Modeling the Impact of Technological Drivers on Investment Attractiveness of Renewable Energy Markets

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Abstract: The study is dedicated to analyzing the relationship between the Renewable Energy Country Attractiveness Index (RECAI) and technology-specific indices of renewable energy technologies to identify key technological drivers of investment attractiveness in renewable energy markets. The methodology is based on applying General Regression Models for 40 countries, where RECAI serves as the dependent variable, and eight technology-specific indices (onshore wind, offshore wind, solar photovoltaics, concentrated solar power, biomass, geothermal, hydro, battery energy storage systems) serve as independent predictors. The results of the regression analysis demonstrate a statistically significant impact of four technologies on RECAI formation. Solar photovoltaics show the most powerful effect, followed by onshore wind, battery energy storage systems, and offshore wind in terms of impact magnitude. The technologies of concentrated solar power, geothermal, hydro, and biomass proved to be statistically insignificant predictors. Three-dimensional visualization confirmed the synergistic nature of the impact of key technologies and the importance of a diversified technological portfolio for maximizing market attractiveness. The practical value of the study lies in creating an empirically grounded tool that provides a foundation for strategic planning by investors and policymakers of investments in renewable energy at the national level.

1 INTRODUCTION

The global energy transition to renewable energy sources (RES) is gaining increasing importance in the context of combating climate change and ensuring energy security [1]-[4]. According to Bloomberg, global investments in renewable energy reached a record USD 2.1 trillion in 2024 [5], indicating sustained growth in interest in this sector from investors and governments. However, the distribution of investment flows between countries remains uneven [6], necessitating a thorough analysis of factors that determine the investment attractiveness of national RES markets.

The Renewable Energy Country Attractiveness Index (RECAI), developed by consulting company EY, is one of the most influential comprehensive indicators for assessing the investment attractiveness of national renewable energy markets [7]. This index considers a wide range of macroeconomic, infrastructural, and political factors, but its composite nature complicates the understanding of the specific contribution of individual technological components to forming a country's overall rating. At the same time, technological differentiation of RES markets is critically important for investors, as different renewable technologies are characterized by distinct risk profiles, levels of technological maturity, and commercialization potential.

Contemporary research on RES investment attractiveness predominantly focuses on analyzing general macroeconomic determinants or considers individual technologies in isolation, without accounting for their synergistic impact on comprehensive market attractiveness assessment [8]-[11]. For instance, D. Doğan et al. analyzed the relationships between renewable energy consumption, carbon dioxide emissions, economic growth, financial development, and energy dependence. The authors used the panel regression method to conduct research for 38 countries over the period 1991–2021 based on RECAI. It was established that financial development affects both carbon dioxide emissions and economic growth [12]. Researchers N. Y. Mohamed Yusoff et al. used autoregressive distributed lag based on annual time series data to analyze macroeconomic indicators, including gross domestic investment, domestic investment, foreign direct investment, trade openness, urbanization, financial development, and carbon emission levels on renewable energy in Malaysia. They determined that greater economic development and urbanization increase the share of renewable energy. Conversely, increases in foreign investment, trade liberalization, and carbon emissions may reduce the use of these clean energy sources [13]. G. Osuma and L. Bonga-Bonga studied the impact of foreign direct investment and technological innovations on renewable energy consumption formation. The authors analyzed their joint effect in 20 EU countries during 2013–2023 using the Method of Moments Quantile Regression. Results showed that technological innovations consistently contribute to growth in renewable energy consumption. In contrast, foreign direct investment has a negative impact on renewable energy consumption. Additionally, inflation positively affects renewable energy consumption, indicating that rising energy prices stimulate the transition to alternative sources [14]. O. Prokopenko et al. used a vector autoregressive model to analyze the impact of long-term investments and research and development expenditures in renewable energy on the financial performance of 10 leading industry companies. The obtained results indicate a positive impact of investments and research and development expenditures on key profitability indicators: taxes, depreciation, earnings before interest and taxes, net profit, and return on investment, emphasizing the economic feasibility of financing innovations in renewable energy [15].

