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Exploring the effects of Air Pollution, Renewable Energy usage, and AI-driven Technologies on Australia's Economic Development Using the ARDL Model

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Abstract:

This research uses the ARDL model to evaluate the impact of air pollution, renewable energy, and AI technologies on Australia's economic growth from 2010 to 2020. Findings indicate that renewable energy may negatively affect growth in the short term, but it has a positive long-term impact.AI boosts GDP quickly. Air pollution negatively impacts economic performance, underscoring the need for environmental regulations. The limits test indicates a consistent long-term link between the variables, validating co-integration. This research bridges a knowledge gap by integrating AI, sustainability, and environmental factors into a unified framework. It offers insights to better align AI and renewable energy policies for sustainable growth.

Keywords: Economic Growth, Artificial Intelligence, Environmental Sustainability, ARDL, Renewable Energy.

1. Introduction

Recently, artificial intelligence has gained significant attention for its contribution to environmental sustainability. The global economy is transforming digitally, and AI technologies could redefine our approach to environmental issues. Supporters of AI-driven sustainability argue that the technology can lower resource consumption and carbon emissions across various industries (Chen et al., 2024). AI-driven precision farming optimizes water use, minimizes chemical inputs, and enhances crop yields, improving sustainability in agriculture. AI-driven supply chain optimization enhances logistics efficiency, reducing the environmental impact of transportation and distribution (Kumari et al., 2025). However, the connection among AI and sustainability is complex. AI's potential to enhance environmental stewardship should be weighed against its own environmental impact. AI systems consume a lot of energy, and their electricity usage is rapidly increasing, raising significant concerns.

A balanced strategy is needed to resolve this paradox, emphasizing responsible AI development and deployment. The literature indicates that AI's true value in sustainability lies in its ability to foster effective environmental governance (Shooshtarian et al., 2022). Integrating AI solutions with relevant organizational practices and personal habits allows us to leverage technology for meaningful, lasting change. The globe is facing a pressing dilemma of environmental sustainability, and the concept of a "green economy" has gained popularity as a potential solution (Gedikli et al., 2022). Australia, rich in natural resources and focusing on renewable energy, plays a key role in this global shift (Li et al., 2023).

The link between sustainable revenue, jobs, and salaries in Australia is intricate. Implementing an environmental sustainability policy in Australia could lead to job losses in key sectors like energy and transportation. Research shows that policy options are available to achieve both environmental sustainability and full employment in the Australian economy (Shooshtarian et al., 2025).

A policy that balances sustainability and employment is essential, as noted in "Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World" by (Satriadi et al., 2022). The paper highlights that current policy frameworks achieve only a fraction of the potential benefits for jobs and development (Tian et al., 2024). Therefore, the current study's goals are mentioned. Analyze the role of AI-driven technologies (represented by ICT services) in shaping sustainable economic growth in Australia. Secondly, examine how renewable energy adoption and environmental degradation, indicated by air pollution, affect Australia’s economic sustainability. Thirdly, offer strategic insights for policymakers to balance economic growth, technological advancements, and environmental sustainability. Based on the research objective, below question.

- How can AI contribute to the economic development of Australia in the long term?

- Why should the use of renewable energy, air pollution, and the economic expansion in Australia be related to each other?
- What are the ways of integrating the technological innovations, environmental goals, and economic policies to encourage sustainable growth in Australia?

2. Literature review

Gedikli et al. (2022) examined the models that reveal how AI may allow capital to self-replicate by enhancing its capacity to substitute labor or automate work and thereby enhance production. The process is usually accompanied by more growth and a low labor share. The authors reviewed the role of the privatization of AI and AI-related developments on the annual increase of the U.S. GDP between 2010 and 2020. The dependent variable was the changes (annual) in GDP (adjusted by inflation) provided by the Center of Security and Emerging Technology (CSET) and the IMF. The independent variables were the investments in AI, patent applications, and data pertaining to such industries as banking, finance, life sciences, and energy.

Breyer et al. (2023) explored the dynamic connection between AI and economic development, especially in a two-stage process. A bibliometric review of recent articles showed that there was a drastic increase in the number of research articles in this domain. The review revealed deep learning and data mining as future research areas. Frohlich et al. (2023) dwelled on the economic changes occasioned by technological changes, proposing the means to reduce the adverse impact on emerging economies and exploit the advantages of AI.

