COMPARISON OF DIFFERENT WIND TURBINES UNDER VARIOUS SEISMIC AND WIND LOADING

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ABSTRACT

COMPARISON OF DIFFERENT WIND TURBINES UNDER VARIOUS SEISMIC AND WIND LOADING

The energy sector can be broadly classified into two main groups that are non-renewable sources and renewable sources. One of the most preferred types of renewable energy for investment is wind energy in consequence of technological improvements on wind energy sector. Making investment is a complex process since it involves economic and technical requirements. This thesis represents technical and economic feasibility of the wind farms. Selection of the site is the first step to be taken for the wind turbine projects. Three places, Çanakkale, Balıkesir and Kayseri, were specified as extremely suitable for making investment. For technical consideration, soil uncertainty was analysed from the viewpoint of soil stiffness that is represented by the subgrade reaction of modulus. Soil uncertainty is a significant issue in the design stage since the stiffness of the soil has an impact on the system natural frequency. Additionally, ultimate bearing capacity of soil was calculated by using Terzaghi's Bearing Capacity Theory to prevent any failure in soil. In the thesis, two different wind turbines models were used whose rated powers are 1.80 MW and 3.45 MW. The behaviours of the systems were investigated in terms of overturning moment, base shear and period values obtained from SAP 2000. Finally, strength checks were done according to the standards of API by checking buckling, bending, and shear stresses of the system. All the analyses were carried out to find the optimum value of design variables, which are the wall thickness of tower, dimension of foundation and tower diameter. For economical consideration, the financial models were created to manage cash flows throughout the lifetime of the projects. When all the alternatives are taking into consideration, one of the most significant findings of this study is that making wind turbine investment is advantageous compared to the acquisition of interest income in bank accounts.

ÖZET

FARKLI RÜZGAR TÜRBİNLERİNİN ÇEŞİTLİ SİSMİK VE RÜZGAR YÜKLERİ ALTINDA KARŞILAŞTIRILMASI

Enerji sektörü yenilenemeyen kaynaklar ve yenilenebilir kaynaklar olmak üzere genel olarak iki ana grupta sınıflandırılabilir. Enerji sektöründeki teknolojik gelişmeler neticesinde yatırım için en çok tercih edilen yenilenebilir enerji türlerinden biri rüzgar enerjisi olmuştur. Yatırım yapmak, teknik ve ekonomik gerekliliklerinden dolayı kompleks bir süreçtir. Bu tez rüzgar türbinleri için ekonomik ve teknik fizibilite çalışması sunmaktadır. Saha seçimi rüzgar türbini projeleri için atılması gereken ilk adımdır. Çanakkale, Balıkesir ve Kayseri'nin yatırım yapmak için çok uygun olduğu belirlenmiştir. Teknik değerlendirme açısından, zemin belirsizliği, yatak katsayısı ile temsil edilen zemin rijitliği açısından irdelenmiştir. Zemin rijitliğinin, sistemin periyodundaki etkisi sebebiyle zemin belirsizliği, dizayn aşamasında önemli bir konudur. Ek olarak, zeminde oluşabilecek muhtemel göçmeyi önlemek için zeminin nihai taşıma kapasitesi Terzaghi Taşıma Gücü Kapasitesi Teorisi ile hesaplanmıştır. Bu çalışmada nominal güçleri 1.80 MW ve 3.45 MW olan iki farklı rüzgar türbini kullanılmıştır. Bu yapıların davranışları SAP 2000 programından elde edilen devrilme momenti, kesme kuvveti ve periyot değerleri açısından irdelenmiştir. Son olarak yapısal dayanım kontrolleri API standartlarına uygun şekilde sistemin kesme, burulma ve eğilme basınçları kontrol edilerek yapılmıştır. Bütün bu analizler dizayn değişkenlerinin yatırım için en uygun değerlerini bulmak amacıyla yapılmıştır. Yapı için tanımlanan değişkenler kulenin et kalınlığı, temelin boyutları ve kulenin çapıdır. Ekonomik değerlendirme açısından, projelerin nakit akışını yönetebilmek için finansal modeller oluşturulmuştur. Bu çalışmanın en önemli bulgularından biri olarak da rüzgar türbini yatırımı yapmanın banka hesapları üzerinden faiz gelirleri elde etmekten daha avantajlı olması gösterilebilir.

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LIST OF SYMBOLS

$1P$	Rotational frequency, Hz
$3P$	Blade passing frequency, Hz
A	Exposed area, m
a	Induction factor
A	Angle of attack, deg
$A(T)$	Spectral Acceleration Coefficient
A_o	Effective ground acceleration coefficient,
A_{rotor}	Area of the rotor disk, m^2
B	Width of the foundation, m
C	Critical elastic buckling coefficient
c	Cohesion of the soil
c_a	Airfoil chord length, m
$CD(\alpha)$	Aerodynamic drag coefficient
c_{fo}	Basic force coefficient for the cross-sectional shape of section i
$CL(\alpha)$	Aerodynamic lift coefficient
c_s	Aerodynamic lift coefficient
d	Diameter of the cross-section, m
D	Outside diameter, m
E	Young's Modulus of elasticity, MPa
EQ	Earthquake
f	Frequency of excitation, Hz
$F(V)$	Distribution function
F_b	Allowable bending stress
f_b	Bending tensile stress
F_D	Aerodynamic drag, N
F_L	Aerodynamic lift, N
f_n	Natural frequency of the system, Hz
F_v	Allowable beam shear stress, MPa

f_v	Maximum beam shear stress, MPa
F_{wind}	Wind load, N
F_{xc}	Inelastic local buckling stress, MPa
F_{xe}	Elastic local buckling stress, MPa
F_y	Yield strength, MPa
H	Height of wind turbine in m
H_o	Reference height in m
I	Building importance factor
K	Effective length factor
k	Modulus of subgrade reaction, kN/m^3
K	Von Karman constant
k_B	Appropriate subgrade reaction value, kN/m^3
I	Unbraced length, m
L	Length of the foundation, m
L	Scale factor called the Monin - Obukhov length
M	Moment, kN.m
m_v	Coefficient of volume compressibility, m^2/kN
N_γ	Terzaghi bearing capacity factor
N_c	Terzaghi bearing capacity factor
N_q	Terzaghi bearing capacity factor
p	Load per unit area, kN/m^2
p_{air}	Air density, kg/m^3
q	Net pressure on the foundation area kN/m^2
r	Radius of gyration, m
r	Distance of blade element to axis of rotation, m
$S(T)$	Spectrum coefficient
s_c	Shape factor
S_{oed}	Settlement, m
t	Wall thickness, m
v	Wind speed to the height H in m/s
v_o	Wind speed to the reference height in m/s

V_{disk}	Wind velocity at airfoil, m/s
v_f	Friction velocity, m/s
V_o	Wind velocity, m/s
V_{rel}	Relative wind speed at a blade section, m/s
V_{rot}	Linear rotation speed at a blade section, m/s
V_{rotor}	Wind velocity at the rotor, m/s
W	Wind
W_i	Resultant wind load in section i
y	Settlement produced under applied loads, m
z	Height of turbine, m
Z	Thickness of compressible layer, m
z_o	Surface roughness length
ϕ	Angle of inflow, deg
γ	Effective density of soil
α	Friction coefficient or Hellman exponent
Ψ	Reduction factor
ΔH	Thickness of compressible layer, m
Δq	Average stress increment in compressible layer, kN/m^2
μ	Mean of the Rayleigh distribution
Δr	Radial length of blade element, m
θ	Pitch angle, deg
σ^2	Variance of the Rayleigh distribution
Ω	Angular rotation speed, rad/s

LIST OF ACRONYMS/ABBREVIATIONS

AHP	Analytical Hierarchy Process
API	American Petroleum Institute
BIMER	Communications Center of Prime Ministry
BS 8004	The British Standard - Code of Practice for Foundations
CAPEX	Capital Expenditures
DIN	German Institute for Standardization
DSR	Debt Service Reserve
EAK 2000	Greek Antiseismic Code
EGE	Aegean Region
EMRA	Electricity Market Regulatory Authority
FEA	Finite Element Analysis
FEM	Finite Element Method
FOS	Factor of Safety
GA	Genetic Algorithm
GH	Garrad Hassan
GIS	Geographic Information Systems
IRR	Internal Rate of Return
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
PBP	Payback Period
RD	Dynamic Amplification Factor
SSI	Soil-Structure Interaction
TEIAS	Turkish Electricity Transmission Company
USD	United States Dollar
V112	V112-3.45 MW^{TM} IEC IA
WT	Wind Turbine

1. INTRODUCTION

The energy sector consists of two alternative sources that are renewable (solar, wind, hydro, wave) and non-renewable (coal, fuel, natural gas) sources. Although, especially after the Industrial Revolution, people have consumed non-renewable sources in modern communities intensively, using renewable energy sources have become popular in recent decades. Growing concerns about environmental problems and fear of possible shortage of fuels are major reasons for people to make investment in environmentally friendly and sustainable energy sources.

One of the well-known types of renewable sources is the wind energy. Basically, a wind turbine is defined as a system that transforms the kinetic energy of the wind into mechanical and/or electrical energy. The sector of wind energy is improving each day since wind turbines have a great potential to be more productive and economical. In comparison to the past, wind turbines are starting to generate more electricity with the increase in their capacities and sizes.

The wind turbines are made up of a foundation, a tower, a nacelle, and a rotor. The structures are consistently under risk of failure since its parts are heavy and they are exposed to varying wind loads continuously. Additionally, seismic loads should be taken into consideration in the seismically active zones. Hence, the design stage of wind turbines is critical to ensure their durability.

According to the results of the thesis, three parameters of design should be determined carefully and in detail to prevent any failure of these structures: the outer diameter of tower, the thickness of the tower wall and the dimension of the foundation. The parameters are determined differently for wind turbines under various wind and seismic loading. Moreover, the thesis aims to obtain the most structurally and economically efficient results for the turbines whose rated power are 1.80 MW and 3.45 MW. Finally, financial models are created to shed light on critical economic issues.

1.1. Literature Review

Various studies have been published concerning the design and economy of wind turbines up to today. In this thesis, firstly, foundation design concepts are examined and summarized for wind turbines.

The types and properties of wind turbine foundation can significantly affect the performance and cost of the overall system. Therefore, structural design of the foundation is significant to ensure safety, efficiency, and economic design of the whole system.

According to Olariu's study [1], knowledge and control of the tower's natural frequencies is necessary to avoid failure. The study reflects that consideration of the soil-structure interaction is very significant in preventing the entry of the resonance range in the Campbell Diagram.

In the study, two case studies are presented. In the first case, namely the case study A, soil, which surrounds the foundation, is modelled by the means of springs. In the second case, namely study B; the entire soil, foundation, and wind turbine system are modelled by using finite element method. Dynamic analysis of the system for different cases shows that the natural frequencies of the systems have a difference of a range of $\pm 10\%$ between the cases. Another result is that consideration of springs, which represents soil in the entire systems, decreases frequencies. Thus, it is crucial to reckon the soil structure interaction in dynamic analyses of wind turbines while designing the wind turbines [1].

In Zaaijer's study [2], various approaches and types for the base support types of the wind turbine are presented and sensitivity of the support structure's natural frequency is discussed.

Although, the effective fixity approach is considered to be appropriate for tubular towers, it poses a large variation depending on the condition of the soil. Randolph's linear elastic model says that there is no behaviour difference between piles that are

longer than the critical length and the infinity length. The Finite Element Method uses stiffness matrix approach, which gives good results in the line with expectations. This method gives better and closer results; however, non-linear soil structure interaction may cause small differences [2].

In a study by Kühn [3], soil stiffness is a critical aspect in the design of support structures in terms of technical and economic performance. Design concepts can be selected as "soft-stiff" or "stiff-stiff", that means a soft tower and a stiff foundation or that both are stiff. Foundation may be soft or stiff by changing the subgrade reaction of the soil surrounding the foundation. The changes lead to differences in the natural frequency of the whole system.

Several investigations about the design parameters show that blade excitation is an important topic for the natural frequency of the soft-stiff system and it leads to a lower dynamic amplification than stiff-stiff one [3].

Soft-stiff support structure is prone to be suitable for most sites but it is not possible to apply for all generic concepts. Soft-soft ones are economically interesting but they deteriorate as a result of the wave fatigue. Hence, a very careful design is necessary [3].

According to Guangling He and Jie Li's study [4], finite element model is used to display the behavior and performance of 1 MW horizontal wind turbine steel. The wind turbine is analyzed under seismic loading, considering the gravity and site-dependent seismic motions. Modifying time history data creates the seismic motions. Deterministic approach is applied to the time history data in order to fit specific design requirements. Soil-structure interaction (SSI) is also taken into consideration to evaluate the performance of the wind turbine system.

Two different finite element models are created. In the first model SSI effect is considered and in the second model SSI effect is not considered in a direct time domain analysis. Figure 1.1 shows the effect of SSI on tower top acceleration and displacement

[4].

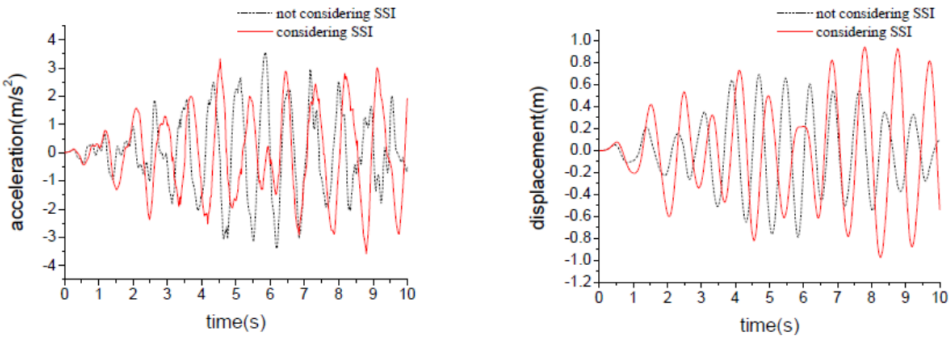


Figure 1.1. Tower Top Acceleration and Displacement.

The study shows that the SSI becomes critical on the global dynamic performance of the system located at a seismically active zone [4].

According to Bhattachary and Adhikari's study [5], estimating the natural frequency of onshore wind turbine systems is one of the significant design considerations. This paper experimentally investigates the behavior of a model wind turbine supported on a foundation, called a monopile. A slender monopile, whose length changes from 2.5m to 4m, is inserted deep into the soil. The aim of the study is to understand the role of flexibility of soil in the dynamics of the wind turbines by developing testing methods for different kinds of soils. The stiffness of the foundation and the frequency of the system are interrelated with each other. Moreover, analytical results for the natural frequencies come close to the outcomes of the experimental results.

In a study by AlHamaydeh and Hussain's [6], various wind turbines, constructed in different sites in Alaska, are studied to reach to an optimum design. Two different types of foundation systems, the large mat and deep piles, are taken into consideration. The main goal of the study is to see whether any difference in natural frequencies of the system results from their foundation designs. The basic parameters for optimization are cost, natural frequency, and structural stability. To reach optimum foundation design, iterations calculate the sizes of the piles. After applying different types of loading, it is seen that the natural frequency of the structure system controls the foundation system

design rather than strength or serviceability [6].

AlHamaydeh and Hussain's study lays emphasis on the importance of the soil-structure interaction (SSI) for the design codes. When SSI is taken into consideration in the created finite-element models, more realistic estimation of the natural frequency values are obtained due to the foundation flexibility [6].

Hongwang's study [7], defines a model involving SSI and P-Δ effects under horizontal and vertical earthquake actions. The SSI means connection between the tower and a support structure, which has translational and rotational springs and dampers. The springs and damper properties are estimated based on the type of the assumed soil. The seismic response model is applied to two different wind turbines whose rated powers are 1.65 MW and 3.00 MW. The turbines are analyzed under six different earthquake records that are taken from the PEER Ground Motion Database for both horizontal and vertical motions.

The outcomes demonstrate that applying SSI decrease the first natural frequency, tower top horizontal acceleration, tower base horizontal moments, tower base horizontal shear load values in the ratio of proximate 7%, 10%, 12% and 5% respectively; however, it does not have impact on the vertical acceleration and axial load of tower. In addition to SSI analysis, the paper shows that P-Δ effecting analysis has impact on the tower base moment insignificantly. Finally, it is seen that consideration of the earthquake loading is important for the vertical load and moment demand on the tower of the selected turbines in reference to the seismic zone [7].

Taddei and Meskouris [8], have stated that the impact of the subsoil on the seismic response of an onshore wind turbine may be vital during the seismic design stage and is necessary to be properly taken into account for the computational model. It is recommended to represent soil as springs according to the standard codes. In their study, they chose a reference wind turbine with 3 blades, whose rated power was 1.5 MW. The turbine has been modeled by using Boundary Element Method (BEM) and Finite Element Method (FEM) to assess the accuracy and applicability of the soil.

The outcomes of the study are:

- The thickness of the soft layer is inversely proportional to the natural frequencies.
- The first frequency has a slight effect.

In addition to the foundation design concepts, it is important to clarify geometrical properties of the onshore wind turbines in the design phase. Hence, various studies have been carried out regarding the issue. Especially, the cross section of the tower is investigated by considering the dynamic behavior of the system.

Lavassas, Nikolaidis, Zervas, Efthimiou, Doudoumis [9], have studied a reference wind turbine with 1 MW rated power and 44,075m high steel tower. The shape of the tower is tubular and the thickness of tower is tapering from the base to the top point.

For the study, two different finite element models are analyzed under different seismic and wind loading in accordance with Eurocodes. Particularly, seismic loading has been defined in the dynamic analysis of the structure in pursuant of the Greek Antiseismic Code (EAK 2000) [9].

It must be underlined that the simplified linear static model is adequate in calculating the basic response as well as the eigenvalues of the structure; however, it does not meet all the design procedures. For a safe design, the system should endure extreme wind loading which is the privileged load combination for the design of the structure [9].

According to Wang, Kolios, Luengo, Liu, [10], an optimal structural design of the tower is essential for efficient, safe, and economic design of the whole system. In this study, wind turbines are developed to optimize the design variables by using GA (Genetic Algorithm) and FEA (Finite Element Analysis). Design variables are the bottom and top diameters, and thickness distributions of the tower. NREL 5 MW wind turbine is chosen as the reference wind turbine whose properties are 87.6m height, 3.87m tower top outer diameter. The aim of the work is to minimize the design

variables, which affect the mass of the wind turbine tower. While determining the variable, the strength checks should be done.

High-fidelity evaluations of the structural performance of the tower have been obtained in the FEA approach; moreover, the GA (genetic algorithm) model offers optimal solutions hereunder. After optimization, the tower weight is reduced to 6.28% in comparison with the initial design [10].

According to Witcher's study [11], earthquakes are an inseparable part of the dynamic analysis of wind turbines in assessing the feasibility of wind sites in the seismically active regions. This study represents alternative approaches to enable computation combined with wind and earthquake loading by using Garrad Hassan (GH) Bladed wind turbine simulation program. The software defines external conditions. A wind turbine is selected to compare the analysis results between the frequency, time, and frequency methods. The reference turbine has 2 MW rated power, 80-m upwind rotor diameter and 60-m high steel tower.

It is interesting to note that the peak tower base moment values from both the time domain and the frequency domain which are very close to each other; however, the results are inapprehensive when the turbine is exposed to high wind speeds [11].

Hoffman and Karst's study [51], explains Rayleigh distribution in two parts. In the first part of the paper, the mathematical properties of the Rayleigh distribution, which consists of the moment generating function, confidence intervals, the density function, the bivariate Rayleigh distribution, and the moment generating function are dealt with. In the second part, applications of the distribution into to the response analyses of marine vehicles to wave excitation are explained. These applications display ocean waves, long-term and short-term bending moment responses of a ship, and the "aim problem".

In addition to the design aspect, economical parameters for the feasibility study should be considered in detail. Studies, which have been carried out for economic

considerations, are summarized below.

Ozerdem, Ozer, Tosun's study [12], presents the technical and economical parameters to obtain the most feasible wind farms. The technical consideration indicates temperature measurements and wind direction. Three different cases are investigated and compared in terms of Internal Rate of Return (IRR), Net Present Value (NPV), and Payback Period (PBP) criteria for economical consideration. Analytical Hierarchy Process (AHP) method explains that Izmir, Turkey is a good location to build up successful wind farms due to its high potential of wind power, easy access to the main roads and proximity to transmission lines. It is considered that five diverging wind turbines, whose rated power are 600 kW, 900 kW, 1000 kW, 1500kW and 1800 kW, are taken into consideration for this work.

According to the results, 600 kW is more feasible than others in accordance with auto producer case; however, 900 kW is the most suitable to construct according to auto producer group and IPP cases. Another outcome of the study is that the increase in the installed capacity may escalate the cost per kWh. Finally, the profitability analysis has shown that, IRR value is higher when larger wind turbines are used [12].

In a study by Dogan, Colakoglu and Kincay [13], there is a brief description about the terminology on wind energy and its benefits. Additionally, a feasibility study has been done for three wind turbines that have different rated powers, 1 MW, 5 MW and 10 MW respectively, through the instrument of RETScreen software in Hatay. The assumptions are as follows; the height of the tower is 70m, average wind speed is 8.4 m/s yearly, and the capacity factor is 35.9%.

When placed in ascending order, it is observed that the cumulative cash flow for the reference turbines becomes positive after 12.5, 10, and 9.5 years after the beginning of operations regarding their rated power. It is also seen that to get more advantage despite the bank interest, preference of a minimum 2 MW capacity wind farm is imperative on the condition that all investment cost is met by equity and the economic life of the turbines are 20 years [13].

In a study by Ertugrul and Kurt [14], it is stated that due to today's increasing energy demand as well as the negative impact of conventional energy resources on the ecosystem and security of supply, renewable and sustainable energy sources are in demand. One of the most popular renewable and clean energy sources is the wind energy. Cost analysis of the wind energy has been carried out based on 1 MW wind turbine, located at a site where the capacity factor is assumed to be 35%.

The assumptions of cost analysis calculations are basically as the following; initial investment cost is EUR 1.35 million, selling price is 0,055 Euro/kWh, expected production amounts to 3.066.000 kWh per year, and operational cost is 0,010 Euro/kWh. After the calculations, the net profit is expected to be EUR 137,970 and the recycling period is 9,8 years. The results display that investment in the wind energy sector seems to be profitable when operational cost is low [14].

Mostafaeipour, Sedaghat, Dehghan-Niri and Kalantar's study [15], investigates the status and wind power potential of the city, Shahrbabak in Iran by controlling the technical and economic demands. Weibull probability density predominantly confirms the performance of wind power systems. Here, the distribution of the wind speed is determined by using Weibull distribution. The critical point of the work is to find Weibull shape parameter and Weibull scale parameter coefficients. Average wind power density, 100 W/m^2, reflects that the site is not suitable to construct large-scale wind power plants. In 2011, the price of electricity was decided to be USD 0.13/kWh by the government. Based upon the calculations, it was obtained that the cost of wind turbine USD 0.18/kWh cents for 1 kWh. Hence, it is suggested to install small-scale wind turbines in the region.