However, such a fragmented approach limits the possibilities for comprehensive understanding of synergistic effects. This creates a methodological gap in understanding how specific technological factors interact with each other and shape the overall investment attractiveness of national RES markets.

The aim of the study is to develop an empirical model of the relationship between the Renewable Energy Country Attractiveness Index and technology-specific indices of renewable energy technologies to identify key technological drivers of RES market investment attractiveness. To achieve the stated goal, the following tasks are planned: conduct correlation analysis of relationships between RECAI and eight technology-specific indices; build a multifactor regression model for quantitative assessment of each technology's impact on overall attractiveness index formation; identify statistically significant technological drivers and perform analysis of synergistic effects of key technologies to understand their combined impact on market attractiveness.

2 METHODOLOGY

To assess factors that determine the investment attractiveness of renewable energy markets in the context of transition to energy independence and achieving grid parity, RECAI is used. The methodology for calculating this index is based on five key dimensions (energy imperative, policy stability, project delivery, capital availability, natural resource diversity), which are aggregated through a system of weighting coefficients into a composite index with scores from 1 to 5. Along with calculating the overall RECAI value, additional calculations are performed for the following technology-specific indices [7]:

- onshore wind – electricity generation using wind turbines located on land;
- solar photovoltaics (PV) – technology that converts sunlight directly into electricity using solar panels;
- concentrated solar power (CSP) – a system that concentrates sunlight using mirrors or lenses to heat fluid and generate electricity through steam turbines;
- biomass – energy production from organic materials such as wood, agricultural waste, organic waste, or specially grown energy crops;
- geothermal – utilization of Earth's internal heat for electricity generation or heating supply;
- hydro – electricity production by harnessing water power, typically through dams or micro-hydroelectric plants;
- battery energy storage systems (BESS) – electricity storage technologies, typically in lithium-ion batteries, for subsequent use during peak demand or when RES generation decreases.

These indicators are not directly included in the RECAI calculation methodology, but are used to identify countries with high technological potential in specific renewable segments while having deficiencies in other aspects of the investment climate. This allows for identifying market opportunities that may remain hidden when analyzing only the overall ranking [7].

2.1 Dataset

The empirical base of our study consisted of RECAI values and technology-specific scores (energy imperative, policy stability, project delivery, capital availability, natural resource diversity) for 2024 for the 40 most attractive countries for renewable energy investment worldwide: Argentina, Australia, Austria, Belgium, Brasil, Canada, Chile, China, Denmark, Egypt, Finland, France, Germany, Greece, India, Ireland, Israel, Italy, Japan, Kazakhstan, Mexico, Morocco, Netherlands, Norway, Peru, Philippines, Poland, Portugal, Romania, Saudi Arabia, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, Turkey, UK, US, and Vietnam.

Numerical calculations were performed using Statistica software [16] based on indicator values published in the "62nd edition of the Renewable Energy Country Attractiveness Index" [7].

2.2 Method

General Regression Models (GRM) represent a comprehensive statistical framework designed to examine relationships between dependent and independent variables across diverse data structures and distributions. The primary purpose of these models extends beyond simple linear associations to accommodate complex, non-linear patterns while providing robust parameter estimation and hypothesis testing capabilities. This methodological approach proves particularly valuable when analyzing composite indices and their underlying components, as it enables the decomposition of multifaceted constructs into interpretable individual effects [17].

The basic mathematical formulation follows the general structure:

$$Y = f(X_1, X_2, ..., X_k) + \varepsilon, \quad (1)$$

where Y represents the dependent variable, X_1 through X_k denote independent variables, $f(\cdot)$ describes the functional relationship, and ε captures the error term.

For multiple linear regression applications, this translates to

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + \varepsilon, \quad (2)$$

where β coefficients represent parameter estimates quantifying the magnitude and direction of each predictor's influence.

The model estimation typically employs ordinary least squares methodology, minimizing the sum of squared residuals:

$$\Sigma(Y_i - \hat{Y}_i)^2, \quad (3)$$

where $\hat{Y}_i$ represents predicted values.

