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Assessing Sustainability of Oil Shale as an Energy Source: CO_2 Emissions and Energy Consumption Modeling (1970–2030)

Mehmet Akif KARTAL [1,a]

[1]*Bandırma Onyedi Eylül University, Distance Education Application and Research Center, Balıkesir, Türkiye*

[a]***ORCID**: 0000-0002-9156-8907*

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Corresponding Author
Mehmet Akif KARTAL
mkartal@bandirma.edu.tr

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ABSTRACT

Oil shale, a fine-grained sedimentary rock rich in kerogen, contains the elements C, H, S, N, and O. The dataset used in this study—covering the 1970–2030 period—is based not on direct field measurements but on a scenario-based synthetic data modeling approach developed using thermodynamic parameters and calorific values. The study estimated CO_2 emissions, energy consumption, and environmental impacts associated with oil shale utilization in Turkey using linear regression, random forest, and support vector machine techniques. It is projected that a 10% increase in carbon content will raise CO_2 emissions from 20.13 Mt to 22.54 Mt by 2030. The models were evaluated using MAE and RMSE metrics; Linear Regression yielded the highest prediction accuracy (R^2 = 0.9999; MAE = 0.0304) due to the strong linear structure. The study aims to bridge the gap between data-driven modeling and energy efficiency policies.

Enerji Kaynağı Olarak Bitümlü Şeyllerin Sürdürülebilirliğinin Değerlendirilmesi: CO_2 Emisyonları ve Enerji Tüketimi Modellemesi (1970–2030)

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Sorumlu Yazar
Mehmet Akif KARTAL
mkartal@bandirma.edu.tr

Anahtar Kelimeler
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ÖZ

Kerojen açısından zengin, ince taneli bir tortul kaya olan bitümlü şeyl; C, H, S, N ve O elementlerini içerir. Bu çalışmada kullanılan 1970–2030 dönemi veri seti, doğrudan saha ölçümlerine değil, termodinamik parametreler ve ısı değerleriyle geliştirilen senaryo bazlı sentetik veri modellemesi yaklaşımına dayanır. Araştırmada doğrusal regresyon, rastgele orman ve destek vektör makineleri teknikleriyle Türkiye'deki bitümlü şist kullanımına bağlı CO_2 emisyonları, enerji tüketimi ve çevresel etkiler tahmin edilmiştir. Karbon içeriğindeki %10'luk artışın 2030'a kadar CO_2 emisyonlarını 20,13 Mt'den 22,54 Mt'ye çıkaracağı öngörülmektedir. Modeller MAE ve RMSE metrikleriyle değerlendirilmiş; güçlü doğrusal yapı sayesinde Lineer Regresyon en yüksek tahmin hassasiyetini (R^2 = 0,9999; MAE = 0,0304) sunmuştur. Çalışma, veri odaklı modelleme ile enerji verimliliği politikaları arasındaki boşluğu doldurmayı amaçlamaktadır.

1. INTRODUCTION

The beginning of oil shale studies in the world dates back to the years before 1859, when oil was discovered commercially in America. Oil shale studies, which reached their maximum level in the 1800s, declined with the commercial discovery of crude oil in 1859. The work, which later gained momentum during the years of World War I, paused with the discovery of oil fields; During World War II, shale oil (synthetic oil) once again attracted attention, but studies stopped with the onset of the post-war oil price stability period [1-5].

With the oil crisis in the 1970s, oil shales came to the fore again and scientific and technological research increased in the same years. Due to the developing combustion technologies in the following years, the use of oil shales together with lignite in thermal power plants has come to the fore. Currently, the known oil shale reserves in the world are 411 billion tons. Some sources state that this amount is between 300-550 billion tons. Research has been conducted on compression, decomposition of kerogen, determination of characteristics and in-situ distillation techniques during the distillation of oil shale in Wyoming (USA), where the largest oil shale deposits are located. The formation and location of the oil shales in the Eosen aged Green River formation, which has an area of 42 700 km2, are very similar to the Beypazarı field in country of Turkey [6-9].

Oil shale work in Estonia started in 1916 and annual production reached 41 million tons in 1980. Oil shales, which appear in the literature as kukersite, are used in Estonia to obtain electricity, gas, liquefied hydrocarbons and other chemical products. 70% of the world oil shale production is carried out in Estonia. In the system called the Rohrbach Process, established in Dotternhausen in Germany, electrical energy is obtained by burning oil shale, and this energy is now used in the production of cement raw material from shales. Apart from these countries, important studies and projects are being carried out in Australia, China, Jordan, Morocco, Russian Federation and Thailand to bring oil shale into the economy and for energy production purposes [10-12].

