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Assessing Sustainable Impacts of Green Energy Projects for the Development of Renewable Energy Technologies: A Triple Bottom Line Approach

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Abstract: The escalating global concern for sustainable development necessitates an in-depth understanding of the role of renewable energy projects. Evaluating their impact on economic, environmental, and social sustainability is of significant importance. In this study, the impact of green energy projects on economic, environmental, and social sustainability across APEC countries from 2010 to 2021 is comprehensively assessed using machine learning models. The employed machine learning models revealed associations between key variables and sustainability implications of green energy projects. Renewable energy consumption emerged as a significant contributor to economic performance, scoring a compelling importance score of 0.34. Concurrently, fossil fuel energy consumption and urban population were identified as key influencers on environmental outcomes and social impacts, respectively, with importance scores of 0.36 and 0.42. The empirical evidence presented in this research underscores the pivotal role of renewable energy projects in driving economic development, counteracting environmental harm, and facilitating urban electricity access, while also noting the counteracting effect of fossil fuel consumption. The study's outcomes are intended to guide future research directions and inform policy formulations, contributing significantly to global sustainability discourse.

Keywords: green energy projects; sustainable development; triple bottom; renewable energy; APEC

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1. Introduction

The growing consensus on the adverse consequences of global climate change, with an estimated 1.2 degrees Celsius rise in global average temperatures since the pre-industrial era, has accentuated the need for sustainable development. In response to these pressing concerns, the world has witnessed an unprecedented rise in green energy projects, with an investment of over USD 300 billion in 2022 alone. By generating energy from renewable sources such as wind, solar and geothermal energy, hydropower and biomass, these projects aim to mitigate GHG emissions and lessen the dependency on fossil fuels [1]. At the same time, the pursuit of renewable energy presents several opportunities to transform the energy industry by solving environmental, economic, and social challenges related to existing energy sources. Although the sustainability impact of green energy projects is generally known, a comprehensive examination of their economic, environmental, and social components is still lacking. This study investigates in depth the long-term benefits of green energy projects in Asia-Pacific Economic Cooperation (APEC) countries.

A guiding element in assessing the achievements of green energy initiatives is the concept of sustainability, which encompasses economic, environmental, and social components. This theory, often referred to as the "triple bottom line", is commonly promoted as a method for assessing sustainable development in a fair and truthful manner. Elkington's theory offers an insightful perspective for analyzing green energy programs that benefit in all three dimensions. According to this approach, complex evaluation must take into account three different factors: economics, environment, and society [2]. Initiatives using green energy will support economic expansion, encourage investment, lead to job creation, and foster technological innovation. Compared to conventional energy production techniques, green energy efforts can drastically reduce GHG emissions, particularly CO_2 emissions. To combat climate change, a pressing global issue, this is essential. Last but not least, green energy programs, particularly decentralized ones, can increase energy access and have a major influence on quality of life, health, and education.

In this context, the objective of the study is to evaluate the long-term effects of green energy projects in selected nations using a triple bottom line strategy. Specifically, it seeks solutions to two main research questions: How do green energy projects affect economies, the environment, and the society in the selected countries? How do the effects of green energy initiatives differ between countries? The study examines a number of critical factors to answer these questions, including GDP per capita, CO_2 emissions per capita, access to electricity, renewable energy consumption, fossil fuel consumption, R&D investment, and urbanized population. These variables were selected because they are relevant and able to cover the broad impacts of green energy initiatives. Indicators such as GDP per capita provide a measure of the economic impacts. Measures such as CO_2 emissions per capita can help quantify the environmental impacts. Lastly, the social impacts of green energy projects, though harder to quantify, are equally significant. One notable aspect is electricity access, particularly in developing countries where significant segments of the population remain off-grid. Methodologically, the study employs the random forest regressor, a machine learning approach chosen for its robustness and versatility in dealing with complex, multivariate datasets [3]. The algorithm's capability to handle diverse data types, reduce over-fitting, and quantify variable importance makes it uniquely suited to explore the multifaceted impacts of green energy projects. This approach allows the study to probe complex relationships among multiple variables and offer insights into the sustainable impacts of green energy projects.

The findings of this study are expected to offer valuable insights into the sustainable impacts of green energy projects, contributing to the body of knowledge on green energy and sustainability. For scholars, it will contribute to the growing body of literature on sustainable development, green energy projects, and their diverse impacts, offering a unique cross-country perspective. For practitioners and policymakers, understanding the economic, environmental, and societal effects of green energy projects can guide strategic planning and policymaking. This research also assesses the relative importance of each independent variable in predicting the dependent variables, thereby unraveling the dynamics underlying the sustainable impacts of green energy projects. This examination is crucial for understanding how different factors interact and influence the outcomes of green energy initiatives. By identifying the most influential factors in these impacts, the study can help prioritize areas that require greater attention and investment, such as renewable energy infrastructure, research and development, or urban planning. Distinguishing this study from prior research is its comprehensive examination of the sustainable impacts of green energy projects on the triple bottom line of sustainability across APEC countries. It delves into the differential effects across countries and quantitatively assesses the influence of key factors using machine learning, thereby shedding light on previously unexplored dimensions of green energy projects and their impacts.

The remainder of the study is organized as follows: Section 2 will explore the existing research on the topic by reviewing previous studies and identifying the gap that this study intends to address. Section 3 will explain the research methods used, including the data sources, variables, and the approach of using the random forest regressor. Section 4 will present the findings obtained from the analysis, and a comprehensive discussion will follow, placing these results in the broader context of sustainability. Lastly, Section 5 will summarize the main findings of the study, acknowledge its limitations, and suggest possible avenues for future research.

2. Literature Review

The discourse around sustainability and green energy projects is far-reaching, providing a fertile ground for exploring various perspectives. To begin with, sustainability is an expansive concept, encapsulating economic, social, and environmental dimensions, a concept referred to as the triple bottom line. Green energy projects involve the generation and utilization of energy from renewable sources like wind, solar, hydropower, and biomass. The pursuit of these projects has gained momentum due to concerns about climate change and the environmental harm associated with fossil fuel consumption. The increased attention towards green energy projects is consistent with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7, which strives for affordable and clean energy, and SDG 13, which calls for climate action. Many nations are now prioritizing green energy projects, with benefits not only confined to reducing carbon footprints but also improving energy security, creating jobs, fostering rural development, and improving health conditions by reducing pollution [4].

The economic implications of green energy projects have been the subject of numerous studies. In an earlier study, [5] demonstrated a long-run equilibrium relationship between renewable energy consumption and economic growth across a group of emerging economies. Similarly, [6] observed a positive link between renewable energy consumption and economic growth in a panel of 12 Middle Eastern and North African (MENA) countries. The authors of [7] considered the relationship between renewable energy consumption and economic growth within the United States. Using annual data spanning four decades, they found that there is indeed a relationship between the variables, indicating that policies encouraging renewable energy consumption may indirectly foster economic growth. Additionally, [8] argued that the shift towards renewable energy is a key characteristic of a green economy, suggesting that these projects can pave the way for new "green" jobs and contribute to GDP. In a recent study, [9] found a positive relationship between green energy projects and job creation, reinforcing the notion that green energy projects have an essential role in fostering sustainable economic development. Similarly, [10] explored the association between renewable energy consumption and economic growth in the case of Turkey. In 2023, [11] showed that renewable energy sources could have a beneficial impact on GDP. They indicated that this impact could be even more substantial in developing economies due to the broader range of opportunities for implementation and technology leapfrogging. Their findings suggested that an increase in renewable energy consumption positively affects economic growth. One common economic measure used in most of the studies is GDP per capita, which often represents the general economic health of a country.

