IMPACT OF CLIMATE CHANGE ON WIND ENERGY PROJECTIONS IN TURKEY UNDER RCP 4.5 AND RCP 8.5 EMISSION TRAJECTORIES

by

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BA in English Language Education, Boğazici University, 2020

Submitted to the Institute of Environmental Sciences

in partial fulfillment of the requirements for the degree of

Master of Science

in

Environmental Sciences

Bogazici University

2023

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DATE OF APPROVAL: 05/06/2023

ACKNOWLEDGEMENTS

First and first, I want to express my gratitude to Prof. Dr. Ayşen Erdinçler, Dr. Berat Haznedaroğlu, and Prof. Dr. Mehmet Levent Kurnaz for supporting my decision to pursue a career in academia in the environmental sciences despite having completed my undergraduate studies in a different field. I knew I had a lot to prove because I switched from another academic discipline to environmental sciences. I am pleased to have demonstrated my abilities by completing such a thesis for my master's degree.

I would like to thank Dr. Cem İskender Aydın and Prof. Dr. Mehmet Levent Kurnaz for their support and guidance. I am grateful of their important contribution to my academic development.

I would like to thank IklimBU, of which I have been a part as a volunteer researcher since 2020, both for providing the necessary data for my thesis on climate modeling and for improving my knowledge and skills in analysing climate data. A special thanks to Zekican Demiralay, who answered all of my questions and provided his suggestions for data analysis during the whole process. I also want to thank Dr. Tufan Turp and Dr. Kamil Çöllü for their significant inputs for my work.

I value the support of the APLUS Energy Family, where I first began my working life. The knowledge I acquired here truly improved my thesis. For their efforts during the thesis-writing process, I would like to thank every one of my colleagues, especially Volkan Yiğit, Kerim Gökşin Bavbek, Elif Koyuncuoğlu, Meriç Tokyay, Adnan Çoksezen, and Ecem Yüksel.

And lastly, I would like to thank my mother Kaniye Sargın, my father Safet Sargın and my brother Furkan Sargın, and all my friends who have supported me throughout my life and supported me in every way during this thesis process.

ABSTRACT

IMPACT OF CLIMATE CHANGE ON WIND ENERGY PROJECTIONS IN TURKEY UNDER RCP 4.5 AND RCP 8.5 EMISSION TRAJECTORIES

A successful transition towards renewable energy sources such as wind, solar and hydropower is indispensable for the efforts to combat climate change. However, these sources are also quite susceptible to changes in climatic conditions and that is why it is critical to understand how future climate change will affect the energy generation from these sources. To that aim, this thesis investigates how the wind energy potential will change for Turkey in the future under different climate change trajectories. For this, the MPI-ESM-MR global climate model was downscaled with RegCM4.4 and model results for 10 m. wind speed data were obtained for Turkey with 10x10km grid resolution, from which the Wind Power Density (WPD) is calculated for the 2021-2050 period under RCP 4.5 and RCP 8.5 scenarios. 30-year WPD averages are calculated for each month, season, and year. The results suggest that while the projected annual averages do not seem to change significantly, average decreases in WPD under both RCP4.5 and 8.5 scenarios are expected, especially during the winter months. Furthermore, some regional disparities are also observed, especially for the Marmara and Aegean regions (with around 75% of the currently installed capacity), where wind energy potential is shown to increase in February, March, and April, and to decline in December and January. Following these results, the thesis concludes with policy recommendations on storage technologies to overcome potential fluctuations in electricity generation from wind and on enhancing R&D such as potential improvements on Wind Energy Potential Atlas (REPA).

ÖZET

RCP 4.5 VE RCP 8.5 EMİSYON SENARYOLARI KAPSAMINDA İKLİM DEĞİŞİKLİĞİNİN TÜRKİYE'DEKİ RÜZGAR ENERJİSİ PROJEKSİYONLARINA ETKİSİ

Rüzgar, güneş ve hidroelektrik gibi yenilenebilir enerji kaynaklarına başarılı bir geçiş, iklim değişikliği ile mücadele için kritiktir. Bununla birlikte, bu kaynaklar aynı zamanda iklim koşullarındaki değişikliklere karşı oldukça hassastır ve bu nedenle, gelecekteki iklim değişikliğinin bu kaynaklardan enerji üretimini nasıl etkileyeceğini anlamak çok önemlidir. Bu amaçla, bu tez, farklı iklim değişikliği senaryoları altında gelecekte Türkiye için rüzgar enerjisi potansiyelinin nasıl değişeceğini araştırmaktadır. Bunun için MPI-ESM-MR küresel iklim modeli RegCM4.4 ile dinamik ölçek küçültme yöntemi kullanılarak 10x10km grid çözünürlüğüne yükseltilmiş ve Türkiye için 10 metre rüzgar hızı verisi için model sonuçları elde edilmiştir. Buradan da RCP 4.5 ve RCP 8.5 senaryoları kapsamında 2021-2050 dönemi için Rüzgar Enerjisi Yoğunluğu (WPD) hesaplanmıştır. Her ay, mevsim ve yıl için 30 yıllık WPD ortalamaları hesaplanmıştır. Sonuçlar, öngörülen yıllık ortalamaların önemli bir değişiklik göstermemesine rağmen, özellikle kış aylarında hem RCP4.5 hem de 8.5 senaryoları altında WPD'de ortalama düşüşlerin beklendiğini göstermektedir. Ayrıca, özellikle Marmara ve Ege bölgeleri için (mevcut kurulu kapasitenin yaklaşık %75'inin kurulu olduğu bölgeler) bazı bölgesel değişimler de gözlemlenmektedir. Bu bölgelerde rüzgar enerjisi potansiyelinin Şubat, Mart ve Nisan aylarında arttığı, Aralık ve Ocak aylarında ise azaldığı görülmektedir. Bu sonuçların ardından tez, rüzgardan elektrik üretimindeki potansiyel dalgalanmaların üstesinden gelmek için depolama teknolojilerine ilişkin politika önerileri ve Rüzgar Enerjisi Potansiyel Atlası'ndaki (REPA) potansiyel iyileştirmeler gibi Ar-Ge'yi geliştirmek üzerine öneriler ile son bulmaktadır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	**Explanation**	**Unit**
ρ	Air Density	(kg/m^3)
WPD	Wind Power Density	(W/m^2)
WS	Wind Speed	(m/s)

Abbreviation	**Explanation**
CDO	Climate Data Operator
CMIP	Coupled Model Inter-Comparison Project
CPI	Consumer Price Index
ECHAM	European Centre Hamburg Model
EXIST	Energy Exchange Istanbul
GCM	Global Climate Model
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System v2
GHG	Greenhouse Gases
HadGEM2	Hadley Centre Global Environment Model v2
IPCC	Intergovernmental Panel on Climate Change
MENR	Ministry of Energy and Resources
MPI-ESM-MR	Max Planck Institute Earth System Model Mixed Resolution
PPI	Producer Price Index
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RegCM	Regional Climate Model
REPA	Wind Energy Potential Atlas
SRES	Special Report on Emission Scenarios
SSP	Shared Socioeconomic Pathways
TEIAS	Turkish Electricity Transmission Company
YEKA	Renewable Energy Designated Area
YEKDEM	Renewable Energy Support Mechanism

1. INTRODUCTION

We are now living in a changed climate, as stated very clearly by the IPCC (2021, p.4): “It is unequivocal that *human influence* has warmed the atmosphere, ocean and land” (emphasis added). The main cause of this warming is anthropogenic greenhouse gas emissions, around three-quarters of which are related to the energy sector, mainly used in industry, transport and buildings (Ritchie and Roser, 2020). Therefore, decarbonizing the energy sector becomes crucial in preventing further climate change. This in turn requires first decarbonizing the electricity generation (currently relying mostly on burning fossil fuels such as coal and gas) and then electrification of the industry and transport sectors, through a quick and just transition towards renewable energy.

Currently, the main strategy for reducing greenhouse gas emissions, as also pointed out by the Paris Agreement, is to use more renewable energy sources such as wind, solar, hydropower and biofuels. From these, solar and wind come to the fore as the two major sources for reducing emissions and generating electricity in all parts of the world (EMBER, 2023). For instance, EMBER (2023) states that global solar and wind generation in 2022 would supply the whole demand for electricity in all EU in 2022. Although there is an increase in the use of wind and solar energy to mitigate climate change, it is important to remember that these energy sources may also be (negatively or positively) impacted by the changing climate.

There is a trend across the world in improving the installed wind capacity. The share of wind in total electricity generation started to increase as a result of the attempts of countries to reduce their GHG emissions from their electricity generation. Figure 1.1 demonstrates the share of wind generation across the world, and it is clear from the figure that the share of wind in total electricity generation is increasing year by year and it is expected to increase further in the coming years.

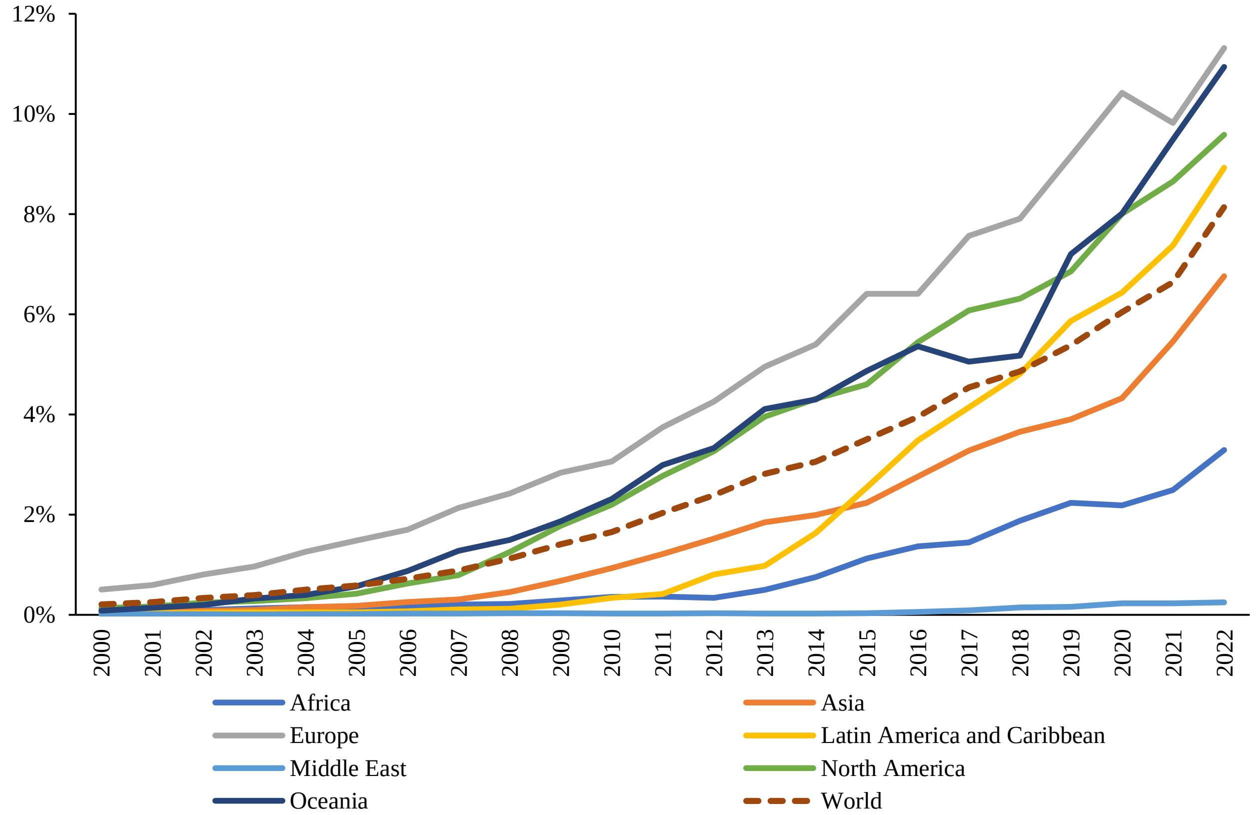

Figure 1. Share of Wind in Electricity Generation (2000-2022) (EMBER, 2023)

This study intends to serve as an example for a more accurate assessment of Turkey's future wind energy potential under different climate change scenarios. To that aim, first, the MPI-ESM-MR global climate model was downscaled with RegCM4.4 and model results for 10 m. wind speed data were obtained for Turkey with 10x10km grid resolution, under RCP4.5 and RCP8.5 scenarios. Then Wind Power Density (WPD) for 100 m. is calculated for the 2021-2050 period. Under both scenarios, 30-year average WPD figures are obtained for each month, season, and year and then they are compared to the historical averages between 1971-2000. My analysis suggests that the projected annual averages are not expected to change significantly under either of the scenarios. However, monthly WPD averages seem to be decreasing compared to the historical data, especially for the winter months. My analysis also suggests some regional disparities for the change in WPD, especially for the Marmara and Aegean regions (with around 75% of the currently installed capacity), where wind energy potential is expected to increase in February, March, and April, and to decline in December and January.

Following these results, I conclude that there may be significant benefits for the stability of the electricity generation system to invest more in electricity storage technologies and the development of hybrid structure power plants. Furthermore, enhancing the research and development on wind energy modelling will also have benefits for both investors and system regulators, such as improving the REPA (Wind Energy Potential Atlas) to include future climate change trajectories.

This thesis is structured as follows. First, the relationship between climate change and wind will be discussed in the second chapter, and studies in related subjects will then be demonstrated. The history of wind energy development in Turkey, its current state, and Turkey's wind energy policies will next be looked at in Chapter 3. Chapter 4 will exhibit the detail of the modelling methodology, followed by the results in Chapter 5. Lastly, chapter 6 will provide a thorough discussion of the results of the model and provide some policy recommendations.

2. CLIMATE CHANGE AND WIND ENERGY

This section will try to show the relationship between the climate and wind, followed by a short investigation of possible impacts of the changing climate on electricity generation from wind. Then a methodological review to assess these possible impacts will be provided with the recent research studies in the literature on this subject, to show to what extent climate change impacts wind energy and how to potentially assess these impacts.

There is a mutual interaction between renewable energy sources and climate change. While renewable energy sources have a huge importance in mitigating climate change, it is also possible that renewable energy generation sources will be affected either positively or negatively because of the climate change that has occurred so far and is expected to occur in the future. Solar, wind, and hydropower sources that are directly dependent on natural cycles and variability, have started to increase their generation share in energy portfolios and according to Solaun and Cerda (2019) renewable energy share should increase up to 85% by 2050 to meet 2-degree target agreed in the Paris Agreement. While the demand for renewable energy generation is increasing, it seems important that future renewable energy policies and planned installations should include many factors such as the susceptibility of renewable energy sources to climate change. Specifically, the wind energy is susceptible to changes as the wind energy depends on the wind speed that can be impacted by climate change.

Wind is formed when the air from a high-pressure area moves to a low-pressure area (Kurnaz, 2019). Two locations with different temperatures have different air pressures. The atmosphere tries to equalize the pressure between these locations by moving the air from the high-pressure area to low-pressure area forming wind. The speed of the wind also depends on the pressure difference between these locations and the higher the pressure difference, the faster the wind speed is. The dependence of wind speed to climate suggests that wind energy that is correlated to wind speed strictly relies on the climate, as well. The formula for calculating the wind power density is shown below:

$$P = \frac{1}{2}\rho \mathrm{WS}^3 \qquad \text{Equation (2.1)}$$

Where:

P = Wind Power Density (W/m^2),

ρ = Air Density (kg/m^3),

WS =Wind Speed (m/s)

The above Equation 2.1 shows that the speed of wind is the major determining factor of the wind power as the cube of wind speed is taken for calculation. Thus, the electricity generation from wind is very sensitive to the changes in wind speed. Small changes in wind speed may tremendously affect the wind energy output since they are positively correlated (Martinez and Iglesias, 2021). Seasonal, daily, and even hourly variations in wind speed may impact wind energy generation easily (Dehghani-Sanij et al., 2022). Pryor and Barthelmie (2010) mention that wind speed change from 5m/s to 5.5 m/s would result in 30% change in the wind energy generation. The susceptible nature of wind to be impacted by small changes suggests that the future wind energy potential calculations should include the impact of climate change (Chen, 2020). Jankevičienė and Kanapickas (2022) state that most of the countries in Europe rush on installing new wind energy plants to achieve their renewable energy targets and fulfill their goals, yet they ignore possible changes on the wind energy potential due to climate change. This then leads to the question of how correct these wind energy calculations for the future would be without taking the impact of climate change on wind energy into consideration.

Climate change may impact wind energy in many ways but most importantly, it may affect the wind speed. Some locations where there is abundant wind energy potential now may experience potential losses in the future due to lower wind speeds compared to the present. Locations that have insufficient wind energy potential may have increased potential in the future. This may affect the wind energy generation of operational wind turbines. A wind turbine would generate less or more than today in the future due to wind speed changes in its area. When there is a reduction on generation due to changes in the future, it may adversely affect the financial viability of the wind energy plants and would reduce the investments in this area (Losada Carreño et al., 2020; Campiglio et al., 2018). Another important problem is that these changes on wind energy potential can impact the electricity system planning, operation and transmission system resulting in supply-demand imbalances in the future (Losada Carreño et al., 2020; Kahrl et al., 2016) because electricity transmission system and electricity suppliers may encounter less or more than expected wind generation from wind power plants in the future.

Climate change can also impact the variability of daily wind speed. Most of the wind turbines that use wind energy to generate electricity start to operate over 3-4 m/s and stop below 25-26 m/s to avoid terminal damage that can be done to wind turbine due to high wind speed (Lu L, 2015). Thus, the possible impact of climate change on the frequency of wind speed that occurs below 3 m/s and above 25-26 m/s may alter wind energy generation in the future. Even though the average wind speed change due to climate change may be insignificant in the future, variability of the wind speed and the extremely high and extremely low wind speed occasions may be less or more in the future impacting the wind energy output.

The variability of seasonal wind speed can also be altered by climate change. Since climate change may affect each season differently, wind speed in any specific location may encounter increased or reduced variability among seasons. While the variability is reduced, it may affect the wind energy generation positively, but increased variability would mean imbalanced energy generation.

All these impacts would occur according to the change in the wind speed. Understanding these impacts would require wind speed data projections for the future. The impact of climate change on wind energy can be examined through modelling of the wind speed in the future and these studies and their findings can demonstrate the projected impact of climate change on wind energy. There are increasing numbers of research studies about the impact of climate change on wind energy, and these modelling studies have variables also shown in Table 2.1.

Table 2.1. Variables of modelling studies.

Location	Global Climate Model	Climate Change Scenario	Projection Year Span	Investigated Climate Data

For wind speed modelling research studies, wind speed data is used to calculate WPD according to the formula shown in Equation 2.1. Studies compare the historical data of WPD and the changes in the future under different scenarios to see the impact of climate change on WPD due to the changes on wind speed. Findings of these modelling studies demonstrate projected changes in wind speed and as a result on WPD. Variability of the wind speed can also be demonstrated by analyzing seasonal wind speed data and comparing wind speed data among seasons. Hours or days that wind speed occurs below 3-4 m/s and above 25-26 m/s can also be projected to show variability of the wind speed that can't be used for wind energy generation. To sum up, after modelling wind speed for the future, they can analyze these data according to intentions of their study and find many results.

The IPCC reports include emission scenario series that are used for climate change modelling studies. These scenarios offer alternative future scenarios and give outputs according to the path followed (Eichelberger et al., 2008). Climate change scenarios that are applied to models change based on the year the research study is conducted because emission scenarios are updated periodically. The first climate change scenarios published by IPCC (2001) were Special Report on

Emission Scenarios (SRES), then Representative Concentration Pathways (RCP) scenarios were published by IPCC (2014) in the 5th Assessment Report. The recent scenarios are Shared Socioeconomic Pathways (SSP) that have been introduced in the 6th Assessment Report by IPCC (2021). Table 2.2 summarizes these different scenarios. Trajectories chosen for the research studies are based on the latest available during the time research study is conducted.

Table 2.2. Climate Change Scenarios (IPCC, 2001; IPCC, 2014; IPCC, 2021).

SRES Scenarios	A1 Storyline			A2 Storyline	B1 Storyline	B2 Storyline
	A1F1(Fossil fuel intensive)	A1T (Predominantly non-fossil fuel)	A1B(Balanced)	A2(High Emissions)	B1(Global Sustainability)	B2(Local Sustainability)
RCP Scenarios	RCP 2.6 Strict Mitigation	RCP 4.5 Intermediate	RCP 6.0 Intermediate	RCP 8.5 Very high GHG Emissions		
SSP Scenarios	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	

SRES scenarios were categorized as A1, A2, B1 and B2 (IPCC, 2001) and 4 RCP scenarios were introduced in 2014 by IPCC according to the emission level pathways in the 21st century. SSP scenarios are the recent scenarios published by IPCC (2021) that also include socioeconomic changes by the end of 21st century. Scenarios differ from each other according to the emission pathway the world chooses to follow. Different emission and radiative forcing would mean different ranges for the impact of climate change. Since which way the world will follow is not uncertain, modelling studies mostly predict and model different scenarios to see the changes on the climate under alternative scenarios. When scenario sets are compared to previous sets, scenarios also seem to be updated version of previous specific scenarios as shown in Table 2.3. While some old scenarios were not updated, some SRES scenario pathways were updated with new findings and variables.

Table 2.3. Correspondence of climate change scenarios (IPCC, 2001; IPCC, 2014; IPCC, 2021).

SSP	SSP2-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
RCP	-	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
SRES	-	-	B1	A1B	A2-A1F1

Emission scenarios are used for models. Model studies require an available model dataset and Global Climate Models (GCMs) are used for these studies. GCMS are representations of the world's climate. They help to understand and predict the future's climate and atmospheric circulation (GFDL, 2023). GCMs used in the projects also vary according to the latest data available at the time of the study. The best way while conducting climate modeling study is to use multi models to increase the reliability of the results. Coupled Model Inter-Comparison Project (CMIP) which is the project to understand the climate of past and predict the future climate under different trajectories within multi-model context (Eyring et al., 2016) is used the most for these projects. As the time and the technology progress, CMIP becomes more extensive and advanced with more models and there are different phases of CMIP that have been used in IPCC reports. While CMIP 3 was used in the 4^{th} Assessment Report by IPCC, CMIP 5 was used in the 5^{th} Assessment Report by IPCC (2014) and the recent CMIP 6 is now available in the 6^{th} Assessment Report by IPCC (2021). CMIP and climate change scenarios both change as the time goes by and more input and model are included in them.

While there are many studies in the literature studying the impact of climate change on wind energy, it may be impossible to investigate and cite all these projects in this paper and they differ from each other in some aspect and when these aspects are observed, the scope of every study can be well-understood. The impact of climate change on wind energy can be seen through these modelling studies. Table 2.4 shows research studies about this subject and elaborates on the differences of their modelling studies.

Table 2.4. Recent studies on the impact of climate change on wind energy.

Author	Study Year	Area	Climate Change Scenario	Time Period	GCM /RCM	Investigated Variable	Main findings
Martinez and Iglesias	2021	Europe	SSP 5-8.5 and SSP2-4.5	2021-2030, 2056-2065, 2091-2100	CMIP6	Wind Speed, Wind Power Density	• 15% WPD decrease in Europe under SSP5-8.5 scenario. • Regional changes in different parts of the Europe • 15% variability increase in Baltic countries and some other countries. • %10 variability increases in Britain, Ireland and Atlantic Ocean • 10% variability decrease in northern regions of the Europe
Chen	2020	North America	RCP 8.5 and RCP 4.5	2031-2060, 2071-2100	CMIP5 and RCM	Wind Speed, Wind Power Density, Extractable Wind Power	• Wind speed decrease in most regions in North America under RCP 8.5 scenario. • Up to 20% Wind speed decrease in Western US in winter under RCP 8.5 scenario. • Up to 20% Wind speed increase in Oklahoma and Texas in summer under RCP 8.5 scenario. • Irregularity and variability increase in Great Plains

Author	Study Year	Area	Climate Change Scenario	Time Period	GCM /RCM	Investigated Variable	Main findings
Costoya et al.	2021	China Offshore	RCP 8.5	2025-2049, 2075-2099	Multi-model ensemble GCM and RCM	Wind Speed, Wind Power Density, Capacity Factor	• WPD decreases in Spring seasons. • WPD increase in Autumn and Winter seasons
Jankevičienė and Kanapickas	2022	Lithuania	RCP 4.5	2041-2050, 2091-2100	3 GCMs and RCM	Wind Speed, Wind Power Density	• 8.8% wind speed decrease and 27.3% WPD decrease in central regions of Lithuania. • 7.3% wind speed decrease and 21.6% WPD decrease in coastal regions of Lithuania
Akinsanola et al.	2021	West Africa	SSP5-8.5	2040-2069, 2070-2099	CMIP6	Wind Speed, Wind Power Density	• 50-60% annual WPD increase for 2040-2069 in Guinea Cost
Davy et al.	2017	Europe and Black Sea	RCP 4.5 and RCP 8.5	2021-2050, 2061-2090	CMIP5	Wind Speed, Wind Power Density, Extractable Wind Power	• No significant change on WPD under RCP 8.5 scenario • Decrease in Extractable Wind Power
Bonanno et al.	2023	Italian Peninsula	RCP 4.5 and RCP 8.5	2021-2050, 2051-2080, 2071-2100	CMIP5 and Multi-model ensemble RCM (Euro-CORDEX project)	Wind Speed, Wind Power Density	• Small changes and uncertainty for 2021-2050 period under both scenarios • Monthly and annual changes for 2071-2100 for different regions under both scenarios.

The impact of climate change on wind speed is demonstrated through different modelling studies. Findings shown in Table 2.4 demonstrate wind speed and wind power density changes observed under different models in different regions. While some studies (Martinez and Iglesias, 2021; Chen, 2020; Costoya et al., 2021; Akinsanola et al., 2021; Jankevičienė and Kanapickas, 2022) found significant changes ranging from %15 to %50-60 annual change on WPD, only Davy et al. (2017) found that there were no significant changes on WPD. However, they found significant changes on extractable wind power, calculated based on the wind turbine calculating the wind speed only between minimum and maximum level that can be harvested to generate electricity.

There were also regional impact differences in the same studies (Bonanno et al., 2023; Martinez and Iglesias, 2021; Chen, 2020; Akinsanola et al., 2021). Thus, this implies that investigating only the average of the wind speed change on the whole area may be wrong due to the locational variability of wind speed and the variability of the degree of the impact of climate change on different regions. Changes on the variability of wind among seasons are also evaluated (Martinez and Iglesias, 2021; Chen, 2020) and it is seen that wind speed change can vary seasonally (Chen, 2020; Costoya et al., 2021). These changes on locations and seasons also imply that impact of climate change on wind speed may not be merely enough and variability of wind across seasons and locations should be investigated so that variability of wind across different regions and different seasons can be shown.

