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An Artificial Neural Network Approach to Predict Environmental Impact of Wind Energy Consumption-A Case Study

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Abstract
In this paper, we present an approach to predict carbon emissions and renewable energy consumption using artificial neural network (ANN). To determine the model relationships between the input variables and the expected carbon emissions and energy consumption, a multilayer forward ANN is used. Experimental results demonstrate that proposed ANN model provides accurate results between predicted and actual values. The results of this study may guide decision makers to select the most efficient combination of renewable energy sources including wind, hydropower and solar, and conventional energy sources including oil and natural gas, in order to meet the growing energy demand while reducing carbon emissions in developing countries.

Keywords: Artificial neural network, Wind energy in Turkey, Renewable energy resources, Carbon emissions.

1.Introduction

With a high growth rate in population and the rapid economic development, energy demand in developing countries has increased rapidly in last two decades. To meet this energy demand, more energy resources, specially, oil and coal, have been used [1]. As a result, carbon dioxide (CO_2) emissions, which is one of the main reasons of climate change, have increased over the years [1], [2]. It is estimated that total CO_2 emissions in world may increase between 9%-27% by 2030, due to using existing energy sources [3]. To decrease the growing rate of CO_2 emissions, especially in developing countries, renewable energy sources including geothermal, solar and wind, should be used widely around the world [4].

Being one of the fastest growing country among Organization for Economic Co-operation and Development (OECD) members, Turkey's energy demand has been increasing and it is listed as 6th largest economy among European countries. Turkey's electricity demand has increased with an annual growth rate of 5.5% since 2002 [5], [6]. The electricity consumption was 305.5 TWh in the year 2018. Due to this high consumption rates, Turkey is listed one of the world's top 20 energy-consuming countries. [7], [8]. Based on current data, Turkey's electricity consumption rate in the year 2023 is predict to rise by 5, 5% to 357, 4 TWh [9].

In Turkey, most of the energy demand is satisfied by the imported non-renewable sources, including natural gas and oil. To reduce this energy dependency, Turkey should create its own energy resources for a sustainable economic growth. For developing countries, to have sustainable economy, they should use their own resources. Therefore, if Turkey wants to meet at least 30% of the total electricity demand from renewable energy resources by 2023, it should increase the renewable energy resources, not just for the sustainable economic growth but also for reducing environmental effects [8],[10]. Figure 1 shows the electricity consumption using different energy sources between years 2000 and 2018. Based on most current data provided in 2019, the electricity production of Turkey is listed as; 28.6%-natural gas, 22.4%-coal, 31.4%-

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hydropower, and 8.1%-wind, 1.6%-geothermal, 6.2%-solar energy and 1.7%- other sources. [9].

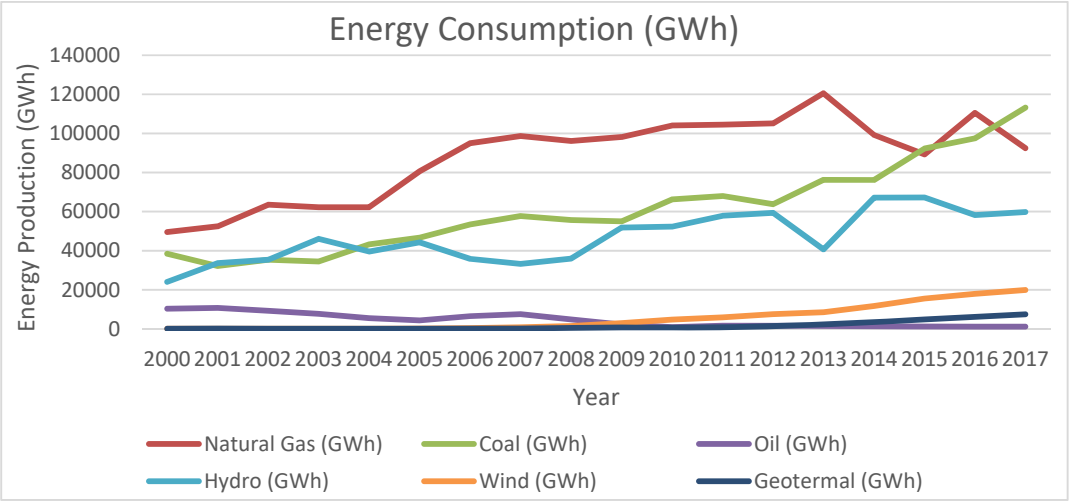

Figure 1. Energy consumption between years 2000-2017 [7]