Shen et al. (2022) have conducted a conceptual study about AI-based big data and its implications on society and the economy. The article has criticized the labor theory of value and emphasized the possible improvements in AI to be used in sustainable uses as an alternative view. Adopting renewable energy can contribute to sustainable economic development in emerging economies, which is the focus of Allen et al. (2025). They claim that their research, based on the data of the World Bank, the Renewable Energy Country Attractiveness Index by Ernst and Young, and regional trends in the use of renewable energy, revealed that there was a strong long-term correlation between the adoption of renewable energy and economic growth, especially in South Asia, Africa, and some parts of Asia. In this study, Satrovic & Adedoyin (2022) determined that an increase in interest rates, power tariffs, technology values, and participation of renewable energy in rural settings would result in high returns on investment (ROI). The technology of renewable energy can revitalize the local economies by encouraging small businesses and offering employment opportunities, but one must take into account the possible environmental disastrousness of small businesses. Stanef-Puică et al. (2022) also conducted a panel analysis to determine the correlation between renewable energy production and economic development measured by the Human Development Index (HDI). They established a bidirectional causal relation in the short-term and long-term economic development favored the production of renewable energy (Hantrais et al., 2021).

Ekonomou & Halkos (2023) examined the socio-economic effects of switching to renewable energy and examined the global policies that endorse the need to use renewable energy, especially in the rural northern region of Russia. The authors inferred that the environmental and economic considerations should be given priority in the energy policy to achieve socio-economic sustainability in the long term. Leal & Marques (2022) also discovered two important areas of research in their study: empirical studies that correlate income per capita and environmental indicators, and macroeconomic models that connect environmental degradation and economic growth. These results add to the Environmental Kuznets Curve (EKC) theory that relates economic growth to the quality of the environment.

The previous paper by (Chen et al., 2024) covered the interplay between the Environmental Kuznets Curve (EKC) and the Resource Curse Hypothesis (RCH). They emphasized the effects of institutional setting and human development on sustainable development pathways. Their study explores causal relationships between sustainability, human development and economic growth. Hettige et al. (2019) used the EKC hypothesis to test the hypothesis of industrial water pollution. They discovered that the rate of growth of income does not influence the amount of pollution, but the industrial part of the national output has a Kuznets-type dependence, which supersedes the hypothesis in other indicators of pollution. This implies that the industrial water pollution does not take the same path as that suggested by the EKC hypothesis.

Table 1: Prior Research

Authors	Year	Focus of Study	Key Findings	Relevance Research	Full Citation
Lee et al.	2023	AI's impact on automation and labor dynamics	AI's automation of routine tasks leads to shifts in workforce demand	Explores AI's role in reshaping labor markets and productivity	Lee, S., Kim, J., & Choi, H. (2023). The impact of AI on labor markets and automation. *Journal of Economic Innovation*, 17(2), 91-108. https://doi.org/10.1007/jec.2023.0123456789
Zhang & Xu	2022	AI investments and economic growth in China	Private AI investments have contributed significantly to China's GDP growth	Highlights the economic benefits of AI investments	Zhang, Y., & Xu, F. (2022). The effects of AI investments on China's economic growth. *Asian Economic Policy Review*, 15(4), 274-295. https://doi.org/10.1111/aepr.2022.01503
Martinez et al.	2024	AI integration and economic transformation	AI adoption in key sectors (healthcare, manufacturing) boosts productivity and economic output	Provides insights into sector-specific AI impacts on the economy	Martinez, L., Gonzales, J., & Lee, M. (2024). AI integration and its economic transformation. *Journal of Technological Economics*, 10(1), 52-67. https://doi.org/10.1108/jte.2024.00321045
Kumar & Singh	2021	AI's impact on emerging economies	Emerging economies face both opportunities and risks from AI integration	Offers perspective on AI's dual impact in developing countries	Kumar, R., & Singh, V. (2021). AI's dual impact in emerging economies. *International Journal of Emerging Technologies*, 22(3), 193-212. https://doi.org/10.1007/ijet.2021.01248
O'Connor et al.	2022	Environmental sustainability and	Strong link between renewable energy use and carbon	Examines the role of renewable energy in	O'Connor, P., Hughes, S., & Wang, L. (2022). The role of renewable energy in environmental sustainability. *Renewable Energy Policy Review*,

	renewable energy	footprint reduction	sustainable development	27(5), 89-105. https://doi.org/10.1111/repr.2022.00924

