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Examination of the Relationship between the Location of Wind Plants and the Earthquake Risk: Case Study Türkiye

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Anahtar Kelimeler

Deprem
Yapısal Hasar
Rüzgar Türbini Göçmesi
Rüzgar Türbini Konumları
Rüzgar Enerjisi Santralleri

Graphical/Tabular Abstract (Grafik Özet)

In order to evaluate the earthquake risk of WPPs, they were classified according to the earthquake hazard map published by AFAD and their proximity to active faults was determined. / RES'lerin deprem riskini değerlendirmek amacıyla AFAD tarafından yayınlanan deprem tehlike haritasına göre sınıflandırılmış ve aktif faylara yakınlıkları tespit edilmiştir.

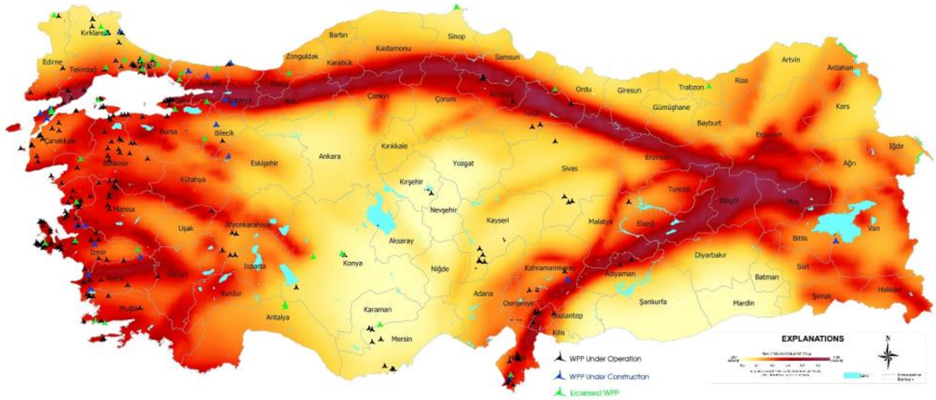

Figure A*: Positions of licensed, unlicensed, and still under-construction WPPs according to the earthquake risk map /* ***Şekil A:*** *Lisanslı, lisanssız ve inşaatı devam eden RES'lerin deprem risk haritasına göre konumları*

Highlights (Önemli noktalar)

- *Statistics on accidents occurring in wind turbine power plants have been created. / Rüzgar türbini santrallerinde meydana gelen kazalara ilişkin istatistikler oluşturulmuştur.*
- *The proximity of the wind power plants in Türkiye to the fault has been determined. Statistical data on the proximity to the fault are presented. / Türkiye'deki rüzgar santrallerinin faya yakınlığı tespit edilmiştir. Faya yakınlığa ilişkin istatistiksel veriler sunulmaktadır.*
- *By comparing the wind potential with the earthquake risk map, location suggestions were made for the wind turbine plants planned in the future. / Rüzgar potansiyeli deprem risk haritası ile karşılaştırılarak gelecekte yapılması planlanan rüzgar türbini santralleri için yer önerilerinde bulunulmuştur.*

Aim (Amaç): *This study focuses on providing a comprehensive analysis of the causes of wind turbine damage, offering statistical insights into this subject. / Bu çalışma, rüzgar türbini hasarlarının nedenlerine ilişkin kapsamlı bir analiz sağlamaya ve bu konuda istatistiksel bilgiler sunmaya odaklanmaktadır.*

Originality (Özgünlük): *The study discusses the various factors influencing the selection of suitable locations for wind turbine power plants, while also exploring relevant international laws and regulations. / Çalışmada rüzgar türbini santralleri için uygun yer seçimini etkileyen çeşitli faktörler tartışılırken, ilgili uluslararası yasa ve düzenlemeler de inceleniyor.*

Results (Bulgular): *When the map showing the proximity of WPPs to active faults was examined, it was determined that only 27% of WPPs were located 25 km or more away from active faults. / RES'lerin aktif faylara yakınlığını gösteren harita incelendiğinde, RES'lerin yalnızca %27'sinin aktif faylara 25 km ve daha uzakta yer aldığı tespit edilmiştir.*

Conclusion (Sonuç): *New locations characterized by low earthquake risk and high wind efficiency are proposed for future wind power plant projects. / Gelecekteki rüzgar santrali projeleri için deprem riski düşük, rüzgar verimliliği yüksek yeni lokasyonlar önerilmektedir.*

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Abstract

The significance of renewable energy resources has become increasingly prominent in light of the global population growth and the inadequacy of existing energy sources. Among these resources, wind energy stands out as a highly efficient option for sustainable power generation worldwide. Türkiye has emerged as an attractive hub in this field with its capacity to accommodate both onshore and offshore wind turbines. Given Türkiye's favourable geographical location, wind energy holds great potential in the country. Consequently, there has been a steady rise in the number of wind power plants established for electricity generation in Türkiye, along with an increase in their installed power capacity. However, the regions hosting these wind power plants face dynamic challenges, such as the risk of earthquakes, which can jeopardize their continuous operation. This study focuses on providing a comprehensive analysis of the causes of wind turbine damage, offering statistical insights into this subject. Additionally, the study discusses the various factors influencing the selection of suitable locations for wind turbine power plants, while also exploring relevant international laws and regulations. An initial step involves creating a map illustrating the existing wind turbine plant locations to initiate the research. The study also presents statistical data regarding the distribution of wind turbine plants in earthquake-prone regions, subsequently, by considering the earthquake map established in Türkiye's 2018 earthquake regulation, an assessment of earthquake risks is conducted based on the existing wind turbine power plant locations. As a result, new locations characterized by low earthquake risk and high wind efficiency are proposed for future wind power plant projects.