As it can be seen from recent data, to achieve the sustainable development goals (SDGs) especially SDG#13, Turkey started using alternative energy resources, such as wind and solar energy due to their low CO_2 emissions in recent years [5]. Compare to other energy sources, wind energy is responsible for only 0.02 to 0.04 pounds of CO_2 equivalent per kilowatt-hour (CO_2E/kWh); solar 0.07 to 0.2 pounds of CO_2E/kWh; geothermal 0.1 to 0.2 pounds of CO_2E/kWh; and hydroelectric between 0.1 and 0.5 pounds of CO_2E/kWh. Instead, natural gas emits 0.6 to 2 pounds CO_2E/kWh; coal emits between 1.4 to 3.6 pounds of CO_2E/kWh [2].

Preferring wind energy due to its low CO_2 emissions can be one of the reason but considering the land of Turkey, 37% of its land has relatively high wind energy potential, makes this energy attractive over other renewable energy resources. Besides, available land, Turkey has been introducing incentives for companies who invest wind power plants. Therefore, considering the low environmental impact and high energy potential of the land, to satisfy growing energy demand, wind energy can become a promising energy resource in Turkey for the near future [11].

The purpose of this paper is to analyze the complex relationships between variables that effect wind energy consumption rate and CO_2 emissions by using the artificial neural networks (ANN) model. This proposed ANN model closes the research gap by contributing followings:

- To the best of our knowledge, the proposed ANN model is the first model that examines the effect of nine different input variables for predicting wind energy consumption rate and associated carbon emissions in Turkey.
- This study includes compression of wind energy and natural gas energy consumption cost and CO_2 emissions derived from both sources to suggest a comprehensive policy framework towards CO_2 emissions reduction. Also, this study may guide decision makers to select the most efficient combination of renewable energy sources including wind, hydropower and solar, and conventional energy sources including oil and natural gas, in order to meet the growing energy demand in Turkey.
- In addition, the proposed method is tested with wind energy and CO_2 emissions data of Turkey in 2000-2019. Thus, this paper also provides detailed energy data to researchers and decision makers involved in renewable energy sector in Turkey.

This paper is organized as follows. In section 2, we provide the literature review. A proposed model structure is outlined in section 3 and input parameters are then presented in sections 3.1. In section 4, the model results are given. Finally, in section 5, we summarize the study findings and conclusions as well as recommendations for future research.

2.Literature Review

In literature, many studies have been completed to analyze the relationship between emissions and energy consumption of renewable energy resources using conventional statistical approaches. Some of these methods are, time series models, regression models, econometric models, decomposition models, integration models, ARIMA models, artificial neural-network models, and so on. Among these techniques, predictions with ANN technique is found to be much more accurate which require small training datasets, more sensitive to noise, and high capability of handling missing data [12, 13]. Due to increasing demand for renewable energy resources, it is important to predict amount of energy needed for future use as well as amount of emission reduction will be achieved by using the renewable energy resource. Therefore, the purpose of this paper is to analyze the complex relationships between variables that effect CO_2 emissions and alternative energy resources by using the ANN model. In the following section, we summarize some of the recent studies conducted using ANN for CO_2 emission prediction for renewable energy resources.

Bilgili [14] used ANN, linear and nonlinear regression methods to estimate the electricity consumption of two different sectors, residential and industrial, in Turkey. In this study, four variables including installed capacity, gross electricity production, population and total subscribership were selected as independent. Based on the results of the three methods, ANN method gave better performance values than both linear and nonlinear models [14].

Vinnychuk et al. [15], used the ANN to predict the amount of emissions using the economic growth as one of main variable for countries under the World Bank classification by the income level. Also, various other factors that have the greatest impact on the predicted rate of CO_2 are analyzed in the article. Using the results of the analysis, one select a set of independent variables, which may provide a better prediction of the studied parameters. This will help to make appropriate economic decisions in order to achieve economic growth in a sustainable development.

Heydari et al. [16] used generalized regression neural network and grey wolf optimization method to forecast the CO_2 emissions from different energy sources, including coal, natural gas, petroleum and renewable energies in Iran, Canada and Italy. It was observed that the methods used are very effective to predict the CO_2 emissions from different energy resources.

