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Comparing GDP Growth Rates between Countries with High and Low Renewable Energy Usage Based on Neural Networks

Abdelsamiea Tahsin Abdelsamiea[1], Mohamed F. Abd El-Aal[2]*

[1]Department of Economics, College of Business, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia, [2]Department of Economics, Faculty of Commerce, Arish University, North Sinai, Egypt. *Email: mohammed.fawzy@comm.aru.edu.eg

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ABSTRACT

This paper utilizes a neural network algorithm to examine the impact of renewable energy consumption on economic growth in countries with both high and low usage rates. The findings indicate a weak inverse relationship between economic growth and renewable energy consumption. In contrast, there is a strong direct relationship between economic growth and the expansion of the industrial and manufacturing sectors. For countries that do not rely heavily on renewable energy, the results are consistent with those of high-consumption countries: renewable energy consumption exhibits a weak inverse relationship with economic growth. Simultaneously, the industrial and manufacturing sectors remain vital to economic growth. The study reveals that the industrial sector is the top contributor to economic growth in all the studied countries, representing 57.2% of Iceland's economy, 52.8% of Russia's, 49.3% of Norway's, and 44.6% of South Africa's. The manufacturing sector ranks next, contributing 36.6% in South Africa, 32.6% in Norway, 30.6% in Russia, and 20.7% in Iceland. In contrast, renewable energy consumption is the least significant contributor, accounting for 22.1% in Iceland, 18.7% in South Africa, 18.1% in Norway, and 16.8% in Russia. Overall, the results suggest that renewable energy consumption has no significant impact on economic growth in the examined countries, regardless of their reliance on renewable sources.

Keywords: Renewable Energy, GDP Growth, Industrial Value Added, Neural Networks.
JEL Classifications: C63, C80, C81, C87

1. INTRODUCTION

The relationship between renewable energy usage and GDP growth has emerged as a key study topic in sustainable development and economic performance. As concerns about climate change grow and the world transitions to greener energy sources, policymakers, economists, and environmentalists must understand the impact of renewable energy on economic growth. This study examines the relationship between renewable energy usage and GDP growth by comparing countries with high renewable energy consumption to those that rely less heavily on these sources, utilizing machine learning techniques for data processing and analysis.

As measured by GDP, economic growth is influenced by several factors, including energy consumption, industrial development, and manufacturing activities. Energy is the foundation for industrial and economic growth, as it supplies the essential inputs needed for manufacturing processes, transportation, and infrastructure development. However, the kind of energy utilized—whether renewable or nonrenewable—significantly affects economic results. Renewable energy sources, such as hydropower, solar, wind, and geothermal, are environmentally friendly and sustainable, ensuring long-term energy security. In contrast, non-renewable energy sources, such as coal, oil, and natural gas, are often associated with higher greenhouse gas emissions, resource depletion, and market instability (Sadorsky, 2009). Bhattacharya et al. (2016), proved that Renewable energy consumption has a positive and significant impact on economic growth in the top 38 countries, driving long-term growth through technological advancement, investment, and job creation.

This study examines two categories of countries: those with high renewable energy usage (Iceland and Norway) and those with low renewable energy usage (Russia and South Africa). Iceland leads the world in renewable energy consumption, generating nearly all its electricity from geothermal and hydroelectric sources (National Energy Authority of Iceland, 2023). Similarly, hydropower accounts for more than 98% of Norway's electricity output, making it one of the most reliant countries on renewable energy (Statistics Norway, 2023). These countries demonstrate how renewable energy can dominate a country's energy mix while driving economic growth.

Conversely, Russia and South Africa primarily rely on non-renewable energy sources. Russia's energy sector heavily depends on natural gas and oil, with renewable energy playing a minimal role in its overall energy mix (International Energy Agency, 2023). Similarly, South Africa's energy infrastructure relies primarily on coal, which accounts for the majority of its electricity generation, with renewable energy contributing a small fraction (Department of Mineral Resources and Energy, South Africa, 2023). These nations exemplify traditional energy consumption models, which, while facilitating industrial growth, also raise concerns about sustainability and environmental issues.