1.2. Objective

The main goal of the thesis is to present the technical and economic feasibility of the wind turbines. Making investment is a complex process since it involves economic and technical requirements. After taking an investment decision, there are a lot of issues that need to be decided, such as the location and the wind turbine type. Hence,

different wind turbines have been compared under different seismic and wind demands. In order to find an optimum investment, various analyses have been carried out. In the thesis, 3 different locations are selected: Çanakkale, Balikesir and Kayseri.

Çanakkale and Balikesir are in the 1st degree seismic zone while Kayseri is in the 4th degree seismic zone; therefore, earthquake effects are taken into consideration and compared in the design stage. However, the mean wind speed in Çanakkale and Kayseri is 8 m/s at 50m., while it equals to 7 m/s at the same height in Kayseri. As a result of the difference in the wind loads, the effects of wind speed on the investment are described. Two different Vestas's wind turbines are used in the analyses of which models are V90-1.8/2.0 MW IEC IIA/IEC IIIA and (V90) V112-3.45 MW^{TM} IEC IA (V112). By means of this, the impact of turbines' rated powers on the investment is compared.

For the technical consideration, design variables that are the bottom and top diameters, thickness distributions of the tower and dimension of foundation have been determined for the reference turbines. While determining them, critical issues have been paid attention in order to avoid any type of failure.

In real life, uncertainty of soil causes differences between actual and analytical frequencies. These differences may bring about failure. Hence, soil uncertainty is analyzed from the viewpoint of soil stiffness that is represented by the subgrade reaction of modulus.

Onshore wind turbines are exposed to dynamic forces throughout their operational life. During the structural frequency, failure may be observed on different sections of the turbines, such as the tower and blades. It is critical to separate excitation frequency and structural frequency of the system to prevent any resonance failure. There are two main design criteria for onshore wind turbines: stiffness and strength. The stiffness criterion specifies that the first and dominant frequency of the structure should be in a region named as soft-stiff region to avoid any resonance. For this reason, the analyses are performed in accordance with the Campbell diagram to

avoid any failure while keeping the investment cost low. Secondly, strength checks are done according to the standards of American Petroleum Institute (API) by checking the terminologies, such as column buckling, local buckling, bending, and shear stresses.

Feasibility study has been carried out in order to answer questions about optimum investment. It also clarifies lifetime costs of the wind turbine investment. In real life, making investment is preferable in the event investors get more money compared to the interest income in bank deposits and cost of the turbine is lower than the market price. With the help of the financial analysis, the cost and revenue of the wind turbine investment can be determined. As a result of financial analysis, financial models are created in order to find the best alternative for investment. The data for the financial model are obtained from different sources.

1.3. Scope

In Section 2, short information about the wind energy, and the historical development of wind turbines, the place of wind energy in the energy sector and the status of wind energy production in the World in recent years are provided.

In Section 3, the importance of the location of wind turbines is emphasized. Site selection is the first step in the wind energy investment. Hence, the locations are determined by using the Resources on Renewable Energy Capacity Atlas, prepared by the Ministry of Energy and Natural Resources, and the criteria tables that are taken from Bennui *et al.* (2007) [27].

In Section 4, the methodology of modeling of wind turbines is elaborated. Hereby, the properties of reference wind turbines are cited (i.e. the geometry of towers, hub, and rotor characteristics). Detailed Finite Element Models (FEM) for the structures are created by including soil springs that represent the soil surrounding the foundation. To check bearing capacity of the foundations, Terzaghi's Bearing Capacity Theory is used. These models are created and analyzed by using SAP 2000 software program.

In Section 5, dynamic behavior of the systems under wind and seismic loading is defined. The wind loads on blade and tower are calculated separately by the use of Blade Element Momentum Theory and German Institute for Standardization (DIN) 1055 / 1056 Codes respectively. The design parameters such as the wall thicknesses and diameters of the towers are determined as the results of the analyses. Frequencies, obtained from SAP 2000, are inserted into the Campbell Diagram to check the resonance of the system.

In Section 6, the use of API RP-2A Codes, in terms of buckling, bending, and shear stresses, performs the structure strength check. The checks should be carried out to find the required thickness of tower that has an impact on the cost of the structures.

In Section 7, the financial models are created to manage the cash flows throughout the lifetime of the projects. Economic parameters, such as investment cost, revenue, etc., are defined in the Section. The Section contains a discussion of the optimum solutions and the numerical results obtained during the solution. The analysis has been conducted for different turbines to find the most advantageous wind turbine investment.

2. WIND ENERGY

Wind, a kind of solar energy, results from the irregularities of heating of the atmosphere surface and rotation of the earth. Modern wind turbines to generate electricity use wind flow, in other words, motion of energy. Wind turbine can be defined as a well-known term for machines with rotating blades that convert the kinetic energy of wind into useful power. Wind energy defines the process by which the wind is used to generate mechanical power [16].

Nowadays, wind power is gaining popularity. It is becoming the fastest growing energy source due to the rise of productivity in wind turbines. Additionally, the following reasons render wind power as a more attractive resource [53].

- It reduces carbon emissions.
- It is an unending source of energy.
- The capacity of wind turbine farm can be easily scaled up.
- The investment cost is very low in comparison with the other resources.
- It doesn't use a lot of land.
- It is available everywhere.

The history of wind power shows that it still needs to improve tremendously. Although, it has made a significant progress so far, it is projected that wind power requiring improvement as an energy resource is going to continue to improve in an increasing scale. In addition to the technical and economic issues, the effects of the wind energy on the environment should be studied in detail. The advantages of wind energy on the environment can be summarized as below:

- Wind turbines do not produce atmospheric emissions that create acid rain or increase health problems, such as asthma or greenhouse gases.
- According to the reports, wind energy has a great potential in reducing cumulative greenhouse gas emissions by 14%, saving $400 billion and avoiding global damage

by 2050.

- Wind power does not use water, unlike conventional electricity sources. Production of coal, nuclear, or gas-fired power uses water to cool while water is globally a scarce resource. Wind power, on the other hand, reduces water consumption.
- Wind is an inexhaustible form of solar energy. Winds result from the atmosphere warming caused by the sun, the rotation of the Earth, and irregularities on the Earth's surface.

In brief, positive, and negative impacts of wind energy should be investigated before its construction. Wind energy reduces water consumption and environmental pollution. On the other hand, it causes visual interference as well as noise pollution, and has negative impacts on the wildlife.

2.1. History of the Wind Energy

Wind turbine has a history of at least 3,000 years. People started to use wind turbines in the Mediterranean region in the form of vertical windmills to grind grain. After the vertical ones, the horizontal-axis windmills came into use and it has been used to generate electricity for 120 years. The development of wind power is always directly related with the fluctuations in the oil price in the market throughout history. During the oil crisis in the 1970s, the technology of wind power acquired importance at first but was undermined afterwards. During the last decade, promotion laws and concessionary policies positively influenced the market towards the wind power industry. This caused a rapid development of the wind market in many countries and the wind turbine technology experienced a great development [17, 18]. This Section includes an overview of the development of wind power throughout the history and its environmental and climatic effects on humans. Although these impacts seem minor when compared to the fossil fuels, the sustainability of the wind energy has a great potential in the long-term.

According to the resources written on wind turbines, the earliest windmills had vertical axes. They were found at the Persian-Afghan border and were simple drag devices used to grind grain. The usage of windmills started in Egypt approximately

3,000 years ago with the purpose of pumping water. After that, the Chinese used wind wheels with a vertical axis of rotation to drain rice fields. Europeans used the same system after centuries. During 12th century, Turkey, developed the first modern vertical wind turbine in Diyarbakir. On the other hand, horizontal axis windmill spread had extended from the Mediterranean to Central Europe. The first windmills were seen in the UK around 1150, in France in 1180, in Flanders in 1190, in Germany 1222 and in Denmark 1259. People who carried the knowledge of windmills from the Mediterranean to Europe were the cause for this spread [20].

The usage of windmill increased dramatically between the 12th and 19th centuries in Europe. A typical European windmill reached to 25m-rotor diameter by the end of the 19th century. People benefited from windmills not only by grinding their grain, but also by pumping water to drain lakes. There were 20,000 modern European windmills in operation in France, by the year 1800 [20].

Thousands of years after its first usage, the first windmill that generates electricity was built in 1887 in Scotland. The first wind machine, built for electricity, was a low speed and high-solidity wind turbine (WT) of 12 kW in Cleveland, Ohio, in 1888. After this year, the capacity of producing energy from the wind turbines started to increase. During the late stages of World War I, people had already reached to 25 kW capacity machines in Denmark. In the Netherlands, 90% of the power used in industry was provided from wind energy. With the onset of Industrialization, a gradual decline in the usage of windmills occurred but, even in 1904, 11% of the Dutch industrial energy was provided from the wind energy and Germany had built more than 18,000 units. On the other side, the popularity of windmills in the US reached its zenith between 1920 and 1930 when approximately 600,000 units were in operation [18, 20].

Significantly, a prototype of the modern horizontal axis wind turbine was first constructed in the US in 1941. Wind turbines using electric power lines were generally able to supply electricity [17]. After World War II, Johannes Juul developed a turbine which generated approximately 2,2 million kWh between 1956 and 1967 as a result of the Danish design philosophy. During the same years, Hütter created a new approach,

known as Hütter's turbine, which became known for its high efficiency. Despite such successful attempts, the large-scale wind power lost its significance after World War II [20].

When the critical milestones in the wind energy are taken into consideration, firstly, the encouragement of the US government in the wind energy research and development comes to mind after the oil crisis of 1973. In the years from 1973 to 1986, the market of wind turbines enlarged from domestic and agricultural (1kW to 25 kW) to utility interconnected wind farm applications (50 kW to 600 kW). The first large-scale wind energy farms were created in California with 16,000 machines, ranging from 20 kW to 350 kW to 1.7 GW by the federal investment and energy loans issued by the USA government. After this, in Europe, wind farm installations increased consistently as a result of higher costs of electricity and the development of perfect wind resources leading to the creation of a small but stable wind market. After 1990, Europe became the center of attraction for the market [18].

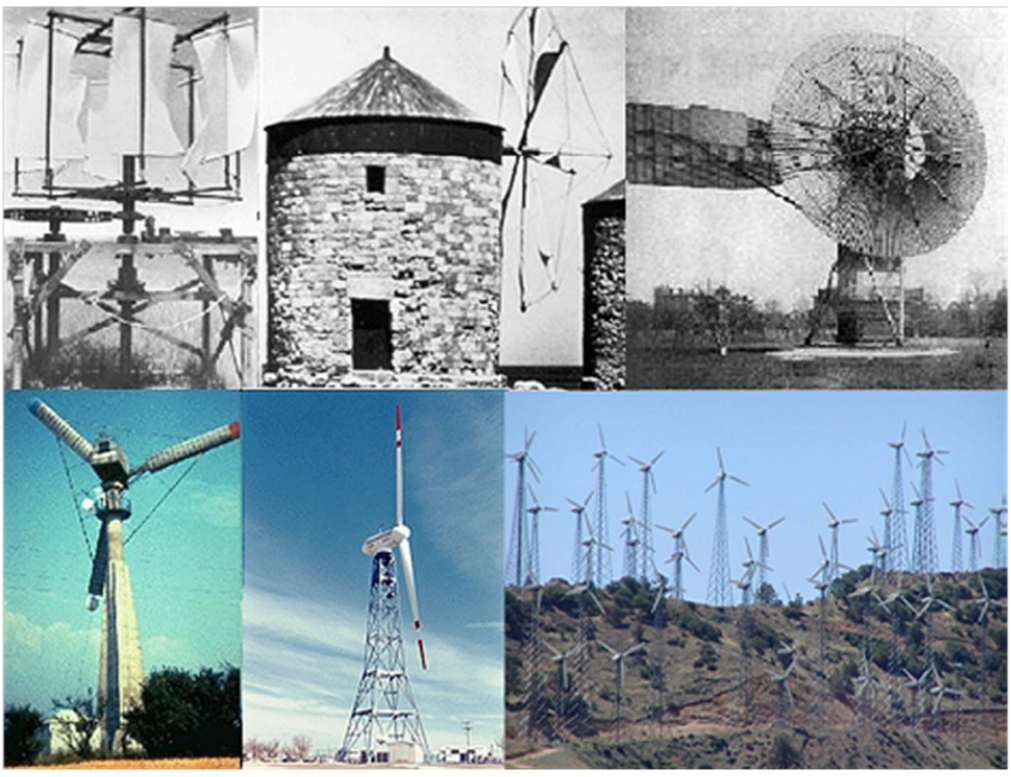


Figure 2.1. From the Early Stages of Wind Energy Evolution [18].

During the 1990s, installed wind energy capacity has started to increase all over the world (especially in Europe and the United States), which attracted the attention of electricity companies, wind farm project owners and researchers towards the prediction of short term, mainly motivated by the necessity of integration of a residual fluctuating amount of wind power. Additionally, after the developments in European countries such as France, Denmark, Germany, and the UK during 19th century, further development of wind generators in the US, inspired by the design of airplane propellers and monoplane wings, displayed that large-scale wind turbines could work. In spite of increasing reliability, mass production and production quality are areas of huge progress; profitability has been the main reason for investment during the century. A 300-kW wind turbine with a 30m-diameter rotor was built in 1989. The progress is obvious since 2.5 MW turbines are constructed in many wind farms 12 years later as shown below table. In the near future, it is expected to see wind turbines with more generated power [17, 18, 19, 20].

Table 2.1. Development of Wind Turbine Size Between 1985 and 2002 [20].

Year	**Capacity (kW)**	**Rotor diameter (m)**
1985	50	15
1989	300	30
1992	500	37
1994	600	46
1998	1500	70
2001	2000	72
2002	2500	8

Additionally, it can be easily stated that people develop wind turbines due to environmental concerns. The history of our planet demonstrates that climate change occurred from time to time. As it is understood, the reasons of climate change are a result of natural phenomena and human activities. One of the most serious problems of environmental threat is the climate change and measures should be taken in order to prevent it since it causes increases in temperatures all around the world. Increasing

temperatures are expected to induce storms, unpredictable weather conditions as well as rising sea levels. To prevent these outcomes, governments have encouraged companies to make investments on renewable energy resources, specifically wind energy.

Wind energy sector has been improving dramatically in recent years. Countries are concentrating on wind energy (WE) nowadays due to following reasons [22].

- WE reduces dependence on the energy import,
- WE has no fuel price constraints,
- WE's productivity is increasing,
- WE supply is secure,
- WE adds to the diversity of energy resources,
- WE does not release greenhouse gas to the atmosphere,
- WE is environmentally friendly.

Wind energy includes two types of wind turbines: onshore and offshore. Onshore wind turbines, in other words, land-based wind turbines, are installed turbines on land far away from the shore. On the other hand, offshore wind turbines generate energy in the sea. The onshore wind turbine technology has improved over the last five years since it maximizes electricity production by using bigger and taller hubs, larger rotors and bigger generators depending on the conditions of the site.

Nowadays, wind turbine manufacturers offer variety in the components of wind turbines. For example, the rotor diameter differs from 40m to 135m, and the hub height differs from 90m to 150m and generators vary from 1 MW to 7.5 MW. Meanwhile, the wind turbine, which has a 7.5 MW generator capacity, is the largest installed onshore wind turbine until now in terms of its generator capacity.

The variety of the wind turbines enabled to set a record year in 2015 with more than 63 GW and a 22% increase over the previous year. The total global installed wind energy capacity reached approximately to 433 GW.

The last record was experienced in 2014 when over 51.7 GW was installed all around the world. The global wind power capacity and annual additions are shown in the below figure [24].

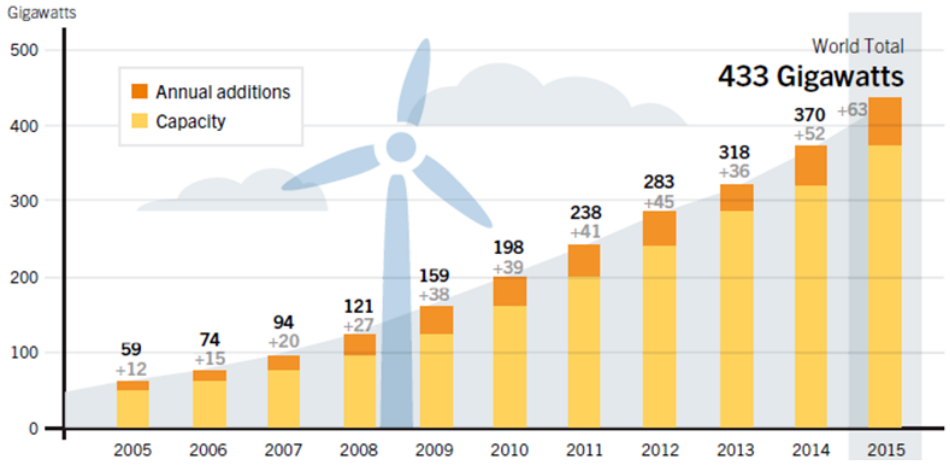
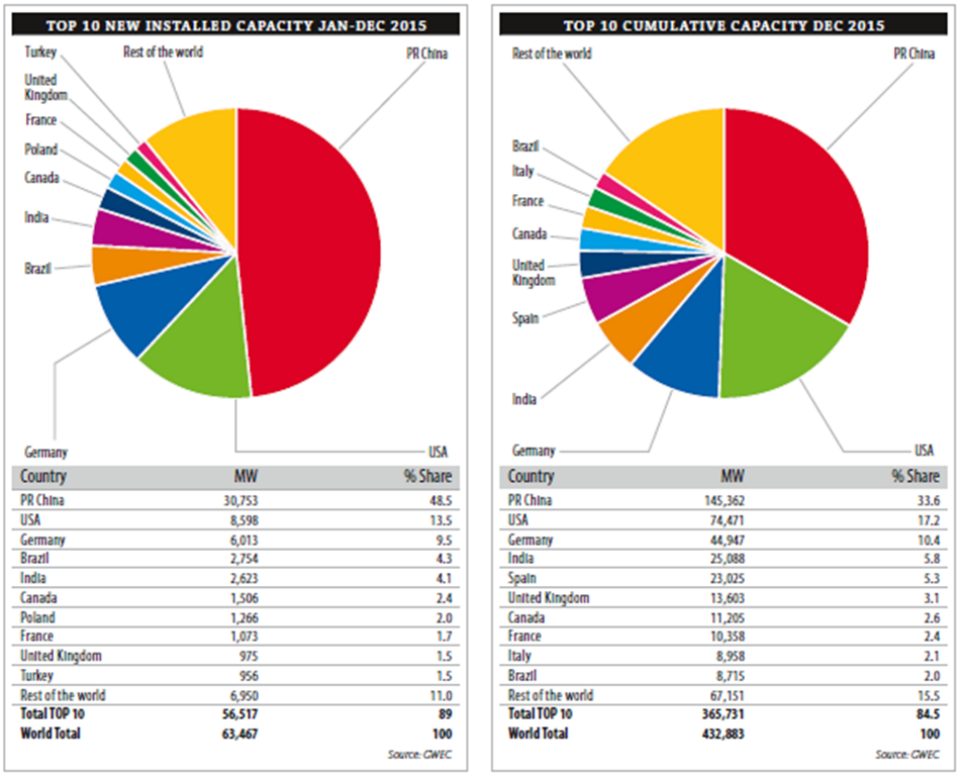


Figure 2.2. Wind Power Global Capacity and Annual Additions (2005-2015) [24].

The wind industry is situated in more than 80 countries, of which 28 countries have more than 1 GW installed capacity, including 1 in Africa; 17 in Europe; 3 in North America; 4 in Asia-Pacific; and 3 in Latin America. China has been the largest wind power market since 2009 and maintained its top position by adding more than 30.7 GW within 2015. The details of wind power capacities and additions for top 10 countries during 2015 are shown in the below figure [25].

Although Turkey added nearly 956 MW wind energy capacity to its portfolio and was listed in the top 10 chart of the new capacities in 2015, Turkey does not rank in the top 10 in accordance with its cumulative capacity according to The Global Wind Energy Council's report for 2015. The cumulative capacity of wind energy reached almost to 5 GW. The details of the status of Turkey's wind power energy are expounded in the below Section.



Country	MW	% Share
PR China	30,753	48.5
USA	8,598	13.5
Germany	6,013	9.5
Brazil	2,754	4.3
India	2,623	4.1
Canada	1,506	2.4
Poland	1,266	2.0
France	1,073	1.7
United Kingdom	975	1.5
Turkey	956	1.5
Rest of the world	6,950	11.0
Total TOP 10	**56,517**	**89**
World Total	**63,467**	**100**

Source: GWEC

Country	MW	% Share
PR China	145,362	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,205	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	67,151	15.5
Total TOP 10	**365,731**	**84.5**
World Total	**432,883**	**100**

Source: GWEC

Figure 2.3. Top 10 Countries Wind Power Capacities and Additions During 2015 [25].

2.2. The Wind Energy Status of Turkey

The Turkish wind energy market has been developing for years. According to The Global Wind Energy Council report of 2015, Turkey has become one of the leading countries in the World. Turkey is 10th largest annual market with a total capacity up to almost 5GW spread over 125 licensed wind farms. The Turkish Wind Power Association forecasts that total installed capacity is expected to reach approximately to 10 GW under the current regulatory framework in the next ten years. Moreover, it is possible to reach to 20 GW with the right encouragements and amendments to the regulatory framework.

Turkey's wind potential is assumed to be approximately 50 GW under the circumstances, which is bigger than 7m/s wind speeds at 50 meters and with capacity factor more than 35%. The total installed capacities regarding regions in the end of 2015 are shown in the below figure. It is shown that the Aegean Region (EGE) is

ranked on the top with a total of 1,78 GW, followed by the Marmara Region with 1.74 GW.