Findings of these studies can be used for more precise calculations of the future wind energy potential. For instance, in the United States, California and the Northwest have an increasing number of new wind energy plant installations while the study by Chen (2020) points out a decrease trend for projected WPD in this area. This shows that future impact of climate change on wind energy should be considered for these projects to minimize the negative impacts and achieve optimum wind energy generation with less variability in the future. Costoya et al. (2021) mention that while the results of the study show a decrease in offshore wind energy potential in China, they also suggest that the wind energy potential is still high and future wind energy installations should be encouraged but the optimal locations and optimal installed capacity for these locations should be allocated taking these possible changes from the climate change into consideration for more favorable generation output in the future. Jankevičienė and Kanapickas (2022) also warn that future wind energy installations should be evaluated considering possible changes on the installation locations in the future.

Recent studies in literature show that due to the wind speed dependency of the wind energy, impact of climate change on wind energy is investigated and there are some significant changes in wind energy potential in some areas all around the world. Variability of wind speed is also projected to be impacted by climate change based on different scenarios at different locations. Thus, while the wind energy is a favorable renewable energy source for the future, it should be noted that climate change is projected to impact it and research studies investigating potential changes in future wind energy should be taken into consideration for more accurate calculations and for more optimum wind power plant installations.

In Turkey, climate modeling has also been used in numerous studies. The impact of climate change on wind was also investigated in some of these studies. These studies, meanwhile, are outdated as they were published years ago. Yet, it is still good that climate change modeling studies were conducted in Turkey in the past. Table 2.5 shows some climate modeling studies conducted in Turkey.

Table 2.5. Some Climate Change Modeling Studies in Turkey.

Author	Study Year	Climate Change Scenario	Time Period	GCM/RCM	Investigated Variable	Main Findings
Turp et al.	2014	RCP 4.5 and RCP 8.5	2020-2050	HadGEM2, MPI-ESM-MR, GFDL-ESM2M and RegCM4.3.5	Temperature, Precipitation	0.5 °C and 4 °C temperature increase and -0.4 mm/day to -1.2 mm/day precipitation change
Demircan et al.	2017	RCP 4.5 and RCP 8.5	2016-2099	HadGEM2, MPI-ESM-MR, GFDL-ESM2M and RegCM4.3.4	Temperature, Precipitation	Temperature increase from 1.0 °C to 5.0 °C and varying precipitation increase
Şen	2013	A2	2041-2070, 2071-2099	ECHAM5 and RegCM3	Temperature, Precipitation, Wind speed, Solar radiation, Sea level rise	Temperature increase, precipitation decrease in southern parts of Turkey and increase in northeastern parts, Wind speed increase in northwestern and decrease in eastern parts
MGM	2015	RCP 4.5 and RCP 8.5	2016-2040, 2041-2070, 2071-2099	HadGEM2, MPI-ESM-MR, GFDL-ESM2M and RegCM4.3.4	Temperature, Precipitation	Temperature increase of 1.5 °C (MPI-ESM-MR, GFDL-ESM2M) and 2.5 °C (HadGEM2) under RCP 4.5, temperature increase of 2.5 °C (MPI-ESM-MR, GFDL-ESM2M) and 3.6 °C (HadGEM2) under RCP 8.5. 10-15 mm/year (GFDL-ESM2M) to 30 mm/year (MPI-ESM-MR) precipitation decrease under RCP 4.5 and 105-110 mm/year (GFDL-ESM2M) to 160 mm/year (MPI-ESM-MR) precipitation decrease under RCP 8.5 scenario.
Turkes et al.	2019	RCP 4.5 and RCP 8.5	2021-2050	MPI-ESM-MR	Precipitation, Precipitation extremes	Decrease in precipitation carrying among regions under both scenarios

Although climate change modeling studies in Turkey are not limited to the studies shown in Table 2.5, these have been selected among the studies related to this thesis. All of the studies above used MPI-ESM-MR GCM (Turp et al., 2014; Demircan et al., 2017; Şen, 2013; MGM, 2015; Turkes et al., 2019), which was also used in this thesis. The RCP 4.5 and RCP 8.5 scenarios were also selected apart from one study, and this is because RCP scenarios were not ready to be studied at the time of the study.

Among the studies in Table 2.5, only Şen (2013) investigates the change in wind speed, using the A2 scenario. They study by Şen (2013) how the wind speed may change between the years 2041-2070 and 2071-2099 as shown in Figure 2. The results seemed parallel with the findings of the model in this thesis. However, the conclusions of Şen (2013) cannot be very helpful in terms of wind energy policies because i) the timespan it examines is so far in the future, ii) the A2 scenario they use is an outdated scenario and iii) the analysis has a lower resolution for making effective policy decisions.

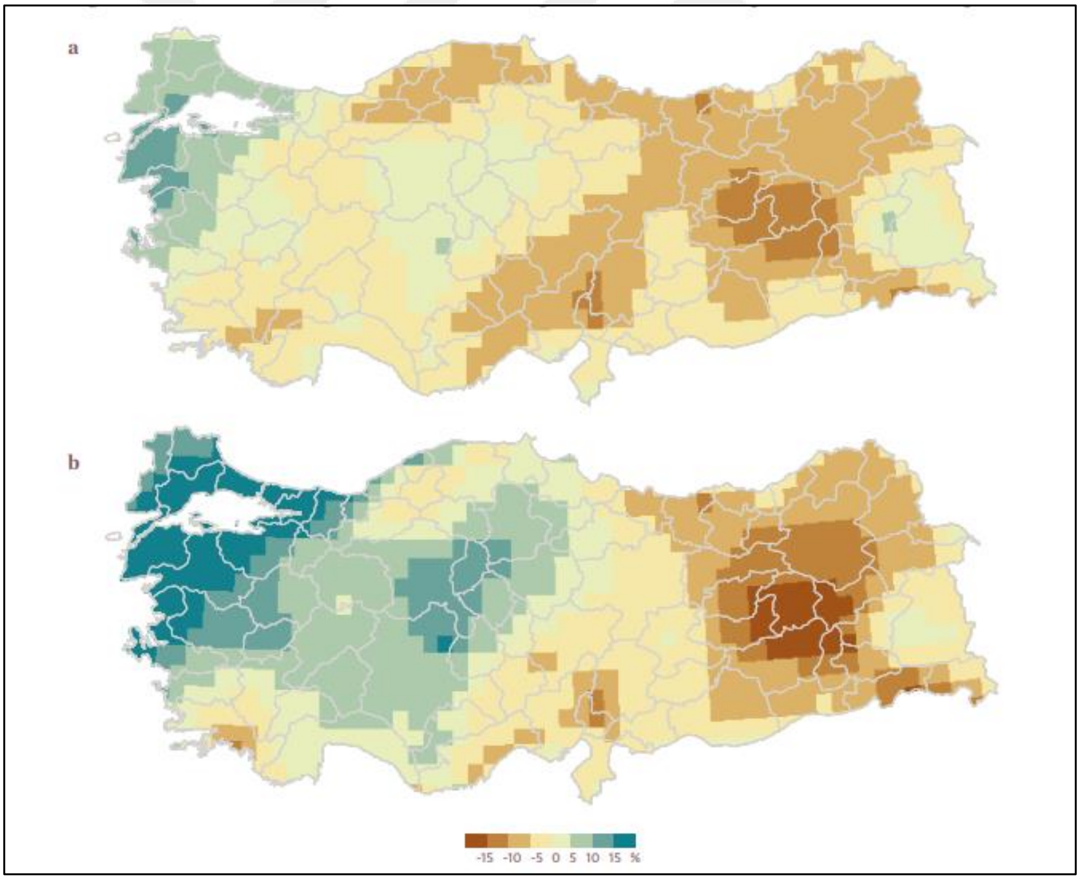

Figure 2. Wind Speed Changes in 2041-2070(a) and 2071-2100(b) periods (Şen, 2013).

The impact of climate change on Turkey's potential for wind energy have so far been the topic of one master's and one doctoral thesis. Using the MPI-ESM-MR GCM, Yılmaz (2016) downscaled the impact of climate change on the potential for wind energy to 10 km^2 resolution with RegCM. He looked at the RCP 4.5 and RCP 8.5 scenarios for 2021-2040, 2041-2070, and 2071-2100 periods. He investigated the wind speed measurements at 80 and 200 meters. In the Aegean region, an increase in wind speed is observed from 2071. In the Mediterranean and Eastern Anatolia, a decrease in wind speed was observed according to his findings. Işık Çetin (2023) conducted a different study as part of his doctoral dissertation. The wind speed at 100 meters was evaluated in the SSP 2-4.5 and SSP 5-8.5 scenarios according to the CMIP6 models using statistical downscaling method. The study's findings show that in summer, an increase of 7.2% was seen in the Aegean region, an increase of 10% in the Marmara region, and an overall decrease of 4.1% in winter in all Turkey.

3. TURKEY AND WIND ENERGY

3.1. Current Situation in Turkey

Increasing energy demand across the world and the negative impacts of fossil fuels on the environment have paved the way for increasing investments renewable energy sources. Wind energy has been one of the most advanced sources of renewable energy. Installed wind power capacity increase across the world in recent 20 years demonstrates the importance of wind energy in supplying energy demand.

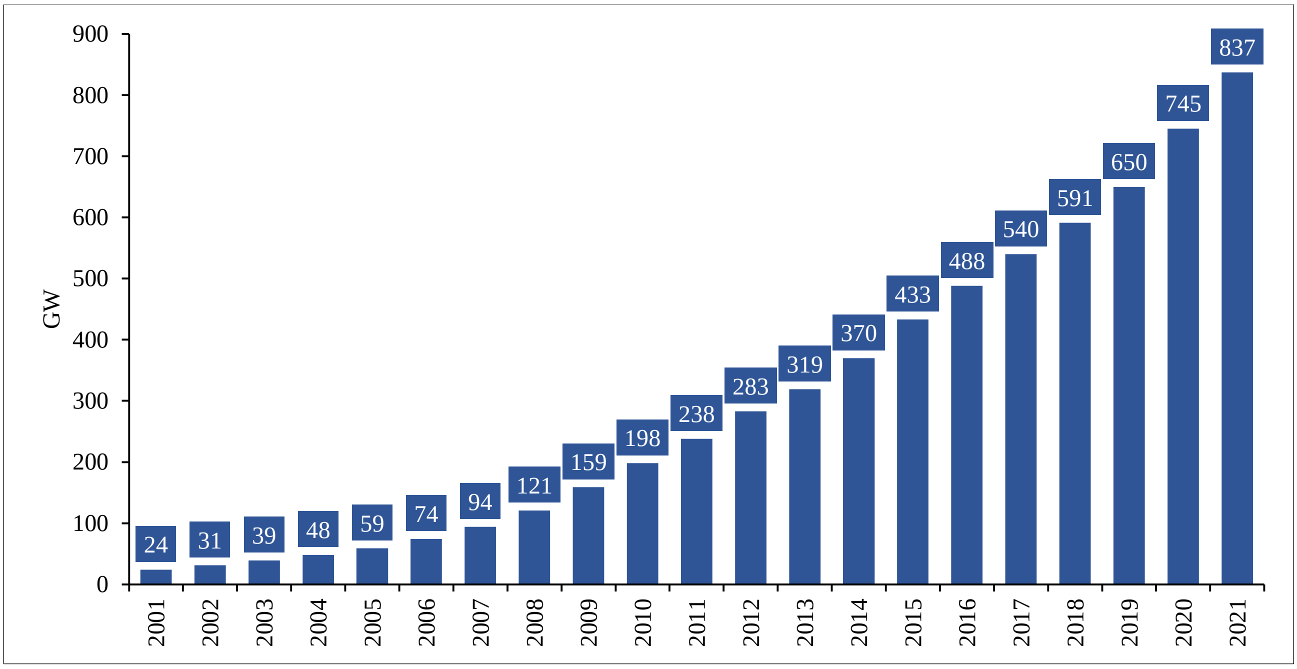

Figure 3. Cumulative Wind Power Installed Capacity Worldwide (2001-2021).

Figure 3 shows that wind power installed capacity worldwide increased from 24 GW in 2001 to 837 GW in 2021. 20 years of development and increasing investments on wind energy shows the importance of wind energy in the future, as well. Among all countries, China has a capacity of 237 GW wind power installed capacity in 2021 which makes it the biggest wind power installed country worldwide (GWEC, 2022).

When we look at the situation in Turkey, we see that although it has a long history with wind energy, its wind power installed capacity has only significantly increased in recent years. The first wind turbine in Turkey was installed in Çeşme in 1985 (Ilkiliç et al., 2011) and the first commercial wind power facility was constructed in 1998 in Alaçatı, Çeşme with an installed capacity of 1.5 MW

(Aras, 2003). In the same year, another wind power facility consisting of 12 turbines with a total installed power of 7.2 MW was put into operation in Alaçatı, Çeşme (Ilkiliç et al., 2011). Then, the third wind power facility was installed in Bozcada, Çanakkale in 2000. Wind power installed capacity stayed still between 2000-2006. After 2006, wind energy installed capacity started to increase more and more on an annual basis and reached 11.396 MW at the end of 2022, as also seen in Figure 4 (TEIAS, 2023). The share of installed wind power capacity in total installed capacity of Turkey is 11% as of at the end of 2022 (TEIAS, 2023).

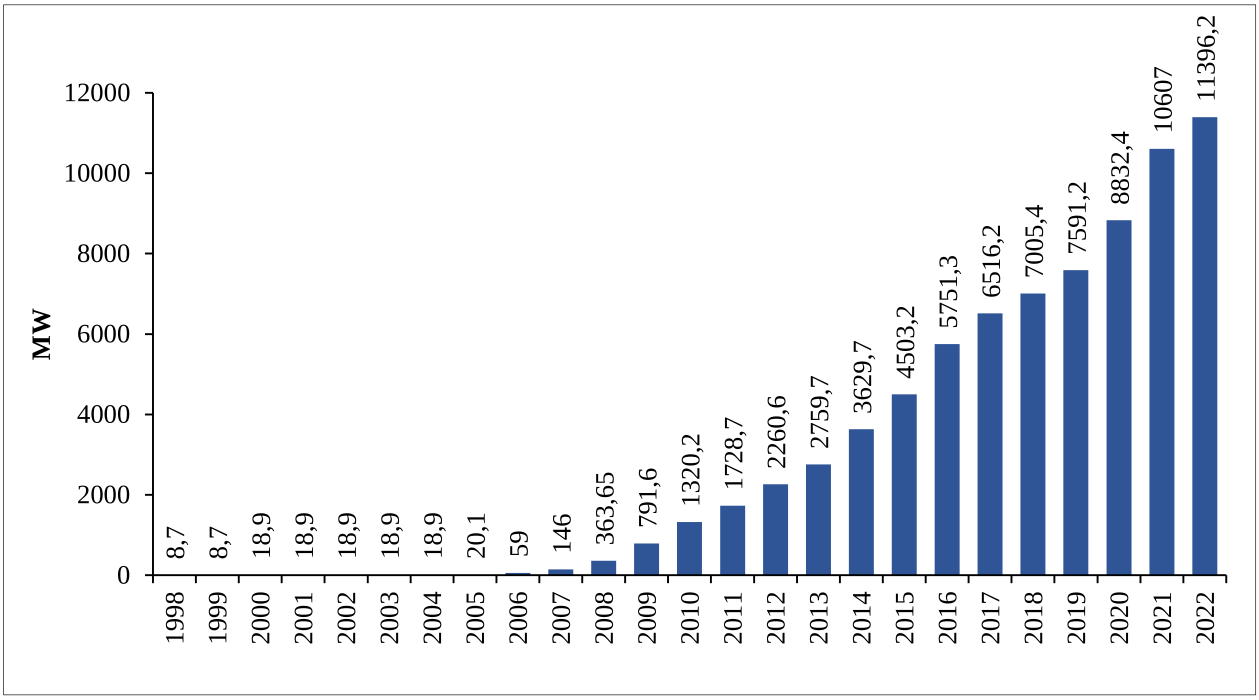

Figure 4. Cumulative Wind Power Installed Capacity Turkey (1998-2022) Source: TEIAS (2023) and EIGM (2023).

The steady increase in installed capacity after 2006 follows the implementation of 'The Renewable Energy Law of Turkey' in 2005 that included tariff support for renewable electricity generation, accelerating renewable energy installations in Turkey (Ilkiliç, 2012). After 2006, policy instruments for renewable energy utilization also progressed increasing renewable energy installations further. While Figure 4 demonstrates the annual development of Turkey to increase its wind power installed capacity in the last 23 years, it is also noteworthy to see the look at the share of the generated electricity from wind power in the recent years, as seen in Figure 5.

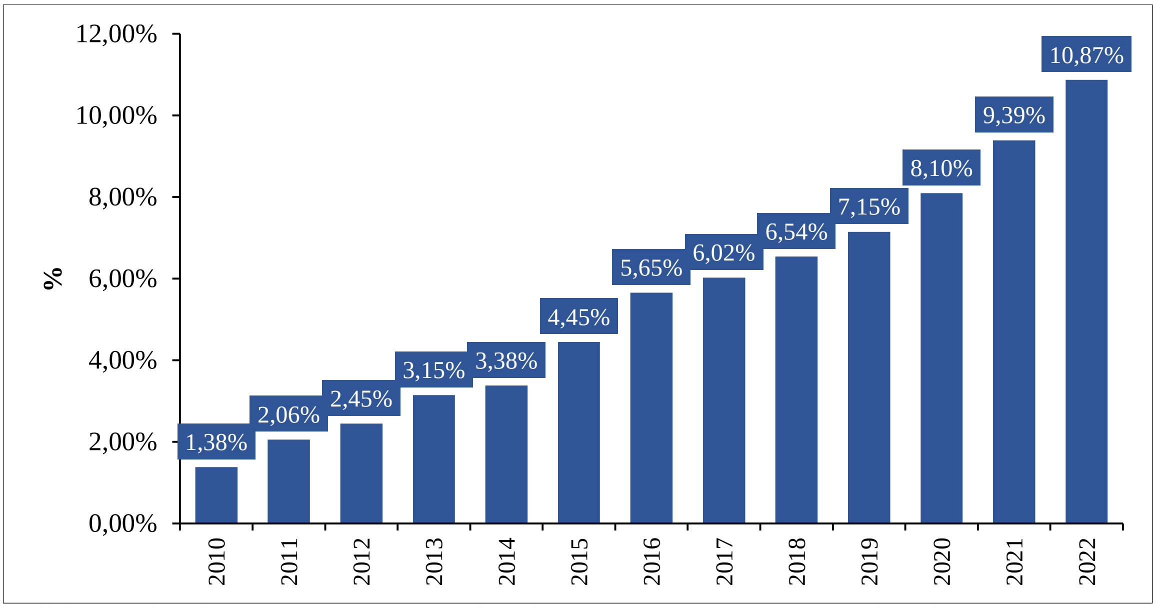

Figure 5. Share of Wind Power Electricity Generation in Total Electricity Consumption of Turkey (2010-2022) Source: TEIAS (2023).

Figure 5 shows that the electricity generation from wind power also increased annually and the rate of the increase also extends especially from 2019 to 2020 and to 2021 (TEIAS, 2023). Another important indicator to look at is the capacity factor of wind energy throughout these years. Capacity factor is the ratio of generated electricity to maximum possible electricity generation on an annual basis. Figure 6 exhibits annual capacity factor of wind power from 2013 to 2022 in Turkey according to the installed capacity and generation data shared by TEIAS and the unlicensed wind electricity generation data from EXIST.

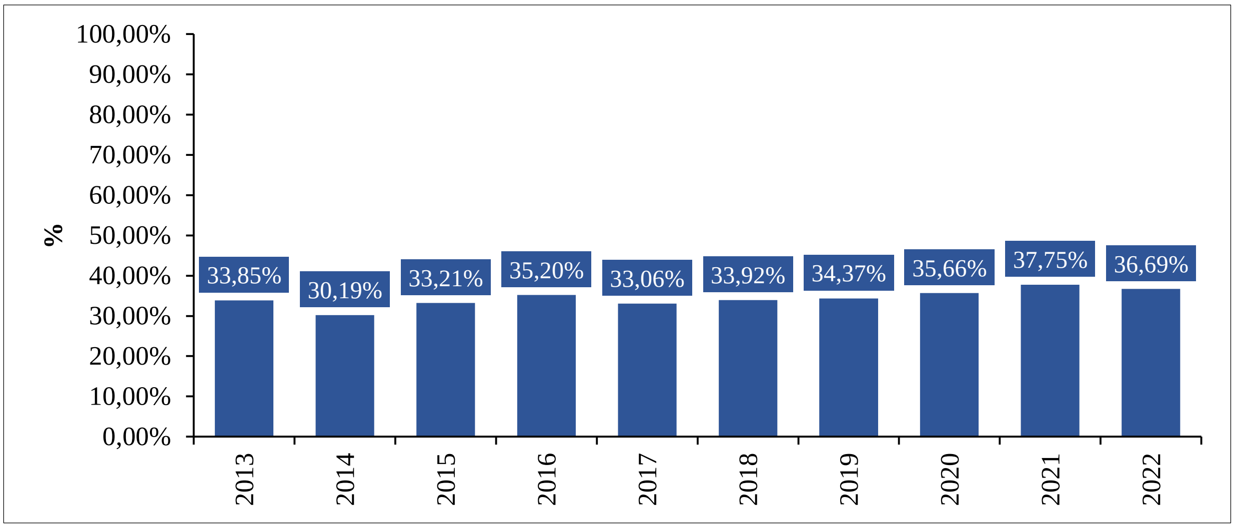

Figure 6. Turkey Wind Power Capacity Factor (2013-2022) Source: EXIST (2023) and TEIAS (2023).

Capacity factor depends on variables such as the technological developments regarding wind turbines and the effective use of wind by the turbines. The capacity factor of Turkey for wind power follows a path with ups and downs, yet, at the end, it increased from 33.9% in 2013 to 36.7% in 2022. To compare this factor with other countries, for instance, the capacity factor of wind energy in EU and UK combined was 24% in 2022 (WindEurope, 2023). Variability of wind speed can be seen as one of the main factors here affecting the electricity output of wind turbines on a year-to-year basis. The advancing technology and improvements on wind turbines also positively improve the capacity factor of wind power (Bošnjaković et al., 2022).

The significant increase on wind energy installed capacity during the last 20 years made Turkey the 6th largest country among European countries in terms of wind energy installed capacity (WindEurope, 2023). This development is achieved mostly through government incentives and policy instruments. The renewable energy policies of Turkey that lead to improvements on wind energy are explained in detail in the following section.

3.2. Wind Energy Policies of Turkey

Following the international trends (e.g. global need for transition towards low emission technologies) and driven also by the pressure from civil society, Turkey had also plans to further increase its installed capacity in renewable energy. Considering that i) the initial cost of renewable energy installations were high and ii) there is a need to increase the speed of transition, incentive policies such as feed-in tariff have been used in Turkey (Kaygusuz, 2010), together with some other policies such as tax exemptions, wavering of license fees, and using special tariffs in case of domestic resource use. However, feed-in tariffs were the main policy tool of Turkey (Dursun and Gokcol, 2014). This incentive basically defines specific prices for different renewable energy sources and would guarantee renewable energy sourced electricity generators to sell their electricity for a fixed price. Turkey has given purchase guarantee to renewable energy generators since 2005, when a comprehensive renewable energy law was put into action.

It is clear from the Figure 4 that the wind power started to pick up after 2005 in Turkey. Turkish government has implemented many policy incentives to promote renewable energy installations after that year (Ilkiliç, 2012). The first policy incentive was ‘The Renewable Energy Law of Turkey’ published on 18th of May 2005 (Official Gazette, 2005). According to this law, electricity generated from renewables were guaranteed to be purchased by the government and the price were to be determined as the average of the Turkish wholesale market electricity price of the previous year. The guaranteed price was also determined to be minimum 5 and maximum 5.5 eurocent/KWh until 2011. This helped investors to install new renewable energy facilities as they were comforted by the purchase guarantee. The Renewable Energy Law of Turkey increased the rate of renewable energy investments and the wind power installed capacity started to increase along with other renewable energy installed capacities.

In 2010, the Renewable Energy Law was revised, and the feed-in tariff prices were updated according to the source of the electricity generated (Yaniktepe et al., 2013). Updated prices after 2011 were as shown in Table 3.1:

Table 3.1. Renewable Energy Support Mechanism (YEKDEM in Turkish) Feed-in Tariff Prices by Sources in 2011.

Renewable Energy Source	**Time Period**	**Price USD Cent/KWh**
Wind	10 Years	7.3
Hydro	10 Years	7.3
Geothermal	10 Years	10.5
Biomass	10 Years	13.3
Solar	10 Years	13.3

Renewable Energy Support Mechanism (YEKDEM in Turkish) prices were fixed as USD cent and the purchase guarantee was convenient for investors at that time. Wind energy installed capacity increased from 1.729 MW to 11.396 MW at the end of 2022 and most of this increase can be attributed to YEKDEM that was put into action after 2011. A facility that benefits from YEKDEM could get purchase guarantee only for 10 years after its first operation (Official Gazette, 2011). This support mechanism also included another incentive for the renewable energy facilities that use specified domestic components to promote the use of domestic equipment (Dursun and Gokcol, 2014). Due to rising exchange rate of USD/TL especially after 2015, the purchase guarantee fixed as USD cent became more and more profitable for investors which increased the rate of renewable energy deployment, as a result wind energy deployment in Turkey.

As the mechanism was introduced to last for 10 years, In January 2021, Turkish government introduced the updated YEKDEM after the mechanism that was published in 2011 has come to an end in 2021. In 2023, the prices and the regulations for the determination of the price were also updated as a response to attract more investors after having witnessed that the YEKDEM prices introduced in 2021 were not enough for the investors (Official Gazette, 2023). The most recent and still active YEKDEM has changed the fixed price payment from USD cent to TRY kurus. Table 3.2 demonstrates the updated feed-in-tariff prices for the facilities that will apply to YEKDEM after 2021 July.

Table 3.2. Comparison of Feed-in Tariff Prices of YEKDEM 2011, YEKDEM 2021 and YEKDEM 2023.

Renewable Energy Source	**YEKDEM 2011 Price USD Cent/KWh**	**YEKDEM 2021 Price TRY Kurus/KWh**	**YEKDEM 2023 Price TRY Kurus/KWh**	**Change in the Price (YEKDEM 2011 vs YEKDEM 2021) %***
Wind	7.3	32	106 (Onshore)/144 (Offshore)	-40%
Hydro	7.3	40	144 (Reservoir) / 135 (Run of River)	-25%
Geothermal	10.5	54	202	-30%
Biomass	13.3	32, 54, 50**	106, 173, 134.9**	-67%, -44%, -49%
Solar	13.3	32	106	-67%

*USD/TRY exchange rate is taken as of 30 January 2021(Publication date of the New Mechanism), as 7.31

**Biomass prices were categorized under 3 different biomass types that are respectively landfill gas, biomethane, thermal disposal facilities.