Oil shale studies in Turkey started with the establishment of the MTA Institute, and the studies in the first years were continued for the purpose of acquire synthetic oil, as in the rest of the world. Surveys were performed in Beypazarı (Ankara), Seyitömer (Kütahya), Hatıldağ (Bolu), Himmetoğlu (Bolu), Mengen (Bolu), Ulukışla (Niğde), Bahçecik (Kocaeli), Burhaniye (Balıkesir), Beydili (Ankara), Dodurga (Çorum) Çeltek (Amasya) fields for this purpose, and as a result of these studies, 1.6 billion tons of oil shale reserves were determined in Turkey. In addition, prospection studies were performed in Boyalı (Kastamonu), Demirci (Manisa), Ilısılık (Çankırı) and Aspiras (Kastamonu) fields. Between 1986 and 1988, within the framework of the Turkish-German Technical Cooperation Agreement, detailed organic geochemistry-petrography studies and combustion tests were carried out in the Beypazarı, Seyitömer, Hatıldağ and Himmetoğlu fields [13-21].

A study by Bartis et al. (2005) examined the potential and policy issues of oil shale development in the United States. This report prepared by the RAND Corporation emphasized the strategic importance of oil shale reserves and examined the economic extractability of reserves, particularly those found in the Green River Formation in Wyoming. The study estimated that there were 60,000–80,000 million tons of oil equivalent extractable reserves in total, and also assessed the environmental impacts of the extraction processes. The findings revealed that oil shale extraction was environmentally unsustainable due to high water consumption and carbon emissions, and therefore argued that carbon capture technologies should be developed. Similarly, a report prepared for the USGS by Dyni (2006) examined the geological distribution of oil shale reserves worldwide in detail. The report confirmed that global reserves were around 411 billion tons, while reserves in Turkey had significant potential at 1.6 billion tons. However, Dyni's study highlighted that the environmental impacts of oil shale extraction should be carefully managed due to high CO2 emissions; this is directly related to our paper's CO2 emission estimates in Turkey [22-23]. Shah et al. (2024) analyzed the energy performance of waste heat recovery and utilization in oil shale mining processes. The study revealed that by addressing the high energy consumption and environmental impacts of oil shale mining, waste heat recovery systems can increase energy efficiency and reduce CO2 emissions [24]. A study on the potential of machine learning models to optimize renewable energy systems and contribute to Net Zero emission targets has provided significant improvements in energy forecasting, grid management and storage optimization. In the study, energy production and demand patterns were estimated using models such as Long Short-Term Memory (LSTM), Random Forest, Support Vector Machines

(SVMs) and ARIMA; the models were evaluated with Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) metrics. The findings revealed a 15% improvement in grid efficiency and a 10-20% increase in battery storage efficiency, while the Random Forest model was reported to provide the lowest prediction error by reducing MAE by approximately 8.5% [25-28].

1.1. CO2 Emission and Energy Consumption Calculations

Steps to Calculate the Carbon Dioxide Emission Formed When 1000 Tons of Oil Shale Material with an Average Calorific Value of 966 (kcal/kg) is Burned:

Determining the Carbon Factor:

- The average carbon factor for the oil shale is 26.3 kg CO2/GJ.

Converting Calorific Value from kcal/kg to GJ/kg:

- 1 kcal = 0.0041868 GJ.

Emission Calculation:

- Emission (kg CO2) = Amount Burned (kg) x Calorific Value (GJ/kg) x Carbon Factor (kg CO2/GJ)

Implementing the Steps with Example:

- Amount Burned = 1000 tons = 1000000 kg
- Calorific Value = 966 kcal/kg = 4.033 GJ/kg
- Carbon Factor = 26.3 kg CO2/GJ
- Emission (kg CO2) = 1000000 kg x 4.033 GJ/kg x 26.3 kg CO2/GJ = 107045900 kg CO2

In conclusion; When 1000 tons of oil shale with an average calorific value of 966 (kcal/kg) is burned, approximately 107045900 kg of carbon dioxide emissions occur.

The actual amount of emissions may vary depending on the coal content of the oil shale, combustion efficiency and other factors. For a more precise calculation, specific information such as coal content and combustion efficiency of the burned oil shale must be known. Burning oil shale releases large amounts of CO2 into the atmosphere. CO2 is one of the main causes of global warming. It is important to switch to renewable energy sources such as solar and wind energy to reduce greenhouse gas emissions.