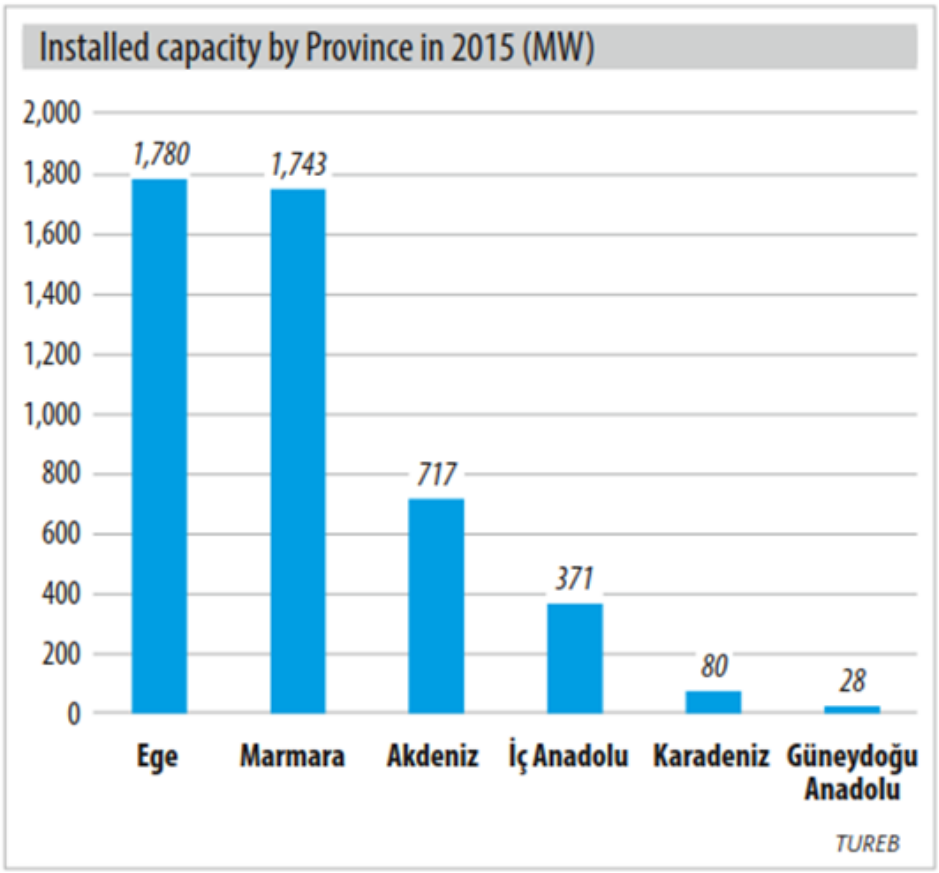


Figure 2.4. Installed Capacity by Province as of the end of 2015 [25].

Currently, Turkey is able to meet its electricity demand by wind power in the ratio of 6%. Nevertheless, Turkey aims to increase the rate to 30% until 2023 due to its limited oil and gas reserves. Therefore, it is essential to make more investments in the energy sector to meet the increasing energy demand. The below figure demonstrates that the gap between consumption and production has been increasing every year.

Below figure shows Turkey's energy portfolio forecast between the years 2005-2020. As seen in the figure, the energy demand has been increasing immensely in conjunction with the energy import. It can be correlated to the fact that Turkey is dependent on the import of primary energy sources, which are oil and natural gas.

To increase investment, Turkey's Renewable Energy Law set the legal framework for supporting electricity generation from wind energy. The incentives can be summarized as below [25].

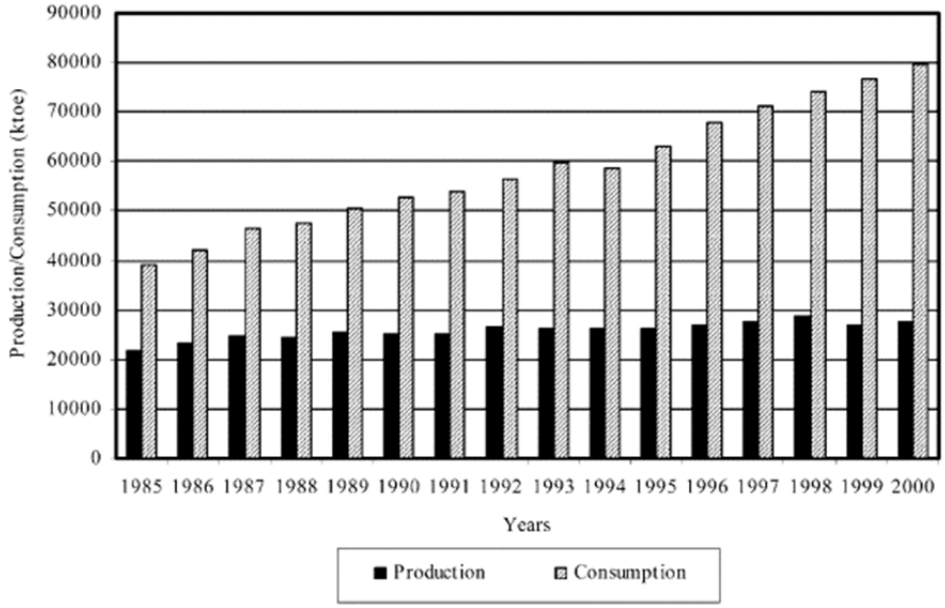


Figure 2.5. Turkey's Primary Energy Production and Consumption During 1985-2000 [26].

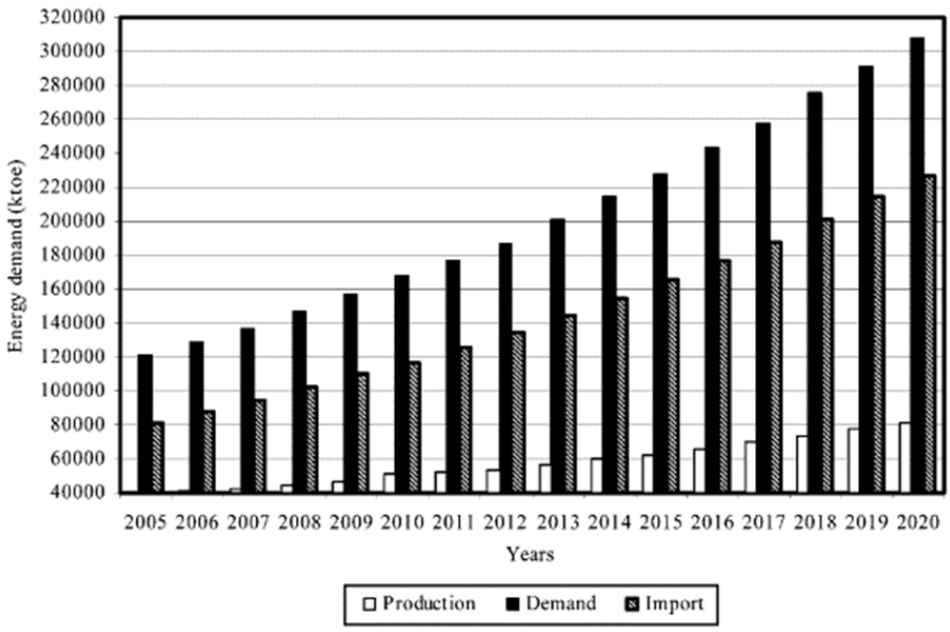


Figure 2.6. Primary Energy Production, Demand and Import in Turkey Between 2005-2020 [26].

- The feed-in tariff is 7.3 cent/kWh for ten years.
- Wind power producers can sell their electricity to the national market.
- The 85% discount for the right of easement on State owned land for transportation and transmission is applied. The discount will apply to the first ten years from the beginning of wind turbine operation.
- An additional bonus of up to USD 3.7 cent/kWh will be given for up to five years for the usage of locally manufactured components.
- Wind projects, whose capacities are below 1 MW, are not required to obtain a generation license from Turkey's Electricity Market Regulatory Authority (EMRA).
- The law allows for the construction of renewable energy projects in protected regions, national and natural parks, wildlife development zones, conserved forests, natural protected areas, special environmental protection zones, provided that the necessary permissions are obtained from the Ministry of Environment and/or regional protection boards.

Turkish Electricity Transmission Company (TEIAS) informs established transformer capacity every year. Additionally, TEIAS also announces how much wind power can be connected to the regional grid system at the same time. It is stated that further work is carried out in order to increase the grid capacity by 3,000 MW.

In addition, the tender for a Ministry of Energy Project - a wind power plant installation in a thousand-megawatt power plant and turbine production which will increase the wind energy production capacity in Turkey by 17 percent and which has an investment amount estimated as 1 billion USD - is planned in 2017. The consortium, which will be the winner of the tender, will build a wind turbine factory with an investment cost of over $ 100 million, required to achieve a 65 percent indigenousness rate. In the plant, 300 to 450 domestic wind turbines will be produced; each will be having at least 2.3 megawatts of power. The consortium will be making R&D studies for 10 years in total five areas including at least three of the following areas; wing, generator design, materials technology and production techniques, software and innovative gearbox. Each year a budget of USD 5 million will be allocated for the afore-

mentioned R&D studies and these R&D activities will be carried out by 50 technical staff consisting of 80% domestic engineers.

3. SITE SELECTION FOR WIND PROJECTS

Site selection is the first step in the investment of wind power. One of the most critical issues for making investment is the decision for the project location. The selection of a site for turbine farm is a complex process since it includes physical, economic, environmental, and technical requirements.

3.1. Wind Speed Map of Turkey

Ministry of Energy and Natural Resources has worked on renewable energy capacity atlases. The atlas informs on the mean wind speed at the height of 50m, capacity factor, substation, and grid system for every city in Turkey. During the preparation of the atlas, Bennui's study is consulted [27].

At first sight, investors are disposed to make an investment in the Aegean and Marmara regions and south of Kayseri city in compliance with the below map. The maps also provide insight about the site selection. The details and factors, which affect the site selection decision, are explained in Section 3.2.

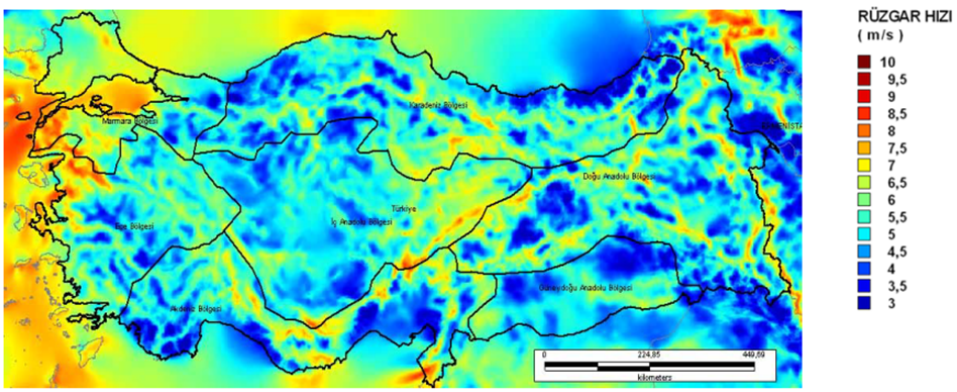


Figure 3.1. Yearly average wind speed distribution map of Turkey (50m) [27].

3.2. Site Selection Process

Selection of the site for the wind turbine projects is a complex process. The process includes considering a comprehensive set of criteria and comparing multiple targets in determining the suitability of a certain area. Taking into consideration multiple disciplines, such as economical, technical, and physical, leads to the best selection. Hence, systematic methods are used for overcoming multi-criteria issues to evaluate the suitability of conditions. One of the best popular techniques is the Geographic Information System (GIS) [27].

A GIS is a useful computer-based tool to capture, store, manipulate, analyze, manage, and present spatial or geographic data. Ten spatial data layers are defined as input to determine the suitable sites for large wind turbines. Each data layer has its own score, which depends upon its suitability and significance. Weighing scores for each criterion is derived directly from a comparison of the substance of one criterion with another. The rules are, basically, if the score is equal to "1", criteria in the columns are less significant than those in the row; if the score is "2", the criteria in the columns are as important as those in the row; if the score is up to "3", the criteria in the columns are more significant than those in the row. The score equal to "0" means the criteria in the columns are the same as those in the row. Table 3.1 shows the ten data layers and their scores [27].

The score for each GIS criterion depends upon its significance and suitability. Each data has 5 or 6 different classes related to their scores. The score for specific buffer/offset zones are determined in the below tables, which are taken from Bennui *et al.* (2007) [27].

The "Suitability function" is divided into 5 classes as shown in Table 3.2. The suitability of sites is determined in accordance with the total scores, obtained from the above tables. According to the Wind Speed Map of Turkey at the height of 50 m and site selection criteria, Çanakkale, Balikesir and Kayseri are chosen for the current study. The wind speeds of these cities are high and the criteria are met; therefore, the

results of analysis show that they are extremely suitable for new investments.

Table 3.1. Weighing Scores for Each Criterion [27].

Decsion Parameters (Criterion)	1. Urban	2. Village, Community	3. Important Places	4.Scenic Area	5. Airport Area	6. Highway	7. Wind Class	8. Surface Roughness	9. Elevation	10. River/Water Body	Total Score	Weigh Score
1. Urban	0	3	1	1	3	3	1	3	1	3	19	0.106
2. Village, Community	1	0	1	1	3	3	1	3	1	3	17	0.094
3. Important Places 4.Scenic Area	3	3	0	2	3	3	1	3	1	3	22	0.122
4. Scenic Area	3	3	2	0	3	3	1	3	1	3	22	0.122
5. Airport Area	1	1	1	1	0	3	1	3	1	3	15	0.083
6. Highway	1	1	1	1	1	0	1	1	1	3	11	0.061
7. Wind Class	3	3	3	3	3	3	0	3	2	3	26	0.144
8. Surface Roughness	1	1	1	1	1	3	1	0	1	3	13	0.072
9. Elevation	3	3	3	3	3	3	2	3	0	3	26	0.144
10. River/Water Body	1	1	1	1	1	1	1	1	1	0	9	0.050
Total											180	1.000

Table 3.2. Ranges and Classes of Suitability Function [27].

Category	**Range of Suitability function**	**Class**
1	0.00-1.00	Unsuitable
2	1.01-2.00	Low suitable
3	2.01-3.00	Moderate suitable
4	3.01-4.00	High suitable
5	4.01-5.00	Extremely suitable

Table 3.3. Ranging Scores for each Layer [27].

Ranging Scores for GIS Layer 1- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-2.5	0	Exclusion Zone
2	2.5-3.5	1	Less suitable
3	3.5-4.5	2	Suitable
4	4.5-5.5	3	Moderate suitable
5	5.5-6.5	4	High suitable
6	>6.5	5	Extremely suitable
Ranging Scores for GIS Layer 2- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-1.0	0	Exclusion Zone
2	1.0-2.0	1	Less suitable
3	2.0-3.0	2	Suitable
4	3.0-4.0	3	Moderate suitable
5	4.0-5.0	4	High suitable
6	>5.0	5	Extremely suitable
Ranging Scores for GIS Layer 3- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-2.0	0	Exclusion Zone
2	2.0-2.5	1	Less suitable
3	2.5-3.0	2	Suitable
4	3.0-3.5	3	Moderate suitable
5	3.5-4.0	4	High suitable
6	>4.0	5	Extremely suitable
Ranging Scores for GIS Layer 4- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-1.0	0	Exclusion Zone
2	1.0-2.0	1	Less suitable
3	2.0-3.0	2	Suitable
4	3.0-4.0	3	Moderate suitable
5	4.0-5.0	4	High suitable
6	>5.0	5	Extremely suitable
Ranging Scores for GIS Layer 5- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-3.0	0	Exclusion Zone
2	3.0-6.0	1	Less suitable
3	6.0-9.0	2	Suitable
4	9.0-12.0	3	Moderate suitable
5	12.015.0	4	High suitable
6	>15.0	5	Extremely suitable

Ranging Scores for GIS Layer 6- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-0.5	0	Exclusion Zone
2	0.5-1.0	1	Less suitable
3	1.0-1.5	2	Suitable
4	1.5-2.0	3	Moderate suitable
5	2.0-2.5	4	High suitable
6	>2.5	5	Extremely suitable
Ranging Scores for GIS Layer 7- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	<100	1	Less suitable
2	100-150	2	Suitable
3	150-200	3	Moderate suitable
4	200-250	4	High suitable
5	>250	5	Extremely suitable
6			
Ranging Scores for GIS Layer 8- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	400	1	Less suitable
2	100	2	Suitable
3	50	3	Moderate suitable
4	10	4	High suitable
5	0.1	5	Extremely suitable
6			
Ranging Scores for GIS Layer 9- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0-40	0	Exclusion Zone
2	40-80	1	Less suitable
3	80-120	2	Suitable
4	120-150	3	Moderate suitable
5	150-200	4	High suitable
6	>200	5	Extremely suitable
Ranging Scores for GIS Layer 10- Urban area			
Category	**Offset (km)**	**Score**	**Class**
1	0.0-0.2	0	Exclusion Zone
2	2.0-0.4	1	Less suitable
3	4.0-0.6	2	Suitable
4	0.6-0.8	3	Moderate suitable
5	0.8-1.0	4	High suitable
6	>1.0	5	Extremely suitable

4. MODELLING

In this part of the thesis, system properties and structural models of the wind turbines are described. In addition, the definition and calculation of modulus subgrade reaction values and modeling of the foundation steps are explained within the scope of this Section.

4.1. General Description

A wind turbine consists of four main parts, namely foundation, tower, rotor, and nacelle. The below figure demonstrates these parts.

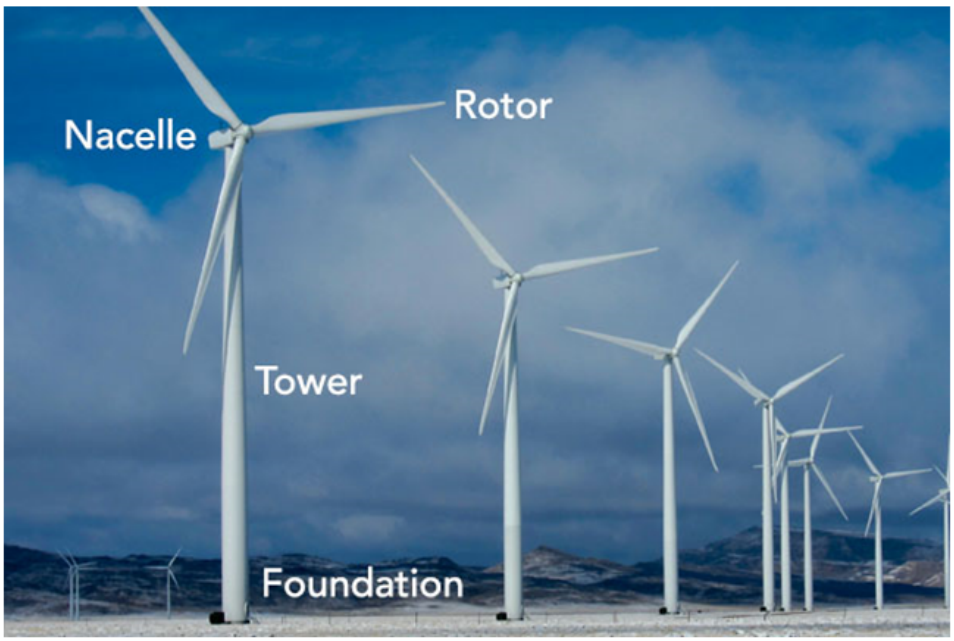


Figure 4.1. The Parts of Typical an Onshore Wind Turbine [28].

Foundation and tower may be thought to be structural parts of the wind turbine; additionally, nacelle and rotor may be considered to be its mechanical parts. Electricity is generated as a consequence of rotating blades; afterwards, it is transmitted to regional grid system that is connected at the level of the foundation.

4.1.1. Wind Turbine Properties

In this thesis, two different wind turbines models are used. Reference wind turbines have been selected with 3 blades and their rated powers are 1.80 MW and 3.45 MW. The turbines are Vestas's wind turbines and their model names are V90-1.8/2.0 MW IEC IIA/IEC IIIA and (V90) V112-3.45 MW IEC IA (V112). The purpose of this selection is as follows:

- Vestas has a share in Turkey's wind power energy market almost at a rate of 25% according to the number of licensed wind power plants in operation.
- Vestas provides advantages for investment in terms of knowledge of the market and its policies, enabling quick procurement of spare parts, and technical capability.
- The models are suitable to install in accordance with wind classes.
- There are emergency-stop push buttons in the hub, nacelle, and bottom of the tower. They provide the option to stop the operation during any emergency cases, such as an earthquake. Therefore, while the turbines are being designed, only extreme wind loading is considered. Seismic loads are excluded in the load combinations.
- The models have been constructed in 9 different cities, including Çanakkale and Balikesir in Turkey previously and experiences show that these are appropriate for the conditions of

The reference wind turbines have been modeled by means of SAP 2000, which is the software package. Their main properties are listed in the table below.

Table 4.1. The Main Properties of Reference Wind Turbines.

Description	**V90-1.80 MW**	**V112-3.45 MW^{TM}**	**Units**
OPERATING DATA			
Rated power	1.800.00	3.450.00	kW
Cut-in wind speed	4	3	m/s
Cut-out wind speed	23	25	m/s
Re cut-in wind speed	25	23	m/s
Wind class	IEC IIA/IEC IIIA	IEC IA	
Standard operating temperature range from	-20 - 40	-20 - 40	°C
SOUND POWER			
Maximum	104	Dependent on site	dB
ROTOR			
Rotor diameter	90	112	m
Swept area	6.36	9.852.00	m^2
Blade Number	3	3	no
Nominal revolutions	14.9	16.1	rpm
Operational interval	9-14.9	8.6-18.4	rpm
TOWER			
Hub heights	80	69	m
	95	94	m
	105		m
NACELLE DIMENSIONS			
Height for transport	4	3.4	m
Height installed (incl. CoolerTop®)	5.4	6.9	m
Length	10.4	12.8	m
Width	3.5	4.2	m
HUB DIMENSIONS			
Max. transport height	3.4	3.8	m
Max. transport width	4	3.8	m
Max. transport length	4.2	5.5	m
BLADE DIMENSIONS			
Length	44	54.7	m
Max. chord	3.9	4	m
WEIGHT			
Nacelle	68	150	tons
Transformer	8	Inc	tons
Rotor	38	38.23	tons
Total Top Weight	114	188.23	tons

4.1.2. Support Structure Properties

The support structures are chosen as mat foundation, composed of reinforced C40 concrete and vertical and lateral springs, which represent the soil. Specific weight of concrete is 2.4 ton/m^3 and the modulus of elasticity of the concrete is 34,000 MPa. The dimensions of foundation are different for reference wind turbine models. For V90, the dimensions are 12 m x 12 m x 3 m while the dimensions are 15 m x 15 m x 3 m for V112. The main properties of the support structures are demonstrated in the table below and an exemplary one is provided in the below figure.

Table 4.2. The Main Properties of Support Structure.

Type of Foundation	Mat Foundation
Dimensions	
For V90	12 m x 12 m x 3 m
For V112	15 m x 15 m x 3 m
Compressive Strength	40 MPa
Concrete Young Modulus	34.000 MPa
Poisson's Ratio	0.30
Specific Weight of Concrete	2.4 ton/m3



Figure 4.2. Example of an Onshore Wind Turbine Foundation [29].

