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RESEARCH ARTICLE

ENERGY CONSUMPTION FORECAST FROM A SUSTAINABLE DEVELOPMENT PERSPECTIVE: 2035 PROJECTION WITH MACROECONOMIC INDICATORS

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Abstract

Predicting the future course of energy consumption in line with sustainable development goals plays a critical role in long-term planning processes in terms of resource management, environmental sustainability, and economic stability. Therefore, in this study, Turkey's energy consumption until 2035 was estimated using the Random Forest machine learning model developed based on macroeconomic indicators. In the modeling process, energy consumption, economic growth, inflation, industrial carbon dioxide emissions and population growth data between 1965 and 2024 were used. These data were obtained from the World Development Indicators (WDI, 2025) and World Energy Statistics (WES, 2025) databases. In the analysis, the Random Forest model, a machine learning method, was preferred. In the established model, energy consumption was estimated to account for the nonlinear and complex interactions of economic growth, inflation, industrial carbon dioxide emissions and population growth variables. The estimation results obtained with the Random Forest model show that Turkey's energy consumption in the 2025-2034 period will follow a fluctuating but generally upward trend. Non-linear transitions have been observed in the forecasts, especially in some years, where there have been sudden jumps and fixations.

Keywords: Energy Consumption, Sustainable Energy, Sustainable Development, Machine Learning
JEL Classification: Q41, Q56, O44

1. Introduction

The process of energy dependency worldwide, which started with the Industrial Revolution, continued throughout the industrialization period. However, towards the end of the 20th century, this energy dependence and usage process changed the agenda of all developed and developing countries owing to reasons such as global warming, climate change, and environmental pollution (IPCC, 2014:4-16; Stern, 2007:15-17). Environmental pollution, especially due to the use of fossil fuels, has become an important topic of discussion for sustainable living and the environment (Sorrell, 2010: 1794-1802; Çetin and Sezen, 2018:137). In particular, in the 20th century, the negative effects of carbon dioxide emissions on global warming and climate change have caused

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policymakers to focus on energy consumption (Shahbaz et al., 2012: 2948–2951). Therefore, to realize the ecological growth and development process, transformation policies have been implemented in the energy sector. In addition, with the 1973 Oil Crisis in the past, countries started to take measures against the consequences of their energy dependency (Hamilton, 1983: 228–240). In addition, the global warming process has caused countries to change their energy policies. Therefore, renewable energy consumption, other than fossil fuels, has started to be encouraged in industrial production and residential consumption. Simultaneously, apart from the initial investment cost of renewable energy, the long-term cost advantage has made the use of these energy resources important (Pata and Yurtkuran, 2018:304). In parallel, the Kyoto Protocol was signed in 1997 in Kyoto, Japan, in accordance with the United Nations Convention on Climate Change and the Environment. Kyoto Protocol: It is an international agreement that contains binding legal provisions for industrialized countries to reduce greenhouse gas emissions to combat global warming and climate change. In this context, the Kyoto Protocol, as a solution to climate change and increasing energy consumption and demand, emphasizes the use of alternative energy sources, that is, the use of renewable energy sources (Çetin and Sezen, 2018:137).

Energy has strategic importance in achieving sustainable development and development goals of developed, underdeveloped, and developing countries worldwide. Especially in the world, energy consumption and energy need are increasing day by day due to reasons such as industrialization, population growth, economic growth, development and welfare increase. Recently, the increase in energy consumption due to population growth continues with economic growth (Es, 2020:772). Therefore, energy appears as an indicator of social development as a requirement of modern life, and energy consumption per capita is considered an indicator of development (Smil, 2018: 1–30). Accordingly, it can be said that energy consumption significantly affects people's quality of life and welfare levels. Simultaneously, the development levels of countries with energy sources in today's world are high. However, the main problem here is that instability in the countries that hold energy resources endangers the security of the energy supply and causes the production costs of other energy-dependent economies to increase (Sadorsky, 2011: 741–743). This situation causes companies in the domestic market to lose their competitive advantages, disrupt long-term production plans, and delay investments in the energy sector. In addition, increases in energy costs cause macroeconomic stability to deteriorate due to high current account and foreign trade deficits (Apergis and Payne, 2010: 652–654). For this reason, determining and planning energy needs is of great importance in ensuring a sustainable energy management in an economy (Çeltek, 2024: 706-707).