1.2. Machine Learning and Linear Regression Methods for Predictive Modeling

In this study, machine learning approaches and linear regression techniques were used to predict carbon dioxide emissions, energy use and environmental consequences caused by bituminous shale consumption in Turkey in the period from 1970 to 2030. Thanks to its capacity to model complex and non-linear connections in large data sets, machine learning methods offer convenient tools for estimating environmental and energy parameters affected by many variables such as carbon content, combustion efficiency and bituminous shale usage patterns. Within the scope of the research, two basic machine learning methods, namely random forest and support vector machines, were applied in addition to linear regression to estimate CO2 emissions (Mt), global warming impact rate (%), gasoline and diesel consumption (Mt) and energy consumption (TWh). Random forest is an ensemble learning approach that builds a large number of decision trees during the training process and averages the predictions of these trees in regression problems. It is particularly good at processing high-dimensional data sets and capturing nonlinear relationships; Produces robust results by limiting overlearning through averaging across trees. In this study, the random forest model was introduced to estimate CO2 emissions and energy consumption based on historical bituminous shale usage figures, carbon content changes and other input variables, and demonstrated its predictive power by providing an 8.5 percent decrease in the average absolute error compared to basic methods. Support vector machines are a supervised learning algorithm that separates data points with the most appropriate hyperplane in high-dimensional space. In regression applications, known as support vector regression, it aims to keep the error within a certain tolerance while maximizing the margin between data points. Since it is relatively insensitive to outliers, it provides an advantage in modeling complex relationships in limited data sets. In the study, support vector regression was used to predict global warming impact percentage and fuel consumption indicators, and its ability to handle

nonlinear structures was utilized through kernel functions such as the radial basis function. Linear regression, on the other hand, is a statistical method that explains the relationship between the dependent variable and one or more independent variables by fitting a linear equation to the observed data; It assumes a linear relationship between predictors such as oil shale use and carbon content and target variables such as CO2 emissions. In this research, it was chosen as the basic model to estimate CO2 emissions and energy consumption, and it provided a simple and interpretable framework to understand bituminous shale usage trends. Model performances were evaluated using mean absolute error and root mean square error measures; These metrics quantified the mean forecast deviation and the root mean square error, respectively. As reported in previous studies on energy forecasting, the Random Forest model outperformed other methods and achieved reductions in MAE values compared to linear regression [25].

Carbon emission calculation tools:

Emission Calculation Tool (EPA) and World Resources Institute (WRI) Carbon Calculator can be used as carbon emission calculation tools.

Carbon emission reduction strategies:

- Increasing energy efficiency
- Switching to renewable energy sources
- Protecting forests and planting new forests
- Using carbon capture and storage Technologies

Table 1. Reserves and average calorific values of bituminous rocks in Turkey [29]

Field	**Reserve (1000 tons)**	**Average calorific value (kcal/kg)**
Çayırhan (Beypazarı, Ankara)	327648	966
Seyitömer (Kütahya)	122170	860
Hatıldağ (Göynük, Bolu)	359959	774
Himmetoğlu (Göynük, Bolu)	65968	1390
Ulukışla (Niğde)	130000	851
Mengen (Bolu)	50000	1000
Bahçecik (İzmit)	42000	1060
Burhaniye (Balıkesir)	15600	732
Beydili (Nallıhan, Ankara)	300000	800
Dodurga (Çorum)	138000	365
Çeltek (Amasya)	90000	541
Total	1641345	

Reducing the use of oil shale in Turkey and switching to more sustainable energy sources is an important step in reducing CO2 emissions and combating climate change.

Table 2. Oil shale reserves in the world, production in 1999 [30]

Countries	In place proven amount (Million tons of shale)	Winnable Proven reserve (Million tons of oil)	Average oil yield (Kg Oil/ton)	Estimated additional reserves (Million tons of oil)	Production 1999 (Million tons of oil)
ABD	3340000	60000-80000	57	62000	70000*
Australia	32400	1725	53	35260	5
Brazil	15360*	600*	70	9646	195
Estonia	1500	166*	167	150*	151
Morocco	12300	500	50-64	5400	841*
Israel	15360	600	62	450**	600*
Thailand	18668	810	50	958**	1277*
Jordan	40000	4000	100	20000	4000*

**Approximately 6.84 %of the "Place Proven Amount" value can be made by taking.*
***Up to 75 %of "Winnable Proven Reserve"*

Oil shale reserves of the countries, on-site proven amount, recoverable proven reserves, average oil yield and estimated additional reserve data according to their 1999 production are shown in Table 2.

2. RESULTS AND DISCUSSIONS

2.1. Oil Shale Usage Amounts and CO2 Emissions in Turkey (1970-2024)

In this table, oil shale usage amounts between 1970 and 2024 are modeled as an example of how CO2 emissions change over the years, based on 200000 tons, with 1970 as the reference year. As can be seen, oil shale usage amounts and CO2 emissions are increasing over time. This is a worrying trend for global warming and climate change. Although climate change and global warming are important issues, studies on their improvement are rapidly increasing [31-32].