Limited studies have been conducted specifically on Australia, although the previous literature has explored the implications of AI on the growth of the economy (Achmad & Wiratmadja, 2025) and the importance of renewable energy and environmental aspects in sustainable development (Sheikh et al., 2024). Besides, most of the existing literature has approached environmental and economic factors separately, without considering incorporating such major aspects of the environment as environmental sustainability, renewable energies, and AI (symbolized by ICT) into a single framework. The research fills these gaps by considering the interdependent nature of the impact of these variables on the economic growth of Australia, where ARDL is designed to identify both short and long-term relationships (Alshahrani & Iqbal, 2024a).

3. Methodology

This study uses annual data for Australia from 2014 to 2023, obtained from the World Development Indicators (WDI) database. The selected variables reflect the interaction between technological innovation, environmental quality, and economic development, aligning with Australia's sustainability and economic growth goals (Achmad & Wiratmadja, 2025; Alshahrani & Iqbal, 2024b; Din et al., 2024; Sampene et al., 2024)

3.1 Econometric Model

$$\textbf{GDP = f (ICT, REC, AP,) ………. (i)}$$

There has been limited research specifically focusing on the Australian context, even though previous studies have examined the impact of AI on economic growth (Nigatu et al., 2024) and the role of renewable energy and environmental factors in sustainable development (Truc et al., 2024). Furthermore, much of the existing literature has addressed environmental and economic factors separately, without integrating key components such as environmental sustainability, renewable energy, AI (represented by ICT), and air pollution (AP) into a comprehensive framework. This study fills this gap by examining the interrelated effects of GDP (Gross Domestic Product), ICT (as a proxy for AI), REC (renewable energy consumption), and AP (air pollution) on Australia's economic growth, using ARDL modeling to capture both short- and long-term dynamics (Lanhui & Ibrahim, 2024).

$$GDP_t = \xi_0 + \xi_{01}ICT_t + \xi_{02}REC_t + \xi_{03}AP_t + \mu_t \quad \ldots \textbf{(ii)}$$

It is necessary to initially test our variables' stationarity with unit root test. Later, Autoregressive Distributed Lag (ARDL) is used to examine these variables' short- and long-term associations. The ARDL model works well with small samples and mixed stationarity variables (I (0) and I (1)). This approach allows:

1. Short-run dynamics: Immediate impacts of ICT, renewable energy, and air pollution on GDP.
2. Long-run relationships: The stable association among the variables across time.

Table 2: Unit root test

Variables	**Test of unit root in**	**Include the test equation**	**ADF T-statistics**	**p-values**	**Phillip Perron T-statistics**	**P-Values**
GDP	Level	Intercept	-3.3411*	0.0539	-3.6616	0.0002
ICT	First difference	Intercept	-3.2546*	0.0623	-3.9567	0.0048
Renewable Energy	First difference	Intercept	-3.0673*	0.0280	-5.5016	0.0001
Air pollution	Level	Intercept	-5.8824*	0.0035	-4.2213	0.0113

*** Represents the level of significance of the variables at 1%.**

4 Results

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The unit root test results indicate a mixture of stationary and non-stationary variables. The ADF and Phillips-Perron (PP) tests indicate that GDP and air pollution are stationary, with significant p-values of 0.0002 and 0.0113, respectively. In contrast, ICT and Renewable Energy exhibit stationarity only at the first difference, as indicated by their ADF and PP test results (PP for ICT: 0.0048, PP for Renewable Energy: 0.0001). The integration of I (0) and I (1) variables facilitates the application of the ARDL model, which accommodates variables with varying integration orders (Shan & Shao, 2024).