Rüzgar Türbinlerinin Konumu ile Deprem Risk Bölgeleri Arasındaki İlişkinin İncelenmesi: Türkiye Örneği

Makale Bilgisi

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Öz

Küresel nüfus artışı ve mevcut enerji kaynaklarının yetersizliği nedeniyle yenilenebilir enerji kaynaklarının önemi giderek daha fazla ön plana çıkmaktadır. Bu kaynaklar arasında rüzgar enerjisi, dünya çapında sürdürülebilir enerji üretimi için oldukça verimli bir seçenek olarak ön plana çıkıyor. Türkiye, hem karadaki hem de denizdeki rüzgar türbinlerini barındırma kapasitesiyle bu alanda cazip bir merkez olarak ortaya çıkmıştır. Türkiye'nin elverişli coğrafi konumu göz önüne alındığında, rüzgar enerjisi ülkede büyük bir potansiyel barındırmaktadır. Sonuç olarak, Türkiye'de elektrik üretimi amacıyla kurulan rüzgâr santrallerinin sayısında ve kurulu güç kapasitesinde istikrarlı bir artış yaşanmaktadır. Ancak bu rüzgar santrallerine ev sahipliği yapan bölgeler, deprem riski gibi dinamik zorluklarla karşı karşıyadır ve bu durum santrallerin sürekli çalışmasını tehlikeye atabilmektedir. Bu çalışma, rüzgar türbinlerinde meydana gelen hasarların nedenlerine ilişkin kapsamlı bir analiz sağlamaya ve bu konuya ilişkin istatistiksel bilgiler sunmaya odaklanmaktadır. Ek olarak, çalışma rüzgar türbini enerji santralleri için uygun yerlerin seçimini etkileyen çeşitli faktörleri tartışırken, aynı zamanda ilgili uluslararası yasa ve düzenlemeleri de incelemektedir. Çalışma kapsamında mevcut rüzgar türbini tesisi konumlarını gösteren bir harita oluşturulmuştur. Ardından rüzgar türbini santrallerinin depreme duyarlı bölgelerdeki dağılımına ilişkin istatistiksel veriler sunulmuştur. 2018 yılında yayınlanan deprem yönetmeliğindeki deprem tehlike haritası dikkate alınarak mevcut rüzgar türbini santral lokasyonları için deprem risk değerlendirmesi yapılmıştır. Sonuç olarak, gelecekteki rüzgar santrali projeleri için düşük deprem riski ve yüksek rüzgar verimliliği ile karakterize edilen yeni lokasyonlar önerilmiştir.

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1. INTRODUCTION (GİRİŞ)

Today, it is known that the traditional methods and fossil fuel types used for energy production have adverse effects on the environment, human health, and natural resources. Therefore, there is an intense focus on renewable energy sources around the world. The leading renewable energy sources are solar, wind, geothermal, hydraulic, biomass, wave, and hydrogen energies. The most important of these groups is wind energy [1,2]. This is because wind is a renewable energy source that produces no greenhouse gases or emissions during power generation. The "fuel" required for production is free and theoretically inexhaustible. As technology advances, the cost of adding new capacity gradually decreases. Wind energy is one of the most widely used renewable, environmental energy sources in the world. The theoretical potential of wind energy power in Türkiye is estimated to be approximately 118,000 MW. The total potential of the turbine installable land areas is 48,000 MW [3]. Electricity generation from wind energy began in 1998, and Türkiye has continued to increase yearly [4]. With 843 MW commissioned in 2022, the total wind installed power reached 11,945 MW. The development of wind energy installed power in Türkiye is shared in Figure 1. Electricity generation from wind power in Scotland exceeded electricity consumption in November 2018. At the end of 2018, the share of electricity generated from wind energy in worldwide electricity use increased from 3.1% to 4.8% compared to 2015 [6]. This is an indication that investments in wind energy continue rapidly in the world. In 2020, the share of Denmark, Uruguay, Lithuania, Ireland, Portugal, England, Germany, Spain, Greece, Sweden, the USA, and China in electricity generation capacity from wind energy is respectively 56%, 40%, 36%, 35%, 23%, 24, 23%, 20%, 18%, 16%, 8%, and 6%. Besides, Türkiye has an installed capacity of 10.81% electricity generation from wind energy in 2022 [7].

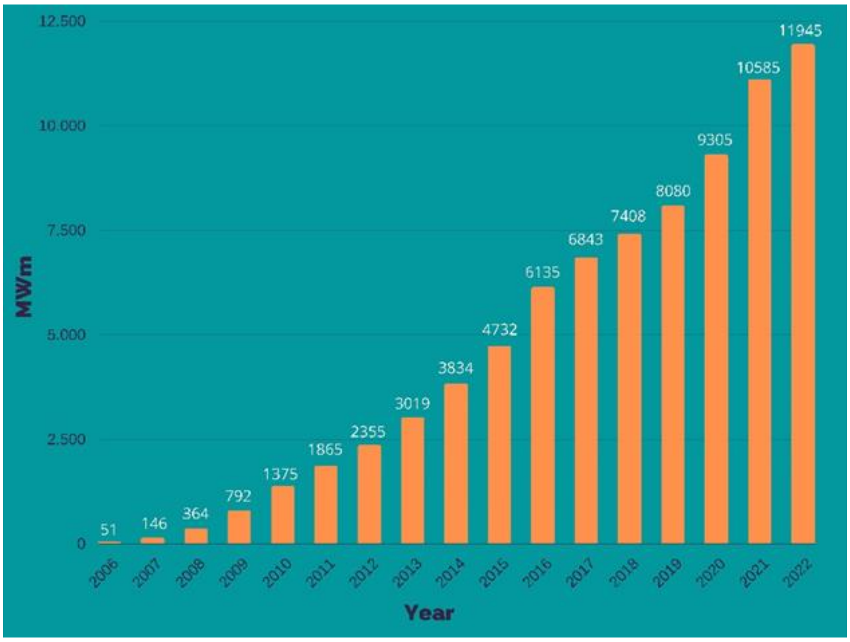

Figure 1. Cumulative wind power installed capacity of Türkiye (Türkiye'nin kümülatif rüzgar enerjisi kurulu gücü) [5]

To use wind energy efficiently, first of all, the correct determination of the wind energy potential and, accordingly, the correct positioning of the wind turbines are of great importance. For an economic investment in a wind power plant, it must have a capacity value of 35% or more. Referring to Figure 2 on the map of Türkiye in wind capacity factor for wind energy, especially in the regions located on the sea coast of the country is seen as a serious potential. The same situation is observed in some parts of the country (Central Anatolia, Black Sea, Aegean, and Mediterranean regions). In addition, annual average wind power density distribution and annual average wind speed distribution maps should be examined for the efficiency of this investment.

