

Investigation of Exergy Potential of Solar Radiation for TR83 Region

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Abstract

Solar energy is one of the sustainable sources of renewable energy. Solar energy plays a vital role in coping with the surging global energy demands and environmental issues arising due to conventional energy sources. In the present work, data collected from meteorological stations measuring air temperature and global solar radiation in the provinces of Amasya, Çorum, Samsun and Tokat in the Central Black Sea Region of Turkey. The exergy values of solar radiation were calculated from the data collected. Jeter's, Spanner's and Petela's exergy models available in literature were employed in this study to obtain four-year data analysis. The exergy-energy ratio values obtained from Petela and Spanner methods are highly similar. The highest exergy-energy ratio values for all provinces were obtained with the Jeter method. While the highest annual solar radiation exergy value was obtained in Çorum and Samsun provinces in 2022, it was obtained in Amasya and Tokat provinces in 2020. The research results are expected to provide information to researchers on optimizing solar energy systems, structuring regional energy systems and contributing to the transition to global sustainable energy solutions.

Keywords: Solar, Solar Radiation, Exergy, TR83

TR83 Bölgesi için Güneş Radyasyon Ekserji Potansiyelinin Araştırılması

Öz

Güneş enerjisi yenilenebilir enerjinin sürdürülebilir kaynaklarından biridir. Güneş enerjisi, artan küresel enerji talepleri ve geleneksel enerji kaynaklarından kaynaklanan çevresel sorunlarla başa çıkmada hayati bir rol oynamaktadır. Bu çalışmada, Türkiye'nin Orta Karadeniz Bölgesi'ndeki Amasya, Çorum, Samsun ve Tokat illerindeki hava sıcaklığını ve küresel güneş radyasyonunu ölçen meteoroloji istasyonlarından toplanan veriler kullanılmıştır. Toplanan verilerden güneş radyasyonunun ekserji değerleri hesaplanmıştır. Bu çalışmada, literatürde bulunan Jeter, Spanner ve Petela ekserji modelleri kullanılarak dört yıllık veri analizi elde edilmiştir. Petela ve Spanner yöntemlerinden elde edilen ekserji-enerji oranı değerleri oldukça benzerdir. Tüm iller için en yüksek ekserji-enerji oranı değerleri Jeter yöntemi ile elde edilmiştir. 2022 yılında en yüksek yıllık güneş radyasyonu ekserji değeri Çorum ve Samsun illerinde elde edilirken, 2020 yılında Amasya ve Tokat illerinde elde edilmiştir. Araştırma sonuçlarının araştırmacılara güneş enerjisi sistemlerinin optimize edilmesi, bölgesel enerji sistemlerinin yapılandırılması ve küresel sürdürülebilir enerji çözümlerine geçişte katkı sağlanması konusunda bilgi sağlaması beklenmektedir.

Anahtar Kelimeler: Güneş, Güneş Radyasyonu, Ekserji, TR83

1.Introduction

Energy is a vital component of existence, powering both human endeavors and natural processes. Because of population increase and technological improvement, the world's energy demand is always rising [1, 2]. Nowadays, the transition from fossil fuels to renewable energy sources has become an urgent need for the clean and sustainable development of the global energy sector. The most important source among renewable energy sources is solar energy. Solar energy is the cleanest and richest renewable energy source with enormous potential [3, 4]. The International Energy Agency (IEA) has projected that solar technologies, including photovoltaic (PV), solar hot water, and concentrated solar power, could supply a significant portion of the world's energy needs by 2060, potentially accounting for one-third of total energy consumption [5]. In the design and analysis of systems that utilize solar energy, data on solar radiation and its components at a particular location are of great importance. In other words, a realistic solar resource availability estimate is required for any site in various solar energy applications such as solar furnaces, concentrator collectors, and indoor lighting in buildings [6].

Exergy is a property that expresses the maximum useful work that can be performed during a process that brings a system into equilibrium with its environment. Thus, exergy is a property of both the state of a system and its environment. Exergy analysis is an exergy-based method that takes into account such irreversibility in each component of the system. Using this approach, an attempt is made to determine the limit of useful work that can be extracted from thermodynamic processes [7].