Mason at al. [17] used an evolutionary optimization algorithm, covariance matrix adaptation evolutionary strategy, to train neural networks to forecast short term power demand, wind power generation and carbon dioxide emission rate in Ireland. This method provided fast convergence and more accurate predictions and robust performance.

Hossein et al. [18] used ANN model to determine the CO2 emissions from different energy sources. In their study, GDP is used as an economic indicator for five countries. The results showed the ANN model gives accurate predicting for CO_2 emissions.

Khan and Khan [19] used the adaptive neuro-fuzzy inference system model against conventional techniques for the CO_2 emissions prediction. The correlation coefficient for these two models were 0.93 for ANN and 0.69 for conventional method, respectively. It was concluded that ANN model is more accurate than the conventional methods.

3. Proposed Artificial Neural Network (ANN) Model Structure

ANN is a machine learning (ML) methodology that models the information processing capabilities by imitating the biological neural networks in the human brain process. The basic structure of Ann consists of

three layers, namely, input layer (entry layer), hidden layer (mid layer) and output layer which is given by Figure 1 [20], [15]. In the first step, the information (independent variables) is transmitted to the network through the input layer. Second, the information is processed in hidden layer, and then sent to the output layer. In this study, backpropagation neural network is used [21].

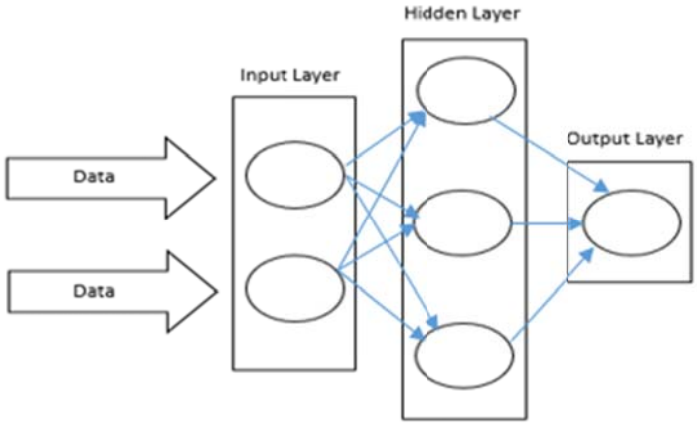

Figure 2. A typical two layer neural network

In this study, a multi-layer feed forward network was used and proposed network consists of an input layer, one hidden layer, and output layer. The input layer consists of eight inputs data total energy consumption, wind, hydropower, geothermal, natural gas, oil, coal, electricity consumption per capita and Gross Domestic Product (GDP-current US$) are used to estimate the wind energy CO_2 emissions covered the years 2000-2018. The hidden layer function is a nonlinear and consists of 3 neuron. The general structure of ANN model proposed in this study is depicted in Figure 3.70% of given data is used for learning, 15% of given data is used for validation and 15% of given data is used for test group.