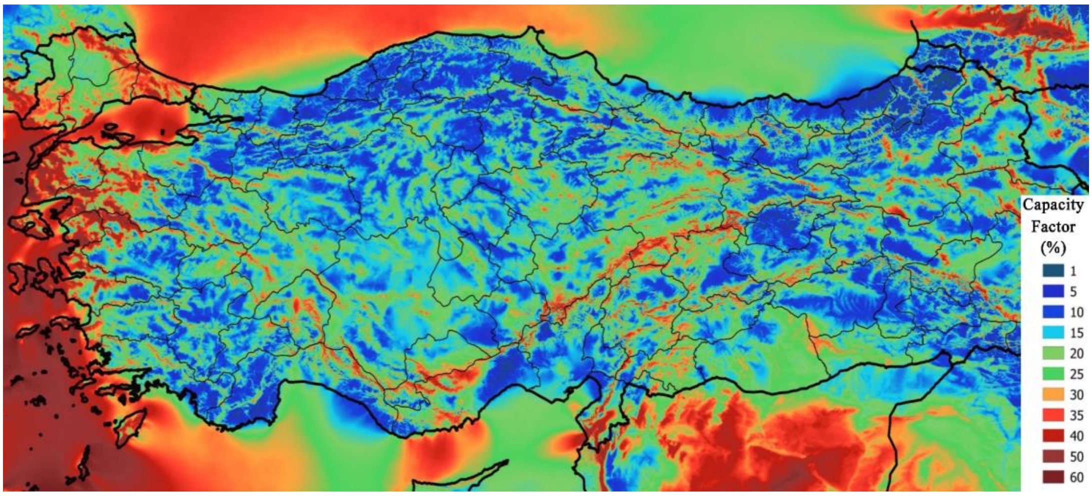

Figure 2. Average capacity factor distribution at an altitude of 100 meters across Türkiye (Türkiye genelinde 100 metre rakımda ortalama kapasite faktörü dağılımı) [8]

In regions where wind power plants are constructed in a continuous manner, such as areas prone to earthquakes, the dynamic effects of these earthquakes become a significant concern. This research initially involved the development of a map indicating the locations of current wind patterns. Furthermore, statistical data regarding the distribution of wind turbine power plants in relation to earthquake-prone regions were analysed. Subsequently, taking into account the earthquake map outlined in the 2018 edition of the new earthquake regulation, an evaluation of earthquake risks was conducted based on the existing locations of wind turbine power plants (WPP). The research also proposed potential future sites for wind power plants that exhibit low earthquake risks and high wind efficiency. In the literature, wind turbine design generally does not consider earthquake loads. This study determined that the risk of earthquakes in our country is high, especially in regions with high wind potential. For this reason, using earthquake load and wind load in the dynamic loads used in the design will yield positive results in both innovation and sustainability. The study also guides in determining new wind turbine locations.

2. EARTHQUAKE RISK PROFILE IN TURKIYE (TÜRKİYE'DE DEPREM RİSK YÖNETİMİ)

Wind turbines consist of three basic structures. These are the foundation, the carrier tower, and the rotary mechanism placed on the tower. Although these turbines are seen as different from other structures, their behaviour against dynamic loads is examined using various methods, as in the designs of other structures. Seismic loads in wind turbine systems developed in Western and Northern European countries, most of which are not seismic zones, are handled and taken into account quite simply when compared to wind. There are two major factors behind this. Firstly, since wind turbines are very delicate structures, their cross-sections are relatively small for their size. The axial pressure caused by the tower structure and the weight of the rotor-nacelle/blades at the tower tip, as well as the bending due to wind loads, are also carried by these cross-sections. In addition to these effects, the effect of earthquake vibrations on the structure can make the structure even more fragile. Secondly, since the wind loads, which means horizontal loads like the earthquake, are more dominant than the earthquake loads (the horizontal loads they create on the turbine tower are larger), it is assumed that the turbines exposed to the severe wind loads predicted in the calculations will also withstand earthquake effects that create smaller forces than them. Although Turkey is an efficient country in terms of wind energy, it may not be a reliable country in terms of earthquakes since it is located in earthquake zones [9]. Modern wind turbines consisting of a tower 70 m and higher have not encountered the high-ground vibrations caused by a devastating earthquake. Even if there is earthquake damage, these are not given in the literature. In recent years, many devastating earthquakes have occurred in Türkiye that have caused loss of life and property. These; 1992

Erzincan, 1995 Dinar, 1998 Adana-Ceyhan, 17 August 1999 Marmara, 12 November 1999 Düzce, 2002 Afyon, 2003 Bingöl, and 2023 Kahramanmaraş earthquakes. Many existing structures were damaged in the earthquakes. After these earthquakes, the application of various performance-based analysis methods gained importance, and the use of non-linear analysis, static, and dynamic analysis methods became widespread [10].

The tectonically active areas in the western part of Türkiye are associated with high tension areas, such as the North Anatolian Fault and the Aegean extensional zone. Numerous devastating earthquakes have been recorded in West and East Anatolia. Some of the biggest earthquakes recorded in the 20th Century and 21th Early Century: Tekirdağ (1912) Ms=7.3, Erzincan (1939) Ms=7.9, Tokat (1942) Ms=7.0, Muğla (1957) Mw=7.1, Van (1976) Ms=7.5, Kocaeli (1999) Mw=7.4, Düzce (1999) Mw=7.2, and Van (2011) Ms=7.2. Finally, earthquakes with a magnitude of Mw=7.7 and Mw=7.6 occurred in Pazarcık and Ekinözü-Kahramanmaraş, which were recorded as February 6 earthquakes in Türkiye [11]. Approximately 38.000 aftershocks of these earthquakes have occurred to date [12]. The most damaging earthquakes were observed along the strike-slip North Anatolian Fault Zone. The North Anatolian Fault Zone consists of 3 branches. Of these, the northern arm passes through the Sea of Marmara, the Middle Arm passes through Bursa, reaching the Aegean Sea, and the southern arm passes south of Bursa. Tectonic activities are active throughout western Anatolia [13]. Due to these tectonic activities, it is of great importance that calculations and construction activities are carried out without ignoring the earthquake risk of all structures, including wind turbine towers to be built in Türkiye.

3. STRUCTURAL DISRUPTIONS IN WPPS
(RÜZGAR ENERJİSİ SANTRALLERİNDEKİ YAPISAL BOZUKLUKLAR)

The primary loads taken into account when designing wind turbine towers are the weight of the structural components themselves and the force exerted by the wind. As a secondary factor, the tower tip mass is taken into account in dynamic and static calculations. Especially in towers with longer bladespan, the weight of the blade and rotor nacelle structure also gains an important place in these calculations. It is crucial for a wind turbine tower to possess adequate moment capacity in order to withstand the maximum wind force anticipated. Additionally, the tower should be designed with sufficient rigidity to withstand varying wind loads at different wind speeds [14]. Designing and constructing wind turbines involves high engineering work. However, despite this, human or mechanical errors and engineering errors combined with defects of the constituent elements and materials still result in hundreds of cases of structural collapse each year [15].