The use of energy in society from the early ages of human history to the present day has made significant contributions to economic and social development. Simultaneously, it is important for ensuring and increasing the continuity of economic growth. Energy is considered the basic input of industrial production and one of the main factors that meet human needs. Therefore, there are important relationships between the amount of energy consumed in an economy and its economic performance. As the rate of economic growth increases, the amount of energy consumption also increases (Akbaş and Lebe, 2015:197). In particular, it is important to maintain uninterrupted energy consumption and supply to ensure the continuity of industrial production and continue its activities without interruption. In this way, the raw material processing capacities of the economies that ensure continuity increase; In parallel with the increases in export rates, foreign trade deficits are closing and foreign exchange reserves are increasing (Halmuratov et al., 2025: 23-26). However, high energy consumption increases environmental carbon dioxide emissions and environmental pollution. In the growth process, energy consumption also increases depending on the increasing production level. Simultaneously, the fact that the energy composition used in production consists of fossil fuels causes environmental pollution to increase even more (Pata and Yurtkuran, 2018:304). In recent years, due to increasing environmental problems, climate change, and environmental degradation in the world and Turkey, the amount of energy consumption of countries and the energy components they use have been examined. The world population is increasing day by day with economic growth, which causes the need for energy to increase. The consumption needs of the growing population are increasing; the increasing amount of consumption leads to an increase in the production of industrial and agricultural products. Because the main input of production is energy, increasing energy consumption further increases environmental degradation and pollution. Increased energy consumption and the high rate of fossil fuel use, which is the primary energy source, further increase carbon dioxide emissions. Therefore, the amount of investment in energy transformation has increased in all production industries worldwide. Environmental pollution can be reduced and environmental sustainability ensured, especially by increasing renewable energy investments (Efeoğlu, 2022:2104).

Uninterrupted energy access and energy supply security are essential for economic development and socio-economic progress. In the current global economy, the strong relationship between energy consumption and key macroeconomic indicators such as gross domestic product has become increasingly prominent (Apergis and Payne, 2010: 650-651). However, this relationship presents a complex dilemma at the heart of the United Nations' 2030 Agenda for Sustainable Development. On one hand, meeting energy demand to support economic growth and prosperity is a prerequisite for SDG 8 (Decent Work and Economic Growth); on the other hand, current energy consumption patterns based on fossil fuels pose a serious threat to SDG 13 (Climate Action), which aims to address climate change. At this juncture, SDG 7 (Affordable and Clean Energy), which ensures the security and accessibility of energy supply while promoting the transition to clean energy sources, plays a crucial role. Therefore, predicting future energy consumption trends based on macroeconomic variables is not only an economic forecasting exercise but also an indispensable tool for designing strategic policies to achieve a sustainable balance between these three key SDGs (IEA, 2023:61-82). This study aims to address this critical gap and provide a scientific basis for policymakers.

In terms of the Turkish economy, the decisions made on January 24, 1980, were an important turning point. These decisions ensured the integration of the country into the globalization trend, and the import substitution industrialization strategy was abandoned and an export-oriented strategy was adopted in its place. This process has initiated intense internal migration from rural areas to cities, resulting in an increase in the urban population. The per capita income and welfare levels of individuals who find job opportunities in cities have increased. The increasing level of welfare has increased the amount of energy consumed throughout the country by increasing individual consumption. From the post-1980 period to the present, Turkey's energy consumption has increased by 223%. The fact that most of the energy consumed consists of fossil fuels poses a major problem in terms of environmental and economic sustainability (Kardaşlar, 2022:386).

For these reasons, countries that are aware of their energy dependencies and engage in strategic energy planning will enable them to become resistant to possible energy crises. The use of alternative and renewable energy sources can reduce environmental pollution by reducing production costs, ensuring sustainable production performance, and enabling a strong political stance by reducing foreign dependency. In this context, this study aims to provide a perspective on the country's energy path by estimating energy consumption for the next 10 years in Turkey. In this direction, based on macroeconomic indicators, Turkey's energy consumption forecast for the next 10 years was realized using the machine learning method, and alternative solutions were offered. The use of machine learning, a new-generation estimation method, in the analysis reveals the original aspect of this study.