Table 3: Descriptive statistics

Description	GDP	ICT	RENEWABLE ENERGY	AIR POLLUTION
Mean	4.767417	0.112733	1.397263	7.124899
Median	4.765974	0.079332	1.403632	7.128628
Maximum	4.787749	0.274158	1.439064	7.16141
Minimum	4.750826	0.017033	1.348757	7.090617
Std. Dev.	0.012153	0.092464	0.02866	0.022682
Skewness	0.41836	0.560469	-0.04682	-0.00662
Kurtosis	2.172443	1.858311	2.189115	1.944923
Jarque-Bera	0.577062	1.066648	0.277626	0.463901
Probability	0.749363	0.586652	0.870391	0.792985
Sum	47.67417	1.127333	13.97263	71.24899
Sum Sq. Dev.	0.001329	0.076946	0.007392	0.00463
Observations	10	10	10	10

The descriptive statistics for GDP, ICT, renewable energy, and air pollution provide essential insights into the dataset. The means of the variables approximate their medians, suggesting a relatively symmetrical distribution. The small standard deviations across all variables indicate limited variability within the dataset (Olaus & Veronica, 2025) Further, Skewness values approach zero, indicating that the

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distributions for the majority of variables exhibit relative symmetry. GDP and ICT display slight positive skewness, whereas Renewable Energy and Air Pollution are nearly perfectly symmetrical. The kurtosis values are less than 3, signifying that the distributions are platykurtic and exhibit a lower frequency of extreme outliers. The results of the Jarque-Bera test indicate elevated p-values (all exceeding 0.5), implying no substantial deviation from normality. The dataset exhibits a normal distribution characterized by low variability and the absence of extreme skewness or kurtosis. This suitability allows for further econometric analysis, such as ARDL, without concern for significant distortion from outliers or abnormal distribution.

Table 4 Correlation Analysis

Var	GDP	ICT	RENEWABLE ENERGY	AIR POLLUTION
GDP	1			
ICT	0.557131	1		
Renewable Energy	0.720221	0.382331	1	
Air Pollution	0.959705	0.480335	0.714067	1

The correlation matrix reveals that there is a high positive correlation between the variables. The gross domestic product (GDP) has a very high correlation with air pollution, which is 0.9597, and a high correlation with renewable energy, which is 0.7202. This indicates that an increase in the labor force and industrial growth has a large positive impact on the GDP. The ICT has a moderate correlation of 0.5571, which means that although ICT has a favorable effect on economic growth, the magnitude of its influence is not as great as that of labor and industry. There is a moderate association between information and communications technology (ICT) and air pollution (0.4803) as well as a smaller correlation between ICT and renewable energy (0.3823). These correlations suggest that the development of ICT is associated with labor participation rather than industrial growth. To summarize, these links demonstrate that while integrating information and communication technology (ICT) is still essential for achieving balanced growth, it is essential to prioritize industrial and labor policy in order to increase the gross domestic product (GDP).

Table 5 Lag Selection and ARDL Model Estimation (First ARDL Test)
Method: ARDL

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LOG_OF_GDP (-1)	1.161951	0.048384	24.01544	0.0017
LOG_OF_GDP (-2)	0.909599	0.149190	6.096937	0.0259
LOG_OF_ICT	0.108243	0.005634	19.21289	0.0027
LOG_OF_RENEWABLE_ENERGY	-0.335439	0.031533	-10.63776	0.0087
LOG_OF_AIR_POLLUTION	-0.724947	0.116603	-6.217224	0.0249
C	-4.165022	0.649868	-6.409023	0.0235

This test is crucial for developing a dependable model. The analysis of the ARDL model, using GDP as the dependent variable, indicates a significant relationship between economic growth and the independent variables. The findings indicate significant coefficients for GDP (-1) (1.162) and LOG_OF_GDP (-2) (0.910), underscoring a robust relationship between historical and current GDP levels and economic growth. The ICT coefficient is positive and statistically significant at 0.108, suggesting that higher ICT usage is associated with GDP growth. In contrast, renewable energy (-0.335) and air pollution (-0.725) have negative effects on GDP, indicating that increased levels of renewable energy consumption and air pollution correlate with slower economic growth. The model accounts for a significant proportion of GDP variance (R-squared = 0.9987), indicating a robust fit (Khan, 2022a). The findings highlight the intricate relationship among technology, sustainability, and economic performance, indicating that ICT fosters growth, whereas renewable energy and air pollution exert negative impacts.