Model performance evaluation relies on metrics such as R-squared, adjusted R-squared, and various information criteria, while statistical significance testing of individual parameters utilizes *t*-statistics and corresponding p-values to assess the reliability of estimated relationships.

3 RESULTS AND DISCUSSION

Table 1 presents the results of applying the GRM method to analyze the relationship between RECAI and the analyzed technology-specific indices of renewable energy technologies. The obtained results demonstrate a statistically significant impact of most technological indices on the formation of the overall attractiveness of renewable energy markets.

Solar PV emerged as the dominant technological driver. This indicator shows the most powerful impact among all technologies with an unstandardized coefficient of 0.43 ($p < 0.001$) and the highest standardized coefficient of 0.42. This confirms the critical role of solar photovoltaics in determining countries' investment attractiveness. Onshore wind ranks second in terms of impact (β = 0.34, standardized β = 0.32, $p < 0.001$), demonstrating the stable significance of onshore wind energy as a key factor in market attractiveness.

Technologies Solar CSP, Offshore wind, and BESS exert a moderate influence. Despite the negative unstandardized coefficient (-0.04), Solar CSP has a positive standardized effect, which may indicate complex interactions with other model variables. Offshore wind (β = 0.13, $p < 0.001$) and BESS (β = 0.18, $p < 0.001$) show a moderate but statistically significant positive impact, reflecting the growing importance of offshore wind energy and energy storage systems.

Table 1: Model parameter estimates.

Sigma-restricted parameterization									
	RECAI Param	RECAI Str. Err	RECAI *t*	-95,00% Cnf. Lmt Raw	+95,00% Cnf. Lmt Raw	RECAI β	RECAI Str. Err β	-95,00% Cnf. Lmt β	+95,00% Cnf. Lmt β
Intercept	15.22	3.50	4.36	0.01	8.10	22.35			
Onshore wind	0.34	0.05	6.27	0.00	0.23	0.45	0.32	0.05	0.21
Offshore wind	0.13	0.03	3.94	0.00	0.06	0.19	0.28	0.07	0.14
Solar PV	0.43	0.08	5.32	0.00	0.27	0.60	0.41	0.08	0.25
Solar CSP	-0.04	0.05	-1.20	0.243	-0.12	0.03	-0.10	0.09	-0.28
Biomass	0.03	0.05	0.56	0.58	-0.07	0.13	0.04	0.07	-0.10
Geothermal	0.03	0.03	1.06	0.30	-0.03	0.09	0.06	0.05	-0.05
Hydro	-0.06	0.03	-1.88	0.07	-0.12	0.02	-0.10	0.05	-0.20
BESS	0.18	0.04	4.66	0.00	0.10	0.26	0.33	0.07	0.19

Table 2: Test of SS Whole Model vs. SS Residual.

Dependent Variable	Multiple R	Multiple R^2	Adjusted R^2	SS Model	df Model	MS Model	SS Resid.	df Resid.	MS Resid.	F	*p*
RECAI	0.97	0.94	0.93	1333.21	8	166.65	83.94	31	2.71	61.55	0.00

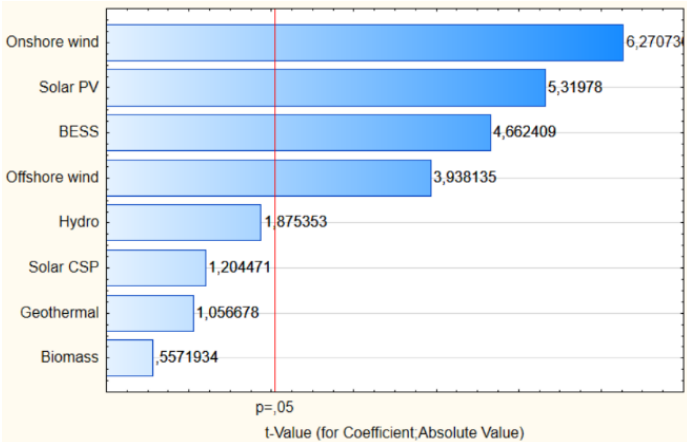

Figure 1: Pareto chart of t-values for coefficients.