In line with these explanations, in the following sections of the study, first, a literature review on energy demand and consumption estimation will be presented, then the data used will be introduced, and the established model and descriptive statistics will be included. Finally, methodological explanations of machine learning analyses are presented, and the findings are discussed in the conclusion section.

2. Literature

When similar studies in the literature on this study, in which Turkey's energy demand in the next decade is estimated by a machine learning method based on the data of energy consumption, economic growth, inflation, carbon dioxide emissions, and population growth in Turkey between 1965-2024, it is seen that causality relationships, cointegration, or simpler regression models are generally used. However, machine learning models can provide more stable and reliable predictions with the ability to capture complex, nonlinear relationships between variables. Stern (1993), one of the prominent studies in this field, analyzed the causality relationship between GDP, energy use, capital, and employment in the USA between 1947-1990 and concluded that there is a causality relationship between energy consumption and GDP. Bekhet and Othman (2011) analyzed the causality relationship between electricity consumption, GDP, CPI, and foreign direct investment in the Malaysian economy between 1971 and 2009 using the vector error correction model (VECM) and concluded that there is a one-way causality relationship from electricity consumption to GDP, FDI, and inflation. Belke et al. (2011) analyzed the long-run relationship between energy consumption, real GDP, and energy prices in 25 OECD countries in the period 1981-2007 with panel cointegration and VECM methods. They concluded that there is a bidirectional causality relationship between energy consumption and economic growth. Shafiei and Salim (2014) analyzed the determinants of carbon dioxide emissions in OECD countries between 1980 and 2011 using the STIRPAT model and concluded that non-renewable energy consumption increases carbon dioxide emissions, whereas renewable energy consumption decreases carbon dioxide emissions. Begum et al. (2015) analyzed the dynamic effects of GDP, energy consumption and population growth on CO2 emissions in Malaysia between 1970 and 2009 using ARDL, DOLS and SLM U-test methods, and concluded that energy and its consumption and GDP have an effect on carbon dioxide emissions, but population growth does not have any effect on carbon emissions. Bozkurt and Okumuş (2015) analyzed the relationship between carbon dioxide emissions, economic growth, energy consumption, trade openness, and population density in Turkey between 1966 and 2011 using the Hatemi-J cointegration test and concluded that there is a cointegration relationship between the variables. Büyükyılmaz and Mert (2015) analyzed the relationship between carbon dioxide emissions, renewable energy consumption per capita and GDP per capita in Turkey between 1960-2010 with the multivariate Markov regime change model (MS-VAR), and concluded that the relationship between the variables in the analysis is not linear, varies according to the regimes, and there is a bidirectional causality relationship between them. Ekinci (2019) found that the ANFIS model predicts electricity consumption more accurately than the ANN model in his study, in which he comparatively analyzed artificial neural networks (ANN) and adaptive network-based fuzzy logic inference system (ANFIS) models in energy demand estimation based on electrical energy data in Turkey between 1970-2015. Yücesan et al. (2019) analyzed the effect of economic growth and energy consumption on carbon dioxide emissions based on 1988-2014 data for 8 middle-income countries (including Turkey) with panel data method, and concluded that there is a bidirectional causality relationship between energy consumption and economic growth and between carbon dioxide emissions and economic growth. Tong et al. (2020) analyzed the relationship between economic growth, energy consumption and carbon dioxide emissions in E7 countries (including Turkey) between 1990-2014 with the bootstrap ARDL bounds test method. They concluded that there is a causality relationship from energy consumption to carbon dioxide emissions in all E7 countries except Indonesia. Ülkü and Yalpır (2021) concluded that the artificial neural network method provides more effective results in electricity estimation. In their study, they estimated the electrical energy demand for 2030 with artificial neural networks and multiple regression analysis methods, based on the energy consumption data between 2009-2018 in Turkey. Özdemir (2021) concluded that the artificial neural network method has high predictive power and can be used in medium-term predictions in his study in which he made medium-term electricity consumption estimation with the artificial neural network method between 2011-2020 in the Iskenderun region of Turkey. Kazanasmaz et al. (2023) analyzed the relationship between economic growth, electricity consumption and carbon emissions in Turkey between 1967-2017 with vector error correction model (VECM), Granger causality and Johansen cointegration tests, and concluded that electricity consumption positively affects economic growth in the long run, while carbon dioxide emissions affect negatively in the long run. Özekenci (2023) concluded that there is a statistically significant and positive relationship between carbon dioxide emissions and foreign direct investments, and energy consumption in their study, in which they analyzed the effect of exports, energy consumption, foreign direct investments (FDI), and economic growth on CO2 emissions in Turkey between 1990-2015 using the ARDL limit test and VECM methods. Gök and Yıldız (2024) analyzed the relationship between economic growth, energy consumption, carbon dioxide emissions, and urbanization in MIST (Mexico, Indonesia, South Korea, and Turkey) countries between 1971-2014 using Durbin-Hausman and LM cointegration tests and concluded that there is a cointegration relationship between the variables.