This study examines the use of renewable energy as a portion of total energy consumption and its relation to growth rates in the industrial and manufacturing sectors. These factors are independent variables, while GDP growth is the dependent variable. By analyzing data with machine learning algorithms, the study aims to reveal complex patterns and relationships between the adoption of renewable energy and economic performance.

Deep learning, specifically neural networks, has evolved into a significant tool in economic analysis, offering enhanced capabilities for organizing vast amounts of information, identifying non-linear relationships, and making precise forecasts. These opposing views underscore the importance of empirical studies, particularly those involving machine learning, in enhancing our understanding of the long-term economic implications of renewable energy adoption. This study contributes to the existing discussion by comparing nations with high and low renewable energy utilization through the application of machine learning. This research addresses key challenges by utilizing algorithms to handle and analyze complex data. Does increasing reliance on renewable energy contribute to faster GDP growth? How do industrial and manufacturing growth affect this relationship? The findings offer valuable insights for countries seeking to balance economic progress with environmental sustainability.

2. LITERATURE REVIEW

Numerous research studies have examined the relationship between economic growth and the use of renewable energy, consistently demonstrating that it has a positive impact on GDP across various countries and industries.

Apergis and Payne (2010) examined OECD countries and identified a strong positive relationship between renewable energy usage and GDP growth. Similarly, Zafar et al. (2019) studied G7 countries. They found that adopting renewable energy spurs economic growth by lessening reliance on fossil fuels and fostering financial stability, especially in highly globalized markets. Sadorsky (2009) expanded this focus to emerging economies, demonstrating that renewable energy consumption has a positive impact on GDP per capita growth. This suggests that developing nations can gain advantages by diversifying their energy portfolios.

Dogan and Ozturk (2017) identified a reciprocal relationship between renewable energy usage and economic growth in Europe, suggesting a feedback loop in which economic growth boosts renewable energy demand, leading to further economic development. Paramati et al. (2017) argued that developed nations gain significant advantages from this dynamic due to their advanced infrastructure, technological capabilities, and supportive policy frameworks that facilitate the efficient adoption of renewable energy. Similarly, Uçaravcı and Akın (2023) examined Germany, France, and Turkey, revealing a one-way causality from GDP to renewable energy consumption in Germany and Turkey, with structural reforms crucial in influencing their energy dependence.

The effects of public policy and technological advancements on the rapid adoption of renewable energy have been extensively studied. A study by Carley et al. (2011) demonstrates that U.S. states that implement strong renewable energy mandates achieve better economic outcomes, highlighting how policies supporting renewable energy increase job creation and economic stability. Marques et al. (2010) investigated European countries and found that governmental support and technological advancements are crucial for enhancing energy efficiency and reducing costs. Lund (2007) evaluated the long-term benefits of transitioning to fully renewable energy systems. His research suggests that although this transition demands a considerable upfront investment, it ultimately leads to financial stability, decreased reliance on fossil fuels, and job creation within the renewable energy sector.

Several studies highlight the role of renewable energy in mitigating economic volatility. Lee and Chiu (2011) found that nations utilizing a higher proportion of renewable energy experience less GDP fluctuation in response to varying oil prices, thereby enhancing economic stability. Similarly, Zhang et al. (2023) examined emerging Asian economies, concluding that while renewable energy fosters long-term economic growth, dependence on non-renewable energy increases carbon emissions and economic unpredictability.

Renewable energy adoption is crucial for promoting economic growth in developing countries while addressing pressing social issues, such as poverty reduction and job creation. Akella et al. (2009) demonstrated that renewable energy initiatives in rural India significantly improved economic and social conditions, leading to increased electricity access and employment opportunities. Zafar et al. (2019) highlighted the potential for job creation through renewable energy in Pakistan, illustrating how green energy investments promote economic and social growth. Koçak and Şarkgüneşi (2017) evaluated wind energy projects in Turkey and found a significant influence on regional GDP and employment creation. Following a similar approach, Bento and

Moutinho (2016) found that investments in solar and wind energy led to economic reforms in Mediterranean countries.

