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The Effects of Climate Change, Carbon Dioxide Emissions and Renewable Energy Consumption on The Economic Development of Botswana

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A B S T R A C T

This study aims to explore the relationship between climate change, renewable energy usage and climate change variations with the economic growth of Botswana, the theoretical framework of the study will be centered around the extended Solow growth model to analyze the long-term impact on Botswana's economic growth, the Solo model is extended to include the effects of climate change and Co2 emissions on total factor productivity. Key findings from literature review shows that climate change has a negative effect on the economic growth of Botswana particularly because it affects the main key sectors such as agriculture and tourism.it also highlights that increase in CO2 emissions contribute to environmental degradation reducing overall productivity in important sectors. Increased renewable energy usage such as solar power offers a pathway for sustainability by reducing reliance on fossil fuels which fuels climate change

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INTRODUCTION

Botswana is a country located in Southern Africa, it faces significant economic challenges which can be attributed to environmental factors, including the effects of climate change, carbon dioxide (CO2) emissions, and the transition towards renewable energy. Being one of the driest countries in the world, Botswana is particularly vulnerable to changes in climate patterns, such as increasing temperatures and shortage of rainfall, which have the potential to exacerbate existing challenges in agriculture, water availability, and energy security. These climate-induced changes pose challenges to sectors critical to Botswana's economy, such as agriculture, mining, and tourism, which together form the backbone of the nation's GDP. Climate change has manifested in Botswana through more frequent droughts, erratic rainfall patterns, and temperature increases, all of which threaten agricultural productivity. With a significant portion of the population relying on agriculture, particularly subsistence farming and livestock rearing, these changes have the potential to destabilize livelihoods, food security, and rural economies. In addition, the agricultural sector's vulnerability to these changes could result in a wider economic downturn, further reducing growth prospects. Furthermore, as global environmental concerns grow, Botswana's reliance on fossil fuels for energy generation and industrial development contributes to the country's carbon footprint. While Botswana's contribution to global CO2 emissions is relatively small, the continued use of coal and other non-renewable energy sources may increase over time, exacerbating global warming and leading to more severe climate-related impacts. This situation presents a paradox, where Botswana must balance its need for economic development with the global demand for climate action.

The intertwined effects climate change as well as carbon dioxide emissions and economic consumption has led to a significant challenge to the economic growth Botswana, a landlocked country in Southern Africa. Botswana is highly vulnerable to climate-related disruptions such as prolonged droughts, little rainfall, and shortage of water, all of which have negative impacts on main economic sectors such as agriculture, water supply, and tourism. The country is also heavily reliant on carbon-intensive industries, particularly mining, which significantly increases its carbon footprint and contributes to global warming, further intensifying the adverse effects of climate change. However, Botswana also possesses considerable potential for renewable energy development, particularly solar power, which could provide a sustainable alternative to fossil fuels, mitigate climate change impacts, and foster economic growth. Despite these opportunities, there is a lack of comprehensive understanding of how climate change, carbon emissions, and renewable energy consumption interact to influence economic performance in Botswana. This research seeks to examine the effects of these factors on Botswana's economic growth, with a particular focus on the potential for renewable energy to drive sustainable development while reducing environmental risks. By identifying the key challenges and opportunities in integrating climate resilience, carbon reduction, and renewable energy consumption, this study will aim to provide policy recommendations for

fostering an economically viable and environmentally sustainable future for Botswana

Research Aims/Purposes

1. To examine the relationship between carbon dioxide emissions and Botswana's economic growth, investigating whether increased CO2 emissions correlate with economic challenges or constraints, and how this relationship influences policy decisions.
2. To analyze the impact of climate change on key sectors of Botswana's economy, including agriculture, tourism, and water resources, and assess how these effects influence the overall economic growth and development of the country.
3. To evaluate the role of renewable energy consumption in mitigating climate change effects and fostering economic growth in Botswana, with a particular focus on solar, wind, and other renewable energy sources.

Theoretical Framework

The theoretical framework for this study is grounded in the interdisciplinary nexus of environmental economics, sustainable development, and macroeconomic growth theories. The framework integrates key theories that explain how climate change, carbon dioxide (CO2) emissions, and renewable energy consumption impact economic growth. Botswana, as a developing country with a growing economy, faces unique challenges and opportunities in this regard.