When the existing studies in the literature are examined, it is seen that the relationships between economic growth, energy consumption, and carbon dioxide emissions have been analyzed retrospectively by econometric methods such as causality and cointegration (Bekhet and Bt Othman, 2011; Belke et al., 2011; Kazanasmaz et al., 2023) or future demand forecasts are made with models such as artificial neural networks (Ekinci, 2019; Ülkü and Yalpır, 2021). In this study, contrary to the studies conducted in the literature, an energy consumption forecast until 2035 is made within the framework of sustainable development goals by combining basic macroeconomic indicators such as economic growth, energy, and population with a sectoral environmental pollutant and price stability indicator, rather than only determining the retrospective causality relationship between variables or estimating with a specific methodology. Therefore, while this multidimensional approach offers a more holistic perspective on energy planning, it differs from other studies in the literature in that it makes more robust and realistic predictions by evaluating economic, environmental, and social factors together. Thus, this study differs from other studies in that it not only predicts energy demand but also provides a policy-oriented and forward-looking roadmap on how this demand can be aligned with sustainable growth goals, filling the gap in the existing literature.

3. Dataset and Model

In this study, Turkey's future energy consumption is estimated within the scope of sustainable development goals, and the effects of economic growth, inflation, industrial carbon dioxide emissions, and population growth on energy consumption are examined using data from to 1965-2024. In the analysis, the Random Forest method, which is a machine learning method, was used. This method can be used to model nonlinear and complex relationships between input variables (economic growth, inflation, industrial carbon dioxide emissions, and population growth) and output variables (energy consumption). The data used in this study were obtained from the World Development Indicators (WDI, 2025) and World Energy Statistics (WES, 2025) databases. In this study, a linear model, which is frequently used in the literature, was chosen to analyse the basic macroeconomic factors that determine energy consumption. The estimated model is expressed as follows:

$$Energy_t = \beta_0 + \beta_1 GDP + \beta_2 Inf + \beta_3 Indust\_CO_2 + \beta_4 \mathrm{Pop} + \varepsilon_t$$

In the model, energy consumption (Energy) is the dependent variable. The energy variable refers to the total primary energy consumption (Energy). The data are in Mtoe (million tonnes of oil equivalent) and adjusted for constant prices. Energy types are not separated in the series; renewable and non-renewable resources are included together in the total energy consumption. This choice was made to ensure that the macro-level effects of energy use were evaluated holistically in the analysis. The variable in question is directly related to SDG 7 (Affordable and Clean Energy). The GDP variable is the growth rate of the Real Gross Domestic Product (GDP). It has been included to assess the environmental impacts of economic growth and ensure the integration of SDG 8 (Decent Work and Economic Growth) and the model. The Inf variable is the annual inflation rate, based on the consumer price index. It is included in the model as an indicator of the macroeconomic stability. Internal interactions are controlled by considering the effects of inflation on both growth and energy demand. $Indust\_CO_2$, Represents CO_2 emissions from industrial sources. This variable is considered a key indicator directly linked to SDG 13 (Climate Action) and represents the environmental costs of energy consumption. As industrial emissions constitute a significant subset of energy-related emissions, they hold a critical place in the environmental sustainability framework that the study focuses on. Pop, this variable shows the proportional change in the total population. It is included in the model to reflect the long-term pressure on energy demand and emissions. There are also aspects that overlap with SDG 11 (Sustainable Cities and Communities) and SDG 3 (Health and Wellbeing). Within the framework, the function defined based on the obtained data is expressed as follows:

Energy Consumption = f (Economic Growth, Inflation, Industrial Carbon Dioxide Emission, Population Growth)