Several studies have adopted a more expansive perspective by examining the effects of renewable energy on various economic contexts. Misbah et al. (2023) examined the impact of renewable energy on economic growth in both industrialized and developing nations, suggesting that governments must collaborate to maximize the benefits of renewable energy projects. Chhabra et al. (2024) investigated the impact of renewable energy in fostering green growth in emerging nations, concluding that while renewable energy promotes sustainable development, trade openness can impede green advancement. Like the prior study, Chen et al. (2022) proposed policies to enhance green energy and economic reform, highlighting the beneficial connection between renewable energy production and economic success.

Elbargathi and Al-Assaf (2024) analyzed global renewable energy adoption, concluding that developed nations experience significant economic benefits while developing countries require further support for sustainable growth. Spetan et al. (2024) also examined the role of renewable energy in economic development across various income levels, reaching similar conclusions. At the same time, Falana and Adebayo (2024) investigated financial development in BRICS and MINT countries, finding that renewable energy promotes economic growth in MINT nations while having an adverse impact on BRICS economies.

Ślusarczyk et al. (2022) found a significant correlation between renewable energy use and economic growth in Sweden and Poland, suggesting that adopting renewable energy contributes to improved economic stability. Boudiaf (2023) examined the role of renewable energy in environmental preservation in low-income countries, showing that while renewable energy reduces CO2 emissions, its direct economic impact on GDP remains uncertain. Similarly, Mohammadi et al. (2023) found that energy consumption has a significant impact on economic growth in both advanced and emerging economies, with renewable energy playing a crucial role in promoting economic stability.

This study distinguishes itself from previous research by employing deep learning techniques to examine the relationship between renewable energy usage and GDP growth. Previous studies used traditional econometric models. Machine learning, on the other hand, uncovers subtle, non-linear relationships that improve forecasting accuracy. Furthermore, examining countries with varying levels of renewable energy consumption offers more in-depth insights into how the adoption of renewable energy impacts economic growth.

3. DATA AND METHODOLOGY

3.1. Data

Data on the dependent variable, economic growth, and the independent variables, renewable energy consumption, industrial value added, and manufacturing value-added, were collected from the World Bank database for the countries studied: Iceland and Norway, as high renewable energy consumers, and Russia and South Africa, as low renewable energy consumers. The period covered varied from country to country due to data availability; for example, the period from 1996 to 2021 was covered in Iceland, the period from 1990 to 2021 was covered in both South Africa and Norway, and the period from 2003 to 2021 was covered in Russia. Tables 1 and 2 shows the statistical description of the data used.

Table 1: Data descriptive statistics for high renewable country consumption

Variables	Source of data	Mean	Mode	Median	Dispersion	Min	Max
Iceland							
GDP growth	World Bank	3.19	−7.66	4.31	1.22	−7.66	8.45
Renewable energy consumption (% of total final energy consumption)	World Bank	70.35	61.9	74.35	0.13	52.3	82.9
Industry value added (annual % growth)	World Bank	2.98	−16.75	4.04	1.76	−16.75	10.98
Manufacturing, value added (annual % growth)	World Bank	2.63	−7.17	2.87	1.5	−7.17	8.88
Norway							
GDP growth	World Bank	2.24	−1.94	2.26	0.72	−1.94	5.28
Renewable energy consumption (% of total final energy consumption)	World Bank	58.5	56	58.8	0.029	56	61.4
Industry value added (annual % growth)	World Bank	1.5	−4.23	1.29	1.81	−4.23	7.14
Manufacturing, value added (annual % growth)	World Bank	0.95	−7.43	1.73	3.19	−7.34	5.65

Source: Compiled by author

Table 2: Data descriptive statistics for low renewable country consumption

Variables	Source of data	Mean	Mode	Median	Dispersion	Min	Max
Russia							
GDP growth	World Bank	3.06	−7.79	4.02	1.31	−7.79	8.49
Renewable energy consumption (% of total final energy consumption)	World Bank	3.39	3.2	3.3	0.065	3.2	3.7
Industry value added (annual % growth)	World Bank	2.65	−10.41	2.8	1.65	−10.41	9.7
Manufacturing, value added (annual % growth)	World Bank	3.19	−14.6	4.38	1.67	−14.61	8.79
South Africa							
GDP growth	World Bank	2.06	−6.16	2.54	1.18	−6.16	5.6
Renewable energy consumption (% of total final enEnergy consumption)	World Bank	12.27	9.7	9.75	0.33	7.6	18.6
Industry value added (annual % growth)	World Bank	0.86	−12.2	0.95	4.1	−12.2	6.53
Manufacturing, value added (annual % growth)	World Bank	1.17	−12.13	1.45	3.78	−12.13	8.1

