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CAPACITY NEEDS FOR CARBON FIBER PRODUCTION IN TÜRKIYE CONSIDERING FUTURE DEMAND FOR OFFSHORE WIND TURBINES

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Abstract

This paper aims to forecast the demand for offshore wind turbines to be in-stalled in Europe and to analyses carbon fiber production capacity for wind turbines in Türkiye between 2023-2027. In the coming years, it is inevitable that Türkiye will need to increase capacity in order to meet the carbon fiber demand resulting from the increase in offshore wind turbine demand in Europe and to reduce dependency on China in terms of carbon fiber demand. Based on this requirement; the first step in this study is the calculation of the wind turbine demand that will be installed in Europe and the second step is determining the capacity requirements of carbon fiber production. This study contributes to be able to strengthen our country's position in the wind energy sector and increase carbon fiber production capacity.

Keywords: Offshore Wind Turbines, Sustainability, Demand Forecasting, Capacity Analysis.
Jel Codes: Q21, Q42, Q56, P28, C53, E22.

AVRUPA'DA AÇIK DENİZ RÜZGAR TÜRBİNLERİ TALEP TAHMİNİNE GÖRE TÜRKİYE'DE KARBON ELYAF ÜRETİMİ İÇİN KAPASİTE ANALİZİ

Özet

Bu çalışma, 2023-2027 yılları arasında Avrupa'da kurulacak açık deniz rüzgar türbinlerine olan talebi tahmin ederek Türkiye'de rüzgar türbinleri için karbon elyaf üretim kapasitesini analiz etmeyi amaçlamaktadır. Önümüzdeki yıllarda, Avrupa'da açık deniz rüzgar türbini talebindeki artıştan kaynaklanan karbon elyaf talebini karşılamak ve karbon elyaf talebi açısından Çin'e olan bağımlılığı azaltmak için Türkiye'nin kapasite artırımına gitmesi kaçınılmazdır. Bu gereklilikten yola çıkarak; bu çalışmada ilk adım Avrupa'da kurulacak rüzgar türbini talebinin hesaplanması, ikinci adım ise karbon elyaf üretimi kapasite gereksinimlerinin belirlenmesidir. Bu çalışma, ülkemizin rüzgar enerjisi sektöründeki konumunu güçlendirebilmesine ve karbon elyaf üretim kapasitesini artırabilmesine katkı sağlamaktadır.

Anahtar Kelimeler: Açık Deniz Rüzgar Türbinleri, Sürdürülebilirlik, Talep Tahmini, Kapasite Analizi

Jel Kodları: Q21, Q42, Q56, P28, C53, E22.

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1. INTRODUCTION

Wind energy has the potential to make a significant contribution to reduce greenhouse gas emissions and meet a large share of global electricity demand as a renewable energy source. On today's statistics, the demand for wind generated energy is increasing day by day and it already meets 15% of Europe's electricity demand, moreover there exist 300,000 people work in this sector, contributes 36 billion Euros to the EU GDP and 8 billion Euros are exported to non-EU countries (WindEurope, 2023a, p.5).

According to industry reports, wind capacity in Europe is 255 GW (Gigawatt). See Figure 1 for electricity generation by technology in the EU. Furthermore, 129 GW of new wind farms are expected to be installed in 2023-2027. To reach the target of 440 GW of installed wind power capacity, the EU needs to build over 30 GW of new wind farms per year (Costanzo et al., 2022, p.7). To support this development, the European Commission has introduced legislation and guidelines to facilitate the permitting of wind energy projects.

The EU Commission mapped out a new EU energy policy which is called RePowerEU. They aim to reduce greenhouse gas emissions by 55% by 2030. According to the commission report, a total of 453 GW (374 GW onshore and 79 GW offshore) of wind power capacity is needed by 2030 (REPowerEU Plan, 2022, p.2).

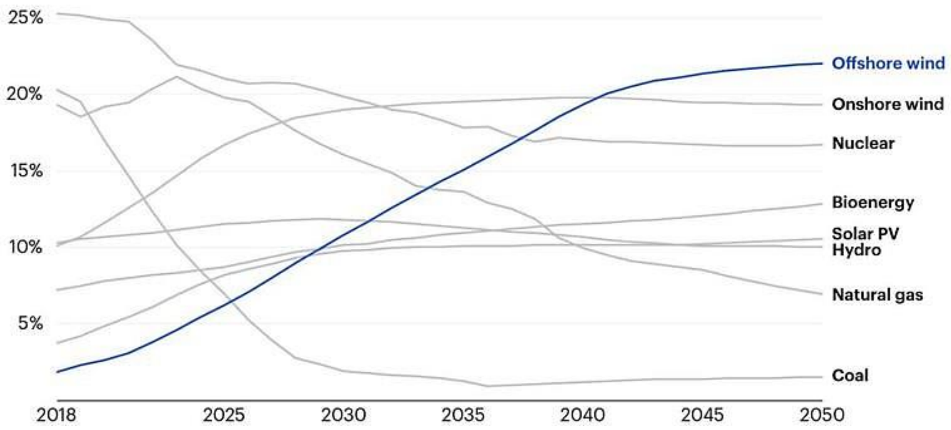

Figure 1. Electricity generation by technology in the EU (Musial et al., 2023, p.54).

As the wind energy sector grows rapidly in the world and could become the largest new power source producing cost-effective zero-emission electricity, capabilities of energy conversion strategies of countries and developments in the world clearly reveal the need for offshore wind turbines. Offshore wind farms are a source of renewable energy that creates jobs and emits no environmental pollutants or greenhouse gases. Capacity factors are higher due to higher wind speeds and the directional consistency of the wind. In this way, the same amount of energy can be produced as onshore wind power plants with fewer offshore turbine installations. Figure 2 shows offshore and onshore installed capacity over the years.

Offshore markets across the world are emerging rapidly. According to the International Energy Agency (IEA), offshore wind has the potential to become Europe's best source of energy production and this target can be achieved by 2042 (Freeman et al., 2019, p.7).