Solow Growth Model and Augmented Endogenous Growth Theory

According to Alatas (2023) the Solow-Swan growth model emphasizes capital accumulation, labor force expansion, and technological progress as the main drivers of economic growth. However, it does not explicitly account for environmental factors. The Augmented Endogenous Growth Theory extends the Solow model by incorporating human capital, technological advancements, and environmental sustainability. After including the energy consumption and climate change factors the modified growth function can be written as

Yt=economic output (GDP)
Kt=Capital stock
Lt=labour
REt=Renewable Energy Consumption
CO2t=Carbon dioxide emissions (negative externality)
CLIMt=Climate change effects (e.g temperature animalities, precipitation variance)

This model asserts that an increase in capital and labour contributes to economic growth. It also denotes that renewable energy consumption may lead to improved technological advancements in Botswana. This theory supports the integration of renewable energy as a contributor to long-term economic growth.

LITERATURE REVIEW

Climate Change Impacts on Botswana's Economy

According to Maswabi (2021), climate models predict that Botswana will experience a decrease in annual rainfall and an increase in the frequency and severity of heatwaves in the coming decades. These climate extremes pose significant risks to Botswana's agricultural sector, which is crucial for food security and livelihoods. According to the World Bank (2023), carbon dioxide (CO_2) emissions in Botswana have increased steadily over the past few decades, largely due to the growth of the mining industry and the continued use of coal for energy. Botswana's energy sector is one of the primary sources of CO_2 emissions, as coal remains the dominant fuel for electricity production. The country's contribution to global emissions, however, remains relatively small on the global scale, but it is significant in the regional context. According to Mogotsi (2021) Botswana has been experiencing significantly warmer temperatures, the average temperatures has been on average increasing by an estimated 1.5 degrees Celsius from the 1900's. This trend together with other factors including low rainfall and persistent drought negatively impact crucial economic sectors (International labour Organization 2024). According to a report by the Government of Botswana (2019) The country's agricultural sector which heavily relies on rainfall for its success has been negatively affected leading to low yields and productivity because of insufficient rainfall. Additionally, the tourism sector which is heavily dependent on biodiversity is faced with climate change as unpredictable and adverse climatic conditions affects wildlife and the state of natural habitats like the Chobe river.

CO2 and Economic Activities

According to Minarta & Ko (2024) climate change is driven by the high levels of greenhouse gases (GHC's) and other anthropogenic emissions. Among the various anthropogenic GHC emissions, carbon dioxide is the main contributor to global warming and climate change. Rangani & Matenda (2024) highlights that the transportation sector is the main source of carbon dioxide emissions ,The International Energy Agency IEA estimated that the main contributor to carbon dioxide emissions is energy ,followed by its industry and the transportation sector at the prominent contributors .Transportation is responsible for 23% of the global CO2 Emissions and energy usage ,with road transportation ,mainly cars being the dominant mode World Bank (2022) . According to Statistics Botswana, transport constitutes to about 43% making it the largest contributor to CO2 emissions followed by the Energy industry. Hlongwane (2023) denotes that Botswana also heavily relies on coal which is its main energy supply even though biomass and waste energy are alternatives. He further states that Botswana uses fossil fuels to generate electricity depending on two major coal-fired power plants (Morupule A and B) and several diesel plants .Botswana has been importing around 94% of its electricity supply to meet its demand but after the recovery of its Morupule B plant ,the share of electricity imports in total supply has reduced to about 15%.Botswana's coal industry faces challenges balancing economic diversification and climate commitments under the Paris Agreement (Tautsagae & Wu 2024) .Botswana has an estimated 200 billion tons of coal ,seen as a diversification opportunity from diamonds. The

government has identified coal as one of its main economic sectors. The global demand for coal especially in India and China conflicts with the Paris Climate Agreement's goals. Coal mining and burning releases a large amount of carbon dioxide, a major cause of global warming. The environmental impacts of coal include forest loss, acid mine drainage and air pollution (Tautsagae & Wu 2024). The heavy reliance on carbon intensive industries calls for a need to adopt a more sustainable alternative source of energy which does not produce a lot of carbon dioxide in order to reduce environmental impacts while also contributing to economic growth.