Source: Compiled by author

3.2. Methodology

Artificial neural networks attempt to mimic human mastering skills by modeling brain neurons using computational simulations. Neurons are nerve cells that form the cortical layer of the nervous system. The design and interactions of neurons in neural networks are described in feedforward and feedback (recurrent). A feedforward networks is a static networks composed of a collection of connected neurons representing a nonlinear data function. Information only moves from inputs to outputs. The neural networks are trained to minimize the loss function, which measures the difference between the model's input and the actual label. In deep learning, recurrent neural networks (RNNs) are helpful. These simulations illustrate how humans absorb knowledge and acquire new information (Abd El-Aal, 2024). We can examine the following equations to clarify how neural networks process data and derive results.

3.2.1. Neural networks input and layer calculations

- Inputs

Let $x_1, x_2., x_n$ denote the neural network's inputs, with n indicating the number of input features, as shown in Figure 1.

- First Layer Computation (Input to Hidden Layer)

Every hidden neuron in the first hidden layer receives a weighted sum of the inputs and a bias term. For the j^{th} hidden neuron Bishop (2006):

$$z_j = \sum_{i=1}^{n} w_{ij} \cdot x_i + b_j \quad (1)$$

Where:

- w_{ij} are the weights between the i^{th} input and the j^{th} hidden neuron.
- x_i represents the i^{th} input value.
- b_j represents the bias term for the j^{th} hidden neuron.
- z_j is the pre-activation value at the j^{th} hidden neuron.

The activation function is utilized on z_j to calculate the output for the hidden layer neurons.

- Common activation functions are:
  - Sigmoid Activation:

$$h_j = \frac{1}{1+e^{-z_j}} \quad (2)$$

Where h_j is the output from the hidden layer.

  - ReLU Activation:

$$h_j = \max(0, z_j) \quad (3)$$

- Output Layer Calculation (Hidden to Output Layer)

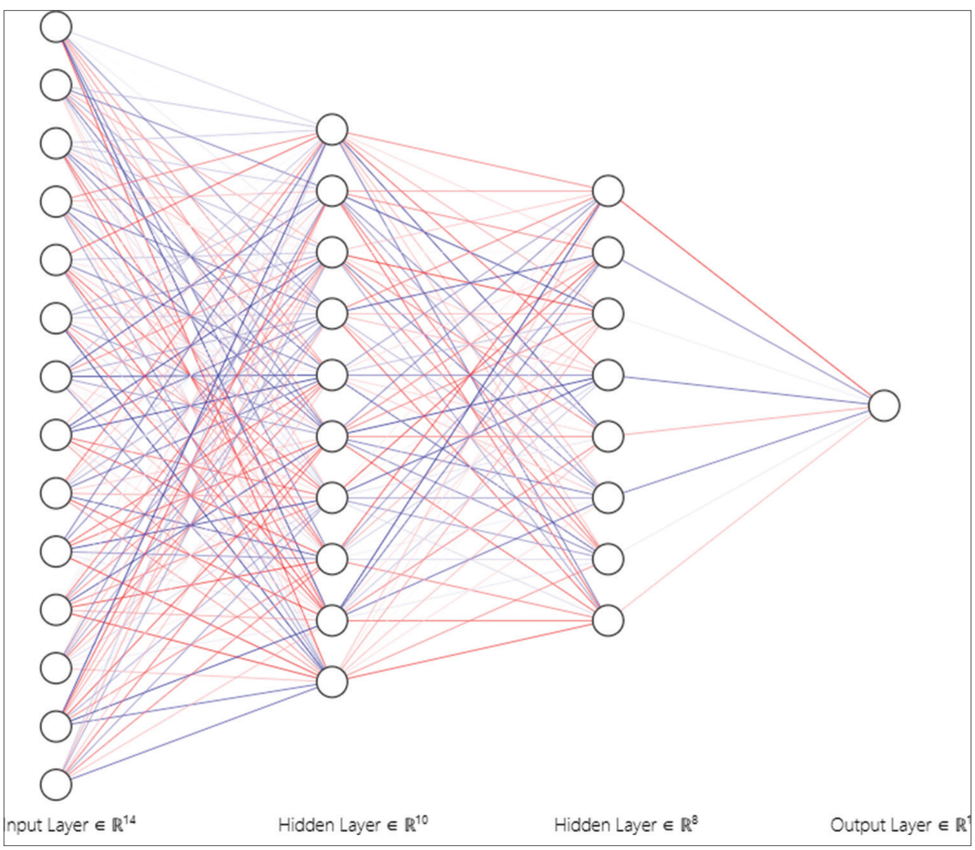
In the output layer, the networks calculate the final output (predicted values) using the following equation:

