A NETWORK INTEGRATION ORIENTED MODEL TO EVALUATE NEW WIND POWER GENERATION PROJECTS

by

Halil Ibrahim Cobuloğlu

B.S., Industrial Engineering, İstanbul Technical University, 2008

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Industrial Engineering
Boğaziçi University
2012

Dedicated to my parents

ACKNOWLEDGEMENTS

First, I would like to express my deepest gratitude to my thesis supervisor, Prof. İlhan Or, for his invaluable guidance, patience, and enlightening ideas. I would like to mention his continuous help and encouragement during the preparation process of my Master's thesis. Also, I would especially like to thank Assoc. Prof. Gürkan Kumbaroğlu for his invaluable contributions and advices on my Master's thesis.

I would like to thank Assist. Prof. Gönenç Yücel and Assoc. Prof. Ekrem Duman for their comments and advices on my Master's thesis. I am grateful to all my friends being with me during those years, especially to Hüseyin Savran, Mustafa Baydoğan and Banu Kabakulak.

I would like to thank experts in EPDK, TEİAŞ and APK for their help and providing me the necessary information and references.

Finally, I am grateful to my parents for their endless support and help during my education.

ABSTRACT

A NETWORK INTEGRATION ORIENTED MODEL TO EVALUATE NEW WIND POWER GENERATION PROJECTS

For a continuous and sustainable economic growth, energy is one of the most important necessities that has to be supplied properly. Not only for a continuous economic growth but also for a better environment, renewable energy sources gain more and more importance, and new investments are made to supply electrical energy from those sources. Turkey, as one of the largest and continuously growing economies in the world, wants to increase the share of renewable energy sources in its overall energy supply. For this purpose recently, legislation featuring new incentives and support for new and existing renewable energy projects has frequently been on the agenda of the Turkish parliament. This thesis is about a specific problem originating from the expected rapid expansion of renewable energy generation projects. It is aimed to provide two basic optimization solutions, focusing on reduction in connection cost and increase in energy delivery and installed capacity, to evaluate the most suitable new wind power generation projects. In order to provide an evaluation of new wind power generation projects, a couple of optimization models have been developed to identify the wind power projects to be invested in especially regarding their connection points, and connection voltage levels. First, necessary information is explained and description of data is provided while establishing the model constraints. Then, data set is introduced to be used in the models for sensitivity analysis. Models are coded in C++ and solved by using the Cplex optimization solver. The results of a series of scenarios are obtained and analyzed, and future research opportunities are explained with addition of some comments on the results.

ÖZET

YENİ RÜZGAR ENERJİSİ SANTRALİ PROJELERİNİ DEĞERLENDİRMEK İÇİN SİSTEME ENTEGRASYON ODAKLI BİR MODEL

Enerji, sürekli ve sürdürülebilir bir ekonomik büyüme için düzgün bir şekilde temin edilmesi gereken en önemli ihtiyaçlardan biridir. Sadece sürekli bir büyüme için değil aynı zamanda daha iyi bir çevre için yenilenebilir enerji kaynakları giderek daha fazla önem kazanmakta ve elektrik enerjisini bu tür kaynaklardan sağlamak için yeni yatırımlar yapılmaktadır. Türkiye, dünyadaki en büyük ve ekonomisi sürekli büyüyen ülkelerden biri olarak, yenilenebilir enerji kaynaklarının genel enerji tedariği içerisindeki payını artırmak istemektedir. Bu amaçla son zamanlarda, yeni ve mevcut yenilenebilir enerji projeleri için yeni teşvikler ve destek sunan kanun Türk parlamentosunun ajandasında sıklıkla yer almaktadır. Bu tez, yenilenebilir enerji üretim projelerinin beklenen hızlı genişlemesinden kaynaklanan spesifik bir problem hakkındadır. En uygun yeni rüzgar enerjisi üretim projelerini değerlendirmek için, bağlantı maliyetini düşürmeye, sisteme verilen enerji miktarını ve yüklü kapasiteyi artırmaya odaklanan iki temel optimizasyon modeli sağlaması amaçlanmaktadır. Yeni rüzgar enerjisi üretim projelerini değerlendirmek için, özellikle bağlantı noktası ve bağlantı voltaj seviyesini belirterek hangi rüzgar enerjisi projelerine yatırım yapılması gerektiğini tanımlama amacıyla bir çift optimizasyon modeli geliştirilmiştir. İlk olarak, modeldeki kısıtlar kurulurken modelde kullanılan gerekli bilgiler açıklanmış ve kullanılan verilerin tanımı yapılmıştır. Daha sonra, modellerde duyarlılık analizi yapabilmek için kullanılacak olan very seti takdim edilmiştir. Modeller C++ ile kodlanmış ve C++ çıktıları Cplex kullanılarak çözülmüştür. Neticede, duyarlılık analizi çıktıları elde edilmiş, sonuçlar üzerinde bazı yorumlarda bulunarak gelecekte yapılabilecek araştırma alanları açıklanmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

B_i	Bidding Value of wind power project *i*
C_k	Unit cost of connection line per kilometer at *kth* voltage level
C_{max}	Maximum acceptable connection cost per wind power project
D_{ij}	Distance (in kilometers) between *ith* wind power project and *jth* substation
E_i	Efficiency of wind power project *i*
F_k	Energy loss factor at *kth* voltage level
L_{max}	Maximum tolerated power loss percentage for any connection line
R_{min}	Minimum power expected from wind power projects
S_{jk}	Short circuit power capacity of *jth* substation at *kth* voltage level
SU_{tk}	Short circuit power capacity of *tth* set of united substations at *kth* voltage level
ToC_{max}	Maximum acceptable overall connection cost for all wind power projects
ToL_{max}	Maximum tolerated power loss percentage for overall connections
W_i	Power production capacity of *ith* wind power project
α	Weight of connection costs in objective function of Model B
β	Weight of bid values in objective function of Model B
Φ	Short circuit power capacity percentage of a substation that can be allocated to wind power generated electricity
#	Number

LIST OF ACRONYMS / ABBREVIATION

EPDK	Turkish Energy Market Regulatory Authority
Model A-I	Maximum Installed Capacity (Submodel 1 of Maximum Energy Output)
Model A-II	Maximum Energy Delivered (Submodel 2 of Maximum Energy Output)
Model B	Minimum Connection Cost / Maximum Profit Model
R1	Regulation 1
R2	Regulation 2
R3	Regulation 3
R4	Regulation 4
TEİAŞ	Turkish Electricity Transmission Company
WPP	Wind Power Plant

1. INTRODUCTION

Lately, energy issue has become a key topic for the world economy since sustainable economic development and growth depend on regular and reliable energy supply. Energy demand is expected to increase rapidly especially in the fast developing Asia and Central and South America regions over the next two decades (World Energy Consumption, 2007). It is assumed that the demand will increase about 4% every year, on average. Thus, world energy consumption is expected to reach 687 quadrillion British thermal unit (Btu) in 2030 from 495 quadrillion Btu in 2007 according to projections(World Energy Demand and Economic Outlook, 2010). Not only for economic growth, but also for a better living standard, energy consumption seems as a vital factor. In this manner, because of limited stock of fossil fuel supplies and increasing negative effects of their consumption on the environment, (primarily due to ever expending levels of greenhouse gas emissions), renewable and environmentally friendly alternatives are started to be used in many countries to satisfy the increasing energy demand.

Essentially, it is a fact that, many countries try to utilize more renewable energy sources in their energy supply portfolios which make renewable generation the world's fastest-growing source of electric power. With government policies and incentives throughout the world supporting the rapid construction of renewable generation facilities, the renewable share of world generation is expected to increase from 18% in 2007 to 23% in 2035 (World Energy Demand and Economic Outlook, 2010). Wind energy, one of the most popular and fast growing renewable energy sources, is seen as a good alternative in many countries to diversify energy supply. Most renewable energy growth in OECD countries is expected to come from non-hydroelectric sources, especially from wind. According to the report, World Energy Demand and Economic Outlook, many OECD countries, particularly those in Europe, have government policies (including feed-in tariffs, tax incentives, and market-share quotas) that encourage the construction of wind and other non-hydroelectric renewable electricity facilities.

Accordingly, wind energy has been increasing its share faster than other renewable sources, among all energy sources, by growing at the rate of 30% annually (Renewable Energy, 2011). Global wind power installations increased by 35800 MW in 2010, bringing total installed capacity up to 194400 MW, a 22.5% increase on the 158700 MW installed at the end of 2009. Wind power accounts for approximately 19% of the electricity generated in Denmark, 9% in Spain and Portugal, 9% in Germany and 14% in Republic of Ireland(Renewable Energy, 2011).

On the other hand, according to a publication by Turkish News Agency (2010), Turkey has been the world’s second fastest growing economy (after China) while experiencing the highest increase in demand for electricity since 2000. As of 2009, Turkey’s annual electricity consumption has been 193.3 billion kWh. To meet this growing energy demand, while aiming to cover more of the energy supply with environmentally friendly sources, Renewable Energy Law is passed in 2005. The goal of the law has been to extend the usage of renewable energy sources for production of electrical energy, to expand the variety of energy sources, to decrease greenhouse gas emissions, and to protect the environment (Enerji Piyasası Düzenleme Kurumu, 2005). Primarily, as a result of this law, a very high interest in wind power projects has arisen and many companies have applied to the Turkey’s Energy Market Regulatory Authority (EPDK) for a wind power plant investment licenses.

Turkey is a developing country where electricity need increases 6 – 8% every year that equals to 6000-8000 MW additional power capacity (Elektrik, 2010). Renewable energy sources are desired to be used more effectively in order to fulfill this demand and diversify the energy sources. Wind energy is one of the renewable energy sources that has the highest potential. Figure 1.1 shows the deployment of wind speed on the map of Turkey (Wind Energy Potential in Turkey, 2012). Especially yellow and red regions constitute the most appropriate wind speed levels to generate energy efficiently. However, in addition to the speed, consistent wind speed from the same direction is another important aspect for energy generation from wind power. Turkey’s wind energy potential is defined as 47849 MW even for the wind speed above 7 m/s. However, only 1329 MW of this potential is evaluated as of 2010 (Altuntaşoğlu, Rüzgar Enerjisi Konusunda Mevcut Durum, 2011).