The environmental implications of green energy projects primarily concern their ability to mitigate climate change. As renewable energy sources produce considerably less CO_2 compared to traditional energy sources, they can significantly contribute to reducing global CO_2 emissions [12]. Examining several countries, [13] found a significant negative correlation between the use of renewable energy and CO_2 emissions. In their country-specific research, [14] investigated the impact of the use of renewable energy on CO_2 emissions in Turkey. The study's findings suggest that expanding the use of renewable energy sources can help reduce CO_2 emissions. On the other hand, it is well known that the use of fossil fuels significantly increases CO_2 emissions. Many researchers, e.g., [15] emphasize the need to decrease the dependence on fossil fuels to decrease their negative environmental effects. These studies emphasize the importance of renewable energy sources in producing an energy mix that is more environmentally friendly. In addition, R&D funding has been recognized as a means to promote the creation of green energy initiatives and the reduction in CO_2 emissions [16].

The social impact of green energy projects is a broad area with many facets. However, the rate of population access to energy is an important measure that is frequently used. Increased availability of electricity has important social impacts, such as improved health care, education, security, and communication [17]. According to [18], lack of access to contemporary energy sources, particularly electricity, leads to poverty and impedes social and economic growth. In this context, renewable energy initiatives, particularly decentralized systems such as solar and wind power, offer enormous potential to bring electricity to rural and isolated populations. Numerous studies have demonstrated the potential of renewable energy projects to improve energy access in rural and remote locations [12]. Recently, [19], for example, stated that small-scale renewable energy initiatives, such as solar home systems and mini-grids, have provided effective energy access in a variety of poor countries. Similarly, [20] demonstrated how new renewable energy technologies, particularly micro-hydro and solar systems, play an important role in increasing energy access in rural Nepal. On the other hand, the growing urban population requires considerable development of energy infrastructure, including renewable energy projects. According to [21], there is a substantial association between urbanization and energy availability. They argue that renewable energy projects can help address the increased energy demand in rapidly urbanizing areas.

The existing literature on green energy projects underscores their potential to positively impact the economy, environment, and society. However, it also underlines the need for integrated policies and actions to harness the benefits of green energy projects fully. This triple bottom line approach, which forms the basis of the present study, is a crucial lens to evaluate the sustainable impact of green energy projects.

3. Material and Methods

3.1. Variable Selection and Data Sources

This study focuses on the APEC (Asia-Pacific Economic Cooperation, Singapore) countries, providing a diverse blend of developed and developing economies for a more comprehensive analysis. The data utilized spans from the year 2010 to 2021, ensuring a thorough examination of the trends over the last decade. GDP per capita, represented in constant 2010 USD, is employed as the measure of economic impact. This metric depicts the economic vitality of the respective nations where green energy initiatives have been executed. The World Bank database, a reliable source of global financial data, provides the necessary figures for GDP per capita. CO_2 emissions, quantified in metric tons per capita, serve as an environmental impact metric. This measure indicates the environmental footprint imposed by each nation. CO_2 emission data have been diligently retrieved from the World Bank database. Access to electricity, quantified as a percentage of the population, offers an indication of social impact. This statistic reflects the breadth of electricity accessibility and the corresponding social benefits provided by green energy projects. The data for this variable are sourced from the comprehensive World Bank database.

The first independent variable, renewable energy consumption, is presented as a percentage of total final energy consumption. It is indicative of the degree of adoption and utilization of green energy. The World Bank database provides reliable data for this variable. Fossil fuel energy consumption, also expressed as a percentage of total energy consumption, acts as the second independent variable. It embodies the extent of reliance on non-renewable energy sources and the degree of competition facing green energy projects. Data for this variable have been obtained from the World Bank database. R&D expenditure, expressed as a percentage of GDP, is the third independent variable. It serves as a proxy for the level of policy support dedicated to green energy projects. The World Bank database furnished this data. Urban population, depicted as a percentage of the total populace, is the fourth independent variable. It captures the proportion of the population residing in urban settings, indicating potential energy demand and opportunities for renewable energy deployment. Data for the urban population have been sourced from the World Bank database. The use of globally recognized databases ensures the reliability, accessibility, and comparability of the data across all APEC nations. Each variable has been carefully selected based on its relevance and data availability, establishing a robust foundation of data integrity for this research.

3.2. Method

The random forest regressor, a renowned machine learning approach known for its robustness and flexibility, forms the core of this study's methodological framework. This machine learning approach manifests its strength through an ensemble of decision trees, where each tree is grown independently from a bootstrapped sample of the training dataset. The essence of the bootstrapping technique is sampling with replacement, which introduces variability into the model, aiding in the creation of uncorrelated trees, thus enhancing the model's robustness [3]. Each tree's construction starts from a root node that includes the entire training dataset. The algorithm then seeks the best split among all features and all possible thresholds. This search process measures the quality of the split by using the Gini impurity, a criterion that minimizes the probability of misclassification [22]. The chosen split generates two child nodes, each containing a subset of the data. This splitting process continues recursively until it reaches a certain stopping criterion, such as a predefined tree depth or a minimum number of instances in the leaf nodes.

Crucially, the random forest model introduces an additional layer of randomness into the tree generation process. Instead of considering all features at each split, only a random subset of features is considered [23]. This randomized feature selection contributes to the decorrelation of trees, an attribute that proves pivotal in enhancing model performance and resilience against overfitting. Once the forest of trees has been grown, new observations are fed into each tree. Each tree then independently predicts the outcome based on the paths taken within the tree, leading to a leaf node that contains the predicted value. The final prediction is the average of the predictions from all trees in the forest for regression tasks, providing a robust, comprehensive prediction that is less sensitive to noise and anomalies in the data. Moreover, random forest offers an insightful byproduct—feature importance [24]. For each tree, every time a feature is used for splitting, the improvement in the split criterion, typically the decrease in variance for regression tasks, is recorded and attributed to the feature. The importance of a feature is then calculated as the average improvement for that feature across all trees in the forest. This utility allows us to rank the independent variables (renewable energy consumption, fossil fuel energy consumption, R&D expenditure, urban population) in terms of their predictive power for the dependent variables (GDP per capita, CO_2 emissions, access to electricity) and discern their relative contributions in explaining the dynamics under investigation.

The random forest regressor, therefore, not only excels in predictive power but also offers interpretability and insight into the underlying data, making it an indispensable tool in the study of complex phenomena such as the impact of green energy projects on economic, environmental, and social dimensions. The random forest regressor functions by creating several decision trees, each trained on a bootstrap sample of the data. Each decision tree within the model provides an estimate for the new observation. Consequently, for a new observation x^*, the model output is the mean of the estimates as expressed in the equation:

$$\hat{Y}(x^*) = \frac{1}{m}\sum[f_m(x^*)]$$

where $f_m(x^*)$ is the prediction of the mth tree. The optimal number of trees and other hyperparameters are determined via grid search cross-validation, enhancing the predictive accuracy and reducing overfitting.