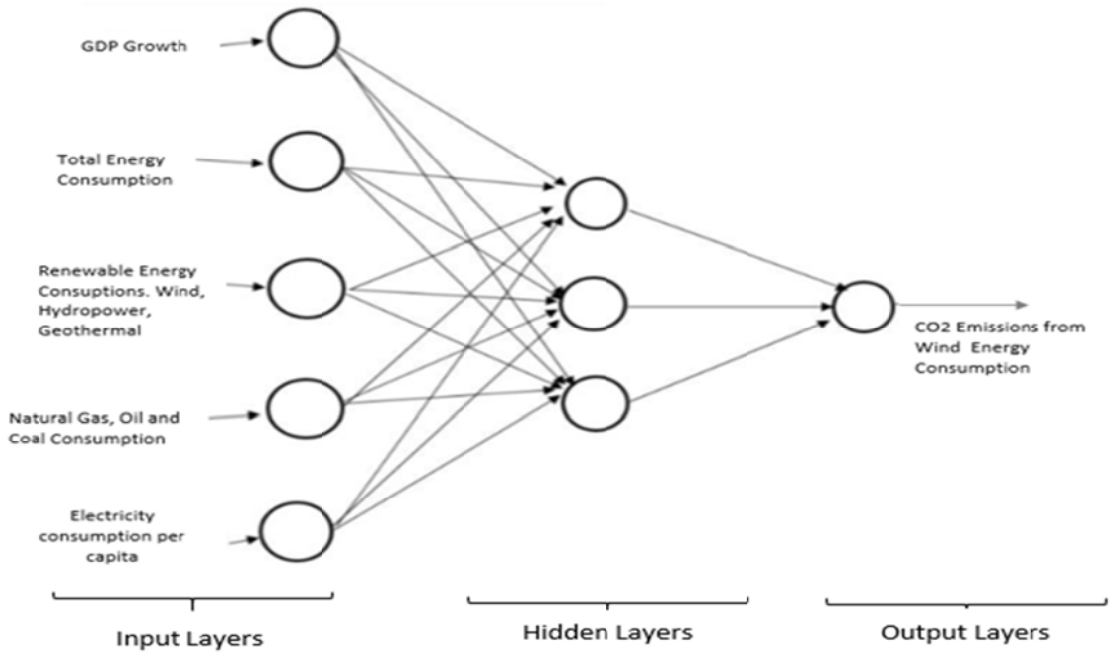

Figure 3. Typical processing elements of an artificial neural network

3.1 Data Set

Independent variables used in this study are total energy consumption, renewable energy consumptions (wind, hydropower, geothermal), natural gas, oil, coal, electricity consumption per capita, whereas the dependent variable is CO_2 emissions from wind energy. The data set used in the analysis is gathered from World Bank, World Development Indicators. The raw data to be used in the development of the ANN must be normalized to see the fluctuations more clearly and to prevent the mistakes in the learning process. In this study, max-min normalization techniques is used and equation 1 is as follows:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

As it mentioned in previous section, each energy source has different CO_2 emission rates (Table 3). Based on energy consumption for each source in Turkey, we calculated the total CO_2 emissions respected to the different energy sources between years 2000-2018. Figure 4 shows the normalized input variables and the corresponding CO_2 values of different energy resources for the years 2000-2019. The cost data for different energy production methods was shown in Table 4.

Table 3. CO_2 emissions rates for different energy sources [22]

Energy Source	**CO_2** *(pounds/kWh)*
Wind	0.02-0.04

Solar	0.07- 0.2
Geothermal	0.1-0.2
Hydroelectric	0.1-0.5
Coal	1.4-3.6
Natural	0.6-2
Oil	1.12

Table 4. Electricity generation costs by fuel type (cent/kWh) [11]

Power source	**Minimum** ***(cent/kWh***	**Maximum** ***(cent/kWh)***
Large hydropower	3.0	13.0
Small hydropower	4.0	14.0
Wind	4.7	7.2
Geothermal	4.7	7.8
Hydraulic	5.2	18.9
Solar PV	28.7	31.0
Natural gas	4.3	5.4
Coal	4.5	7.0