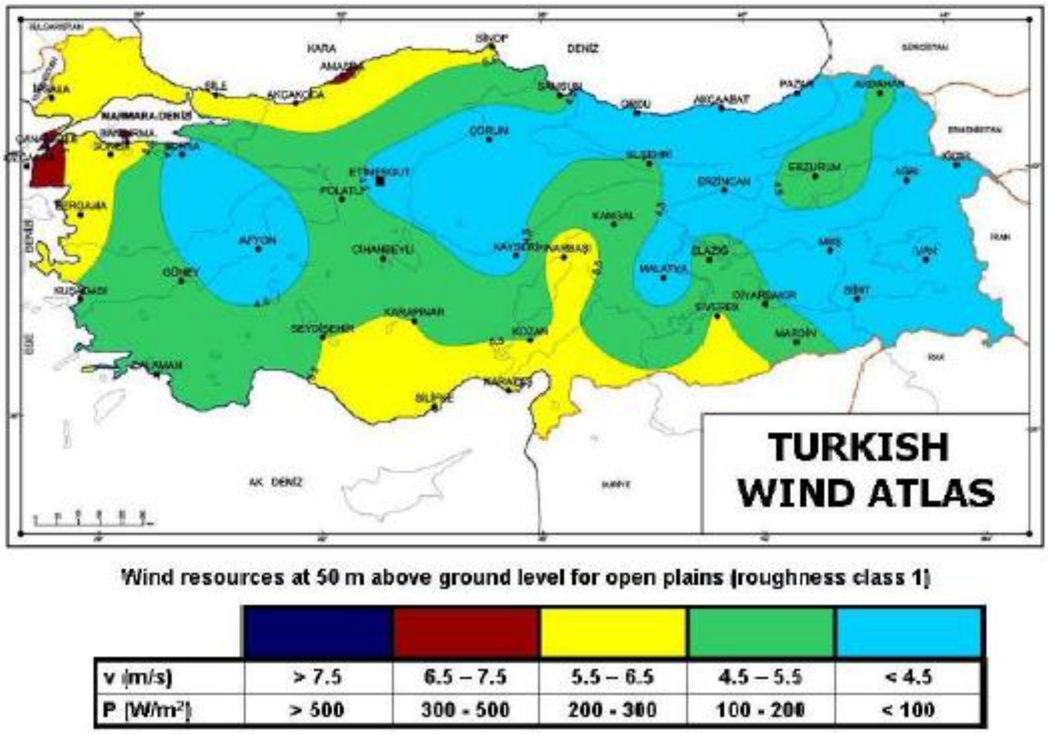


Figure 1.1. Wind Atlas of Turkey

This study is focused on optimal selection of wind power plant projects along with their connection to the current grid network. One of the two essential goals of the related optimization models is achieving connection with minimum cost between connection points on the grid and wind powers plants by selecting appropriate projects, while the second one is having maximum energy output with these selected wind power projects. In this research, in order to realize these goals and to have a reliable energy supply, some system requirements and constraints are taken into consideration, which are explained in the following chapters. This study is implemented on a real case of Turkey that takes into account the existing conditions. By using real data obtained from interviews with energy institutions and using web publications, it is determined which alternatives (among the pool of submitted project proposals) should be selected in order to have maximum energy output and minimum connection cost. Having the exact coordinates of wind power projects and possible connection points, Google Earth has been used to calculate the distances. On the other hand, mathematical models have been solved under the Cplex system, while C++ programming language is deployed for the coding of mathematical models. In that sense, this study is a novel study reviewing the connection requirements of wind power plants to the grid network, optimizing the connection by selecting the best alternatives, and having an application by using real data.

The following chapter of the study features a literature review on renewable energy, wind power and other studies on the connection of wind power plants to existing grid networks. The explanation of the mathematical model, objective function and constraints is covered in Chapter 3. Chapter 4 introduces and explains the software that are used, real case data, and their usage in the developed models. Chapter 5 features an analysis of the model outputs and comparison of the outputs of various different scenarios. Scenarios are generated by different combinations of parameter which are used in the models. Furthermore, interpretation of sensitivity analyses and results are explained in that section. Finally, in Chapter 6 summary of the study and future research opportunities are provided.

2. LITERATURE REVIEW

2.1. Renewable Energy Sources and Wind Power

Before moving deeper into the modelling of the main problem about integration of wind power plants into an existing grid, it is worthwhile to give some definitions, explanations, and general information about renewable energy sources and wind power systems. Renewable energy sources are defined as natural sources which come from the nature and replenish themselves in reasonable short times and never run out. Sun is seen as a basic natural source and most renewable energy comes either directly or indirectly from the sun (Department of Energy, 2012). Solar, wind, hydroelectric, biomass, hydrogen, geothermal, and ocean (wave) are regarded as renewable energy sources, while gasoline, coal, natural gas, diesel and other commodities derived from fossil fuels, as well as minerals like copper and others, are considered non-renewable. Thus, energy produced by these renewable sources called renewable energy(Renewable Energy, 2011).

Wind power is one of the primary renewable energy types and globally there is a huge energy potential to be used for electricity. It is claimed that the worldwide wind capacity has reached to 200 GW by June 2011 and wind power covers currently almost 3% of the global electricity demand (World Wind Energy Association, 2011). A comprehensive study in 2005 found the potential of wind power on land and near-shore to be 72 TW and it asserts that converting as little as 20% of this potential wind energy to electricity could satisfy the world's entire electrical energy demand (Cristina L. Archer, 2005). However, the researchers caution that there are still considerable practical barriers to reaping the wind's potential energy. The next section points the difficulties encountered while integrating wind power plants to existing electricity networks along with the review of academic studies conducted on this issue.

2.2. Integration of Wind Power Plants into the Grid Network

In this section, literature on optimization methods implemented on wind power plants, especially studies about integration of wind power plants to existing grid, are investigated. In the literature, there are many studies dealing with wind energy and electricity production by wind farms. The most recent and relevant of these studies are examined as follows.

A large part of the studies about wind energy is on energy production and its optimization. As mentioned previously, a big potential of wind energy waits to be harnessed. Thus, many scientists have studies regarding the energy production increase, particularly location of wind turbines and wind turbine types along with their number and size.

As a literature survey study, Kahn (2010) summarizes a variety of recent researches on wind integration studies, especially looking into optimization and simulation studies. The first research he refers in his study is CRA Simulation (Cullen, 2011) which runs a number of power flow simulations to find those flows matching generation with load. It is stated that transmission reinforcements are required to meet the reliability constraints. The second research in the survey, Bushnell's Optimization Study (Bushnell and Chen, 2009), finds the optimal mix of conventional generation plants for different wind energy penetration levels considering a major role for energy market prices. In another study, possible renewable resource selection and transmission expansion decisions are evaluated to meet a 33% renewable energy target by 2029, by answering basic questions about which renewable resources might be most attractive to that load zone and what amount and location of transmission might be needed to access those resource (Mills, Phadke, and Wiser, 2010). After investigation of the studies in his literature review, Kahn states that optimizing transmission for large-scale renewable generation is a major integration problem regarding wind energy.

Ibrahim *et al.* (2011) present the technical challenges regarding integration of wind energy into electricity systems. The major issue is stated as the intermittency nature of wind power production. While there is no technical limit on the integration into a grid, large scale integration increases the difficulty to control voltage and frequency. This study also addresses the complex issues about active power, reactive power and power factor. On the other hand, there are few technical improvements in the wind turbine technology such as wind turbines which use doubly fed induction machines facilitating control of voltage and frequency. The main solution to the variability and intermittent nature of wind power is suggested as the construction of new transmission lines enabling bigger grids and thereby balancing wind power plants by more traditional (conventional) ones.

Le and Bhattacharyya (2011) investigate the integration of wind power plants into the British System in 2020 by using the EnergyPLAN, an integrated-energy-system model, to analyze the problem. Demand and production of electricity, capital cost, fuel and CO_2 cost are taken as input data in the simulation. Consumption, production and investment results are obtained as outputs of the model under different scenarios, where wind power production is 0-50% of total electricity generation in 2020. Optimal share of wind power chosen changes based on total cost.

Mills *et al.* (2011) also evaluate 40 transmission studies to find transmission cost of wind energy. In addition, they try to figure out different transmission planning approaches and the ones that seem most able to identify incremental transmission costs associated with wind energy. The most significant difference among the studies they cover for the evaluation of transmission investments is the focused area. The first group concentrates on congestion, while the second set of studies focus on distribution of energy. In order to calculate unit cost of transmission required to connect wind power, they propose a simplified method while comparing 40 studies. In that sample, cases with higher levels of wind power penetration are investigated. Information on the mileage and voltage of transmission lines, along with assumed cost per mile of different transmission configurations are used as data. The estimation of $/kW-wind is found by simply dividing the transmission upgrade cost by the capacity of incremental wind energy while $/MWh-wind is found by dividing transmission cost by annual energy production expected from new facilities. Their suggestion, based on the economies of scale, is to oversize transmission line capacity than to size them exactly for needs. Top-down studies on national basis do not incorporate detailed physical modeling of the transmission system. It is concluded that unit transmission cost in those studies are nearly equivalent to the median cost of their sample of 40 bottom-up transmission planning studies.

Kahraman and Kaya (2010) present a study regarding evaluation of new renewable energy alternatives for İstanbul. They use VIKOR-AHP method to select the best alternative based on selection criteria such as technical, economic, environmental and social impacts. Fuzzy logic is applied in the methodology where they first decide on the most appropriate renewable energy type. In the second phase, same method is used to select the production sites for wind power plants among various alternative locations in Istanbul.

Another fuzzy AHP methodology is used by Liu *et al.* (2012) to evaluate wind integration schemes. This paper focuses on technical aspects of wind integration such as reliability, transient stability, or short circuit current levels. Triangular fuzzy numbers are used for expert scores on decision criteria. Finally, they implement the method on a case and find the best scheme.

On the other hand, there are numerous studies which deal with wind farm layout optimization (Emami and Noghreh, 2009) (Ituarte-Villarreal and Espiritu, 2011). Gonzalez *et al.* (2010) present a wind farm layout optimization study. The proposed evaluation algorithm for the wind turbine positioning problem includes net present value in order to obtain more profit during the life cycle of the wind power plant. It also includes other parameters such as wind speed, tower heights, investment cost of wind turbines and etc. A genetic algorithm is used to accomplish global optimization on the locations, number, type and height of wind turbines.

Chowdhury *et al.* (2011) propose another wind farm layout study by using the Unrestricted Wind Farm Layout Optimization (UWFLO). Specifications of wind turbines such as rotor diameters are selected in order to yield maximum power generation. The proposed model is implemented on different cases which have various options on wind turbine characteristics. Farm efficiency and cost per kW of power produced are analyzed in the results section for various number of wind turbines in the wind power plant.

Eroğlu and Seçkiner (2012) propose a model (and its solution) considering the wake of wind turbines on each other for the problem of wind farm layout optimization. They implement their model on three different scenarios with different wind speed and direction. However, wind turbine specifications are the same, and the number of wind turbines is fixed in all scenarios. The mathematical model is solved by the application of an ant colony optimization heuristic in order to maximize power output.

Moreno *et al.* (2011) deals with the same problem via a greedy heuristic algorithm. They propose a realistic model on wind turbine placement solutions on different wind farm shapes to maximize economical benefits. Various parameters such as investment cost, wind speed and direction, wind farm geography are evaluated during the solution procedure.

According to the literature research conducted, along with those studies mentioned above, there are not any optimization studies onto the wind power plants selection by dealing with the connection requirements which are explained in the further sections.

3. OBJECTIVES OF THE STUDY

As mentioned before, the objective of the study is to develop an optimization based model in order to find the best alternatives among an existing wind power project pool which provides maximum energy output along with minimum connection cost. For this purpose and in order to get insights of listed regulations and rules, many interviews are done with electric power experts working in governmental institutions and local business. Regulations and rules provided by the Turkish Energy Market Regulatory Authority (EPDK) and Turkish Electricity Transmission Company (TEİAŞ) are used to establish the basic model constraints and related parameters. Based on the interviews, it is understood that the authorities want to connect wind power plants as much as possible in order to maximize the electric power obtained from wind energy. At the same time, they want to control and minimize the connection cost which is regarded as the responsibility of the State. Thus, the developed model is expected to be used as a decision making tool to have a balance between the authorities' desire to have maximum energy output from wind power plants and to limit the cost of the connection.