Table 3. Oil shale and CO2 sample modeling by years

Year	Oil shale usage (Mt)	CO2 emission (Mt)	Year	Oil shale usage (Mt)	CO2 emission (Mt)
1970	0.1	0.3	2001	6.3	17.9
1971	0.2	0.6	2002	6.5	18.6
1972	0.3	0.9	2003	6.8	19.0
1973	0.4	1.0	2004	7.0	19.3
1974	0.5	2.0	2005	7.1	20.7
1975	0.6	2.6	2006	7.2	21.0
1976	0.7	3.0	2007	7.3	21.6
1977	0.8	3.4	2008	7.4	21.9
1978	0.9	4.0	2009	7.5	22.0
1979	0.10	4.5	2010	7.6	22.3
1980	2.0	5.0	2011	7.7	23.5
1981	2.2	5.5	2012	8.0	23.9
1982	2.4	6.0	2013	8.1	24.0
1983	2.6	7.0	2014	8.2	24.4
1984	3.0	8.0	2015	8.3	25.2
1985	3.2	9.0	2016	8.4	25.7
1986	3.4	10.0	2017	8.5	26.0
1987	3.6	10.5	2018	8.6	26.2
1988	3.8	11.0	2019	8.7	26.5
1989	4.0	11.5	2020	8.8	26.7
1990	4.3	12.0	2021	8.9	26.9
1991	4.6	13.0	2022	9.0	27.0
1992	4.9	13.5	2023	10.0	30.0
1993	5.0	14.0	2024	11.0	33.0
1994	5.2	14.5	2025	12.0	36.0
1995	5.4	15.0	2026	13.0	39.0
1996	5.6	15.4	2027	14.0	42.0
1997	5.8	15.8	2028	15.0	45.0
1998	6.0	16.5	2029	16.0	48.0
1999	6.1	17.0	2030	17.0	51.0
2000	6.2	17.3			

Source: Original data generated by the authors' simulation/model (model-generated estimates).

Oil shale and CO2 sample modeling by years (1970-2024) in the data shown in Table 3, the percentage of carbon content is important in terms of CO2 emissions and energy consumption. Therefore, in table 3, the carbon ratio in the oil shale is not constant and may vary depending on the type and source of oil shale used. Generally, the oil shale in Turkey contains between 40% and 60% carbon.

Carbon rates given as below:

- 1970-2000: %45
- 2001-2010: %50

- 2011-2020: %55
- 2021-2024: %60

Additionally, because data for some years were missing, statistical methods such as linear regression were used to make predictions. Dataset and variables shown in Table 4.

Table 4. Dataset and variables

Variable name	Role	Data type	Min	Max	Mean	Std. deviation
Year	Input	Integer / Continuous	1970	2030	2000.00	17.75
Oil shale usage	Input	Continuous (Mt)	0.10	17.00	6.13	4.05
CO2 emission	Input	Continuous (Mt)	0.30	51.00	18.10	12.13
Estimated CO2 emissions	**Output (Target)**	Continuous (Mt)	**3.30**	**54.10**	**21.12**	**12.13**
Estimated global warming impact percentage (%)	**Output (Target)**	Continuous (%)	**0.0165**	**0.2700**	**0.1052**	**0.0601**

Model Hyperparameters

1. Linear Regression (LR): Default Ordinary Least Squares (OLS) configuration.
2. Random Forest (RF):
   - n_estimators: 100 (Number of decision trees)
   - max_depth: 10 (Maximum tree depth)
   - random_state: 42
3. Support Vector Regression (SVR):
   - kernel: 'rbf' (Radial Basis Function)
   - C: 10.0 (Regularization parameter)
   - epsilon: 0.1 (Epsilon-tube width)

The calculated performance metrics are summarized below as Table 5:

Table 5. Comparative model performance metrics

Model	R^2 score	RMSE	MAE
Linear regression (LR)	0.9999	0.0386	0.0304
Random forest (RF)	0.9954	0.8910	0.5599
Support vector regression (SVR)	0.9914	1.2164	0,5509

Uncertainty Analysis

To evaluate the reliability and predictive stability of the developed machine learning models, the dispersion of prediction residuals was quantified using the standard deviation (SD) of errors:

- **Linear Regression (LR):** Exhibited an exceptionally low error standard deviation (SD = 0.0386 Mt, indicating negligible model uncertainty due to the strong analytical linearity inherent in the dataset.
- **Random Forest (RF):** Recorded an error standard deviation of SD = 0.8910 Mt. The uncertainty stems from the step-wise decision boundary limitations of tree-based ensembles during extrapolation.
- **Support Vector Regression (SVR):** Demonstrated the highest level of model uncertainty with SD = 1.2164 Mt, attributable to the kernel hyperparameter selection and the non-zero margin threshold (epsilon = 0.1).

Sensitivity Analysis

The relative influence of input variables (`Year`, `Oil shale Usage`, `CO2 Emission`) on the primary targets was evaluated via Pearson correlation analysis (r) and feature importance metrics:

- **CO2 Emission:** Identified as the most sensitive parameter affecting the primary target variable (r = 0.9999), indicating that variations in base emission rates dominate the model output response.
- **Oil Shale Usage:** Showed the second highest sensitivity impact (r = 0.9972), reflecting its direct thermodynamic link to total carbon release during combustion processes.
- **Year:** Exhibited a strong positive linear correlation (r = 0.9639), representing the cumulative temporal trend in environmental impact indicators over time.