Here, the function "f" represents the complex relationship between the input and output variables. By learning this function, the Random Forest model analyzes in depth how each variable, alone and in combination with other variables, affects energy consumption. In this context, the descriptive statistics of the variables used in the analysis are presented in the table below:

Table 1: Descriptive Statistics on Variables

Variables	Energy Consumption	GDP	CO_2 Emissions	Inflation	Population
Average	708.3643	4.7249	22.6189	34.2865	1.6623
Median	579.2473	5.0395	20.8623	21.4148	1.6707
Maximum	1667.24327	11.4393	54.2197	105.2149	2.5965
Minimum	84.6708	-5.7500	5.3762	1.1196	0.1608
Std. Error	496.9684	3.9304	16.2971	28.7002	0.5763
Skewness	0.5273	-0.7033	0.5093	0.7215	-0.414
Kurtosis	1.9566	3.3650	2.0480	2.2381	2.7965
Jarque-Bera	5.5023	5.2808	4.8601	6.6580	1.8211
Probability	0.0638	0.0713	0.0880	0.0358	0.4022

When the descriptive statistics of the dataset in the table and defined in the function are examined, significant differences in the distribution characteristics of the variables are observed. The variables of energy consumption and carbon dioxide emissions exhibited a right-skewed distribution, with limited differences between the mean and median values and positive skewness coefficients. In contrast, the GDP variable has a left-skewed structure with a negative skewness coefficient. The inflation variable, on the other hand, shows both high variance and positive skewness, and according to the result of the Jarque-Bera test, the normal distribution assumption cannot be rejected. Simultaneously, the assumption of normality in the variables of energy consumption, GDP, carbon dioxide emissions and population could not be rejected. When kurtosis values were examined, it was found that the variables of energy consumption and carbon dioxide emission were flattened; It was determined that the GDP variable showed a sharp distribution.

4. Random Forest Model

The Random Forest method has been proposed as a method that can work as a classification and regression algorithm that creates a tree structure by using random vectors sampled based on the input vector developed by Ho in 1998 and Breiman in 2001 (Orhan and Sağlam, 2023:178). The Random Forest method is based on a decision tree-based machine learning algorithm. It is considered one of the approaches that provides the most stable results among the machine learning methods. This method is created by generating more than one decision tree structure and is therefore called a "forest." In the Random Forest model, the number of trees (N) and the number of variables to be randomly selected in each tree (m) are determined exogenously. Each tree structure is created through variables randomly selected from the training data and is therefore defined by the expression "random" (Sevgen and Aliefendioğlu, 2020:304).

In the Random Forest method, each randomly generated decision tree structure is considered to be of equal importance. In this respect, Random Forest, which is among the supervised machine learning algorithms, is based on a set of randomly generated decision trees. Based on the averages of the created random decision trees, reliable and stable results can be produced (Orhan and Sağlam, 2023:178). The Random Forest algorithm is a fast-running model that produces stable and consistent results for both small and large sample groups. In this context, the Random Forest algorithm produces effective and consistent results for both regression and classification problems (Sungur and Bakır, 2024:50). In this model, obtaining effective and consistent results in solving classification and regression problems, which form the basis of other supervised and unsupervised machine learning methods, is considered one of the biggest advantages of the model. Another advantage of the Random Forest model is that it eliminates the problem of memorizing data because decisions are made based on the averages of the randomly generated decision tree regression (Arslankaya and Toprak, 2021:182). Therefore, the stochastic decision tree structures created using the Random Forest method can be created in the form of both a classification tree and a regression tree. For this reason, the nodes in the created decision tools are segmented based on an optimization logic within themselves (Kumral et al., 2022:1318).

In the Random Forest method, multiple randomly generated decision trees are built for the same dependent variable, and the final decision is made with an optimization based on majority selection. In this direction, the decision tree structure created is the estimation of the nth random tree obtained from the set of N different regression trees;

$$\hat{C}_{rf}^{N} = \frac{1}{N}\{\hat{C}_N(X)\}_1^N$$

It is expressed as. In this context, Random Forest regression is expressed as a learning algorithm created by taking regression averages for each randomly generated dataset. Therefore, there are two important variables in the regression algorithm, namely the parameter and the number of trees (Akay et al., 2019:8-9).