The maximum exergy of solar energy, or equivalently, the maximum conversion efficiency related to thermal radiation, decides its optimal utilization [8]. Due to the entropy content of solar energy, it cannot be fully converted and hence its exergy value remains below 100%. In fact, depending on atmospheric conditions, the exergy content of the solar radiation energy reaching the Earth may vary between 50% and 80%. For this reason, thermodynamic analyses of solar energy systems are conducted to determine the exergy content of solar radiation energy [6]. Investigations on the exergy potential of solar radiation have drawn considerable attention in recent literature, which itself is an indication of the rising awareness of its importance in optimizing solar energy systems and improving their efficiency. Exergy is the maximum useful work obtainable from a system, and because of this context, exergy has been a very relevant resource in the realm of solar energy, where one could understand the quality of the radiation and go for better design and operational strategies regarding solar collectors and photovoltaic systems. Recent studies emphasize the need to have accurate models in order to quantify the exergy of solar radiation. Rodríguez et al. [9] critically reviewed various expressions adopted to model solar radiation exergy, related both to optimizing flat-plate collectors and also in the determination of the exergy budget on the Earth's surface. Their pioneering work indicates that exergy analysis is valuable for the pinpointing of sources of irreversibility in all types of solar energy conversion systems; therefore, exergy has an important contribution to the rationalization of efficient engineering design techniques of the system.

In addition to theoretical developments, experimental analyses have also illustrated the importance of exergy analysis in solar technologies. Miskat and Rashedi [10] examined an

exergy efficiency analysis of photovoltaic systems in Nepal. They showed how exergy analysis can identify the inefficiencies in solar energy use and help develop further improvements. Dash et al. [11] studied the exergy performance of solar dryers and found that energy and exergy efficiencies are greatly influenced by changes in the intensity of solar radiation. These findings are corroborated by other studies that have linked exergy performance to operational parameters such as mass flow rate and inlet temperature, further emphasizing the multifaceted nature of exergy analysis in solar applications. Beyazit et al. [12] performed an analysis using solar radiation data measured for the Diyarbakır province, applying the exergy methods of Jeter, Petela, and Spanner in their study. They determined the exergy/energy ratio of global solar radiation as well as demonstrated the energy of solar radiation. In addition, they developed a correlation for predicting solar radiation exergy. Kurtgoz et al. [13] used the Petela, Spanner, and Jeter approaches to calculate the exergy values of solar radiation in their study. They developed exergy-energy ratios and exergy value maps for Turkey and made environmental economic analysis based on these results. Meteorological and geographical factors affecting solar radiation were taken into consideration in the study done by Kurtgoz and Deniz [14] who used artificial neural networks to predict global solar radiation for the Göksun Station in Turkey. The exergy analyses of the predicted and measured global solar radiation values were performed through the Jeter, Spanner, and Petela methods. In a study conducted by Yeşilbudak et al. [15], detailed analyses of parameters such as global solar radiation, sunshine duration, and air temperature, based on long-term measurement data for Ankara province, were performed. For each parameter, models were developed using three separate empirical methods, and the performance of these models was statistically compared. It was noted that the models exhibiting the best statistical results were successful in modeling the solar characteristics of the region, and these models would serve as an important resource for other regions with similar climatic conditions. Uckan [16] made an exergy analysis of solar radiation based on measurement data in the Van province between 1993 and 2007 and then calculated exergy/energy ratios with the help of different exergy models in their study. Kaltakkıran [17] performed the exergy analysis of solar radiation based on the measurement data between 2010-2021 for Erzurum province. He used three different models of Jeter, Spanner and Petela to obtain the exergy values. The study includes calculating the exergy/energy ratios and exergy values with the help of different exergy models. In summary, the latest literature on solar radiation exergy potential reveals a dynamic field of research that combines theoretical modelling, empirical analysis, and innovative material applications. The ongoing exploration of exergy in solar energy systems not only improves our understanding of energy conversion processes but also paves the way for more sustainable and efficient solar technologies.