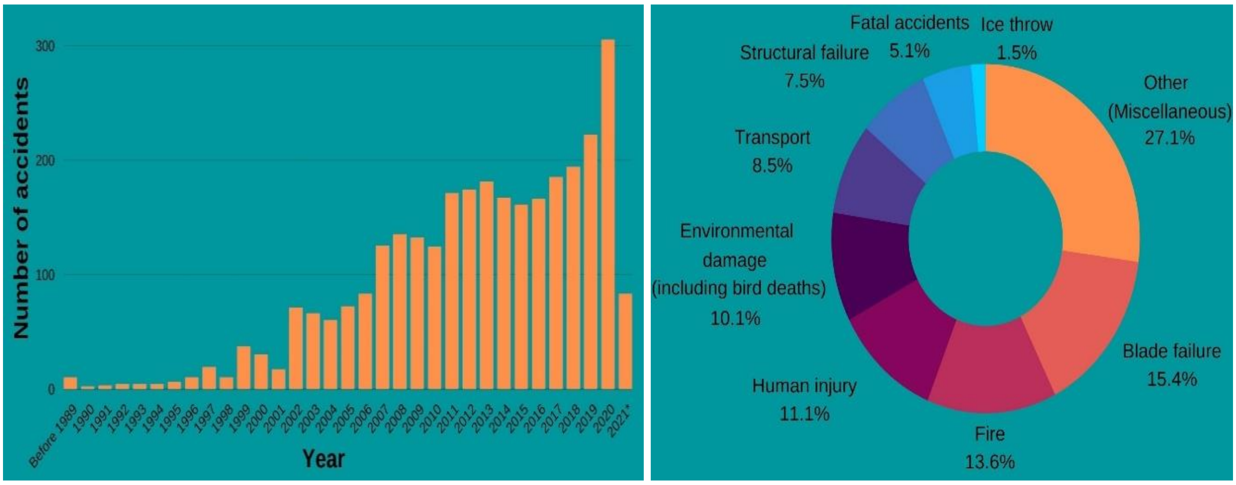

Figure 3 (a) Number of accidents in WPP between 1980 and 2021 (**b)** Failure type distribution of wind turbine incidents recorded between 2006 and 31 March 2021*(a) 1980 ve 2021 yılları arasındaki rüzgar enerji santralleri kaza sayıları b) 2006 ile 2021 yılları arasında kaydedilen rüzgar türbini olaylarının arıza türü dağılımı* [16]

Figure 3(a) presents the number of accidents in WPP between 1996 and 2021*. Figure 3(b) shows that the highest number of cases, 17.9% of the total, is caused by blade failure, followed by fire with 14.5%. Structural failure, including tower collapse and turbine damage, was the fourth-largest type of damage on the list, accounting for 9.2% of total damage. The Caithness Windfarm Information Forum 2021 report caught out that there have been 3033 wind tribune accidents in the last four years and up to 31 March 2021. Table 1 presents the number of accidents in wind power plants in detail according to the years and the reason for their occurrence.

The general collapse patterns of wind turbine components resemble a time-varying bathtub curve. The Bathtub curve includes three typical stages: Early use, normal operation, and wear out, as shown in Figure 4.

Table 1. Distribution in the number of accidents in Global Wind Power Plants according to the year and reasons of occurrence (Küresel Rüzgar Enerji Santrallerinde meydana gelen kaza sayılarının yıllara ve meydana gelme nedenlerine göre dağılımı) [16]

Accident Types	**Years**													
	Before 2008	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	***21**
Fatal accidents	61	8	8	15	17	5	3	8	6	9	3	5	6	2
Human injury	66	9	14	12	15	9	9	9	10	13	4	48	118	2
Blade failure	160	26	20	20	29	36	32	22	21	18	27	24	29	4
Fire	134	18	16	22	23	26	19	20	28	25	27	23	22	9
Structural failure	85	16	9	13	10	15	13	12	11	14	9	7	10	2
Ice throw	27	4	1	1	1	0	1	1	3	1	2	3	1	0
Transport	50	11	11	24	17	14	17	14	16	19	14	18	23	10
Environmental damage (including bird deaths)	55	13	20	20	20	16	21	18	22	16	24	25	24	12
Other (Miscellaneous)	130	27	25	44	42	60	52	57	49	70	84	69	72	42
Number of accidents	768	132	124	171	174	181	167	161	166	185	194	222	305	83

The infant mortality curve represents failures resulting from design errors, poor adjustments, and manufacturing errors. These failures tend to happen early in the lifetime of a system or component and are often resolved through improvements or modifications, making them less likely to reoccur. On the other hand, the wear-out curve illustrates failures caused by the deterioration of components over time. These failures become more frequent as the system or component ages and experiences normal wear and tear. The constant failure rate curve, also known as random failures, is characterized by failures that occur evenly throughout the lifetime of the system or component. These failures seem to follow a Poisson process with a constant failure rate. Random failures are unpredictable, as components can transition directly from a healthy state to a failed state without any warning. Preventive maintenance is typically employed for deteriorating components, where there is an intermediate damaged state between the healthy and failed states. Implementing preventive maintenance can be beneficial in these cases, as it helps to address potential issues before they lead to failure. However, it is crucial to balance maintenance efforts, as excessive preventive maintenance can result in increased costs without significant benefits. Increasing maintenance efforts can reduce failure costs but may also increase preventive maintenance costs. The optimal level of maintenance is the one that minimizes the total costs associated with failures and preventive maintenance [17]. It is important to find the right balance to achieve cost-effectiveness in maintenance strategies.