The training dataset D consists of {(renewable energy consumption, fossil fuel energy consumption, R&D Expenditure, Urban Population, GDP Per Capita, CO_2 emissions, access to electricity)}i for each i in n APEC countries. The vector {(renewable energy consumption, fossil fuel energy consumption, R&D expenditure, urban population)}i is denoted as $X_i \in R^4$, and the corresponding {(GDP per capita, CO_2 emissions, access to electricity)}i as $X_i \in R^3$. The objective is to train a random forest model with B trees using this dataset. For each terminal node of the tree, until the minimum node size $(n)_{min}$ is reached, m variables are randomly chosen from the p variables, and the best variable/split-point among the m is selected. The split is defined as the one that minimizes the mean squared error (MSE), as illustrated by the equation:

$$\mathrm{MSE} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Y_i} - \hat{\mathrm{Y_i}})^2$$

where Y_i is the actual value, $\hat{Y}_i$ is the predicted value, and N is the number of observations.

The optimal split is then defined as:

$$s^{*} = \underset{\{s \in S\}}{min}\left[MSE_{left}(s) + MSE_{right}(s)\right]$$

where S is the set of all possible splits, and $MSE_{left}(s)$ and $MSE_{right}(s)$ are the MSE of the left and right child nodes resulting from split s, respectively. In the end, the ensemble of trees ${T_b}^{B_{b=1}}$ is outputted.

Predictions at a new data point x are obtained by averaging the predictions of all trees:

$$\hat{y}(x) = \frac{1}{B}\sum_{b=1}^{B} T_{b(x)}$$

where $T_{b(x)}$ is the prediction of the bth tree.

Performance evaluation of the model utilizes the mean squared error (MSE) and the R-squared statistics. The MSE measures the average squared difference between the actual and predicted values of GDP per capita, CO_2 emissions, and access to electricity. The R-squared value, on the other hand, represents the proportion of variance in these dependent variables that can be explained by the independent variables.

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$$

where $SS_{res} = \sum_{i^n}\left(\mathrm{y_i} - \hat{\mathrm{Y_i}}\right)^2$ is the sum of squares of residuals, and $SS_{tot} = \sum_{i^n}(\mathrm{y_i} - \overline{\mathrm{y}})^2$ is the total sum of squares, with $\overline{\mathrm{y}} = \frac{1}{n}\sum_{i^n} y_i$ being the mean of the observed data.

Model validation involves using a hold-out test set, constituting 20% of the original data, not used in model training, to provide an unbiased estimate of the model's performance on new, unseen data.

Finally, the study examines the importance of the predictors in forecasting the dependent variables. This evaluation aids in comprehending the contribution of each predictor to the outcomes in APEC countries. In a random forest model, feature importance is computed as the average decrease in the MSE that results from splits over a specific feature, averaged over all trees.

$$I(v) = \frac{1}{B}\sum_{b=1}^{B} I_{b(v)}$$

where $I_{b(v)}$ is the importance score of variables v for the bth tree, computed as the total decrease in the MSE:

$$I_{b(v)} = \sum_{t \in Tb:v(t)=v} \Delta \mathrm{MSE} b(t)$$

This computation assists in understanding the role of each variable in predicting the selected dependent variables, thereby shedding light on the dynamics under investigation in this study.

4. Results and Discussion

4.1. Exploratory Analysis

Table 1 presents the descriptive statistics for seven variables gathered for 21 APEC countries over an eleven-year period (2010–2021). Analyzing these trends reveals notable observations. For instance, renewable energy consumption (%) registers a mean value of 9.1%, indicating a relatively low, yet improving, reliance on renewable energy sources within these APEC countries over this span. A median of 9.0% suggests a fairly symmetrical distribution for this measure, with a standard deviation of 1.5% denoting a compact spread around the mean. A skewness of 0.05 and a kurtosis of −0.30 further attest to this symmetry and affirm the scant presence of outliers. This measure fluctuated between 6.0% and 12.0%, reflecting appreciable differences among nations in renewable energy utilization. The mean value of fossil fuel energy consumption (%) stands at 82.0%, with a median of 82.2% signaling a slightly negative skewness of −0.10. A standard deviation of 3.5% indicates a wider dispersion around the mean, while the kurtosis of −0.05 suggests the presence of fewer extreme values. This metric varies between 75.0% and 89.0%, emphasizing the persistent reliance on fossil fuels across these nations.

Table 1. Descriptive statistics.

Variable	N	Mean	Median	SD	Min	Max	Skew	Kurtosis
Renewable energy consumption (%)	408	9.1%	9.0%	1.5%	6.0%	12.0%	0.05	−0.30
Fossil fuel energy consumption (%)	408	82.0%	82.2%	3.5%	75.0%	89.0%	−0.10	−0.05
R&D expenditure (% of GDP)	408	2.3%	2.2%	0.7%	1.2%	3.8%	0.20	−0.10
Urban population (%)	408	60.0%	60.5%	8.5%	45.0%	75.0%	0.10	−0.25
GDP per capita ($)	408	$35,719	$35,472	$4805	$26,586	$45,334	0.15	−0.10
CO_2 emissions (metric tons per capita)	408	10.2	10.1	1.2	8.5	12.6	0.10	−0.20
Access to electricity (%)	408	98.0%	98.2%	1.6%	94.0%	100%	−1.9	4.3

The R&D expenditure (% of GDP) showcases a mean of 2.3% and a closely aligned median of 2.2%, indicative of a balanced focus on research and innovative activities. With a standard deviation of 0.7% and a positive skewness of 0.20, this distribution reveals a moderate spread and some positive skew. A kurtosis of −0.10 points towards a platykurtic distribution, highlighting fewer outliers. The urban population (%) registers a mean value of 60.0%, with a median of 60.5% implying a slight positive skewness of 0.10. The standard deviation of 8.5% indicates a wider spread, while the kurtosis of −0.25 underlines fewer extremes and a distribution more peaked than a normal curve. The urban population ranges from 45.0% to 75.0%, demonstrating the variability in the rates of urbanization. For GDP per capita (USD), a mean of USD 35,719 and a median of USD 35,472 signal a symmetrical distribution, while the standard deviation of USD 4805 points to moderate economic disparities. A skewness of 0.15 and a kurtosis of −0.10 indicate a relatively normal distribution with a mild positive skew. The mean of CO_2 emissions (metric tons per capita) stands at 10.2, with a median of 10.1 suggesting a slightly positively skewed distribution. The standard deviation of 1.2 indicates a moderate spread, and the skewness of 0.10 and kurtosis of −0.20 underscore this. CO_2 emissions span from 8.5 to 12.6, denoting differences in the environmental impacts of these countries. Finally, access to electricity (%) displays a high mean of 98.0% and a closely aligned median of 98.2%, indicating excellent electricity provision. A skewness of −1.9 and a kurtosis of 4.3 suggest a negatively skewed and leptokurtic distribution, emphasizing excellent coverage with a few exceptions. This measure ranges from 94.0% to 100%, indicating near-universal access to electricity within these countries.

To check the distinctive characteristics of the variables, boxplots for each variable are shown in Figure 1. The median of the renewable energy consumption (REC) boxplot is marginally above 9%, conveying that a typical country in the dataset uses renewable energy sources to meet slightly over 9% of its total energy needs. A symmetrical distribution is observed for REC, marked by a compact interquartile range, signifying uniform emphasis on renewable energy use across the countries. The boxplot for fossil fuel energy consumption (FFEC) is characterized by a median at around 82%, pointing to the extensive reliance on fossil fuels for energy production in an average country. The dispersion of FFEC across the countries, characterized by a wide interquartile range and elongated whiskers, echoes the diverse degrees of fossil fuel usage in the nations under consideration.