Unlike the YEKDEM 2011, the new feed-in tariff (YEKDEM 2021) additionally included that the price would be updated every three months and shared the formula for this update. Prices are revised in accordance with a methodology that takes economic variables like the exchange rate from previous periods, PPI, and CPI into account. Yet the YEKDEM 2021 seemed less attractive for new renewable energy investments. However, according to the recent update (Official Gazette, 2023), a different price was determined for power plants with storage as well. While the prices determined as of May in the updated YEKDEM 2023 prices have increased compared to the previously updated prices according to the formula published in 2021, the details of the update have also changed. In YEKDEM 2023, which will now be updated monthly, the rate of increase due to the exchange rate has also increased, making the foreign currency loyalty rate 60%. This new update can be better for the future of YEKDEM, yet it is still not clear.

Wind energy installations, before the deadline of the YEKDEM 2011, which is July 1 of 2021, and the installations after that time can be seen in Table 3.3 to compare the decreasing trend in new installed capacity increase (EIGM, 2023). While before the deadline in July 2021, the monthly average wind installations were 103.4 and 164.4 in 2020 and 2021 respectively, the monthly average in 2021 after the deadline reduced to 131.4 MW. In 2022, the monthly average of wind installation was only 65.8 MW. This shows how the investors lost their interest in wind energy installation within YEKDEM 2021.

Table 3.3. Licensed Wind Energy Installations in 2020-2023.

Year	**Annual Total (MW)**	**Monthly Average (MW)**
2020	1241.2	103.4
First Half of 2021(Before the Deadline)	986.3	164.4
Second Half of 2021(After the Deadline)	788.3	131.4
2022	789.2	65.8

Although the feed-in-tariff was the main policy incentive for renewable energy deployment in Turkey, tender auctions for designated renewable energy areas (Renewable Energy Designated Area, abbreviated as YEKA in Turkish) decided by Ministry of Energy and Resources were another medium to attract investors for renewable energy investments. To increase the wind energy deployment and attract more investors, Turkish government decided to designate areas available for wind energy installation and through tenders and investors competed among each other to win these tenders by offering the lowest feed-in price per kW/h (MENR, 2023c). 1 GW wind power plant capacity was allocated to the winner of the first YEKA tender in August 2017. These tenders also required winners to use local manufacturing equipment and conducting research and development (Trade Council of Denmark in Istanbul, Turkey, n.d.). The tender of the second YEKA for wind energy was also made and 4 different locations of 250 MW, 1 GW capacity in total was allocated for the winners of the tender in 2019. Tender for the third YEKA for wind energy, in which designated areas were updated and the capacity allocated reduced, was also conducted in July 2022 announcing the winners of the tender.

In Turkey, investors had to either meet the requirements for YEKDEM or win a YEKA tender if they wanted to build a licensed solar or wind power plant. Due to this requirement, only these two investment vehicles could be used to create wind and solar power plants. The control of the transmission network was one of the justifications for this limitation. However, investors who agree to construct a storage facility will be able to establish power plants for wind and solar power plants without being included in YEKA or YEKDEM thanks to the new incentive that was published in the Official Gazette on July 5, 2022(Official Gazette, 2022a). These investments will also be able to get support from the YEKDEM (Official Gazette, 2022b). The details for this incentive were published afterwards and the wind power facility applications for this incentive announced to be over 110.000 MW by the President of the Energy Market Regulatory Authority in April 2023 (Anadolu Agency, 2023). This incentive is expected to increase wind energy installations in Turkey.

Another step was taken in 2020 (Official Gazette, 2020) to include definitions of hybrid power plants that may use more than one source to generate electricity in a power plant. This regulation change stated that the power plants would generate electricity using a second source inside the boundaries of the licensed power plant site without exceeding the licensed installed capacity. The aim of this legislative change was to increase the capacity factors of power plants by giving them a chance to use more resources and give more electricity to the grid. To exemplify, a wind power plant would be able to install solar panels in the power plant and use the electricity generated from solar panels when there is low wind energy and increase its capacity factors especially in daytime. The first hybrid powerplant in Turkey is a hydropower plant with 500 MW hydro and 80 MW solar installed capacity. While 500 MW hydro capacity was in use before the legislation, 80 MW solar capacity was installed in 2021 and started its operation that year. This incentive is also expected to increase especially wind and solar investments in the following years.

In addition to feed-in tariff and tender incentives, there are also other policy incentives for renewable energy investments. New renewable energy investments can get support from general incentive systems such as value added tax exemption, other exemptions in the previously announced 1st, 2nd, 3rd, 4th, 5th and 6th regions (IEA, 2021). Another policy initiative from Turkey for renewable energy was that in the case of a founding a renewable energy generation facility, forests and public lands could be allocated or rented to these facilities by the Ministry of Environment and Forestry (Güler, 2009). According to ‘Electricity Market Licensing Regulation’, renewable energy facilities have been also exempted from paying annual licensing fee for the first eight years after they start their operations (Ilkiliç et al., 2011) and these facilities also pay only 1% of the total licensing fee.

Turkey has been attempting to increase the renewable energy installations in line with their renewable and wind energy targets. According to Turkey's 'Climate Change Adaptation and Action Plan' published in 2011, Turkey aimed to increase its renewable energy share by 30% in electricity generation by 2023 (Ministry of Environment, Urbanization and Climate Change, 2012). The government also published 'Turkey National Renewable Energy Action Plan' in 2014 and renewable energy installed capacity target for wind energy was stated as 20 GW by the year of 2023 (MENR, 2014). Turkey also wants to install 1 GW annual new wind and solar capacity by 2027 (IEA, 2021). After Turkey has accepted to sign Paris Agreement, the president of Turkey also claimed that Turkey aims to achieve net-zero by 2053 and the roadmap for achieving net-zero is underway. The recently published plan also sets updated targets for renewable energy. Wind power installed capacity goal for the year 2035 is established as 29.6 GW. The share of wind in total electricity generation is also aimed to be 17.7% at the year of 2035 (MENR, 2023). All these plans, aims and claims show that Turkey will try to increase its wind energy capacity along with renewable energy.

YEKDEM in 2011 was very effective in terms of increasing renewable energy investments as the USD purchase guarantee protected investors from the volatility of currency. Yet, as the YEKDEM published in 2021 fixed prices on TRY, investors seem less motivated to invest in renewable energy to get a purchase guarantee for 10 years in TRY as the USD/TRY currency is predicted to increase more soon. Thus, investors, especially wind investors, started to focus on YEKA tenders, turning their facilities into hybrid facilities and installing wind power facilities with storage facilities as they are more favorable compared to YEKDEM in 2021. YEKA regions are determined according to the renewable energy source potential in the area according to the IEA (2021). While two wind energy YEKA tenders were completed, winners still haven't fully installed their capacity in these areas. In addition to that, the third YEKA areas have been updated and the allocated capacity was reduced from 2 GW to 850 MW while the regions were reduced from 42 to 20 regions (Official Gazette, 2022c). These may also indicate that the YEKA tenders are also not fully effective in increasing wind power capacity.

As YEKA regions seem to be the one of the most favorable mechanisms for wind energy installations soon, it is important to choose the optimum areas for wind energy potential. According to regulations, the wind potential of the area had to be measured before the installation of a licensed wind power facility for at least a year using a wind measuring mast. However, YEKA and wind power installations with storage facility do not have this obligation according to the legislation change (Official Gazette 2022b), which makes REPA the only reliable source for potential in such areas. Turkey has been using REPA that was generated in 2006, updated in 2020, to analyze its wind energy potential for the whole country. YEKA regions are selected according to the data from REPA. Yet, as the data is calculated from the historical wind data, it seems to be ignoring the impact of climate change on the wind energy in Turkey. The analysis of REPA is explained to analyze how the wind energy potential is calculated in the following section.

3.3. Wind Energy Potential Atlas (REPA) of Turkey

Due to Turkey's location, Turkey has different air masses that result in wind energy potential in different locations of the country especially winds from north and black sea in winter (Ilkiliç et al., 2011). Thus, to be able to understand the potential of wind energy in Turkey, many studies have been conducted. In 2001, the General Directorate of Electrical Power Resources Survey and Development Administration (EIE) conducted a wind energy potential study for Turkey showing wind speed and WPD. The study by EIE also included the topographic, roughness and nearby obstacle information of the Turkey (DMİ, 2010). In 2006, more detailed and comprehensive wind energy potential map of Turkey was prepared by MENR.

REPA-V1 is a wind energy potential map of Turkey first prepared by using micro-level wind flow model and medium-scale weather forecasting model in 2006 (Çalışkan, 2018). The wind speed data was gathered for Turkey using wind measurement stations in many locations in Turkey. The spatial resolution of this first atlas was 200mx200m, which was quite a detailed spatial resolution. Topography and local barriers were also included in this atlas to get more accurate output and the model also excluded the parts where wind energy can't be used using geographical information (Çalışkan, 2018). The global climate model and regional climate model that REPA used is not openly shared to public. The output for the estimation of wind energy is given as WPD, which is the same formula used in this modeling study, given in Equation 2.1. The model outputs of REPA-V1 are shown in Table 3.4.

Table 3.4. 2006 REPA-V1 Model Outputs.

Height	**Output**
30m	Annual Wind Speed
50m	Annual Wind Speed, Annual WPD, Capacity Factor of a 1 MW facility
70m	Annual Wind Speed
100m	Annual Wind Speed, Annual WPD, Capacity Factor of a 1 MW Facility

While calculating the wind potential of Turkey, it was assumed that over 50 meters and where wind speed is over 7.5 m/s, a 5 MW wind power facility could be installed per square meter (MENR, 2023b). According to this assumption, REPA-V1 calculated that wind energy potential of Turkey was 48,000 MW. The total area corresponding to this potential was only 1.3% of Turkey's total surface area. Figure 7, Figure 8 and Figure 9 are results of REPA-V1. Figure 7 shows the wind speed at 50 meters, and Figure 8 demonstrates the WPD at 50 meters. Figure 9 shows the capacity factor of an assumed 1 MW wind power facility at 50 meters.

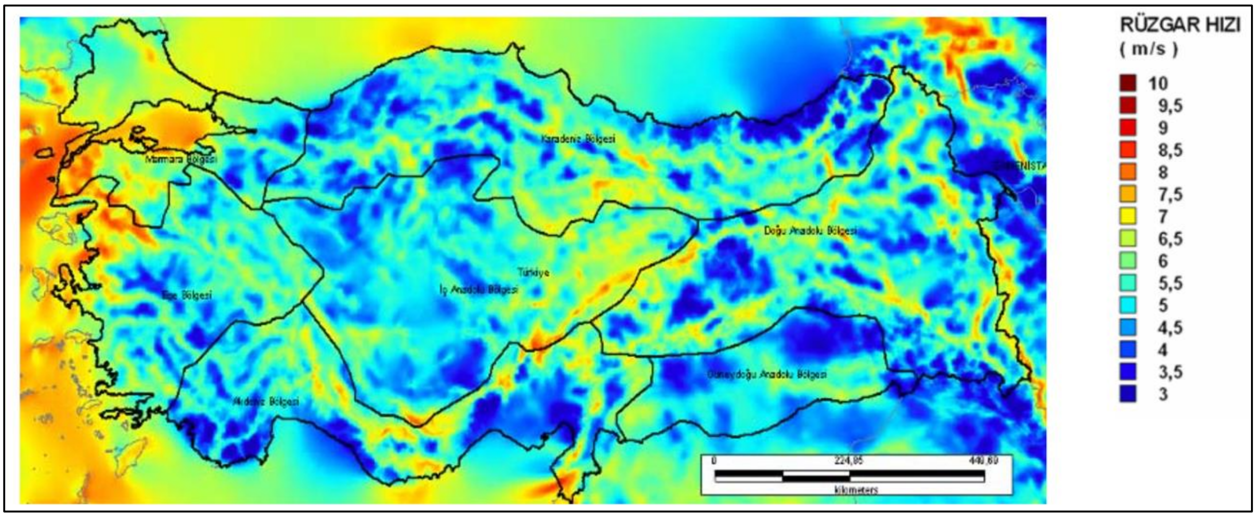

Figure 7. Annual Average Wind Speed - 50 Meters (REPA-V1).

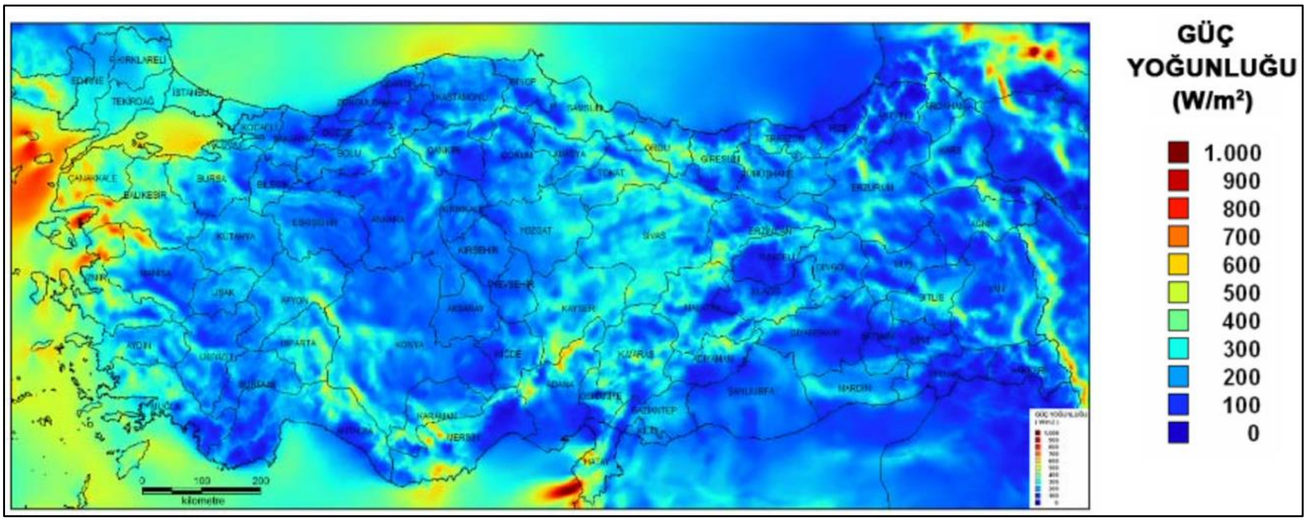

Figure 8. Annual Average Wind Power Density – 50 Meters (REPA-V1).

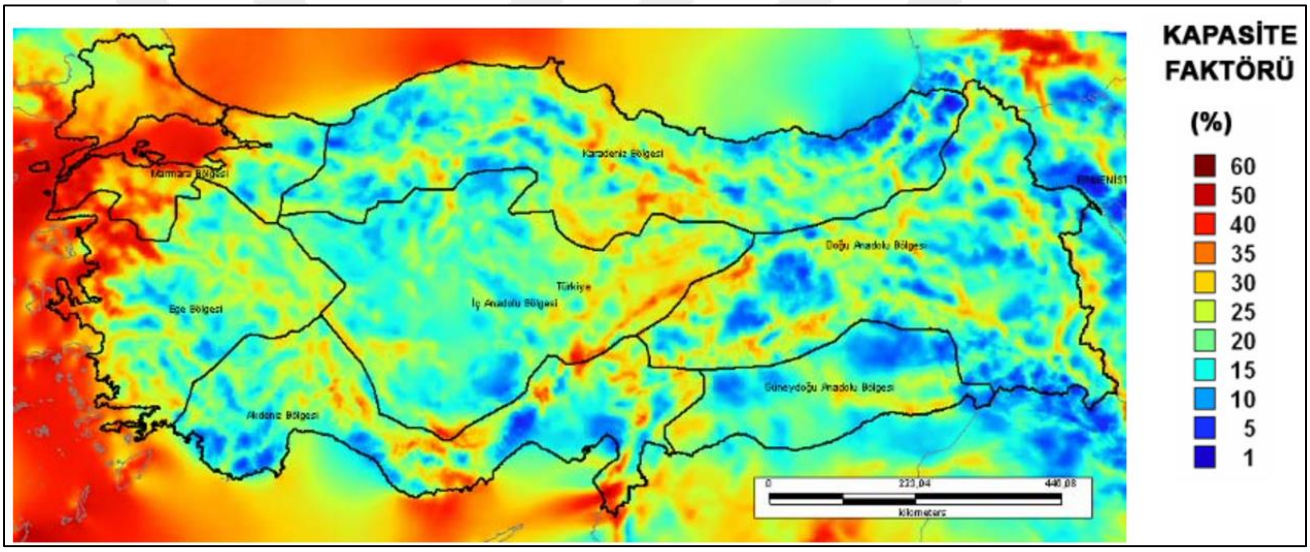

Figure 9. Annual Average Capacity Factor of 1 MW Wind Power Facility – 50 Meters (REPA-V1).

As it is stated on the MENR website, REPA was updated in 2020 and the spatial resolution was increased to 100mx100m, which is a better resolution. Table 3.5. shows the output of the data for the updated REPA and it is noted that the calculations are still ongoing for REPA according to MENR (MENR, 2023b). Figure 10, Figure 11, and Figure 12 are the maps of updated REPA in 2020. Figure 10 shows the wind speed at 100 meters, Figure 3.9 depicts the WPD at 100 meters and Figure 3.10 shows the capacity factor of a 3 MW wind power facility at 100 meters.

Table 3.5. 2006 REPA-2020 Model Outputs.

Height	**Output**
30m	Annual Wind Speed, Annual WPD, Capacity Factor of a 3 MW facility
60m	Annual Wind Speed
100m	Annual Wind Speed, Annual WPD, Capacity Factor of a 3 MW facility
150m	Annual Wind Speed

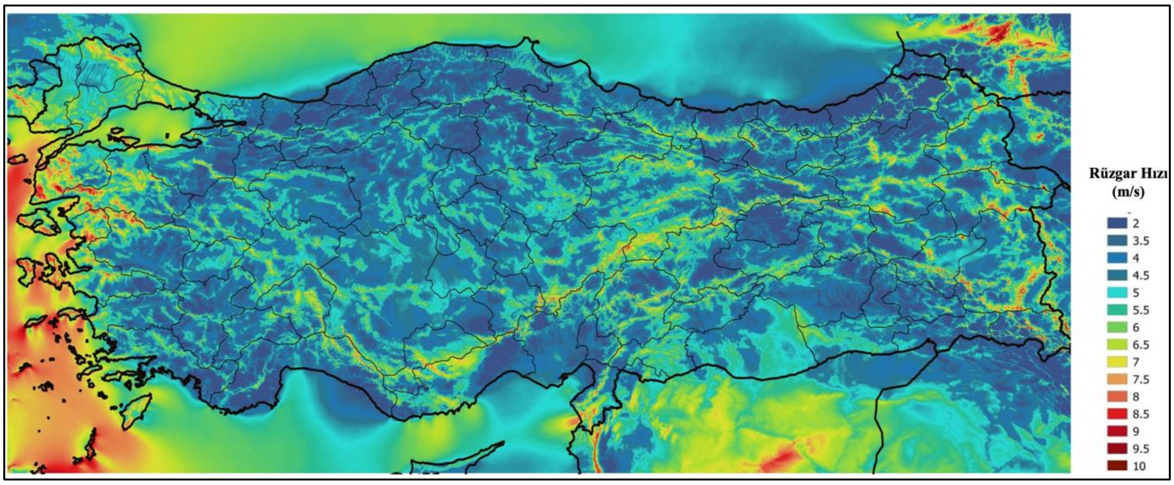

Figure 10. Annual Average Wind Speed - 100 Meters (REPA-2020).

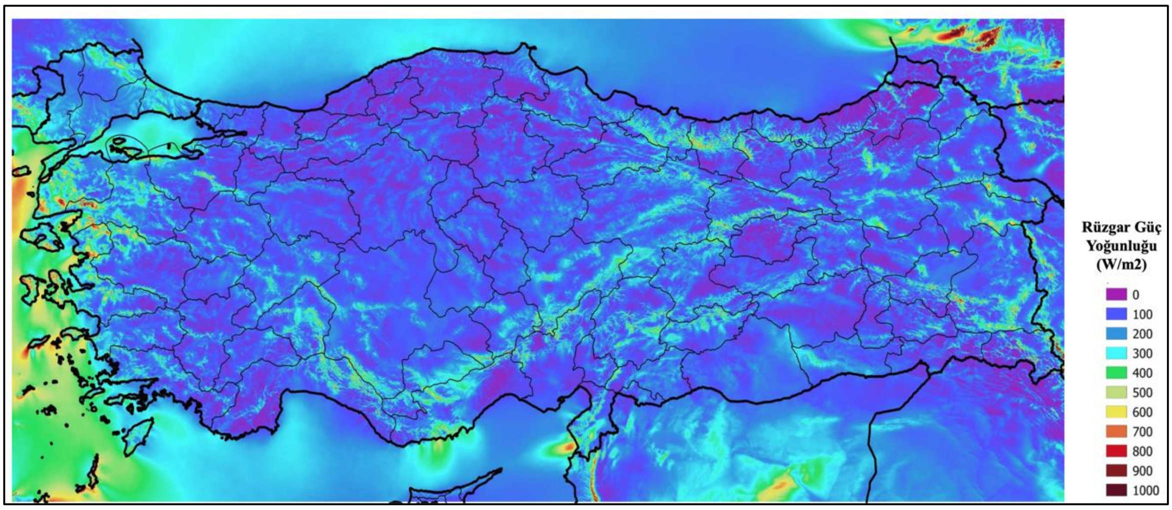

Figure 11. Annual Average Wind Power Density – 100 Meters (REPA-2020).

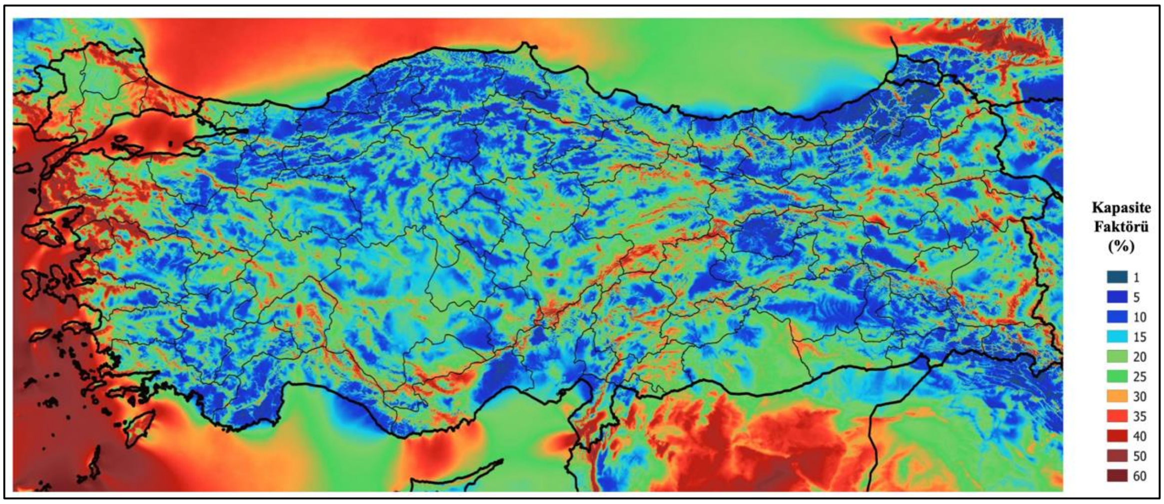

Figure 12. Annual Average Capacity Factor of 3 MW Wind Power Facility – 100 Meters (REPA-2020).

REPA is the most detailed and main guide for wind energy potential of Turkey. It is used to pre-select areas for the auctions for new wind energy plants, and YEKA tenders. Apart from YEKA applications and applications within the scope of electricity generation facility with storage, a wind measuring mast is required to measure the wind speed in the selected area for at least 1 year in the past 8 years to get more accurate wind speed data to get the license for the facilities (Official Gazette, 2022b). Thus, REPA is quite important in the lack of measure requirement for YEKA tenders and applications within the facility with storage.

According to the regulation on technical evaluation of applications for wind energy facilities published in 2015, if the average WPD of the measured area was lower than 150 W/M^2, the generation license was not given. If not, the generation facility was granted the generation license after requirements were completed (Official Gazette, 2015). However, with the regulation change published on 29 December 2022 in the Official Gazette (2022d), this article was removed from the relevant regulation. According to the latest regulation there is no minimum limit in WPD for the application to be accepted.

As the wind turbines mostly last around 30 years (Wiser & Bolinger, 2019), it is quite important to investigate the future wind speed data so that the wind turbines can be installed on the most optimum places and already installed plants can use most of the wind energy potential in the selected area. Yet, during the licensing procedure, only historical wind speed data is required both by wind measuring mast and the REPA also use the historical data to measure wind speed and calculate the wind energy. While the global climate change is expected to impact the climate, it is important to model the future wind energy potential of Turkey under different climate change scenarios and compare it with the historical data to understand how the climate change may impact the wind energy potential of Turkey.

It can be done by using climate modeling under RCP scenarios and analyze wind speed data to see the future wind speed data. The next section will explain the modeling analysis and the methodology used in this modeling analysis to understand the extent of the impact of the climate change on the wind energy potential of Turkey.

4. MODELING METHODOLOGY

The modeling study in this thesis is conducted to look at the future impacts of climate change on wind energy potential in Turkey. It consists of the analysis of the results of the climate modeling, assessing the potential changes in wind energy source in Turkey and combining the findings of the analysis to current and future wind energy policies of Turkey to reevaluate these policies based on the results.

For a modeling study, as it is stated in chapter 2 and Table 2.4, global climate models are being used. The scenarios chosen, the time period and the variables looked at on the model in this thesis is given on Table 4.1.

Table 4.1. Modeling Study Details.