Larger turbines produce more power. To produce a given amount of electricity, it is less costly to have a few large turbines rather than a few smaller turbines. This means less space occupation, material use, and maintenance. Economically, it amortizes its cost much faster.

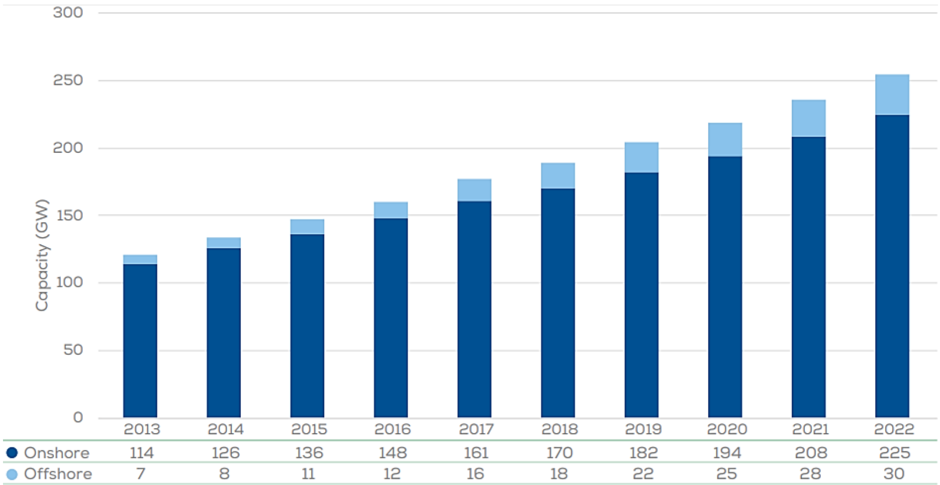

Figure 2. Installed wind power capacity in Europe (Costanzo et al., 2022, p.29).

Regarding this issue, the blade length of the wind turbines in offshore turbines is getting longer and the amount of materials used is also increasing (Nixon-Pearson et al., 2022, p.12). The amount of increase in the coming years, the required capacities, and appropriate strategies should be discussed. To benefit from offshore wind energy, it is important to satisfy the potential demand.

There is a carrier beam made of composite material called a "spar cap" on the blades of the turbines. CFRP (Carbon fiber reinforced polymers) pultrusion laminates are used in these spar caps and one of the raw materials of them is carbon fiber which is an important material for the aviation, automotive, and wind energy sectors. Carbon fiber can be produced by very few countries nowadays, so the production of it is a high added value.

Carbon fiber is already a proven technology that supports technological developments for turbine manufacturers. Thanks to the high strength and low density of carbon fiber, lighter and thinner blades can be produced for wind turbines. The lighter weight of the turbine blades enables the entire system to become lighter. Therefore, the use of fewer durable materials and less carbon emissions becomes possible. Wind turbine blades in offshore wind systems benefit from the superior properties of carbon fiber and will continue.

The leading companies in the sector have also focused on the use of carbon fiber in recent years and the demand for carbon fiber in the wind sector is expected to increase like other sectors. Resources estimate that 81,000 wind turbine blades will be produced by 2019 and that the carbon fiber usage rate will be 6% for each blade. Based on the International Energy Agency report, wind energy may be Europe's first energy source by 2027 and has critical importance for the 2040 carbon-neutral targets (IEA, 2022, p.10).

Due to the limited number of carbon fiber manufacturers in Türkiye, increasing production capacity to meet the demand for offshore wind turbines in the coming years is becoming very important. This opportunity will reduce our country's dependence on China in terms of carbon fiber production and will be beneficial for a sustainable future.

In this context; the main contribution of this study is the presentation of demand forecasts for offshore wind turbines that can be installed in Europe for the next 4,5 years and scenarios for the required carbon fiber production capacity (tone/year) in Türkiye corresponding to these forecasts. These scenarios consider the carbon fiber volume fraction of the composite plate and how much of the wind turbine blade by weight is formed with carbon plate. The information provided by this study is important for our country to be competitive and sustainable in the offshore wind turbine market and to be prepared to increase production capacity to reduce external dependency on carbon fiber to be used in these turbines. In the next section, the methodology followed in this study is presented and the section 3 concludes the paper and gives the recommendations.

2. METHODOLOGY

This study complied with research and publication ethics. The methodology is structured to forecast the demand for offshore wind turbines to be installed in Europe in the coming years and to reveal the need for carbon fiber capacity for wind turbines. The first subtitle of this section answers that how much installed wind turbine demand there will be in Europe. At the second subtitle the carbon fiber amount to satisfy the forecasted installed wind turbine found at the first subtitle was calculated. Finally, meeting the carbon fiber demand to a certain extent from Türkiye, considering global sustainability targets, the capacity analysis for the production of carbon fiber was made.

2.1 Forecasting of Offshore Wind Turbine Demand in Europe

In this study, we aim to make a demand forecast for the next 4.5 years in Europe from 2023 to 2027 by using installed offshore wind turbines in MW (Megawatt) - half yearly data from previous years (GWEC, 2023, p.7) (see Table 1).

Table 1. Installed offshore wind turbines in MW-half yearly.