Technologies with limited impact are Geothermal, Hydro, and Biomass. Geothermal energy demonstrates a statistically insignificant effect (*p* = 0.30), which is logically explained by its geographical specificity and limited resource availability. Hydro shows a weak negative impact (β = -0.06, *p* = 0.07), which may reflect the saturation of traditional hydroelectric capacity in developed countries or environmental constraints on new projects. Biomass has the smallest positive effect (β = 0.03, *p* = 0.59), remaining statistically insignificant, which may indicate limited investment interest in this technology at the global level.

Onshore wind, Solar PV, BESS, and Offshore wind have statistically significant coefficients ($t_{emp} > t_{table}$) even at the strict level α = 0.01. Hydro, Solar CSP, Geothermal, and Biomass do not achieve statistical significance ($t_{emp} < t_{table}$) at α = 0.05 (Fig. 1).

Table 2 presents the results of the multiple regression model.

Analysis of the regression model results demonstrates a differentiated impact of various renewable technologies on the formation of overall RECAI with high statistical significance for most predictors. The model reveals high explanatory power and statistical validity of the overall specification.

The F-statistic is 4.37 (*p* = 0.00), which confirms the statistical significance of the model as a whole and rejects the null hypothesis that there is no relationship between the predictors and the dependent variable. This indicates that at least one of the technology-specific indices has a significant impact on RECAI.

Based on the results of the conducted analysis, we constructed an analytical model of RECAI dependence on key technological drivers (the regression equation includes only statistically significant predictors):

$$RECAI = 15.22 + 0.34 \times Onshore\_wind + 0.431 \times Solar\_PV + 0.13 \times Offshore\_wind + 0.18 \times BESS. \quad (4)$$

The constant (15.22) represents the baseline RECAI value in the absence of technological indices influence, reflecting the minimum level of renewable energy market attractiveness regardless of specific technological capabilities. The Solar PV coefficient (0.43) is the largest among all predictors. This confirms the dominant role of solar photovoltaics in forming investment attractiveness. The Onshore wind coefficient (0.34) indicates a strong positive impact of onshore wind energy, confirming the critical importance of wind resources. The BESS coefficient (0.18) demonstrates the growing role of energy storage systems in market attractiveness assessment, reflecting the importance of energy infrastructure for renewable energy integration. The Offshore wind coefficient (0.13) shows a moderate but significant impact of offshore wind energy, which may reflect the more limited geographical availability of this technology compared to onshore alternatives.

The exclusion of statistically insignificant variables (Solar CSP, Geothermal, Hydro, Biomass) improves model efficiency and provides more reliable RECAI forecasting through key technological drivers.

To visualize the relationships between the four influential technological predictors and the dependent variable RECAI, we constructed three-dimensional diagrams (Fig. 2-7).

The interdependency diagram of RECAI, Onshore wind, and Solar PV (Fig. 2) demonstrates a quite steep surface rise, reflecting the strong positive impact of both technologies on RECAI. The highest investment attractiveness values are achieved only with simultaneously high indicators of both technologies, indicating their synergistic impact on the renewable energy market attractiveness.

Fig. 3 shows a three-dimensional diagram visualizing the relationship between RECAI, Offshore wind, and BESS. A less steep rise is observed compared to the previous visualization, which corresponds to the smaller regression coefficients of these technologies. The lowest RECAI values are concentrated in the area of low indicators for both offshore wind energy and energy storage systems. Maximum values are achieved only with high indicators of both technologies, but the overall variation range is smaller compared to the main technologies.