Area	**Climate Change Scenarios**	**Time Period**	**GCM /RCM**	**Investigated Variable**
Turkey	Historical, RCP 8.5 and RCP 4.5	1971-2000 2021-2050	Max Planck Institute (MPI-ESM-MR), RegCM 4.4	Wind Speed, Wind Power Density

Max Planck Institute (MPI-ESM-MR) global climate model is developed by Max Planck Institute for Meteorology (Max Planck Institute, 2017) MPI-ESM-MR Global climate model was used for many other studies investigating the impact of climate change on Turkey (MGM, 2015; Demircan et al., 2017; Gürkan et al., 2015; Turp et al., 2014; Turkes et al., 2019) so this model was also used for this study as it is a reliable global climate model, and also its data is accessible for this study. Global climate models have a spatial resolution of roughly 100–250 km, which is inadequate for studies that want to investigate impacts on smaller scales (Ekström et al., 2015). As this study is focusing on Turkey, a finer spatial resolution is required for a more accurate study. The method for increasing the spatial resolution of global climate models is called the 'Downscaling method'. The downscaling method is also split into two categories, and they are 'Statistical Downscaling' and 'Dynamic Downscaling' (Keller et al., 2022). The dynamic downscaling method is increasing spatial resolution of global climate models using regional climate models for a specific region (Keller et al., 2022). RegCM 4.4 is a regional climate model developed by The Abdus Salam International Centre for Theoretical Physics (Turp et al., 2014). The RegCM 4.4 program was used to downscale the global modeling results to high spatial resolution of 10kmx10km for Turkey region in this study. The RCP 4.5 and RCP 8.5 scenarios, which are generally preferred for modeling studies (MGM, 2015; Demircan et al., 2017; Gürkan et al., 2015; Turp et al., 2014), developed with the MPI-ESM-MR global climate model were upgraded to a higher resolution for a better analysis for this study. The regional climate model used in this study was run on the servers at the Boğaziçi University Center for Climate Change and Policy Studies (İklimBU).

As mentioned earlier in chapter 2, IPCC develops potential scenarios to examine the impacts of climate change, namely SRES, RCP and SSP scenarios. In this thesis RCP scenarios will be used since SSP scenarios currently lack dynamically downscaled high-resolution data for regional scales. Martinez and Iglesias (2021) investigated the Europe and Akinsanola et al. (2021) investigated the West Africa and they both could use SSP scenarios because the investigated area in their study didn't require regional scale and the data available for SSP scenarios could be used in their studies at that time. Yet, the other studies that used RCP scenarios needed higher resolution data for SSP for their investigated area and couldn't use SSP scenarios because of that.

Climate normal is a term to demonstrate normal values of a location within a 30-year span (NOAA, 2023). Climate normal base a reference period to see the changes in the future with the modeling studies (NOAA, 2023). 1971-2000 climate normal period was chosen in this study as this 30-year span is the latest available data for MPI-ESM-MR. To see how climate change will impact Turkey's wind power potential in the near future, the years 2021–2050 have been chosen in this study. For recommendations regarding wind energy policy, the model's time span for the near future also makes much more sense. Since wind turbines typically last 30 to 40 years, any policy recommendations regarding wind energy after 2050 may be premature.

Near-surface (10m) wind speed data is the only available climatic wind speed data from a modeling study, and the studies mentioned before base their projections on that data. 70-100 meters are usual wind turbine hub heights according to Lackner et al. (as cited in Chen, 2020). Turkish Wind Energy Potential Atlas (REPA) also investigates the wind speed and WPD at 100m (MENR, 2023b). Thus, to be in line with the REPA, wind speed data at 100m was needed for this study. The most common method for extrapolation of 10m wind speed data to higher heights is the power law method (Emeis, as cited in Akinsanola et al., 2021; Sisterson et al., as cited in Albani and Ibrahim, 2017; Bonanno et al., 2023; Tobin et al., 2015; Hueging et al., 2013). Most of the studies use the power law method in the Equation 4.1:

$$WSE = \left(\frac{EWSH}{OWSH}\right)^{\alpha} * OWSH$$ Equation (4.1)

α=Power law exponent, assumed as:1/7
WSE= Wind Speed at Extrapolated Height
EWSH= Extrapolated Wind Speed Height
OWSH= Original Wind Speed Height

Extrapolation of 10m wind speed data to 100m turbine hub height is calculated according to this formula. The power law exponent is included as the topography of the site, and it is a region-specific value. For better and precise calculations, it is preferred to have location specific atmospheric and terrain information (Touma, 1977). Yet, it is common for studies that don't have that specific information to assume that value as 1/7 (Crippa et al., 2021; Şen et al., 2012). Many studies on the literature assumed that value as 1/7 assuming the topography an open land terrain (Albani and Ibrahim, 2017; Tobin et al., 2015; Bonanno et al., 2023; Pryor et al., 2005; Pryor & Barthelmie, 2011; Emeis, as cited in Akinsanola et al., 2021). For this modeling study, wind speed data was also extrapolated to 100m to get the wind speed data for turbine hub height using the power law method.

The outputs of the regional climate modeling are stored as a NetCDF file as 3-hour wind speed data. CDO software is used to command NetCDF files. Wind speed data at 100m height is then calculated from the modeling outputs as it is seen in Equation 4.2, using Climate Data Operator (CDO). CDO is a collection of operators to use commands for climate data.

$$WS100 = \left(\frac{100}{10}\right)^{1/7} * 10$$ Equation (4.2)

WS100=Wind Speed at 100 meters

Wind turbines have cut-in and cut-out values. They start to operate around 3-4 m/s and they stop their operation around 25-26 m/s to stop damage from extreme wind speeds. (Lu L, 2015). Turkish State Meteorological Service states 3 m/s as cut-in value and 26 m/s as cut-out value for a reference turbine on their calculations for wind energy potential (DMİ, 2010). Thus, the wind speed values outside of 3-26 m/s range at 100m according to the modeling results were also extracted from the dataset.

After having wind speed data on 100m height, WPD at 100m was calculated according to the formula in Equation 2.1 using CDO software. The air density is considered to have a constant value of 1.225 kg/m^3 under standard conditions according to International Standard Atmosphere (Hueging et al., 2013). The formula used is demonstrated in Equation 4.3.

$$WPD100 = \frac{1}{2} * 1.225 * (WS100^3) \qquad \text{Equation (4.3)}$$

WPD100=Wind Power Density at 100 meters

After the 3-hour WPD at 100m data is calculated, the data was investigated using CDO commands. CDO was used to calculate monthly, seasonal, and annual averages for RCP 4.5, RCP 8.5 for 2021-2050 timespan and historical data for 1971-2000 timespan.

The visualization of the model results is important to see the impact of climate change on areas. CDO is used to create maps according to the model results. Annual, seasonal, and monthly average wind speed data on 100m and average WPD on 100m were mapped for 2021-2050 under both RCP4.5 and RCP 8.5 scenarios. To be able to see the impact of climate change, 1971-2000 historical wind speed data from MPI-ESM-MR was also printed and compared with both scenarios. Details of the period, scenario and the model output is shown in Table 4.2.

Table 4.2. Model Outputs.

Year	**Scenario**	**Averaged Period**	**Investigated Variable**
1971-2000	Historical Data	Annual, Seasonal, Monthly	100m Wind Speed, 100m Wind Power Density
2021-2050	RCP 4.5	Annual, Seasonal, Monthly	100m Wind Speed, 100m Wind Power Density
2021-2050	RCP 8.5	Annual, Seasonal, Monthly	100m Wind Speed, 100m Wind Power Density

5. RESULTS

5.1. Modeling Results of RCP 4.5 and RCP 8.5 Scenarios

This section includes results of the MPI-ESM-MR modelling study for RCP 4.5 and RCP8.5 scenarios and the comparison of these scenarios with the historical period of 1971-2000 from the same model. Although there are many variables in the modelling results, WPD variable on 100 meters is used for comparison as REPA also uses demonstrates wind energy potential of Turkey as WPD on 100 meters as well.

The modeling results are used to print maps to see the difference visually. To understand the monthly and seasonal differences in addition to yearly average, three different maps for each scenario showing the WPD at 100 meters monthly, seasonal and annual averages were created using CDO software.

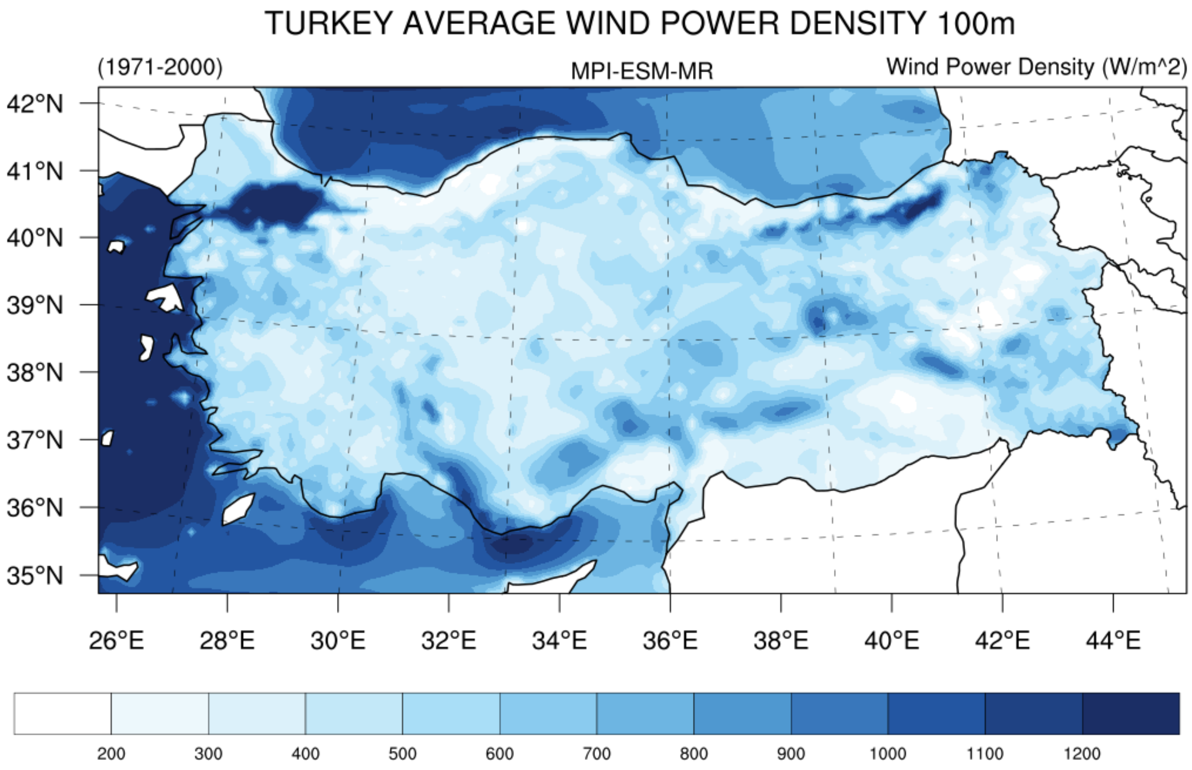

Figure 13. Turkey Average Wind Power Density 100m Historical Data Results (1971-2000).

At Figure 13, for the period of 1971-2000, average WPD at 100m for Turkey is shown including sea is 601.9 W/m^2. The minimum WPD that can be harvested at Turkey including sea is 78.1 W/m^2 and maximum WPD is 1561.3 W/m^2. Average WPD at 100m for Turkey excluding sea for the same period is 495.5 W/m^2. Minimum WPD excluding sea in Turkey is 130.8 W/m^2 and maximum is 1508.4 W/m^2. The average value is the average of all Turkey. The minimum and maximum values show the average of locations that have the minimum and maximum value for the given period.

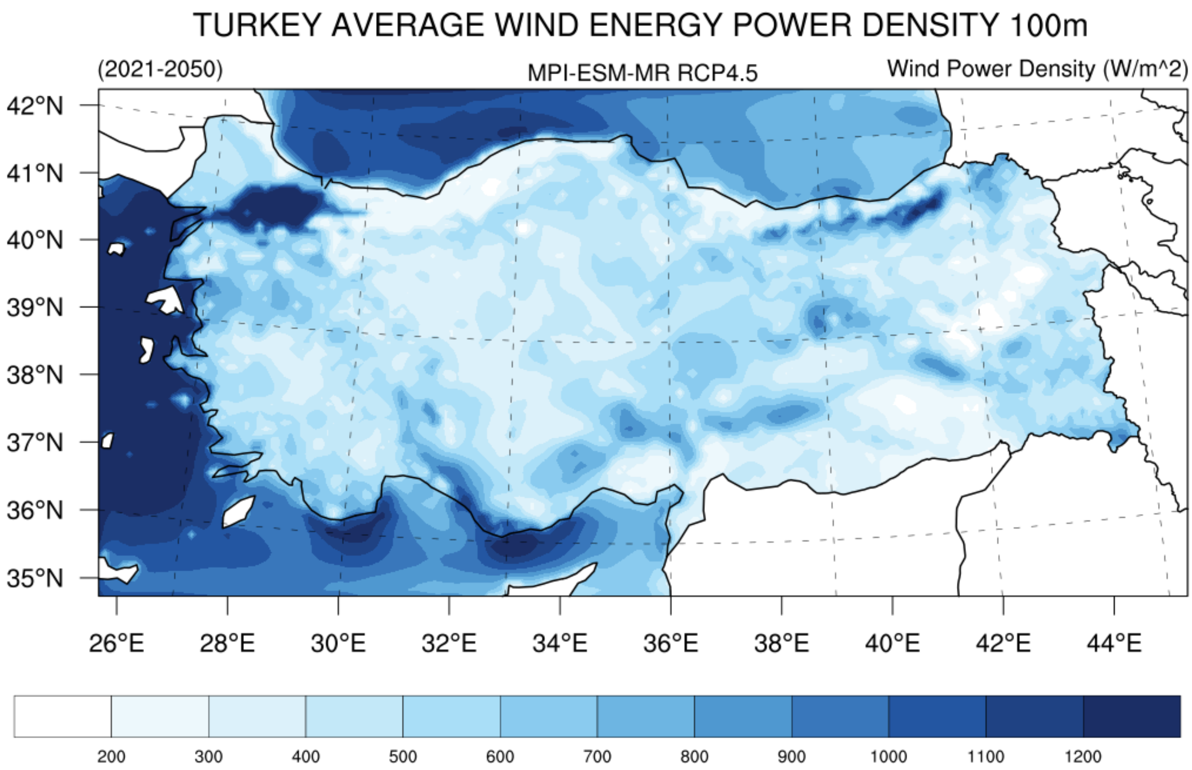

Figure 14. Turkey Average Wind Power Density 100m RCP4.5 Scenario Data Results (2021-2050).

Figure 14 shows the results of RCP 4.5 scenario by MPI-ESM-MR Global Climate Model for Turkey for the period of 2021-2050. For this period, average WPD at 100m for Turkey including sea is 593.4 W/m^2. The minimum WPD is 75.6 W/m^2 and maximum WPD is 1557.6 W/m^2 for Turkey including sea. Average WPD excluding sea for Turkey is 486.8 W/m^2 under the RCP 4.5 scenario. The minimum WPD is 132.8 W/m^2 and maximum is 1386.0 W/m^2 excluding sea.

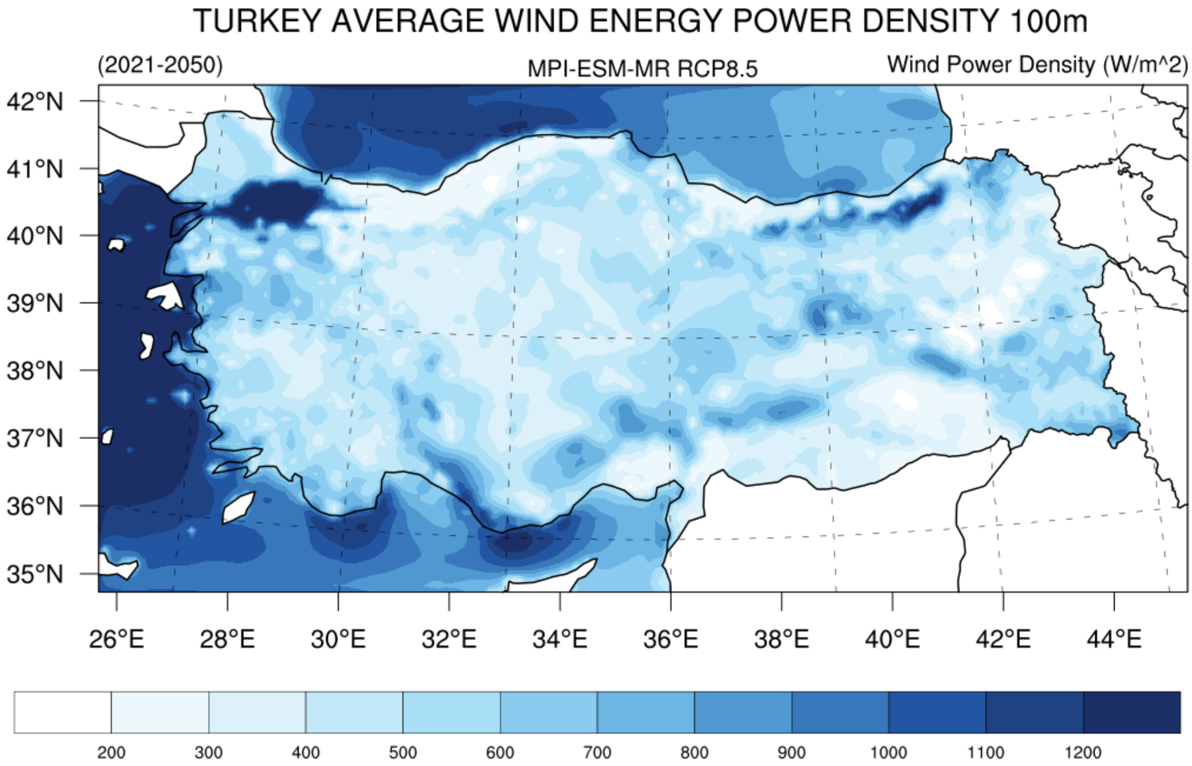

Figure 15. Turkey Average Wind Power Density 100m RCP8.5 Scenario Data Results (2021-2050).

At Figure 15, according to the results of RCP 8.5 scenario, the average WPD at 100m for Turkey including sea is 600.4 W/m^2. Minimum WPD for RCP 8.5 is 78.0 W/m^2 and maximum WPD is 1564.5 W/m^2 including sea. Average WPD for Turkey excluding sea is 491.97 W/m^2. Minimum WPD is 133.9 and maximum WPD is 1419 W/m^2 excluding sea for Turkey.

Figures 5.1, 5.2 and 5.3 visualize the 30-year average of WPD at 100m for Turkey including sea. Table 5.1 summarizes the values for each scenario for 30-year average.

Table 5.1. Comparison of Historical Data, RCP 4.5 and RCP8.5 Scenario 30-Year Average WPD (W/m2) at 100m

		Minimum WPD	Mean WPD	Maximum WPD
Including Sea	Historical	78.1	601.9	1561.3
	RCP 4.5	75.6	593.4	1557.6
	RCP 8.5	78.0	600.4	1564.5
Excluding Sea	Historical	130.8	495.5	1508.4
	RCP 4.5	132.8	486.8	1386.0
	RCP 8.5	133.9	492.0	1419.0

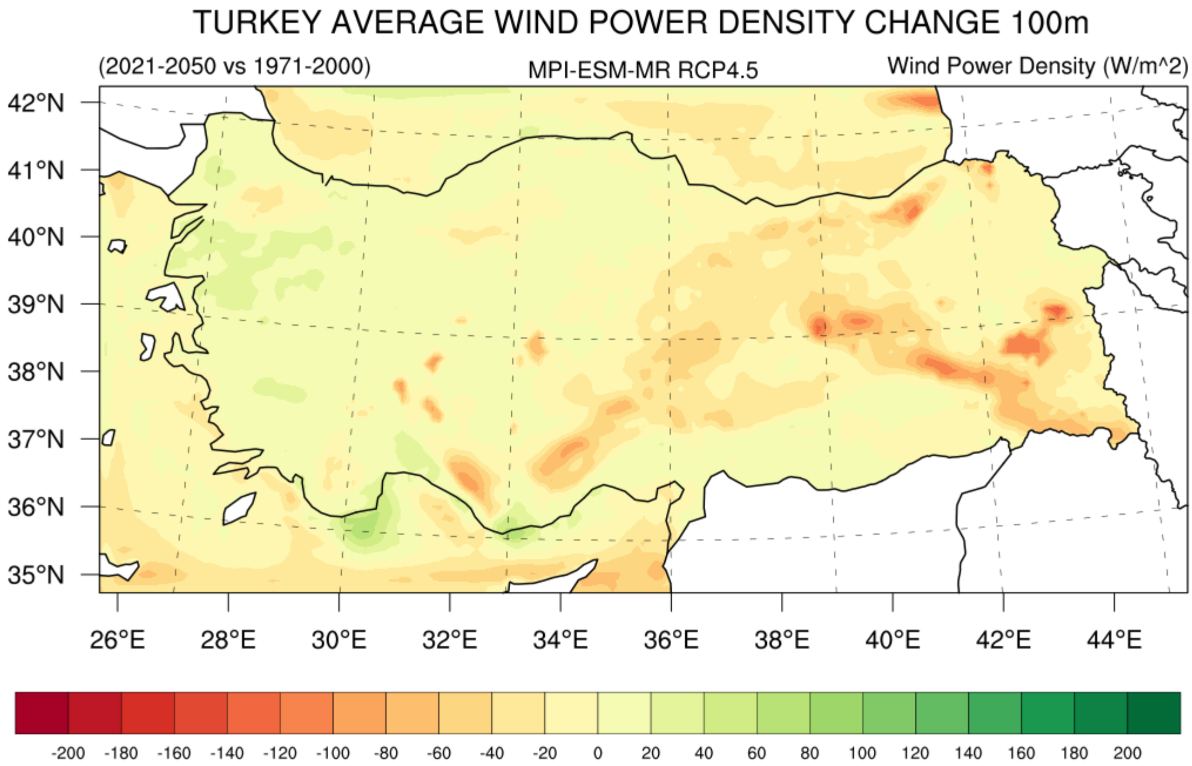

Figure 16. Turkey Average Wind Power Density Change 100m RCP4.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

Figure 16 shows the difference of average WPD at 100m under RCP 4.5 scenario compared to historical data by MPI-ESM-MR. The map shows that while there are changes in some areas when we look at Turkey as a whole, some regions have slight changes or have not changed at all. Average WPD at 100m has increased in some areas while declining in others looking at the 30-years span.

There are slight increases in the Marmara region of Turkey and some parts in Aegean region under RCP4.5 scenario for the 2021-2050 period. Most of the wind power facilities are based in Marmara and Aegean regions in Turkey. Thus, changes in these regions of Turkey will be more important than other regions. It is also seen that 30-year average of WPD at 100m in some parts in the Mediterranean region will increase compared to 1971-2000 levels. This increase is seen both on-shore and off-shore of the Mediterranean coast of Turkey.

Some changes are also visible in southeastern and northeastern parts of Turkey under RCP4.5. There seem to be decreases in average WPD for 2021-2050 period compared to 1971-2000 average WPD in these parts. For the rest of the country, there are slight changes under RCP4.5 scenario for the 30-year average WPD at 100m.

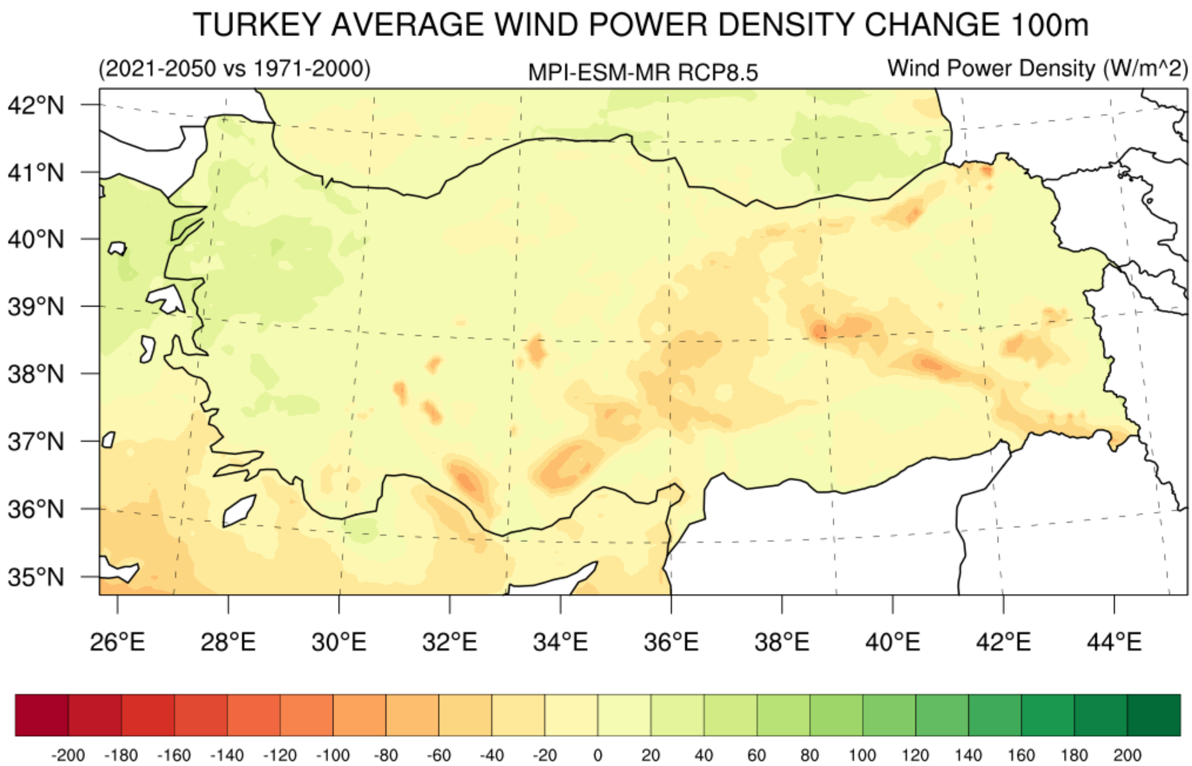

Figure 17. Turkey Average Wind Power Density Change 100m RCP8.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

Figure 17 illustrates the difference of 30-years average of WPD at 100m under RCP 8.5 scenario to historical data. The pattern of the changes seems in line with the difference of RCP 4.5 scenario to historical data as it is shown in Figure 16. However, compared to RCP4.5 scenario, RCP8.5 scenario demonstrates more increase in Marmara and Aegean regions and less decrease in southeastern and northeastern parts of Turkey.

Although the 30-year average gives insight about the differences among scenarios and historical data, monthly 30 year-average results are also investigated and the difference maps between historical data and both RCP scenarios for 30-years average and monthly 30-years average were printed.

As wind is very variable and dependable on the season and months, it is also important to check the results of RCP scenarios of modeling study monthly. Figures 5.6 and 5.7 show monthly 30-year average change of WPD at 100m under RCP 4.5 and RCP 8.5 scenario respectively.