Period	Installed Turbine (MW)-Half yearly	Period	Installed Turbine (MW)-Half yearly
2007-H1	157	2016-H1	811
2007-H2	161	2016-H2	752
2008-H1	195	2017-H1	
2008-H2	178	2017-H2	1602
2009-H1	214	2018-H1	1120
2009-H2	368	2018-H2	1537
2010-H1	425	2019-H1	1927
2010-H2	463	2019-H2	1720
2011-H1	348	2020-H1	1172
2011-H2	535	2020-H2	1745
2012-H1	756	2021-H1	1343
2012-H2	412	2021-H2	1449
2013-H1		2022-H1	
2013-H2		2022-H2	1950
2014-H1	781	2023-H1	2144
2014-H2	696		
2015-H1			
2015-H2	1481		

In this study; Trend analysis and ARIMA models are applied and compared to each other. Among the short-term forecasting approaches, ARIMA is the most basic model which can only perform well on stationary time series. However, time-series, like offshore wind tribunes, have features of seasonality and trend. The Trend analysis is additionally employed in order to obtain trend equation. Minitab program is used for all statistical analysis. MAPE values are examined as performance measurement parameters. Analysis results for each analysis type (Trend and ARIMA) are evaluated individually. After this; the demand forecast model for offshore wind tribunes that gives the best results is determined and its outputs are recorded to be used for capacity analyses for the production of carbon fiber in Türkiye using the sustainability perspective in section 2.2 and 2.3.

2.1.1 Data Pre-Preparation and Transformation

The 33 half-yearly data reported between 2007-2023 on installed turbines are considered (see Table 1). The data of turbines currently under construction and turbines whose installation has been completed but has not been connected to the grid are not included in the calculation. Offshore turbine orders in 2022 averaged 12.2 in MW. The expectation is that these values will increase starting from 2023 because more powerful turbines are expected to enter the market.

In this study, before proceeding to time series analysis, it is investigated whether there are any missing observations in the series. The five missing data are determined by checking basic statistics and imputed to the data set by regression model based quadratic trend model analysis (see Table 2). Figure 3 shows graph of full data used with imputation.

Table 2. Missing data imputation.

Period-Half Yearly	Installed Tur. (MW)-Half Yearly	Trend
2013-H1	*	701
2013-H2	*	757
2015-H1	*	930
2017-H1	*	1171
2022-H1	*	1829

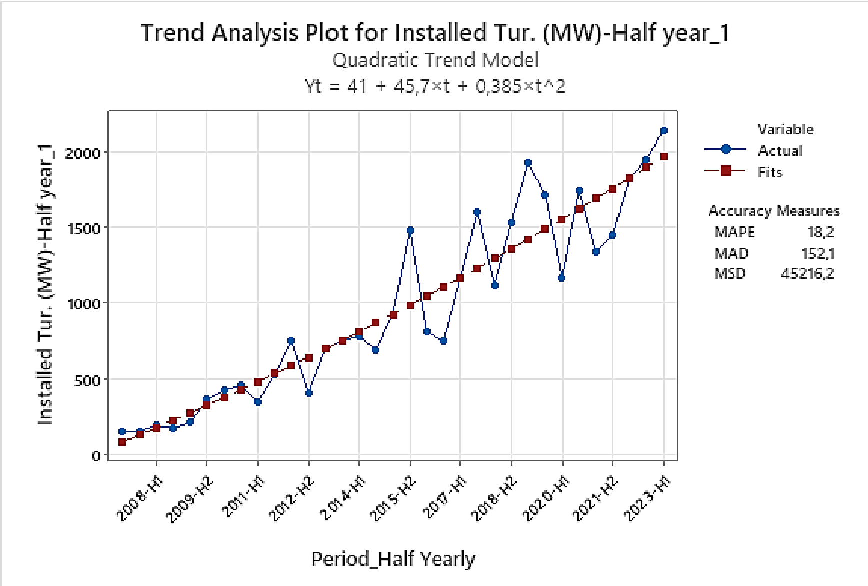

Figure 3. Graph of full data used with imputation.

To perform parametric tests on existing data, the required assumptions have been checked. If the assumptions are not met, it is supposed to choose nonparametric tests. The first of these assumptions is that the data conforms to normal distribution. 3 different parameter tests are performed (Anderson-Darling, Ryan-Joiner, Kolmogorov-Smirnov), and found data is consistent with a normal distribution and there is no need for a transformation.

2.1.2 Evaluation of Methods

Trend & Seasonality Analysis: In this section, seasonality analysis is performed. Demand forecasts are calculated with trend models and ARIMA models. We know that if the data has seasonality, demand forecasting is calculated by Winter's method (see Table 3). Three smoothing constants α, γ and β are determined whether MAD (Mean Absolute Deviation), MSD (Mean Squared Deviation) and MAPE (Mean Absolute Percentage Error) give the minimum value (Dhali et al., 2019, p.100).

Table 3. Winter's method.

Constant α	Constant γ	Constant β	MAPE	MAD	MSD
0.2	0.2	0.1	20.6	190.7	64823.3
0.2	0.2	0.2	20.9	195	69330.2
0.2	0.3	0.2	21.1	197.4	71264.2
0.2	0.2	0.3	21.2	200.3	74113.3
0.3	0.2	0.2	21.7	202.6	73449.1
0.3	0.3	0.3	22.6	211.7	81863.4

From the graphical inspection and the basic statistics, it is determined that a seasonal variation with respect to time did not occur for the actual data. Trend analysis is made with Linear, Quadratic (Polynomial), and Growth Curve (Exponential) models as the results can be seen in Table 4.

Table 4. Trend analysis results.

Trend model	Equation	Adjusted R^2	MAPE (%)
Linear	y = -35.4 + 58.82 t	0.8717	21.6
Quadratic (Polynomial)	y = 41 + 45.7 t + 0.385 t^2	0.8744	18.2
Growth Curve (Exponential)	y = 199.506 × 1.08064t	0.8152	24.3