Renewable Energy Initiatives in Botswana

According to Nguyen (2023) developing countries are searching for alternative and sustainable sources of energy to reduce CO2 emissions and achieve trade sustainability. He further states that renewable energy sources are more less harmful to the environment as compared to non-renewable energy sources Saad et.al (2024) denotes that it is important to reduce greenhouse emissions and Botswana has committed to a 15% reduction by 2030.This commitments are supported by renewable energy projects outlined in the Integrated Resource Plan and the adoption of a climate change policy which was done in 2021.The main aim of this initiatives is to enhance accessibility to carbon markets ,climate finance and clean technologies ,harnessing a shift towards sustainable energy consumption. According to Mochotlhi (2023) Botswana is making efforts to invest in renewable which will bring an important transition in the country's energy sector by promoting renewable alternatives and improved access to electricity. Botswana has a vast and yet unexplored sources of renewable energy. The report further says that the country aims to increase its share of renewable energy to 30% of its energy mix by 2030 and 50% by 2036 .Potadar (2024) says that the significant milestone in transitioning to renewable energy is the investment in grid infrastructure including the establishment of a 50MW battery storage system and making electricity available in rural areas ,this initiatives were launched in 2024 and it is supported by the World Bank through the Renewable Energy and access Accelerates (RESA) project .Other major solar powers anticipated to be launched include the 120MW Mmadinare Solar Power Station and the 50 MW Selebi -Phikwe Solar Power station both developed by Norwegian Company Scatec .This initiatives marks Botswana 's robust efforts to improving and exploiting its abundant solar resources to promote and increase energy availability ,sustainability and resilience in the face of climate change (Puso 2024)

Economic Implications of Renewable Energy Adoption

The adoption of renewable energy comes along with both opportunities and challenges to the economic prospects of a country (Goodarzi & Li 2022). The transition to renewable energy sources in Botswana indicates far-reaching economic benefits that can greatly transform the country's energy landscape and ultimate economic growth (Runyowa & Fourie 2021) .One of the benefit will be employment creation due to the Fact that implementation of the large scale solar projects such as Mmadinare ,Jwaneng and Tati solar power stations will create job opportunities during their different stages of implementation (Odiambo 2021).These projects will not only create direct jobs but they will also boost

employment indirectly into other sectors such as transport ,engineering and other services. Maswabi et.al (2021) further says that by diversifying the economy away from common sectors like mining, Botswana can reduce its susceptibility to global commodity price fluctuations and develop a less vulnerable economic structure. The shifts towards renewable energy will also provide self-sufficiency and security by a reduction on imported electricity, especially during demanding periods and stabilizing local energy prices, this will be especially important to Botswana which imports around 15% of its electricity from neighboring countries (Koubon 2021). According to Kaseem et.al (2023) Botswana 's renewable energy is level by 30% in 2030 and 50% in 2036 is attracting foreign investors leading to an influx of foreign Direct Investments and technological innovation. This influx of FDI will not only enable infrastructure development but it will also promote knowledge and skills transfer helping to build local capacity in the renewable energy sector

METHODOLOGY

The variables used for this research are outlined in the table below. The empirical analysis data was sourced from World Development indicators (WDI). The data used was from 1974 to 2023.The results of the data are illustrated in table 1.

Table 1. Data Results

variable	Explanation	Source of data
Gdp	Gross Domestic Product	WDI
Co2i	Carbon emissions from industries	WDI
Co2b	Carbon emissions from	WDI
Co2e	Carbon emissions from	WDI
Fdi	Foreign Direct Investments	WDI
Pre	Precipitation	WDI
Temp	Temperature	WDI
Rec	Renewable energy consumption	WDI
urb	Urban population migration	WDI
Co2t	Carbon emissions from	WDI

Autoregressive Distributive Lag Model

The ARDL bounds testing approach was first introduced by Pesaran and Shin in 1998 and it was further developed by Pesaran and other authors in 2001 and implemented by Narayan in 2004 in a study on the tourism demand model. Analysis of the long -run and short run relationships between GDP, Carbon dioxide emissions, renewable energy consumption in Botswana were done. The interactions of the long-term and short-run relationships were analyzed using the ARDL approach with the unrestricted error model (UECM). In this paper, the model was approximated separately for the short-run and long -run relationships.

RESULT AND DISCUSSION

The results of this study show critical insights in the relationship between climate change, carbon dioxide emissions, renewable energy consumption and economic growth in Botswana over the study period. By using descriptive statistics, unit root testing, ARDL modelling and causality analysis allows for a more detailed understanding of both the short run dynamics and long run equilibrium relationships between the variables.