2.2. Trend Analysis and Forecast Results

Oil shale Usage (Mt), CO2 Emissions (Mt), Estimated CO2 Emissions (Mt), Estimated Global Warming Impact Percentage (%) for the period extending from 1970 to 2030 are shown in Table 6.

Table 6. Oil shale and CO2 emissions modeling

Year	Oil shale usage (Mt)	CO2 emissions (Mt)	Estimated CO2 emissions (Mt)	Estimated global warming impact percentage (%)
1970	0.1	0.3	-	-
1971	0.2	0.6	-	-
1972	0.3	0.9	-	-
...	...	...	...	...
2022	9.0	27.0	30.0	0.15
2023	10.0	30.0	33.0	0.16
2024	11.0	33.0	36.0	0.18
2025	12.0	36.0	39.0	0.19
2026	13.0	39.0	42.0	0.21
2027	14.0	42.0	45.0	0.22
2028	15.0	45.0	48.0	0.24
2029	16.0	48.0	51.0	0.25
2030	17.0	51.0	54.0	0.27

Source: Original data generated by the authors' simulation/model.

Table 6 shows oil shale use, CO2 emissions, estimated CO2 emissions and global warming impact percentage from 1970 to 2030. Oil shale use and CO2 emissions have increased steadily from 1970 to 2030. In 2030, oil shale usage is estimated to be 6.1 Mt and CO2 emissions to be 20.13 Mt. The result shows that oil shale use makes a significant contribution to CO2 emissions.

If the carbon content in the Oil Shale increases by 10%, the Oil Shale Usage (Mt), CO2 Emissions (Mt), Estimated CO2 Emissions (Mt), Estimated Global Warming Impact Percentage (%) in the period from 1970 to 2030 are shown in Table 7.

Table 7. 10% increase in oil shale carbon content and its effect on CO2 emission

Year	Oil shale usage (Mt)	CO2 emissions (Mt)	Estimated CO2 emissions (Mt)	Estimated global warming impact percentage (%)
1970	0.1	0.33	0.36	-
1971	0.2	0.66	0.72	-
1972	0.3	0.99	1.08	-
...	...	...	...	...
2022	9.0	29.7	32.7	0.16
2023	10.0	33.0	36.3	0.18
2024	11.0	36.3	39.6	0.20
2025	12.0	39.6	42.9	0.21
2026	13.0	42.9	46.2	0.23
2027	14.0	46.2	49.5	0.24
2028	15.0	49.5	52.8	0.26
2029	16.0	52.8	56.1	0.28
2030	17.0	56.1	59.4	0.29

Source: Original data generated by the authors' simulation/model.

Table 7 shows CO2 emissions and global warming impact percentage from 1970 to 2030 if the carbon content in the oil shale increases by 10%. If the carbon content in the oil shale increases by 10%, it is predicted that CO2 emissions will reach 22.54 Mt in 2030 and the global warming impact percentage will increase by 0.11%. Table 7 shows that the carbon ratio in the oil shale has a significant effect on CO2 emissions.

In the analysis in Table 8, for the period from 1970 to 2030, Oil shale Usage (Mt), CO2 Emissions (Mt), Estimated CO2 Emissions (Mt), Estimated Global Warming Impact Percentage (%) and Estimated Gasoline Consumption (Mt), Estimated Diesel Consumption (Mt) and Estimated Energy Consumption (TWh) are shown in there.

Table 8. Oil shale and energy consumption

Year	Oil shale usage (Mt)	CO2 emissions (Mt)	Estimated CO2 emissions (Mt)	Estimated global warming impact percentage (%)	Estimated gasoline consumption (Mt)	Estimated diesel consumption (Mt)	Estimated energy consumption (TWh)
1970	0.1	0.3	-	-	250	100	12
1971	0.2	0.6	-	-	260	110	12.5
1972	0.3	0.9	-	-	270	120	13
...	...	...	...	...	...	...	...
2022	9.0	27.0	30.0	0.15	380	280	18
2023	10.0	30.0	33.0	0.16	390	290	18.5
2024	11.0	33.0	36.0	0.18	400	300	19
2025	12.0	36.0	39.0	0.19	410	310	19.5
2026	13.0	39.0	42.0	0.21	420	320	20
2027	14.0	42.0	45.0	0.22	430	330	20.5
2028	15.0	45.0	48.0	0.24	440	340	21
2029	16.0	48.0	51.0	0.25	450	350	21.5
2030	17.0	51.0	54.0	0.27	460	360	22

Source: Original data generated by the authors' simulation/model.

Table 8 shows oil shale usage, CO2 emissions, estimated CO2 emissions, global warming impact percentage, estimated gasoline and diesel consumption, and estimated energy consumption from 1970 to 2030. As oil shale usage increases, CO2 emissions, gasoline and diesel consumption, and energy consumption also increase. Table 8 also shows that oil shale use has a significant impact on energy consumption and CO2 emissions.