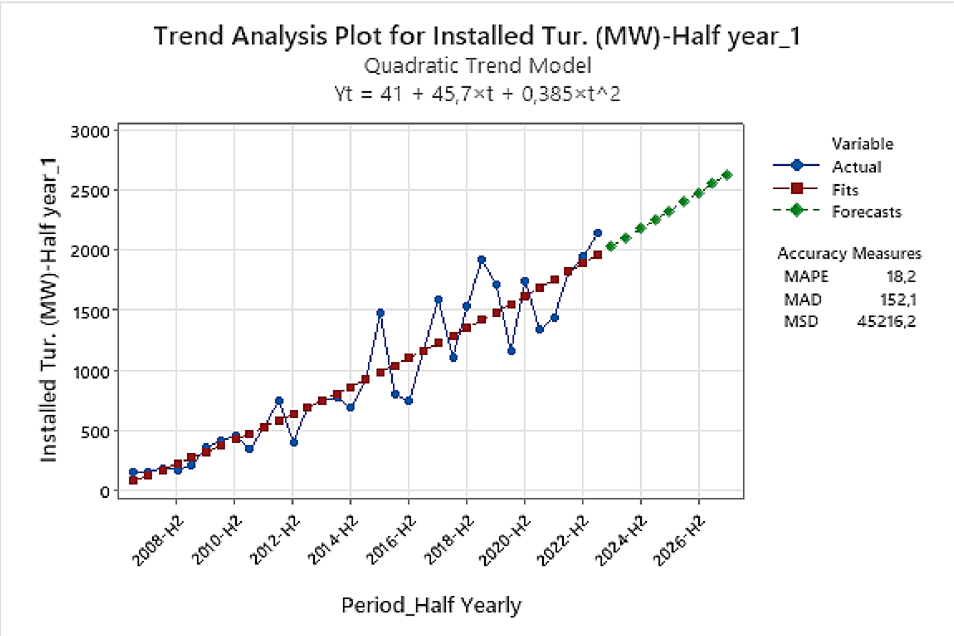

Figure 4. Quadratic (polynomial) model.

The quadratic trend model can be considered best with the lowest error (MAPE = 18.2%) among all the trend analysis models. The graph of the model is seen in Figure 4 with forecasted values.

ARIMA Model: To make forecasting with ARIMA models, it is necessary for the dataset being studied to be stationary. Augmented Dickey-Fuller (ADF) is a statistical test and is used to test whether a time series is stationary. In this study, the ADF test is done via the Minitab tool. The test statistic is 0.165357 > critical value of -2.98649 which means that we fail to reject the null hypothesis and consider first-order differences to make the data stationary. After taking the first difference and analyzing the ACF/PACF plots, it is concluded that stability has been achieved. As a result of a statistical analysis, ARIMA (0,1,1) is decided to be used for the forecasting. Parameter results is seen at Table 5.

Table 5. Parameter results.

Type	Coef	SE Coef	T-Value	P-Value
MA 1	0.970	0.149	6.52	0.000
Constant	59.57	5.12	11.64	0.000

At Figure 5, the graph of the original data with forecast results by using ARIMA (0,1,1) can be seen.

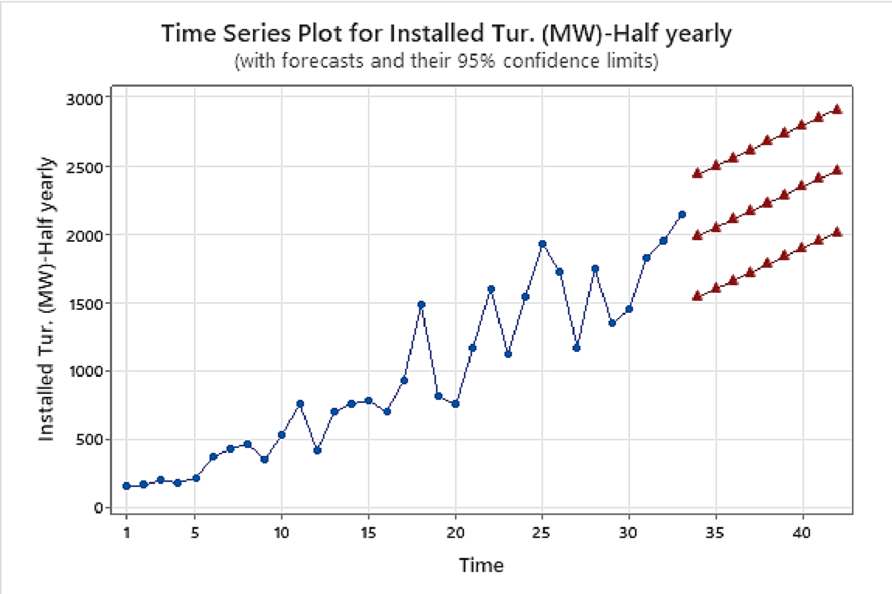

Figure 5. Forecast ARIMA (0,1,1).

2.1.3 Determination of Optimal Model

When the selected models of trend analysis and the ARIMA models are compared, the trend analysis model-quadratic (polynomial) is seen as more accurate than the ARIMA (0,1,1) model-based Adjusted R2 and MAPE values (see Table 6).

Table 6. Final estimates of parameters.

Model Type	Equation	Adjusted R^2	MAPE (%)
Quadratic (Polynomial)	$y = 41+45.7\ t+0.385\ t^2$	0.8744	18.2
ARIMA (0,1,1)	-	0.8618	20.1

So, trend analysis model quadratic (polynomial) is selected in this study for the forecasting of offshore wind power demand in Europe from 2023 to 2027. Forecasted values for offshore wind power demand in Europe from 2023 to 2027 is summarized at Table 7.

Table 7. Forecasted values for offshore wind power demand in Europe from 2023 to 2027.

Period	Installed Turbine (MW) Forecast
2023-H2	2041
2024-H1	2113
2024-H2	2186
2025-H1	2260
2025-H2	2335
2026-H1	2410
2026-H2	2486
2027-H1	2563
2027-H2	2641

2.2 Carbon Fiber Demand Calculation

Spar caps are the most common application of carbon fiber in the blade. Pultrusion can produce spar caps very cost-effectively and with repeatable performance. Market share of offshore wind turbines at below (Figure 6).