In this study, the exergy values of solar radiation were calculated for long-term meteorological data such as global solar radiation and air temperature measured by meteorological stations in the provinces of Amasya, Çorum, Samsun and Tokat located in the Central Black Sea Region of Turkey. In this context, solar radiation exergy values were calculated with the Jeter, Spanner and Petela exergy methods available in the literature and comparisons were made between the provinces.

2. Materials and Methods

Research area

In this study, the region located within the Black Sea region of Turkey, known as the TR83 region, has been selected. The TR83 region is composed of the four provinces such as Amasya, Çorum, Samsun and Tokat. The TR83 region has some unique climatic and geographical features that shape solar radiation availability and its exergy potential. In this context, the most recent global solar radiation values from the past four years and the average temperature values of the region, measured by the General Directorate of Meteorology stations, have been obtained. The location, latitude-longitude coordinates, altitude, and the years during which the measurement data were recorded are provided in detail in Table 1.

Table 1. Station information of selected areas

Location	Longitude (East)	Latitude (North)	Altitude (m)	Data series	Total years
Amasya	40,8594	36,1031	1157	2020-2023	4
Çorum	40,5461	34,9362	776	2020-2023	4
Samsun	41,2303	36,4986	6	2020-2023	4
Tokat	40,3312	36,5577	611	2020-2023	4

Methods

Radiation heat transfer is critical for engineering applications. The principle of maximizing the use of solar energy challenges the limits of energy conversion systems. Therefore, it is essential to determine the maximum benefit that can be derived from solar radiation. In this context, determining the exergy value is crucial for identifying the maximum conversion efficiency of solar energy. The most widely recognized models based on solar radiation exergy are the Petela, Spanner, and Jeter models, according to literature research. Petela's method is based on the second law of thermodynamics and evaluates the exergy of solar radiation considering the entropy generation during the interaction between solar radiation and a receiving surface. The Petela method is a widely used approach for calculating the exergy of solar radiation. It considers the sun as a blackbody radiator and accounts for entropy generation in the interaction between solar radiation and the environment. On the other hand, Jeter first proposed the Carnot efficiency for the continuous conversion of extraterrestrial radiation into work, with the sun being the constant heat source. Petela approach was equal to the exergy of radiation, Jeter approach was the heat engine cycle work, and Spanner approach was absolute work. As an input, Petela and Spanner assumed radiation energy, while Jeter assumed heat [18].

$$\varepsilon_{petela} = 1 + \frac{1}{3} \left(\frac{T_0}{T_s} \right)^4 - \frac{4}{3} \left(\frac{T_0}{T_s} \right) \quad (1)$$

$$\varepsilon_{spanner} = 1 - \frac{4}{3} \left(\frac{T_0}{T_s} \right) \quad (2)$$

$$\varepsilon_{jeter} = 1 - \left(\frac{T_0}{T_s} \right) \quad (3)$$

where T_s is the solar radiation temperature with 5777 K and T_0 is the environmental temperature. This paper, evaluates the exergy potential of solar radiation in the TR83 region using long-term data and hence provides useful information about the capability of the region in terms of efficient utilization of solar energy. Understanding the potential of exergy thus allows the policy makers, researchers, and energy planners to optimize solar energy use in the TR83 region, contributory to sustainable energy strategies with reduced dependence on conventional energy sources.

3. Results and Discussions

Between 2020 and 2023, the monthly and annual averages of the measured ambient temperature and global solar radiation values, recorded by a meteorological station, were calculated. Missing data points were interpolated using a linear approach. The accuracy of the radiation sensors is $\pm 2\%$, and the temperature sensors have an accuracy of $\pm 0.1^\circ\text{C}$. All data were quality-checked and prior to analysis. Using three different exergy models (Jeter, Spanner, and Petela) from the literature, the exergy of solar radiation was determined. The exergy–energy ratio values obtained from the Petela and Spanner models were statistically similar ($p > 0.05$), while Jeter consistently produced higher ratios. The exergy/energy ratios, calculated on a monthly and annual basis for stations in TR83 region—Amasya, Çorum, Samsun, and Tokat—are presented in detail in Table 2. The measured outdoor temperature “ T_0 ” is included as the reference temperature in Kelvin for the calculations. Here, the symbol “ ε ” represents the maximum energy potential or the exergy/energy ratio that can be derived from solar radiation.