5. Empirical Applications

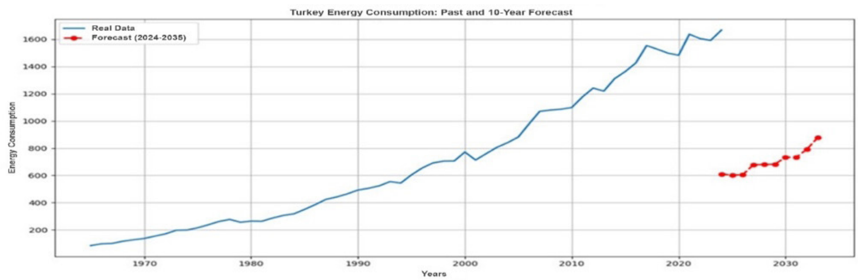
The Random Forest method, which is a machine learning model, can directly learn the intrinsic trends and seasonal patterns in the data structure. Therefore, the unit root test, that is, whether the data used in the analysis are stationary or not, is not a mandatory prerequisite for predictions made with such models. Therefore, based on the previous year's data in the analysis function, an estimate of the direct energy consumption can be made. The results of the energy consumption estimation within this framework are presented in table below.

Table 2: Energy Consumption Estimation Results

Duration	Years	Estimated Energy Consumption
Year	2025	609.882019
Year	2026	602.453446
Year	2027	604.564837
Year	2028	678.888830
Year	2029	679.590310
Year	2030	682.320063
Year	2031	732.639448
Year	2032	732.639448
Year	2033	791.953484
Year	2034	876.833310

The table shows the estimated energy consumption values obtained from the Random Forest regression model between 2025 and 2034 in Turkey. The established Random Forest model made predictions for the next decade based on the data of the past year and predicted that energy consumption would generally fluctuate but follow an upward trend. Although the estimated energy consumption in 2025 is 609.88 units, this value is predicted to increase to 876.83 units in 2034. However, the estimated results show nonlinear transitions between years. In particular, there is a significant jump in 2028, and a relatively flat course is observed in the following years (for example, the same consumption value is repeated in 2031 and 2032). This shows the sensitivity of the model to fluctuations in the input variables and that energy can increase unsteadily over the years.

Chart 1: Turkey's Energy Consumption Estimation Graph



In the graph, the years are on the horizontal axis and the energy consumption amounts are on the vertical axis. The historical data shown by the blue line indicate a generally stable and ever-increasing trend in energy consumption since 1965. The forecast values shown by the red dots represent the energy consumption levels predicted by the model for the post-2024 period. According to the estimation results obtained from the study, energy consumption in Turkey has fluctuated over the years and is expected to increase towards 2034. This shows that the model is highly sensitive to annual changes in input data, such as inflation, GDP, carbon emissions, and population growth. The rise observed, especially after 2028, shows that the model responds to the acceleration in economic growth or demographic factors. In this context, the heat map showing the Pearson correlation coefficients between the variables used in the energy consumption estimation with a color scale is shown in figure below.

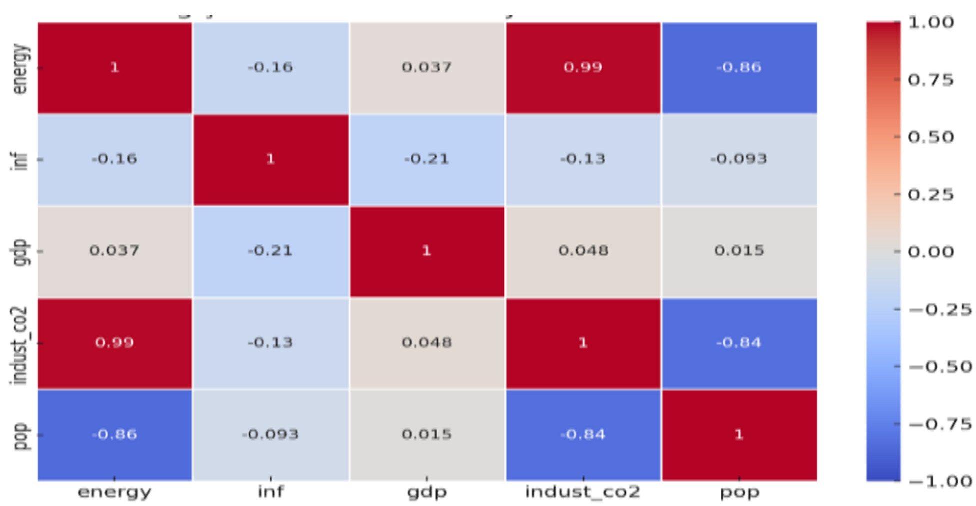
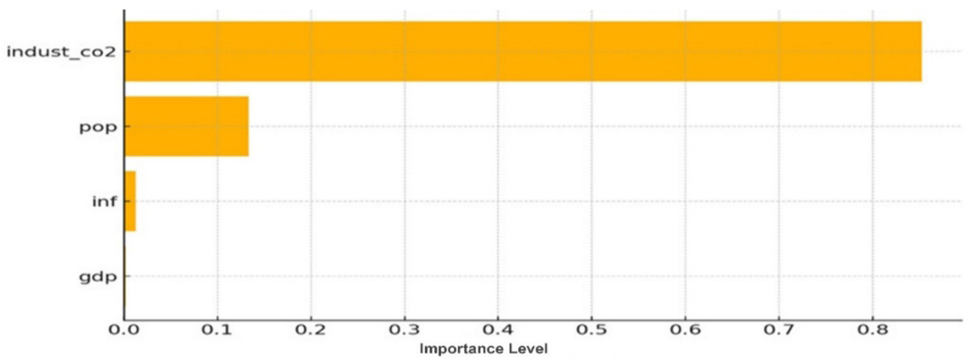