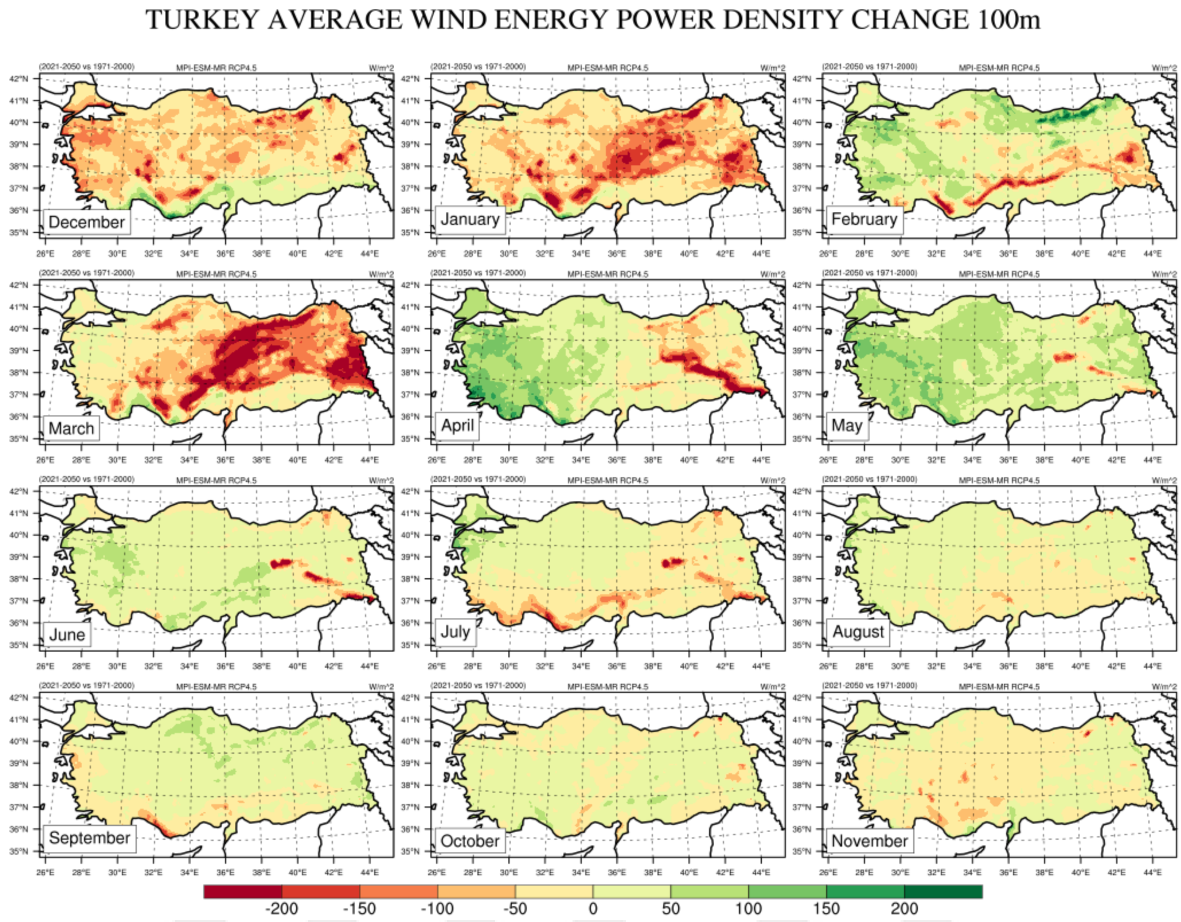

Figure 18. Turkey Monthly Average Wind Power Density Change 100m RCP4.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

At Figure 18, it is seen that while there are slight changes all over Turkey on some months, on some monthly averages such as December, January, February, March, April and May, there are very significant changes on specific parts of Turkey under RCP 4.5 scenario compared to the historical data.

- In December and January averages for the 2021-2050 period, apart from the Mediterranean coast of Turkey, there seems to be a decrease in the whole country. There seems to be an increase in the Mediterranean coast of Turkey in December and January. The same pattern continues for the March average, yet the decrease seems more significant.
- For the same period in February, increases in WPD average are observed for the Black Sea region and the western part of the country. There seems to be a decrease in WPD average for the southern and southeastern parts of the country.
- In April and May averages, the average WPD increase is the highest among 12 months. In April, the eastern part of the country is observed to have a decrease in WPD average. In May, the WPD average in most of the eastern parts of the country also seems to be increasing in contrast to April.

- In June average for the 2021-2050 period, the change is little, increasing more in some parts in the west of the country and some southern parts in Central Anatolia. There seems to be a slight decrease on the Black Sea coast of the country and a more significant decrease in some parts in the southeastern side of the country.
- For the Marmara and Thrace regions, there appears to be an increase in the average WPD in July. However, the Mediterranean region and some specific areas of the country's eastern parts face decreases.
- In August, September, October, and November averages; the change under RCP4.5 scenario for WPD average is less among other months.

The Marmara and Aegean regions, where wind farms are mostly located, there are important increases in in February, April, and May months. There are also changes in some parts of these regions in June and July. There seem to be decreases in the same regions in December and January.

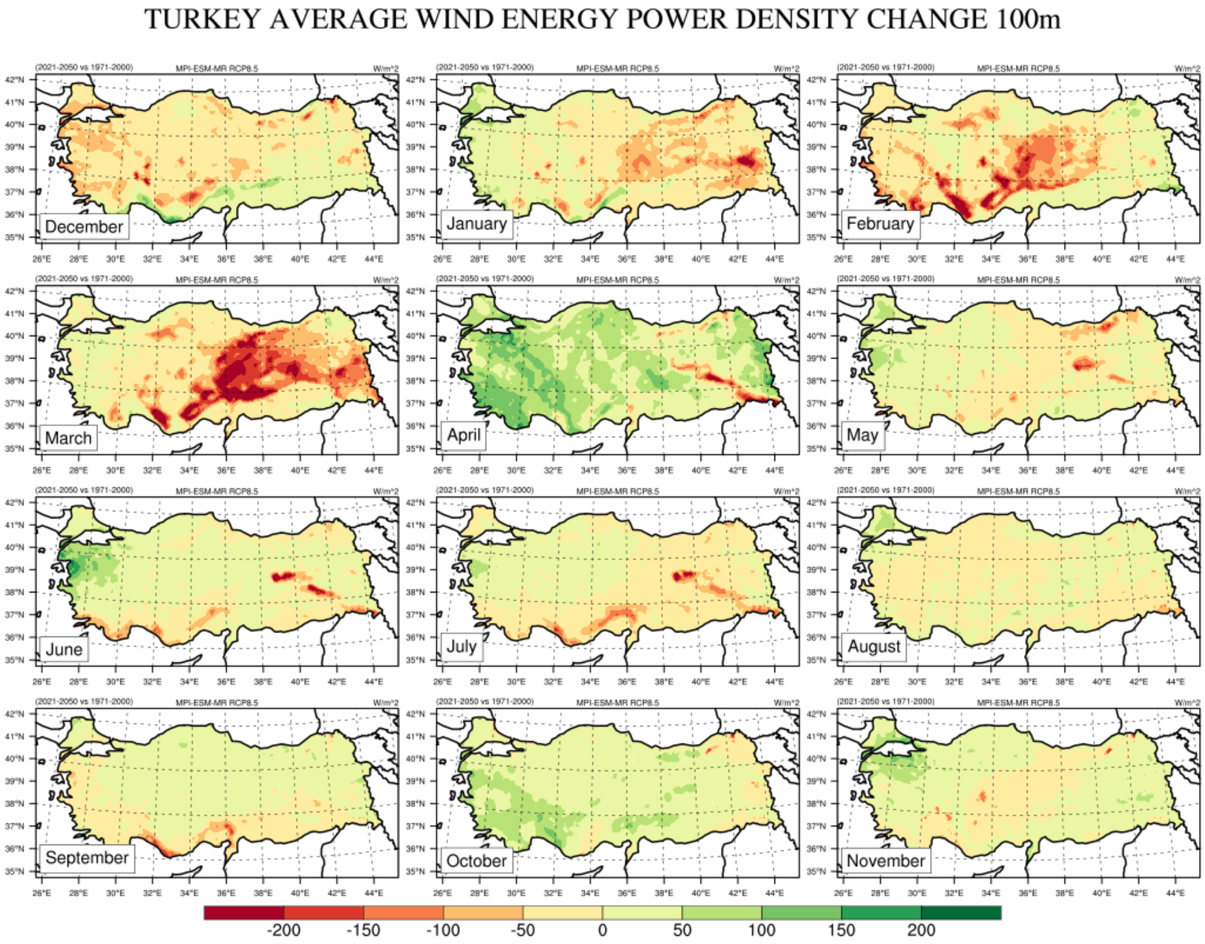

Figure 19. Turkey Monthly Average Wind Power Density Change 100m RCP8.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

Figure 19 demonstrates the 30-year monthly average difference of RCP8.5 scenario to historical data. There are significant increases and decreases on average WPD at 100m at specific locations between different months. Although the change pattern seems the same with RCP 4.5 scenario, there are also changes between the two RCP scenarios. Figure 20 depicts the monthly 30-year average WPD at 100m differences between RCP 4.5 and RCP 8.5 scenarios.

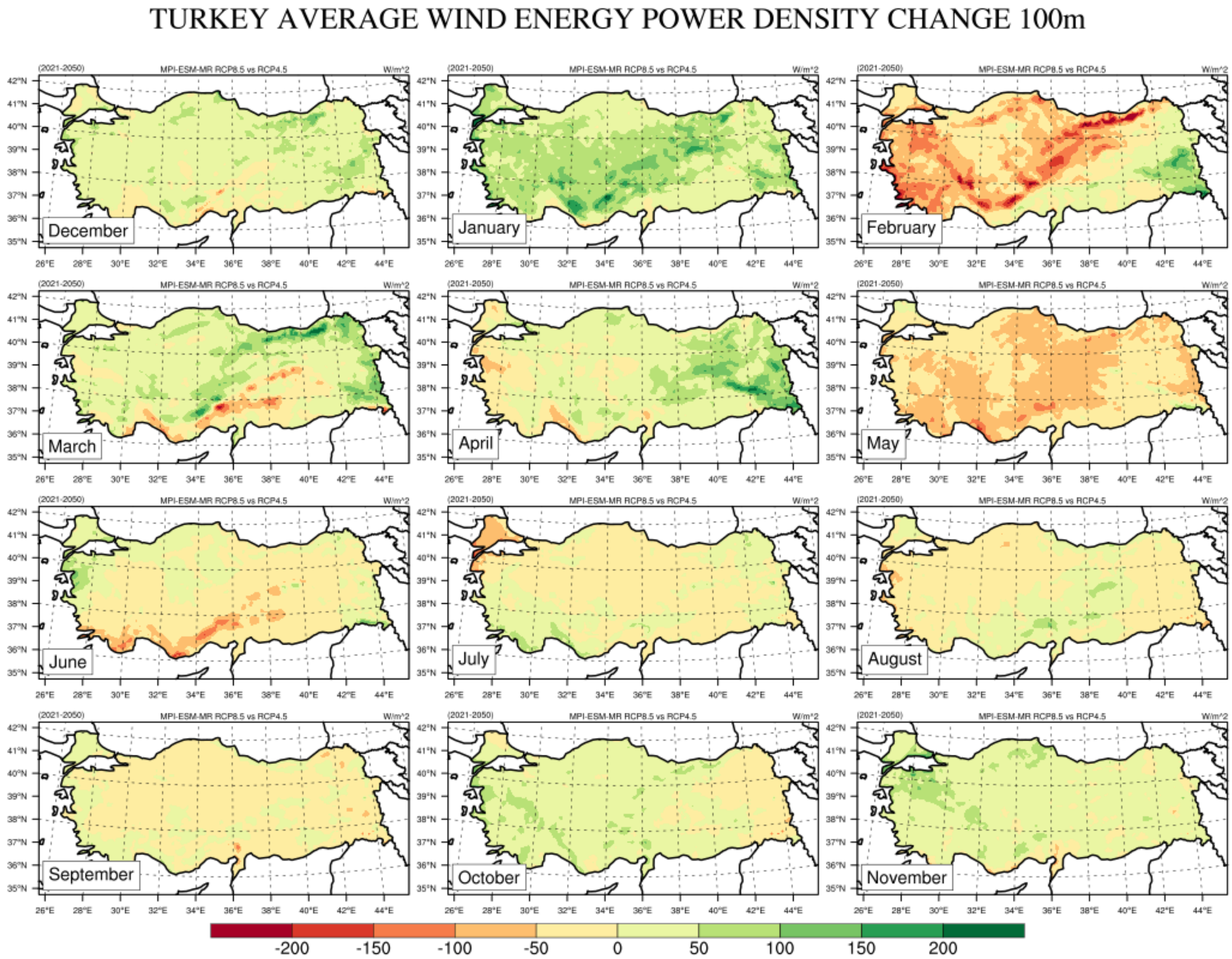

Figure 20. Turkey Monthly Average Wind Power Density Change 100m RCP8.5 Scenario vs RCP4.5 Scenario Data Results (2021-2050).

At Figure 5.8, it is shown that there are also significant differences between RCP 4.5 and RCP 8.5 scenarios especially on January, February, March, and April. This shows that two different scenarios may have different impacts on average WPD according to the modeling outputs.

When the monthly averages of the model results excluding sea are compared, monthly changes are observed. These changes are given in Table 5.2 below as percentage difference.

Table 5.2. Turkey Monthly Average WPD at 100m Change Between RCP Scenarios and Historical Data (Excluding Sea).

Month	**RCP 4.5 vs Historical Data**	**RCP 8.5 vs Historical Data**	**RCP 8.5 vs RCP 4.5**
January	-11%	-2%	10%
February	1%	-6%	-7%
March	-13%	-9%	5%
April	7%	14%	6%
May	11%	0%	-10%
June	6%	0%	-3%
July	-2%	-3%	-1%
August	1%	-1%	-1%
September	4%	2%	-2%
October	2%	7%	5%
November	-3%	3%	6%
December	-8%	-3%	5%

From Table 5.2, model results show that although the annual average difference between scenarios, as shown in Table 5.1 seem insignificant, the variation within the year demonstrates much more distinctly how climate change is impacting the potential for wind energy. The difference in spring and winter season is especially clearer in both RCP scenarios compared to historical data. Both scenarios suggest a decrease in March and increase in April compared to the historical data. The difference between RCP 4.5 and RCP 8.5 scenarios are attributed to the different radiative forcing pathways they follow.

Even though the numerical outputs of the model results offer us a result for comparison, since average values take the average of the entire Turkey, it is essential that we look at the maps where we observe the point differences of the entire Turkey.

For instance, according to the monthly RCP4.5 scenario results, the western part of the country experiences an increase in February on average, with the Black Sea region experiencing a higher rate of increase, while other regions of the country experience decline. Yet, in February under RCP4.5 scenario, there seems to be only 1% increase in 30-year February average. That value may give us the impression that there hasn’t been much change in the difference for the country while there are significant regional variations throughout the country.

This study's goal is to demonstrate that regional climate modeling can show how the wind potential can change due to climate change, and to emphasize the need for further research into this topic in future studies of wind energy potential.

5.2. Comparison of the Modeling Study and REPA Modeling

With this modeling study and the analysis of this modeling study, it is intended to show that the estimation of Turkey's wind energy potential can be more accurately determined by considering the impacts of climate change into account. In the IPCC report presented in 2022, it is stated that the impact of climate change on wind changes depending on the season and the region (Burnett, Barbour and Harrison, 2014; Cradden et al, 2015; Fant, Schlosser and Strzepek, 2016; as cited in IPCC, 2022). This modeling study and the REPA model has similarities and differences as REPA is a model run by the resources provided by Turkish government with more precise inputs and funding. Thus, although the impact of climate change on wind energy in Turkey can be clearly seen from this modeling study, further research is required on REPA model to estimate the wind energy potential of Turkey in the future taking the impact of climate change into consideration.

This model and the REPA model have their similarities and differences. It is impossible to compare the results of this model to REPA results precisely because the global climate models, regional modeling, and other software applications used in REPA are not openly shared to the public. It is only stated that micro-level wind flow model and medium-scale weather forecasting model was used for REPA (MENR, 2023b).

Çalışkan (2018) presented some specific information about the REPA model and explained that using data from geographic information systems, the REPA model identified the regions where wind turbines could not be installed and did not consider these areas when calculating the wind energy potential. The model study assumes that locations such as residential areas, sloping lands, roads and railroads, and national parks cannot have wind turbines installed. The main distinction between this model analysis and REPA is that it didn’t include the geographic information system as an input.

Other than these model inputs, the wind speed and wind power density was calculated at 100m on this study as it was on REPA V-1 and V-2. The formula to calculate WPD is given in Equation 2.1 and this formula is a universal formula to calculate the Wind Power Density, this formula is also presented in the MENR website as the formula to calculate wind energy potential (MENR, 2023a).

Yet, the power law exponent, calculated based on the topography of the site, used in extrapolating the wind speed at 10m to 100m in REPA model is also not openly shared and thus unknown.

In other words, the inputs of the REPA that are publicly shared were taken the same in this model study. However, information that is not available to the public, such as Turkey's geographic information systems data, unfortunately could not be included in this study. Therefore, a detailed one-to-one comparison between the two models is not possible.

REPA is managed by the government and receives funding from the European Union Finance and the European Union Development Bank. The model can also incorporate geographic data that the government would not typically disclose. Therefore, REPA is a model study that is therefore more sophisticated than this model study. Yet, REPA only analyzes historical wind data and does not demonstrate the impacts of climate change in the model. The model study examined in this study demonstrates that there may be a difference in the wind energy potential over the next 30 years, especially monthly, depending on the RCP 4.5 and RCP 8.5 scenarios.

The average WPD between 1971 and 2000 as well as the average WPD under the RCP4.5 and RCP8.5 scenarios for the years 2021 to 2050 are both examined in this model research. In this study, the differences between historical data and two possible future scenarios are compared and the results are demonstrated both analytically and visually. REPA, on the other hand, did not take into consideration the impacts of future climate change. For REPA, it may be more inclusive to integrate the scenarios where the impacts of climate change on wind energy can be seen into the model and to see the difference with the historical data.

6. DISCUSSION AND POLICY IMPLICATIONS

The results of the model from this study indicate that the wind energy potential at 100 meters in Turkey will change between the years 2021 and 2050 when compared to the average for the years 1971 to 2000 based on the RCP4.5 and RCP8.5 scenarios.

When the average of the 30-year span is compared, the difference in the average appears to be insignificant, but it turns out that there are intra-annual changes for the average of Turkey and intra-annual location-based changes. According to RCP 4.5 results, WPD at 100m 30-year average for the 2021-2050 period will slightly increase in Marmara and Aegean regions. The change will be higher according to RCP 8.5 results for these regions. Some specific locations in the eastern parts of Turkey will see decreasing WPD at 100m 30-year average for the 2021-2050 period according to both RCP 4.5 and RCP 8.5 scenarios.

Monthly averages for the period of 2021-2050 show more significant changes throughout the country. The results indicate an increase and decrease between months for various regions. The point to be derived from this may be that the extractable wind energy potential at 100m will shift more variably between months in the future according to the model results. The share of wind energy generation is increasing in total electricity generation in Turkey (TEIAS, 2023). Thus, the variability of the wind energy potential that seems to be impacted by climate change, may pose risks for energy security monthly when the dependency on wind energy increases in the future.

Currently installed wind power plants in Turkey are mostly stationed in the Marmara and Aegean regions of Turkey where strong wind patterns are common and the terrain is available for wind turbine installations. It is also clear from Figure 6.1 that many wind power plants are in the Thrace region and western coasts of Turkey (EMRA, 2023). Thus, the changes in these regions may be more important than changes in other regions.

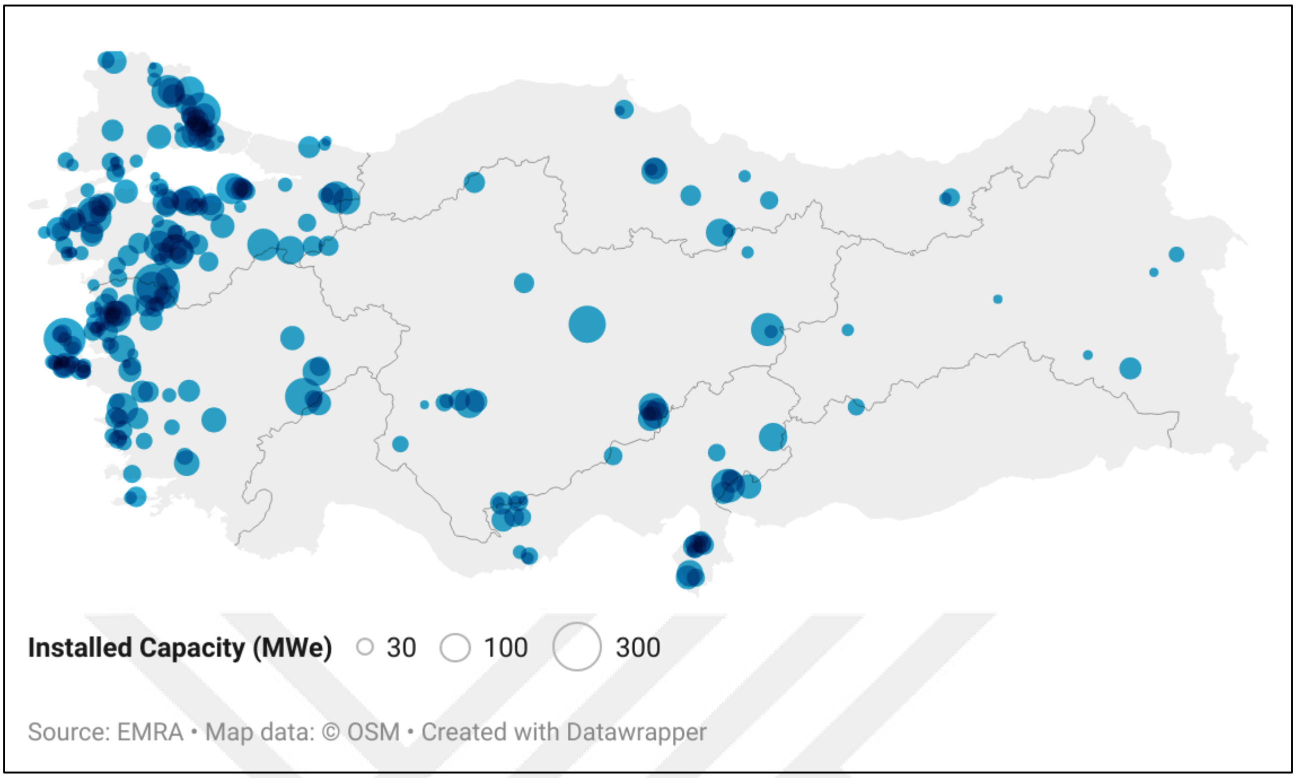

Figure 21. Turkey Installed Wind Power Facilities as of April 2023.

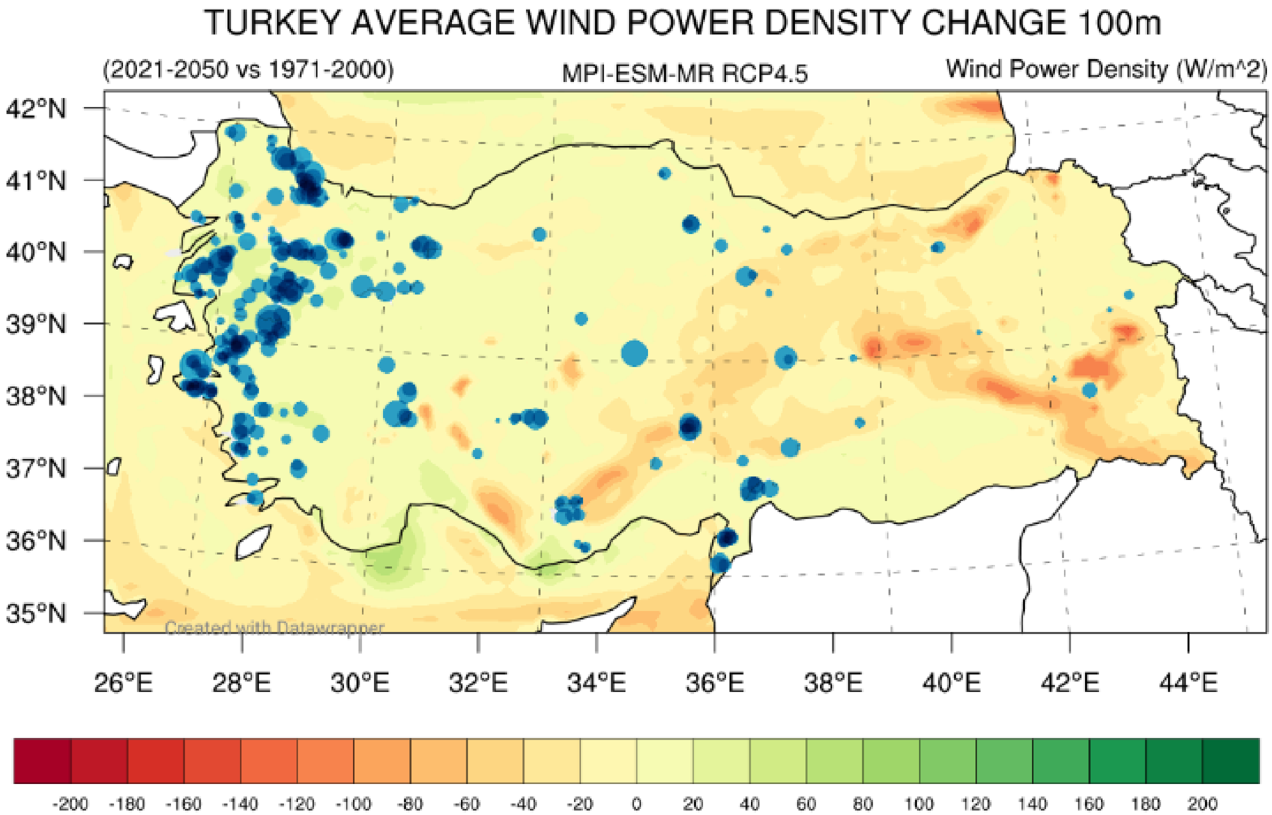

Figure 22. Projected Changes under RCP 4.5 scenario on Installed Wind Power Facilities in Turkey as of April 2023.