4.1.3. SAP 2000 Software

SAP 2000 program is used to model and analyze wind turbines. 3-D modeling of the turbines is integrated with the foundation according to material properties and dimensions and their material specification in SAP 2000. Afterwards, the goal is to make analysis to determine frequency, mode shapes and optimize the structural properties under defined loads.

4.2. Tower Modeling

In this Section, the structures are modeled in SAP 2000 to determine their structural frequencies and mode shapes.

Wind turbine towers are usually made of steel. The grade of the steel is S 355. The towers are designed as a cantilever beam. The height of towers is 95 m and 94 m for V90 and V112, respectively. The diameter and thickness change regarding the type and location of wind turbines but it is a general rule that they decrease from the base to tower gradually. More clearly, the towers are divided into 32 Sections whose length is generally 3 m. The diameter and thickness of each Section is determined separately.

It should be highlighted that the rotor and nacelle are defined as a mass, in other words, tower top mass. The center of mass is found, 0.3 m away from the center of tower in upwind direction, and assigned in three directions to integrate the modal analysis.

After the modal analysis, frequencies and mode shapes are acquired for all the cases. In figures below, the first and third modes for the turbine can be observed.

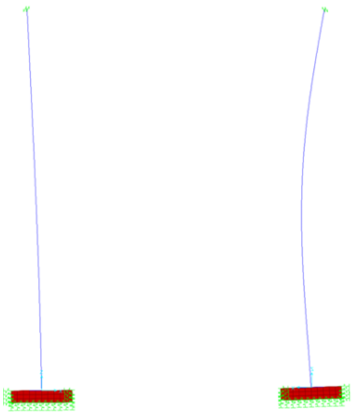


Figure 4.3. The First and Third Modes of the System.

4.3. Foundation Modeling

After describing the material of foundation in Section 4.1.2 in SAP 2000 model, identification of soil properties is important since the type of soil directly affects the frequency of the system. Hence, foundation of the system has modeled as fixed base and with springs. The results show that the structural frequency value is obtained higher in the fixed base foundation, as expected. Figure 4.4 shows onshore mat foundation with soil springs, created in SAP 2000. To reach more realistic results, mat foundation is modeled together with elastic springs, which are applied laterally and vertically to represent the soil. These are denominated as t-z (vertical) and p-y (lateral) springs. The analogy and calculations are shown in Section 4.3.1.2.

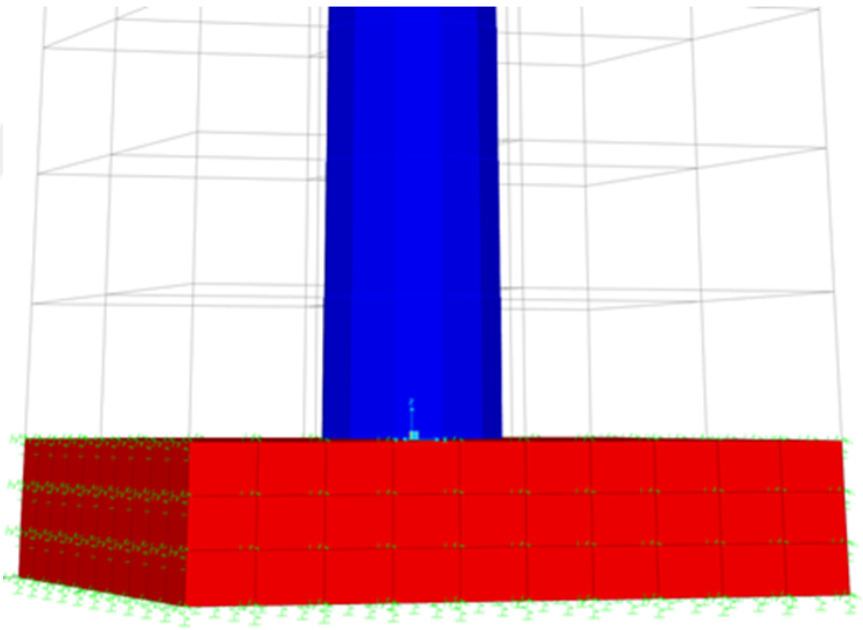


Figure 4.4. Onshore Mat Foundation.

4.3.1. Structural Design of Mat Foundations

There are two methods for the structural design of mat foundations [30].

- Conventional Rigid Method
- Approximate Flexible Method

4.3.1.1. Conventional Rigid Method. According to conventional rigid design method, the mat foundation is supposed to be infinitely rigid. Besides, the distribution of soil pressure resembles a straight line and the centroid of the soil pressure matches the line of action of the resultant loads.

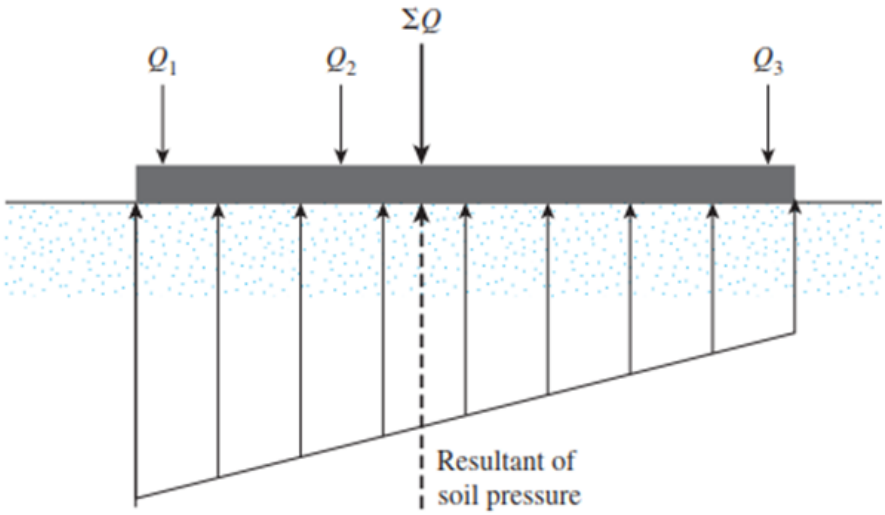


Figure 4.5. Principles of Design by Conventional Rigid Method [30].

4.3.1.2. Approximate Flexible Method. According to approximate flexible method, reaction of the soil is modelled as a series of linear independent elastic springs in the model. There is no continuity between the springs through the mat. This assumption is called as the Winkler foundation. The elastic constant of the springs called as subgrade reaction, k. This method is closer to real life conditions.

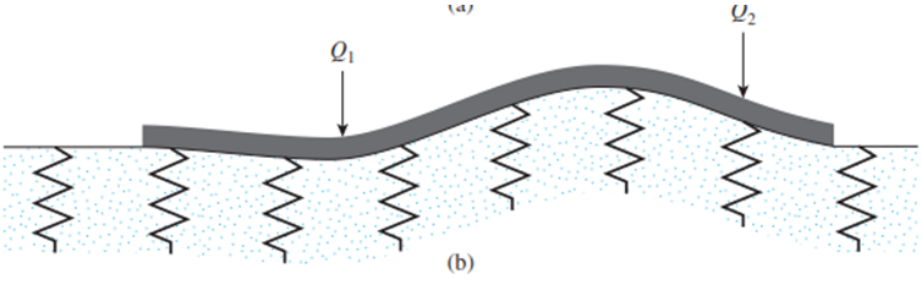


Figure 4.6. Principles of Approximate Flexible Method [30].

Modulus of subgrade reaction of soil surrounding the foundation is analyzed. For the study, it is assumed that wind turbines are constructed on dense sand soil. The common formula that is given below is used to find out approximate modulus of subgrade reaction value:

$$k = \frac{p}{y} \tag{4.1}$$

where k is modulus of subgrade reaction in kN/m^3, p is load per unit area in kN/m^2 and y is settlement produced under applied loads in m.

In this equation, load per unit area can be found by summation of dead loads that include tower top mass, self-weight of tower and foundation divided by the surface area of the foundation. Settlement should be calculated by using certain theorems; one of them is Boussinessq Theorem.

Settlement calculation is considered to be a long-term consolidation to get a long-term representative subgrade reaction value. The equation of the long-term settlement is as follows:

$$S_{oed} = m_v \times DH \times Dq \tag{4.2}$$

where S_{oed} settlement in m, is the m$_v$ coefficient of volume compressibility in m^2/kN, is the ΔH thickness of compressible layer in m, is the Δq average stress increment in compressible layer in kN/m^2.

In settlement equation coefficient of volume compressibility value is chosen for dense sand as 1.5x10^{-5} m^2/kN and thickness of compressible layer is equal to 1.5 times of the width of the foundation.

When a footing is placed on soil, the stress of the soil layer increases [31]. To find Δq, or $\Delta\sigma$, approximate 2:1 method is used. According to the method, the increase in

stress at depth is found by the following formula;

$$\mathrm{q} = \frac{\mathrm{qBL}}{(B+z)\,(L+z)} \tag{4.3}$$

where, q is net pressure on the foundation area kN/m^2, B is the width of the foundation in m, L is the length of the foundation in m, z is the thickness of compressible layer in m.

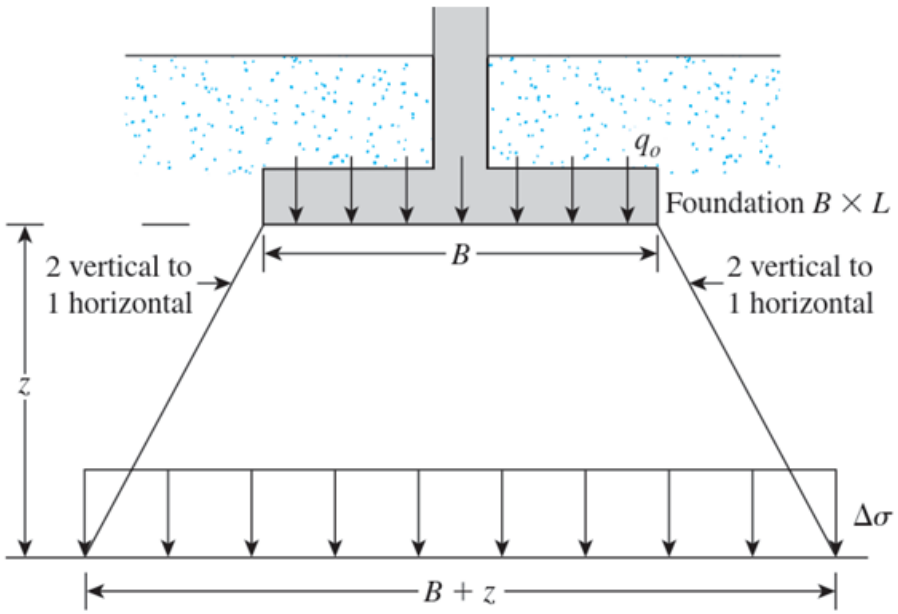


Figure 4.7. Stress Increase under a Foundation According to 2:1 Method [30].

The below calculations are made for V90 under wind loading caused by 9.10 m/s average wind speed. The used foundation in the dead load of the wind turbine above is given as:

- The tower structure is 194.33 tons, 1,906.33 kN,
- Tower top mass is 114 tons, 1,118.34 kN,
- Foundation mass is 1036.80 tons, 1,0171.01 kN
- Total weight is 1,345.12 tons, 13,195.68 kN

Net pressure on the foundation area, q is:

$$\mathrm{q} = \frac{\mathrm{Totalweight}}{Areaoffoundation} = \frac{13,195.68}{144.00} = 91.64\mathrm{kN/m^2} \tag{4.4}$$

$$\mathrm{q} = \frac{\mathrm{qBL}}{(B+z)(L+z)} = \frac{91.64 \times 12\mathrm{x}12}{(12+18) \times (12+18)} = 14.66\mathrm{kN/m^2} \tag{4.5}$$

The equation of the long-term settlement is:

$$S_{oed} = m_v \times DH \times Dq \tag{4.6}$$

$$S_{oed} = \left(1.50 \times 10^{-5}\right) \times 18.00 \times 14.66 = 3.96 \times 10^{-5} m \tag{4.7}$$

The subgrade reaction value is:

$$k = \frac{p}{y} = \frac{91.64}{3.96 \times 10 - 5} = 23,148.15 kN/m^3 \tag{4.8}$$

Subgrade reaction value depends not only on the soil but also foundation dimensions and its depth of embedment. Terzaghi (1955) studied parameters, which affect the coefficient of subgrade reaction. The study showed that the value of the coefficient decreases with the width of the foundation [32].

According to Terzaghi's study, the coefficient of subgrade reaction for a foundation with width B is:

$$k_B = k \times ((B+0.3)/2 \times B)^2 \tag{4.9}$$

$$k_B = 23,148.15 \times ((12+0.3)/2 \times 12)\,2 = 6,080.01 kN/m^3 \tag{4.10}$$

Figure 4.4 represents the lateral and vertical soil springs. In this model, the foundation divides into meshes with dimensions of 1.5 m x 1.5 m. kB value, multiplied by the surface area, 2.25 m^2, of the meshes. The reason for this is that k values are obtained by division of pressure by displacement instead of division of stress by displacement. The one-dimensional spring coefficient is calculated as 13,680 kN/m. The lateral soil springs are two thirds of vertical ones [32].

The same calculations are made for V 112 and vertical spring coefficient is found to be 10,837 kN/m while the lateral one is found to be 7,225.00 kN/m. The values are less than V90 ones since the dimensions of the foundation are bigger than V90 ones. As shown in the formulas above, the values are inversely proportional to the foundation dimensions.

4.4. Terzaghi's Bearing Capacity Theory

Terzaghi studied and formulated that the soil under the footing could generate a pressure triangle as shown in the below figure. The bearing capacity of the soil is developed in a footing owing to three properties of soil that are friction, cohesion, and density.

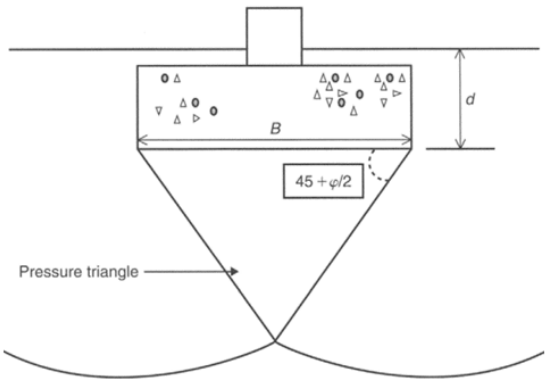


Figure 4.8. Stresses Based on Terzaghi's Soil Bearing Capacity Theory [30].

The ultimate bearing capacity (qult) is defined as the maximum gross pressure intensity level at the base of the foundation of the system where the soil does not sink.

The general ultimate bearing capacity of the foundation formula is given below [30].

$$q_{ult} = (c \times N_c \times s_c) + (q \times N_\gamma) + (0.5 \times B \times N_\gamma \times \gamma \times s_\gamma) \tag{4.11}$$

Cohesion term shows the strength of the soil owing to cohesion that is represented as the first part of the formula.

$$Cohesionterm = cxN_cxs_c \tag{4.12}$$

where c cohesion of the soil, is the N_c Terzaghi bearing capacity factor, is the s_c shape factor.

Surcharge term reflects bearing capacity strength enhanced due to the surcharge. It is calculated in the second part of the formula.

$$Surchargeterm = q \times N_q \tag{4.13}$$

where q the effective stress at the bottom of footing, is the N_q Terzaghi bearing capacity factor.

Density term represents the strength of the soil and it is calculated in the third part of the formula.

$$Densityterm = 0.5 \times B \times N_\gamma \times \gamma \times s_\gamma \tag{4.14}$$

where B width of the shorter dimension of the footing, is the N_γ Terzaghi bearing capacity factor, is the γ effective density of soil, is the s_γ shape factor.

It should be highlighted that effect of friction angle (ϕ) is included in the Terzaghi bearing capacity formula indirectly since all the bearing capacity coefficients (N_c, N_q,

and N_γ) are obtained from the tables, which result from the friction angle. The angle depends on the soil type. The value of the angle is directly proportional with the bearing capacity; in other words, increase in the angle causes increase in the bearing capacity.

Bearing capacity of the foundation should be considered during the design stage of the wind turbines. In order to give an example, the most critical scenario among the cases in the thesis is selected. The wind turbine, V90, under wind loading, developed by 25 m/s average wind speed, and seismic loading is the most critical alternative for the thesis. The calculations, which are shown below, are made for the scenario.

The general formula

$$q_{ult} = (c \times N_c \times s_c) + (q \times N_q) + (0.5 \times B \times N_\gamma \times \gamma \times s_\gamma) \tag{4.15}$$

- c = 0 kPa, since cohesion in sand is usually considered to be zero.
- s_c and s_γ are 1.3 and 0.8 for square footings, respectively.
- In the thesis soil type is assumed as dense sand; therefore, friction angle (ϕ) is 30°. The coefficients for 30° friction angle are: $N_c = 37.20$, $N_q = 22.5$, $N_\gamma = 19.7$.
- $q = \gamma$ x d where d is distance from ground surface to the bottom of the footing and equals to 3m, γ is effective density of soil and equals to 15 kN/m^3 q = 15 kN/m^3 x 3 m = 45 kN/m^2.
- B is the width of the shorter dimension of the footing and is equal to 12 m.

In the light of above information, the ultimate bearing capacity (q_{ult}) can be computed as 2,430.90 kN/m^2.

The dead load of the wind turbine is calculated below:

- The tower structure is 1,286.53 tons, 12,620.88 kN,
- Tower top mass is 114 tons, 1,118.34 kN,
- Foundation mass is 1036.80 tons, 1,0171.01 kN

- Total weight is 2,437.33 tons, 23,910.23kN

Net pressure on the foundation area, q is:

$$\mathrm{q} = \frac{\mathrm{Totalweight}}{Areaoffoundation} = \frac{23,910.24}{144.00} = 166.04\mathrm{kN/m^2} \tag{4.16}$$

A factor of safety should be consulted due to the uncertainties of the soil parameters such as friction angle and cohesion. Suggested factor of safety (FOS) value is 3.0 in accordance with BS 8004 (The British Standard - Code of Practice for Foundations) [30].

F.O.S is calculated as 14.64 for the scenario and it is bigger than 3. Hence, the foundation design is on the safe side in accordance with Terzaghi's Bearing Capacity Theory.

5. DYNAMIC ANALYSIS

In this chapter, dynamic behavior of the systems is defined and dynamic analyses are summarized for the reference wind turbines.

5.1. The Basics of Dynamics

Wind turbine systems consist of certain elements such as tower, rotor, and generator. They have impact on the dynamic behavior of the system. Hence, it is important to design turbine systems as a complete integrated system.

To explain the dynamic effects briefly, the system can be considered as a Single Degree Freedom system as shown in Figure 5.1 [34].

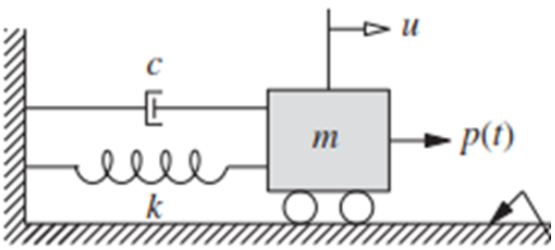


Figure 5.1. Single Degree of Freedom Mass-Spring-Damper System [34].

P(t) represents applied excitation force, c is a viscous damper. The magnitude and phase of the response depends upon the excitation frequency (ω). Therefore, the excitation frequency should be considered seriously to avoid any failure on the system.

The response of the system can be categorized into three cases:

- Quasi-static, $f < f_n$
- Resonance, $f = f_n$
- Inertia dominated, $f_n < f$

where f_n is the natural frequency of the system in Hz and f is excitation frequency in Hz [33].

For the quasi-static case, the displacement of the system is almost the same with the displacement, which is excited due to a static force [34].

For the resonance case, the excitation frequency and natural frequency of the system are close to each other. In this case, the response of the system is larger than its static response. This case is called as resonance [34].

In the third case, the frequency of excitation is lower than the natural frequency of the system. During this case, the mass cannot track the movement [34].

Excitation and natural frequencies should be considered during the design stage since the system response can be higher in values than expected owing to the resonance effect.

5.2. Aerodynamic Analysis

Aerodynamic is a phenomenon, which studies forces and motions of subjects through the air. It enables us to measure the lift forces, which overcome gravity, and drag forces, which display resistance against moving objects through the air.

Wind loading is one of the most important loading types for wind turbine systems. In the thesis, various wind loads are calculated with different wind speeds. Wind loads have influence not only on the blades but also on the tower. The parameters and theories for calculation of wind loads are explained in Section 5.2.

5.2.1. Wind on Blades

The relationship between power and wind speed is significant to determine the optimization and limitation. The power curve enables to calculate how much power is

extracted from the incoming wind.

Wind turbines have operation limits with regards to wind speeds. When the wind speed is higher than a specific value, which is named as cut-in speed, the wind turbine starts to operate. When the wind speed reaches the rated speed, the blades start to rotate in a constant speed. Typically, when a turbine produces energy at a wind speed between the rated speed and cut-out speed, it is considered to be ineffective for cost. Extreme wind speed may affect the wind turbine negatively. Hence, the turbine stops to operate and turns itself in a parked position to prevent damage on any of its units when the wind speed is above the cut-out speed [36].

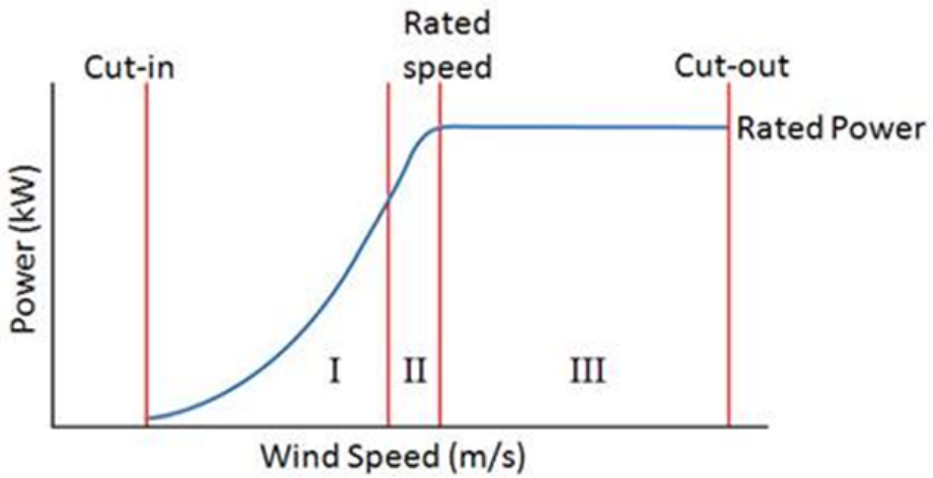


Figure 5.2. Ideal Wind Turbine Power Curve [36].

In Figure 5.4, the power curve is split into three explicit regions. Region I includes low wind speeds. It is under the rated turbine power. On the other hand, Region III involves high wind speeds and the power is equal to the rated turbine power. The turbine controls the generated power while the wind turbine operates in this region. Finally, Region II is a passing region to reach to the rated power.

