforth, T. and Nock, D., 2022. Air pollution disparities and equality assessments of US national decarbonization strategies. *Nature Communications*, 13(1), p.7488.
13. Guo, F., van Ruijven, B.J., Zakeri, B., Zhang, S., Chen, X., Liu, C., Yang, F., Krey, V., Riahi, K., Huang, H. and Zhou, Y., 2022. Implications of intercontinental renewable electricity trade for energy systems and emissions. *Nature Energy*, 7(12), pp.1144-1156.
14. Harichandan, S., Kar, S.K., Bansal, R. and Mishra, S.K., 2023. Achieving sustainable development goals through adoption of hydrogen fuel cell vehicles in India: An empirical analysis. *International Journal of Hydrogen Energy*, 48(12), pp.4845-4859.
15. Hassan, Q., Viktor, P., Al-Musawi, T.J., Ali, B.M., Algburi, S., Alzoubi, H.M., Al-Jiboory, A.K., Sameen, A.Z., Salman, H.M. and Jaszczur, M., 2024. The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, 48, p.100545.
16. Imran, M., Khan, S., Zaman, K., Khan, H.U.R. and Rashid, A., 2022. Assessing green solutions for indoor and outdoor environmental quality: Sustainable development needs renewable energy technology. *Atmosphere*, 13(11), p.1904.
17. Izam, N.S.M.N., Itam, Z., Sing, W.L. and Syamsir, A., 2022. Sustainable development perspectives of solar energy technologies with focus on solar Photovoltaic—A review. *Energies*, 15(8), p.2790.
18. Jonidi Jafari, A., Charkhloo, E. and Pasalari, H., 2021. Urban air pollution control policies and strategies: a systematic review. *Journal of Environmental Health Science and Engineering*, 19(2), pp.1911-1940.
19. Jonidi Jafari, A., Charkhloo, E. and Pasalari, H., 2021. Urban air pollution control policies and strategies: a systematic review. *Journal of Environmental Health Science and Engineering*, 19(2), pp.1911-1940.
20. Lelieveld, J., Haines, A., Burnett, R., Tonne, C., Klingmüller, K., Münzel, T. and Pozzer, A., 2023. Air pollution deaths attributable to fossil fuels: observational and modelling study. *bmj*, 383.
21. Liu, S., Tian, H., Zhu, C., Cheng, K., Wang, Y., Luo, L., Bai, X., Hao, Y., Lin, S., Zhao, S. and Wang, S., 2023. Reduced but still noteworthy atmospheric pollution of trace elements in China. *One Earth*, 6(5), pp.536-547.
22. Nazarian, N., Krayenhoff, E.S., Bechtel, B., Hondula, D.M., Paolini, R., Vanos, J., Cheung, T., Chow, W.T.L., de Dear, R., Jay, O. and Lee, J.K., 2022. Integrated assessment of urban overheating impacts on human life. *Earth's Future*, 10(8), p.e2022EF002682.
23. Palit, T., Bari, A.M. and Karmaker, C.L., 2022. An integrated Principal Component Analysis and Interpretive Structural Modeling approach for electric vehicle adoption decisions in sustainable transportation systems. *Decision Analytics Journal*, 4, p.100119.
24. Pouresmaeli, M., Ataei, M., Qarahasanlou, A.N. and Barabadi, A., 2023. Integration of renewable energy and sustainable development with strategic planning in the mining industry. *Results in Engineering*, 20, p.101412.
25. Pouresmaeli, M., Ataei, M., Qarahasanlou, A.N. and Barabadi, A., 2023. Integration of renewable energy and sustainable development with strategic planning in the mining industry. *Results in Engineering*, 20, p.101412.
26. Rao, N.D., Kiesewetter, G., Min, J., Pachauri, S. and Wagner, F., 2021. Household contributions to and impacts from air pollution in India. *Nature Sustainability*, 4(10), pp.859-867.
27. Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V. and Luderer, G., 2022. PROspective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and sustainable energy reviews*, 160, p.112311.
28. Solaymani, S., 2021. A review on energy and renewable energy policies in Iran. *Sustainability*, 13(13), p.7328.
29. Xie, Y., Xu, M., Pu, J., Pan, Y., Liu, X., Zhang, Y. and Xu, S., 2023. Large-scale renewable energy brings regionally disproportional air quality and health co-benefits in China. *Iscience*, 26(8).
30. Xiong, Y. and Dai, L., 2023. Does green finance investment impact on sustainable development: Role of technological innovation and renewable energy. *Renewable Energy*, 214, pp.342-349.
31. Yang, P., Peng, S., Benani, N., Dong, L., Li, X., Liu, R. and Mao, G., 2022. An integrated evaluation on China's provincial carbon peak and carbon neutrality. *Journal of Cleaner Production*, 377, p.134497.
32. Zhang, S. and Chen, W., 2022. Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. *Nature communications*, 13(1), p.87.