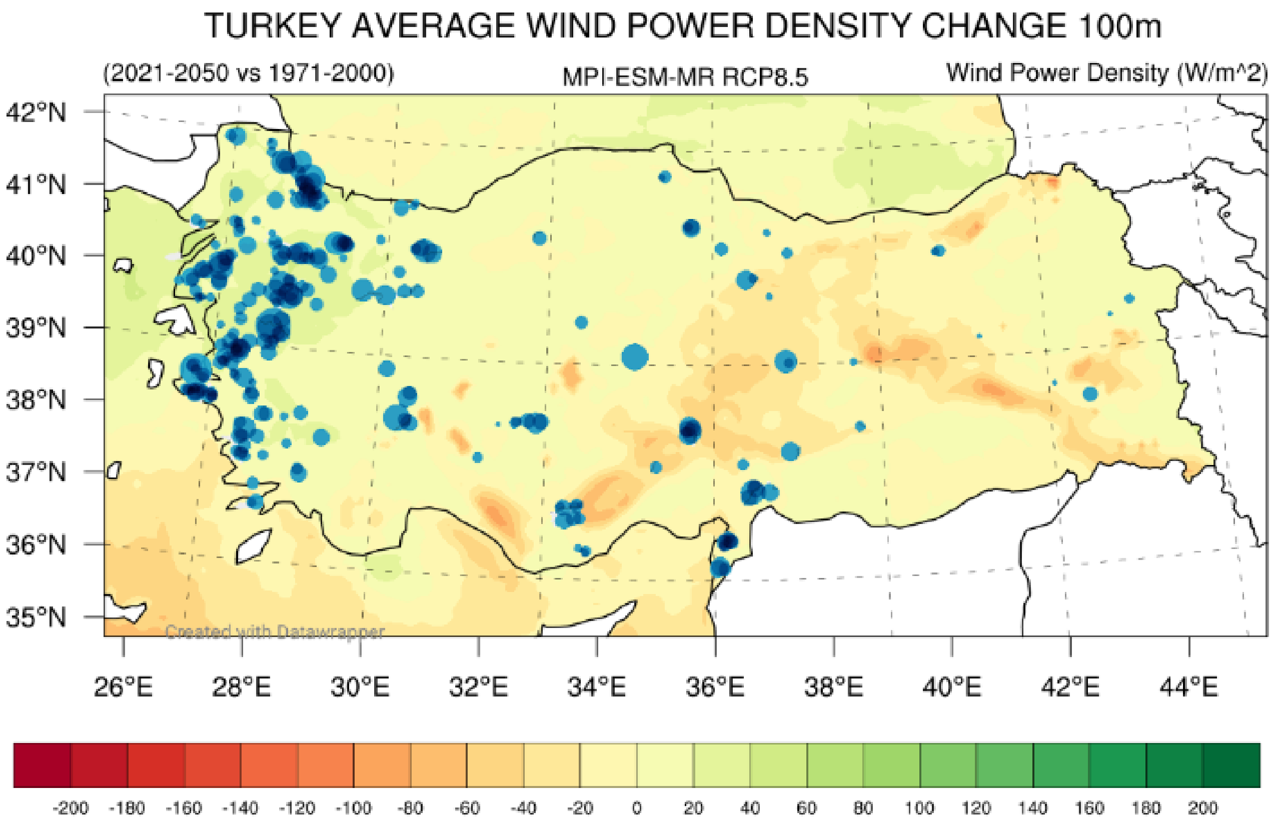

Figure 23. Projected Changes under RCP 8.5 scenario on Installed Wind Power Facilities in Turkey as of April 2023.

Figures 6.2 and 6.3 demonstrate how the model's projections for the 30-year WPD average under RCP 4.5 and RCP 8.5 scenarios will change on the currently operational wind power plant locations. The findings of the model indicate that the effects of climate change may cause the wind energy potential in some parts of the Mediterranean coast of Turkey to increase. Yet, it is seen that there is not any operational wind power facility in that part of the country. It is also seen that the energy potential in Marmara and Aegean regions will increase. The model's findings suggest that it's possible that the Marmara and Aegean regions' wind energy potential, which is expected to slightly increase in the future, may not be completely exploited by the currently installed power plants. In the same regions, monthly variations in the 30-month average may appear as an inability to utilize the potential for monthly wind energy generation or as less energy generated than projected. Even though similar circumstances are present in other areas, it is anticipated that the change in Marmara and Aegean regions will be of greater importance due to the high number of currently installed wind power plants in these regions. One important result for the wind turbines in these areas is also the fact that the average for the period 2021 to 2050 in this region won't decrease compared to the 1971-2000 reference period according to the model findings.

As indicated above, the results of the model indicate that climate change may change Turkey's wind energy potential, particularly monthly, as this is seen both visually and in the numbers above.

While in certain areas the potential difference on an annual basis is negligible, it is projected that the potential would increase in multiple locations along the Mediterranean coast. There aren't many wind power plants in these areas right now. This demonstrates that the potential in the area can be evaluated more precisely if the future wind potential is examined using climate change models.

Remarks and points derived from the results of this thesis, which used a 10kmx10km downscaled grid size of the MPI-ESM-MR GCM to estimate the WPD in Turkey for the 2021-2050 period under RCP 4.5 and RCP 8.5 scenarios, were given below. However, it should also be noted that both this model study and studies on climate modelling have some limitations. Ebinger & Vergara (2011) state that it may not be enough to simply analyze the average results of climate models to see the impact of climate change. Additionally, there isn't a measure in the climate model results that can indicate how climate change impacts the variables. The impact of climate change on the potential for wind energy cannot be completely observed through the analysis of the modelling results as wind is not a progressively changing climate data. Climate modelling studies aim to show the most probable scenario, with the information available in the current situation.

A more accurate result is always obtained when more GCMs are used together in climate modelling studies. However, due to limitations on the IklimBU servers from where I obtained the modelling data, only one GCM could be used for this study. When evaluating the results of this study, these limitations should also be considered. This project also aims to encourage studies regarding the impacts of climate change in Turkey on wind energy and other variable renewable resources like solar and hydropower.

Modelling the future impacts of climate change on wind energy has merit for an effective energy policy because ignoring these impacts may result in the following issues:

- The inability of the currently installed wind power plants to generate the planned amount of electricity due to decreasing energy potential in the future. Thus, having a reduced capacity factor for these plants as a result.
- The inability of the installed wind power plants to use the wind energy potential will increase in the future if the potential WPD exceed their installed power limits. Thus, not fully exploiting the available wind power potential.
- The intra-annual changes in the energy potential in the currently installed power plant sites, differing from the past trend, cause problems on the supply-demand side with the variability in electricity generation.

- Changes in the energy potential in the locations chosen for the new installations of wind power plants may have an adverse economic impact on the investment and result in inefficient operation of the plant.
- Locations, where the wind energy potential is measured not high enough to install a power plant, may have increasing wind energy potential in the future, resulting in not exploiting the potential in these areas.

The assumption that the data observed in the past will continue in the same pattern in the future for wind energy potential calculations is the primary cause of the problems mentioned above. Changes from historical data are identified in the studies that estimate and model the impact of climate change on wind energy. Studies using climate modelling are used to illustrate the scope and significance of such problems. Possible challenges will be discussed in this study along with how to address these issues through policy recommendations following the analysis of the climate model's results.

Together with the findings of this model study, it is crucial to consider how wind power plants are built in Turkey and learn the regulations to evaluate the wind energy potential of these areas to give more accurate policy recommendations. The regulations for installing a wind power facility in Turkey have been detailed in section 3.2. Apart from YEKA and facilities with storage capacity installations, wind speed measurements must be conducted for at least one year over the previous eight years to build a wind turbine in Turkey. In the past, the average WPD value had to be over 150 W/m2 according to these measurements, yet this requirement was changed in 2022 (Official Gazette, 2022d). The average generation of the wind turbine, which will be in use for roughly 20–30 years, was projected in accordance with the prior regulation, along with the wind measurement mast used in the location chosen for the wind power plant sites. The measured data was also used to determine the installed capacity of the wind turbines to be installed. This implies that future climate change-related changes in the power plant area were not taken into consideration. After the legislation change (Official Gazette, 2022d) on the 29th of December 2022, the minimum average 150 W/m2 requirements were also removed, and measurement requirements were excluded for YEKA and wind power facilities with storage facilities (Official Gazette, 2022b) meaning that the responsibility for the site selection for wind energy installations has been left to the investors.

In Turkey, wind speed and wind potential calculations in the region where the power plants are located are made using past observation data to acquire a license for power plant installations. REPA, a wind energy potential atlas created for Turkey, is also based on past measurements, ignoring possible climate change impacts in the future. It is very likely that the YEKA areas, which the state previously established, benefited from the REPA map to determine the locations, even though it is not explicitly stated how these areas are determined. It is obvious that future changes are not taken into consideration in the site selection for any wind power plant in Turkey since there is no wind energy potential modelling study in Turkey taking the impact of climate change into account.

Moreover, after the legislation change, even past wind speed data measurement requirement is not required for YEKA and wind energy facilities with storage which are expected to be more favourable in the future. The licensing of wind power plants without any assessment work on a highly variable energy source like wind energy may lead to some issues that will get worse as climate change impacts occur in the future.

The following policy recommendations might be helpful in addressing any issues that may develop according to the existing problems in regulations for wind energy in Turkey and the according to the results of this study examining the impact of climate change on wind energy in Turkey.

- Compared to the model used in this study, REPA can generate results that are significantly more accurate and detailed. However, REPA doesn't consider the future impacts of climate change on Turkey's wind energy potential, therefore the potentials of positive or negative change are not considered either. With the wind measuring mast obligation removed for YEKA and for the storage integrated facilities after the recent legislation change, REPA will be the most important source for determining the location of the wind turbine power plants to be built. In that regard, REPA needs to update Turkey's wind energy potential in a far more detailed and precise manner considering the future climate change impacts under different scenarios.
- The government should fund studies that investigate how climate change will affect renewable energy sources like wind, solar, and hydro, and how these changes may have an impact on the energy system in the future under the general concept of climate change adaptation. An important portion of Turkey's future energy demand is projected to be met by wind, according to the country's national energy plan (MENR, 2023). Therefore, initiatives to conduct research and development in this area are crucial to ensure energy security in the future.
- The absence of any measurement requirements for wind energy, during the licensing procedure, may result in improper utilization of the nation's potential and the incorrect placement of turbines. Encouraging and incentivizing investors to conduct wind energy potential studies that consider the impact of climate change is essential for this reason.

- Wind power plants to be given licenses are chosen from a huge number of applications through YEKA, YEKDEM, or storage power plant applications. The criteria for choosing projects over others while issuing the license are not clearly explicit except for YEKA. If a study on the potential impacts of climate change on wind energy in the related area would prioritize the projects during this choosing period, it would provide a strong incentive for investors to conduct research and development on the impact of climate change on wind energy on smaller scales.
- Batteries may decrease the fluctuation in the electricity supply to the grid when they are combined with intermittent renewable energy sources. While doing so, they can offer a balanced electricity output for a resource like wind, whose fluctuations are unpredictable. Power plants can minimize potential issues in the energy system by storing the electricity generated and hence delivering more balanced power to the grid, even though the fluctuation in generation increases with the effects of climate change. Incentives should be provided to encourage investors to install wind power facilities with storage capacity to achieve this.
- The hybrid power plant idea is another way to improve the balance of the electricity supplied to the grid, particularly for renewable energy sources. For example, even if the power plant produces less energy from the wind (usually during the hours when the sun shines), it can balance the lack of wind energy generation from a solar power plant integrated into the same facility, within the scope of its license. As a result, monthly variations caused by climate change can be minimized in the future.

The country's plans regarding other energy sources will be impacted by the future potential of wind, which will increase its share in energy generation in the future. The sources that will, in a way, replace the wind will be dependent on how much the wind will increase or decrease. This model's output indicates that climate change will have different levels of impact on Turkey's wind energy potential. I hope that this study leads the way for subsequent in-depth research studies that will analyze this effect in greater detail.

7. CONCLUSION

In conclusion, this thesis study examined the impact of climate change on wind energy potential in Turkey in two different scenarios. In both scenarios, Turkey 30-year average WPD change and location-based WPD changes throughout the country were found as a result. Thrace, Marmara and Aegean regions where the majority of wind power plants are located, seem to experience WPD increase in the future under both scenarios. Moreover, when analyzed monthly, there are increases and decreases for these locations and for the rest of the country. Especially monthly changes in both scenarios show that there could be fluctuations in WPD in the future monthly. This can create problems for Turkey as wind energy is projected to have an increasing share in supplying electricity according to the official energy plan published in 2023.

This study shows that changes in locations may impact both currently installed wind power plants and new wind energy installations. Currently installed wind power plants may experience decreased wind energy generation or increased wind energy generation in the future. Due to their currently installed capacity limit, they may not be able to exploit increasing wind energy potential in the area. When they also generate decreased wind energy generation in the future, it may adversely impact the supply-demand chain and it can result in reduced profit for investors. Ignoring the impact of climate change can also result in not investing in the areas with low WPD where WPD will increase in the future. Monthly WPD changes throughout the country also imply that projected fluctuations may create problems for energy supply-demand in the future. Anticipated problems above when ignoring the impact of climate change showed the importance of conducting this thesis.

According to the results of this thesis and the current situation of wind energy in Turkey, following policy recommendations are stated:

- REPA should update itself including the impact of climate change under different scenarios.
- R&D studies should be incentivized by the government about the impact of climate change on wind energy.
- Investors should be motivated to conduct R&D studies during the licensing procedure. One example incentive would be giving priority to the applications which conduct such impact studies in the power plant location.
- Enhancing battery technology is essential. Batteries play an important role for delivering electricity generated from wind energy to the system in a balanced way, as climate change

may cause wind unpredictability to increase in the future. The installation of batteries, which are quite expensive, should be encouraged.

- Another way to balance the electricity output is hybrid power plants. These plants may balance the electricity generated in the future even if the fluctuations increase due to climate change.

This thesis tried to show that climate change can affect the wind energy potential in Turkey in various ways. In Turkey, where the share of wind energy is planned to increase according to the national energy plan, the calculation of such potential effects is important for future energy security. Further research using more complex models with higher resolution, however, is necessary to understand this matter in more detail.

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APPENDIX A: FORMULAS AND THE CODE USED IN THIS STUDY ANALYSING THE GLOBAL CLIMATE MODEL RESULTS

The formulas and the code used in CDO software to analyze MPI-ESM-MR Historical 1971-2000 wind speed data results

#Wind Speed at 100M Calculation

```
cdo
aexpr,'ws100=ws*1.389495494373137637129985217353011622113046714491000204945628679
0' Turkey_MPI_dn_SRF.1971-2000_3hr_ws.nc Turkey_MPI_dn_SRF.1971-2000_3hr_ws100.nc
```

#Excluding the Wind Speed out of Cut-in-Cut-out range

```
cdo mul -gtc,3 Turkey_MPI_dn_SRF.1971-2000_3hr_ws100.nc -ltc,26
Turkey_MPI_dn_SRF.1971-2000_3hr_ws100.nc Turkey_MPI_dn_SRF.1971-
2000_3hr_ws100_masked.nc
cdo setctomiss,0 -mul Turkey_MPI_dn_SRF.1971-2000_3hr_ws100.nc
Turkey_MPI_dn_SRF.1971-2000_3hr_ws100_masked.nc Turkey_MPI_dn_SRF.1971-
2000_3hr_ws100_corrected.nc
```

#Wind Power Density Calculation

```
cdo aexpr,'wpd100=0.5*1.225*(ws100*ws100*ws100)' Turkey_MPI_dn_SRF.1971-
2000_3hr_ws100_corrected.nc Turkey_MPI_dn_SRF.1971-2000_3hr_wpd100_corrected.nc
```

#Average Wind Power Density Calculation

```
cdo timmean Turkey_MPI_dn_SRF.1971-2000_3hr_wpd100_corrected.nc MPIHist_1971-
2000_Avg.nc
```

#Seasonal and Monthly WPD Average Calculation

```
cdo -yseasmean Turkey_MPI_dn_SRF.1971-2000_3hr_wpd100_corrected.nc MPIHist_1971-2000_SeasAvg.nc
cdo -ymonmean Turkey_MPI_dn_SRF.1971-2000_3hr_wpd100_corrected.nc MPIHist_1971-2000_MonAvg.nc

cdo -splitseas MPIHist_1971-2000_SeasAvg.nc MPIHist_1971-2000_SeasAvg
cdo -splitmon MPIHist_1971-2000_MonAvg.nc MPIHist_1971-2000_MonAvg
```

The formulas and the code used in CDO software to analyze MPI-ESM-MR RCP 4.5 scenario 2021-2050 wind speed data results

#Wind Speed at 100M Calculation

cdo
aexpr,'ws100=ws*1.389495494373137637129985217353011622113046714491000204945628679
0' Turkey_MPI_45_dn_SRF.2021-2050_3hr_ws.nc Turkey_MPI_45_dn_SRF.2021-
2050_3hr_ws100.nc

#Excluding the Wind Speed out of Cut-in-Cut-out range

cdo mul -gtc,3 Turkey_MPI_45_dn_SRF.2021-2050_3hr_ws100.nc -ltc,26
Turkey_MPI_45_dn_SRF.2021-2050_3hr_ws100.nc Turkey_MPI_45_dn_SRF.2021-
2050_3hr_ws100_masked.nc

cdo setctomiss,0 -mul Turkey_MPI_45_dn_SRF.2021-2050_3hr_ws100.nc
Turkey_MPI_45_dn_SRF.2021-2050_3hr_ws100_masked.nc Turkey_MPI_45_dn_SRF.2021-
2050_3hr_ws100_corrected.nc

#Wind Power Density Calculation

cdo aexpr,'wpd100=0.5*1.225*(ws100*ws100*ws100)' Turkey_MPI_45_dn_SRF.2021-
2050_3hr_ws100_corrected.nc Turkey_MPI_45_dn_SRF.2021-2050_3hr_wpd100_corrected.nc

#Average Wind Power Density Calculation

cdo timmean Turkey_MPI_45_dn_SRF.2021-2050_3hr_wpd100_corrected.nc MPI45_2021-
2050_Avg.nc

#Seasonal and Monthly WPD Average Calculation

cdo -yseasmean Turkey_MPI_45_dn_SRF.2021-2050_3hr_wpd100_corrected.nc MPI45_2021-
2050_SeasAvg.nc

```
cdo -ymonmean Turkey_MPI_45_dn_SRF.2021-2050_3hr_wpd100_corrected.nc MPI45_2021-2050_MonAvg.nc

cdo -splitseas MPI45_2021-2050_SeasAvg.nc MPI45_2021-2050_SeasAvg
cdo -splitmon MPI45_2021-2050_MonAvg.nc MPI45_2021-2050_MonAvg
```

The formulas and the code used in CDO software to analyze MPI-ESM-MR RCP 8.5 scenario 2021-2050 wind speed data results

#Wind Speed at 100M Calculation

cdo
aexpr,'ws100=ws*1.38949549437313763712998521735301162211304671449100020494562867 9
0' Turkey_MPI_85_dn_SRF.2021-2050_3hr_ws.nc Turkey_MPI_85_dn_SRF.2021-
2050_3hr_ws100.nc

#Excluding the Wind Speed out of Cut-in-Cut-out range

cdo mul -gtc,3 Turkey_MPI_85_dn_SRF.2021-2050_3hr_ws100.nc -ltc,26
Turkey_MPI_85_dn_SRF.2021-2050_3hr_ws100.nc Turkey_MPI_85_dn_SRF.2021-
2050_3hr_ws100_masked.nc

cdo setctomiss,0 -mul Turkey_MPI_85_dn_SRF.2021-2050_3hr_ws100.nc
Turkey_MPI_85_dn_SRF.2021-2050_3hr_ws100_masked.nc Turkey_MPI_85_dn_SRF.2021-
2050_3hr_ws100_corrected.nc

#Wind Power Density Calculation

cdo aexpr,'wpd100=0.5*1.225*(ws100*ws100*ws100)' Turkey_MPI_85_dn_SRF.2021-
2050_3hr_ws100_corrected.nc Turkey_MPI_85_dn_SRF.2021-2050_3hr_wpd100_corrected.nc

#Average Wind Power Density Calculation

cdo timmean Turkey_MPI_85_dn_SRF.2021-2050_3hr_wpd100_corrected.nc MPI85_2021-
2050_Avg.nc

#Seasonal and Monthly WPD Average Calculation

cdo -yseasmean Turkey_MPI_85_dn_SRF.2021-2050_3hr_wpd100_corrected.nc MPI85_2021-
2050_SeasAvg.nc

```
cdo -ymonmean Turkey_MPI_85_dn_SRF.2021-2050_3hr_wpd100_corrected.nc MPI85_2021-2050_MonAvg.nc

cdo -splitseas MPI85_2021-2050_SeasAvg.nc MPI85_2021-2050_SeasAvg
cdo -splitmon MPI85_2021-2050_MonAvg.nc MPI85_2021-2050_MonAvg
```

The formulas and the code used in CDO software to analyze MPI-ESM-MR RCP 4.5, RCP 8.5 scenarios and historical data differences

#WPD Difference Calculation

cdo sub Turkey_MPI_45_dn_SRF.2021-2050_3hr_wpd100_corrected.nc Turkey_MPI_dn_SRF.1971-2000_3hr_wpd100_corrected.nc 45-Hist_dif_21-50.nc
cdo sub Turkey_MPI_85_dn_SRF.2021-2050_3hr_wpd100_corrected.nc Turkey_MPI_dn_SRF.1971-2000_3hr_wpd100_corrected.nc 85-Hist_dif_21-50.nc
cdo sub Turkey_MPI_85_dn_SRF.2021-2050_3hr_wpd100_corrected.nc Turkey_MPI_45_dn_SRF.2021-2050_3hr_wpd100_corrected.nc 85-45_dif_21-50.nc

 # Seasonal and Monthly WPD Average Calculation

#RCP 4.5 vs Hist

cdo timmean 45-Hist_dif_21-50.nc 45-Hist_dif_21-50avg.nc

cdo -yseasmean 45-Hist_dif_21-50.nc 45-Hist_dif_21-50_SeasAvg.nc
cdo -ymonmean 45-Hist_dif_21-50.nc 45-Hist_dif_21-50_MonAvg.nc

cdo -splitseas 45-Hist_dif_21-50_SeasAvg.nc 45-Hist_dif_21-50_SeasAv
cdo -splitmon 45-Hist_dif_21-50_MonAvg.nc 45-Hist_dif_21-50_MonAvg

#RCP 8.5 vs Hist

cdo timmean 85-Hist_dif_21-50.nc 85-Hist_dif-21-50avg.nc

cdo -yseasmean 85-Hist_dif_21-50.nc 85-Hist_dif_21-50_SeasAvg.nc
cdo -ymonmean 85-Hist_dif_21-50.nc 85-Hist_dif_21-50_MonAvg.nc

cdo -splitseas 85-Hist_dif_21-50_SeasAvg.nc 85-Hist_dif_21-50_SeasAv
cdo -splitmon 85-Hist_dif_21-50_MonAvg.nc 85-Hist_dif_21-50_MonAvg

#RCP 8.5 vs RCP 4.5

```
cdo timmean 85-45_dif_21-50.nc 85-45_dif_21-50avg.nc

cdo -yseasmean 85-45_dif_21-50.nc 85-45_dif_21-50_SeasAvg.nc
cdo -ymonmean 85-45_dif_21-50.nc 85-45_dif_21-50_MonAvg.nc

cdo -splitseas 85-45_dif_21-50_SeasAvg.nc 85-45_dif_21-50_SeasAvg
cdo -splitmon 85-45_dif_21-50_MonAvg.nc 85-45_dif_21-50_MonAvg
```

APPENDIX B: 30-YEAR-AVERAGE ANNUAL, SEASONAL AND MONTHLY WPD AT 100M MAPS OF HISTORICAL, RCP 4.5 AND RCP 8.5 DATA

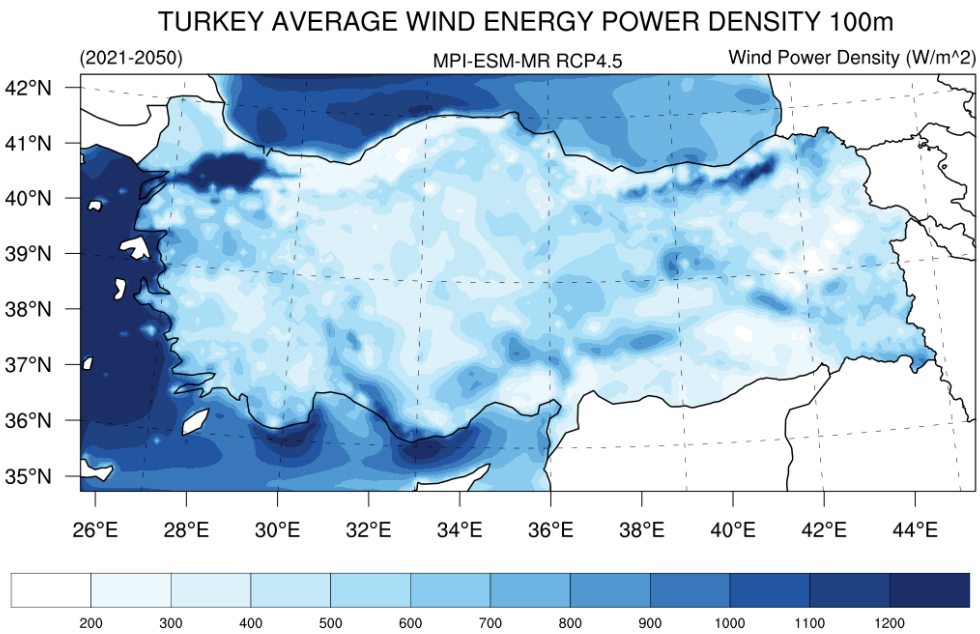

Figure B.1. Turkey Average Wind Power Density 100m RCP 4.5 Results (2021-2050).