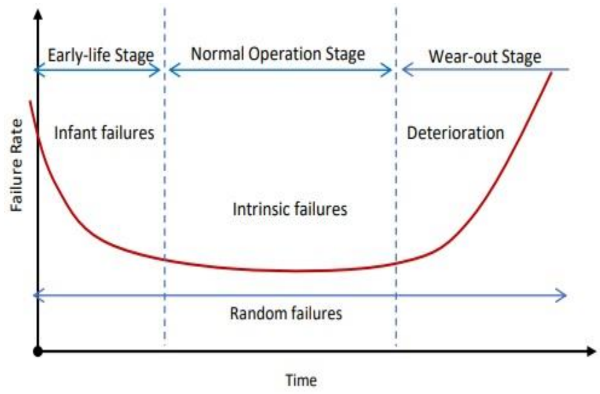

Figure 4. A Bathtub Curve for Failure Rate-Time
(Zamanla meydana gelebilecek göçme olasılığı için bathtub eğrisi)

Structurally, bolted connections are required to fasten the shell constituent components to provide sufficient rigidity in the turbine tower. Its known cyclic bending moments induced by changing wind loads and earthquakes that cause oscillation/vibration on the tower affect the rigidity of the connections, causing the flange plates to separate and the bolts to loosen. The fracture phenomenon in the material due to repeated application of the loads that create the stress values below the maximum static stress value is called fatigue failure. The effect of cyclic loading on a turbine tower can cause fatigue damage to structural members and their fasteners. The fatigue failures end in bolt loosening, which reduces the interlocking force treater on the joint. Then shear happens, causing the bolt to be subjected to bending loads, immediately afterwards to fracture by fatigue. Typhoon Jangmi, which occurred in Taiwan in 2008, caused buckling and bolt ruptures in wind turbine towers [18]. In another example, the wind turbine called number 43 at the Cin Zuoyun wind tribune can be examined. While this turbine was under normal weather conditions due to insufficient maintenance of the bolts and flanges connecting its lower and middle components, it broke from this region and caused the collapse. In addition, in the same report, it was stated that although turbine tower number 63 is standing, approximately 40% of the bolts connecting the components in the tower were broken [19]. Bäckstrand and Hurtig examined the tower collapse incident in Lemnhult, Sweden, in 2015. Subsequent investigation revealed that the collapse was caused by bolt fatigue, which may have resulted from inadequate pre-tensioning force applied during the construction phase[20]. Similarly, bolts failure was seen in accidents in the USA in 2004, Denmark in 2008, and Germany in 2014. During the design process of a wind turbine tower, it is crucial to assess the fatigue performance of its components, particularly the bolts. Evaluating the stress ranges in the bolts and conducting calculations to ensure their adequacy is necessary, which helps to ensure the structural integrity and reliability of the tower under operational conditions. For this purpose, studies on structural health monitoring have been developed improve tower damage detection strategies [21,22]. In 2012, Bas et al. created a database covering two years of their studies. Through this database, it was possible to evaluate the relationship between risk factors, including stresses on the tower, nacelle rotation, rotation speed, wind speed, angle of inclination, and temperature [23].

The factors that cause damage in Table 1 have great importance in the material loss in wind turbines. The financial impact of a complete tower collapse can range from an average of £500,000 to £5,000,000, depending on the specific configuration of the wind turbine, but construction cost would be around ten percent of the total enterprise. On the other hand, electrical components, blades, and nacelles can be fixed in the event of failure, and all blade energy harvesting to go on. Therefore, the structural safety of the turbine tower interacts with the stability of the end-to-end structure directly;

however, there are differences in its relationship with other devices such as mechanical or electrical components [24]. The increasing global adoption of wind energy suggests that more wind tribunes will be constructed in regions prone to seismic activity, which poses a potential risk as entire arrays of wind turbines with similar designs could be simultaneously affected during an extreme seismic event [25,26]. In addition, a sudden transition to the Wear-out stage without seeing the Early-life and Normal operation stages specified in Figure 4 with seismic effects or passing these stages quickly creates great risk. Therefore, it is essential to understand the behaviour of these structures and their constituent parts under realistic assessments of seismic loading [27-28].

4. CURRENT WIND TURBINE LOCATIONS AND EARTHQUAKE RELATIONSHIP IN TURKIYE (TÜRKİYE'DEKİ GÜNCEL RÜZGAR TÜRBİNİ KONUMLARI VE DEPREM İLİŞKİSİ)

As of January 2022, 3,983 turbines have been built in 273 power plants in many parts of the country, and a total installed power of 11,102 MW has been reached. The distribution of wind power plants in terms of installed power is in Marmara Region, with 41.72% at most. The installed power ratios of other regions are respectively 33.49% Aegean Region, 10.30% Mediterranean Region, 9.36% Central Anatolia Region, 3.55% Black Sea Region, 0.84% South East Anatolia Region, and finally 0.74% East Anatolia Region. When the distribution by provinces is examined, the highest installation power is found in İzmir, with 16.99% and 1887 MW power. İzmir is followed by Balıkesir with 12.39% (1375 MW), Çanakkale with 8.26% (917.00 MW), Manisa with 6.55% (728 MW), and İstanbul with 6.16% (684 MW). WPPs still under construction are located in the Marmara region, with a rate of 86.04%; and in the Central Anatolia Region, with a rate of 8.52%. When the distribution by provinces is analysed, İstanbul ranks first with 22.56% and 181 MW of power. After İstanbul, Bursa (19.33%) is ranked second with an installed power of 155 MW, Sakarya (14.28%) with an installed power of 115 MW is the third, and Kayseri (8.52%) is the fourth with an installed power of 68 MW [29]. When the wind map of Türkiye is examined, it is seen that the windiest locations are in the Aegean and Marmara Regions, followed by the Mediterranean and the Black Sea coastlines.