In order to reach to the stated aims, two sets of models that deal with the integration of new wind power plants into existing grid networks are established. The first model set actually has two submodels focusing on maximum installed capacity and maximum energy delivered, respectively. The second model approaches the selection of wind power plants from cost and revenue perspectives.

Another goal of the study is to find different results for each input dataset. The model parameters playing the most significant role on the results are expected to be identified. In order to achieve this goal, various input datasets are prepared and used in the models. According to different expectations and changing values of parameters such as budget, capacity allocation percentage for wind power plants, scenarios are developed based on various combinations of these parameter values. Scenario analysis is conducted and outputs of scenarios are compared with one another in order to detect most significant parameters. Thus, it provides opportunity to discover effects of various constraints and coefficients on the results.

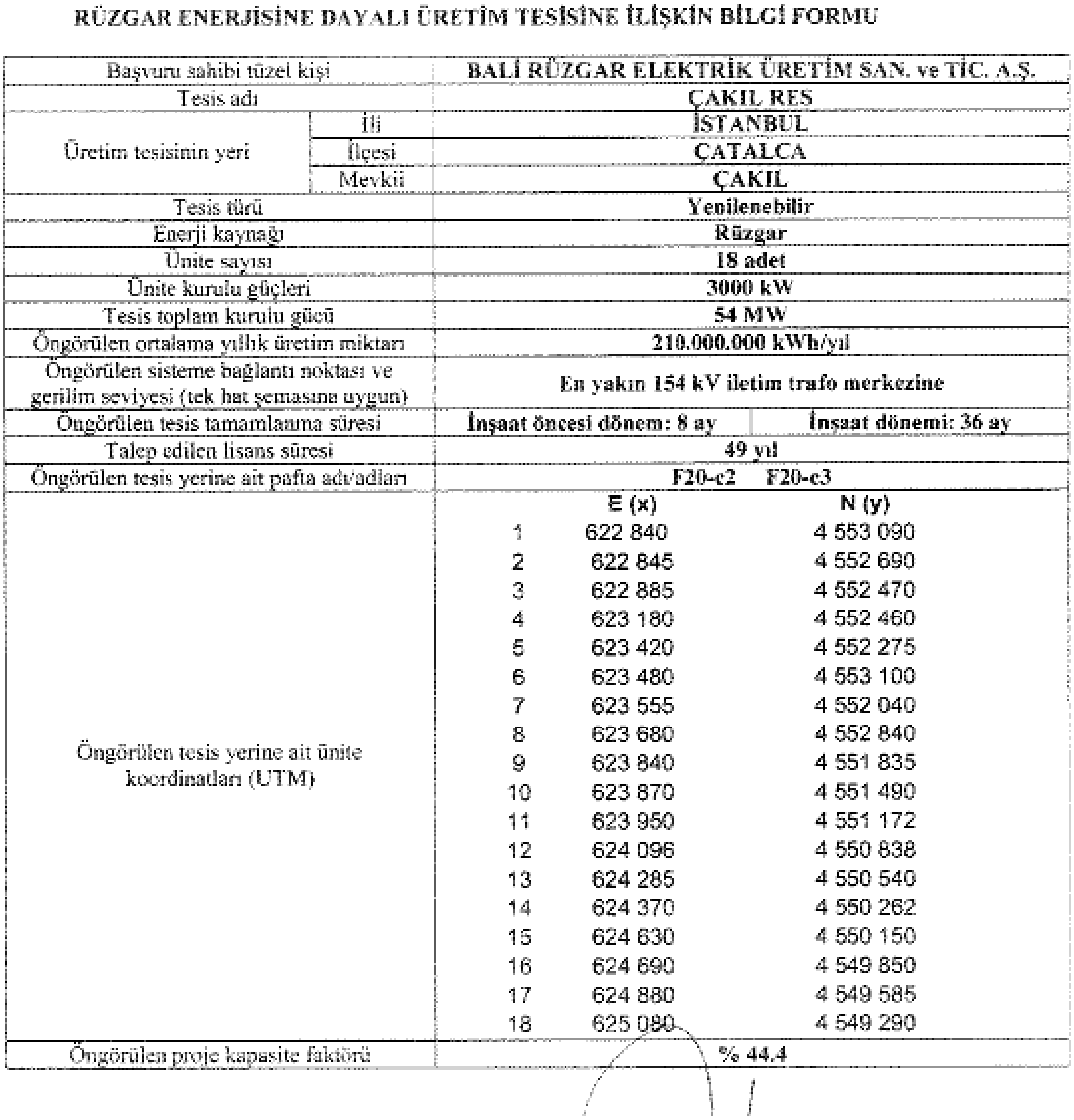
Besides these general objectives, number of high voltage level connections and medium voltage level connections are determined for each run. Since there is a very different unit cost for each connection type, it is worthwhile to see the effects of different connection options on the results. On the other hand, since one of the biggest obstacles of the system for the connection of wind power plants is the capacity of the substations, the substations to which wind power projects are connected are identified for various scenarios. Detailed explanation of high voltage connection and medium voltage connection along with the substation capacity is given in the next section. In addition to that, total connection cost and revenues obtained from the bids along with the delivered power and installed capacity are given and compared for each scenario.

The developed model is implemented on a real case in Turkey. It is important to have a study applied on a real case to see the differences between model outputs and the actual decisions made by the responsible authorities. Equally important is the usage of the model as a tool for decision makers, not only to balance the cost and energy delivery, but also to foresee the results in advance before they move on their steps. Since model parameters which have significant effects on the results are also provided, authorities are able to update necessary parameters based on changing conditions in order to make accurate decisions in the future.

3.1. The Problem Environment

After the Turkish parliament passed new legislation which provides incentives to new renewable energy plants, many potential wind power plant investors have applied to have production licenses and connection permits to the grid. However, there are some obstacles, such as insufficient budget or capacity of the current system. Therefore, the authorities need a well defined and structured procedure in order to better evaluate new wind power plant applications. Before decision making, all of the applications are collected in a wind power project pool. Figure 3.1 shows an example of the application form the wind power plant companies. The information provided in the application report are location of the wind power plant, installed capacity, number of wind turbines in that plant along with their longitudes and latitudes, and capacity factor which gives the availability factor of this plant. (Availability factor is simply called as efficiency in this study.)

However, technology to be used in this plant, investment cost, effects on the environment are not provided these data set.



RÜZGAR ENERJİSİNE DAYALI ÜRETİM TESİSİNE İLİŞKİN BİLGİ FORMU

Başvuru sahibi tüzel kişi		**BALİ RÜZGAR ELEKTRİK ÜRETİM SAN. ve TİC. A.Ş.**	
Tesis adı		**ÇAKIL RES**	
Üretim tesisinin yeri	İli	**İSTANBUL**	
	İlçesi	**ÇATALCA**	
	Mevkii	**ÇAKIL**	
Tesis türü		**Yenilenebilir**	
Enerji kaynağı		**Rüzgar**	
Ünite sayısı		**18 adet**	
Ünite kurulu güçleri		**3000 kW**	
Tesis toplam kurulu gücü		**54 MW**	
Öngörülen ortalama yıllık üretim miktarı		**210.000.000 kWh/yıl**	
Öngörülen sisteme bağlantı noktası ve gerilim seviyesi (tek hat şemasına uygun)		**En yakın 154 kV iletim trafo merkezine**	
Öngörülen tesis tamamlaama süresi		**İnşaat öncesi dönem: 8 ay**	**İnşaat dönemi: 36 ay**
Talep edilen lisans süresi		**49 yıl**	
Öngörülen tesis yerine ait pafta adı/adları		**F20-c2 F20-c3**	
Öngörülen tesis yerine ait ünite koordinatları (UTM)		**E (x)**	**N (y)**
	1	622 840	4 553 090
	2	622 845	4 552 690
	3	622 885	4 552 470
	4	623 180	4 552 460
	5	623 420	4 552 275
	6	623 480	4 553 100
	7	623 555	4 552 040
	8	623 680	4 552 840
	9	623 840	4 551 835
	10	623 870	4 551 490
	11	623 950	4 551 172
	12	624 096	4 550 838
	13	624 285	4 550 540
	14	624 370	4 550 262
	15	624 630	4 550 150
	16	624 690	4 549 850
	17	624 880	4 549 585
	18	625 080	4 549 290
Öngörülen proje kapasite faktörü		% 44.4	

Figure 3.1. Application Form of a Wind Power Plant Project

Total power capacity of the wind generation projects in the pool is about 78000 MW. However, the total capacity at the connection points, (which are generally substations), is about 8449 MW, as declared by TEİAŞ in 2010 (Altuntaşoğlu, Rüzgar Enerjisi Konusunda Mevcut Durum, 2011).

Substation is an important component of the electricity system. It performs several significant functions such as fault control, voltage regulation, frequency control, and so on.

It may also include transformers in order to convert high voltage to low voltage or vice versa (Electrical Substation, 2012). It is located as node at endpoints of transmission lines which constitutes networks. Addition to that, it provides connection between medium voltage network and high voltage network. In other words, it is an intersection of two electricity network at different voltage levels. In this specific problem, substations are considered as connection points to the existing grid by TEİAŞ.

One of the critical factors playing a significant role on connection of wind power plants is capacity of substation. Capacity is defined by short circuit power which is shortly described as total power arriving substation from conventional power plants. Only a certain percentage of this capacity can be allocated to wind power plants due to their intermittent power supply.

In addition to lack of sufficient capacity at the connection points, cost of the construction of the connection lines comprises a major issue because all of these lines has to be constructed by TEİAŞ in case of permission for connection. Limited budget is one of the major constraints this problem.

Before selecting wind power projects which are already technically eligible, the authorities organize an auction in order to get bidding values from the project owners; each project owner submits a bid. This offer includes installed capacity of the wind power plant project, location of the project, and the money that they can pay as connection and operating license fee.

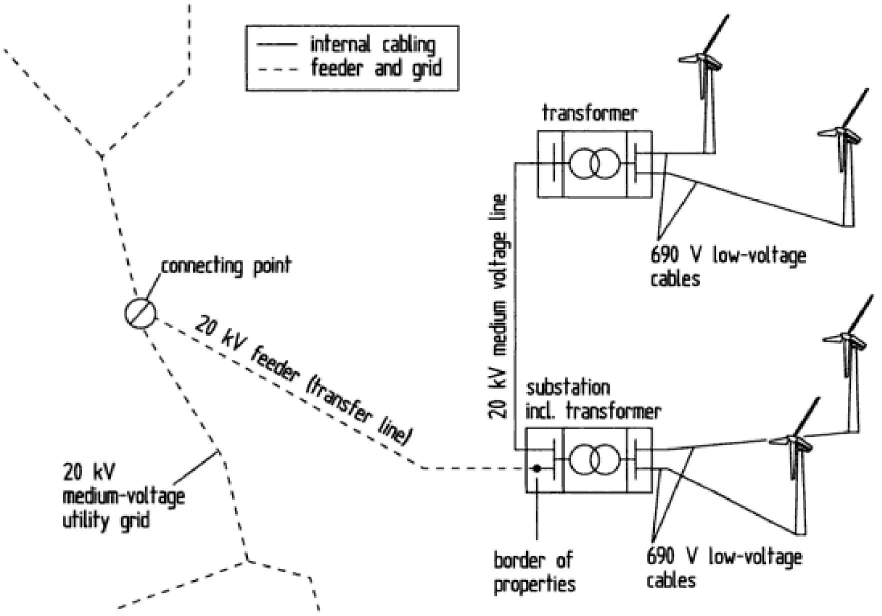


Figure 3.2. Wind Power Plant and Its Connection to the Grid

Figure 3.2 shows a typical wind power plant and its connection to the grid (Hau, 2006). As can be seen in the figure, wind power plants consist of several wind turbines that produce electricity by converting wind energy first into mechanical power and then into electricity. Wind turbines are located on towers that are generally longer than 30 meters. In Turkey's electricity system, the output voltage level of a wind turbine in most plants is around 690 kV(Hau, 2006) and its frequency is 50 Hz. Electricity is transmitted to the transformer inside the plant and converted into higher voltage whose level depend on the voltage level on the intended connecting point to the grid. In this study, connection point is named as "substation" which is a node on the grid proving the connection of (usually) multiple generation facilities to the grid. Actually, there are two distinct "grids" and related sets of connection points/substations:

(i) A medium voltage grid (at 34.5 kV) which features lesser investment costs (per unit distance of transmission line) but carries higher transmission losses,

(ii) A high voltage grid (at 154 kV) which features higher investment costs (per unit distance of transmission line) but carries fewer transmission losses.