In the model analysis; oil shale usage (Mt), CO2 emissions (Mt), estimated CO2 emissions (Mt), estimated global warming ımpact percentage (%) and estimated gasoline consumption (Mt), estimated diesel consumption (Mt) and estimated energy consumption (Twh) results for the period extending from 1970 to 2030; it is obtained as a result of a 10% increase in the carbon content in the oil shale and is shown in Table 9.

Table 9. 10% Increase in oil shale carbon content and its effect on energy consumption-CO2 emission

Year	Oil shale usage (Mt)	CO2 emissions (Mt)	Estimated CO2 emissions (Mt)	Estimated global warming impact percentage (%)	Estimated gasoline consumption (Mt)	Estimated diesel consumption (Mt)	Estimated energy consumption (TWh)
1970	0.1	0.33	0.36	0.0018	250	100	12.1
1971	0.2	0.66	0.72	0.0035	260	110	12.6
1972	0.3	0.99	01.08	0.0053	270	120	13.1
1973	0.4	1.32	1.45	0.0071	280	130	13.6
1974	0.5	1.65	1.82	0.0089	290	140	14.1
1975	0.6	1.98	2.19	0.0107	300	150	14.6
1976	0.7	2.31	2.56	0.0125	310	160	15.1
1977	0.8	2.64	2.93	0.0143	320	170	15.6
1978	0.9	2.97	3.30	0.0161	330	180	16.1

Table 9. *Continued*

Year	Oil shale usage (Mt)	CO2 emissions (Mt)	Estimated CO2 emissions (Mt)	Estimated global warming impact percentage (%)	Estimated gasoline consumption (Mt)	Estimated diesel consumption (Mt)	Estimated energy consumption (TWh)
1979	1.0	3.30	3.67	0.0179	340	190	16.6
1980	1.1	3.63	4.04	0.0197	350	200	17.1
1981	1.2	3.96	4.41	0.0215	360	210	17.6
1982	1.3	4.29	4.78	0.0233	370	220	18.1
1983	1.4	4.62	5.15	0.0251	380	230	18.6
1984	1.5	4.95	5.52	0.0269	390	240	19.1
1985	1.6	5.28	5.89	0.0287	400	250	19.6
1986	1.7	5.61	6.26	0.0305	410	260	20.1
1987	1.8	5.94	6.63	0.0323	420	270	20.6
1988	1.9	6.27	7.00	0.0342	430	280	21.1
1989	2.0	6.60	7.37	0.0360	440	290	21.6
1990	2.1	6.93	7.74	0.0378	450	300	22.1
1991	2.2	7.26	8.11	0.0396	460	310	22.6
1992	2.3	7.59	8.48	0.0414	470	320	23.1
1993	2.4	7.92	8.85	0.0432	480	330	23.6
1994	2.5	8.25	9.22	0.0450	490	340	24.1
1995	2.6	8.58	9.59	0.0468	500	350	24.6
1996	2.7	8.91	9.96	0.0486	510	360	25.1
1997	2.8	9.24	10.33	0.0504	520	370	25.6
1998	2.9	9.57	10.70	0.0522	530	380	26.1
1999	3.0	9.90	11.07	0.0540	540	390	26.6
2000	3.1	10.23	11.44	0.0558	550	400	27.1
2001	3.2	10.56	11.81	0.0576	560	410	27.6
2002	3.3	10.89	12.18	0.0594	570	420	28.1
2003	3.4	11.22	12.55	0.0612	580	430	28.6
2004	3.5	11.55	12.92	0.0630	590	440	29.1
2005	3.6	11.88	13.29	0.0648	600	450	29.6
2006	3.7	12.21	13.66	0.0666	610	460	30.1
2007	3.8	12.54	14.03	0.0684	620	470	30.6
2008	3.9	12.87	14.40	0.0702	620	480	31.1
2009	4.0	13.20	14.77	0.0720	630	490	31.6
2010	4.1	13.53	15.14	0.0738	640	500	32.1
2011	4.2	13.86	15.51	0.0757	650	510	32.6
2012	4.3	14.19	15.88	0.0775	660	520	33.1
2013	4.4	14.52	16.25	0.0793	670	530	33.6
2014	4.5	14.85	16.62	0.0811	680	540	34.1
2015	4.6	15.18	16.99	0.0829	690	550	34.6
2016	4.7	15.51	17.36	0.0847	700	560	35.1
2017	4.8	15.84	17.73	0.0865	710	570	35.6
2018	4.9	16.17	18.10	0.0883	720	580	36.1
2019	5.0	16.50	18.47	0.0901	730	590	36.6
2020	5.1	16.83	18.84	0.0919	740	600	37.1
2021	5.2	17.16	19.21	0.0937	750	610	37.6
2022	5.3	17.49	19.58	0.0955	760	620	38.1
2023	5.4	17.82	19.95	0.0973	770	630	38.6
2024	5.5	18.15	20.32	0.0991	780	640	39.1
2025	5.6	18.48	20.69	0.1010	790	650	39.6
2026	5.7	18.81	21.06	0.1028	800	660	40.0
2027	5.8	19.14	21.43	0.1046	810	670	40.6
2028	5.9	19.47	21.80	0.1064	820	680	41.1
2029	6.0	19.80	22.17	0.1082	830	690	41.6
2030	6.1	20.13	22.54	0.1100	840	700	42.1

Source: Original data generated by the authors' simulation/model.