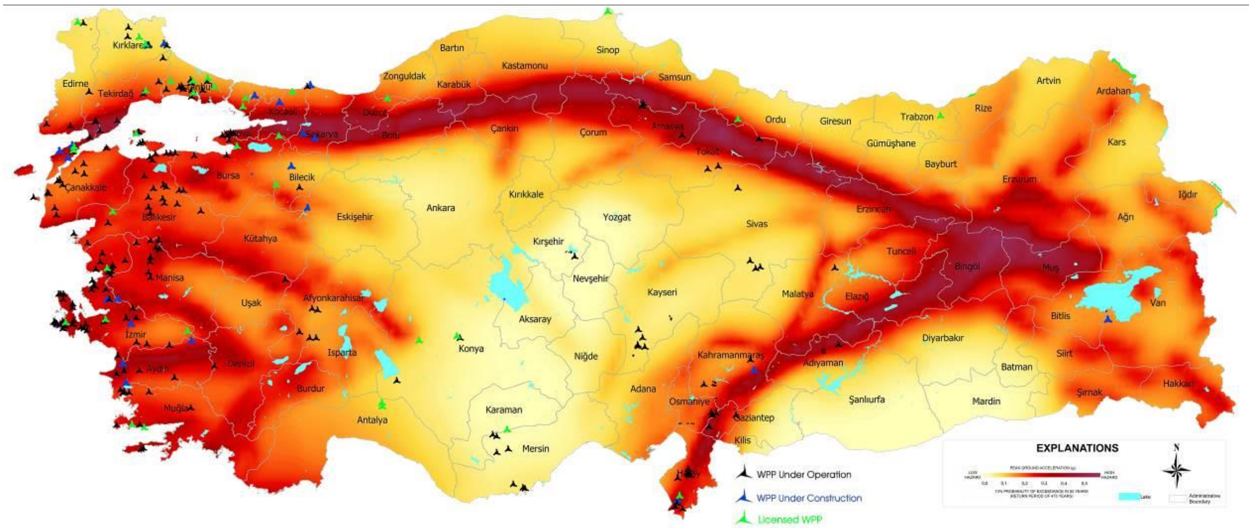

Figure 5. Positions of licensed, unlicensed, and still under-construction WPPs according to the earthquake risk map (Lisanslı, lisanssız ve inşaatı devam eden RES'lerin deprem risk haritasına göre konumları)

The scope of this study involved analysing the current status of Wind Power Plants (WPP) in Türkiye. To identify the locations of these plants, the Turkish Wind Energy Association (TWEA) released a report in January 2020. In order to assess the earthquake hazards associated with these WPP locations, seismic data from the Turkish Building Seismic Code (TBDY-2018) were utilized. Subsequently, using the information provided by AFAD (Disaster and Emergency Management

Authority) and Turkish Atlas, the identified WPP locations were marked on a map, indicating the earthquake hazard levels associated with each site [29]. The fault map and earthquake hazard map used in this study were prepared using the maps published after the February 6 Kahramanmaraş earthquakes. Figure 5 shows the locations of Licensed, Unlicensed, and still under-construction WPPs according to the earthquake risk map. The earthquake risk map of Turkey, published by AFAD in 2018, was created based on the Peak Ground Acceleration (PGA) values. PGA is generally used in the analysis of the effect of earthquakes and earthquake hazard analysis. Figure 6 is created using the active fault map published by AFAD to evaluate the proximity of the mentioned WPPs to active faults.

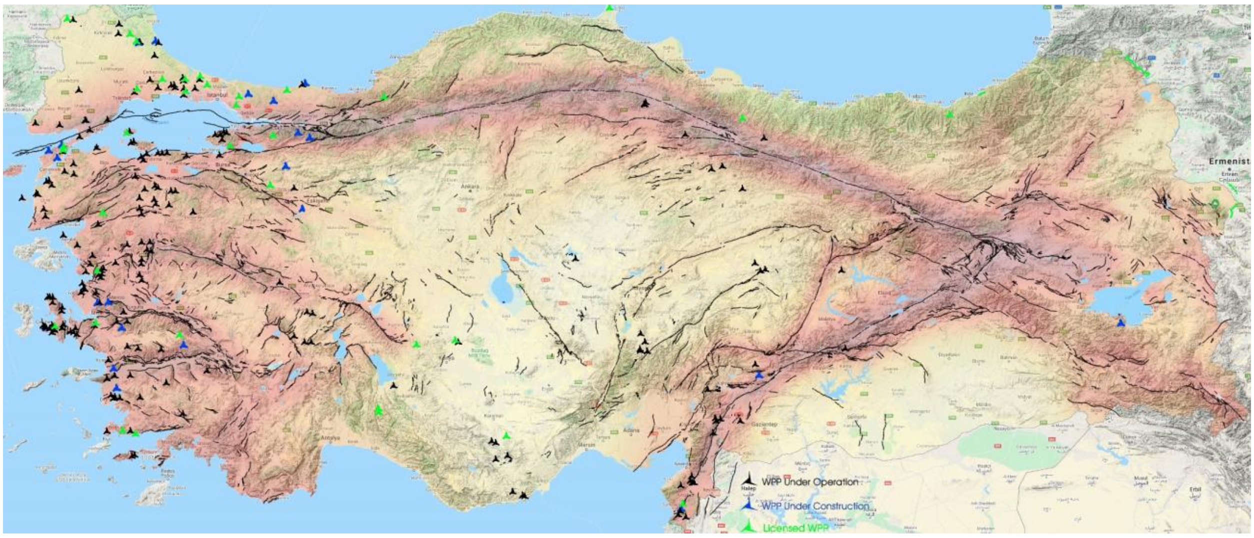

Figure 6. The proximity of licensed, unlicensed, and currently under-construction WPPs to active living faults (Lisanslı, lisanssız ve inşaatı devam eden RES'lerin aktif faylarına yakınlığı)