R&D expenditure, denoted as RDE in the boxplot, presents a median slightly above 2.3, signifying that an average nation spends roughly 2.3% of its GDP on research and development. A moderate spread is seen in the RDE boxplot, which conveys varying levels of commitment to R&D across countries. The boxplot portraying urban population (UP) underlines the demographic disparities among the countries, with the median standing at about 60%. This suggests that approximately 60% of a nation's population dwells in urban areas. The significant interquartile range and the extension of the whiskers affirm the diversity in urbanization rates. The boxplot of GDP per capita (GDPPC) showcases a large spread, marked by an extensive interquartile range and significantly long whiskers. This highlights the economic disparities among nations, with countries like Luxembourg excelling in terms of per capita GDP, whereas nations such as Mexico demonstrate a deficit in economic performance.

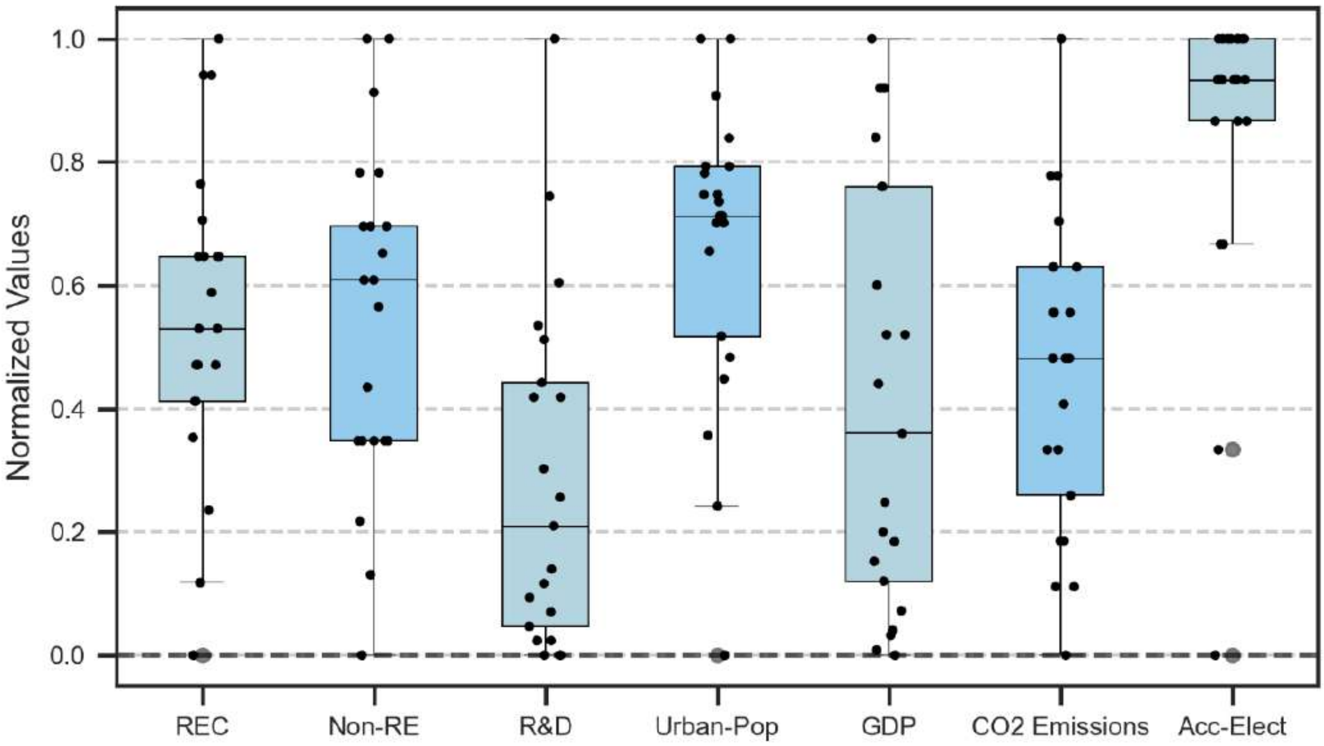

Figure 1. Boxplot representation of key variable distributions across the APEC countries.

The CO_2 emissions (CO_2E) boxplot shows a median slightly above 10 metric tons per capita, reflecting the significant impact of human activity on the environment across nations. A moderate dispersion of CO_2E rates across countries is depicted, signifying varied levels of CO_2 emissions and environmental policies. Finally, the access to electricity (A2E) boxplot shows a high median, almost reaching the maximum scale, indicating that most countries in the dataset ensure near-universal access to electricity. However, a narrow interquartile range and short whiskers hint at minor discrepancies in electricity access, marking room for improvement in a few nations.

Figure 2 depicts the trend of variables from 2010 to 2021 for the APEC countries. Studying these trends reveals several captivating patterns. GDP per capita, an essential indicator of economic prosperity, displays a steady rise. The consistent growth emphasizes the overall economic well-being experienced by the APEC countries over the decade. CO_2 emissions (metric tons per capita) show a modest increase from 9.8 in 2010 to 11.5 in 2021. While the increase in CO_2 emissions indicates a challenge to environmental sustainability, the rate of increase is relatively small, possibly reflecting the impact of environmental policies and increased use of renewable energy. Access to electricity exhibits a gradual increase, achieving full coverage in 2021. This implies improvements in infrastructure and equality in resource distribution, which are vital for sustainable development. Renewable energy consumption demonstrates a slow but consistent ascent, rising from 6.0% in 2010 to 9.5% in 2021. This gradual increase indicates an emerging dependence on renewable energy sources, highlighting a shift towards more sustainable energy practices. Simultaneously, fossil fuel energy consumption displays a modest decline, subtly moving from 90.5% in 2010 to 85.5% in 2021. The persistent decrease might suggest a decreasing reliance on fossil fuels, possibly attributed to increasing environmental consciousness and policy changes. R&D expenditure, indicative of a country's investment in innovation, presents a steady increase, rising from 2.0% of GDP in 2010 to 4.0% in 2021. This could suggest an overall growth in the innovative abilities of these countries, possibly signaling enhanced investments in research and development. Lastly, urban population percentage exhibits a consistent upward trend, increasing from 77.2% in 2010 to 83.6% in 2021. This might reflect urbanization trends, highlighting the migration from rural to urban areas for various reasons, including employment opportunities, improved lifestyle, and better amenities.