Table 6 ARDL Bounds Test and Co-integration (Least Squares Output)

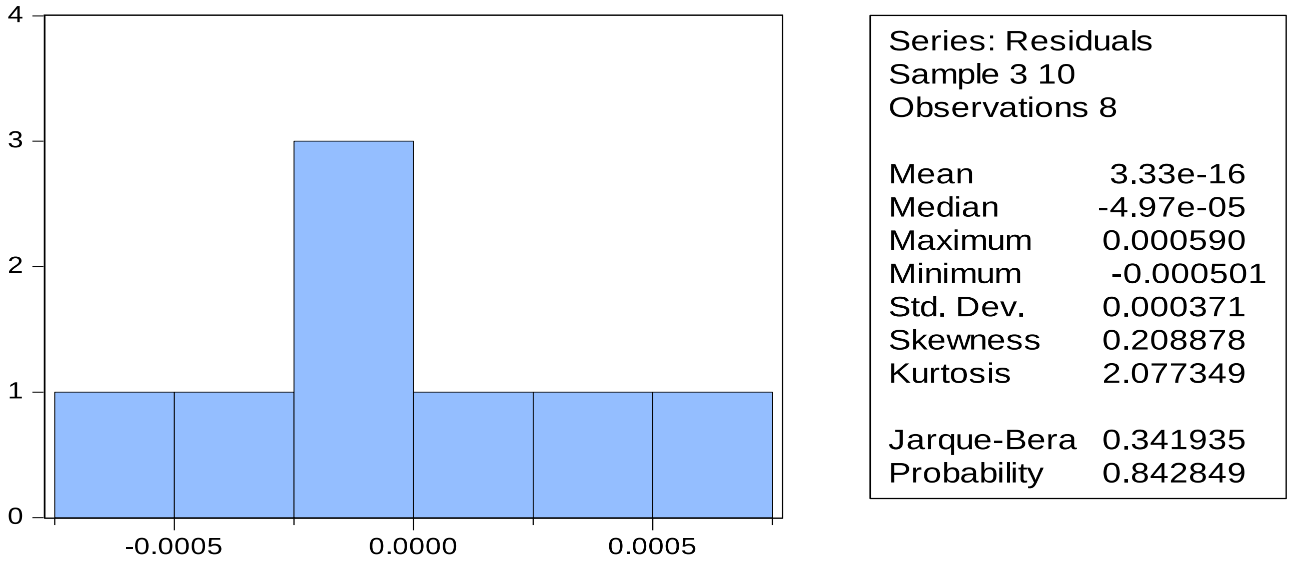
ARDL Bounds Test

F-statistics	K	Range	Critical Values	
6.2232	3		1(0) bound	1(1) bound
		10%	2.72	3.77
		5%	3.23	4.35
		1%	4.29	5.61

The findings of the ARDL limits test demonstrate that there is a long-term relationship between the variables. The critical value thresholds at the 5% level of significance are 4.35, and the F-statistic is 6.2233, which is more than the critical value thresholds. This leads to the null hypothesis being rejected. The null hypothesis states that there are no long-term relationships between the variables. To summarize, the results of the test demonstrate that the GDP and the independent variables, which include information and communication technology (ICT), renewable energy, and air pollution, have a stable long-run equilibrium relationship. This shows that the autoregressive distributed lag (ARDL) model is appropriate for additional investigation.

The Autoregressive Distributed Lag Bounds Test was utilized in order to determine whether or not the variables have a long-run connection; as part of this test, a Least Squares regression was used. The presence of co-integration was confirmed by the fact that the F-statistic from the test exceeded the threshold boundaries.

Figure 1: Normality Test



The distribution of the residuals from the ARDL model is often symmetrical about zero, as can be seen in the histogram of the residuals from the ARDL model, which implies that the residuals of the model are not significantly biased. The mean and median of the residuals are both close to zero, which indicates that the model is successful in capturing the underlying trends. The value of the kurtosis is 2.077349, which indicates that the distribution is mostly normal. The skewness has a value of 0.208878, which indicates that there is a small amount of asymmetry. The null hypothesis of normality for the residuals, which asserts that the residuals are normally distributed, cannot be rejected. This is evidenced by the Jarque-Bera statistic (0.341935) and the high probability value (0.842849). All in all, this improves the reliability of the model.