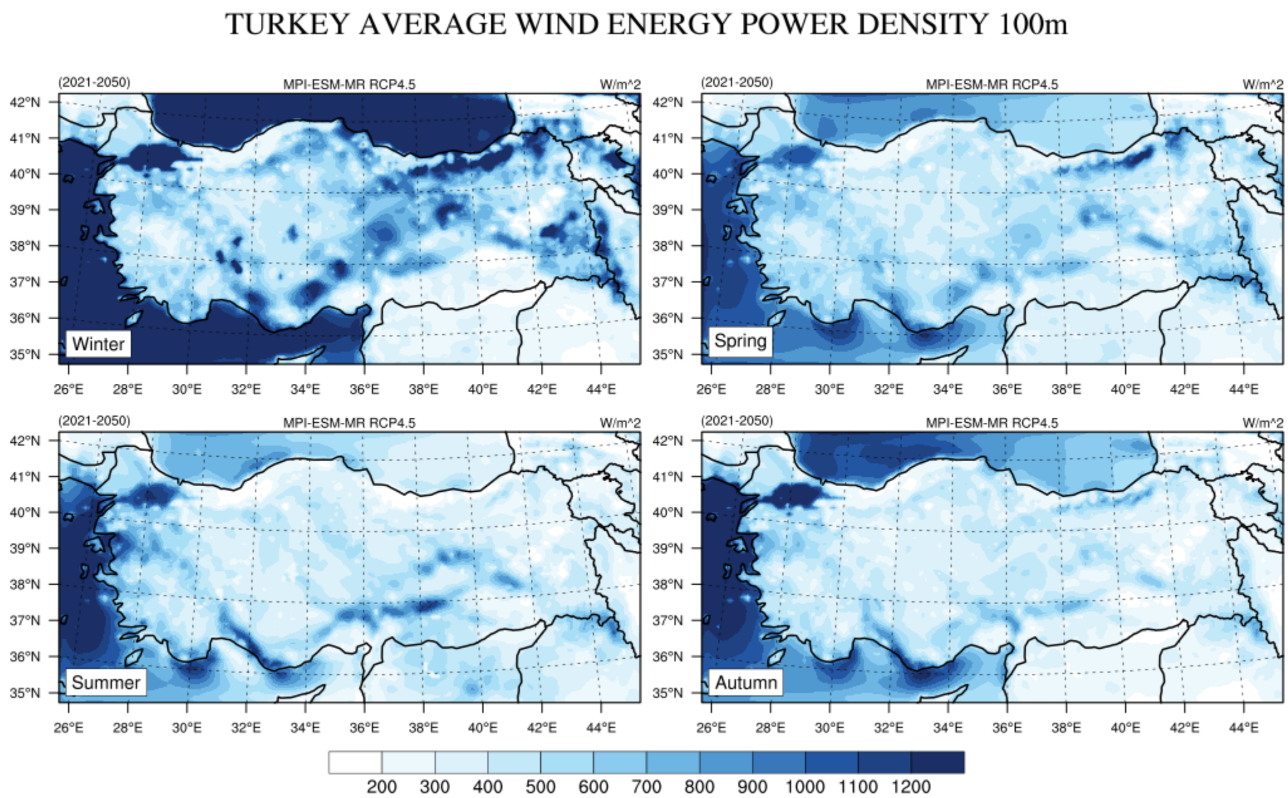

Figure B.2. Turkey Seasonal Average Wind Power Density 100m RCP 4.5 Results (2021-2050).

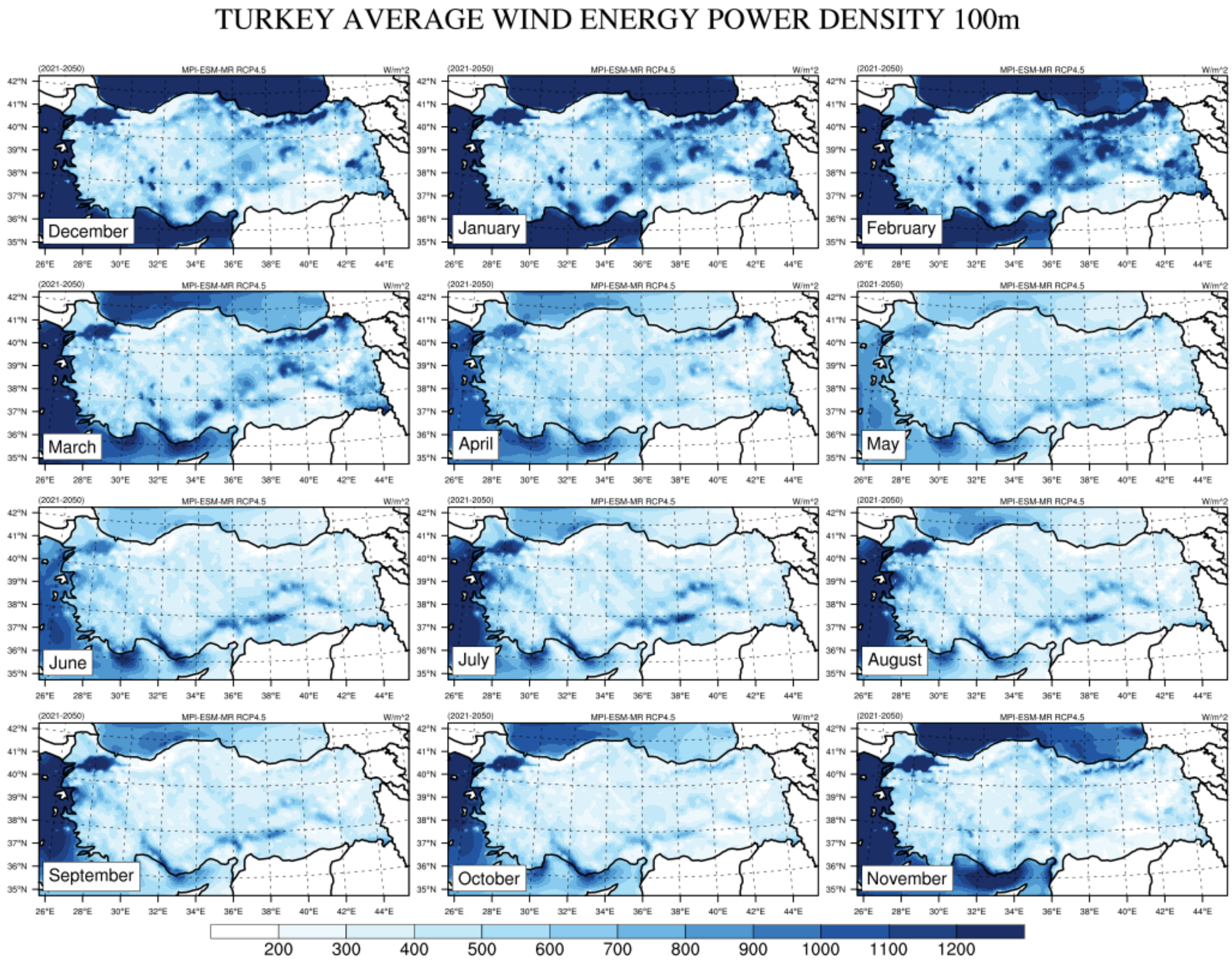

Figure B.3. Turkey Monthly Average Wind Power Density 100m RCP 4.5 Results (2021-2050).

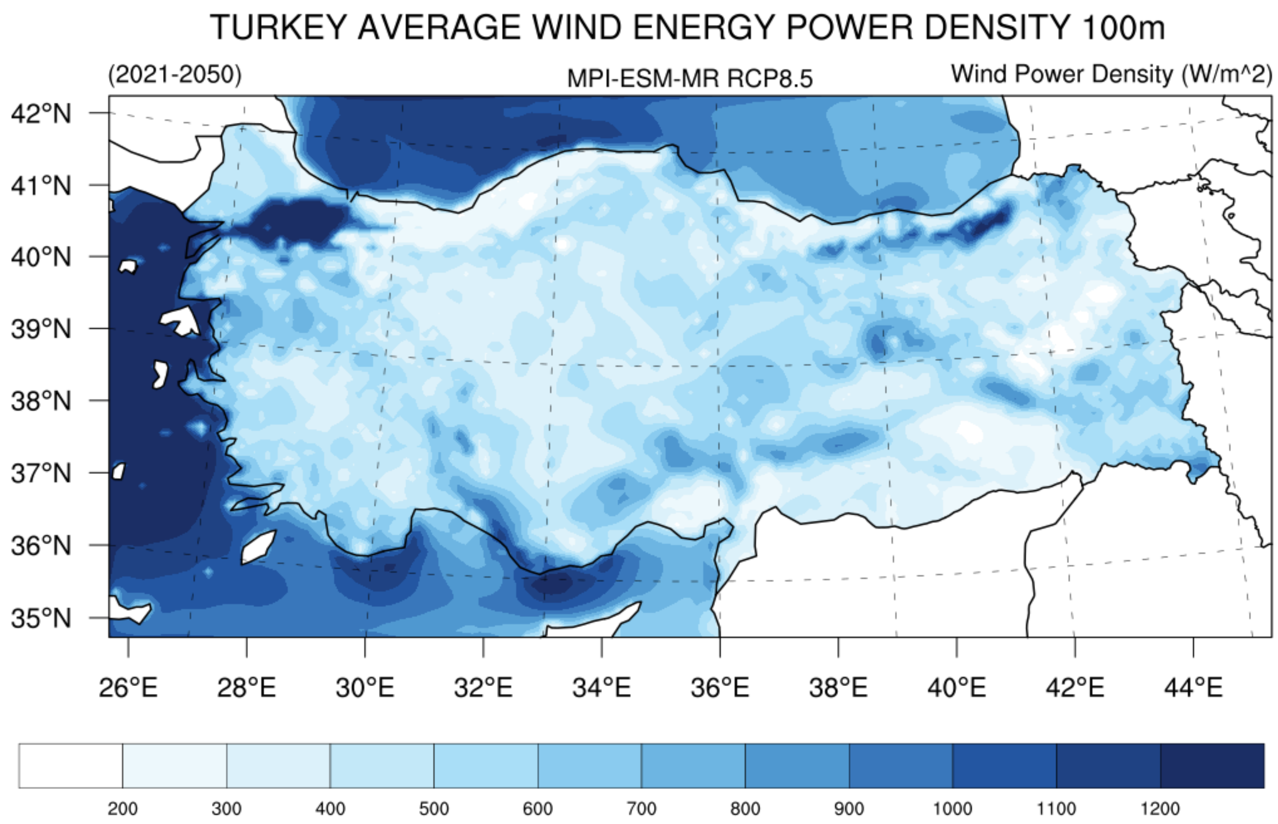

Figure B.4. Turkey Average Wind Power Density 100m RCP 8.5 Results (2021-2050).

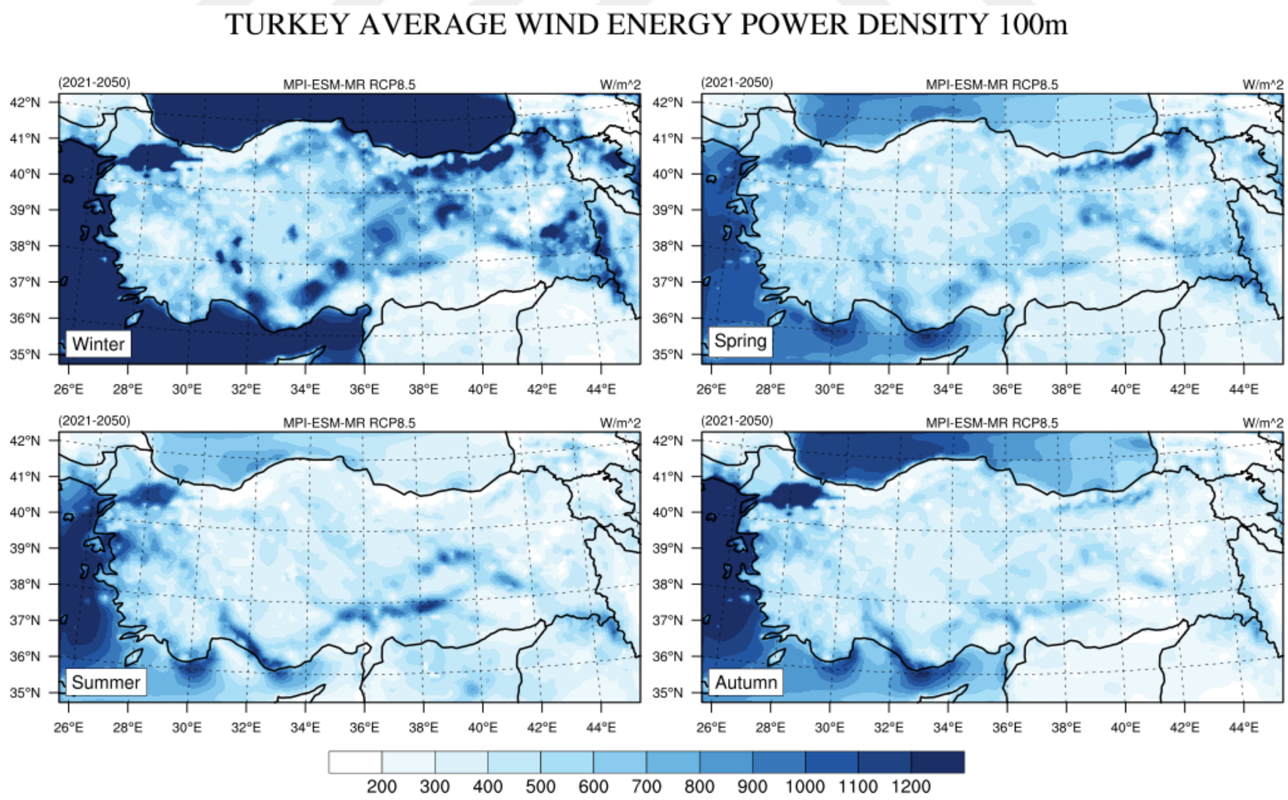

Figure B.5. Turkey Seasonal Average Wind Power Density 100m RCP 8.5 Results (2021-2050).

TURKEY AVERAGE WIND ENERGY POWER DENSITY 100m

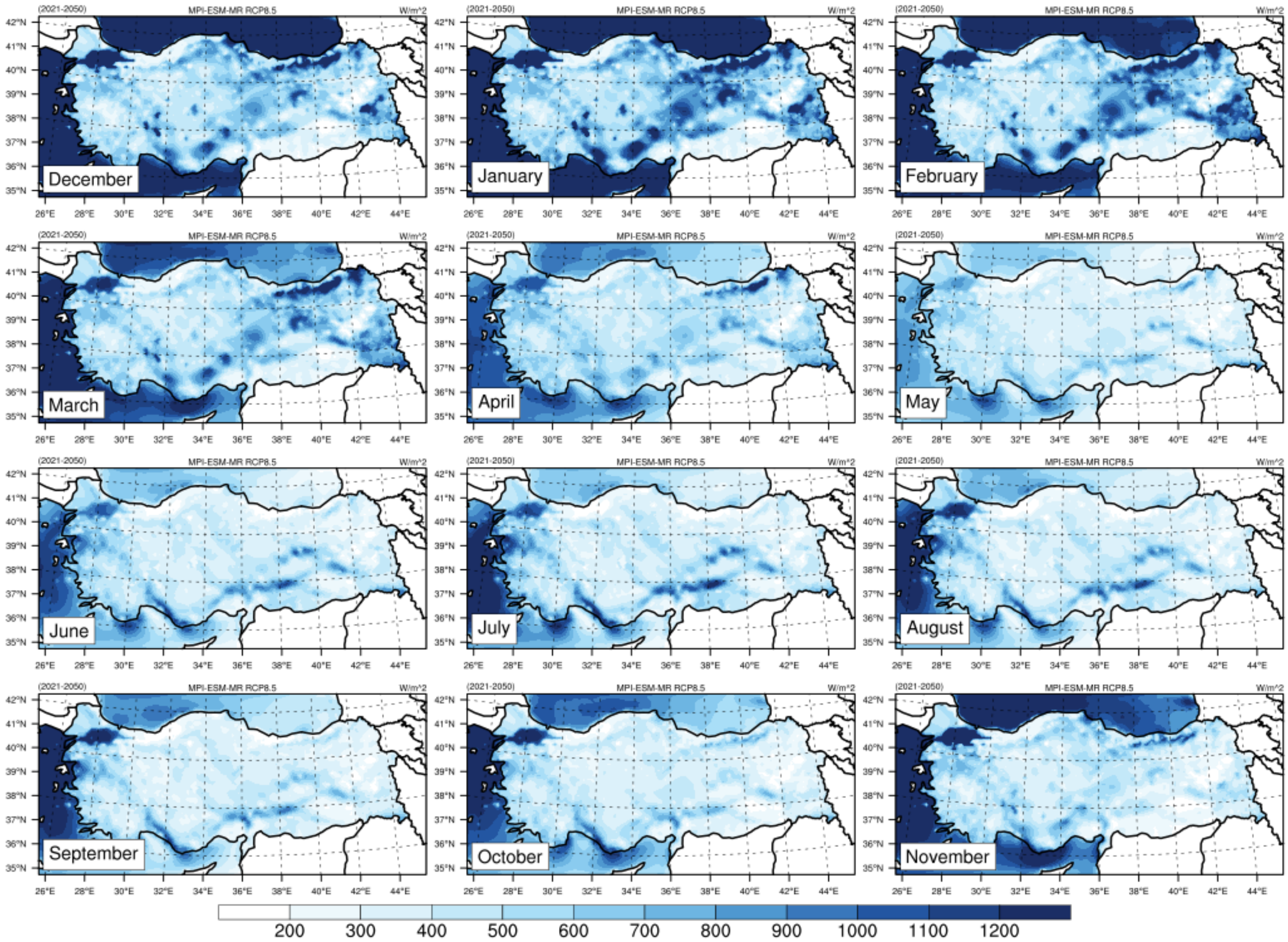

Figure B.6. Turkey Monthly Average Wind Power Density 100m RCP 8.5 Results (2021-2050).

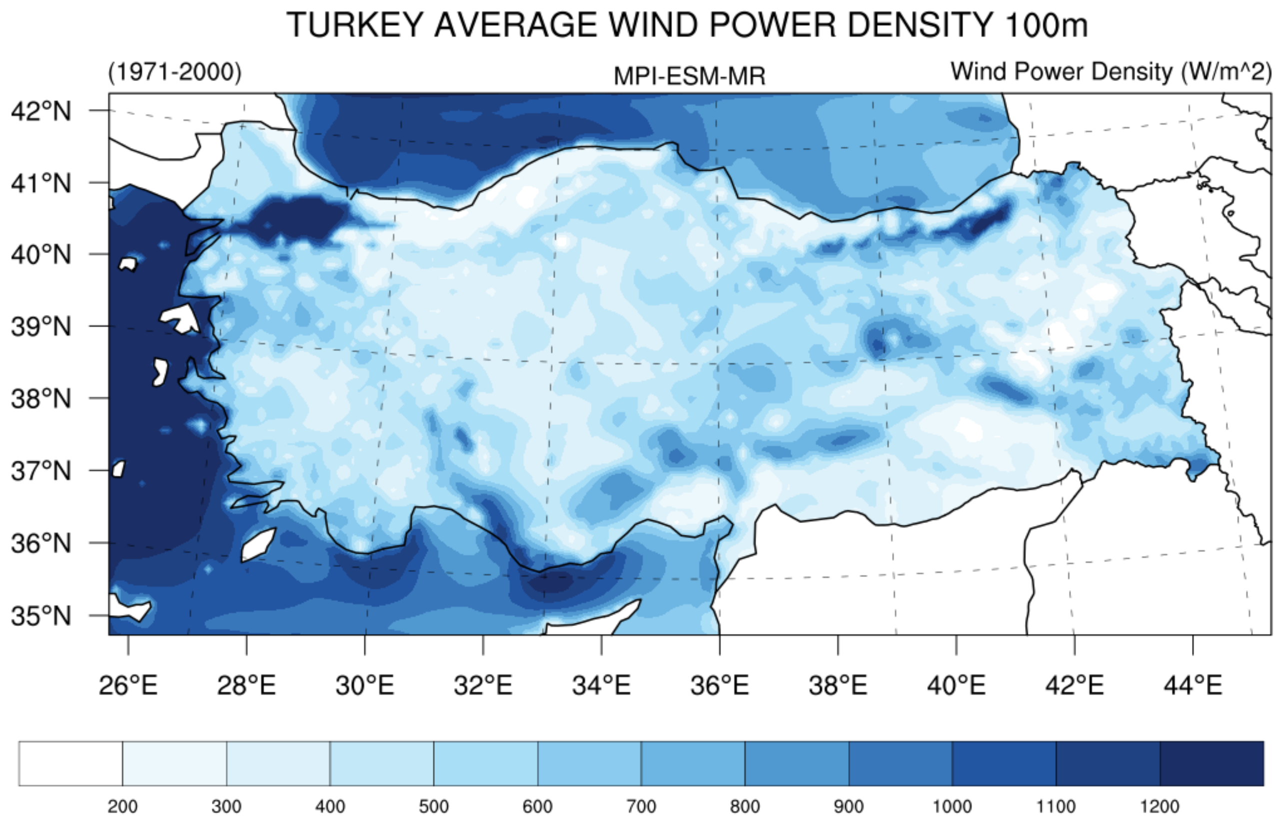

Figure B.7. Turkey Average Wind Power Density 100m Historical Data Results (1971-2000).

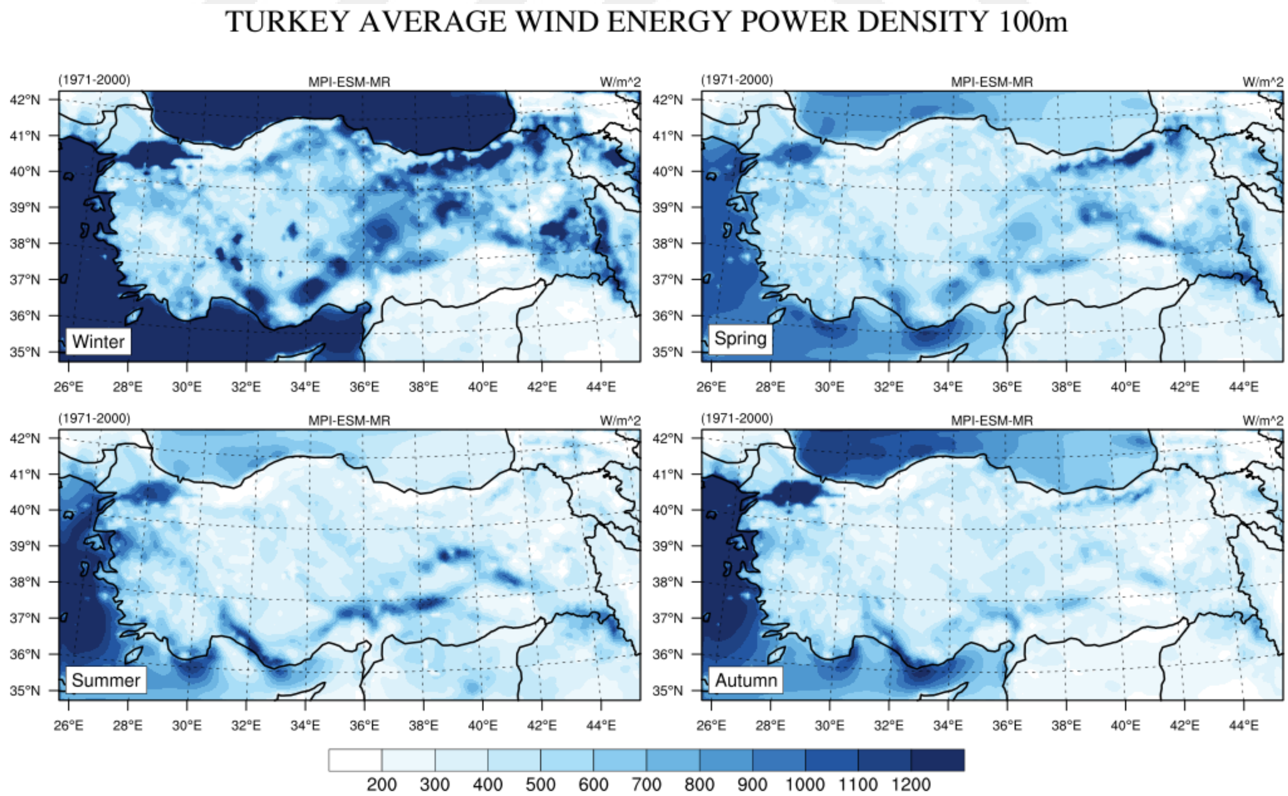

Figure B.8. Turkey Seasonal Average Wind Power Density 100m Historical Data Results (1971-2000).

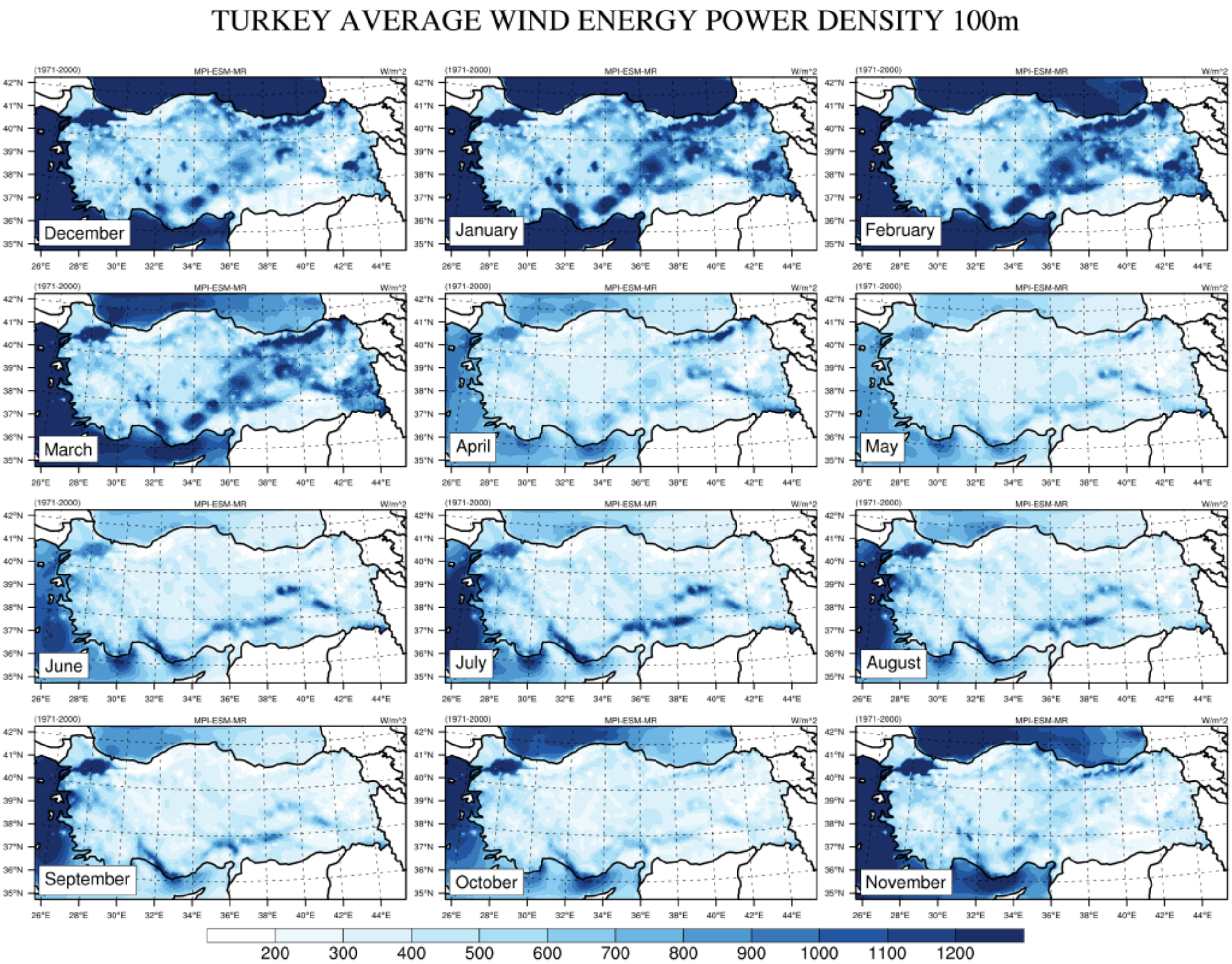

Figure B.9. Turkey Monthly Average Wind Power Density 100m Historical Data Results (1971-2000).