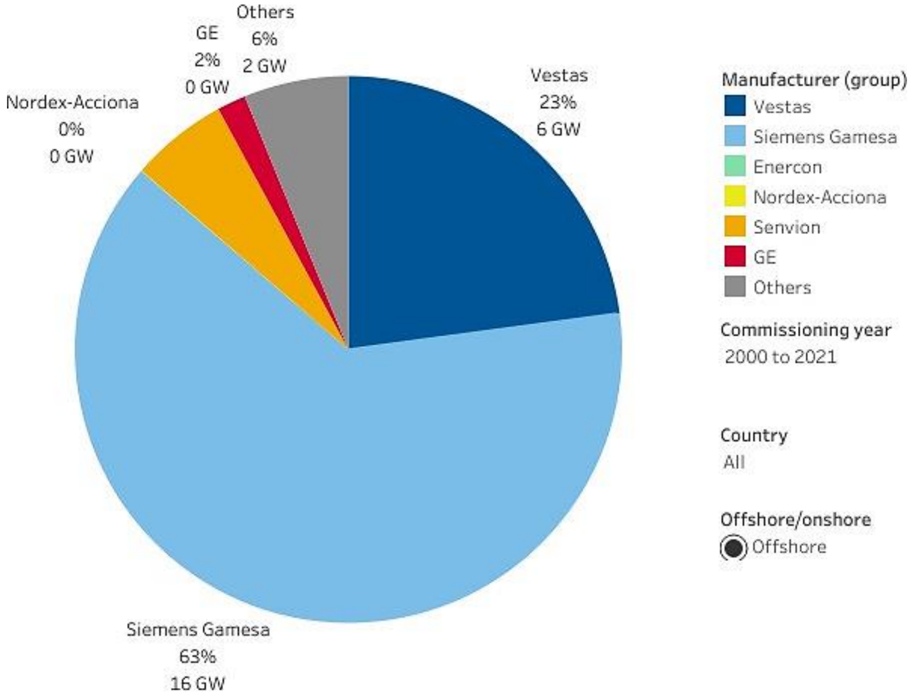

Figure 6. Market share of offshore wind turbines.

Until the end of 2027, we assume that the market share of offshore wind turbines will remain the same. Denmark Technical University has collaborated with Vestas Wind System and published a report on a 10 in MW reference wind turbine. The report shows the variation in carbon fiber weight according to blade length (Zahle et al., 2013, p.4) as seen at Figure 7.

Siemens Gamesa and Vestas' combined offshore market share is 86% (WindEurope, 2023a). We use turbine blades from these two original equipment manufacturers as a reference in our calculations.

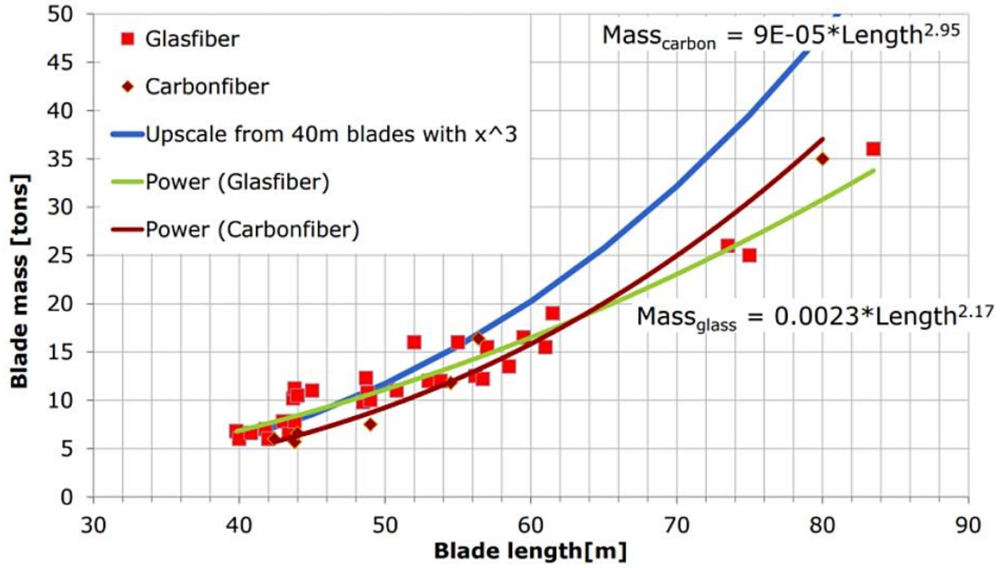

Figure 7. Upscaling blades (Zahle et al., 2013, p.3).

We can say that the new generation V236-15MW (Vestas) and SG14-236 (Siemens Gamesa) will come to the forefront in the coming years when we examine offshore turbines. As taking IEA 15 MW as a reference, key parameters for the offshore turbines and their values can be seen at Table 8.

Table 8. Key parameters for the reference offshore turbine (IEA 15 MW, p.5).

Parameters	Units	IEA 15 MW	Parameters	Units	IEA 15 MW
Power rating	MW	15	Rated Wind Speed	m/s	10.59
Turbine Class	-	IEC Class 1B	Cut-out Wind Speed	m/s	25
Rotor Orientation	-	Upwind	Min. Rotor Speed	rpm	5
Number of Blades	-	3	Max. Rotor Speed	rpm	7.56
Rotor Diameter	m	240	Blade Mass	ton	65
Hub Height	m	150	Rotor Nacella Assmb. Mass	ton	1017
Cut-in Wind Speed	m/s	3	Tower Mass	ton	860

Using the 15MW reference table in our calculations, we estimate the weight of the V236 and SG14 blades and the amount in use of the pultruded CFRP laminates. When the blade named V236-15.0 is installed instead of V174-9.5 MW, 65% higher annual energy production is achieved and it is installed with 34 fewer turbines for a 900 in MW offshore wind farm. Table 9 shows turbine and blade quantities based on forecasted values found and is shown in Table 7.

For 13 in MW wind turbine structural design and optimization, the carbon spar cap mass ratio is reported as 25% of the total blade mass. Additionally, for wind turbine blades a wide range of CFRP pultruded laminate products starting from 60% FVF (Fiber volume fraction) to 70% FVF are used (Yao et al., 2021, p.2). An FVF of 60–70% in CFRP has been shown to result in optimal mechanical properties.