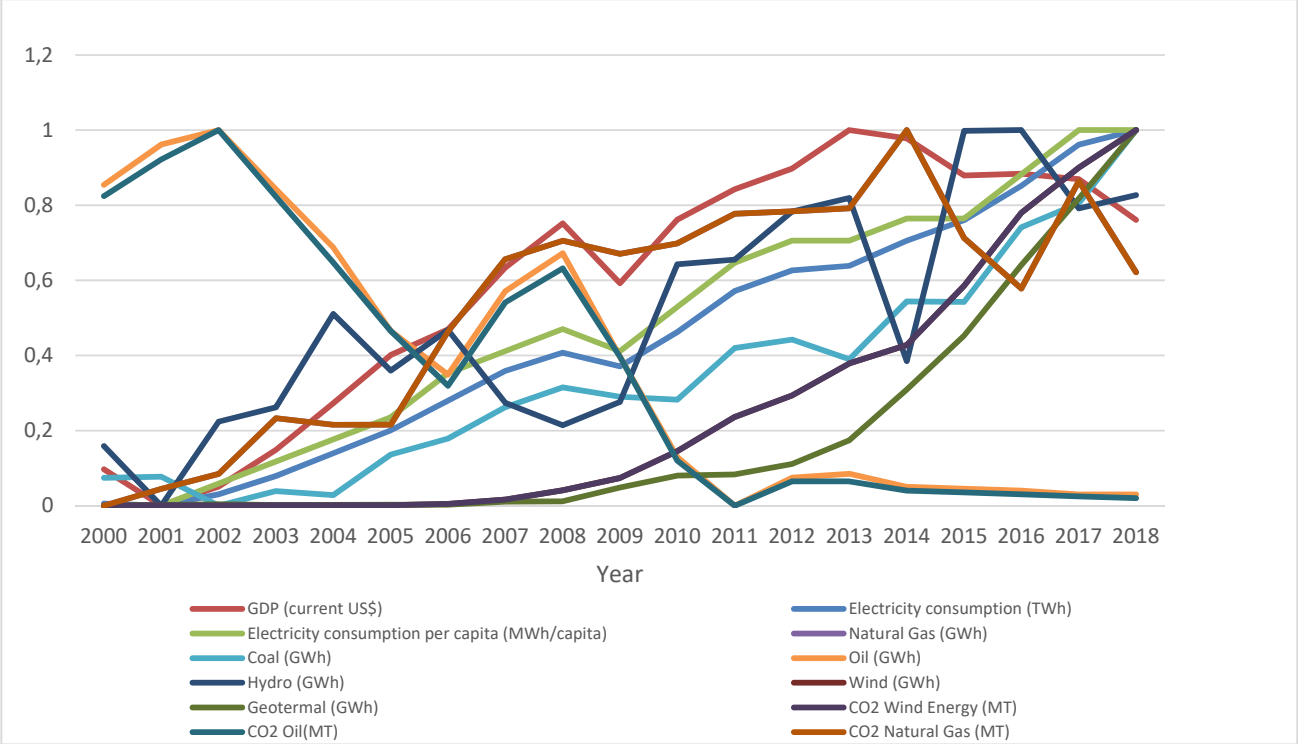

Figure 4. Primary energy consumption and independent variables (2000-2018)

4. Model Results

In Three different scenarios are created to determine the relationship between input variables and the target variable. The summary table for the scenario analysis is given in Table 5. For the three scenarios, we consider wind energy CO_2 emissions as target variable. The results of each scenario are given in the following section.

Table 5. Scenario analysis summary table

Scenario	**Total Energy *Consp. per capita** *(GWh)*	**Total Energy Consp.** *(GWh)*	GPD	**Natural Gas Consp.** *(GWh)*	**Coal Consmp.** *(GWh)*	**Oil Consp.** *(GWh)*	**Hyro Ener. Cons.** *(GWh)*	**Geoth.** *(GWh)*	**Wind Ener.Conp.** *(GWh)*	**CO_2 Wind** *(MT)*
Sneairo-1	x	x	x	x	x	x	x	x	x	x-Target
Sneairo-2	x		x				x	x	x	x-Target
Sneairo-3									x	x-Target

*Consp. (Consumption)

For each scenario, we pick the input variables and examine the effect of these variables to target variable. Based on the sensitivity analysis results, we pick different input variables to see their effect on target variable. The summary for the sensitivity analysis are given in Table 6.

Table 6. Sensitivity Analysis Results for each scenario

	Wind	GDP	Total Electricity *Consp. per capita	Total Electricity *Consp.	Hydropower	Coal	Natural Gas
Sensitivity-1	58.1590	15.31809	10.25802	9.83758	6.71266	6.64359	2.412205
Sensitivity-2	44341.1	13.75919	8.92315		6.83480		

*Consp. (Consumption)

For the first scenario, we examine the effect of nine variables to target wind energy CO_2 emission. The result of the ANN analysis and sensitivity analysis for this run are given in Figure 5.

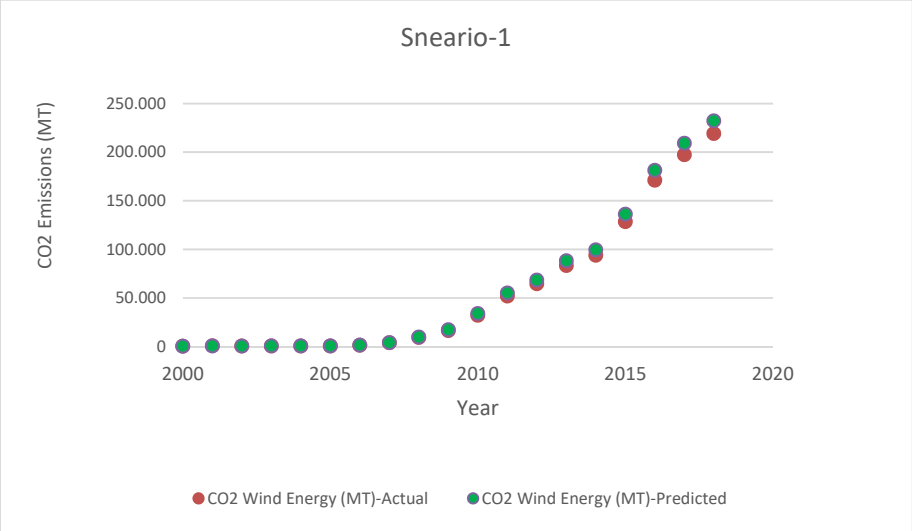

Figure 5. The results for the scenario 1

The result of the first scenario sensitivity analysis show that wind energy consumption, geothermal consumption rate and electricity consumption per capita have the higher effects on wind energy CO_2 emissions. It is also observed that ANN predicted model results and actual values shows the similar trend.