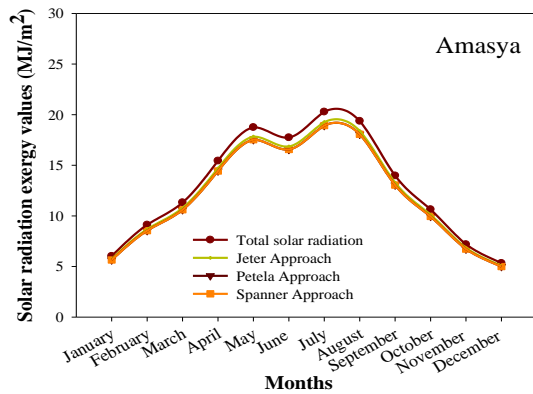
For the purpose of comparison, three distinct methods were employed: those proposed by Petela, Spanner, and Jeter. As illustrated in these tables, the exergy-to-energy ratio values derived from the Petela and Spanner approaches exhibit a high degree of similarity. The highest rate for all provinces was obtained with the Jeter method. The highest annual average temperature for Amasya and Çorum provinces was recorded in 2023, while for Samsun and Tokat provinces, it occurred in 2022.

Table 2. The Ratios of Solar Radiation Exergy to Solar Radiation Energy for TR 83 region

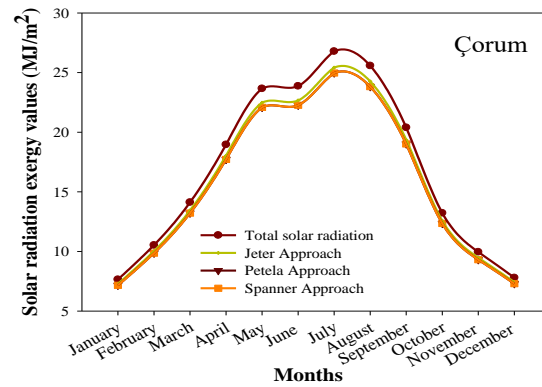
Years	Methods	Amasya	Çorum	Samsun	Tokat
2020	ε_{jeter}	0,951065	0,950448	0,950132	0,950333
	ε_{petela}	0,934752	0,933928	0,933508	0,933775
	$\varepsilon_{spanner}$	0,934754	0,93487	0,934943	0,934666
2021	ε_{jeter}	0,951152	0,950531	0,950127	0,950407
	ε_{petela}	0,934868	0,934039	0,933501	0,933874
	$\varepsilon_{spanner}$	0,93393	0,934041	0,934259	0,934057
2022	ε_{jeter}	0,951207	0,950694	0,950104	0,950418
	ε_{petela}	0,934941	0,934257	0,93347	0,933888

	$\epsilon_{spanner}$	0,93351	0,933503	0,933472	0,933311
2023	ϵ_{jeter}	0,950999	0,950543	0,949984	0,950308
	ϵ_{petela}	0,934664	0,934055	0,933309	0,933742
	$\epsilon_{spanner}$	0,933777	0,933876	0,93389	0,933744

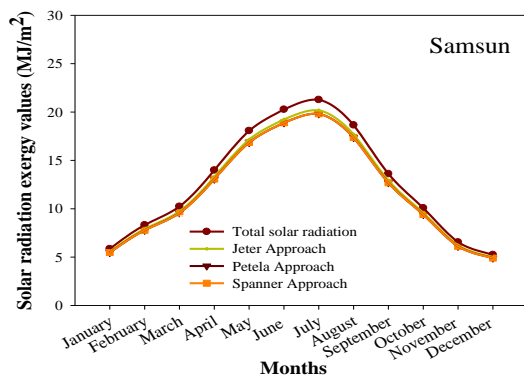
In Amasya, the annual maximum and minimum temperatures were observed in August 2023 (293.40 K) and January 2022 (271.48 K), respectively. According to the Jeter approach, the exergy-to-energy ratio for Amasya reached its peak in 2022 on an annual average basis. For Çorum, the highest and lowest annual average temperatures were recorded in August 2023 (297.67 K) and January 2022 (273.13 K), respectively. Similarly, the exergy-to-energy ratio for Çorum, based on the Jeter approach, achieved its highest annual average value in 2022. In Samsun, the annual maximum and minimum temperatures were observed in August 2022 (299.01 K) and March 2022 (279.05 K), respectively. The exergy-to-energy ratio for Samsun, peaked in 2020 on an annual average basis. For Tokat, the highest and lowest annual average temperatures were recorded in August 2022 (298.78 K) and January 2022 (274.84 K), respectively. The exergy-to-energy ratio for Tokat, based on the Jeter approach, reached its highest annual average value in 2022.