When the wind flow touches the blades, two aerodynamic forces occur on the blades. These forces are called as lift and drag forces. To explain and calculate the forces, Blade Element Momentum Theory is used in Section 5.2.3.

5.2.2. Wind Speed Data at Different Heights

The power of the wind turbine depends on various factors, among which it is worthy to note are humidity rating, geographic properties of the area, and height above the ground level; however, the main factor is the wind speed.

Various methods are used to calculate the wind speed at a certain height. The reference wind speed at the 50m height has been measured by the Ministry of Energy and Natural Resources. The data for the thesis has been taken from its study named as Turkey Wind Energy Potential Map [41].

There are various theoretical ways used for determining the wind speed at a certain height. One of them is Monin-Obukhov method that is used to point to the wind speed, v at height, z by favor of a log-linear profile. It is clearly expressed by: [40].

$$v\,(z) = \frac{vf}{K}\left[ln\frac{z}{zo} - \left(\frac{z}{L}\right)\right] \tag{5.1}$$

where z the height of turbine, is the v_f the friction velocity, is the K the von Karman constant (normally assumed as 0.4), is the z_0 the surface roughness length, is the L a scale factor called the Monin - Obukhov length, is the $\zeta(\frac{z}{L})$ the solar radiation at the site under survey.

$$\frac{v}{v_0} = \left(\frac{\ln(H/z_o)}{\ln(H_o/z_o)}\right)^{\alpha} \tag{5.2}$$

z_0 is called the roughness coefficient length in m. It depends on the type of land and it ranges from 0.0002 up to 1.6 or more. Furthermore, the value can vary during the year.

The last and simpler method is Hellmann exponential law. It correlates to the

wind speed readings at two different heights, described by [40].

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^{\alpha} \tag{5.3}$$

where H height of wind turbine in m, v is the wind speed to the height H in m/s, v_0 the wind speed to the reference height in m/s, H_0 is the reference height in m and, α the friction coefficient or Hellman exponent.

Hellmann exponential law is a widely used method to determine the wind speeds. For this thesis, this method is used. The table below shows the Hellman exponents for various areas.

Table 5.1. Friction Coefficient, a for a Variety of Landscapes [40].

Landscape type	**Friction coefficient** α
Lakes, ocean, and smooth hard ground	0.10
Grasslands (ground level)	0.15
Tall crops, hedges, and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

The landscape type of selected areas for the study can be defined as shrubs, hedges, and tall crops. Hence, α value is chosen as 0.20 for all scenarios. The mean wind speed in Çanakkale and Kayseri is 8 m/s at 50 m; on the other side, it is equal to 7 m/s at the same height in Kayseri in accordance with Yearly Average Wind Speed Distribution Map of Turkey (50m) as shown in Figure 3.1.

The height and average wind speed relationship by using Hellmann exponential law for reference cities are shown below.

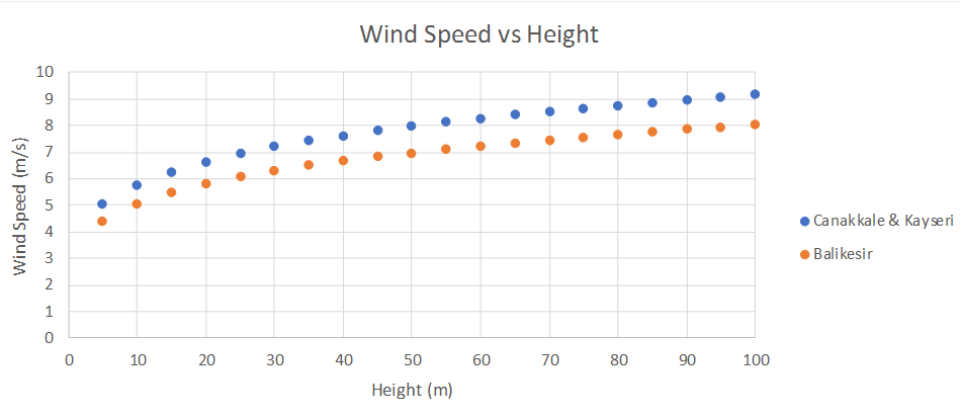


Figure 5.3. Height and Mean Wind Speed Relationship.

5.2.3. Blade Element Momentum Theory

Blade Element Momentum Theory mentions two methods in the same equation for clarifying how a wind turbine operates. The first method describes balance of momentum on a rotating annular stream tube passing through a turbine. The second one investigates aerodynamic forces which are produced by the aerofoil lift and drag coefficients on Sections along the blades. As compared with any other methods, this method states simplifications and idealisations to make it more practical for using [37].

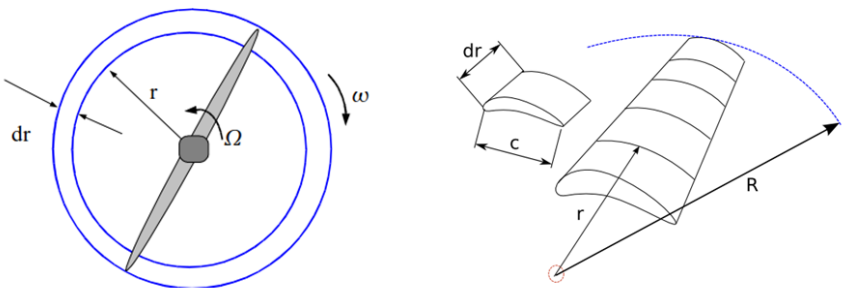


Figure 5.4. The Blade Element Model [38].

Blade Element Momentum Theory has two key assumptions:

- Blade elements do not interact to each other.
- The aerodynamic forces on the blades are only determined by the lift and drag

coefficients.

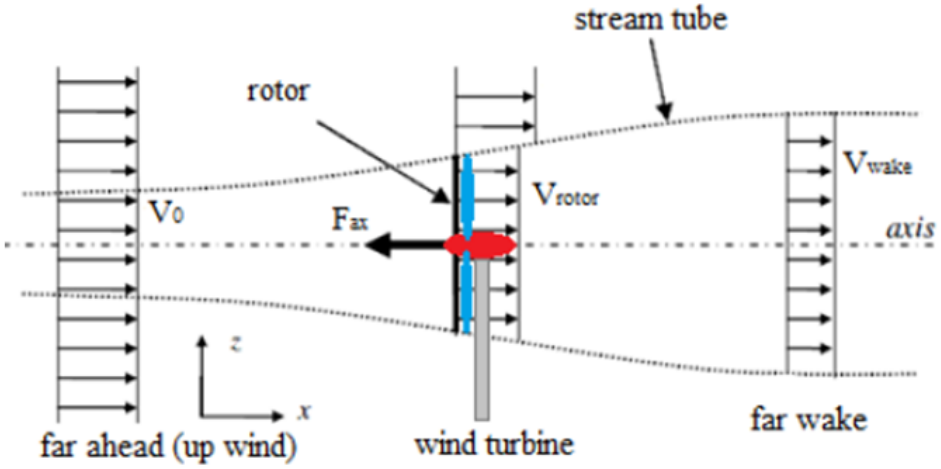


Figure 5.5. Model of Turbine Rotor with Stream Tube [39].

The resulting force on the rotor can be calculated by using Bernoulli equation as shown below:

$$F_{ax} = \frac{1}{2} A_{rotor} x p_{air} x V_0^2 x 4a\,(1-a) \tag{5.4}$$

where α induction factor, $a = \frac{v_o - v_{rotor}}{v_o}$, V_o is the wind velocity, m/s, V_{rotor} is the wind velocity at the rotor, m/s, p_{air} is the air density, kg/m^3, (1.225 kg / m^3), A_{rotor} is the area of the rotor disk, m^2. The wind force on a blade element can be calculated with a below equation.

$$F_{wind} = \frac{1}{2} c_s x p_{air} x A x V_{rotor}^2 \tag{5.5}$$

where F_{wind} is the wind load, N, c_s is the aerodynamic lift coefficient ($c_s = 0.6$), A is the exposed area, m. To find the drag and lift loads on a blade the relative wind velocity should be determined. The relative velocity is calculated as:

$$V_{rel} = \sqrt{V_{disk}^2 + V_{rot}^2} \tag{5.6}$$

$$V_{disk} = V_o\,(1-a) \quad and \quad V_{rot} = xr \tag{5.7}$$

where V_{rel} is the relative wind speed at a blade Section, m/s, V_{disk} is the wind velocity at airfoil, m/s, V_{rot} is the linear rotation speed at a blade Section, m/s, Ω is the angular rotation speed, rad/s, r distance of blade element to axis of rotation, m.

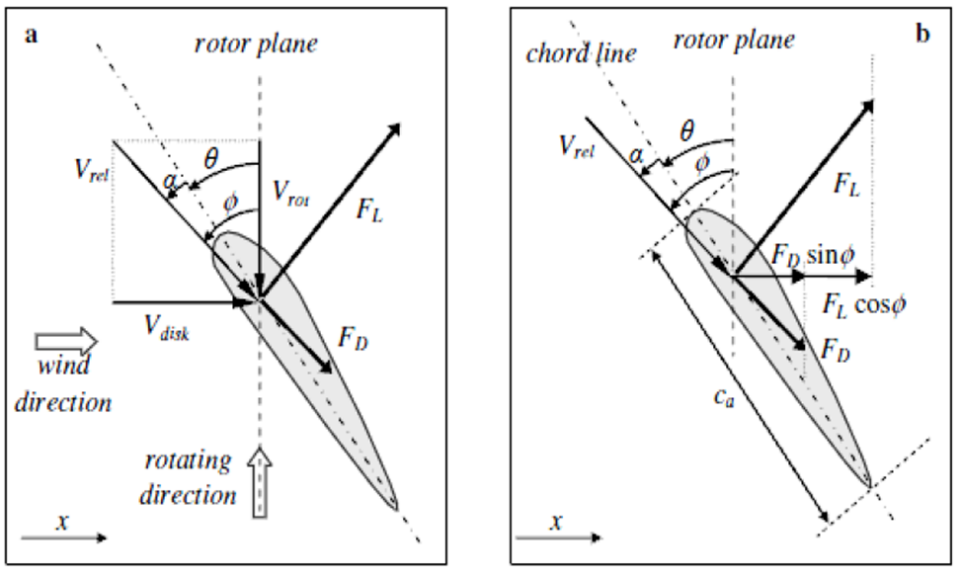


Figure 5.6. a) Lift and Drag Load on a Blade Element B) Resulting Loads in the x Direction [39].

The lift and drag forces are demonstrated in above figure clearly. Below formulas calculate the forces:

$$F_L = \frac{1}{2} C_L\,(\alpha)\, x p_{air} x V_{rel}^2 x C_\alpha x \Delta r \tag{5.8}$$

$$F_D = \frac{1}{2} C_D\,(\alpha)\, x p_{air} x V_{rel}^2 x C_\alpha x \Delta r \tag{5.9}$$

where F_L is the lift force, N, F_D is the drag force, N, $C_L(\alpha)$ is the aerodynamic lift coefficient, $C_D(\alpha)$ is the aerodynamic drag coefficient, p_{air} is the mass density of air, kg/m^3, c_a is the airfoil chord length, m, Δr radial length of blade element, m,α is the angle of attack, deg, θ pitch angle, deg, ϕ angle of inflow, deg.

As shown above formulas, lift force (F_L) and drag force (F_D) are directly proportional with the aerodynamic lift coefficients. The coefficients can be obtained by experimentally in wind tunnels. They also depend on blade shapes, blade cross Sections and angle of attack.

The total axial load for 3 blades in x direction is;

$$F_{ax} = 3x \sum_{r=root}^{r=tip} F_{x,r} \tag{5.10}$$

F_x axial load on blade, $F_x = F_L \cos + F_D \sin$.

5.2.4. Distribution of Wind Speed

In Blade Element Momentum Theory, the wind speed is assumed as the constant; however, it varies according to time. The wind turbines are designed in accordance with the extreme wind speed to avoid failure. Therefore, to find the extreme wind speed, it is necessary to describe the behavior of wind velocity at a given site that can be specified as a probability distribution function, $F(V)$. The variation of wind speed can be described by using Weibull distribution and Rayleigh distribution. The Rayleigh distribution is a special case of the Weibull distribution with the shape factor 2. Rayleigh distribution is used for the current study.

In this Section, density and distribution functions are presented, that are shown in the below figures.

The density function of Rayleigh distribution is defined as below [51].

$$f(V) = \frac{V}{c^2} e^{-\frac{V^2}{2c^2}}, V \geq 0 \tag{5.11}$$

where c is called the scale parameter where the domain of V is the continuous in real numbers. Thus, it is seen that the Rayleigh distribution is skewed to the right and

contains one parameter c, which depend on the principal properties of the distribution. Distribution function, $F(V)$, which is taken from the density function, gives the probability of occurrence for a random variable.

$$F(V) = 1 - e^{-\frac{V^2}{2c^2}}, V \geq 0 \tag{5.12}$$

Below formulas can be used to get the mean, μ and variance, σ^2 of the Rayleigh distribution.

$$\mu_{Rayleigh} = c\frac{\sqrt{\pi}}{2} \tag{5.13}$$

$$\sigma^2_{Rayleigh} = c^2\,(2 - \pi/2) \tag{5.14}$$

In the thesis, the mean value of wind speed is taken from Wind Speed Map of Turkey at the height 50 m for different locations. The mean speed is found at different heights by using Hellmann exponential law, as described in Section 5.2.2.

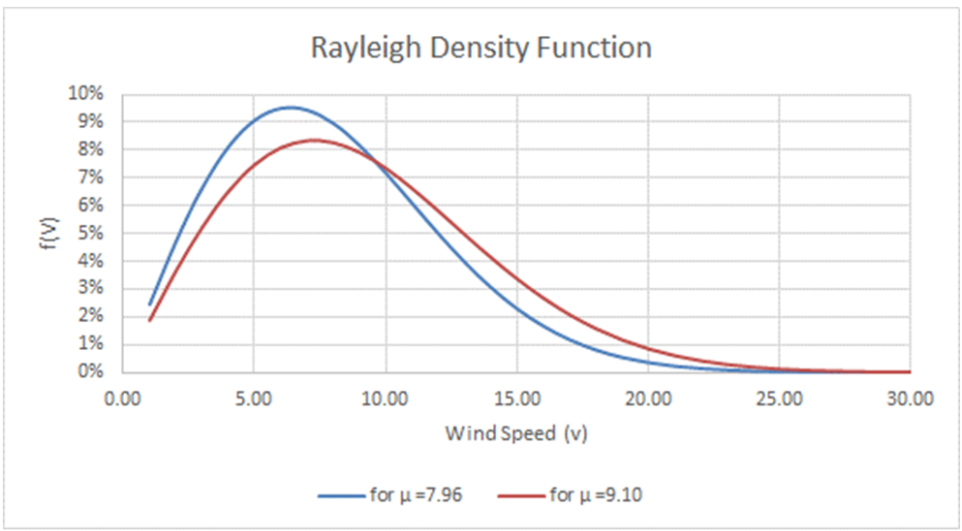


Figure 5.7. Density Function.

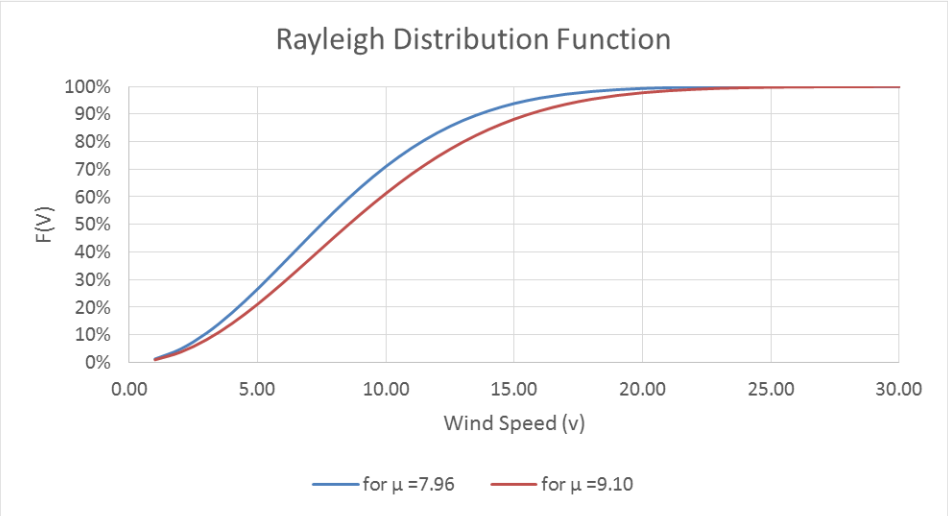


Figure 5.8. Distribution Function.

The extreme wind speeds are obtained by using distribution function. They are assumed to be the wind speeds which satisfies $F\ (V < \mu + 3\sigma) = 0.97$ equation.

Designers need to find optimum designs for tubular steel towers by mainly taking into consideration the extreme wind speeds.

In brief, the mean wind speed value is 7.96 m/s at 95 m in Balikesir region and the extreme wind speed value is obtained as 22 m/s. On the other side, the mean wind speed value is 9.10 m/s at 95 m in Çanakkale and Kayseri region and the extreme wind speed value is 25 m/s. Wind turbines should be designed by using the values in these areas.

5.2.5. Forces on Tower

The wind load that acts on the tower of the structure should be factored in calculations in addition to the wind loads on blades. The wind pressure force that acts on the projected area is normal to the wind direction. This force can be calculated independently according to German Institute for Standardization (DIN) 1055 / 1056 Codes. Then, it should be added to aerodynamics forces obtained by Blade Element

Momentum Theory.

The force acts on the tower as a distributed load that depends upon the height of tower. To get real values, the towers have been divided into 32 pieces, each part has a 3-m height. The force increases from the base to the top of the tower. Therefore, the distribution of the loads has been calculated separately for each part by using the below formulas. The below figure shows the forces, which act on a tower.

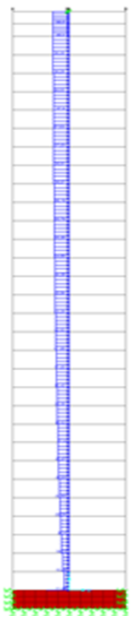


Figure 5.9. The Forces Acting on a Tower.

The resultant wind load in Section i (W_i) is calculated [42].

$$W_i = c_{fi} x q_i x A_i \tag{5.15}$$

where c_{fi} is aerodynamic coefficient of force for Section i, A_i is the reference area in m, q_i which is dynamic pressure at height z_i in kg/m^2 that can be taken from;

$$\begin{aligned} &\mathrm{q_i} = \mathrm{V2/16} \\ &\mathrm{q} = (0.75)\mathrm{x}(1 + \mathrm{h}/100)\mathrm{q_i}(\mathrm{h} > 50\mathrm{m}) \end{aligned} \tag{5.16}$$

The aerodynamic coefficient of force depends on several factors such as cross-Sectional shape of Section, and the height of tower. The formula of the coefficient is:

$$c_{fi} = Y x c_{fo} \tag{5.17}$$

where c_{fo} the basic force coefficient for the cross-Sectional shape of Section i. It can be obtained from the table and for this thesis the shape of tower is circle and the value is 1.2, Ψ reduction factor, it can be calculated as:

$$\Psi = \begin{cases} 0.65 + 0.0035\left(\frac{h}{d}\right), \left(\frac{h}{d}\right) \leq 100 \\ 1, \left(\frac{h}{d}\right) > 100 \end{cases} \tag{5.18}$$

where h the height of the tower above ground level in m, d diameter of the cross-Section in m.

The forces, which impact on blades and towers, are calculated separately in Section 5.2.3 and 5.2.5. The forces are applied in the SAP 2000 models as wind loads. In addition to the wind loads, earthquake loads should be considered and calculated.

5.3. Seismic Analysis

In order to assess the earthquake risk, several parameters should be defined according to the local ground conditions. To mitigate the effect of an earthquake, the structural design will be undertaken to resist the earthquake loads.

The seismic zone on which the wind turbines are constructed determines the effective ground acceleration, which is used for the dynamic analysis of the structures. The seismic zoning map of Turkey, prepared by the Turkish Ministry of Public Works and Settlement, divides the country into five seismic zones, with Zone 1 being the most critical. The earthquake zones 1 - 5 are determined by using the acceleration contour map and are calculated with the probabilistic method.

2 different locations are chosen to understand the effects of earthquake loading, one of them is in the 1st degree earthquake zone, and the other one is in 4th degree zone.

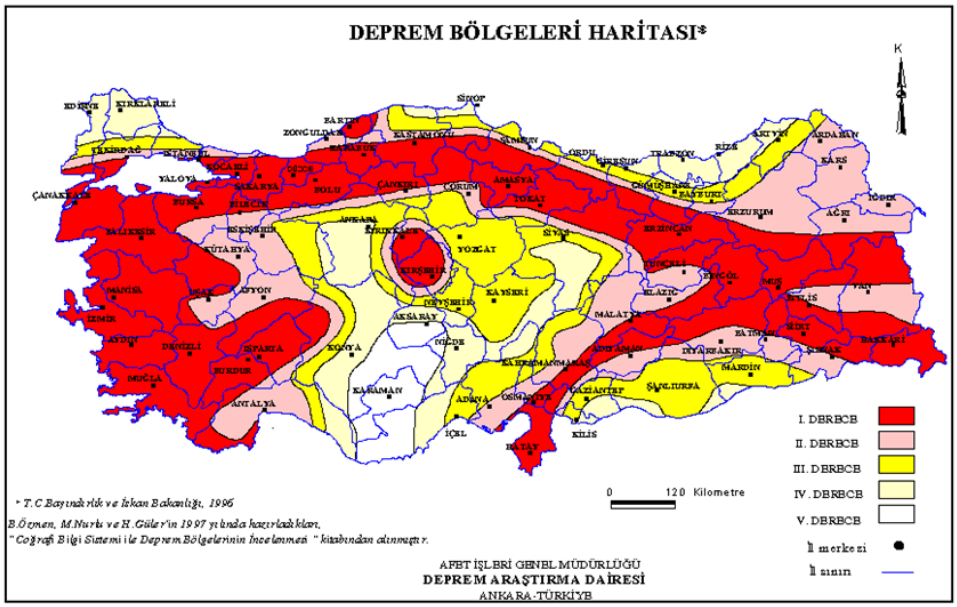


Figure 5.10. Seismic Map of Turkey [46].

Many design samples of turbines showed that dynamic analysis is more accurate and reliable method. Dynamic analysis takes the soil and structure interaction into account. Design earthquakes are specified as modal response analysis by applying direct integration techniques or using spectrum [42].