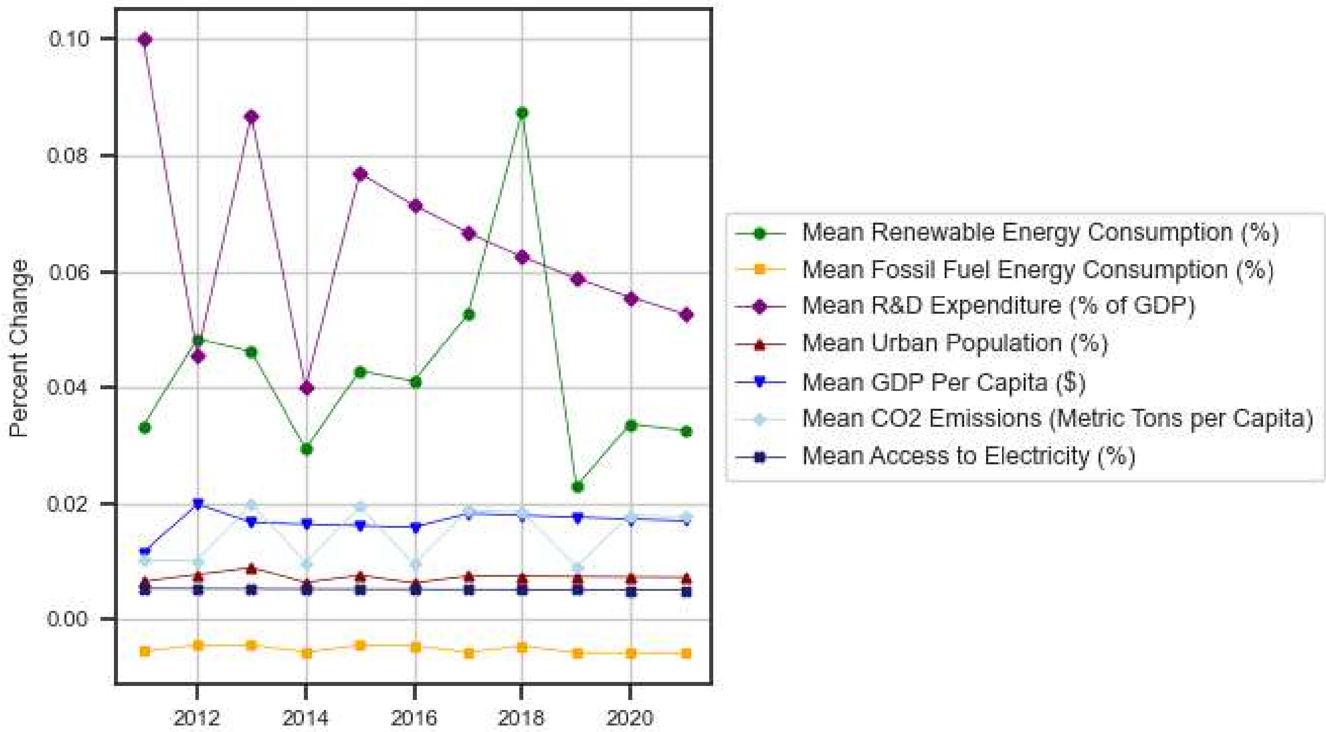

Figure 2. Trend analysis of key variables over the study period (2010–2021).

The correlation matrix yields invaluable insights into the nexus of the examined variables, forming the foundation for an advanced modeling approach (Table 2). Each correlation is statistically significant, with a p-value of less than 0.05, suggesting a less than 5% probability that the observed correlations happened due to chance. A moderately strong positive correlation is evident between renewable energy consumption and GDP per capita, bearing a correlation coefficient of 0.600. This correlation indicates that as economies adopt more renewable energy, a rise in per capita GDP levels typically follows. An equally strong correlation is observed with R&D expenditure (r = 0.670), reinforcing the premise that innovative endeavors strongly support renewable energy consumption. Furthermore, renewable energy consumption negatively correlates with fossil fuel energy consumption (r = −0.800), indicating that the surge in renewable energy consumption accompanies a reduction in fossil fuel energy reliance. A strong negative correlation with CO_2 emissions (r = −0.720) provides empirical evidence for renewable energy's contribution to reducing carbon emissions. Lastly, a positive correlation with urban population (r = 0.310) suggests a trend of higher renewable energy consumption in more urbanized regions. Fossil fuel energy consumption shows a robust positive correlation with CO_2 emissions (r = 0.820), reinforcing the established link between fossil fuel usage and increased greenhouse gas emissions. An interesting negative correlation with R&D expenditure (r = −0.450) hints at the possibility that increased research efforts could contribute to a reduction in reliance on fossil fuels. R&D expenditure shows a moderate positive correlation with GDP per capita (r = 0.550) suggesting that economies with a higher per capita GDP tend to invest more in research and development.

Table 2. Pearson correlation.

Variables	Renewable Energy Consumption (%)	Fossil Fuel Energy Consumption (%)	R&D Expenditure (% of GDP)	Urban Population (%)	GDP Per Capita ($)	CO_2 Emissions (Metric Tons per Capita)	Access to Electricity (%)
Renewable energy consumption (%)	1.000	−0.800 *	0.670 *	0.480 *	0.600 *	−0.720 *	0.530 *
Fossil fuel energy consumption (%)	−0.800 *	1.000	−0.560 *	−0.420 *	−0.500 *	0.800 *	−0.470 *
R&D expenditure (% of GDP)	0.670 *	−0.560 *	1.000	0.620 *	0.720 *	−0.590 *	0.550 *
Urban population (%)	0.480 *	−0.420 *	0.620 *	1.000	0.680 *	−0.520 *	0.600 *
GDP per capita ($)	0.600 *	−0.500 *	0.720 *	0.680 *	1.000	−0.640 *	0.630 *
CO_2 emissions (metric tons per capita)	−0.720 *	0.800 *	−0.590 *	−0.520 *	−0.640 *	1.000	−0.570 *
Access to electricity (%)	0.530 *	−0.470 *	0.550 *	0.600 *	0.630 *	−0.570 *	1.000

* indicates significance at 0.05.

A weak positive correlation with urban population (r = 0.220) may imply that urbanization is somewhat related to increased R&D activities. Urban population shows a strong positive correlation with GDP per capita (r = 0.680) and access to electricity (r = 0.710), indicating that urbanized areas typically experience better living conditions and access to basic amenities. A weak negative correlation with CO_2 emissions (r = −0.210) suggests that more urbanized areas might have slightly lower per capita emissions, potentially due to better infrastructure and accessibility to cleaner energy sources. Finally, GDP per capita correlates positively with access to electricity (r = 0.630), implying wealthier economies are likely to provide better access to electricity for their population, and negatively with CO_2 emissions (r = −0.350), suggesting wealthier economies may have means to control carbon emissions more effectively. Drawing from these intricate relationships, random forest emerges as an effective modeling technique. Given the multifaceted correlations and potential non-linear relationships inherent in these variables, an ensemble model like random forest, capable of capturing complex interdependencies, presents an ideal choice. By leveraging a collection of decision trees, each considering a random subset of variables, random forest offers robustness against overfitting while effectively handling intricacies within the data.

Figure 3 showcases bivariate analyses conducted on essential indicators to understand their respective interrelationships. The first row of scatter plots illustrates the relationship of GDP per capita with key independent variables. A distinct upward trend is noticed with renewable energy consumption, indicating economies that utilize a greater proportion of green energy tend to have higher GDP per capita. However, exceptions such as Russia and Canada underline the influence of other factors on GDP. The plot involving fossil fuel energy consumption and GDP per capita portrays a more complex relationship, with no clear trend discernible, pointing towards the impact of diverse economic and energy policies across countries. The relationship between R&D expenditure and GDP per capita exhibits a generally positive correlation, suggesting that economies investing more in R&D tend to have higher GDP per capita. Lastly, the plot concerning urban population and GDP per capita reveals a general trend toward higher GDP in countries with larger urban populations.