In order to stay connected to the system, there are three things that have to be equal both at output of wind power plant and substation: voltage level of connection line (transfer line), frequency, and phase angles of the electricity provided. In some cases such as when wind speed is very low (technically called as cut-in wind speed, at which level a turbine starts to operate and produce electricity) or very high (cut-out wind speed where the turbine shuts down to protect the rotor blades), it is not possible to provide stable conditions in voltage level, frequency and phase angle. Thus, its connection with the grid is cut off to prevent destabilization in electricity supply (Urban Wind Turbines, 2011). Other requirements regarding connection of wind power plants are explained in the assumption and regulations section.

All of these requirements are under the responsibility of management of wind power plant. Thus, the most significant issue that authorities need consider is the construction of connection lines. All the other technical issues related with the connection lines such as power loss, short circuit capacity at substations are introduced and discussed in further sections.

4. THE DEVELOPMENT OF THE MODELS

In this section, description of the parameters, input data and variables used in the models are introduced along with the explanation of the each model. First, definitions of terminology and assumptions regarding the regulations that are used in this study are given.

4.1. Terminology

Since this study includes many electricity and electric power related terms which some readers may not be familiar with, it is worthwhile to give some necessary information and terminology that are used in the study. This section provides the reader explanatory definitions of the terms in electricity and wind power area that are frequently used in the study, and how they are named.

Wind power plant: It is an electricity generation plant that transforms kinetic energy of wind power into electricity. It is composed of a set of transformers, distribution lines and a group of wind turbines which are interconnected to a common power provider system (Wind Power Plant, 2011). Usually they include one plant transformer to transform the electricity produced by wind turbines at low voltage into high voltage for connection to an existing grid. Such a subsystem is called “wind power plant” in this study, while wind farm and wind power generation station are other commonly used terms in the literature (Glossary, 2012).

Substation: As discussed before, in the problem environment subsection, substation is a part of an electricity network which fulfills some electrical control functions related to the flow of electricity in a transmission network and facilitates the connection (to the network) of generation plants. Substations also enable interconnection of two different (low and high) transmission voltages (Electrical Substation, 2011). Although there different types of substations for specific purposes, it is simply called as substation in this study.

Electricity Grid: It is a network covering a large area whose nodes are substations (providing electrical power to the network) or demand centers (consuming power from the network) and whose arcs are transmission lines carrying electrical power, at various voltage levels (high and medium voltage). It connects power plants to end users with the additional connection lines in order to deliver electricity from suppliers to customers (Electrical Grid, 2011). There are other names for it such as power network, power grid, or electrical network. In our study, it is called as grid. Figure 4.1 presents electric grid of Turkey as an example (Ucoz, 2011). Red lines indicate the very high voltage grid network of Turkey while black lines show the lower voltage levels. The intersection of the lines with a circle displays locations of substations.

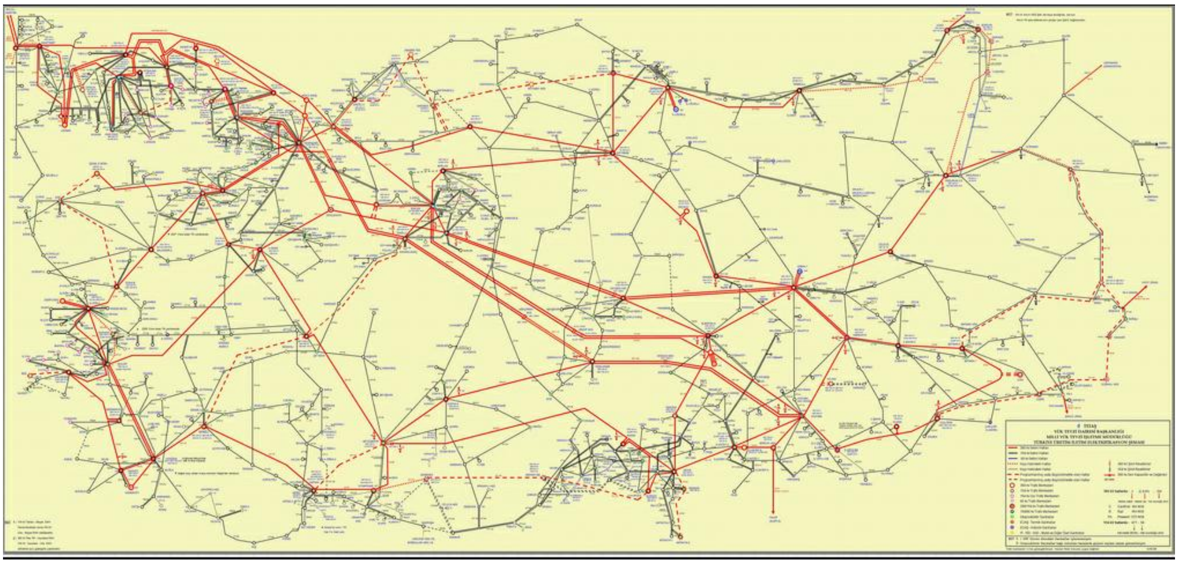


Figure 4.1. Electricity Grid of Turkey

Short Circuit Power: It is the maximum power that can be transmitted to the earth when a connection fault occurs. In this study, short circuit power is the total power coming from conventional generation plants to a substation. Therefore, it also determines the capacity amount to be allocated for wind power plants at each substation.

Voltage: It is also named as tension which is electrical potential difference between two points per unit charge. It is shown with the letter V, measured in volts or joules per coulomb (Voltage, 2011). As mentioned before, two voltage levels are considered regarding the transmission of the electricity generated at various wind power plants to the existing grid in this study. In other words, each wind power plant can be connected to the 34.5 kV network, which is the medium voltage network or to the 154 kV network, which is the high voltage network.

Current: It an electric circuit, it represents the flow of electric charge past a given point. It is shown with the letter I, measured in Amperes or Coulombs/second (Electric Current, 2008).

Electric Power: It is the rate of transferred electricity in the electrical network. It is shown with the letter P, measured in Watts (Electric power, 2011). The simple formula for electric power (P) is P = I*V. Additionally, MVA is the apparent power, MW is the real power and, MVAR is reactive power (Electric Power and Transmission and Distribution Forum, 2005). The formulation to calculate MVA is,

$$\mathrm{MVA}^2 = \mathrm{MW}^2 + \mathrm{MVAR}^2.$$

Frequency: It represents the frequency of oscillations during power transmission (Utility Frequency, 2011). In Turkey, the desired utility frequency is 50 Hz, which is same as in Europe, while it is 60 Hz in Americas.

4.2. Assumptions and Regulations

The regulations guiding and the assumptions underlying the models developed in this study are mostly attained by interviews with experts working in electricity distribution companies and government agencies. This section explains the connection requirements of wind power plants to an existing grid, without affecting quality and stability of the electricity system. The assumptions along with the conditions of Turkey’s electricity system are also explained.

4.2.1. Electricity Network Requirements

Theoretically, for wind power plants to be connected to the grid there are three requirements, which are power control and frequency range, power factor and voltage control, and transient fault behavior within voltage operating range (Alboyacı and Dursun, 2008).

TEİAŞ controls the system frequency at about 50 Hertz (Hz) with the upper and lower bounds 50.2 Hz and 49.8 Hz respectively. These bounds cannot be violated longer than 10 minutes.

Conventional voltage levels of the transmission network are 380 kV, 154 kV, 66 kV and 34.5 kV. However, the authorities in TEİAŞ indicated that 66 kV voltage lines are being converted to 34.5 kV or 154 kV lines and thus eliminated from Turkey’s existing grid. Based on the announced substation connection points, wind power plants can only connect to the existing grid at 154 kV and 34.5 kV level among all these transmission voltage levels (TEİAŞ Supply Reliability and Quality Regulation of the Electrical Transmission Systems, 2010).

It is not desired to connect wind power plants to the 380 kV transmission network since this transmission system is regarded as the main structure of the grid, where authorities do not want to damage its stability with intermitted power source of wind power plants. On the other hand it is not desired to have wind power plants on the 66 kV network since TEİAŞ is already in the process of converting these lines into other voltage levels. Thus, the only two remaining connection voltage levels, (namely, 154 kV and 34.5 kV), are considered in this study for possible connection of wind power plants to the grid.

4.2.2. Principle Regulations

There are some strict regulations providing a basis for the connection of wind power plants to the grid. Many of them are reflected in the developed minimum cost – maximum energy output models as connection constraints. The regulations are provided by electricity experts working on this area and they are verified through the literature survey.

Regulation 1 (R1): The most important rule regulating the connection of wind power plants to the grid is the short-circuit power of the substation, through which the wind power plant is connected to the grid via a transfer line. As indicated before, short-circuit power is the power that currently comes from conventional power plants. It is stated that only 5% of the short-circuit power of a substation can be allocated to electric energy arriving at that substation from wind power plants (Alboyacı and Dursun, 2008), (TEİAŞ Supply Reliability and Quality Regulation of the Electrical Transmission Systems, 2010). The reason behind this rule is that, since wind power plants have a nature of intermitted power supply, they ought to be compensated with conventional power plants where the technical characteristics of the electricity generation is more stable and easily controlled. On the other hand, some experts in the literature claim that up to about 20% of a substation load can be allocated to wind base electrical energy without major control problems (Hau, 2006). Thus, the allocation percentage of short-circuit power is used as a parameter in the scenario analysis section of this study.

Regulation 2 (R2): It is stated that wind power plants having installed capacity of more than 50 MW have to be connected to the existing grid at 154 kV voltage level, while plants having less than 10 MW installed capacity have to be connected at 34.5 kV voltage level. Plants having installed capacity between 10 MW and 50 MW can be connect at either 154 kV or 34.5 kV levels (Electricity Market Grid Regulation, 2003).

Regulation 3 (R3): The parameters playing major roles on power loss during the transmission of the energy are voltage level, connection line length, and cross-sections. In the literature, it is argued that power transmission losses up to the grid should not exceed 2% even for the large wind power plants (Hau, 2006). However, based on interviews with EPDK experts, losses up to 3% on individual connection lines to the grid are assumed to be tolerable.

Regulation 4 (R4): The percentage of total power losses on the transmission and distribution lines in Turkey is given as 2.55% by EPDK experts. Thus, total power loss percentage after connections of wind power plants to the grid is not desired to exceed 2.55%. In other words, overall power losses in the connection lines cannot exceed 2.55% of the installed capacity.