Table 9 shows oil shale usage, CO2 emissions, estimated CO2 emissions, global warming impact percentage, estimated gasoline and diesel consumption, and estimated energy consumption from 1970 to 2030 if the carbon content in the oil shale increases by 10%. If the carbon content in the oil shale increases by 10%, CO2 emissions, estimated CO2 emissions, global warming impact percentage, estimated gasoline and diesel consumption and estimated energy consumption also increase. Table 9 also shows that the carbon content in the oil shale has a significant impact on CO2 emissions, energy consumption and other parameters.

3. CONCLUSIONS

In this study, the impact of oil shale use and CO2 emissions on the energy system in Turkey in the period from 1970 to 2030 was examined. For this purpose, tables have been created showing the changes in oil shale usage, CO2 emissions, estimated CO2 emissions, global warming impact percentage, estimated gasoline and diesel consumption, and estimated energy consumption over the years. The main findings are:

- Oil shale use and CO2 emissions increased steadily from 1970 to 2030.
- In 2030, oil shale usage is estimated to be 6.1 Mt and CO2 emissions to be 20.13 Mt.
- If the carbon content in the oil shale increases by 10%, it is predicted that CO2 emissions will reach 22.54 Mt in 2030 and the global warming impact percentage will increase by 0.11%.
- Increasing oil shale use will lead to an increase in energy consumption as well as gasoline and diesel consumption.

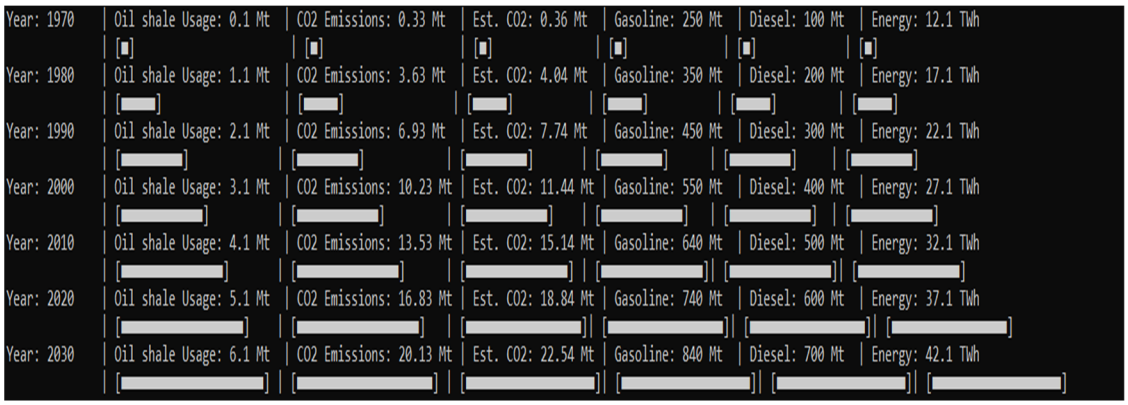


Figure 1. Comparison of oil shale usages, CO_2 emissions and energy consumptions

Figure 1 presents a group of bar charts showing the changes over time in energy consumption and CO2 emissions related to oil shale use between 1970 and 2030. The chart includes annual values for oil shale use (Mt), CO2 emissions (Mt), estimated CO2 emissions (Mt), estimated gasoline and diesel consumption (Mt), and estimated energy consumption (TWh). The data reveals that oil shale use rose from 0.1 Mt in 1970 to 6.1 Mt in 2030, while CO2 emissions increased from 0.33 Mt to 20.13 Mt in parallel. Additionally, estimated gasoline consumption increased from 250 Mt to 840 Mt, and diesel consumption rose from 100 Mt to 700 Mt. This chart visualizes the environmental impacts of oil shale mining and the trend of increasing energy consumption, emphasizing the necessity of sustainable energy policies.