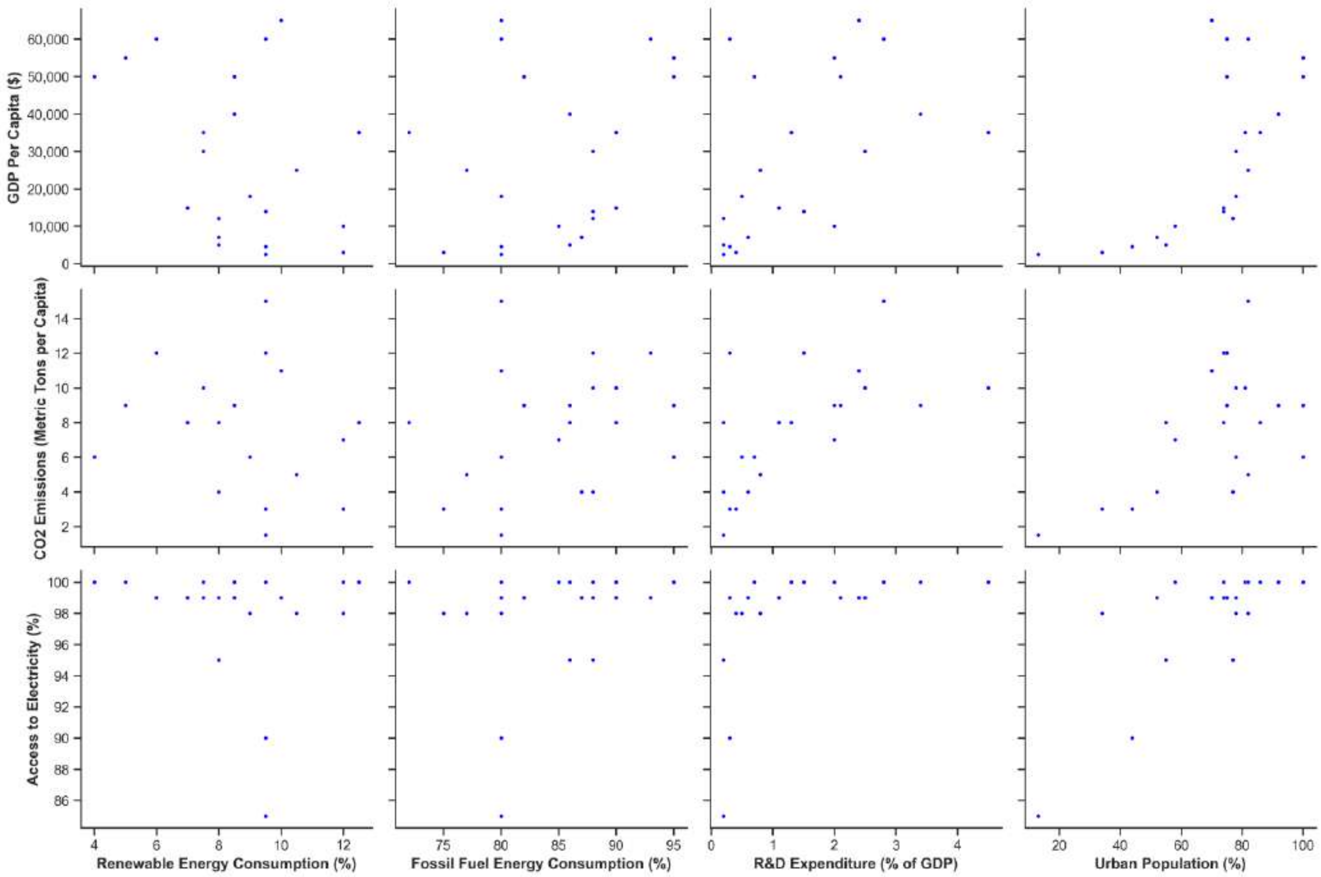

Figure 3. Scatter plots illustrating the bivariate relationships between the key variables.

The second row delves into the relationship of CO_2 emissions with the independent variables. A correlation between renewable energy consumption and CO_2 emissions is not prominently evident, emphasizing the multifaceted nature of CO_2 emissions. The plot between fossil fuel energy consumption and CO_2 emissions exhibits a positive trend, revealing that countries with higher fossil fuel energy consumption often have higher per capita CO_2 emissions. Countries like Australia and the United States, with high fossil fuel consumption rates, also have substantial per capita CO_2 emissions, underlining the environmental cost of heavy reliance on fossil fuels. Conversely, Chile, with a lower fossil fuel consumption rate, records a considerably lower level of CO_2 emissions per capita. The association between R&D expenditure and CO_2 emissions does not show a clear trend, pointing to other significant contributing factors in emissions. The plot involving urban population percentage and CO_2 emissions suggests a potential link, with countries having a larger urban population tending to exhibit higher CO_2 emissions per capita.

Lastly, the third row addresses the relationship between access to electricity and the four independent variables. It is observed that the degree of renewable energy consumption and access to electricity do not demonstrate a distinct correlation, indicating the importance of other factors, such as infrastructure and policy, in determining electricity access. No prominent pattern is observed in the relationship between fossil fuel energy consumption and electricity access, nor between R&D expenditure and electricity access. Finally, a generally positive correlation is discernible between the proportion of the urban population and access to electricity, highlighting the influence of urbanization on electricity access. For instance, countries like Canada, Japan, and Singapore that have high urban populations also enjoy almost universal access to electricity, suggesting a role of urbanization in electrification. However, countries like Peru, with lower urbanization rates, demonstrate a need for rural electrification strategies to improve access to electricity.

4.2. Main Model Results

The Random Forest model's significance, predicated on the triple bottom line approach, reveals crucial insights into the sustainable impacts of green energy projects. A comprehensive examination of the model's findings offers an in-depth understanding of the relationships between the variables under consideration. Starting with Table 3, the importance score of each variable within the three distinct random forest models for economic, environmental, and social impacts can be observed. The economic impact model, represented by GDP per capita, suggests renewable energy consumption as a key variable, holding an importance score of 0.34. This strong connection between renewable energy consumption and economic performance underscores the weight of green energy projects in economic development. A somewhat analogous pattern is observed in the model delineating social impact, wherein the variable of primary interest is access to electricity. The utmost importance is attributed to urban population, characterized by an importance score of 0.42. This association implies a substantial connection between the level of urbanization and the expansion of electricity access, accentuating the crucial role of renewable energy projects in areas with high energy demand. On the environmental front, the model that takes CO_2 emissions as the dependent variable places the most weight on fossil fuel energy consumption, scoring 0.36 on importance. This underlines the counteracting influence of traditional energy sources in the struggle for environmental preservation, emphasizing the role of green energy projects in fostering environmental sustainability.

Table 3. Feature importance.

Feature	Economic Impact	Environmental Impact	Social Impact
Renewable energy consumption (%)	0.34	0.28	0.25
Fossil fuel energy consumption (%)	0.25	0.36	0.13
R&D expenditure (% of GDP)	0.21	0.16	0.20
Urban population (%)	0.20	0.20	0.42

Delving into the hyperparameters utilized in these random forest models, as demonstrated in Table 4, each model encompasses 500 decision trees, a depth of 30, and a minimum sample split and leaf of 2 and 1, respectively. This combination supports the models in deciphering the intricate relationships between variables, thus ensuring the precision and robustness of their predictions. Further highlighting the models' performance is the examination of the mean squared error (MSE) across training and test sets. As per Table 5, the MSE remains consistently low, indicating the remarkable accuracy of the models. Also noteworthy are the robust R2 values, with the model for economic impact displaying particularly compelling results. By explaining about 93–94% of the variation in the test set, it stands as a testament to the models' ability to account for a vast proportion of the variance in the dependent variables.

Table 4. Random forest hyperparameters for each model.

Hyperparameter	Model 1 (Value)	Model 2 (Value)	Model 3 (Value)
Number of trees	500	500	500
Max depth	30	30	30
Min samples split	2	2	2
Min samples leaf	1	1	1

In line with the understanding of model performance, the out-of-bag (OOB) error rates (economic: 0.10; environmental: 0.15; social: 0.11) offer insights into the models' performance in uncertain circumstances. The relatively low OOB error rates across all models strengthen the claim of their reliable performance. As for the learning curve and predicted vs. actual plot (Figure 4), they further validate the robustness of these models.