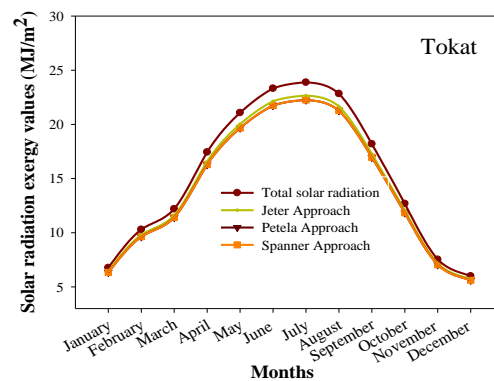
(a)



(b)



(c)



(d)

Figure 1. Total solar radiation and exergy changes of TR83 region provinces by months

Figure 1 presents the variations in total solar radiation and exergy on a monthly basis. The lowest exergy values were obtained using the Petela approach, whereas the highest exergy values were determined using the Jeter approach. For Amasya, the minimum exergy value was recorded in December at 4.9895 MJ/m², while the maximum exergy value was observed in July at 19.2646 MJ/m². Similarly, for Çorum, the lowest exergy value was calculated as 7.1629 MJ/m² in January, whereas the highest value was recorded in July at 25.41 MJ/m². Examination of the data for Samsun reveals that the minimum exergy value, 4.8998 MJ/m², was observed in December, while the maximum exergy value, 20.18 MJ/m², was recorded in July. In the case of Tokat, another province in the region, the lowest exergy value was computed as 5.6149 MJ/m² in December, whereas the highest exergy value was observed in July at 22.65 MJ/m²

Monthly average solar radiation and exergy changes of the provinces in the TR83 region are shown in Figure 2.