Descriptive Statistics

Table 2. Descriptive Statistics

	GDP	C02T	CO2B	CO2E	CO2I	FDI	NRE	PRE	REC	TEMP	URB
Mean	22.55134	-0.183834	-2.096601	-4.994308	-0.611928	0.783934	4.103482	5.979053	3.603469	3.083125	3.716867
Median	22.79657	0.077270	-1.942912	-4.840893	-0.536691	0.727305	4.156288	5.981148	3.678778	3.087171	3.950220
Maximum	23.61068	0.899633	-0.918543	-3.755019	0.189628	2.746895	4.313319	6.496700	3.908015	3.129826	4.288636
Minimum	20.69585	-2.257612	-3.457768	-8.111728	-3.085657	-3.777819	3.869669	5.447427	3.242592	3.023834	2.407846
Std. Dev.	0.843971	0.965779	0.731283	0.841085	0.599351	1.086103	0.128364	0.184347	0.236170	0.023131	0.570875
Skewness	-0.729333	-0.670861	-0.522460	-1.318414	-2.217895	-1.524899	-0.512867	-0.047393	-0.276260	-0.558542	-1.036138
Kurtosis	2.367739	2.189219	2.269550	6.122319	9.410984	7.702479	1.913714	4.115253	1.449971	3.169759	2.692540
Jarque-Bera	5.265536	5.119963	3.386282	34.79528	126.6186	65.44703	4.650305	2.609944	5.641392	2.659784	9.143451
Probability	0.071879	0.077306	0.183941	0.000000	0.000000	0.000000	0.097769	0.271180	0.059564	0.264506	0.010340
Sum	1127.567	-9.191719	-104.8300	-249.7154	-30.59640	39.19668	205.1741	298.9526	180.1734	154.1562	185.8434
Sum Sq. Dev.	34.90203	45.70371	26.20398	34.66380	17.60185	57.80136	0.807386	1.665202	2.733038	0.026218	15.96904
Observations	50	50	50	50	50	50	50	50	50	50	50

The descriptive data indicates considerable variability in carbon dioxide and similar variables, implying that the environmental factors have varied significantly with time, which might be because of the dynamic industrial activity and energy policies.

Table. 3 Descriptive Data

	GDP	C02T	CO2B	CO2E	CO2I	FDI	NRE	PRE	REC	TEMP	URB
GDP	1	0.99611596...	0.82791627...	0.91202744...	0.76520456...	-0.1518416...	0.90823990...	-0.1962408...	-0.7359830...	0.74736286...	0.98752081...
C02T	0.99611596...	1	0.83480237...	0.89899216...	0.76367884...	-0.1549000...	0.92078006...	-0.1851057...	-0.7567032...	0.75346472...	0.98163570...
CO2B	0.82791627...	0.83480237...	1	0.67893474...	0.79885434...	-0.1283387...	0.82656865...	-0.2376457...	-0.4249507...	0.60812259...	0.87113645...
CO2E	0.91202744...	0.89899216...	0.67893474...	1	0.79612010...	0.00201040...	0.81066303...	-0.3148688...	-0.6081601...	0.71992023...	0.89804825...
CO2I	0.76520456...	0.76367884...	0.79885434...	0.79612010...	1	0.19440348...	0.65227874...	-0.4104140...	-0.3819021...	0.68040964...	0.78114356...
FDI	-0.1518416...	-0.1549000...	-0.1283387...	0.00201040...	0.19440348...	1	-0.2260377...	-0.2520879...	0.12949710...	-0.0397491...	-0.1756466...
NRE	0.90823990...	0.92078006...	0.82656865...	0.81066303...	0.65227874...	-0.2260377...	1	-0.1415255...	-0.6736607...	0.67671015...	0.90729389...
PRE	-0.1962408...	-0.1851057...	-0.2376457...	-0.3148688...	-0.4104140...	-0.2520879...	-0.1415255...	1	-0.1672870...	-0.4992074...	-0.2514874...
REC	-0.7359830...	-0.7567032...	-0.4249507...	-0.6081601...	-0.3819021...	0.12949710...	-0.6736607...	-0.1672870...	1	-0.5136394...	-0.6431868...
TEMP	0.74736286...	0.75346472...	0.60812259...	0.71992023...	0.68040964...	-0.0397491...	0.67671015...	-0.4992074...	-0.5136394...	1	0.74993223...
URB	0.98752081...	0.98163570...	0.87113645...	0.89804825...	0.78114356...	-0.1756466...	0.90729389...	-0.2514874...	-0.6431868...	0.74993223...	1