In this study, a full factorial design of 3 different FVF ratios (60, 65, and 70 %) and also, 2 different spar cap mass ratios (20 and 25 %) is generated by taking reference to IEA 15 MW offshore turbine key parameters shared at Table 8.

Table 9. Turbine and blade quantities based on forecasted values.

Period	Installed Turbine (MW)-Half yearly Forecasts	15 MW turbine quantity (set)	Blade quantity(pcs)
2023-H2	2041	136	408
2024-H1	2113	141	423
2024-H2	2186	146	438
2025-H1	2260	151	453
2025-H2	2335	156	468
2026-H1	2410	161	483
2026-H2	2486	166	498
2027-H1	2563	171	513
2027-H2	2641	176	528

For 2023, an example of total carbon fiber demand (ton) is shown in Table 10 based on the formulation below and the forecasted value of 2041 in MW which is found in the previous section.

$$FWF = \frac{\rho_f * FVF}{\rho_m + (\rho_f - \rho_m) * FVF} \quad (1)$$

FVF = Fiber volume fraction, FWF = Fiber weight fraction, ρf = fiber density, ρm = matrix density

Calculations are made according to the use of epoxy resin and carbon fiber in the light of below shown densities in Table 10 (Joven and Minaie, 2018, p.5).

Table 10. FVF and FWF table.

RunOrder	CFRP laminate FVF ratio (%)	Carbon fiber density (g/cm^3)	Epoxy Resin density (g/cm^3)	CFRP laminate FWF ratio (%)
1	60			67
2	65	1.78	1.29	72
3	70			76

It is assumed that there is not air gap in pultruded laminate. Carbon fiber demand (ton) calculation's example for 2023 H2 is at Table 11.

Table 11. Carbon fiber demand (ton) - calculation example for 2023 H2.

Run Order	Period	Forecast (MW)	Spar cap mass ratio (%)	CFRP Spar cap mass per blade (ton)	CFRP laminate FWF ratio (%)	CF Qty per blade (ton)	Blade Qty (pcs)	Total Carbon Fiber Demand (ton)
1	2023-H2	2041	20	13.00	67	8.71	408	3554

For oncoming years, the same calculation is made. The total carbon fiber demand (ton) results for other terms are shown in Table 12.

In total, it is calculated that there would be a carbon fiber demand of 36687 ton in the minimum scenario and 52018 ton in the maximum scenario in the 4.5 years. Also, on a 6-month basis, it is found a minimum demand of 3554 ton and a maximum demand of 6521 ton.

Table 12. Summary of carbon fiber demand (ton) for upcoming years.

#	Spar cap ratio (%)-FVF (%)	2023	2024		2025		2026		2027	
		H2	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**
Total CF demand (ton)	20-60	3554	3684	3815	3946	4076	4207	4338	4468	4599
	20-65	3819	3959	4100	4240	4380	4521	4661	4802	4942
	20-70	4031	4179	4327	4476	4624	4772	4920	5068	5217
	25-60	4442	4605	4769	4932	5095	5259	5422	5585	5749
	25-65	4774	4949	5125	5300	5476	5651	5827	6002	6178
	25-70	5039	5224	5409	5595	5780	5965	6150	6336	6521
Minimum		3554	3684	3815	3946	4076	4207	4338	4468	4599
Maximum		5039	5224	5409	5595	5780	5965	6150	6336	6521
Minimum	Total	**36687**								
Maximum	Total	**52018**								

2.3 Capacity Analysis for The Production of Carbon Fiber in Türkiye Using the Sustainability Perspective

Türkiye has 12 GW of onshore wind turbines and generates 11% of its electricity today. By 2035, an additional 28 GW of capacity is targeted to be added, of which 3 GW will be offshore wind projects. There are currently 26 GW of onshore wind projects under development. The government is also negotiating a Memorandum of Understanding with a UAE developer for 2.5 GW of offshore wind in the Sea of Marmara (WindEurope, 2023b).

With 13 factories producing towers, blades, gearboxes, and generators, Türkiye's Izmir province has a strong wind energy supply chain today and 80% of what is produced is exported, mostly to Europe. (WindEurope, 2023b). Türkiye is becoming an important part of the European wind energy supply chain and is open to further growth. It is also an opportunity for further economic development and local employment (Durak, 2023, p.16).

Türkiye produces the carbon fibers that are used in wind turbine blades too. There is only one carbon fiber producer in Türkiye currently and according to the stakeholder engagement plan published by the company in January 2023, it plans to increase its production capacity which would also help reduce the market`s dependence on China for carbon fiber.

There is also competition in the pultruded CFRP laminate wind turbine blades market. Some of the leading companies in the sector can be expressed as Zoltek, Guangwei, Aosheng, DowAksa, Gurit, Hexcel, Avient, SGL Carbon, Exel, and Fiberline. While some of these companies produce their carbon, others are just pultrusion producers.

2.3.1 Cost Analysis

Initial investment for carbon fiber production is high, its unit costs are low, and special purpose machines are required for bulk production. (Gill, Summers and Mears, 2016). While demand is continuous and high, the form of mass production at high speeds can be integrated. The production type can be also continuous. Having a fully integrated production line (precursor-carbon fiber-pultrusion) enables it to gain competitive power in terms of production quantity rates to serve global companies and increases its role in the global supply chain. Figure 8 shows general arrangement of carbon fiber production line.

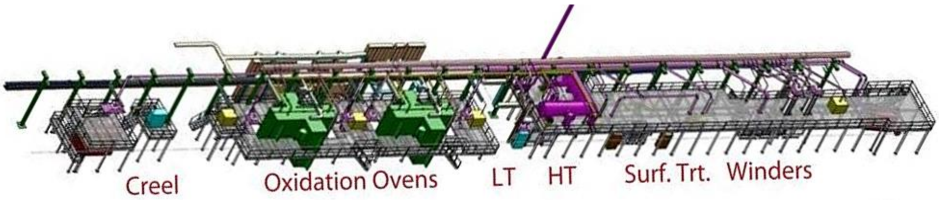

Figure 8. General arrangement of carbon fiber production line.