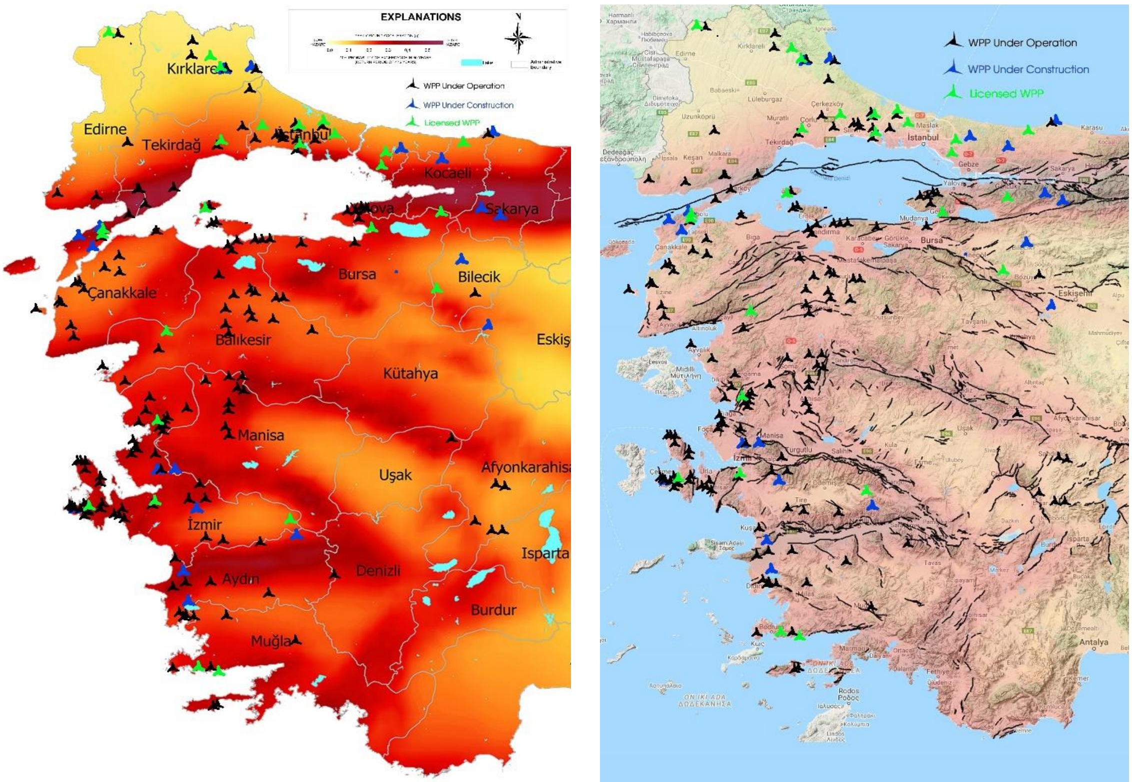

Figure 7. Status of WPPs in the Aegean and Marmara Regions (Ege ve Marmara Bölgesinde bulunan RES'lerin lokasyonları)

It has been determined that 73.17% of the total installed power of 8056 MW is located in the Aegean and Marmara regions. For this reason, Figure 7 is created to make a detailed examination covering these two regions. The examination of the locations of installed wind turbines and earthquake risk maps for the Aegean and Marmara regions reveals the current situation. However, due to wind energy potential in these regions, wind turbine installations are rapidly continuing. Therefore, wind energy capacity factor distribution maps and earthquake risk maps are compared for these two regions in Figures 8 and 9. It is believed that this comparison will establish a roadmap when considering earthquake risks for future wind turbine installations in these regions.

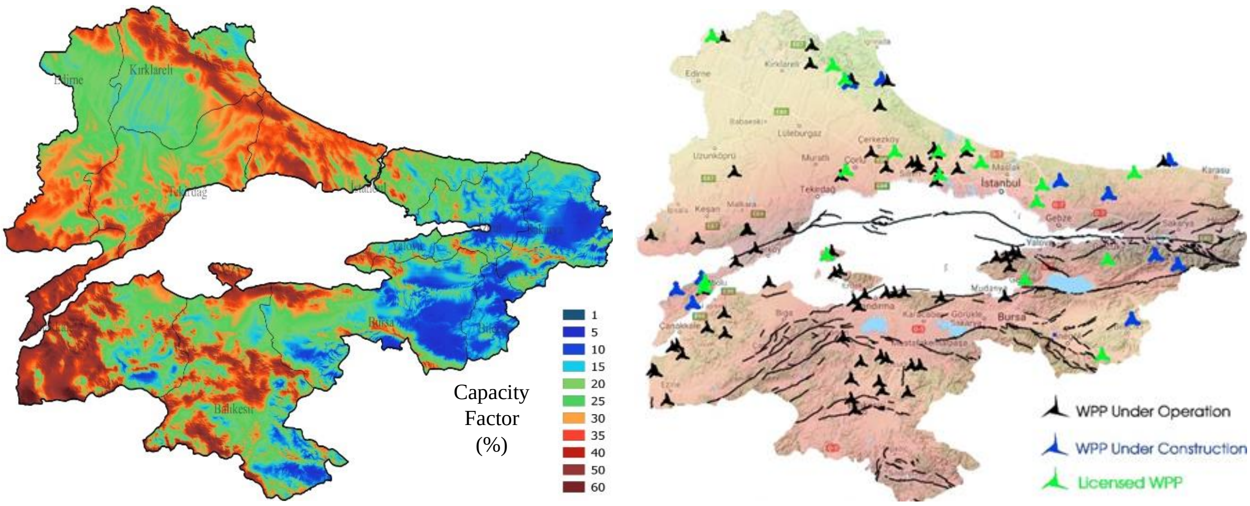

Figure 8. Wind energy capacity factor and earthquake risk maps for the Marmara (Marmara Bölgesi için rüzgar enerjisi kapasite faktörü ve deprem risk haritaları)

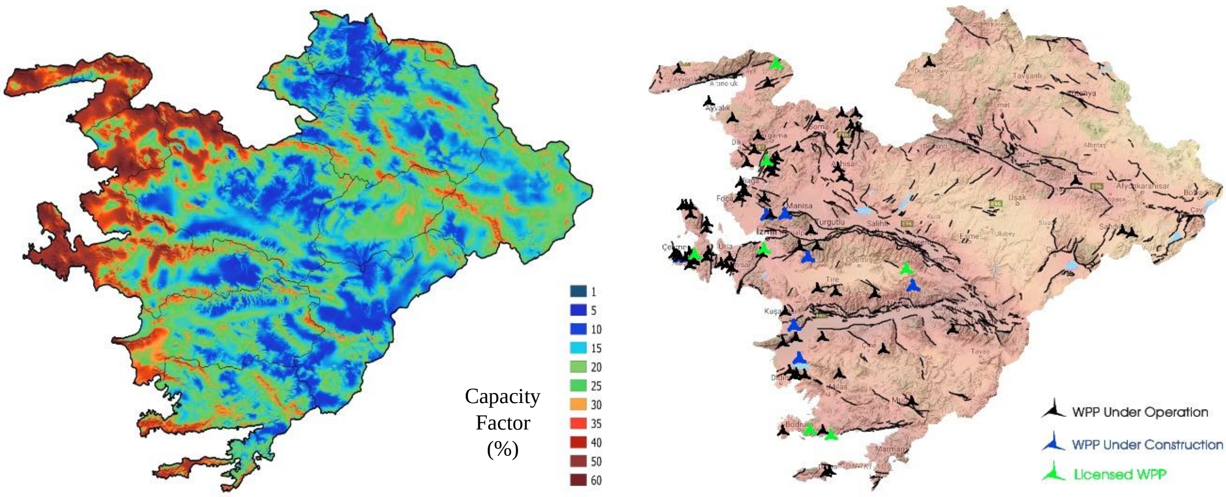

Figure 9. Wind energy capacity factor and earthquake risk maps for the Aegean (Ege Bölgesi için rüzgar enerjisi kapasite faktörü ve deprem risk haritaları)