4.2.3. Underlying Assumptions

In this study, real power is used in the formulation of the constraints since data for installed capacities of wind power plants are provided as of MW (real power) units by TEİAŞ.

Precise energy output point in actual wind power plants are at the geographic coordinates of wind turbines in the facility. Unfortunately, exact coordinates of energy output points are not available for the project proposals in the project pool used in this study. So, it is assumed that the location of output is at the middle of two wind turbines farthest to each other. The longitude and latitude of output is found by taking the middle point of furthest wind turbines with regard to their longitude and latitude values.

Further technical requirements of substations such as load flow, voltage transformation capacity analyses, and connection requirements such as power control, frequency range, power factor value and transient fault behavior with voltage operating range are not explicitly considered in the developed models.

It is possible to achieve grid connection by connecting the transmission line coming from a wind generation plant to some point on any existing transmission line on the grid. This type of “line connection” (versus substation connection) is represented in the optimization models in a simplified from: Line connection may be accomplished at one of three locations on the intended grid transmission line: either at one of the substations at the endpoints of the transmission line in consideration or at its center. As such, the so called “united substation” triplets (consisting of the two endpoint substation and one middle point substation for every potential line connection) are defined in the optimization models.

Transmission capacity of the grid beyond the substations where connection to the considered wind power plants is established is assumed to be sufficient and thus not considered in the model.

4.3. Description Parameters and Decision Variable

In this study, there are two sets of models which deal with the integration of new wind power plants to the existing grid. The first set of models aims to maximize the total power of wind power plants to be connected to the existing grid, while the second model focuses on the cost minimization. Before detailed explanation of each model, definitions of the notation and parameters used in these models are provided in Tables 4.1 and 4.2 below.

Table 4.1. Notations Used in the Mathematical Models

Notation	**Description**
i	Index of wind power plant projects
j	Index of substations
k	Index of substation voltage levels
t	Set index for united substations
U_t	Set of united substations
M	Set of wind power plant projects with proposed power production capacity more than 50 MW
N	Set of wind power plant projects with proposed power production capacity less than 10 MW

The list of parameters along with their description is given in Table 4.2. Detailed explanations of the parameters are provided in Section 4.5.1.

Table 4.2. Parameters Used in the Mathematical Models

Parameter	**Description**
W_i	Power production capacity of *ith* wind power project
D_{ij}	Distance (in kilometers) between *ith* wind power project and *jth* substation
S_{jk}	Short circuit power capacity of *jth* substation at voltage level
SU_{tk}	Short circuit power capacity of *tth* set of united substations at *kth* voltage level
C_k	Unit cost of connection line per kilometer at *kth* voltage level

Table 4.2. Parameters Used in the Mathematical Models (cont.)

E_i	Efficiency of wind power project *i*
B_i	Bidding Value of wind power project *i*
F_k	Energy loss factor at *kth* voltage level
Φ	Short circuit power capacity percentage of a substation that can be allocated to wind power generated electricity
α	Weight of connection costs in objective function of Model B
β	Weight of bid values in objective function of Model B
L_{max}	Maximum tolerated power loss percentage for any connection line
ToL_{max}	Maximum tolerated power loss percentage for overall connections
C_{max}	Maximum acceptable connection cost per wind power project
ToC_{max}	Maximum acceptable overall connection cost for all wind power projects
R_{min}	Minimum power expected from wind power projects

The decision variable used in the mathematical models is X_{ijk}. It is 1 if *ith* wind power plant project is accepted to be connected to the grid at *jth* substation and at *kth* voltage level, 0 otherwise.

4.4. Explanation of the Optimization Models

Mathematical representations of objective functions and constraints used in optimization models are given below. Since they have linear objective functions and linear inequality constraints, these optimization models are classified as binary integer programming models.

Model-A-I: The model aiming to maximize installed wind power plant capacity

Objective:

$$\text{Max } \sum_i \sum_j \sum_k W_i \, X_{ijk}$$

Subject to;

Substation Constraints:

$$\sum_i W_i \, X_{ijk} \le \Phi S_{jk} \qquad \forall\, j,k \qquad \textit{Short Circuit Power Capacity} \tag{1}$$

$$\sum_i \sum_{j \in U_t} W_i \, X_{ijk} \le \Phi \, SU_{tk} \qquad \forall\, k,t \qquad \textit{Capacity for United Substations} \tag{2}$$

Connection Line Constraints:

$$W_i \, F_k \, D_{ij} \, X_{ijk} \le L_{\max} \qquad \forall\, i,j,k \qquad \textit{Max Power Loss per Connection} \tag{3}$$

$$\sum_i \sum_j \sum_k W_i^2 \, F_k D_{ij} X_{ijk} \le ToL_{\max} \sum_i \sum_j \sum_k W_i \, X_{ijk} \qquad \textit{Max Power Loss of All Connections} \tag{4}$$

Cost Constraints:

$$C_k \, D_{ij} \, X_{ijk} \le C_{\max} \qquad \forall\, i,j,k \qquad \textit{Cost per Connection} \tag{5}$$

$$\sum_i \sum_j \sum_k C_k \, D_{ij} \, X_{ijk} \le ToC_{\max} \qquad \textit{Total Cost of All Connections} \tag{6}$$

Connection Rules:

$$\sum_{i \in M} \sum_j X_{ij1} \le 0 \qquad \textit{Connection to 34.5 kV not allowed} \tag{7}$$

$$\sum_{i \in N} \sum_j X_{ij2} \le 0 \qquad \textit{Connection to 154 kV not allowed} \tag{8}$$

$$\sum_j \sum_k X_{ijk} \le 1 \qquad \forall\, i \qquad \textit{Connection to Only One End} \tag{9}$$

Decision Variable Constraints:

$$X_{ijk} \in \{0,1\} \qquad \forall\, i,j,k \qquad \textit{Binary Decision Variable} \tag{10}$$

Model-A-II: The model aiming to maximize energy delivered from wind power plants

Objective:

Max $\sum_i \sum_j \sum_k E_i W_i X_{ijk}$

Subject to;

Substation Constraints:

$\sum_i W_i X_{ijk} \leq \Phi S_{jk}$	$\forall j,k$	*Short Circuit Power Capacity*	(1)
$\sum_i \sum_{j \in U_t} W_i X_{ijk} \leq \Phi SU_{tk}$	$\forall k,t$	*Capacity for United Substations*	(2)

Connection Line Constraints:

$W_i F_k D_{ij} X_{ijk} \leq L_{\max}$	$\forall i, j,k$	*Max Power Loss per Connection*	(3)
$\sum_i \sum_j \sum_k W_i^2 F_k D_{ij} X_{ijk} \leq ToL_{\max} \sum_i \sum_j \sum_k W_i X_{ijk}$		*Max Power Loss of All Connections*	(4)

Cost Constraints:

$C_k D_{ij} X_{ijk} \leq C_{\max}$	$\forall i, j,k$	*Cost per Connection*	(5)
$\sum_i \sum_j \sum_k C_k D_{ij} X_{ijk} \leq ToC_{\max}$		*Total Cost of All Connections*	(6)

Connection Rules:

$\sum_{i \in M} \sum_j X_{ij1} \leq 0$		*Connection to 34.5 kV not allowed*	(7)
$\sum_{i \in N} \sum_j X_{ij2} \leq 0$		*Connection to 154 kV not allowed*	(8)
$\sum_j \sum_k X_{ijk} \leq 1$	$\forall i$	*Connection to Only One End*	(9)

Decision Variable Constraints:

$X_{ijk} \in \{0,1\}$	$\forall i, j,k$	*Binary Decision Variable*	(10)

Model-B: The model aiming to maximize profit and minimize connection cost

Objective:

Max $\beta \sum_i \sum_j \sum_k B_i X_{ijk} - \alpha \sum_i \sum_j \sum_k C_k D_{ij} X_{ijk}$

Subject to;

Substation Constraints:

$\sum_i W_i X_{ijk} \le \Phi S_{jk}$ $\forall j,k$ *Short Circuit Power Capacity* (1)

$\sum_i \sum_{j \in U_t} W_i X_{ijk} \le \Phi SU_{tk}$ $\forall k,t$ *Capacity for United Substations* (2)

Connection Line Constraints:

$W_i F_k D_{ij} X_{ijk} \le L_{\max}$ $\forall i, j,k$ *Max Power Loss per Connection* (3)

$\sum_i \sum_j \sum_k W_i^2 F_k D_{ij} X_{ijk} \le ToL_{\max} \sum_i \sum_j \sum_k W_i X_{ijk}$ *Max Power Loss of All Connections* (4)

Cost Constraints:

$C_k D_{ij} X_{ijk} \le C_{\max}$ $\forall i, j,k$ *Cost per Connection* (5)

Required Capacity Constraints:

$\sum_i \sum_j \sum_k W_i X_{ijk} \ge R_{\min}$ *Min. Required Energy from WPP* (6)

Connection Rules:

$\sum_{i \in M} \sum_j X_{ij1} \le 0$ *Connection to 34.5 kV not allowed* (7)

$\sum_{i \in N} \sum_j X_{ij2} \le 0$ *Connection to 154 kV not allowed* (8)

$\sum_j \sum_k X_{ijk} \le 1$ $\forall i$ *Connection to Only One End* (9)

Decision Variable Constraints:

$X_{ijk} \in \{0,1\}$ $\forall i, j,k$ *Binary Decision Variable* (10)

Model A-I: As stated before, objective of the first submodel of the maximum energy output model is to maximize the installed power capacity of wind powers plants connecting to the grid. It is subject to the constraints explained below.

- Constraint set (1) corresponds to article R1 explained in the regulations section. Total capacity of all wind power plants due to connect to a particular substation cannot exceed the allowed wind power capacity at this point. Allowed wind power capacity is the predefined percentage of that substation's short circuit power capacity (at the intended voltage level).
- Constraint set (2) also fulfills the requirements of R1 regarding united substations. Total energy from wind power plants connected to any point on this line cannot exceed the short circuit capacity since all three points share the same capacity. In other words, short circuit capacity is same at all of these three points. Exceeding energy of wind power plants connections to those points are avoided by the second constraint in the mathematical model.
- Constraint set (3) is associated with R3. During the transmission of the energy from wind power plants to the connection point, rate of power loss occurs according to the energy amount transmitted, the length of the connection line and voltage level of the connection. This constraint provides for the maximum power loss limitation per each connection.
- Constraint set (4) corresponds to the requirement pointed by R4. There is a certain amount of tolerable power loss percentage in the current grid network. Authorities do not want this rate to increase after the addition of new connection lines. Thus, the forth constraint set ensures that the power loss rate in the connection lines cannot exceed the tolerance limits for the existing grid.
- Constraint set (5) reflects the limited budget of TEİAŞ for new connection lines. One of the most significant constraints while adding new wind power plants to the grid is the connection line building cost. This cost depends on length and voltage level of the connection. Fifth constraint set in the modeling does not only achieve that goal, but also supports third and fourth constraint sets by discouraging the length of the connection line to be very long.
- Constraint set (6) provides a limitation on total cost of all connection lines. Authorities does not want investment cost of all connection lines between wind

power plants and connection points to exceed the available budget. Thus, total cost arising from connection line investments is formulated accordingly.