For the second scenario, based on sensitivity analysis result of the first scenario, we examine the effect of the most dominant variables on the target variable, which is CO_2 emissions. As the wind energy consumption and GDP are the most effective variable among the others, for the third scenario, we use wind energy and GDP as input variables and CO_2 emissions as target. The result for the second scenario is given in Figure 6.

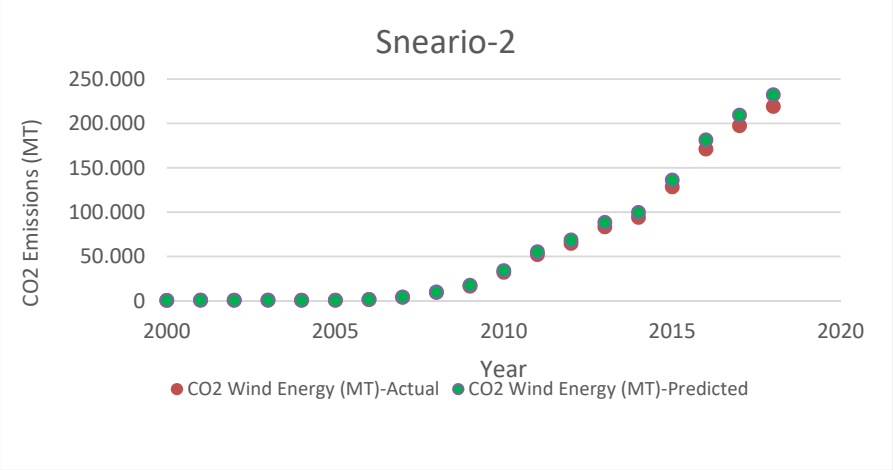

Figure 6. The results for the scenario 2

For the third scenario, based on the result of the second, scenario, it was observed that the most dominant variable is wind energy production is the emissions. Therefore, for the third scenario, we use wind energy as input variable and CO_2 emissions as target. The results for the third scenario is given in Figure 7.

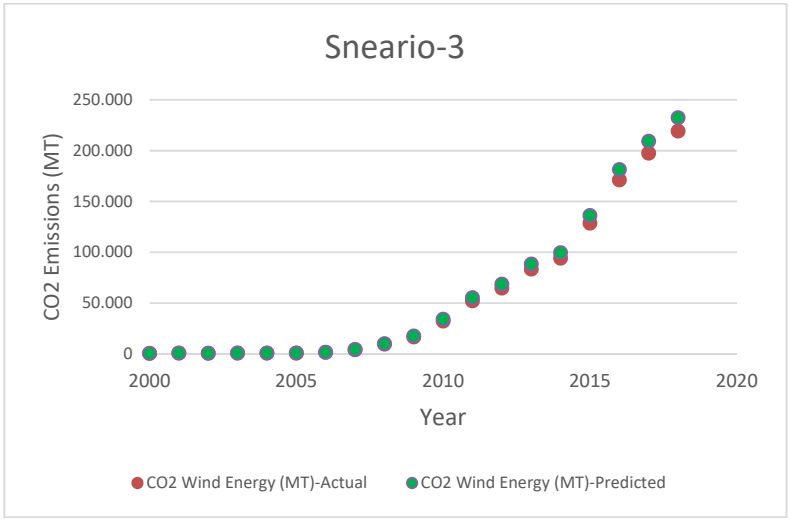

Figure 7. The results for the scenario 3

The results of the third scenario suggest that wind energy consumption has the highest effect on CO_2 emissions.

Based on all three scenarios, it is clear that ANN predicted model results and actual values shows the similar trend for three scenarios. The correlation coefficients between actual and predicted values for three scenarios are 98.9, 98, 5 and 99.9, respectively. Determination coefficients values indicate a good match between the observed and predicted data for these three scenarios. It is observed that the constructed neural networks can be used to predict the amount of CO_2 emissions quite well.