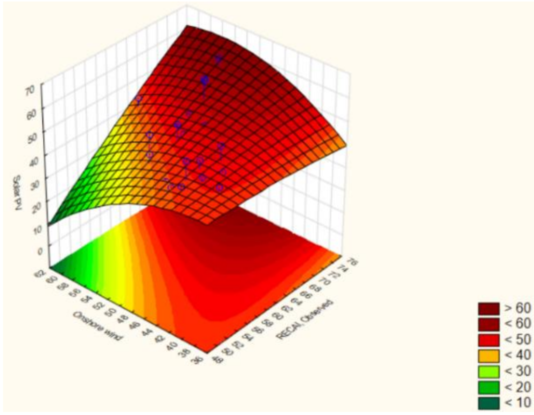

Figure 2: 3D Surface Plot of RECAI against Onshore wind and Solar PV.

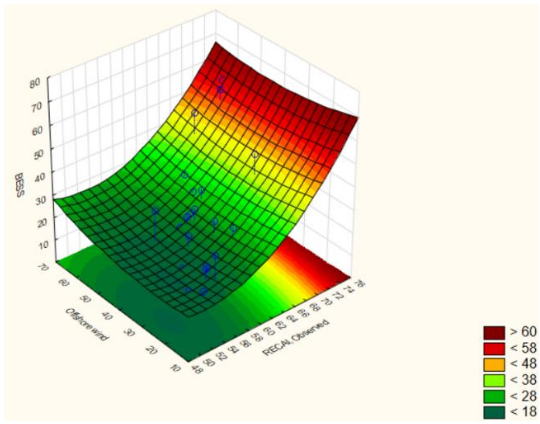

Figure 3: 3D Surface Plot of RECAI against Offshore wind and BESS.

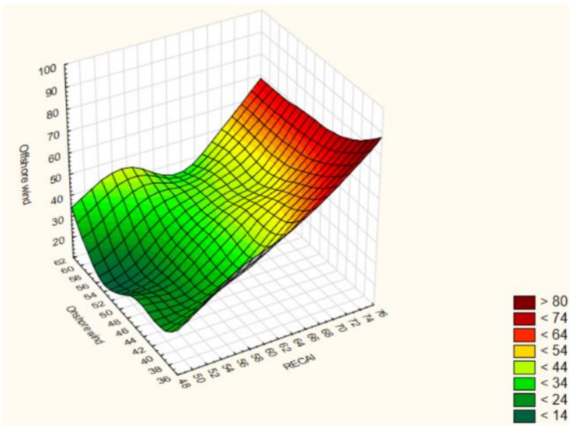

Figure 4: 3D Surface Plot of RECAI against Offshore wind and Onshore wind.

The diagram presented in Fig. 4 demonstrates a moderate synergistic effect between the two wind technologies. The surface has a smooth rise with a greater slope towards onshore wind energy, indicating its dominant influence on RECAI in this technology pair.

Fig. 5 shows an interaction diagram of energy storage systems with onshore wind energy. The surface demonstrates a uniform rise, where both technologies have approximately equal importance for forming high RECAI values, confirming their complementarity.

The 3D diagram shown in Fig. 6 displays a powerful synergistic effect between energy storage systems and solar photovoltaics. The surface has a steep rise, particularly pronounced in the Solar PV direction, which emphasizes the critical importance of this technology.