- Constraint set (7) is associated with regulation R2. This constraint prevents connection of wind power plants with a capacity of more than 50 MW at the 34.5 kV level.
- Constraint set (8) also fulfills the requirements of R2 Wind power plants with less than 10 MW capacities cannot connect to the grid at the 154 kV level.
- Constraint set (9) ensures that only one connection line can be built for any wind power plant.
- Constraint set (10) is about the decision variable in the model. The decision variable of the problem is whether to build a connection between the power plant and end point of a substation. Thus, it is set as a binary decision variable in the tenth and the last constraint of the first submodel.

Model A-II: The objective of the second submodel of the maximum energy output model is to maximize the power delivered to the grid from wind powers plants. Therefore, power capacity values are multiplied with efficiency factors of each wind power plant project to calculate the actual power to be supplied. This submodel, when making a connection decision, gives priority to the wind power plants which have higher efficiency rates. All the constraints in this submodel are same with those in the first submodel, model A-I.

Model B: This model minimizes the cost (or maximizes the profit) associated with all wind power project acceptance and connection location decision. All the constraints in that model ensure the same rules and regulations used in submodel A-I. However, instead of total cost constraint (6), there is a minimum energy requirement constraint to ensure that the model accepts a reasonable subset of the proposed projects (to satisfy the energy needs) even under the cost minimization objective. Otherwise, model would set all decision variables to zero to decrease the cost even further.

- Constrain set (5) in the third and last model sets a minimum goal for the installed power supplied from wind power plants (WPP). Therefore, this model ought to force some of the decision variables to be 1 even for the cost minimization analysis that is explained in the further sections. That constraint reflects the expectations of TEİAŞ since authorities desire to define minimum energy level that is supplied from wind power plants.

4.5. Input Data Used for the Case Study and Their Explanation

Data set used in the case study for parameters are provided in Table 4.3. Detailed explanations of data set are given in the next section.

Table 4.3. Values of parameters and notations used in the model

Parameter & Notation	**Data Set**
i	1,2,…677
j	1,2,…158
k	1 if voltage level is 34.5 kV. 2 if voltage level is 154 kV
U_t	8 set of united substations. Specific values are given in the Appendix A
W_i	Provided in Appendix A
D_{ij}	Provided in Appendix A
S_{jk}	Provided in Appendix A
SU_{tk}	Provided in Appendix A
C_k	35000 Euro for 34.5 kV and 80000 Euro for 154 kV per kilometer
E_i	Provided in Appendix A
B_i	Provided in Appendix A
F_k	$92.348*10^{-6}$ for 34.5 kV and $1.897*10^{-6}$ for 154 kV
Φ	5%, 8% and 12%
α	Different Values of α used for Sensitivity Analysis
β	Different Values of β are used for Sensitivity Analysis
L_{max}	3%
ToL_{max}	2.55%
C_{max}	2400000 Euro
ToC_{max}	200000000 Euro and 300000000 Euro
R_{min}	3000-4000-5000 MW

4.5.1. Explanation of the Data Set Used for Case Study

This study represents a case in Turkey which involves 751 wind power plant applications with total 78000MW installed capacity (as of November 2009) (1 Kasım RES Başvuruları, 2010). Some of the projects are eliminated from the application pool due to insufficient information about the project data, such as exact project location. Therefore, after eliminations, project pool consists of 677 wind power plant applications that have all necessary information. There is a picture showing the locations of wind power plant application on the map of Turkey in the figure 4.2 below (Mevlüt Akdeniz, 2009).

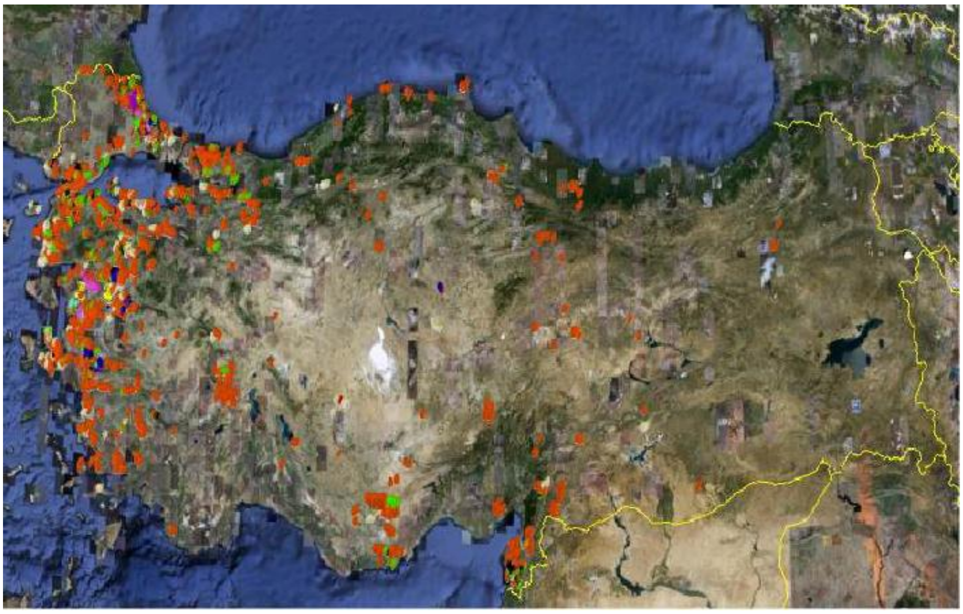


Figure 4.2. Regional Deployment of Wind Power Plant Applications

Total number of available substations including their suitable capacity for new wind power input is obtained from a report by TEİAŞ in 2010 (RES Bağlanabilir Kapasiteleri, 2010). Their coordinates are also given in this report. Since there are also some transmission lines where wind power plants can connect to any point on that line, the number of possible connection points on those lines is decreased to three. The total number of potential connection points is 158. This number includes the united substations. There are 8 set of united substations which means 24 of 158 connection points belongs to united substations.

Voltage level at which wind power plants can connect to the grid are declared as 34.5 kV and 154 kV by TEİAŞ, where they are represented via the index k=1, 2 as explained in previous sections.

U_t is used for united substations in this study. The number of united substations in this case is 8 sets.

W_i represents the proposed installed capacity of each wind power plant *i*. Capacity data of all wind power plants (in MW unit) is provided in the appendix.

D_{ij} represents the distance between wind power plants (i) and substations (j), (including the connection points on united substations). The closest three connection points for each wind power project are calculated and relevant data is provided in the appendix as well.

S_{jk} represents the short circuit capacity for *kth* voltage level of *jth* substation (or connection point). As it is noted before, those capacities are declared by TEİAŞ. On the other hand, SU_{tk} is used for the united substations where t shows which set those points belong to and k shows the voltage level. All information can be found in appendix.

C_k represents the cost of connection line per km. It is stated as 35000 Euro and 80000 Euro for 34.5 and 154 kV respectively by one of the contractor companies (Wind Energy Contracting, Capabilities and Solutions, 2012) which builds the most of the wind power connection lines in Turkey. These values represent average values since geographical conditions which may increase or decrease the construction cost of connection lines is not included in this study.

E_i gives the expected availability percentages of individual of wind power projects. Based on the location of the plant, each project may feature different availability rates which give delivered energy when multiplied with installed capacity. For example, if installed capacity of a plant is 50 MW and efficiency rate of that plant is 45%, the actual delivered energy becomes 50MW*45% = 22.5MW. Efficiency rates for each wind power plant are provided in the appendix.

F_k is the power loss factor for different voltage levels. The constraint regarding F_k controls the loss rate which is calculated by P(lost) / P(produced). Based on the literature it is taken as $92.348*10^{-6}$ for 34.5 kV level connection lines, and as $1.897*10^{-6}$ for 154 kV level connection lines.

Φ shows the maximum percentage of short circuit capacity of substations that may be allocated to wind power generated electricity. As indicated before, some sources in the global literature mention a percentage as high as 20%. However, Turkish authorities have set it as 5% in order to be more conservative against any problem that may arise from instability of energy supply. In this study, three levels as 5%, 8% and 12% are considered in the sensitivity analysis. 5% is advised to Turkish authorities by various experts. Therefore, it is deployed as the lowest level of Φ in this model. Approximately average value (12%) of wind power penetration rates in Republic of Ireland and Germany, 14% and 9%, is taken as the high value of Φ. Addition to that, the level 8% for Φ in sensitivity analysis is considered as moderate value between 5% and 12%.

β and α parameters are used in model B, which is about overall cost. They represent the weights of bidding values and connection line construction costs associated with individual wind power projects in the objective function. (As such, β represents the weight of income to be gained by granting a certain wind power project, while α represents the weight of expenditure to provide connection to that project.) (1, 0), (0.5, 0.5), (0.2, 0.8) and (0, 1) values for these parameters are used in the sensitivity analysis. Reasons for choosing these values are explained in the next section.

L_{max} is used for individual connections and the value for this parameter is 3% as suggested by authorities.

ToL_{max} is used for sum of all connections and the value for this parameter is given as 2.55% by experts in APK.

Based on the data given by one of the construction companies (ZRD Muhendislik, 2010), connection lines C_{max} is chosen as 2.4 million Euro which allows maximum 30km connection line for 154kV lines and 68.5 km for 34.5kV.

ToC_{max}, maximum total cost of new connection lines for wind power plants, is chosen as 200 and 300 million Euro based on the fact that TEİAŞ has 500 million TL investment fund in 2010 (Türkiye Elektrik İletim Anonim Şirketi).

R_{min} represents the amount of power to be supplied from wind power plants for Model B. Estimates from the authorities are obtained regarding such a minimum energy requirement for the cost minimization case. 3000 MW, 4000 MW and 5000 MW are the values applied for R_{min}.

In Model-B bidding values for each wind power project are needed since the objective function of this particular model computes the cost or profit based on the bidding values. Since these financial data could not be obtained (as it is deemed sensitive), they were estimated based on the some straight forward "value of electricity generated" based computations. The formula below is used to estimate the bid values which are expected to be offered by the owners of wind power projects.

$$E_i * W_i * 1000 * P * 365 * 24$$

First, W_i is multipled E_i to find the delivered power as of MW. This amount is multipled by 1000 to convert MW values to kW, and then multiplied with 365*24 to convert it to kWh/year. P equals to 0.07 Euro/kWh which is guaranteed by TEİAŞ. Thus, this formula gives the amount in Euros that would be earned in one year after the sale of the energy produced by any wind power plant.

It is assumed that companies define the bidding amount according to their expected income and they set bid value as 10% of their income. As an example, the bidding values for the first 20 projects are displayed in Table 4.4.

Table 4.4. Estimated Bidding Values for the First 20 Wind Power Projects

Power Capacity (MW)	**Power Efficiency**	**Bidding Values (Euro)**
54	0.44	1470208
50	0.41	1241730

Table 4.4. Estimated Bidding Values for the First 20 Wind Power Projects (cont.)

90	0.39	2168888
3	0.25	45990
172	0.38	4007875
9	0.44	248223
394	0.44	10630435
720	0.40	17660160
952	0.45	26269488
20	0.40	490560
150	0.44	4047120
120	0.40	2943360
10	0.40	244053
20	0.33	404712
3	0.30	55188
2	0.34	41697
15	0.40	367920
850	0.46	23976120
500	0.48	14716800
800	0.45	22075200

4.6. The Data Set Used in Sensitivity Analysis

First parameter considered in the sensitivity analysis is the allocation percentage (Φ) of short circuit power capacity of substations. It is used in the sensitivity analysis for first set of submodels (Model A-I and Model A-II). Values of Φ are set to 5%, 8% and 12%. The second parameter used in sensitivity analysis of Model A-I and A-II is the total budget allocated for the connection lines of wind power plants. 200 million and 300 million Euro is used as total budget set aside by TEİAŞ. The different combinations of these parameters are listed for Model A-I and Model A-II in the Table 4.5 and Table 4.6 respectively.