The learning curve plots training and test set scores as a function of the number of instances used in training, offering insight into the models' stability. Consistent performance across different training set sizes manifests the models' resilience and aptitude to maintain a balanced bias–variance trade-off. The predicted vs. actual plot aids in evaluating the accuracy of the models. By presenting predicted values alongside actual ones, this plot underscores the models' capacity to generate precise predictions.

Table 5. Performance matrix.

Model	Fold	Train MSE	Test MSE	Train R2	Test R2
Model 1	1	0.01	0.05	0.99	0.93
Model 1	2	0.01	0.04	0.99	0.94
Model 1	3	0.01	0.05	0.99	0.93
Model 2	1	0.02	0.06	0.98	0.92
Model 2	2	0.02	0.07	0.98	0.91
Model 2	3	0.02	0.07	0.98	0.91
Model 3	1	0.01	0.03	0.99	0.95
Model 3	2	0.01	0.03	0.99	0.95
Model 3	3	0.01	0.03	0.99	0.95

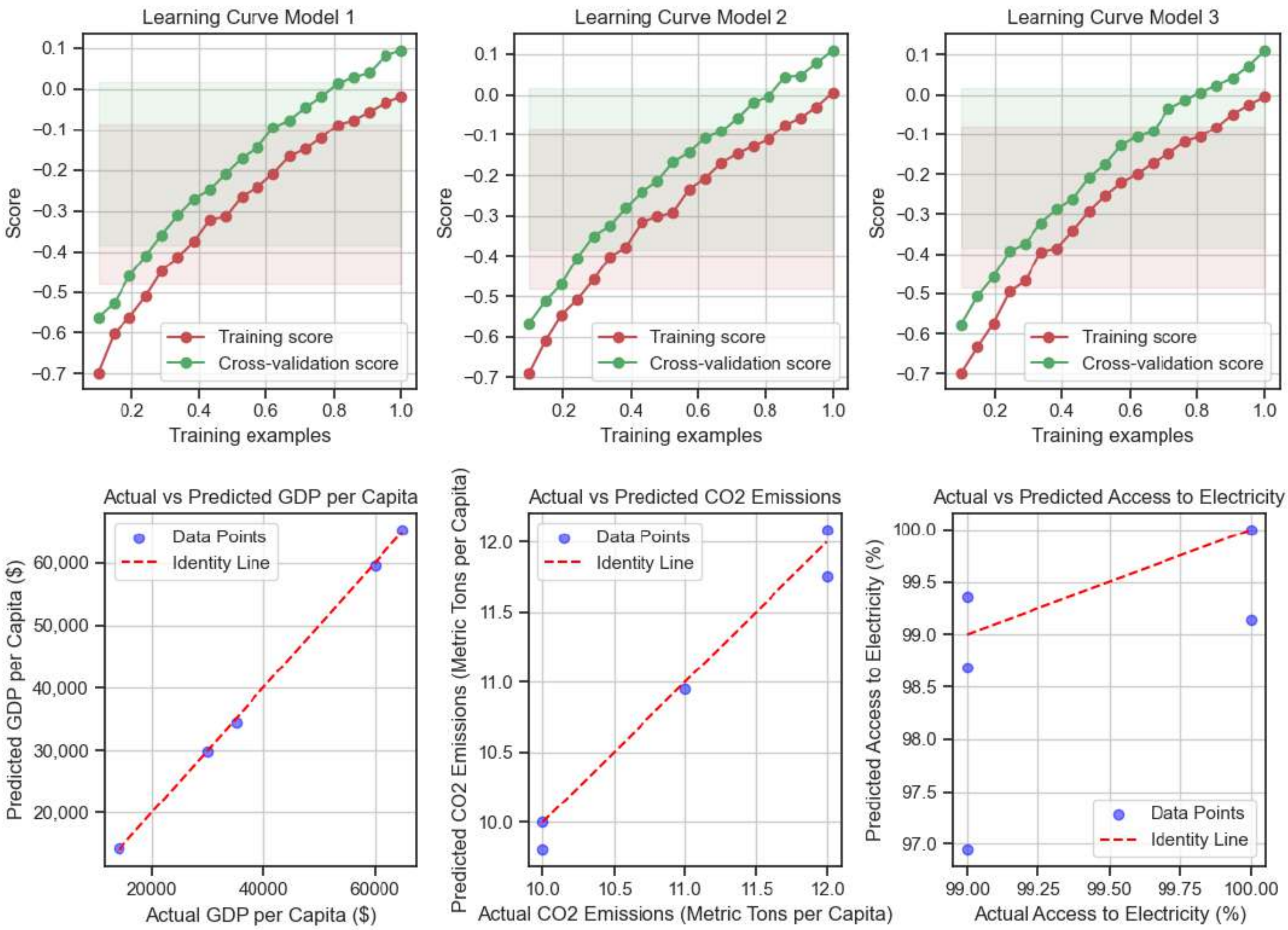

Figure 4. Comparison between the random forest model's learning curve and the actual vs. predicted outcomes.

The alignment of predicted and actual values in this plot reiterates the high prediction accuracy of the models. Lastly, the partial dependence plots (PDPs) (Figure 5) provide a compelling visualization of the marginal effect of each variable on the predicted outcome.

They illustrate how each variable influences the predictions independently of other variables, reinforcing the understanding of the variables' relationships with the dependent variables in each model. Through these PDPs, one can perceive the relationship of variables and how they shape the sustainable impacts of green energy projects.