APPENDIX C: 30-YEAR-AVERAGE ANNUAL, SEASONAL AND MONTHLY WPD AT 100M MAPS OF HISTORICAL, RCP 4.5 AND RCP 8.5 DATA DIFFERENCES

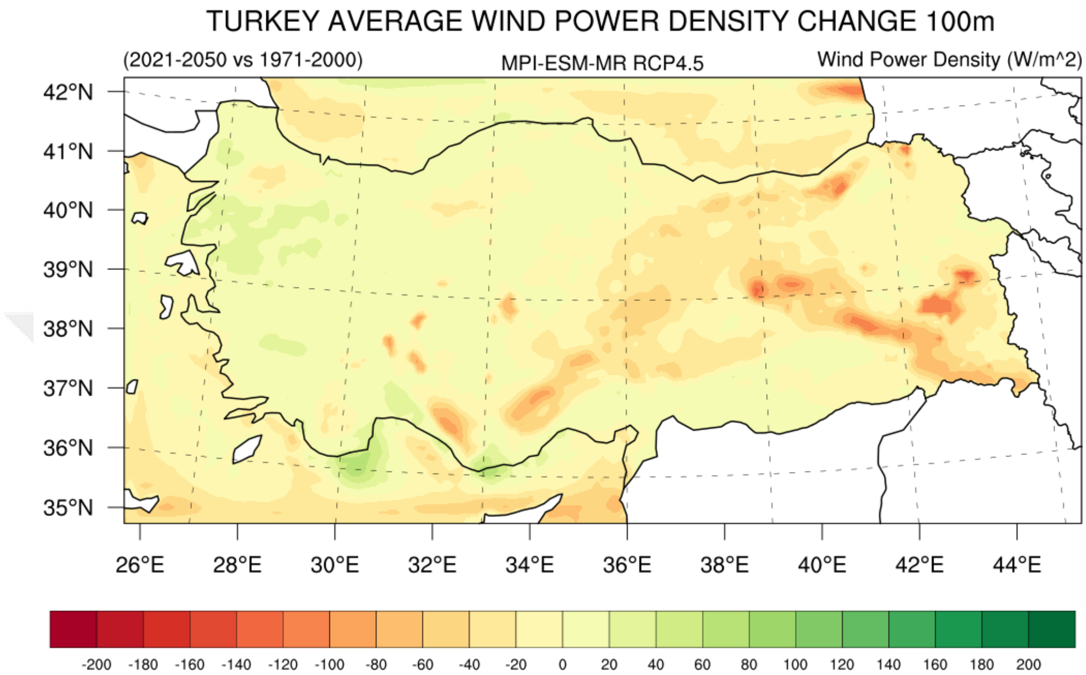

Figure C.1. Turkey Average Wind Power Density Change 100m RCP4.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

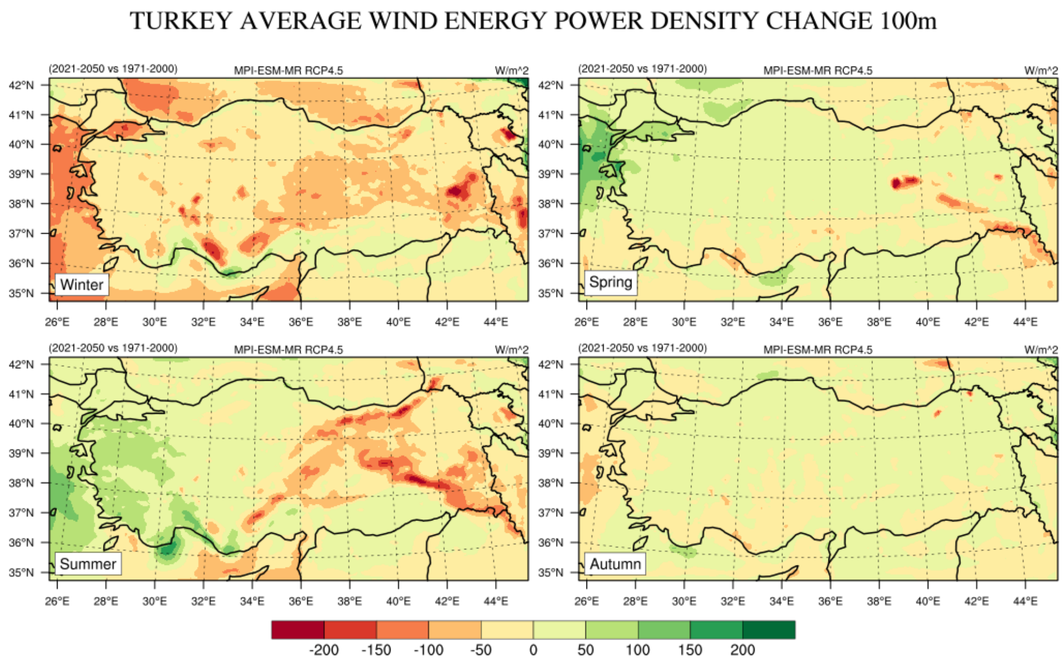

Figure C.2. Turkey Seasonal Average Wind Power Density Change 100m RCP4.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

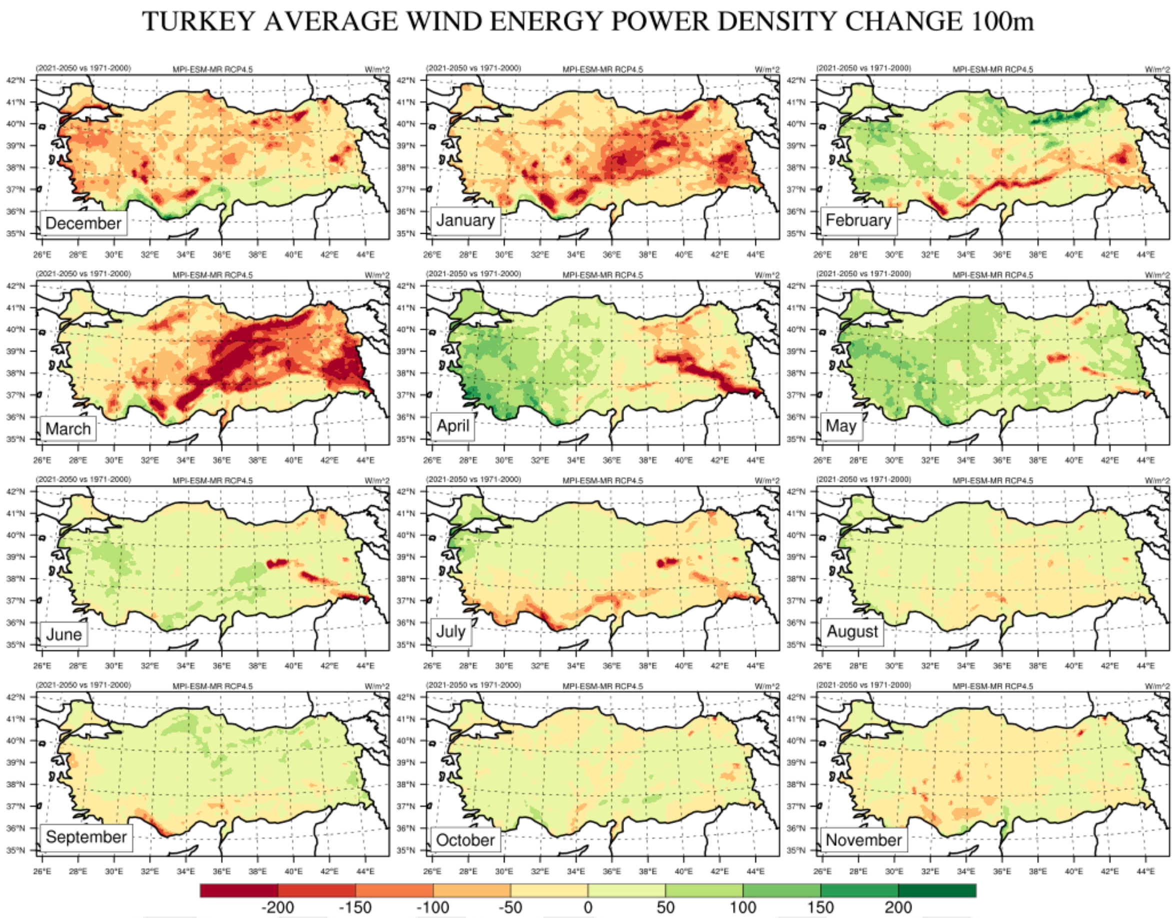

Figure C.3 Turkey Monthly Average Wind Power Density Change 100m RCP4.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

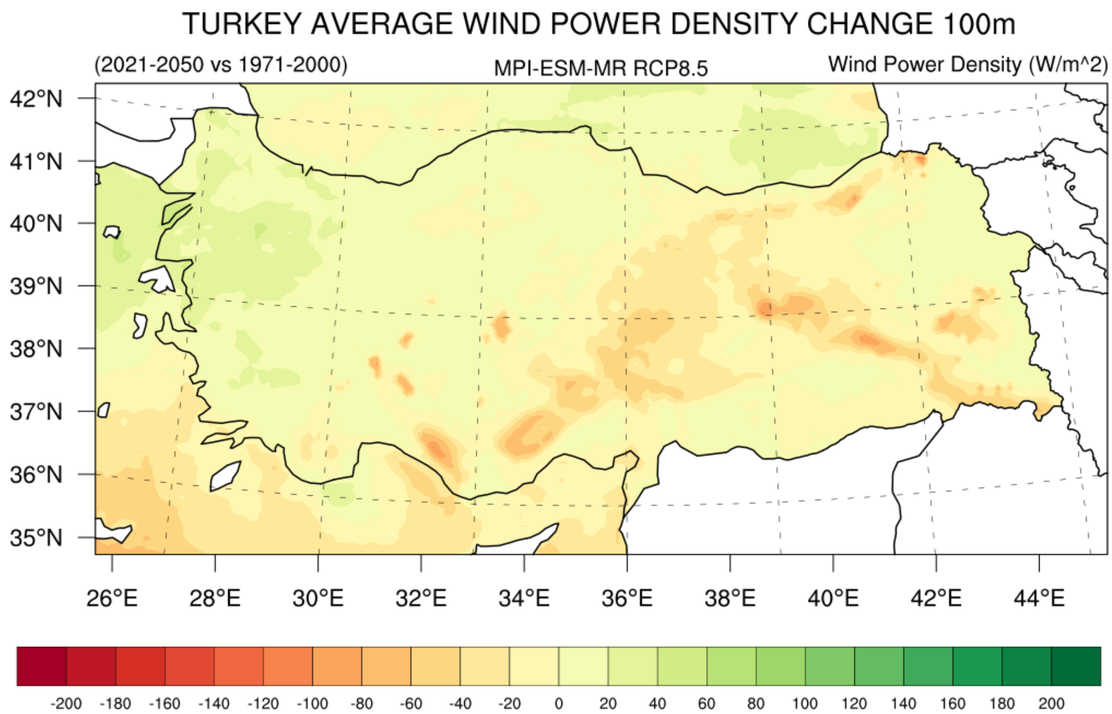

Figure C.4. Turkey Average Wind Power Density Change 100m RCP8.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

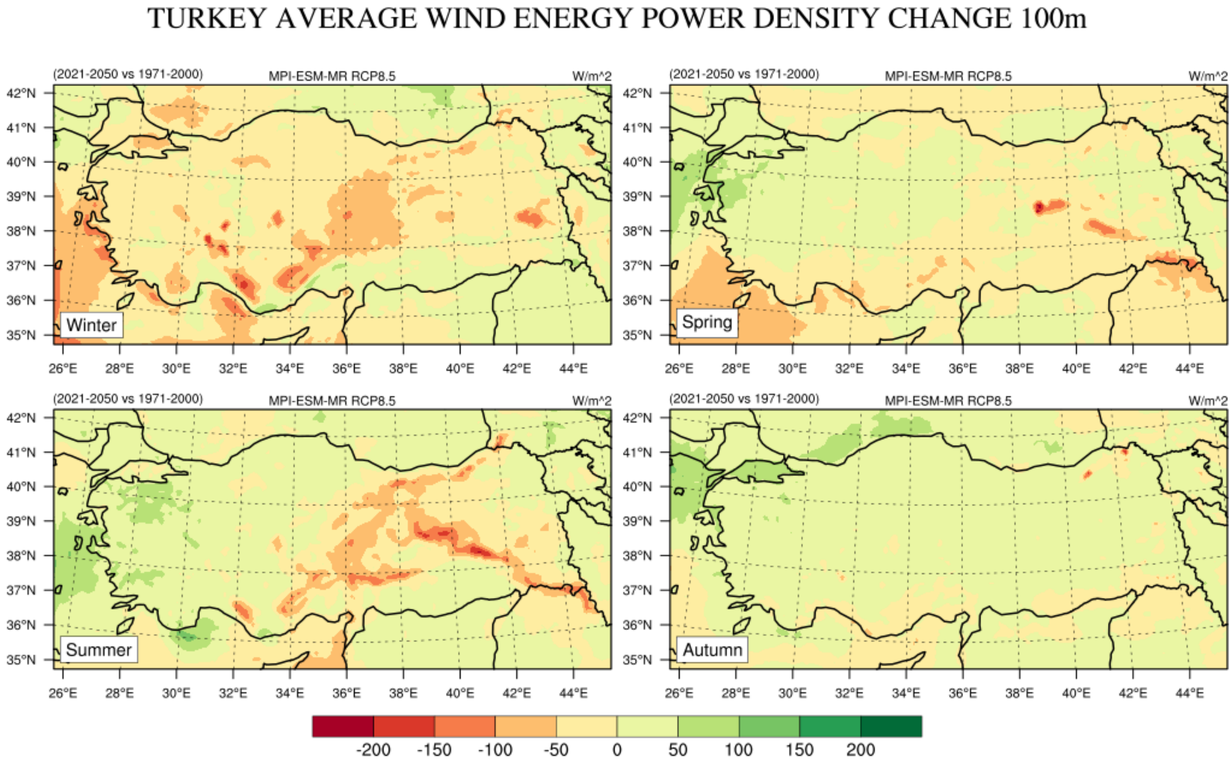

Figure C.5. Turkey Seasonal Average Wind Power Density Change 100m RCP8.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

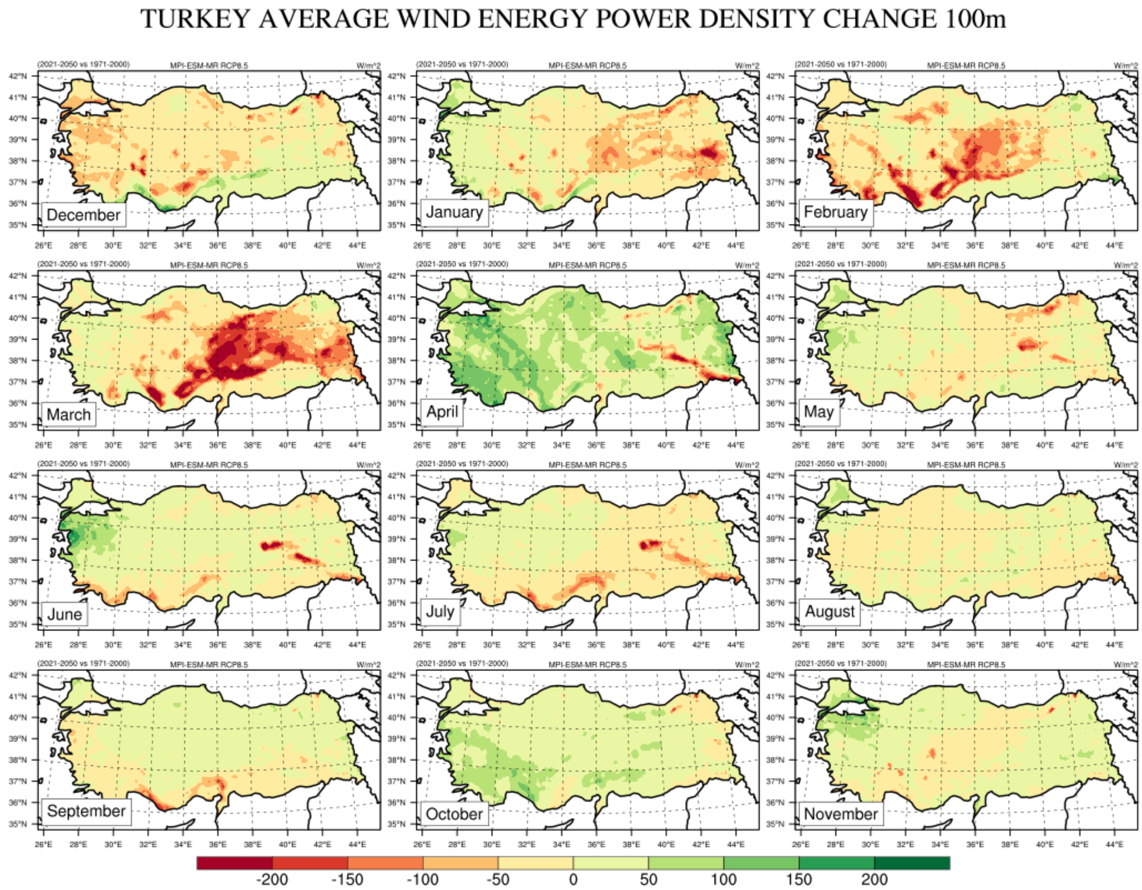

Figure C.6. Turkey Monthly Average Wind Power Density Change 100m RCP8.5 Scenario vs Historical Data Results (2021-2050 vs 1971-2000).

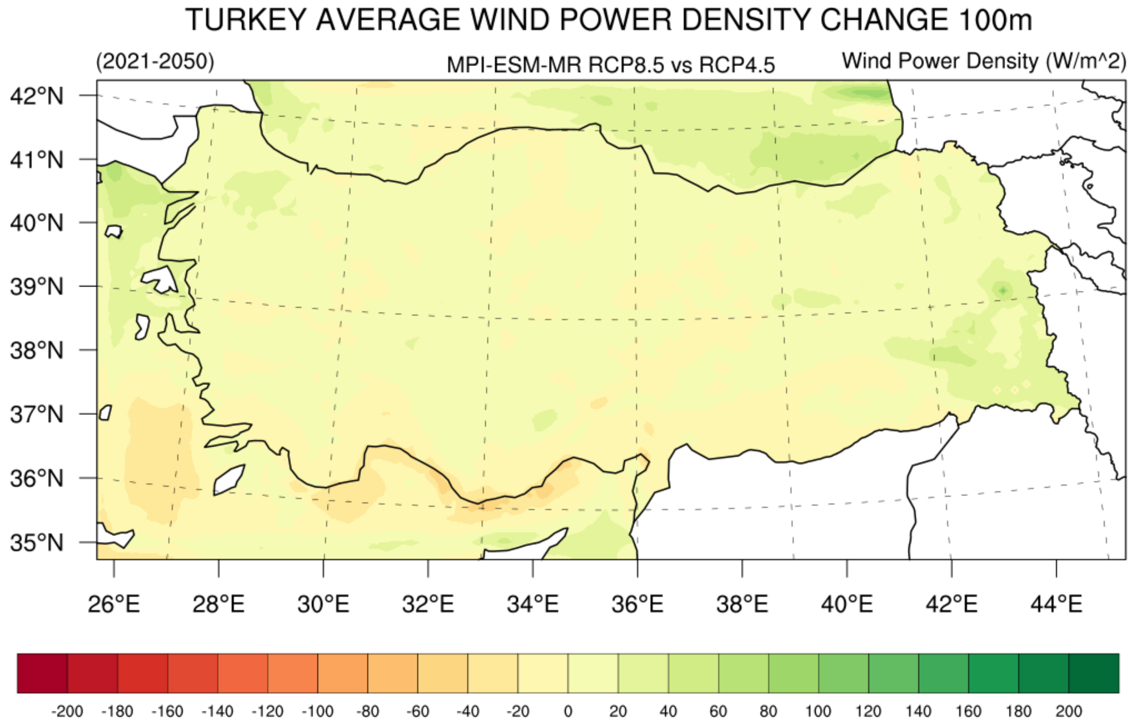

Figure C.7. Turkey Average Wind Power Density Change 100m RCP8.5 Scenario vs RCP4.5 Scenario Data Results (2021-2050)

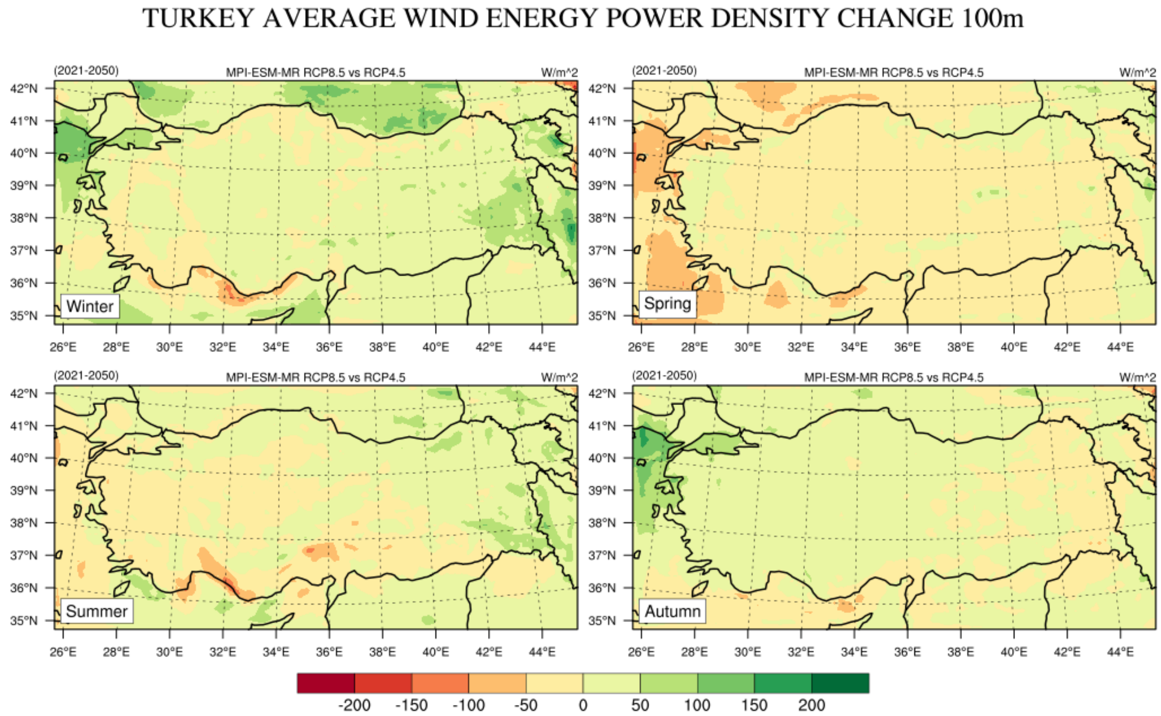

Figure C.8. Turkey Seasonal Average Wind Power Density Change 100m RCP8.5 Scenario vs RCP4.5 Scenario Data Results (2021-2050).

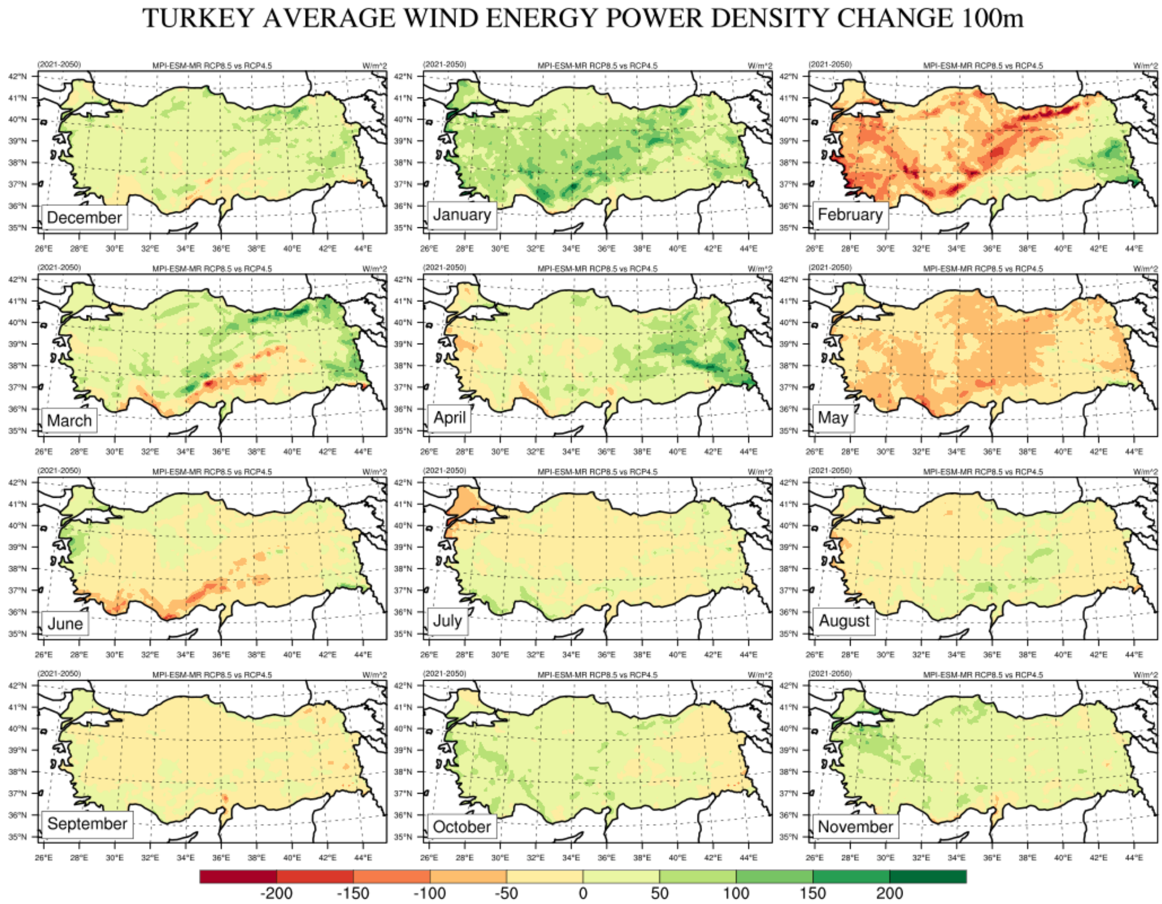

Figure C.9. Turkey Monthly Average Wind Power Density Change 100m RCP8.5 Scenario vs RCP4.5 Scenario Data Results (2021-2050).