Table 4.5. Sensitivity parameters for Model A-I

Scenarios	**Φ**	**Budget (€)**
1	5%	200 million
2	5%	300 million
3	8%	200 million
4	8%	300 million
5	12%	200 million
6	12%	300 million

Table 4.6. Sensitivity parameters for Model A-II

Scenarios	**Φ**	**Budget (€)**
1	5%	200 million
2	5%	300 million
3	8%	200 million
4	8%	300 million
5	12%	200 million
6	12%	300 million

In addition to allocation percentage (Φ) of short circuit power, different values for β and α are used in sensitivity analysis of Model B. β and α define the weights of bidding (revenue) and total connection cost in the objective function respectively. The first setting of these values parameters is (1, 0) (in other words, just giving consideration to income to be gained from accepted projects). The second setting is (0, 1) which gives consideration to just expenses (connection establishment costs) associated with the accepted project. The third scenario (0.2, 0.8) gives 20% weight to bid values and 80% weight to connection costs. Finally, the forth scenario i.e. (0.5, 0.5) takes both income and expenses equally into consideration.

Another sensitivity parameter for Model B is the minimum energy requirement (R_{min}) which shows the minimum amount of power to be provided from accepted wind power projects. Since the maximum amount of substation capacity that can be allocated to wind power plants at 5% allocation rate is declared as 8449 MW, sensitivity values for this parameter is set as 3000MW, 4000 MW, and 5000 MW. It is worthwhile to see the effects of this parameter on the output, especially for the case when β and α are (0, 1). In that case, minimum required energy is the only constraint which force model to make some connection lines. Scenarios generated by considering different combinations of all sensitivity parameters for Model-B are listed in Table 4.7.

Table 4.7. Sensitivity Parameters for Model B

Scenarios	β	α	Φ	R_{min} (MW)
1	1	0	5%	3000
2	0.5	0.5	5%	3000
3	0.2	0.8	5%	3000
4	0	1	5%	3000
5	1	0	5%	4000
6	0.5	0.5	5%	4000
7	0.2	0.8	5%	4000
8	0	1	5%	4000
9	1	0	5%	5000
10	0.5	0.5	5%	5000
11	0.2	0.8	5%	5000
12	0	1	5%	5000
13	1	0	8%	3000
14	0.5	0.5	8%	3000
15	0.2	0.8	8%	3000
16	0	1	8%	3000
17	1	0	8%	4000
18	0.5	0.5	8%	4000
19	0.2	0.8	8%	4000
20	0	1	8%	4000
21	1	0	8%	5000
22	0.5	0.5	8%	5000
23	0.2	0.8	8%	5000
24	0	1	8%	5000
25	1	0	12%	3000
26	0.5	0.5	12%	3000
27	0.2	0.8	12%	3000
28	0	1	12%	3000
29	1	0	12%	4000
30	0.5	0.5	12%	4000
31	0.2	0.8	12%	4000
32	0	1	12%	4000
33	1	0	12%	5000
34	0.5	0.5	12%	5000
35	0.2	0.8	12%	5000
36	0	1	12%	5000

Both Model A-I and Model A-II have 6 individual scenarios for sensitivity analysis while, Model B has 36 scenarios. There are 48 scenarios in total for sensitivity analysis in order to explore the effects of changing parameter values on the output of models. Results and interrelations between outputs and parameters are analyzed in the next section.

5. ANALYSIS AND RESULTS

In this section output of the model scenarios and analysis of the results according to various sensitivity parameters are presented. The outputs of the model scenarios are evaluated from some different and critical aspects. Since the output of the model gives the wind power plants to be selected along with connecting substation and connection voltage information, the list of output values below are calculated and defined for each scenario:

- Number of substations to provide connection to the selected wind power plants.
- Number of wind power plants selected.
- Number of connections at high voltage level.
- Number of connections at medium voltage level.
- The cost of connection lines to be built and revenues from accepted projects.
- Total installed power capacity and delivered power.

All mathematical models are coded in C++ and the full codes are available in Appendix B. The Cplex solver output for each scenario is given in Appendix C.

As indicated before, binary integer programming optimization models are used in this study. There are 4062 decision variables (677 wind power plants, 3 potential connectable substations and 2 voltage level) in each model. Models are solved under IBM ILOG Academic Research Edition version 12.4. by using a computer with a 2.53 GHz cpu and 4 GB RAM. Solution time range of these scenarios changes between 21.06 seconds and 0.20 seconds which are also given in Appendix C.

5.1. Analysis of the Results of the Maximum Installed Capacity Model (Model A-I)

In this section, the results of the first submodel, Model A-I, are analyzed. As mentioned before, the objective function of this model is the maximum installed capacity of the selected wind power plant projects. Results are introduced in a table to summarize the findings. After exhibition of results for each scenario according to various different parameter values, an overall evaluation is provided in the next section.

Sensitivity parameters used in these scenarios are the Φ values and the overall budget. The values for the remaining parameters are same with the values presented previously in input data section.

5.1.1. Model A-I Scenario 1 Results

Sensitivity parameters used in this scenario are set as 5% for Φ, and 200 million Euro for the overall budget. This scenario represents the most conservative case which results in the minimum capacity allocation for wind power plants and in the minimum budget for connection lines. As can be seen in Table 5.1, 162 wind power plants are selected, while there are 98 substations. It also means some substations serve more than one wind power plant connection. Almost two third of the connection lines (109) are at high voltage level. Total installed capacity of plants is slightly larger than 5300 MW.

Table 5.1. Results of 1st Scenario for Model A-I

Outputs	Values
# of Wind Power Plants to be Invested in	162
# of Substations that Plants will Connect	98
# of High Voltage Level Connections	109
# of Medium Voltage Level Connections	53
Total Connection Cost	188816470 (€)
Total Revenue	124847520 (€)
Total Installed Capacity	5330 (MW)
Total Delivered Power	2036 (MW)

5.1.2. Model A-I Scenario 2 Results

Sensitivity parameters used in this scenario are set as 5% for Φ, and 300 million Euros for the overall budget. Wind power capacity allocation rate in this scenario is the same with the rate of the previous scenario, while the overall budget is higher. As can be seen in Table 5.2, 165 wind power plants are selected, while 98 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has slightly increased (to 113). Total installed capacity of plants is very close to the installed capacity of the previous case.

Table 5.2. Results of 2nd Scenario for Model A-I

Outputs	Values
# of Wind Power Plants to be Invested in	165
# of Substations that Plants will Connect	99
# of High Voltage Level Connections	113
# of Medium Voltage Level Connections	52
Total Connection Cost	186621975 (€)
Total Revenue	124602240 (€)
Total Installed Capacity	5330 (MW)
Total Delivered Power	2031 (MW)

5.1.3. Model A-I Scenario 3 Results

Sensitivity parameters used in this scenario are defined as 8% for Φ, and 200 million Euros for the overall budget. In this scenario, while wind power capacity allocation rate at the substations is moderate, budget for all connection lines is low. As can be seen in Table 5.3, 191 wind power plants are selected, while 112 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has significantly increased (to 127). There is a big increase in total installed capacity of wind power plants which is about 8800 MW. Total installed capacity is significantly higher than total installed capacity (5300 MW) of the base scenario.

Table 5.3. Results of 3rd Scenario for Model A-I

Outputs	Values
# of Wind Power Plants to be Invested in	191
# of Substations that Plants will Connect	112
# of High Voltage Level Connections	127
# of Medium Voltage Level Connections	64
Total Connection Cost	199930745 (€)
Total Revenue	213025680 (€)
Total Installed Capacity	8803 (MW)
Total Delivered Power	3474 (MW)

5.1.4. Model A-I Scenario 4 Results

Sensitivity parameters used in this scenario are set as 8% for Φ, and 300 million Euros for the overall budget. In this scenario, while wind power capacity allocation rate at the substations is moderate, budget for all connection lines is high. As can be seen in Table 5.4, 224 wind power plants are selected, while 114 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has significantly increased (to 150). Total installed capacity of wind power plants has slightly increased to 8887 MW. There is a significant increase in total installed capacity compared to amount (5300 MW) of the base scenario.

Table 5.4. Results of 4th Scenario for Model A-I

Outputs	**Values**
# of Wind Power Plants to be Invested in	224
# of Substations that Plants will Connect	114
# of High Voltage Level Connections	150
# of Medium Voltage Level Connections	74
Total Connection Cost	279087570 (€)
Total Revenue	212473800 (€)
Total Installed Capacity	8887 (MW)
Total Delivered Power	3465 (MW)

5.1.5. Model A-I Scenario 5 Results

Sensitivity parameters used in this scenario are defined as 12% for Φ, and 200 million Euros for the overall budget. In this scenario, while wind power capacity allocation rate at the substations is at its highest level, budget for all connection lines is low. As can be seen in Table 5.5, 194 wind power plants are selected, while 111 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has significantly decreased (to 138) compared to previous scenario. However, this scenario has significantly higher number of high voltage connections compared to base scenario (109). There is a big increase in total installed capacity of wind power plants which is about 12600 MW. This value is also significantly higher than total installed capacity (5300 MW) of the base scenario.

Table 5.5. Results of 5th Scenario for Model A-I

Outputs	Values
# of Wind Power Plants to be Invested in	194
# of Substations that Plants will Connect	111
# of High Voltage Level Connections	138
# of Medium Voltage Level Connections	56
Total Connection Cost	199958225 (€)
Total Revenue	310463160 (€)
Total Installed Capacity	12562 (MW)
Total Delivered Power	5063 (MW)

5.1.6. Model A-I Scenario 6 Results

Sensitivity parameters used in this scenario are set as 12% for Φ, and 300 million Euro for the overall budget. This scenario represents the most relaxed case which results in the maximum capacity allocation for wind power plants and in the maximum budget for connection lines. As can be seen in Table 5.6, 260 wind power plants are selected, while 119 substations are deployed to connect these wind power plants to the network. Almost two third of the connection lines (177) are at high voltage level. This amount is significantly higher than that of the base scenario. Total installed capacity of wind power plants has reached its maximum value which is about 12900 MW. Note that, the number of connections at high and medium voltage levels along with the other results reach their maximum values in this scenario, as expected.

Table 5.6. Results of 6th Scenario for Model A-I

Outputs	Values
# of Wind Power Plants to be Invested in	260
# of Substations that Plants will Connect	119
# of High Voltage Level Connections	177
# of Medium Voltage Level Connections	83
Total Connection Cost	294957605 (€)
Total Revenue	316288560 (€)
Total Installed Capacity	12923 (MW)
Total Delivered Power	5158 (MW)

5.1.7. Analysis of the Model A-I

It can be observed that, when wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments does not have significant effect on total installed capacity. The effect on other output values is also small. As can be seen in Figure 5.1, when the allocation percentage is set at 8%, change in the total budget does not have a major impact on total installed capacity and total delivered power. On the other hand, when the capacity allocation rate is 12%, an increase in the total budget slightly affect total installed capacity of selected wind power plants.