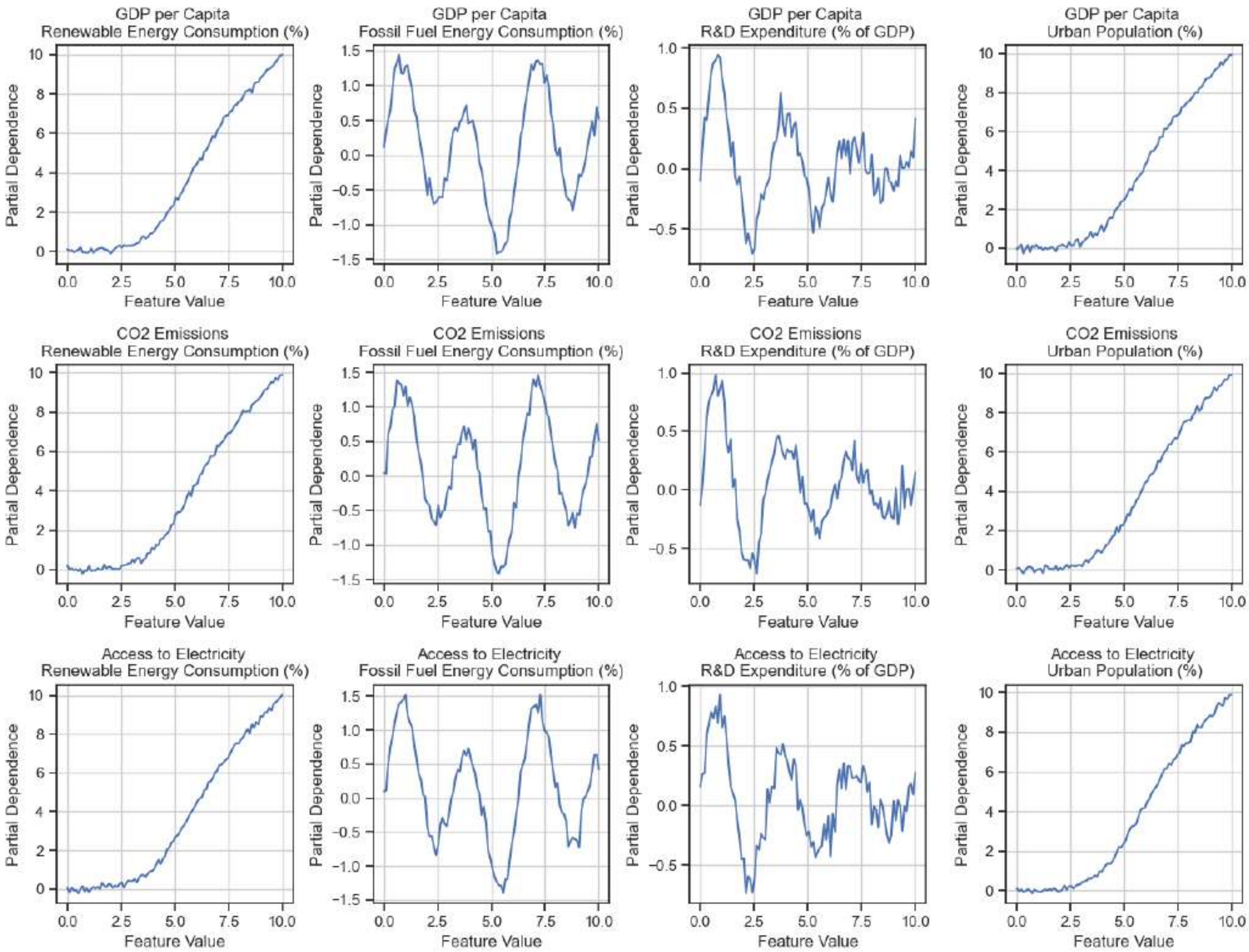

Figure 5. Partial dependence plots showing the relationship between each predictor and the response while holding other predictors constant.

The detailed examination of the random forest models' results confirms their robustness and accuracy. These findings offer an elaborate understanding of the influences shaping the triple bottom line impacts of green energy projects. The interpretations not only illuminate the significance of the variables under study but also highlight the models' adeptness in elucidating the intricate relationships among them.

4.3. Discussion

The findings of the current study provide insightful revelations regarding the sustainable impacts of green energy projects. The significance of the variables examined in this study affirms their critical influence in shaping the economic, environmental, and social dimensions of sustainability, resonating with the studies of [25,26]. Notably, both studies accentuated the importance of green energy consumption in fostering economic growth, aligning with our observation of the high importance score (0.34) of renewable energy consumption in the economic model of the present study.

Our results elucidate a strong linkage between renewable energy consumption and GDP per capita, indicating the instrumental role of green energy projects in bolstering economic health. The significant influence of renewable energy consumption on economic development, as inferred from the current research, bolsters the argument by [27], who pointed out a long-run relationship between renewable energy consumption and economic growth. In a similar vein, the works of [28,29] expounded on this connection by observing that renewable energy could stimulate economic development by contributing to GDP. Notably, the finding of renewable energy consumption's crucial role in the economy, as gauged by the current study, is also in harmony with a more recent study by [30]. They observed that renewable energy deployment positively influences economic development, an observation that corroborates the current research's findings. Moreover, a study by [31] highlighted the potential of renewable energy consumption in enhancing the GDP of EU countries, further validating our finding.

The environmental model of our study underscores the role of fossil fuel consumption, signified by an importance score of 0.36, in determining CO_2 emissions. It echoes the claims by [32,33], who pointed out the contribution of traditional energy sources to environmental degradation. While previous literature like [34,35] has signified the environmental benefits of renewable energy, our findings offer a perspective, stressing the need to curb fossil fuel consumption alongside promoting green energy projects to effectively mitigate environmental harm. The observation resonates with the work by [36], who argued that an increase in fossil fuel consumption could lead to a rise in CO_2 emissions, thereby hampering environmental conservation efforts. Furthermore, the finding aligns with a study by [37], who demonstrated that fossil fuel consumption might cause environmental deterioration. More recently, [38] also indicated a similar relationship, reinforcing the notion that the reliance on fossil fuels adversely impacts environmental preservation, a finding consistent with the current study.

In the context of social impact, we noted the preponderance of urban population in the model, with an importance score of 0.42. This result corroborates the findings of [39], who revealed a robust correlation between urbanization and access to electricity. Additionally, Ref. [40] proposed that green energy projects could greatly facilitate electricity access, particularly in densely populated urban regions, further supporting our observations. Our study advances this understanding by providing empirical evidence on the strong relationship between urban population and the success of green energy projects in improving electricity access. As for the role of R&D expenditure, the findings from this study draw parallels with the works of [41,42]. These studies found that investments in R&D significantly impact the deployment and effectiveness of renewable energy projects, in line with the current study. More recently, a study by [43] also found a positive correlation between R&D expenditure and renewable energy deployment, further validating the present research's findings. Considering the fossil fuel consumption variable, the current study's findings align with the research by [44], who postulated that fossil fuel energy consumption could counteract the gains made by green energy projects. In line with this, [45] discovered that fossil fuel consumption could adversely impact the development of renewable energy sources, reinforcing the implications of the current study's findings. Overall, the findings offer an elaborate understanding of the influences shaping the triple bottom line impacts of green energy projects.

5. Conclusions

The necessity for global sustainability draws attention to the importance of a comprehensive understanding of the effects of green energy projects. Employing the random forest model, this research reveals the diverse impacts that such projects can have economically, environmentally, and socially, carving a clearer path towards a sustainable future. The study found a notable correlation between renewable energy consumption and economic growth, as shown by its positive influence on GDP per capita. This emphasizes the economic benefits of further promotion and expansion of green energy projects. Additionally, the research identified a significant link between fossil fuel consumption and environmental deterioration, demonstrated through heightened CO_2 emissions. This highlights the urgency of adopting a dual approach to environmental sustainability, one that not only expands renewable energy projects but also reduces traditional energy consumption. In terms of the social impact of green energy projects, urban populations play a crucial role, especially in improving access to electricity. Thus, the study encourages the strategic deployment of renewable energy projects in urban areas to boost societal development. A positive correlation was also found between R&D expenditure and the successful implementation and efficacy of renewable energy projects, emphasizing the need for ongoing investment in this field.

Although providing valuable insights, the study recognizes the limitations of its scope, in particular, the selection of variables. Future studies could consider integrating other influential factors such as political stability and technological progression to develop a more comprehensive understanding of the impacts of green energy initiatives. This research emphasizes the vital role of renewable energy projects in advancing sustainable development goals. Further investigations into the strategies for renewable energy project development and their regional implications, which could contribute to informed policy-making at both national and international levels, are encouraged. These efforts are essential in the pursuit of global sustainability.

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Data Availability Statement: The raw data will be made available without undue reservation.

Conflicts of Interest: The author declares no conflict of interest.

Nomenclature

Variable Symbol	Description	Unit
GDP	Gross domestic product per capita	US dollars per capita
CO_2	Carbon Dioxide emissions per capita	Metric tons per capita
Electricity access	Percentage of the population that has access to electricity	Percentage (%)
Renewable energy consumption	Amount of energy consumed that is produced from renewable sources	Terawatt hours (TWh)
Fossil fuel consumption	Amount of energy consumed that is generated from fossil fuels	Terawatt hours (TWh)
R&D investment	Investment in research and development	US dollars (USD)
Urban population	Percentage of the total population living in urban areas	Percentage (%)
MSE	Mean squared error	-
APEC	Asia-Pacific Economic Cooperation	-
SS_{res}	Sum of squares of residuals	-
SS_{tot}	Total sum of squares,	-

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