$$y = \sum_{j=1}^{m} w_j \cdot h_j + b \quad (4)$$

Where:

- w_j are the weights between the j^{th} hidden neuron and the output neuron.

Figure 1: Neural networks generator



- h_j represents the output from the hidden layer.
- b is the bias term in the output layer.

The output is then processed through an activation function (such as sigmoid or softmax) to obtain the predicted probabilities for classification tasks.

- Sigmoid Activation for Binary Classification:

$$\hat{y} = \frac{1}{1+e^{-y}} \tag{5}$$

Where $\hat{y}$ is the probability prediction for a binary class output.

- Softmax Activation for Multi-class Classification:

$$\hat{y}_i = \frac{e^{y_i}}{\sum_{k=1}^{C} e^{y_k}} \, for\, i = 1,2,\ldots,C = \frac{1}{1+e^{-y}} \tag{6}$$

Where C is the number of classes.

3.2.2. Loss function calculation

The loss function quantifies the discrepancy between the predicted values and the actual ground-truth values. Different loss functions are employed for various tasks, including regression and classification.

- Mean Squared Error (MSE) for Regression Tasks

$$L = \frac{1}{n}\sum_{i=1}^{n}\left(y_{true} - y_{predicted}\right)^2 \tag{7}$$

Where:

- y_{true} is the actual target value.
- $y_{predicted}$ is the predicted value.

- Cross-Entropy Loss in Classification Tasks:

$$L = -\sum_{i=1}^{C} y_i \cdot \log\left(p_i\right) \tag{8}$$

Where:

- Is the ground-truth one-hot encoded vector?
- p_i is the predicted probability for class I, as determined from the softmax output.
- C is the number of classes.

3.2.3. Optimization: Gradient descent

The neural network weights are adjusted using an optimization technique, most commonly known as Gradient Descent. This process aims to minimize the loss function by iteratively updating the weights Hecht-Nielsen (1992).

The gradient of the loss function to each weight w_i. The computation occurs, and the weight is adjusted in the opposite direction of the gradient to minimize the loss:

- Weight Update Equation using Gradient Descent

$$w_i = w_i - \eta \frac{\partial L}{\partial w_i} \tag{9}$$

Where:

- w_i is the weight being updated.
- η is the learning rate, a hyperparameter controlling the step size.
- $\frac{\partial L}{\partial w_i}$ is the partial derivative of the loss function concerning the weight w_i.

This step is repeated iteratively for several epochs (or iterations), gradually minimizing the loss function and thereby improving the model's performance.

- Backpropagation:

Backpropagation computes the gradient of the loss function for each weight involving:

1. Forward Pass: Computing the network's output based on the current weights and inputs
2. Backward Pass: Calculating the gradients of the weights using the chain rule of calculus, starting from the output layer and moving backward through the layers.

4. EMPIRICAL RESULTS

The neural networks generate predictions by passing inputs through the layers until they arrive at the output. The output values typically represent probabilities for classification, which are then compared to the actual class labels using the loss function.

4.1. Performance Evaluation Metrics

The model depends on five metrics to determine its accuracy:

- R-squared (R^2): Indicates the model's ability to fit the data effectively
- Mean Squared Error (MSE): Measures the closeness of the predicted values to the actual values
- Root Mean Squared Error (RMSE): Calculates the square root of the average squared discrepancies between expected and actual values, indicating the extent of prediction errors. A lower RMSE suggests a better model fit
- Mean Absolute Error (MAE): Calculates the average absolute difference between the anticipated and actual values, providing a straightforward measure of prediction accuracy that does not emphasize more significant errors
- Mean Absolute Percentage Error (MAPE): This measure calculates the average percentage error by comparing the absolute differences between projected and actual values with the exact values, thereby reflecting prediction accuracy as a percentage.