As it is known, response analysis of the structures may be carried out by using response spectra. In the thesis, for the horizontal acceleration time histories, a set of seven earthquake records have been used for the sites. These earthquake records are taken from the PEER Ground Motion Database [47]. The below figure demonstrates the selected earthquakes response spectra.

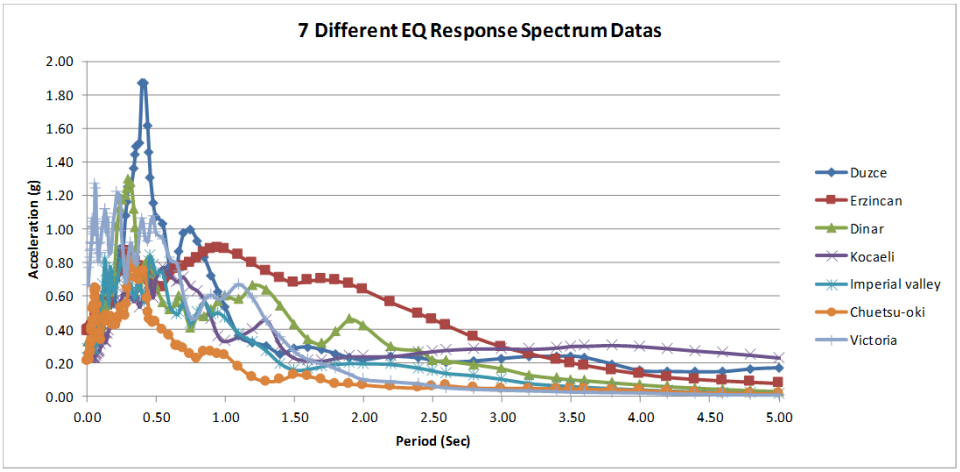


Figure 5.11. Response Spectra of 7 Different Earthquakes.

The ground motion level is used in the seismic design of the structure and the target performance level has been determined according to the Turkish Earthquake Code (2007).

The Spectral Acceleration Coefficient, A(T), which can be considered as the basis for the determination of seismic loads is given by:

$$A(T) = A_o I S(T) \tag{5.19}$$

where A_o the effective ground acceleration coefficient, I the building importance factor, $S(T)$ the spectrum coefficient.

The Effective Ground Acceleration Coefficient, A0 value depends on the seismic zone and it is between 0.40 and 0.10. Çanakkale and Balikesir are in the 1st seismic zone; on the other side Kayseri is in the 4th degree seismic zone as shown Figure 5.12. Hence, the effective ground acceleration coefficient, A0, is taken as 0.40 for Çanakkale and Balikesir; however, it is 0.10 for Kayseri.

The Building Importance Factor, I, is determined according to type and importance of structures (1.5 for important or densely populated buildings such as hospi-

tals, communication buildings, museums, schools, power generation and distribution facilities and 1.0 for ordinary buildings such as hotels, residential, and office, etc.). Therefore, I value is taken as 1.5 into calculations.

The Spectrum Coefficient, S(T), shall be determined by using the below equations. The coefficient depends on the structure natural period and the local site conditions:

$$S\left(T\right) = 1 + 1.5\frac{T}{T_A}, \left(0 \leq T \leq T_A\right) \tag{5.20}$$

$$S\left(T\right) = 2.5, \left(T_A \leq T \leq T_B\right) \tag{5.21}$$

$$S\left(T\right) = 2.5\left(\frac{T_B}{T}\right)^{0.8}, \left(T \leq T_B\right) \tag{5.22}$$

It is necessary to make the assessment of Soil Group and Local Site Class of the site according to Turkish Earthquake Code (2007) to determine T_A and T_B values.

Soil Group is used for sizing of the foundation elements. Soil Group A represents the strongest ground conditions such as solid rocks, very dense granular and very stiff cohesive materials. Soil Group B represents competent ground composed of very stiff clay and silty clay. Soil Group C is defined as medium dense sand and gravel, medium stiff clay, and silty clay. The weakest soil group is represented by Soil Group D, which includes weak sands and alluvium with high water content. Minimum requirements for cross Sectional areas and reinforcement for foundation tie beams are specified according to the Soil Group. It is assumed that the Soil Group for the sites is classified as A soil type.

Local Site Class is used to determine the change in the ground motion among the soil layers and hence the uppermost level ground motion level. Because, the nature of

the soil dictates how it amplifies the earthquake waves, it defines the spectrum periods, which are based on Local Site Class. This is used to calculate the earthquake loads. The Local Site Class is defined as dense sand, which is also the Z1 local site class (first best soil class) as described in Table **??** of the Turkish Earthquake Code (2007). For these studies, T_A and T_B values are equal to 0.10 and 0.30 since local site class Z1 is used.

Liquefaction is not expected as the ground consists of clay underlain by clay stone materials.

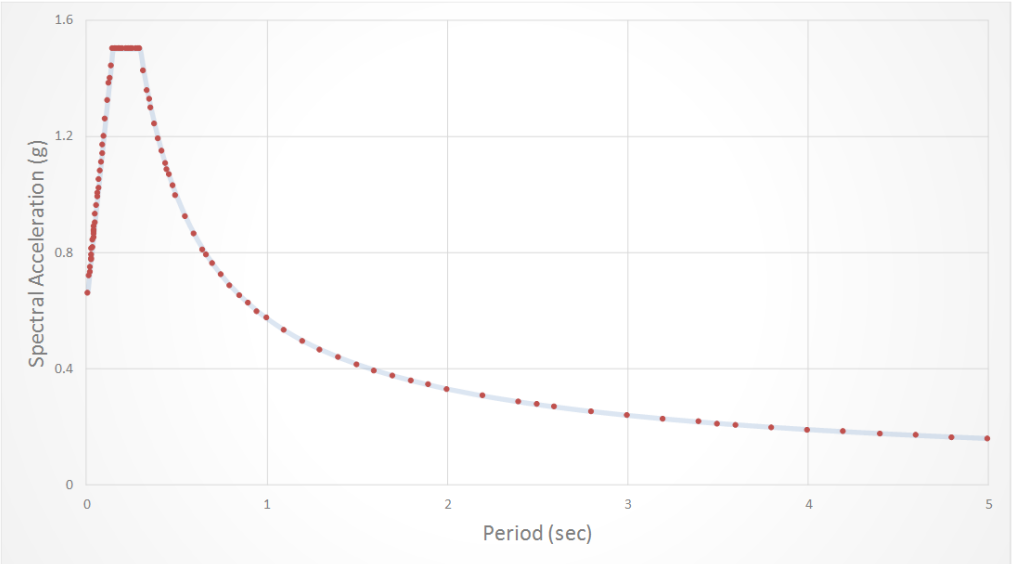


Figure 5.12. A typical Spectral Acceleration vs. Period Graph.

Below figures show the response spectra of chosen earthquake records against the target response spectrum of the sites by applying scale factors. The figures are for the 1st degree earthquake zone and 4th degree one. Damping ratio is taken as 5%.

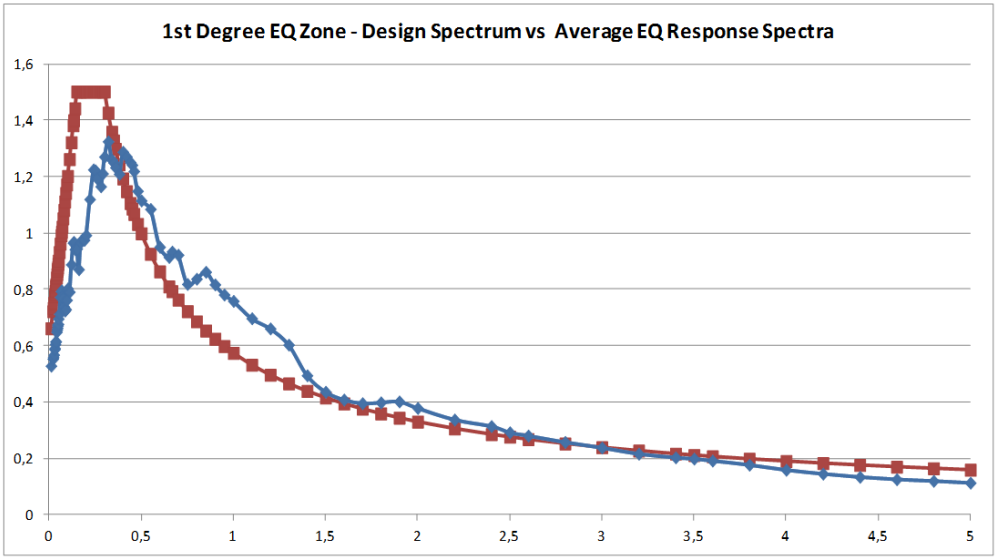


Figure 5.13. Design Spectrum and Mean of Response Spectra Data of 7 Different Earthquakes in 1st Degree EQ Zone.

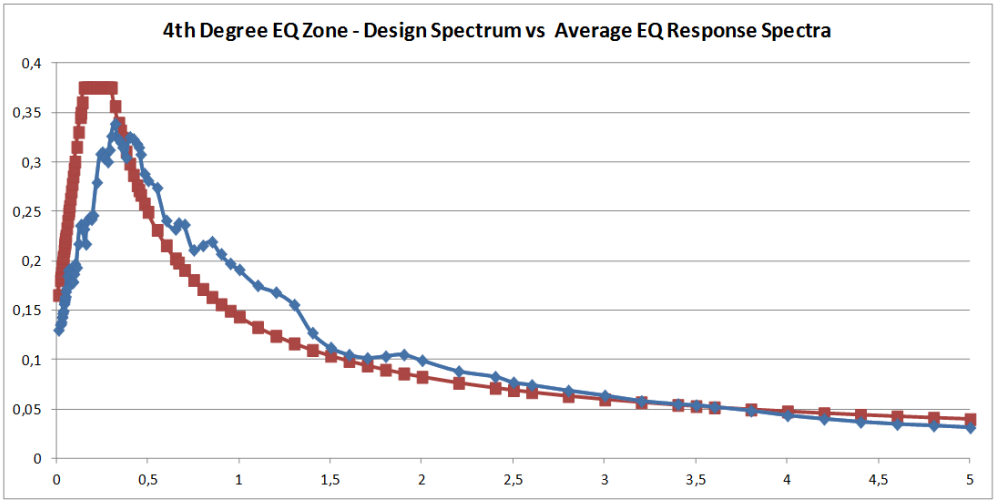


Figure 5.14. Design Spectrum and Mean of Response Spectra Data of 7 Different Earthquakes in 4st Degree EQ Zone.

5.4. Analysis of the Models

In Section 5.4, the structures are analyzed with regards to the base shears and overturning moments according to wind and seismic data. SAP 2000 program is used for carrying out the dynamic analyses of the structures.

Figure 5.15 represents base shears and overturning moments values, developed under only wind loading. The figure shows that these values are altering in direct proportion to wind speed. The figure also demonstrates that base shears and overturning moments values of V112 are higher than V90 ones.

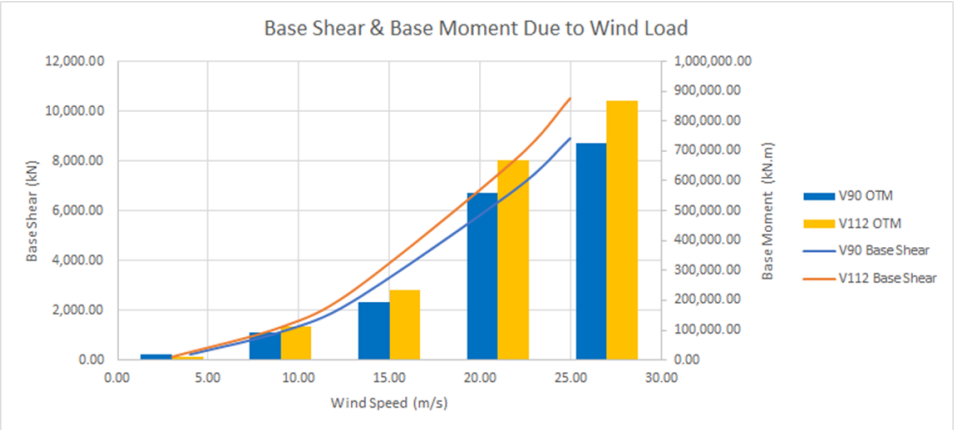


Figure 5.15. Base Shear and OTM Due to Only Wind Load.

The below figures demonstrate base shears occurring under wind and seismic loading. In the figures, the blue line means base shear under only wind loading, the orange line represents base shears under both wind loading and seismic loading in Zone 4 and the last one shows base shear under both wind loading and seismic loading in Zone 1. The comments of the figures are:

- The blue and orange lines are close to each other; it means that the seismic loading has slight effect in the Zone 4.
- The gap is high between base shears in Zone 1 and Zone 4. It shows that earthquake load is significant for design stage in Zone 1.
- In the lower wind speed, the seismic loading is dominant in comparison with wind loading. The impact of seismic loading decreases with higher wind speeds.
- In brief, the wind load is generally preliminary load for wind turbines.

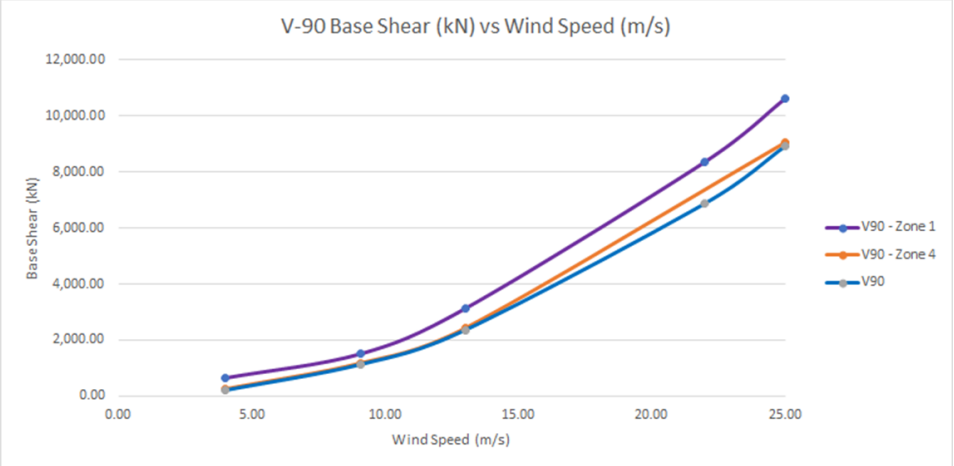


Figure 5.16. Base Shear for V90.

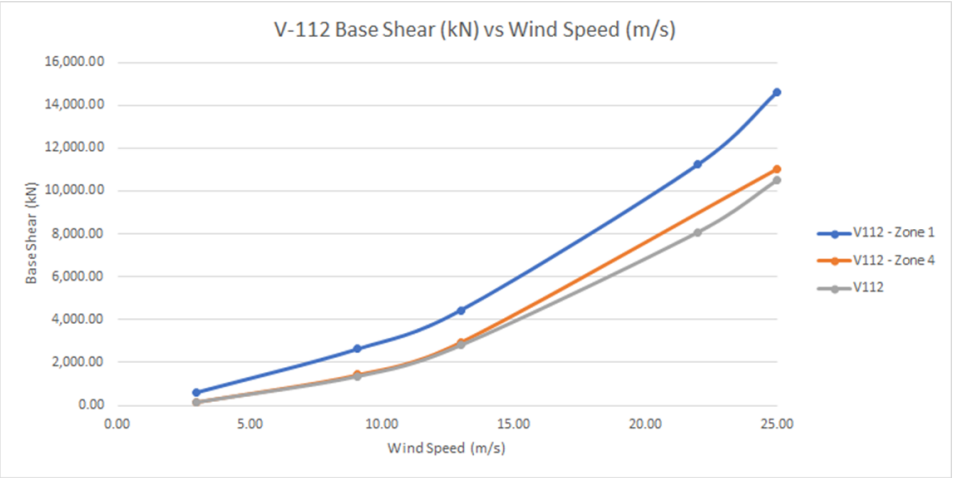


Figure 5.17. Base Shear for V112.

The below figures demonstrate base moments occurring under wind and seismic loading. In the figures, the grey line means base moment only under wind loading, the orange line represents base moment under both wind loading and seismic loading in Zone 4 and the last one shows base moment under wind loading and seismic loading in Zone 1. Base shear and moment graphs show similarity with each other.

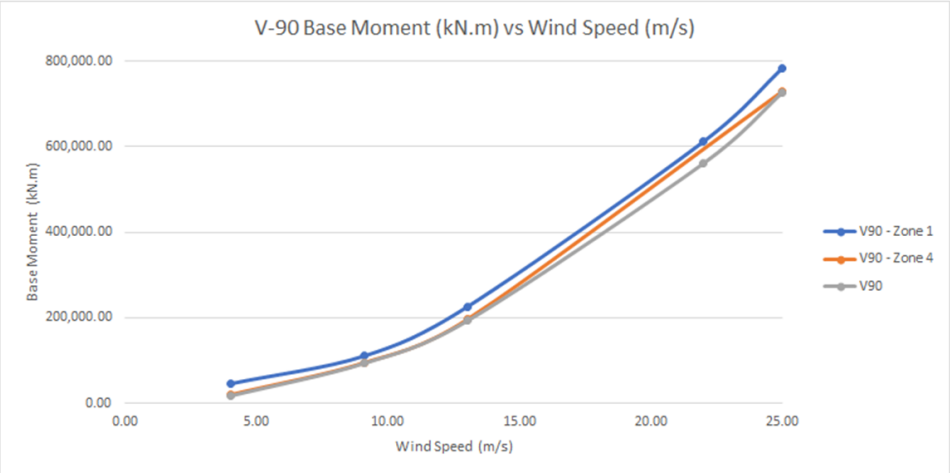


Figure 5.18. Base Moment V90.

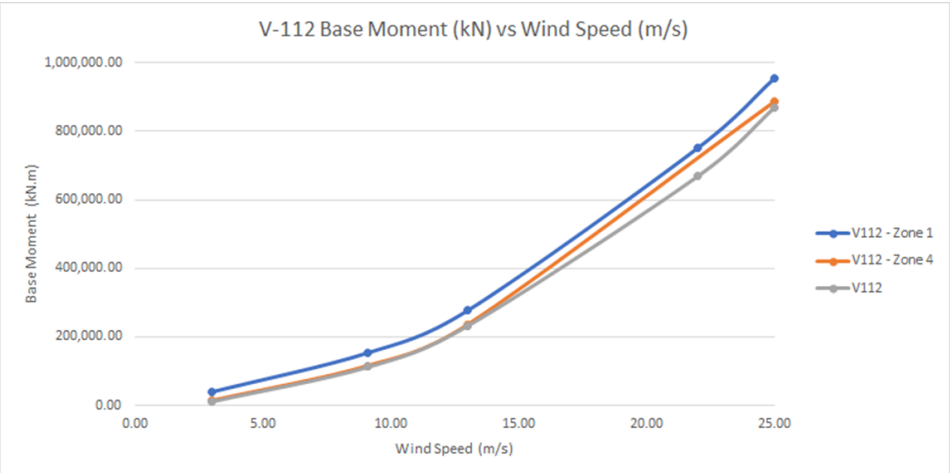


Figure 5.19. Base Moment V112.

The design variables, which are outer diameter of the tower base, outer diameter of the tower top and thickness of the tower wall are key elements to ensure efficient, safe, and economic design of the whole system. The elements have a significant impact on the mass and material cost of towers since standard trailers can transport all tower components. Therefore, it is aimed to reduce the size of towers for the decreasing transportation cost. In brief, optimization of the design variables is a critical issue for the advantageous wind turbine investment.

The thickness and weight of tower information, whose results from the analyses, are shown in Table 5.2. The table enables to make comparison for different wind

turbines under various seismic and wind demands.

Table 5.2. The Thickness and Weight of Tower for Various Load Combinations.

Type of Turbine	EQ Zone	Wind Speed (m/s)	Load Combination	Thickness of The Tower Base (m)	Thickness of The Tower Top (m)	Weight of Tower (ton)
V90-1.8 MW®	Z1	4.00	E + W	0.02523	0.01644	94.51
V90-1.8 MW®	Z1	9.10	E + W	0.05203	0.03391	194.33
V90-1.8 MW®	Z1	13.00	E + W	0.0965	0.06289	358.66
V90-1.8 MW®	Z1	22.00	W	0.23559	0.15353	862.28
V90-1.8 MW®	Z1	22.00	E + W	0.2672	0.17413	974.50
V90-1.8 MW®	Z1	25.00	W	0.31329	0.20417	1.136.73
V90-1.8 MW®	Z1	25.00	E + W	0.3563	0.23219	1.286.53
V90-1.8 MW®	Z4	4.00	E + W	0.0146	0.00951	54.75
V90-1.8 MW®	Z4	9.10	E + W	0.0459	0.02991	171.53
V90-1.8 MW®	Z4	13.00	E + W	0.08598	0.05603	319.93
V90-1.8 MW®	Z4	25.00	W	0.31329	0.20417	1.136.73
V90-1.8 MW®	Z4	25.00	E + W	0.31429	0.20482	1.140.22
V112-3.45 MW^{TM}	Z1	3.00	E + W	0.02329	0.01518	86.62
V112-3.45 MW^{TM}	Z1	9.08	E + W	0.06981	0.0455	258.31
V112-3.45 MW^{TM}	Z1	13.00	E + W	0.11819	0.07702	434.97
V112-3.45 MW^{TM}	Z1	22.00	W	0.28705	0.18707	1.036.85
V112-3.45 MW^{TM}	Z1	22.00	E + W	0.33106	0.21574	1.189.89
V112-3.45 MW^{TM}	Z1	25.00	W	0.38521	0.25104	1.376.10
V112-3.45 MW^{TM}	Z1	25.00	E + W	0.4356	0.28387	1.547.21
V112-3.45 MW^{TM}	Z4	3.00	E + W	0.01288	0.00839	47.94
V112-3.45 MW^{TM}	Z4	9.08	E + W	0.05459	0.03558	202.33
V112-3.45 MW^{TM}	Z4	13.00	E + W	0.10216	0.06658	376.65
V112-3.45 MW^{TM}	Z4	25.00	W	0.38521	0.25104	1.376.10
V112-3.45 MW^{TM}	Z4	25.00	E + W	0.3964	0.25832	1.414.25

5.5. Campbell Diagram

Campbell diagram, also named as interference diagram, shows response spectrum of a system as a function of its oscillation regime. In other words, it represents the relation between rotor speed and excitation frequency [44].

The main concern for wind turbine design is to avoid entering the resonance because resonance causes serious damage to the whole system or to the units of the system.

Figure 5.21 and Figure 5.22 represent Campbell Diagrams for V90 and V112 wind turbines. To understand Campbell Diagram, parameters, which create the diagram, should be defined.