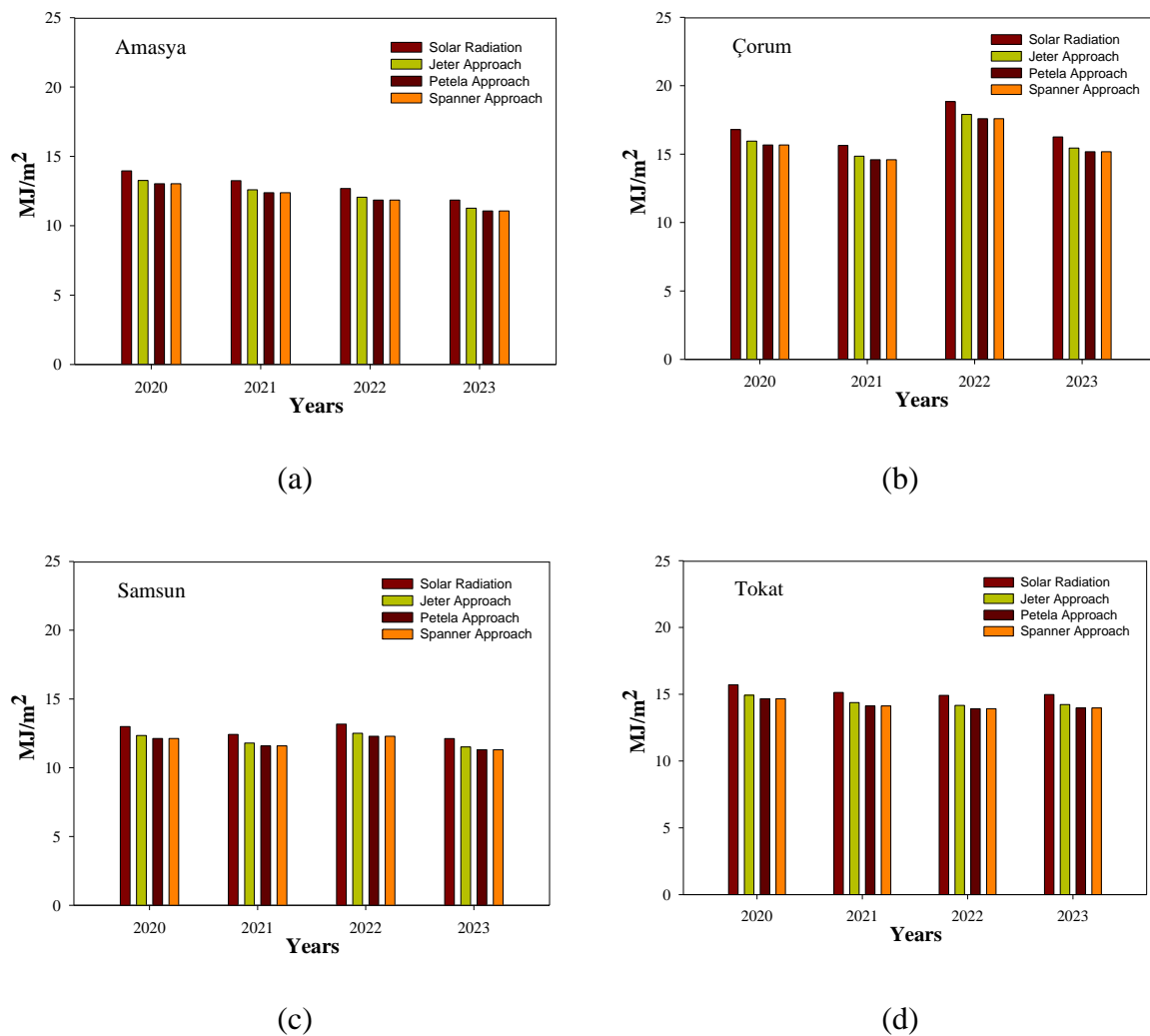


Figure 2. Monthly average solar radiation and exergy changes of the provinces in the TR83 region

As seen in Figure 2, the province with the highest solar exergy value in the TR83 region is Çorum. Tokat, Amasya and Samsun provinces, respectively follow it. Upon examining the averages, the exergy values were determined as 16.10 MJ/m² for Çorum, 14.48 MJ/m² for Tokat, 12.34 MJ/m² for Amasya, and 12.09 MJ/m² for Samsun, respectively.

4. Conclusion

Solar energy is one of the most abundantly available and sustainable renewable energy sources carrying a significant role in meeting the rising global energy demands and fighting environmental problems initiated by conventional energy sources. The prospective study area, TR83 in Turkey, is endowed with climatic and geographical diversities that greatly influence the availability of solar radiation and its exergy potential. With solar radiation as an important resource and high solar insolation, the TR83 region is a unique case in Turkey's energy planning to evaluate the actual potential of solar energy resources. However, the exergy efficiency of solar radiation potential of the region has not been investigated in detail over long periods, despite the advantages. This study aims to fill this gap by detailed exergy analysis of solar radiation with an account of the long-term meteorological data obtained from TR83. It is hoped that this study will provide insight into the region's capability to harness solar energy effectively and sustainably. Furthermore, the findings of this study underline the importance of developing province-level solar–exergy maps to guide regional investment planning, encouraging photovoltaic agriculture and rooftop installations in high-exergy areas, and promoting the adoption of exergy-based building performance standards by municipalities. Integrating exergy potential data into both national and regional sustainable energy policy frameworks will strengthen decision-making processes and enhance the alignment of local strategies with global sustainability goals. The research results are therefore expected to inform policymakers, energy planners, and researchers' decisions regarding optimizing solar energy systems, structuring regional energy systems, and contributing to the shift toward global sustainable energy solutions.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

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