Table 3 shows that neural networks are accurate algorithms for data analysis, giving us great accurate results in the case of South

Table 3: Neural networks accuracy

Country	MSE	RMSE	MAE	MAPE	R^2
Iceland	6.99	2.43	1.97	0.47	0.61
Norway	1.82	1.35	0.94	0.6	0.31
Russia	5.08	2.25	1.66	0.71	0.69
South Africa	1.27	1.13	0.87	0.44	0.79

Source: Compiled by the author

Africa, then Russia, Iceland, and last, Norway (in the case of Norway, R2 is more minor than its value in other countries, but MSE is lowest after South Africa).

4.2. Neural Networks' Prediction Performance

To ensure accuracy in future predictions, we must compare actual GDP growth values with the neural network's prediction values. This is shown in Figure 2a-d for all countries (Iceland, Norway, Russia, and South Africa). The figures show excellent neural network prediction performance.

4.3. Variables Correlation

Pearson correlation determines the relationship between variables at a given time; Table 4 shows the variable relations for every country.

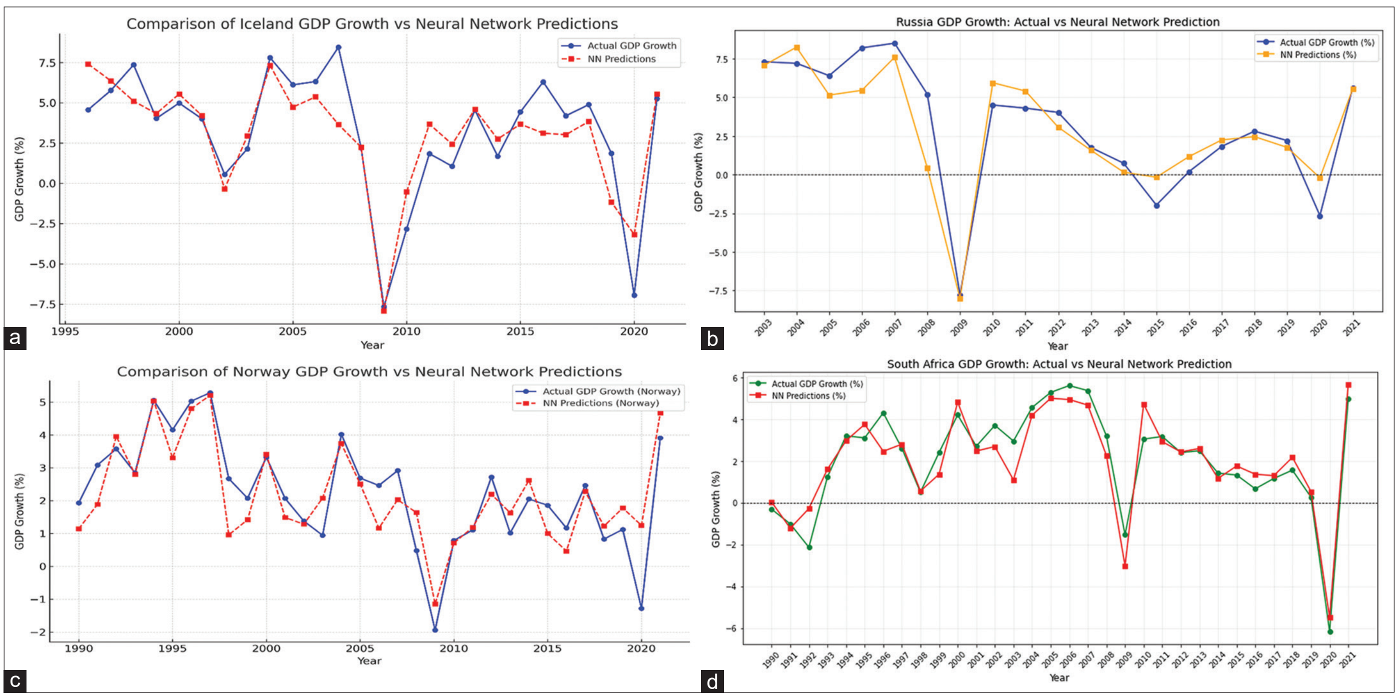
From the Table 4, we find that in the case of countries that depend on renewable energy consumption, there is a weak inverse relationship between the economic growth rate and the rate of renewable energy consumption. There is also a strong direct relationship between the economic growth rate and the growth rate of the industrial and manufacturing sectors. As for countries that do not depend on renewable energy consumption, we find the same situation as the previous countries: there is a weak inverse relationship between renewable energy consumption and economic growth, but there is a strong direct relationship between the economic growth rate and the growth of both the industrial sector and the manufacturing sector.