The correlation matrix below showed a stronger positive relationship between GDP and different CO2 emission indicators, implying that economic growth in Botswana has historically coincided with increased emissions. Nonetheless the relationship needs to be explored further in a casual manner

Table .4 Matriks Korelasi

	ADF		
Variables	**Level**	**1st Difference**	**Order of integration**
ln GDP	-1.806237	-7.403203***	I (1)
ln CO2T	-0.761308	-7.378039***	I (1)
ln CO2B	-0.934943	-9.445533***	I (1)
ln CO2E	-6.824124***	-5.843397***	I (0)
ln CO2I	-4.918717***	-6.685809***	I (0)
ln FDI	-7.851706***	-7.206088***	I (0)
ln NRE	-1.223230	-6.759844***	I (1)
ln PRE	-5.342404***	-12.07890***	I (0)
ln REC	-2.386374	-7.419076***	I (1)
ln TEM	-5.427482***	-8.272093***	I (0)
ln URB	-2.654896	-4.161144***	I (1)

The stationery tests show that most of the variables were integrated of order one, while other few variables where at level. This mix confirms the use of the ARDL bounds testing approach, which confirmed the existence of a long-term relationship between variables.

Granger causality tests shows that GDP granger causes carbon dioxide emissions and temperature anomalies indicating that economic activities are causing environmental changes .At the same time ,emissions and temperature were found to granger cause GDP ,suggesting a bidirectional causality and showing the existing interdependence between economic growth and environmentally sustainability .Renewable energy consumption was found to be influenced by GDP rather than the reverse ,assuming that energy policy shifts may be reactive than proactive

Table 5. Stationary test

ARDL Error Correction Regression
Dependent Variable: D(GDP)
Selected Model: ARDL(3, 3, 3, 3, 2, 2, 3, 3, 3, 1, 2)
Case 2: Restricted Constant and No Trend
Date: 03/17/25 Time: 06:59
Sample: 1974 2023
Included observations: 47

ECM Regression
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(GDP(-1))	0.244941	0.036681	6.677660	0.0002
D(GDP(-2))	0.191603	0.033293	5.755118	0.0004
D(C02T)	-0.034954	0.032538	-1.074252	0.3140
D(C02T(-1))	-0.561723	0.035544	-15.80358	0.0000
D(C02T(-2))	-0.320376	0.032789	-9.770845	0.0000
D(CO2B)	-0.220731	0.009571	-23.06349	0.0000
D(CO2B(-1))	0.032574	0.007950	4.097374	0.0035
D(CO2B(-2))	-0.024277	0.007489	-3.241818	0.0118
D(CO2E)	0.037602	0.010577	3.555088	0.0075
D(CO2E(-1))	0.100055	0.009314	10.74264	0.0000
D(CO2E(-2))	0.050663	0.008056	6.288843	0.0002
D(CO2I)	0.180046	0.011858	15.18331	0.0000
D(CO2I(-1))	-0.116103	0.009781	-11.86997	0.0000
D(FDI)	0.036050	0.001728	20.86133	0.0000
D(FDI(-1))	-0.017460	0.001727	-10.10874	0.0000
D(NRE)	0.157213	0.054006	2.911017	0.0196
D(NRE(-1))	-0.269729	0.047361	-5.695224	0.0005
D(NRE(-2))	0.529894	0.049423	10.72158	0.0000
D(PRE)	0.175965	0.010311	17.06555	0.0000
D(PRE(-1))	-0.349044	0.015544	-22.45536	0.0000
D(PRE(-2))	-0.150153	0.011151	-13.46491	0.0000
D(REC)	-0.302053	0.035671	-8.467690	0.0000
D(REC(-1))	-0.301782	0.033191	-9.092166	0.0000
D(REC(-2))	0.201613	0.035976	5.604176	0.0005
D(TEMP)	-0.283890	0.085046	-3.338076	0.0103
D(URB)	2.674855	0.139742	19.14133	0.0000
D(URB(-1))	-2.100561	0.144260	-14.56098	0.0000
CointEq(-1)*	-1.135596	0.041073	-27.64802	0.0000

R-squared	0.993453	Mean dependent var	0.058140
Adjusted R-squared	0.984149	S.D. dependent var	0.057465
S.E. of regression	0.007235	Akaike info criterion	-6.734036
Sum squared resid	0.000995	Schwarz criterion	-5.631821
Log likelihood	186.2499	Hannan-Quinn criter.	-6.319265
Durbin-Watson stat	3.252358		

The Error Correction Model (ECM) indicated a significant and a high negative coefficient, showing a strong tendency for GDP to return to its long-run equilibrium path affecting short-term shocks. This finding reinforces the robustness of the identified long-term relationships.