In addition to these three scenarios, we examine the effect of different input variables on wind energy consumption rate. Wind energy is selected as target variable and the rest of the parameter are selected as input variables. The results of sensitivity analysis and model are given in Table 7 and Figure 8.

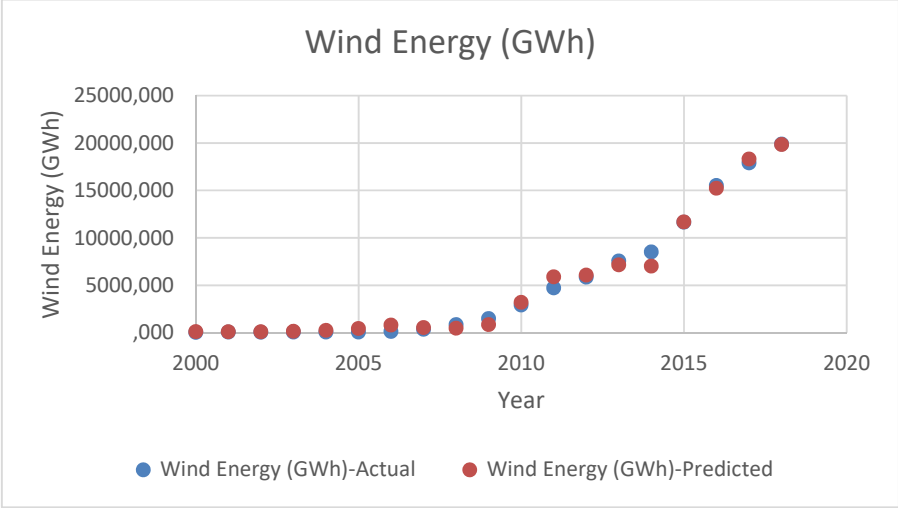

Figure 8. Wind energy consumption rate prediction

Table 7. Sensitivity Analysis Results for each scenario

	GDP	Geothermal	Hydropower
Average	223.2596	26.06253	6.61396

Based on the sensitivity analysis, it is determined that the most dominant input variable is GDP, which affects the wind energy consumption the highest. This is expected as increasing GDP growth causes increase in total energy consumption. Therefore, with increasing trend in GDP value, seeing an increasing trend in wind energy is expected.

4.1 Cost and CO2 emissions comparison for renewable and non-renewable energy sources

As the most of the energy sources in Turkey, such as natural gas, are imported from the neigboorhod countries, it is important to use wind energy as energy source Compare to other renewable energy resources, wind energy produce low CO_2 emissions and relatively has lower cost. To be able to compare the effect of the wind energy and natural gas in terms of economic and environmental, we calculate the natural gas cost and CO_2 emissions using the wind energy consumption rates for the period of 2000 to 2019. The electricity generation costs data and emissions date are taken form Table 3 and 4. The results are depicted in Figure 9 and 10. It can be seen that the cost of wind energy is 9% higher than natural gas, but CO_2 emissions of natural gas is higher than wind energy. Eventhough energy cost of the wind energy is higher than the natural gas, there are many uncertainties should be considered when comaparing the cost data. As natural gas is imported from other countries, there is unexpected market price increase which Turkey has no control over it. Therefore, with unstable energy cost, it may seems econmically wise to import the natural gas but strategically, it is safer to invest wind energy in long run.