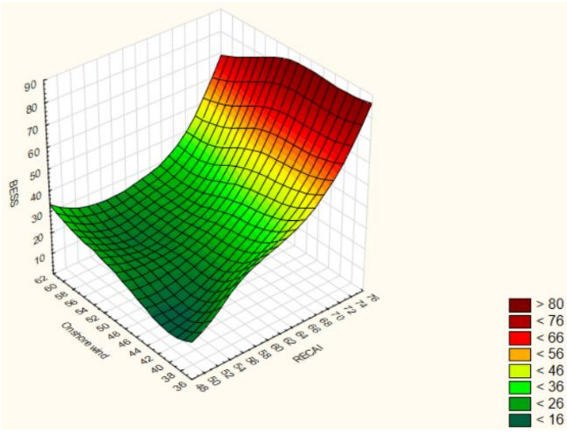

Figure 5: 3D Surface Plot of RECAI against BESS and Onshore wind

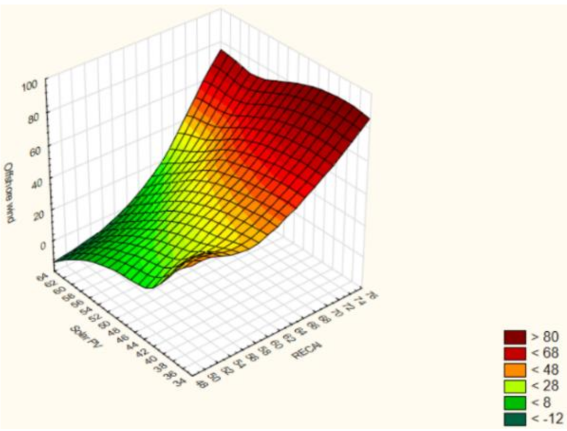

Figure 6: 3D Surface Plot of RECAI against Offshore wind and Solar PV.

The diagram presented in Fig. 7 demonstrates an asymmetric impact of technologies, where Solar PV has a significantly greater effect compared to offshore wind energy. The surface shows that solar energy is a key driver of high RECAI values in this combination.

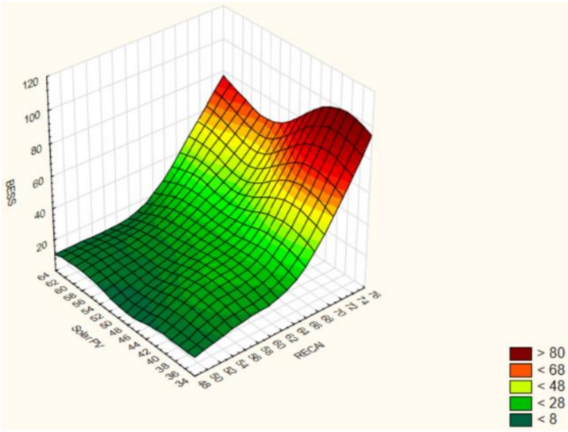

Figure 7: 3D Surface Plot of RECAI against BESS and Solar PV.

The results of the graphical analysis confirm the fundamental importance of synergistic development of renewable energy technologies for maximizing the investment attractiveness of markets, with Solar PV and Onshore wind acting as the most influential technologies, while Offshore wind and BESS play an important but supporting role in shaping overall market attractiveness.

5 CONCLUSIONS

The conducted study of the relationship between the Renewable Energy Country Attractiveness Index and technology-specific indices using General Regression Models allowed for the identification of key patterns in the formation of investment attractiveness of renewable energy markets and the identification of dominant technological drivers at the global level.

The results of the regression analysis demonstrate the differentiated impact of various renewable technologies on the overall attractiveness of markets. Solar PV and Onshore wind proved to be the most influential predictors with the highest statistically significant coefficients (0.43 and 0.34, respectively), confirming their critical role in shaping the investment climate. These technologies are characterized by the highest t-statistics (5.32 and 6.27), indicating the reliability of their impact on RECAI regardless of other factors.

BESS and Offshore wind demonstrated moderate but statistically significant positive impact on investment attractiveness with coefficients of 0.18 and 0.13 respectively. This reflects the growing importance of energy storage systems and offshore wind energy in the modern energy transition, although their impact is smaller compared to traditional renewable technologies.

The technologies Solar CSP, Geothermal, Hydro, and Biomass proved to be statistically insignificant predictors of RECAI, which can be explained by their geographical specificity, technological limitations, or saturation of corresponding markets. Particularly indicative is the insignificant impact of hydropower, which may reflect the depletion of traditional hydro resource potential in developed countries.

The three-dimensional visualization of relationships confirmed the synergistic nature of the impact of key technologies on RECAI, demonstrating that the highest levels of investment attractiveness are achieved with simultaneously high indicators of several renewable technologies. This emphasizes the importance of a diversified technological portfolio for maximizing market attractiveness.

The obtained results can provide relevant information to investors and policymakers regarding key technological drivers of investment attractiveness and contribute to the formation of more effective national renewable energy development strategies and optimization of investment portfolios in this sector.

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