Türkiye's first and only carbon fiber producer (DowAksa Advanced Composites) has decided to invest in a capacity increase in order to meet the demand, especially in the wind sector (DowAksa, 2023, p.6). In 2021, it published its stakeholder engagement plan and announced that it would increase its capacity from 5500 tons/year to 10500 tons/year. According to that, a new integrated plant on an area of 117 thousand square meters is built and started carbon fiber production on its new lines in 2023. It is shared with the stakeholders that the total cost of the investment is 120 million dollars. These values are taken as a reference in our calculations.

Table 13. Carbonization process-scales up.

Scale	Size Range (tow-band width)	Capacity
Commercial Production Line	1000-4200 mm	500-4000 (ton/year)

Floor space requirements for carbon fiber productions are up to 300 m long and 20-40 meters wide per line. Different scenario investments are taken as consideration for the calculation of total production (tons/years) (see Table 14).

Table 14. Carbonization line with different capacity factor scenarios.

#	Scale up factor	Filaments (per mm)	Scale up factor	Linewidth (m)	Scale up factor	Line speed (m/min)	Total scale up factor	Production (Ton/year)
Baseline	1	2500	1	3	1	10	1	2500
Scenario 1	1	2500	1	3	1.2	12	1.2	3000
Scenario 2	1.5	3750	1	3	1	10	1.5	3750
Scenario 3	1	2500	2	6	1.2	12	2.4	6000
Scenario 4	1	2500	2	6	1.5	15	3	7500

As a result, the required demands can be met with different scenario investments. If we take the baseline scenario as a basis and predict that we will operate (2 lines) at 2500 (ton/year)/line. Its comparison as a product/demand ratio with the pessimistic and optimistic carbon fiber demand forecasts in Europe from 2023 to 2027 which had been found in Table 12 is shown in Table 15.

Conducting feasibility studies early, providing the necessary financing, and making investment or expansion decisions are important in determining how much share of this demand will be received. An investment budget of more than 100 million dollars will be needed to establish 2 carbon lines, each with a capacity of 2500 (ton/year)/line.

If we take the base scenario as a basis and predict that we will operate at (2 lines) 2500 (ton/year)/line and full capacity, our demand response rates to forecasted installed power (MW) data of offshore wind turbines installed in Europe we had found will be 38 % at the lowest and 70 % at the highest in 6-month periods (see Table 15).

Table 15. Production/Demand rates for carbon fiber.

		2023	2024		2025		2026		2027	
		H2	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**
Products/ Demand ratios	Min.	0.70	0.68	0.66	0.63	0.61	0.59	0.58	0.56	0.54
	Max.	0.50	0.48	0.46	0.45	0.43	0.42	0.41	0.39	0.38

Finally, under the umbrella of carbon fiber production costs, various factors such as material, labor, equipment, energy, maintenance, taxes, etc. contribute to the final manufactured cost of carbon fibers (Nunna et al., 2019, p.4) (see Table 16).

Table 16. Costs overview by cost type carbon fiber.

Cost types	**Contribution %**	**Cost types**	**Contribution %**
Raw material	19.1	Energy	34.0
Process materials	8.8	Maintenance	7.0
Labor	6.8	Insurance	1.2
Equipment	18.2	Taxes	2.3
Building	2.6		
TOTAL			100 %

2.3.2 Labor Analysis

The needed capacity of the workforce and their skills required for production can be estimated, after determination and selection of the machinery, tools and equipment required for the production are determined.

Considering 3 shifts are worked and 135 people are employed for each line, a total of 270 people will be required to be employed.

The quality of labor and raw materials will affect the choice of capacity. If these resources are limited, small scale may be preferred instead of establishing a large-scale facility and keeping it idle. To make this decision, the factor market (raw materials and labor) should be well researched. There are 3 main sections in production: dope, oxidation and carbon fiber (see Table 17).

Table 17. Production stages of carbon fiber.

<table>
<tr><th colspan="2">Stage I</th><th colspan="2">Stage II</th><th colspan="2">Stage III</th></tr>
<tr><td rowspan="8">Dope Unit</td><td rowspan="2">Dope</td><td rowspan="8">Precursor Unit</td><td>Coagulation Bath</td><td rowspan="8">Carbon fiber Unit</td><td>Oxidation</td></tr>
<tr><td>Baths</td><td>(Carbonization) Low Temperature Furnace</td></tr>
<tr><td rowspan="3">Heat Exchanger</td><td rowspan="2">Drawing Baths</td><td>(Carbonization) High Temperature Furnace</td></tr>
<tr><td>Electrolyze Bath</td></tr>
<tr><td>Dryers</td><td>Washing Bath</td></tr>
<tr><td rowspan="3">Filters</td><td>Steam Drawing</td><td>Sizing</td></tr>
<tr><td rowspan="2">Winding</td><td>Drying</td></tr>
<tr><td>Winding</td></tr>
</table>

The capacity utilization rate also should be considered. The number of employees, shifts are shown in Table 18.

The growth of the wind industry is accelerating and the workforce is becoming increasingly important. As wind energy becomes more widespread, the need for well-trained labor is increasing day by day.

Table 18. Labor information.