Figure 1: Inter-Variable Correlation Heatmap

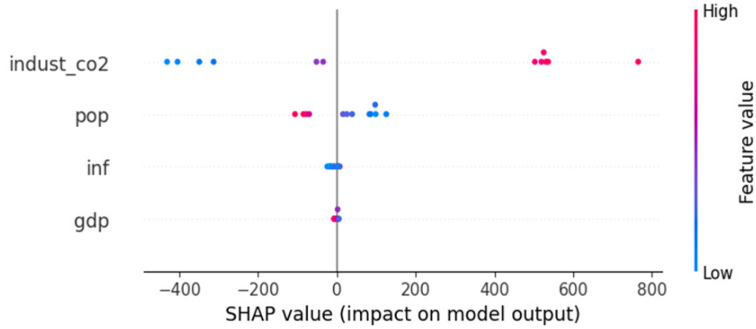
According to the Pearson correlation coefficients in the figure, the most striking relationship between the variables was observed between energy consumption and industrial carbon emissions (r ≈ 0.99), indicating that industrial activities are directly related to energy demand. There is also a strong negative relationship between energy consumption and population (r ≈-0.86). This situation can be evaluated as a decrease in energy use per capita despite the increasing population or that population growth is balanced by factors that increase energy efficiency. However, the correlation between energy consumption and GDP appears to be quite low (r ≈ 0.04), which can be considered a direct and strong effect of economic growth on energy consumption in the model. The inflation variable, on the other hand, exhibits weak relationships with all other variables. As a matter of fact, the graph showing the level of importance of the variables in the analysis is given below.

Chart 2: Importance Level Graph for Variables



The relative importance of the independent variables on energy consumption was presented according to the Random Forest regression model. The variable to which the model attributes the most weight is industrial carbon dioxide emissions (indust_co2), and the importance coefficient of this variable was calculated as 0.852. This high rate clearly shows that the most direct determinant of energy consumption is the emissions from industrial activities. The population (pop) variable ranked second in the model and contributed 0.133. This indicates that demographic factors are important determinants of energy consumption. In contrast, the variables inflation (inf) and GDP (GDP) have very low significance values (0.0128 and 0.0020). This shows that the model could not detect the decisive effect of these economic indicators on energy consumption during the learning process. In particular, the low effect of GDP coincides with the weak correlation (r ≈ 0.04) obtained in the correlation analysis. In general, the model considers environmental (emission) and demographic (population) variables to be more deterministic.

Chart 3: SHAP (SHapley Additive exPlanations) Value Summary Chart



The figure presents a SHAP (SHapley Additive exPlanations) summary that visualizes the relative effects of the four key independent variables used in the model on energy consumption. This graph describes not only the order of importance of variables, but also the direction and magnitude of the effect of variable values on the model output. The horizontal axis shows the contribution (positive or negative SHAP value) of the variable on the energy consumption estimate for each observation; The color scale indicates whether the value of the variable in question is low (blue) or high (red).