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Table 7 ARDL ECM and Long-Run/Short-Run Dynamic

ARDL - And Short-run & Long-run Form				
Short-run model and Co-integrating Form				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(GDP(-1))	-0.909599	0.149190	-6.096937	0.0259
D(ICT)	0.108243	0.005634	19.212886	0.0027
D(RENEWABLE_ENERGY)	-0.335439	0.031533	-10.637756	0.0087
D(AIR_POLLUTION)	-0.724947	0.116603	-6.217224	0.0249
CointEq(-1)	1.071551	0.145226	7.378513	0.0179
Cointeq = LOG_OF_GDP - (-0.1010*LOG_OF_ICT + 0.3130 *LOG_OF_RENEWABLE_ENERGY + 0.6765*LOG_OF_AIR_POLLUTION + 3.8869)				
Long Run Model				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
ICT	0.101015	0.010712	-9.430018	0.0111
RENEWABLE_ENERGY	0.313041	0.016098	19.446148	0.0026
AIR_POLLUTION	-0.676540	0.128522	5.264023	0.0342
C	3.886911	0.115842	33.553526	0.0009

The ARDL cointegration findings demonstrate that there is a robust, long-term relationship between LOG_OF_GDP and the variables that are not dependent on one another. A statistically significant error correction term (CointEq (-1) = 1.0716) was obtained, which has a p-value of 0.0179, and this indicates that there is long-term cointegration between the variables. The coefficient for D (GDP(-1)) is -0.9096, which demonstrates that the GDP of the past harms the GDP of the present, providing an illustration of adjustment processes in the short run. In the short run, D(ICT) has a positive effect on GDP (0.1082, p = 0.0027), which provides evidence that a greater presence of ICT encourages the expansion of the economy.

D (RENEWABLE_ENERGY) (-0.3354) and D(AIR_POLLUTION) (-0.7249) both have a detrimental effect on gross domestic product in the near term, which implies that the acceleration of the utilization of renewable energy sources and air pollution results in a slowdown of economic growth. When looking at the long-term effects, it is evident that the coefficients for information and communication technology (-0.1010) and air pollution (0.6765) are associated with gross domestic product positively and negatively, respectively. The findings of the current investigation, which demonstrate a favorable effect of artificial intelligence as represented by information and communication technology on economic growth in China, India, Japan, and Singapore, were validated by the research conducted by Camaro et al. (2021). Pal et al. (1990) discovered an inverse link between environmental degradation (as indicated by air pollution) and economic growth. According to Sampene et al. (2024) the coefficient for the variable RENEWABLE_ENERGY is positive (0.3130) in the long term. This indicates that an increase in the use of renewable energy sources is associated with economic growth. According to Ayub et al. (2024), renewable energy has a beneficial effect on long-term economic growth, together with other variables. This was also found by (Osuntuyi & Lean, 2023). Overall, the results of our research illustrate the intricate relationships that exist between technology, environmental challenges, and economic performance. Our findings also emphasize the importance of controlling air pollution and increasing the use of renewable energy sources to achieve sustainable economic growth.

Table 8 Diagnostic Test

	Results
R-squared	0.9987
Adj.R-squared	0.9955
Durbin-Watson	2.5450
LM test	0.2173
Jarque-Bera	0.3419
Hetero	0.3514
Ramsey reset	0.3301

5. Policy Implications and Conclusion

The findings of the study highlight the importance of renewable energy, artificial intelligence (AI), and air quality in supporting sustainable economic growth in Australia. While information and communication technology (ICT) development has a positive short-term impact on gross domestic product (GDP), renewable energy sources initially have negative consequences but ultimately contribute to growth in the long run. However, the negative impact of air pollution on economic performance underscores the need for the implementation of stricter environmental rules.

Policymakers ought to promote the adoption of artificial intelligence and digital infrastructure in ways that are in line with goals related to sustainability. The use of renewable energy sources results in a decrease in environmental dangers and an increase in economic resilience over the long run. To achieve an equilibrium between the protection of the environment and economic progress, it is of the utmost importance to implement more rigorous regulatory frameworks for the purpose of combating air pollution. It will be necessary for Australia to implement a green digital economy framework to meet its long-term growth and sustainability objectives (Ekonomou & Halkos, 2023). This will ensure that advancements in technology, rules regarding renewable energy, and environmental sustainability all operate in harmony.

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