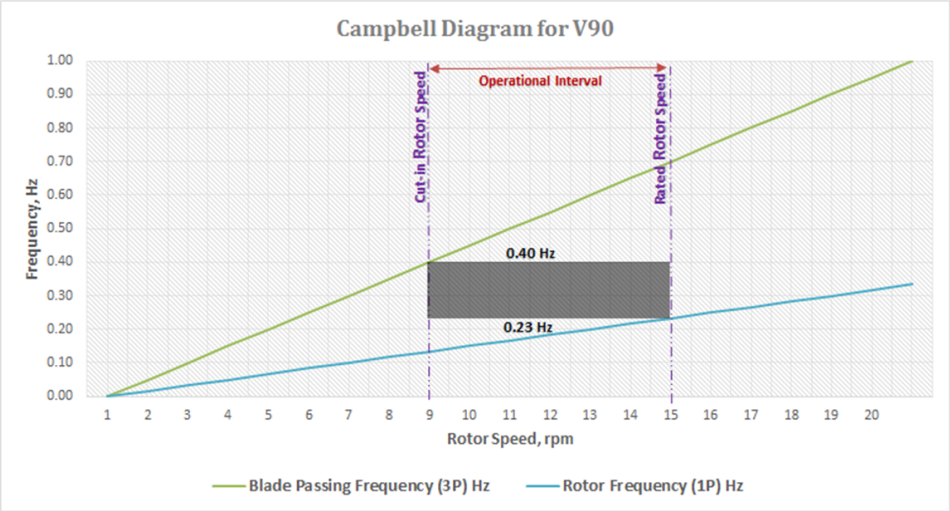


Figure 5.20. Campbell Diagram for V90.

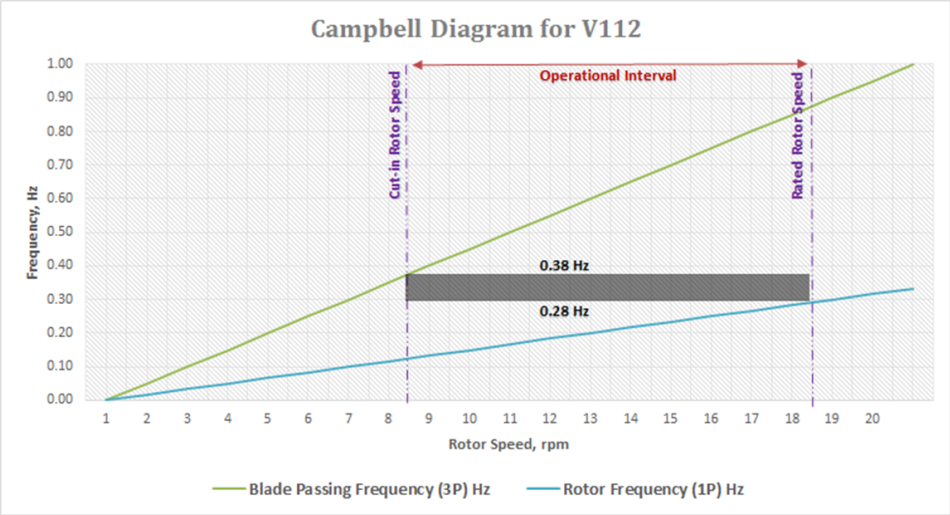


Figure 5.21. Campbell Diagram for V112.

Firstly, the excitation frequencies should be identified. One of the most important sources of excitation in a wind turbine system is the rotor. It is assumed that the turbine has a constant rotational speed. The blades may have different masses and the center of gravity of rotor moves with an eccentricity. This frequency is denominated as rotational frequency, 1P.

The wind load on tower causes the second excitation frequency. The wind leads to produce loading on the tower, when the blades pass in front of the tower where the

wind is blocked and vanishes load at the same time. This happens Nb (the number of rotor blades) times in a completion of a full cycle of the rotor. This frequency is known as tower shadow, and it is also called as the blade passing frequency, referred to as 3P for a three-bladed rotor.

The blue and green lines represent the 1P and 3P in the above Campbell Diagrams, respectively. The area between the two vertical lines is defined as the operating range of the wind turbine. The operational interval starts with cut-in rotor speed and ends with the rated rotor speed. The interval area information is given in Table 4.1.

The wind turbine rotor rotations are very important when the rotor speed is in the operational phase. When the blades start to rotate from the park position, vibration frequency increases along with their speed. The increase in the rotational speed causes the operational frequency to get closer to the system natural frequency, which can lead to resonant amplification. The condition creates higher dynamic forces, which may lead to a serious damage on the system. Fatigue damage may occur even so the forces do not reach to the elastic limit and the system cannot meet structural strength conditions. This situation clarifies the significance of the rotor speed in the design phase [5].

Figure 5.22, which is simplified figure of Campbell Diagrams, represents the frequency intervals for a typical turbine system. To prevent resonance failure, structural frequency should be outside of 1P or 3P zones. This means that three possible intervals are supposed to be considered. The areas are called soft-soft, soft-stiff, stiff-stiff structural areas [39].

For onshore wind turbines, resonance avoidance is often achieved by using the "soft-stiff" design approach, ensuring that the tower fundamental resonance frequency lies in the frequency band between the rotor and blade passing rates over the operating speed of the turbine. Hence, the structural frequency of the V90 wind turbine system should be between 0.23 Hz and 0.40 Hz. For V112 wind turbine system, the structural frequency should be between 0.28 Hz and 0.38 Hz.

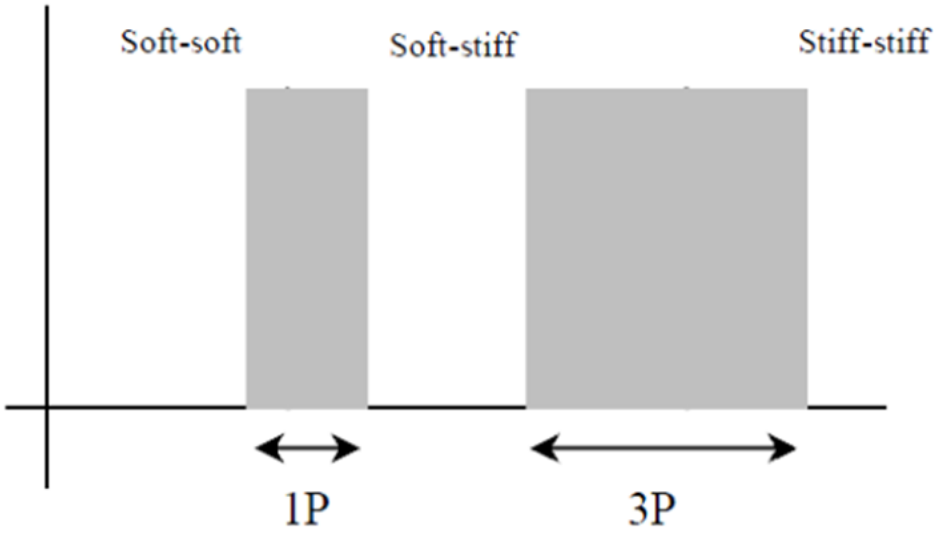


Figure 5.22. Frequency Intervals for a Turbine System [39].

The structural frequency values are read from SAP 2000 after the results of dynamic analyses. For V90 wind turbines, the frequencies are 0.29, 0.28 and 0.29 in case they are constructed in Balikesir, Çanakkale and Kayseri, respectively. For V112 wind turbines, the frequencies are 0.34, 0.32 and 0.33 in case they are constructed in Balikesir, Çanakkale and Kayseri, respectively.

Briefly, structural frequencies of each scenario are in range 1P and 3P as targeted in the operating range; therefore, the systems are prevented from entering the resonance range. Additionally, these frequencies are close to 1P frequency. It means that the optimum design has been achieved in conformity with technical and economic considerations.

6. STRENGTH CHECK

Section 6 involves the methodology and calculations of the strength checks which are carried out to ensure durability of the whole system. The across wind loads and earthquake loads are considered for strength check since they cause higher demand value. These checks are done according to the standards of American Petroleum Institute (API) by checking buckling, bending, and shear stresses of the system.

The scenario that is V90, under wind loading developed by 25 m/s wind speed and seismic loading, has been investigated in the following equations.

As mentioned in Section 4.2, the towers are divided into 32 Sections whose length is generally 3 m. Section 1 which is the undermost Section of tower is studied. The outside diameter (D) is 4.30 m and the wall thickness (t) is 0.36 m of the Section. The tower of the wind turbines is made of steel and its grade is considered as S355.

6.1. Axial Compression

6.1.1. Column Buckling

The allowable axial compressive stress, F_a, should be calculated from the following formulas for members with a D/t ratio equal to or less than 60:

$$\frac{D}{t} = \frac{4.30}{0.36} = 12.07 in \;\; our \;\; design \tag{6.1}$$

$$F_a = \frac{\left[1 - \frac{(Kl/r)^2}{2{C_c}^2}\right] F_y}{\frac{5}{3} + \frac{3(Kl/r)}{8C_c} - \frac{(Kl/r)^3}{8{C_c}^3}} for Kl/r < C_c \tag{6.2}$$

$$F_a = \frac{12^2 E}{23\left(\frac{Kl}{r}\right)^2} for Kl/r < C_c \tag{6.3}$$

where

$$C_c = \left(\frac{2^2 E}{F_y}\right)^{0.5} \tag{6.4}$$

E Young's Modulus of elasticity in MPa taken as 199.900 MPa, K is the effective length factor taken as 1, l is the unbraced length in m taken as 95m, r is the radius of gyration in m, F_y is the yield strength in MPa taken as 345 MPa, C critical elastic buckling coefficient.

$$\frac{Kl}{r} = \frac{1x95}{1.46} = 65.13 \tag{6.5}$$

$$C_c = \left(\frac{2\Pi^2 E}{F_y}\right)^{0.5} = 106.95 \tag{6.6}$$

$$F_a = 150.54 MPa \tag{6.7}$$

In the design, the compression stress, f_a, is;

$$f_a = \frac{Total Wight of Structure}{Area} = 5.06 MPa < 150.54 MPa \tag{6.8}$$

For compression strength check fa ¡ Fa should be satisfied.

6.1.2. Local Buckling

When the D/t ratio is greater than 60, unstiffened cylindrical members that are manufactured from structural steels should be examined for local buckling owing to axial compression. In case of the D/t ratio is greater than 60 and less than 300, with

wall thickness t > 6 mm, both the inelastic local buckling stress (F_{xc}) and the elastic local buckling stress (F_{xe}) can be computed from below equations. Overall column buckling should be determined by substituting the critical local buckling stress (F_{xe} or F_{xc}, whichever is smaller) for F_y in the formulas that are used to find the allowable axial compressive stress and in the equation for computing C_c.

6.1.2.1. Elastic Local Buckling Stress. The elastic local buckling stress, F_{xe}, should be calculated from:

$$F_{xe} = 2CEt/D \tag{6.9}$$

$$F_{xe} = 19,876MPa \tag{6.10}$$

where C is the critical elastic buckling coefficient taken as 0.60, D is the outside diameter in m, t is the wall thickness in m.

6.1.2.2. Inelastic Local Buckling Stress. The inelastic local buckling stress, F_{xc}, should be calculated from:

$$F_{xc} = F_y \times \left[1.64 - 0.23(D/t)^{1/4}\right]. \leq F_{xe} \tag{6.11}$$

$$F_{xc} = F_y for\,(D/t)\ \leq 60 \tag{6.12}$$

$$F_{xc} = 345MPa \tag{6.13}$$

$$F_{y,new} = Smaller\,(F_{xe}, F_{xc})\ = 345MPa \tag{6.14}$$

6.2. Bending

The allowable bending stress, F_b, should be calculated from:

$$F_b = \begin{cases} 0.75F_y, \frac{D}{t} \leq 10,340/F_y \\ \left[0.72 - 0.58\frac{F_y D}{Et}\right] F_y, \frac{D}{t} > 20,680/F_y \\ \left[0.84 - 1.74\frac{F_y D}{Et}\right] F_y, 10,340/F_y < \frac{D}{t} \leq 20,680/F_y \end{cases} \tag{6.15}$$

D/t is computed as 12.07 in Section 6.1.1 and the allowable bending stress, F_b, is,

$$F_b = 258.75MPa \tag{6.16}$$

In the design, the bending tensile stress, f_b is,

$$f_b = \frac{Mxy}{I} \tag{6.17}$$

where M is the Moment that is outcome of the analysis in kNm, y is the sectional length in m, I is the inertia of the member Section in m^4.

$$I = \Pi \frac{\left({d_{out}}^4 - {d_{in}}^4\right)}{64} = 4.91m^4 \tag{6.18}$$

Moment value is read as 784,112.89 kN.m from Sap 2000.

$$f_b = 239.63MPa < F_b = 258.75MPa \tag{6.19}$$

For compression strength check $f_b < F_B$ should be satisfied.

6.3. Shear

The allowable beam shear stress, F_v, should be calculated from:

$$F_v = 0.4F_y = 138MPa \tag{6.20}$$

The maximum beam shear stress, f_v, is;

$$f_v = \frac{V}{0.5A} \tag{6.21}$$

where f_v the maximum shear stress in MPa, V the transverse shear force in MN. The value is read from analysis as 10,6 MN, A the cross-Sectional area in m^2 computed as 2.31 m^2.

$$f_v = 9.22MPa < F_v = 138MPa \tag{6.22}$$

For shear strength check $f_v < F_V$ should be satisfied.

6.4. Combined Stresses for Cylindrical Members

Finally, combined compression and bending stresses should be checked by using below formula;

$$\frac{f_a}{0.6F_y} + \frac{f_b}{F_b} \leq 1.0 \tag{6.23}$$

$$(5.96/\,(0.6x345) + 239.63/258.75) = 0.95 \leq 1.0 \tag{6.24}$$

The strength analysis shows that the system is on the safe side in accordance with API RP 2A Codes.

Table 6.1 shows strength checks for all analyses under seismic and wind loading in terms of buckling, bending, shear and combined axial compression and bending.

Table 6.1. Strength Checks for All Analyses Under EQ and Wind Loading.

Type of Load	**EQ Zone**	Wind **Turbine**	Force **/ Moment**		**Buckling**	**Bending**	**Shear**	Utilization **Ratio**
EQ+Wind (4,00 m/s)	Zone 1	V90	624.12	Allowable	130.15	189.55	138.00	1.00
			46.066.63	From Design	12.04	176.97	7.35	0.99
EQ+Wind (3,00 m/s)	Zone 1	V112	624.79	Allowable	128.44	184.64	138.00	1.00
			40.370.52	From Design	17.19	167.90	7.96	0.99
EQ+Wind (9,10m/s)	Zone 1	V90	1.496.97	Allowable	146.84	219.86	138.00	1.00
			111.366.82	From Design	8.66	209.43	8.57	0.99
EQ+Wind (9,08 m/s)	Zone 1	V112	2.637.54	Allowable	153.43	227.13	138.00	1.00
			153.573.87	From Design	9.37	216.58	11.28	1.00
EQ+Wind (13,00 m/s)	Zone 1	V90	3.114.11	Allowable	152.90	243.63	138.00	1.00
			225.808.84	From Design	7.19	232.55	9.66	0.99
EQ+Wind (13,00 m/s)	Zone 1	V112	4.441.13	Allowable	153.51	252.11	138.00	1.00
			277.219.71	From Design	7.77	234.89	11.28	0.97
EQ+Wind (22,00 m/s)	Zone 1	V90	8.370.90	Allowable	151.36	258.75	138.00	1.00
			612.717.79	From Design	6.11	241.97	9.57	0.96
EQ+Wind (22,00 m/s)	Zone 1	V112	11.234.05	Allowable	151.61	258.75	138.00	1.00
			749.733.57	From Design	6.29	244.41	10.45	0.97
EQ+Wind (25,00 m/s)	Zone 1	V90	10.632.38	Allowable	150.54	258.75	138.00	1.00
			784.112.90	From Design	5.96	239.63	9.22	0.95
EQ+Wind (25,00 m/s)	Zone 1	V112	14.597.51	Allowable	150.65	258.75	138.00	1.00
			952.354.97	From Design	6.10	244.83	10.45	0.98
EQ+Wind (4,00 m/s)	Zone 4	V90	241.43	Allowable	114.03	146.68	138.00	1.00
			19.964.45	From Design	16.82	132.07	4.91	0.98
EQ+Wind (3,00 m/s)	Zone 4	V112	173.42	Allowable	110.21	133.09	138.00	1.00
			14.389.33	From Design	26.68	107.85	3.99	0.94
EQ+Wind (9,10 m/s)	Zone 4	V90	1.176.25	Allowable	144.43	216.04	138.00	1.00
			95.208.11	From Design	9.08	202.54	7.63	0.98
EQ+Wind (9,08 m/s)	Zone 4	V112	1.435.16	Allowable	148.73	221.20	138.00	1.00
			115.629.59	From Design	10.46	207.42	7.83	0.99
EQ+Wind (13,00 m/s)	Zone 4	V90	2.421.52	Allowable	152.99	237.99	138.00	1.00
			196.098.08	From Design	7.40	225.83	8.42	0.98
EQ+Wind (13,00 m/s)	Zone 4	V112	2.946.33	Allowable	153.65	246.19	138.00	1.00
			235.714.83	From Design	8.13	229.76	8.64	0.97
EQ+Wind (25,00 m/s)	Zone 4	V90	9.057.06	Allowable	150.93	258.75	138.00	1.00
			729.647.84	From Design	6.02	249.07	8.86	0.99
EQ+Wind (25,00 m/s)	Zone 4	V112	11.017.96	Allowable	151.01	258.75	138.00	1.00
			885.167.17	From Design	6.16	246.62	8.63	0.98

7. FINANCIAL ANALYSIS

The financial analysis of the project has been carried out by creating financial models. The analysis has been conducted for all the reference turbines. The financial models must have reliable cost estimation to get realistic results.

As domestic and global wind markets mature, information for wind turbine costs are easier to obtain. To manage and organize this cost data, a structure is prepared to see components of a wind turbine at varying degrees of cost detail. It is important to make a standardized way for characterizing total lifetime expenditures for wind projects at the component level, including both physical costs (e.g., labor, equipment, and materials) and financial costs (e.g., insurance, ground rent, project management) [49, 50].

Wind energy installations are complex and capital-intensive projects. A diverse combination of labor, equipment, and service providers is required to bring each project to a successful completion. Hence, a project's true installed cost contains not only the cost of installation labor and equipment, but also cost in association with the construction interest expense, financing, conducting investor due diligence, and designing. Total installed costs can be modeled in many ways. In the thesis, installed costs are considered as in aggregate dollars per kilowatt installed.

Initial capital expenditures dominate the major cost of many renewable energy projects; however, the annual fixed and variable costs also affect a project's economics. Annual charges are often referred as "operations and maintenance" (O&M) and this term indicates an incomplete picture of a facility's annual cost obligation. The full annual cost to operate a wind energy facility also consists of insurance, project management, land lease, permit and site maintenance, and other probable variable and fixed costs. As a result, to create a reliable financial model it is important to include both fixed and variable operating expenses. The costs are represented as dollars per kilowatt per year in financial models.

In the thesis, the investment cost information has been taken from 3 different sources, which are benchmark analysis, Communications Centre of Prime Ministry (BIMER) and current project data. For benchmark analysis 15 different wind turbine projects have been considered. The main characteristic of the projects is that they have been in operation for maximum 10 years. The below figure represents the total investment cost per MW. In the figure, blue points show each project's total investment cost per MW value and the grey line demonstrates the mean value. The comparison of the cost information of the sources is shown in the below table. In the thesis, their average is used for investment and operation and maintenance cost to construct V90 wind turbine, which is under wind loading in Balikesir region.

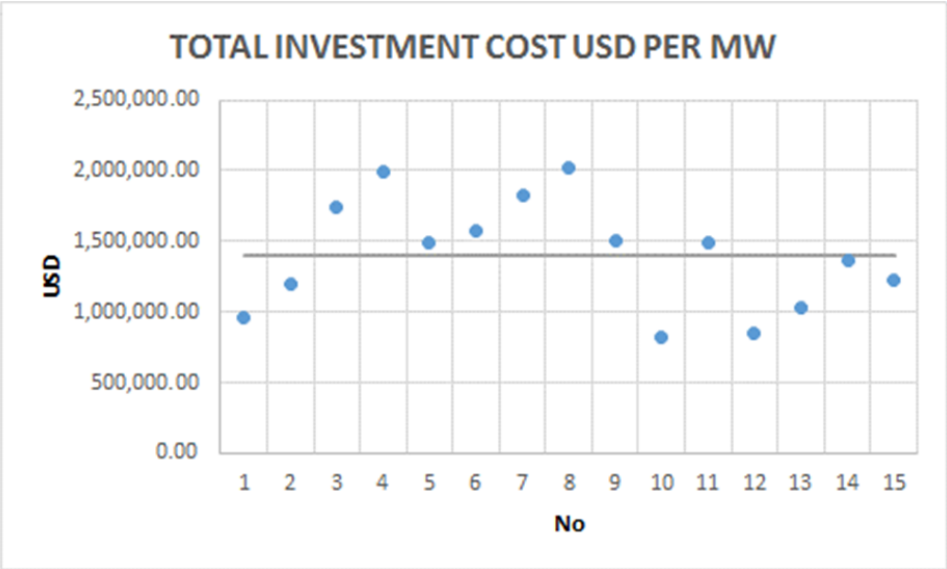


Figure 7.1. Benchmark Analysis for Cost Data.

Table 7.1. Comparison of Cost Data.

Provided by	**Investment Cost (USD / mW)**	**O&M Cost (USD/ mW year)**
Benchmark Analysis	1.400.000.00	
Bimer	1.200.000.00	40.000.00
Current Project	1.194.444.44	46.000.00
For Cost Analysis	1.264.814.81	43.000.00

The capital expenditures (Capex), in other words investment cost, can be categorized into three major components that are wind turbine, balance of system and financial costs. The cost breakdown of the Capex by percentage is shown below.

Table 7.2. Investment Cost Breakdown [49].

Investment Cost Breakdown (USD / mW) of Onshore Wind Turbine	
Total	**100%**
Turbine	**71%**
Tower	13%
Nacelle	41%
Rotor	17%
Balance of System	**20%**
Foundation	3%
Development	2%
Engineering Management	1%
Site Access & Staging	3%
Assembly and Installation	2%
Electrical Infrastructure	9%
Financial	**9%**
Contingency	6%
Construction Finance	3%

The wall thickness of tower and foundation of the systems are different for each scenario. Hence, the Capex is changing in the ratio of the above table, named as Investment Cost Breakdown. The summary of the investment cost for each scenario is represented below. The financial models are created to manage cash flows throughout the lifetime of the projects. The acceptances in the models are that project life is 20 years, debt ratio is 70%, and debt term is 8 years in the line with real life conditions. After defining the cost of the projects, it is also significant to define the income. As mentioned in Section 2.3, Turkey's Renewable Energy Law sets the legal framework for the support of electricity generation from renewable sources to increase investment. The feed-in tariff is set at 7.3 cent/kWh within the scope of the incentives.