		Pcs-Qty	Salary	No. of shifts
Line workforce	Operators/shift	18	#	3
	Supervisors/shift	3	#	3
	Dope/polym/recovery	3	#	3
Support service	Chiller unit	2	#	3
	Effluent plant	2	#	3
	Distillation	2	#	3
	Steam	2	#	3
	Maintenance	2	#	3
	Lab	1	#	2
	Filtration	2	#	3
Management	Managers	3	#	1
	Admin officers	3	#	1
	HR	3	#	1
Handling services	Forklift operators	2	#	3
	Packaging	2	#	3
	Tool store	2	#	2

2.3.3 Environmental Analysis

Türkiye signed the Paris Agreement (on climate change mitigation, adaptation, and finance under the United Nations Framework Convention on Climate Change) in 2016. According to the agreement, the increment of the global temperature can be constricted by prudent work. (Republic of Türkiye Ministry of Environment, Urbanization and Climate Change Directorate, 2018).

For greenhouse gas emissions from the company's economic activities, scope 1, 2, and 3 emissions are determined. These calculations are based on ISO 14064, Greenhouse Gas Protocol Corporate Accounting Reporting and Corporate Value Chain (Scope 3) Standard. (Greenhouse Gas Protocol, 2011, p.5). While scope 1 emissions include direct impacts from the company's activities such as stationary and mobile combustion, scope 2 includes emissions from purchased electricity and other energy sources, and scope 3 includes indirect emissions from purchased raw materials, employee services, business travel, etc.

The global warming potential is calculated in carbon dioxide equivalents (CO2-Eq.). If we rank the sources of emission values of a reference carbon fiber production facility which has 7500 tons/year capacity from largest to smallest, the first three rows are in Table 19.

Table 19. Carbon hotspot analysis.

Hotspots	Unit	Emissions	Percentage
Raw Material	ton CO2 Eq	65654	29%
Electricity consumption		89998	40%
Purchased steam and cooling		47706	21%
Other		20112	9%

Based on these calculations, companies identify and prioritize their hotspots and try to reduce their consumption and emission levels. The calculations made within the framework of Scope 1, 2, and 3 are based on all direct and indirect activities. Carbon fiber production's carbon footprint based on scope 1-2-3 is at Table 20.

Table 20. Carbon fiber production's carbon footprint (scope 1-2-3).

CF production carbon footprint	Unit	Emissions	Percentage
Scope 1	ton CO2 Eq.	11293	4%
Scope 2		156071	51%
Scope 3		135989	45%
Total Scope 1 & 2		167364	36%
Total Scope 1 & 2 & 3		303353	100%

As a result, for a capacity of 5000 tons, it can be predicted that there will be approximately 202 thousand tons of CO2 Eq (for total Scope 1 & 2 & 3).

Carbon producing companies should focus on efficient resource utilization, waste reduction, the inclusion of waste as an input to production, and the protection of biodiversity and ecosystems.

Moreover, one of the carbon fiber producers in Europe has announced that obtained ISCC Plus certification which allows to allocation and use of biomass or recycled materials through the mass balance approach to produce and supply carbon fiber (Toray Carbon Fibers, 2023). The ISCC standard is a multi-stakeholder developed, internationally recognized sustainability certification system used to verify the sustainable production of biomass, biofuels, and other renewable raw materials. Obtaining the ISCC plus certificate for carbon fiber manufacturers may put them at the forefront of the market.

Wind turbines generally work effectively for around 20-30 years. With today's technology, the majority of retired wind turbine blades (80-90 %) can be recycled depending on the turbine variant and configuration (Vestas Sustainability Strategy, 2020, p.35). Each of the major wind turbine manufacturers has a target recycle rate value. Vestas Wind System Company has the targets of gaining 50% recyclability by 2025 and 55% by 2030, targeting the rotor, which means the blades and the hub.

3. CONCLUSIONS AND RECOMMENDATIONS

In this study; data of offshore wind turbines installed in Europe between 2006 and 2023 are collected. The data is pre-prepared for performing parametric analysis and a future period of 4.5 years is forecasted using trend analysis methods and the ARIMA model. The results of the models are compared with the performance parameters and the most suitable model is decided as the (polynomial) trend model which has given the lowest MAPE (18,2 %).

Forecasted values for offshore wind turbine demand in Europe from 2023 to 2027 are used to calculate carbon fiber demand and the scenarios table is produced regarding Spar cap mass ratio (%) CFRP laminate FVF ratio (%). In total, it is calculated that there would be a carbon fiber demand of 36687 ton with the scenario (minimum) and 52018 ton in the scenario (maximum) for the next 4.5 years. When we examine it on a 6-month basis, there is a minimum demand of 3554 ton and a maximum demand of 6521 ton. Based on these calculations; the amount of production that the enterprise can realize in a certain period of time is defined as "capacity". In the light of sustainability goals, companies should play an active role in creating a market for recycled composites wind turbine blades and support material streams for recycled composites. Regarding the sustainability approach the authors also revealed the cost analysis, environmental analysis and labor needs in detail.

If we take the base scenario as a basis and predict that we will operate at (2 lines) 2500 (ton/year)/line and full capacity, our demand response rates to forecasted installed power (MW) data of offshore wind turbines installed in Europe will be 38 % at the lowest and 70 % at the highest in 6-month periods. It is determined that establishing a capacity of this size will require an investment budget of more than 100 million dollars. It is mentioned for the scenarios where demand response rates are low, production capacity can be increased by using capacity factors (filaments, linewidth, and line speed).

In the light of findings in this study; carbon fiber producers in Türkiye should hold themselves ready taking in to account of cost, environmental and labor needs analysis. The government should make permitting procedures faster and easier. Beside these; there are a limited number of original equipment manufacturers (OEMs) producing wind turbines and limited production capacities. In this growth trend, it is important that all stakeholders provide the necessary support to this growth process. In addition to production and technical difficulties, there are more important issues in this process. The first of these is qualified manpower. To achieve the targets, several times the number of qualified workforces will be needed to take part in the production, installation and maintenance of wind turbines. Another issue is the logistical difficulty of transporting turbines whose heights and rotor diameters have increased due to technological developments. Special equipment is required for the installation of offshore wind turbines. There are also critical points such as safety issues and installation time. Experience and equipment in offshore oil/gas activities can be transferred to this sector and used well in the installation and maintenance of wind turbines.

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