To determine the relationships between variables in the future, we can rely on the features identified by the neural network algorithm, which are analyzed in the following paragraphs.

4.4. Neural Networks Feature Importance

Table 5 shows the features identified by the neural network algorithm for each country separately:

Figure 2: (a-d) Comparison of GDP growth versus neural networks predictions



Source: Compiled by author

Table 4: Correlation between dependent and independent variables

Independent variables	Dependent variables	Iceland score	Norway score	Russia score	South Africa score
Renewable energy consumption (% of total final energy consumption)	GDP growth	−0.38	0.30	−0.013	−0.067
Industry (including construction), value added (annual % growth)	GDP growth	0.85	0.74	0.89	0.94
Manufacturing, value added (annual % growth)	GDP growth	0.49	0.59	0.84	0.90

Source: Compiled by author

Table 5: Neural networks feature importance

Variables	Iceland scowre	Norway score	Russia score	South Africa score
Renewable energy consumption (% of total final energy consumption)	0.221182	0.181062	0.1677	0.18703
Industry (including construction), value added (annual % growth)	0.571802	0.492524	0.52581	0.446397
Manufacturing, value added (annual % growth)	0.207017	0.326414	0.306491	0.366574

Source: Compiled by author

From Table 5, we find that: The industrial sector is the most significant contributor to economic growth in all countries, with percentages of 57.2% in Iceland, 52.8% in Russia, 49.3% in Norway, and 44.6% in South Africa. The manufacturing sector increased by 36.6% in South Africa, 32.6% in Norway, 30.6% in Russia, and 20.7% in Iceland. Lastly, Renewable energy consumption is the least contributor in all countries by 22.1% in Iceland, 18.7% in South Africa, 18.1% in Norway, and 16.8% in Russia. Hence, we find that renewable energy consumption does not significantly impact the countries under study, whether those with high or low consumption levels.

5. CONCLUSION

Using neural networks, this study examined the relationship between renewable energy consumption and economic growth, focusing on Iceland, Norway, Russia, and South Africa. The findings highlight that the impact of renewable energy on GDP growth varies across different economic structures and levels of energy dependence. While some countries utilize more renewable energy, others continue to rely on traditional energy sources to drive economic growth.

Renewable energy sources are vital to Iceland's economic growth. A 2.06% rise in renewable energy consumption results in a 1% increase in GDP, highlighting a significant positive correlation. Developing the manufacturing and industrial sectors is also crucial for enhancing economic performance. On the other hand, Norway provides a clear example of a situation in which increased economic growth is associated with lower renewable energy consumption. However, sustained growth in the manufacturing and industrial sectors is essential to maintaining economic expansion.

On the other hand, Russia and South Africa show an inverse relationship between renewable energy consumption and GDP growth. Reduced renewable energy usage results in higher economic growth, indicating that these economies still rely heavily on non-renewable energy sources. Growth in the industrial and manufacturing sectors emerges as the main factor driving economic performance in these countries, underscoring the ongoing significance of conventional energy sources.

Overall, the results underscore the necessity for customized energy policies that harmonize economic growth with sustainability. While adopting renewable energy is essential for long-term environmental advantages, its short-term economic effects differ depending on national energy frameworks. Policymakers must consider industry-specific requirements, energy efficiency, and economic diversification to develop sustainable energy strategies that promote growth and environmental stability.

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