It is known from the studies that earthquakes can cause more damage to structures close to the fault [31-34]. Since most earthquake codes do not have obvious statements about this issue, more care should be taken in the design of structures. For example, there is no statement on this subject in the Iran 2800 code [35]. Studies have determined that the seismicity of the northwestern region of Iran is higher than the seismicity of the eastern Anatolian region of Turkey. Despite this, according to the Iranian Code of Practice for Seismic Resistance Design of Buildings Standard [Iran National Standard No. 2800], there is no restriction on the distances of the structures to be constructed from the fault [36]. FEMA instructions include optimizations in structures close to the fault line. In the UBC 1997

(Uniform Building Code) regulation, the coefficients to be applied for buildings located 2 km, 5 km, and 10 km from the fault line are defined as different values [37]. Also, The Fault Law in the State of California, the USA, requires the creation of bonding boundaries. Since 1977, the banding limits have been 150 meters from the main fault, passed through distances of 60 to 90 meters from precisely defined minor faults. These criteria are valid only for strike-slip faults. However, these criteria have yet to be validated for locally complex faults, dip-slip reverses, and normal faults. When the regulations in Türkiye are examined, while the same acceleration coefficient is used in the same earthquake region in the Turkish Earthquake Code (TDY 2007) [38] spectrum, the spectral acceleration coefficients change according to the proximity to the fault in the latest published TBDY-2018 regulation. Earthquake ground motion spectra used in building design are calculated in a standard way, based on spectral acceleration coefficients, fault proximity coefficients, and local ground effect coefficients, for a 5% damping ratio, based on reference ground conditions for a certain earthquake ground motion level. In addition, in 2007, TDY only acts A_o in the vertical direction, while in the new regulation, spectral acceleration coefficients, proximity to the fault, and local ground amplitudes change.

The data obtained as a result of the study were interpreted within the limitations of maps and regulations and supported by some statistical data. By giving the results obtained in the conclusion part, new sites for future wind power plants that have a low risk of earthquakes and are highly efficient in harnessing wind resources.

5. CONCLUSIONS (SONUÇLAR)

Within the scope of the study, firstly, a map with the existing WPPs locations was created. It was observed that 73.17% of the 198 WPPs used were found in the Aegean and Marmara regions. It is observed that these powers are generally clustered in İzmir-Manisa, Balıkesir-Bursa, Istanbul European Side, and Hatay-Antakya regions. In the study, statistical data on the distribution of wind power plants by earthquake regions were created. Accordingly, about 14% of the currently licensed and actively produced WPP under construction were found to be in locations with peak ground acceleration values greater than 0-0.2 g, 41% 0.2-0.4 g, 40% 0.4-0.6 g, and 5% 0.6 g. It has been determined that there are 10 WPPs, especially in the North Anatolian Fault Zone and in the region with an acceleration value greater than 0.6 g. In the Marmara and Aegean regions, all WPPs, except Edirne and Kırklareli, are either in areas with high acceleration values or are quite close to fault lines. In addition, WPPs in the Hatay-Antioch region were found on/near the Antioch fault zone and the Eastern Anatolian Fault Zone. It is also seen that there are WPPs located in the Konya-Mersin line and Kayseri, where the earthquake risk is the least.

When the map showing the proximity of WPPs to active faults was examined, it was determined that only 27% of WPPs were located 25 km or more away from active faults. It has been observed that approximately half of the WPPs used in mapping are installed/constructed in areas with high earthquake risk. As a result of these facts, the following suggestions and recommendations were made:

- With the growth in global wind energy, wind tribunes will be built in seismically active regions; increasingly, the entire structure of the array and similarly designed simultaneously suggests that under extreme seismic events may be at risk of deterioration. Therefore, the behaviour of these structures needs to be studied in detail under realistic assessments of seismic loading.
- It is important to monitor the earthquake movements in the regions where WPPs are located and to control the elements/parts/resources that provide the structural integrity of the turbines in the power after intense movements.
- During prolonged ground motions such as earthquake storms, the structural elements and the connection parts that provide load transfer from these elements should be checked frequently, and precautions should be taken. It is known that efficiency is critical in the energy sector. For this reason, the correct use of the existing natural resources in the country is of great importance. With the

earthquake-appropriate design and modelling to be made before the construction of the WPP, the early detection of defects and structural defects that may occur later during the construction will prevent major losses.

- The concentration of WPPs to be newly constructed by relevant institutions/organizations in the Konya-Mersin line, Kayseri, Edirne, Kırklareli, and Mardin-Siverek regions will prevent earthquake and secondary risks (landslide, rockfall, flood, tsunami, and avalancheto be caused by earthquakes is considered.
- Regulations limiting structural use due to proximity to faults were examined. However, there are many different opinions. Turkey's earthquake regulations have no restrictions on bonding boundaries related to proximity to any fault. Policies and criteria regarding the establishment of these interdiction boundaries should be established.
- When establishing bonding boundaries, conditions should be developed according to the use of the building.
- In the design preparations of wind turbine power plants, it should be mandatory to make designs based on the assumption that they will be exposed to surface faulting and high earthquake effects in any direction.
- In addition to the wind energy efficiency maps used in the literature, regional maps requiring frequent business maintenance intervals may prevent such accidents.

The study shows a need to perform fatigue analysis on wind turbine towers when they are exposed to effects such as earthquakes and wind for a long time. It is essential to examine the behavior that may occur on the fasteners. As a result of these analyses, it will be possible to create maintenance-repair programs to be carried out in different periods for wind turbine power plants located in regions with high seismicity and to conduct studies on the benefits to be obtained.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

No conflict of interest was declared by the authors. The short version of this work was presented at the ACE 2021 conference.

Bu çalışmada herhangi bir çıkar çatışması yoktur. Bu çalışmanın kısa versiyonu ACE 2021 konferansında sunulmuştur.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

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AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Anıl ÖZDEMİR: He created the maps, conducted a literature review, and performed the writing and reviewing process.

Haritaları oluşturmuş, literatür taraması yapmış, yazım ve düzeltme sürecini gerçekleştirmiştir.

Murat PINARLIK: He created graphs and tables, conducted a literature review, the writing and reviewing process.

Grafik ve tabloları oluşturmuş, literatür taraması yapmış, yazım ve düzeltme sürecini gerçekleştirmiştir.

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