Table 7.3. Investment Cost for Each Scenario.

Location	**Turbine Type**	**EQ Zone**	**Load Combination**	**Foundation (m)**	**Max Speed at the Top of Tower (Design Speed)**	**Max Tower Thickness (m)**	**Min Tower Thickness (m)**	**Average Speed at 95m (Top of Tower)**	**Investment Cost (USD / mW)**
Balikesir	V90-1.8MW®	Zone 1	W	12 x 12 x 3	22.00	0.2356	0.1535	7.96	1.264.814.81
Balikesir	V90-1.8MW®	Zone 1	E+W	12 x 12 x 3	22.00	0.2672	0.1741	7.96	1.286.213.93
Çanakkale	V90-1.8MW®	Zone 1	W	12 x 12 x 3	25.00	0.3133	0.2042	9.10	1.317.148.16
Çanakkale	V90-1.8MW®	Zone 1	E+W	12 x 12 x 3	25.00	0.3563	0.2322	9.10	1.345.714.02
Kayseri	V90-1.8MW®	Zone 4	W	12 x 12 x 3	25.00	0.3133	0.2042	9.10	1.317.148.16
Kayseri	V90-1.8MW®	Zone 4	E+W	12 x 12 x 3	25.00	0.3143	0.2048	9.10	1.317.813.51
Balikesir	V112-3.45 MW^{TM}	Zone 1	W	15 x 15 x 3	22.00	0.2871	0.1871	7.96	1.319.445.85
Balikesir	V112-3.45 MW^{TM}	Zone 1	E+W	15 x 15 x 3	22.00	0.3311	0.2157	7.96	1.348.629.01
Çanakkale	V112-3.45 MW^{TM}	Zone 1	W	15 x 15 x 3	25.00	0.3852	0.2510	9.10	1.384.137.06
Çanakkale	V112-3.45 MW^{TM}	Zone 1	E+W	15 x 15 x 3	25.00	0.4356	0.2839	9.10	1.416.766.09
Kayseri	V112-3.45 MW^{TM}	Zone 4	W	15 x 15 x 3	25.00	0.3852	0.2510	9.10	1.384.137.06
Kayseri	V112-3.45 MW^{TM}	Zone 4	E+W	15 x 15 x 3	25.00	0.3964	0.2583	9.10	1.391.412.37

The natural aging of the mechanical components of a wind turbine generator may lead to a drop-in turbine availability (or efficiency), and therefore production, over time. Annual Production Degradation may be between 0% and 2% per year. The value is clarified as 0.5% for Çanakkale and Balikesir, 1.5% for Kayseri since the weather condition is worse in Kayseri region, especially in winters.

Making investment is preferable if investors get more advantage compared to bank interest income, which is taken as 3.5% for USD currency. The bank interest rate is the maximum value in today's condition.

The below Cash Flows represent the financial positions of the projects in each year. The blue lines represent the revenue of the projects, calculated by multiplying production and selling price. It decreases with a low gradient due to decline in the Annual Production. The red blocks typify the expenses of the projects. However, the calculation of the expenses depends on fixed and variable costs, the major of them are the discharge of debt to banks. Therefore, the block is bigger for 8 years and on the positive side. The blocks are on the negative side in years between 9-10 due to Debt Service Reserve (DSR), which requires the project owner to establish a reserve account prior to the commencement of operations to ensure that loan repayments occur in full and on time even if the project has insufficient operating cash flow in a specific period due to lower than the expected production, higher costs, or both. DSR is the calculated value based on the number of months of required reserve, the capital structure, and the associated periodic debt obligation while it is assumed to be for 6 months. The purple lines represent the cumulative cash flow of the projects. The projects payback period is almost 8.5 years from the beginning of the operation. After 9th year, the cumulative cash flow line is on the positive side.

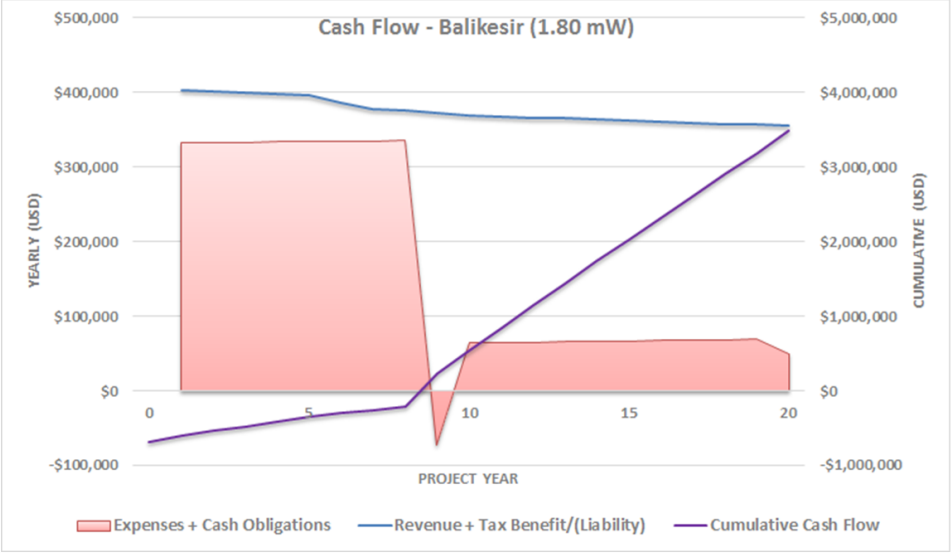


Figure 7.2. Cash Flow for V90-1.80MW in Balikesir.

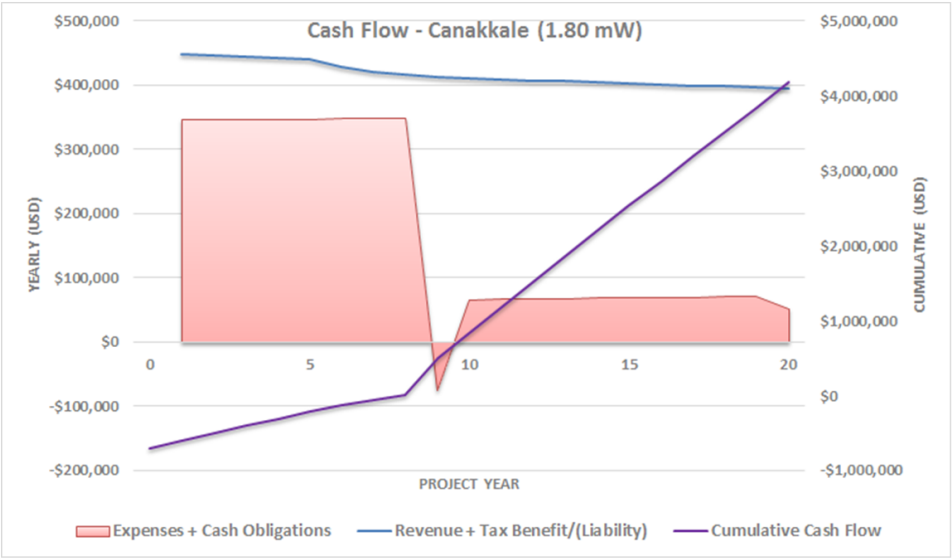


Figure 7.3. Cash Flow for V90-1.80MW in Çanakkale.

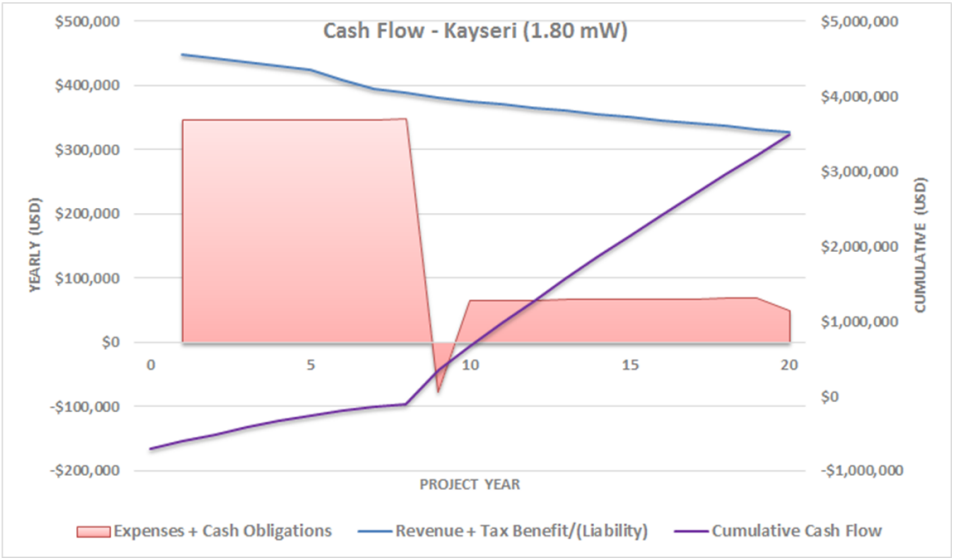


Figure 7.4. Cash Flow for V90-1.80MW in Kayseri.

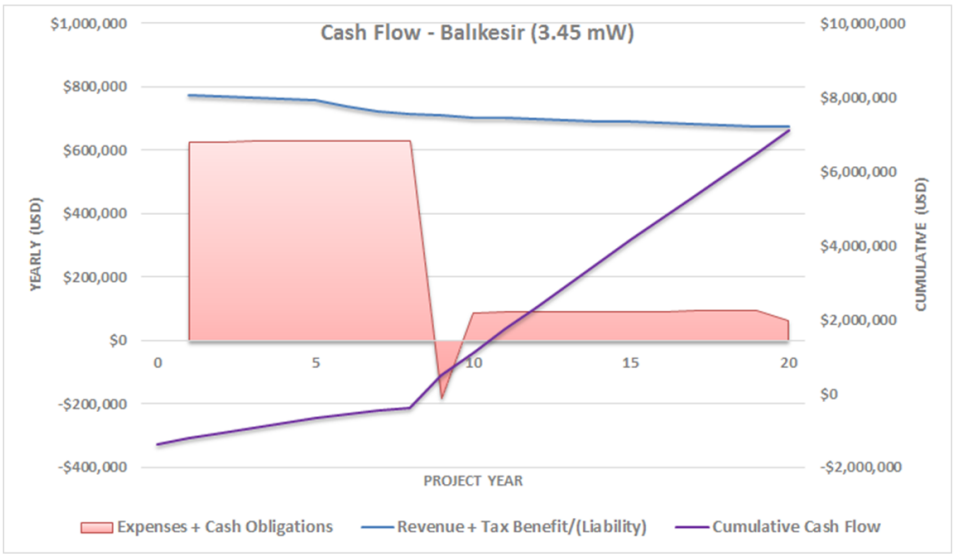


Figure 7.5. Cash Flow for V112-3.45 MW in Balikesir.

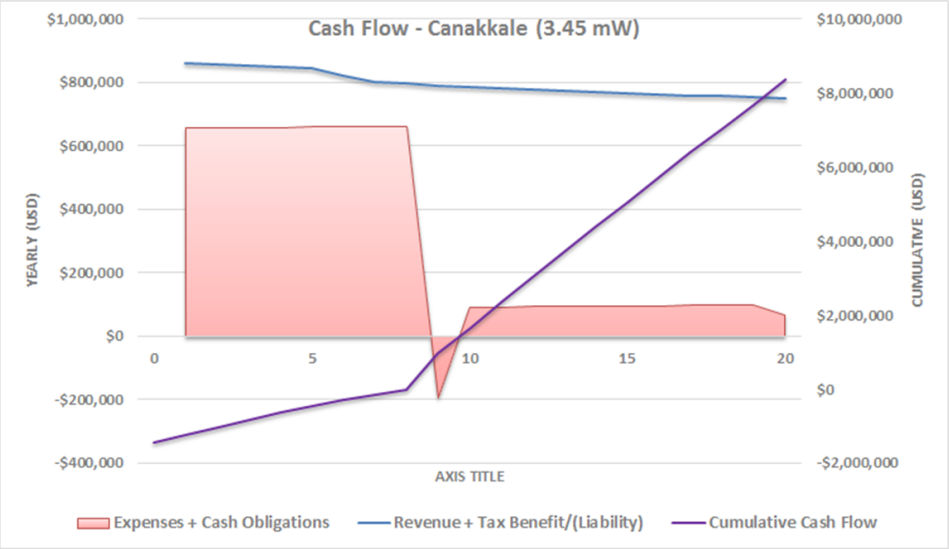


Figure 7.6. Cash Flow for V112-3.45 MW in Çanakkale.

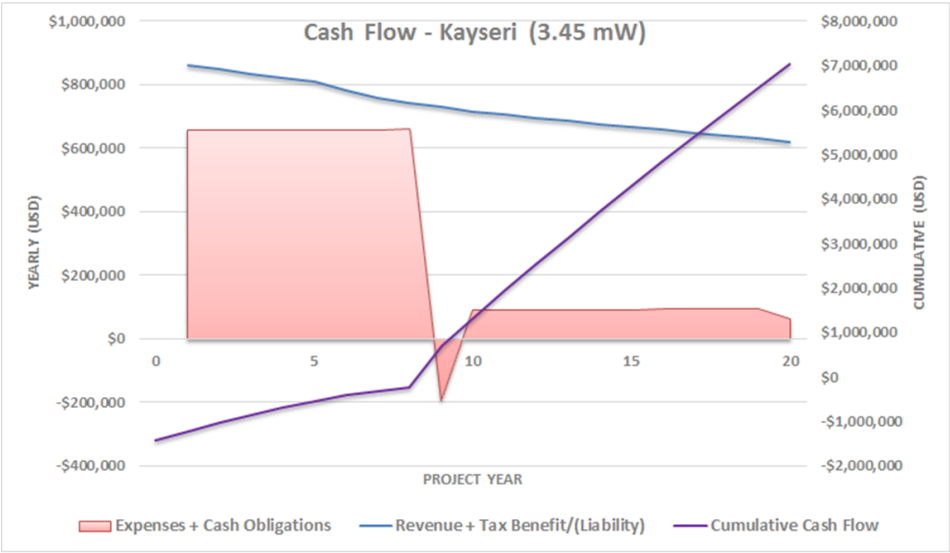


Figure 7.7. Cash Flow for V112-3.45 MW in Kayseri.

The summary of the alternatives is shown in the below tables in respect of the economic perspectives. The first table compares alternatives from the point of constructing only one wind turbine. In addition, the second one answers the question, "Which is more feasible, constructing two wind turbines whose rated power is 1.80 MW or constructing one wind turbine whose rated power is 3.45 MW?"

Table 7.4. Summary of Alternatives-1.

Alternatives	**Scenerio 1**	**Scenerio 2**	**Scenerio 3**	**Scenerio 4**	**Scenerio 5**	**Scenerio 6**
Location	Balikesir	Balikesir	Çanakkale	Çanakkale	Kayseri	Kayseri
Turbine Type	V90-1.8/2.0 MW®	V112-3.45 MW^{TM}	V90-1.8/2.0 MW®	V112-3.45 MW^{TM}	V90-1.8/2.0 MW®	V112-3.45 MW^{TM}
Turbine Rated Power (mW)	1.80	3.45	1.80	3.45	1.80	3.45
Number of Turbines	1.00	1.00	1.00	1.00	1.00	1.00
Project Useful Life	20	20	20	20	20	20
Net Capacity Factor, Yr 1	35.0%	35.0%	39.0%	39.0%	39.0%	39.0%
Annual Production Degradation (%)	0.5%	0.5%	0.5%	0.5%	1.5%	1.5%
Average Production for 20 years (kWh)	5.264.357.00	10.090.017.00	5.865.998.00	11.243.162.00	5.347.286.00	10.248.964.00
Net Installed Cost (USD)	$2.276.667	$4.552.088	$2.370.867	$4.775.273	$2.370.867	$4.775.273
Operating Expenses (USD)	$791.393	$1.267.883	$827.385	$1.341.011	$804.208	$1.296.589
Project Equity (USD)	$683.000	$1.365.626	$711.260	$1.432.582	$711.260	$1.432.582
Equity IRR	17.5%	18.0%	20.5%	20.5%	19.0%	18.8%
Project Debt (USD)	$1.593.667	$3.186.462	$1.659.607	$3.342.691	$1.659.607	$3.342.691
Debt Interest Rate (%)	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
Debt Term (Years)	8.00	8.00	8.00	8.00	8.00	8.00
Cost of Energy (∅/kWh)	7.3	7.3	7.3	7.3	7.3	7.3
Cumulative Cash Flow After 20 Years	$3.493.917	$7.097.748	$4.189.093	$8.375.894	$3.493.725	$7.043.105
Capital w/ 20 years Bank Interest Income	$1.227.600	$2.454.528	$1.278.393	$2.574.871	$1.278.393	$2.574.871
Advantage of Making Investment	$2.266.317	$4.643.220	$2.910.700	$5.801.023	$2.215.332	$4.468.234

Table 7.5. Summary of Alternatives-2.

Alternatives	**Scenerio 1**	**Scenerio 2**	**Scenerio 3**	**Scenerio 4**	**Scenerio 5**	**Scenerio 6**
Location	Balikesir	Balikesir	Çanakkale	Çanakkale	Kayseri	Kayseri
Turbine Type	V90-1.8/2.0 MW®	V112-3.45 MW^{TM}	V90-1.8/2.0 MW®	V112-3.45 MW^{TM}	V90-1.8/2.0 MW®	V112-3.45 MW^{TM}
Turbine Rated Power (mW)	1.80	3.45	1.80	3.45	1.80	3.45
Number of Turbines	2	1	2	1	2	1
Project Useful Life	20	20	20	20	20	20
Net Capacity Factor, Yr 1	35.0%	35.0%	39.0%	39.0%	39.0%	39.0%
Annual Production Degradation (%)	0.5%	0.5%	0.5%	0.5%	1.5%	1.5%
Average Production for 20 years (kWh)	10.528.714.00	10.090.017.00	11.731.996.00	11.243.162.00	10.694.572.00	10.248.964.00
Net Installed Cost (USD)	$4.553.333	$4.552.088	$4.741.733	$4.775.273	$4.741.733	$4.775.273
Operating Expenses (USD)	$1.582.786	$1.267.883	$1.654.770	$1.341.011	$1.608.416	$1.296.589
Project Equity (USD)	$1.366.000	$1.365.626	$1.422.520	$1.432.582	$1.422.520	$1.432.582
Equity IRR	17.5%	18.0%	20.5%	20.5%	19.0%	18.8%
Project Debt (USD)	$3.187.333	$3.186.462	$3.319.213	$3.342.691	$3.319.213	$3.342.691
Debt Interest Rate (%)	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
Debt Term (Years)	8.00	8.00	8.00	8.00	8.00	8.00
Cost of Energy (∅/kWh)	7.3	7.3	7.3	7.3	7.3	7.3
Cumulative Cash Flow After 20 Years	$6.987.833	$7.097.748	$8.378.186	$8.375.894	$6.987.450	$7.043.105
Capital w/ 20 years Bank Interest Income	$2.455.199	$2.454.528	$2.556.786	$2.574.871	$2.556.786	$2.574.871
Advantage of Making Investment	$4.532.634	$4.643.220	$5.821.400	$5.801.023	$4.430.664	$4.468.234

8. CONCLUSION

In this study, the aim was to obtain the most advantageous wind energy investment in terms of technical and economic aspects. This study has shown that the most appropriate structural design of the systems is required. In addition, investment cost should be minimum and all structural safety criteria should be met for an optimum investment. The alternatives, which are taken under review, are shown in Table 8.1.

Table 8.1. The Alternatives for Making Investment.

Alternative	**Location**	**Turbine Model**	**EQ Zone**	**Average Wind Speed at 50m**
1	Balikesir	V90-1.80 MW®	Zone 1	7.00
2	Çanakkale	V90-1.80 MW®	Zone 1	8.00
3	Kayseri	V90-1.80 MW®	Zone 4	8.00
4	Balikesir	V112-3.45 MW^{TM}	Zone 1	7.00
5	Çanakkale	V112-3.45 MW^{TM}	Zone 1	8.00
6	Kayseri	V112-3.45 MW^{TM}	Zone 4	8.00

All through the study, various themes about the wind turbine designs have been investigated. To give examples:

- To understand the effect of seismic load, comparison of the alternatives 2 and 3, 5 and 6 is used.
- To understand the effect of wind load, comparison of the alternatives 1 and 2, 4 and 5 is used.
- To understand the effect of rated power of wind turbines, comparison of the alternatives 1 and 4, 2 and 5, 3 and 6 is used.

Additionally, the analyses were conducted under various wind speeds for all alternatives, which are cut-in, rated, extreme and annual average speeds of locations to

understand the design variables and wind speed relationship.

As stated, all the analyses were carried out to find the optimum value of design variables, which are the wall thickness of tower, dimension of foundation and tower diameter. The results of this investigation show that the variations in the variables have an important effect on the mass and cost of the wind turbine systems.

The additional outcomes of the study are summarized as below.

- Soil uncertainty is a significant issue in the design stage since the stiffness of the soil has an impact on the system natural frequency.
- Wind turbine foundations have been considered as a fixed base. Additionally, they have been designed as mat foundation with springs, which represents the soil. The outcome is that structural frequency value obtains a higher value when foundations have been considered as fixed bases.
- The seismic loading has a slight effect on the wall thicknesses when wind loading, which is developed under extreme wind speeds, is applied on the system. The wall thickness is higher in the ratio of almost %13 (if they are installed in Zone 1) and %2 (if they are installed in Zone 4) in case the seismic loads are applied with wind loads concurrently. The variation has influenced the total investment cost at the rate of only 2.17% and 0.05%, respectively.
- The wind loads are dominant loading types for design. To give an example, changing wind speed from 22 m/s to 25 m/s increased the wall thickness in the rate of 34% in the same zone and for the same wind turbine.
- The first natural frequencies of each scenario are in range 1P and 3P as targeted. These values are close to 1P frequency for economic reasons.
- The structural strength checks are done by using API RP-2A Codes in terms of bending, buckling and shear.
- Annual Production Degradation may lead to a drop-in turbine availability (or efficiency), and therefore production, over time. The value is clarified as 0.5% for Çanakkale and Balikesir, 1.5% for Kayseri.

When all the alternatives are taking into consideration, one of the most significant findings of this study is that making wind turbine investment is preferable and advantageous compared to the acquisition of interest income in bank accounts. Especially, Alternative 5 can be considered as the best alternative, which is construction V112 model wind turbine in Çanakkale.

The outcomes of this research have thrown up many topics in need of further investigation:

- The use of software programs can generate the stochastic wind data.
- Soil behavior can be considered in detail.
- The fatigue life estimation can be determined by making fatigue analysis.

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