According to the findings in the graph, the industrial carbon dioxide emission variable stands out as the most dominant determinant in the model. High industrial CO_2 emission values (red) strongly increase the estimated energy consumption; Low emission values (blue) have a reducing effect on consumption. This situation reveals that there is a positive and strong relationship between energy consumption and the environmental reflection of industrial activities. In addition, this finding is consistent with previous variable significance analyses. The population variable, which ranks second, produced both positive and negative SHAP values in the model's estimates. This shows that the effect of population growth on energy consumption varies, that is, it does not have a one-way effect. Under certain conditions, the model considered population growth as an energy consumption enhancer, while in some cases it attributed limiting or neutral effects.

In contrast, inflation and gross domestic product variables have a lower impact on the model. The SHAP values of both variables are largely concentrated in the center of the horizontal axis, and their effects on energy consumption are limited. In particular, the fact that the SHAP values of the gross domestic product variable are almost zero shows that this variable does not make a significant contribution to the model output and is not directly related to energy consumption.

6. Result and Conclusion

In this study, Turkey's energy consumption projection was considered from a sustainable development perspective and modeled using the Random Forest algorithm based on macroeconomic indicators. Estimates up to 2035 were obtained based on key indicators such as energy consumption, economic growth, inflation, industrial carbon dioxide emissions and population growth for the period 1965–2024. The findings reveal that energy policies should be restructured not only on the axis of economic indicators, but also in a way that takes into account environmental and demographic dynamics.

According to the estimates made with the Random Forest model, Turkey's energy consumption generally follows an upward trend in the 2025-2034 period. However, this increase does not exhibit a linear structure, but reveals a fluctuating appearance with periodic jumps and stagnation. Especially in 2028, a significant jump is observed; In the following years, consumption values are fixed from time to time. This shows that the model is sensitive to annual changes in the variables it uses as inputs; thus, changes in economic, environmental, and demographic conditions can cause significant fluctuations in energy demand. Correlation analysis and SHAP value analyses allow us to understand the inner workings of the model in more depth. According to the Pearson correlation coefficients, there is a very strong positive relationship between energy consumption and industrial carbon dioxide emissions ($r \approx 0.99$). This finding clearly establishes the dominant role of industrial activities in energy demand. On the other hand, a strong negative relationship ($r \approx -0.86$) was found between energy consumption and population. This situation can be evaluated as a decrease in energy use per capita, especially despite the recent population growth, or that the increasing population is balanced by more efficient energy systems. Traditional economic indicators such as gross domestic product (GDP) and inflation, on the other hand, do not show a significant relationship with energy consumption. In particular, the correlation value of GDP and the contribution of SHAP have been close to zero. This result can be expressed as the effect of economic growth on energy consumption in Turkey is limited or indirect. According to SHAP analysis, the variable with the greatest impact on energy consumption is carbon emissions from industry. The model considered this variable as the most important determinant. The population variable is in second place, but its effect varies in positive and negative directions. This shows that the impact of the population on energy consumption can vary depending on certain conditions. Inflation and GDP variables, on the other hand, have a limited impact on the model in terms of both their importance and contribution.

These findings point to several key points in guiding energy policies. First, the fact that emissions from the industrial sector are the strongest determinant of energy consumption shows that the industry should be at the center of environmentally oriented policies and energy efficiency strategies. Promoting low-carbon technologies for industry, increasing investments that provide energy efficiency in production processes, and gradually implementing environmental regulations such as carbon taxes can both reduce energy demand and contribute significantly to environmental sustainability. Secondly, the variability of population growth reveals that energy planning should be differentiated at local and regional levels. In large cities, it is important to increase the capacity of the energy infrastructure depending on the population density and to manage the energy demand sustainably. Energy-efficient housing projects, smart city applications, and regional energy policies are among the priorities in this area. Third, traditional economic indicators, such as GDP and inflation, have a limited impact on energy consumption, suggesting that energy policies may not be directly aligned with economic growth targets.

In general, the findings of this study show that environmental and demographic factors are key determinants of Turkey's future energy consumption, emphasizing that energy policies should be reshaped from a sustainable development perspective. Achieving the balance between energy supply security, reducing environmental impacts and meeting societal needs may be the main strategic goal of energy management in the 2035 and beyond period.

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