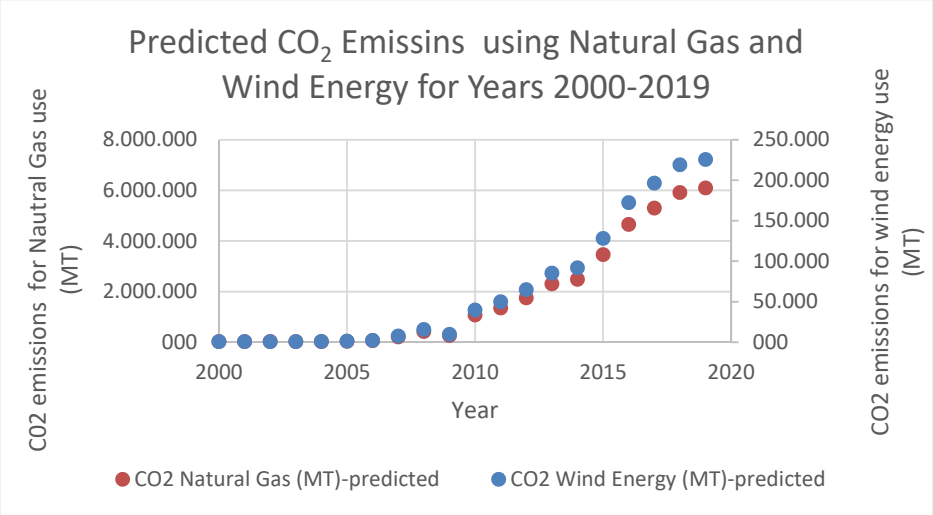

Figure 9. Predicted CO_2 Emissions for Years 2000-2019

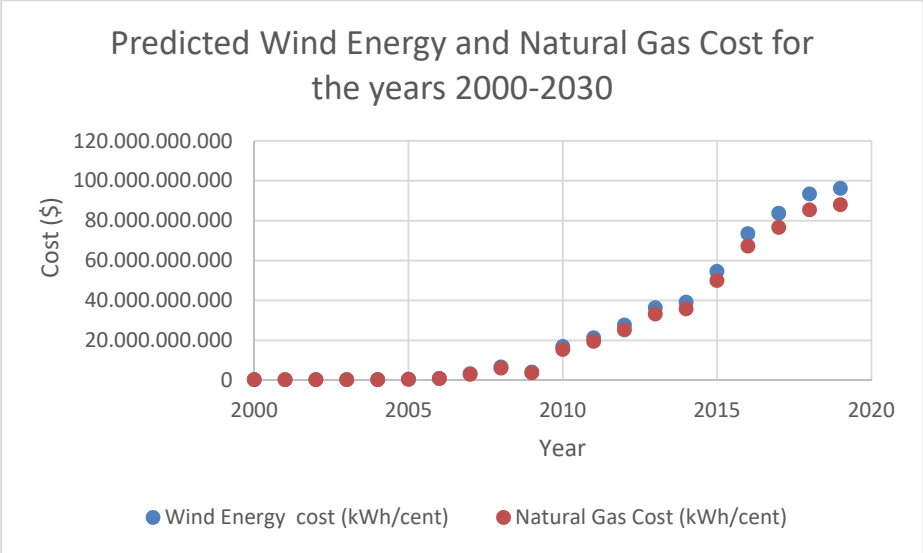

Figure 10. Predicted Wind Energy and Natural Gas Cost for the Years 2000-2019

5.Conclusion

According to 2019 data, the total energy consumption in Turkey reached 304.2 billion kWh, which made Turkey among the world's top 20 energy-consuming countries. With this energy increase, the carbon emissions were reached to 430 million in 2018 and this number placed Turkey among the world 'top 15 carbon emitted countries [7], [8], [23]. As indicated in previous sections, to meet the energy demand, Turkey mostly relies on imported natural gas and oil. Due to high volatility and uncertainty in oil and natural gas prices, Turkey economy would become vulnerable and this significant effects on sustainable economic growth in long run. Countries similar to Turkey, which rely on imported energy sources should take measure to decrease their dependency on international energy market. These measures are using more renewable

energy resources and technological alternatives to make production processes less natural gas or oil intensive [24].

In this study, we predict wind energy consumption and respected CO_2 emissions for the year's 2000- 2019 using ANN model. The precise prediction of wind energy consumptions and CO_2 emissions show that the selected input variables are the most influential factors on the CO_2 emissions. In addition, in this study we compare the cost and CO_2 emissions for different energy sources. Based on the model results, it was concluded that even though using wind energy seems costly, considering other factors such as increasing energy prices or uncertain energy policies, using wind energy is more sustainable both in economic and environmental. The results of this study may guide decision makers to select the most efficient combination of renewable energy sources including wind, hydropower and solar, and conventional energy sources including oil and natural gas, in order to meet the growing energy demand while reducing carbon emissions in developing countries.

In addition, to reduce the CO_2 emissions for the target years 2030 and 2050, more realistic emissions projections needed to implement the environmentally-friendly energy policies. Therefore, for the future studies we propose using forecasting technique for long-term CO_2 emissions prediction. In the energy sector, it is highly important to precisely predict future wind energy demands and its environmental impact during planning, scheduling and policy making.

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