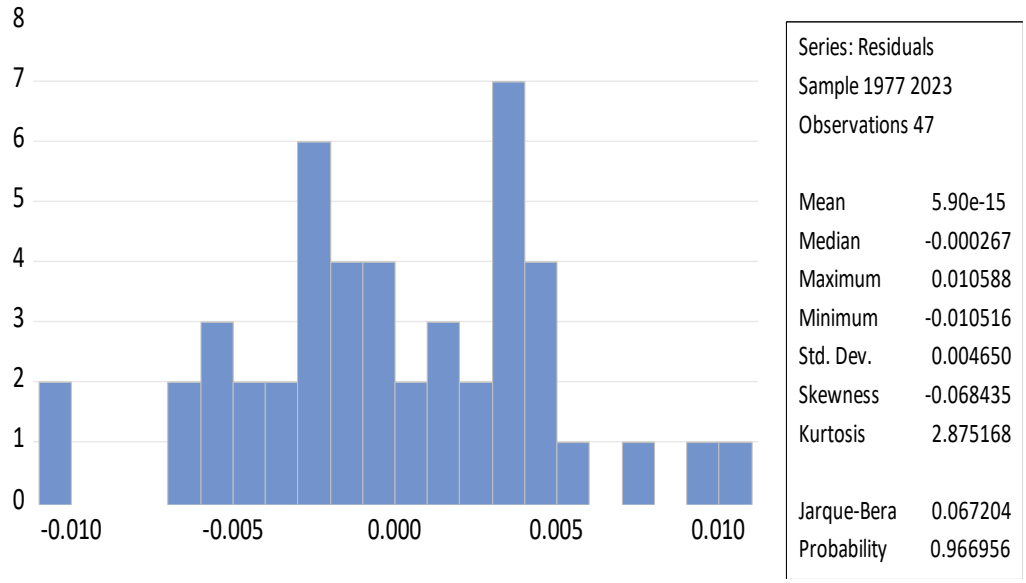

Image .1 The Error Correction Model (ECM)

Table. 6 Diagnostic Test

Breusch-Godfrey Serial Correlation LM Test:
Null hypothesis: No serial correlation at up to 3 lags

F-statistic	18.81972	Prob. F(3,5)	0.0037
Obs*R-squared	43.17632	Prob. Chi-Square(3)	0.0000

Heteroskedasticity Test: Breusch-Pagan-Godfrey
Null hypothesis: Homoskedasticity

F-statistic	0.807786	Prob. F(38,8)	0.6957
Obs*R-squared	37.28320	Prob. Chi-Square(38)	0.5024
Scaled explained SS	1.012762	Prob. Chi-Square(38)	1.0000

The Diagnostic tests indicate that while the model test is generally well specified and homoskedastic, it does suffer from serial correlation which would affect the precision of some co-efficient

CONCLUSION AND RECOMMENDATIONS

Conclusion

The study provides strong evidence that climate change and carbon emissions negatively impact Botswana's economic development in the short run and long run relationships. On renewable energy currently contributes positively to GDP while renewable energy seems not yet impactful. Temperature increases, likely from climate change, also harm GDP, These insights call for strategic investments in cleaner energy, emission mitigation and climate adaptation for sustainable growth.

Recommendations

To mitigate these risks and promote economic development, Botswana should develop an integrated set of policy actions. First the government should fasten investment in renewable energy by expanding support for solar, wind and bio-energy projects, and encouraging public-private partnerships to scale on clean energy infrastructure. Also, it should implement emission reduction strategies such as carbon pricing and emissions caps, while aligning national regulations with global climate commitments. Climate adaptation policies must also be prioritized through investments in climate resilient agriculture, water management systems and infrastructure, supported by comprehensive risk assessment that inform national development planning.

The establishment of robust national data systems for monitoring climate, energy and economic linkages along with the promotion of local research, will enable evidence-based policy-making and ongoing evaluation of environmental impacts of economic growth.

This study underscores the urgent need for Botswana to transition towards a low carbon, climate resilient economy. A proactive integrated policy response will be essential to safeguarding economic stability and promoting sustainable development in the face of global climate challenges

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