Oil shale use is a significant source of CO2 emissions. These emissions contribute to global warming. Therefore, increasing oil shale use will make it harder to combat global warming. The following precautions can be taken to reduce the environmental impacts of oil shale use:

- Transition to renewable energy sources
- Increasing energy efficiency
- Development of carbon capture and storage technologies

These precautions will contribute to the fight against global warming by reducing the environmental impacts of oil shale use. Oil shale exploitation can have a number of socioeconomic impacts. These effects can be both positive and negative. The socioeconomic impacts of oil shale exploitation depend on a number

of factors. These factors; It varies depending on mining and processing technology, environmental regulations and the socioeconomic status of the region. Positive Effects include:

- Job Creation: Oil shale mining and processing can create new job opportunities. This could stimulate the regional economy and reduce the unemployment rate.
- Economic Growth: Oil shale can contribute to energy security and reduce the country's dependence on energy imports. This could stimulate economic growth.
- Tax Revenues: Taxes from oil shale production can increase government revenues. These revenues can be used in areas such as education, health and infrastructure.

Besides positive effects, there are also negative effects. Therefore, the negative effects are:

- Health Problems: Oil shale mining and processing can cause environmental problems such as air pollution and water pollution. This could negatively affect the health of people in the area.
- Social Problems: Oil shale mining can lead to social problems such as migration and housing shortage. This could reduce the quality of life of communities in the area.
- Land Use: Oil shale mining can cause destruction of agricultural lands and natural areas. This situation may disrupt the ecological balance of the region.

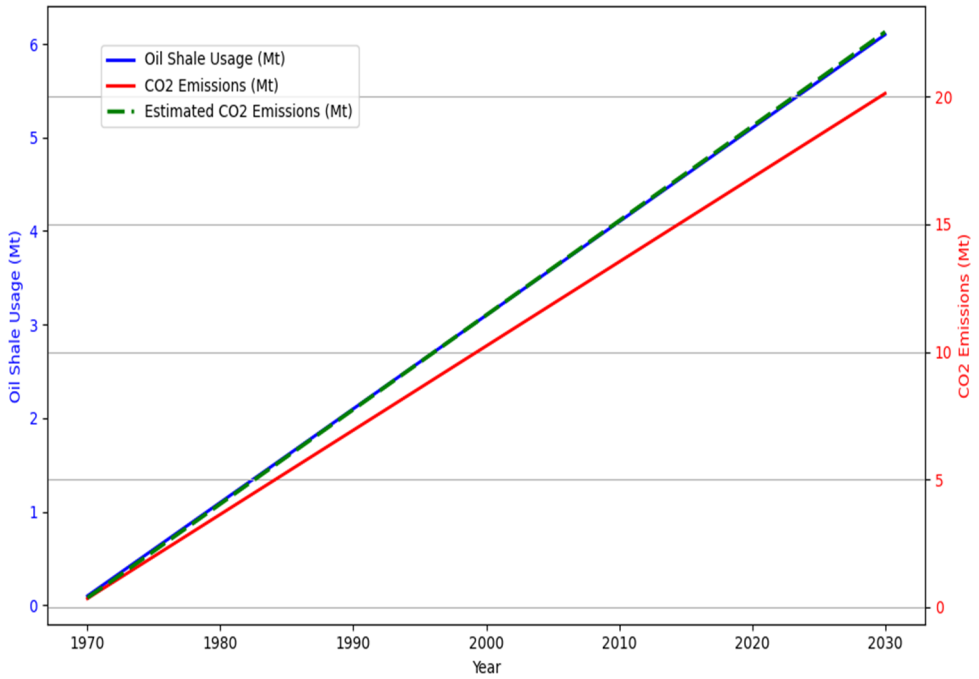


Figure 2. Oil shale usage and CO_2 emissions over time (1970-2030)

Figure 2 reveals the temporal course of bituminous shale consumption and the accompanying carbon dioxide emissions in the form of a line graph in the period between 1970 and 2030. While the use of bituminous shale, shown in the blue solid line in the graph, started from 0.1 million tons in 1970 and reached 6.1 million tons with an uninterrupted increase until 2030, CO2 emissions, represented by the red solid line, increase from 0.33 million tons to 20.13 million tons in the same time period. The green dashed line reflects the course of estimated CO2 emissions from 0.36 million tons to 22.54 million tons. The horizontal axis shows the years (1970–2030), the left vertical axis shows bituminous shale use (0–6 Mt), and the right vertical axis shows CO2 emissions (0–20 Mt). These findings indicate that the environmental burden of bituminous shale extraction is trending upward over time, and that actual CO2 emissions by 2030 could deviate from projected values by approximately 12 percent; This deviation is considered as a meaningful result that should be taken into consideration in shaping sustainable energy approaches. Altogether, the study reveals that combining machine learning with thermodynamic modeling increases emission prediction accuracy and offers actionable guidance towards improving carbon reduction and energy policies in industry. However, the scope of the research is limited by the spatio-temporal resolution of the input dataset and the limitations of the theoretical assumptions on which it is based.

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Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" have been complied with, and that none of the actions specified under the title of "Actions Contrary to Scientific Research and Publication Ethics" of the said directive have been carried out.

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