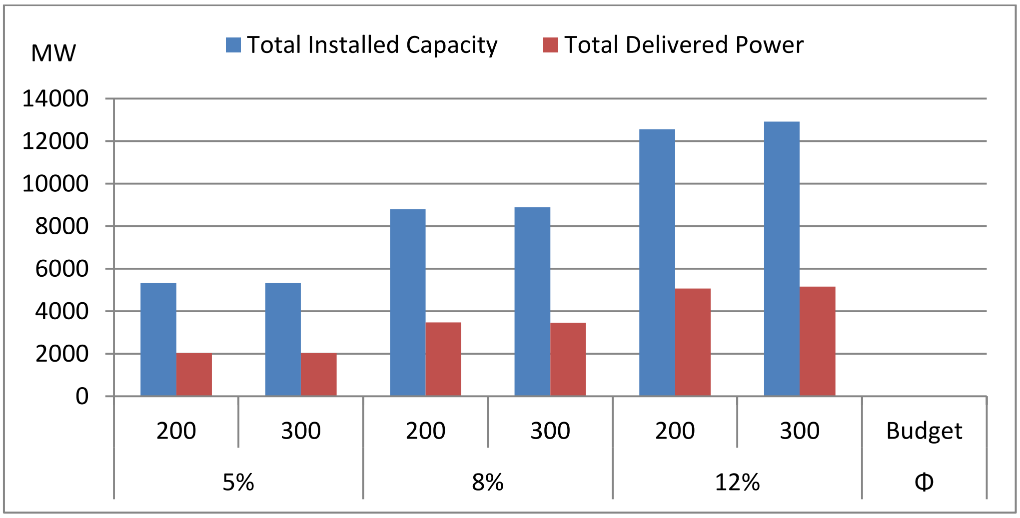


Figure 5.1. Total Installed Capacity and Total Delivered Power for the Model A-I

From a different point of view, when total budget is considered alone, there is a significant response to the capacity allocation rate. Fixing total budget at 200 million Euro, an increase in wind power capacity allocation rate has very big impact on the installed capacity values. There is about 50% increase in value of installed capacity at each increment of allocation percentage from 5% to 8% and 8% to 12%. Similarly, when the total budget is 300 million euro, installed capacity of connected wind power plants responds significantly to any change at the wind power capacity allocation rate.

According to the Figure 5.2, when wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments does not have significant effect on number of wind power projects selected and substations which connect these wind power plants to the network. On the other hand, when the allocation percentage is set at 8%, change in the total budget has a major impact on number of wind power plants and substations. Similarly, when the capacity allocation rate is 12%, an increase in the total budget affects the number of selected wind power plants significantly.

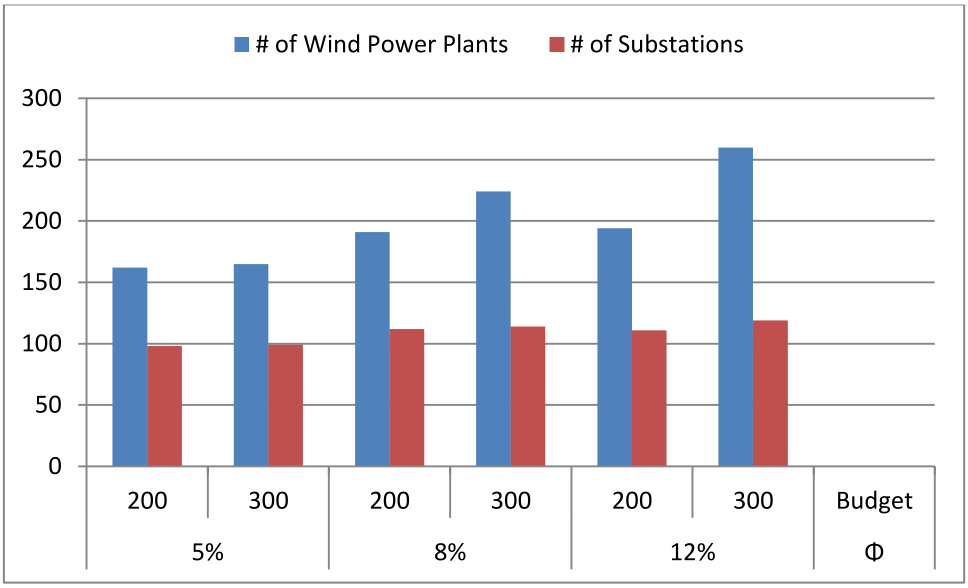


Figure 5.2. Number of Substations and Wind Power Plants for the Model A-I

From a different point of view, when total budget is considered alone, there is a significant response in number of selected wind power plants to capacity allocation rate. Fixing total budget at 200 million Euro, an increase in wind power capacity allocation rate from 5% to 8% has very big impact on the installed capacity values, while changing the allocation rate from 8% to 12% does not affect number of wind power plants. Similarly, when the total budget is 300 million euro, number of wind power plants selected responds significantly to any change at the wind power capacity allocation rate.

Figure 5.3 displays the number of connections at high and medium voltage levels. When wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments has a minor effect on the number of connections at high voltage level. On the other hand, when the allocation percentage is set at 8%, change in the total budget results in 18% increase at number of connections at high voltage level. Similarly, when the capacity allocation rate is 12%, an increase in the total budget leads to a major change in number of high voltage connections, from 138 to 177.

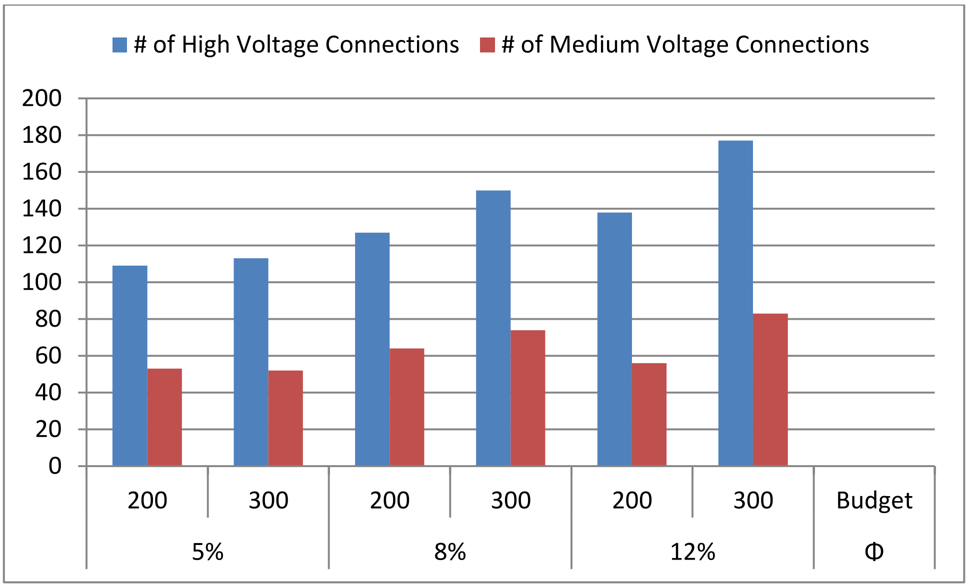


Figure 5.3. Number of Connections at High and Medium Voltage Level for the Model A-I

Furthermore, fixing total budget at 200 million Euro, an increase in wind power capacity allocation rate from 5% to 12% leads to 22% increase in number of connections at high voltage level. On the other hand, when the total budget is 300 million Euro, percentage increase in number of connections at high voltage level is about 55%. Similarly, connections at medium voltage level respond more significantly to any change at the wind power capacity allocation rate when the total budget is 300 million Euro. Another interesting observation is that when the overall budget is 200 million Euro, the number of connections at medium voltage level decrease when wind power allocation rate changes from 8% to 12%.

As it can be observed in Figure 5.4, when wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments has no effect on total connection cost and total revenue. On the other hand, when the allocation percentage is set at 8%, change in the total budget has a major impact on total connection cost of selected wind power plants. Similarly, when the capacity allocation rate is 12%, an increase in the total budget significantly affects the total connection cost, while it slightly affects the total revenue.

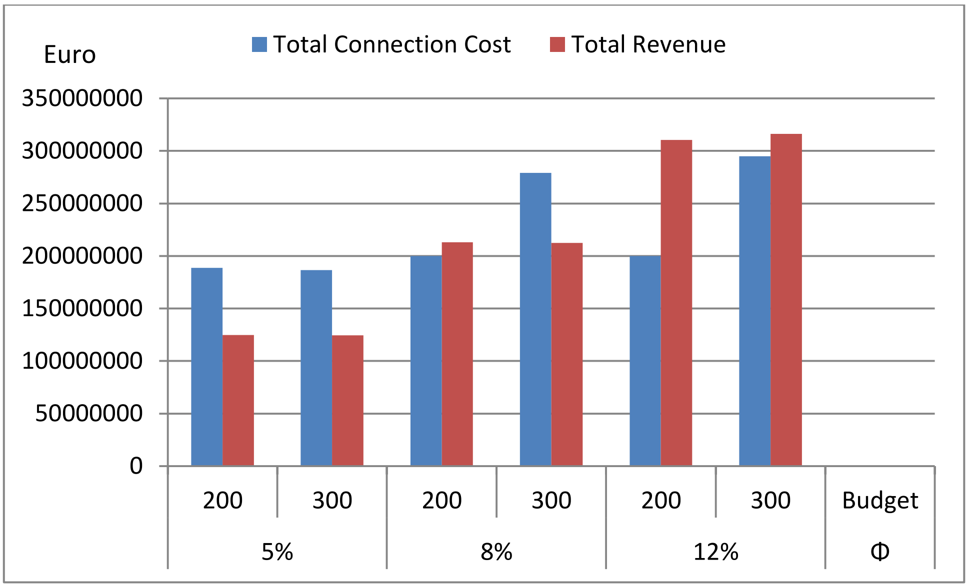


Figure 5.4. Total Connection Cost and Revenue for the Model A-I

From a different point of view, fixing the total budget at 200 million Euro, an increase in wind power capacity allocation rate slightly affects the total connection cost. Another interesting result can be observed when the total budget is set as 300 million Euro. An increase in wind power capacity allocation rate has significant effect on both total connection cost and total revenue. One important result to be pointed is that the total revenue/total connection cost ratio reaches its higher value (about 1.5) at the scenarios when total budget is set as 200 million Euro and wind power capacity allocation rate is set as 12%.

There is one important note to add about specific wind power plants selected for various scenarios. It is seen that number of wind power plants with installed capacity more than 100MW is 4 for the first two scenarios. Then, it jumps to 15 and 28 for the next two scenarios. The reason behind this increase is the change of wind power capacity allocation rate from 5% to 8% which creates bigger capacity in substations. Finally, this number is 28 and 24 for the last two scenarios. Although the last scenario has highest values for capacity allocation rate and total budget, there is a decrease in number of wind power plants with installed capacity more than 100 MW since the optimization process tries to fill spare capacities in substations with smaller wind power plants.

There are 162 WPP selected in the first scenario of Model A-I. This number increases to 260 in the last scenario. Only 66 of wind power plants are commonly selected for all scenarios of Model A-I. This means that changing the budget or wind power capacity allocation rate also changes the combination of WPP selected. Therefore, there are not many WPP selected for all scenarios of Model A-I.

5.2. Analysis of the Results of the Maximum Delivered Energy Model (Model A-II)

In this section, the results of the second submodel, Model A-II, are analyzed. As mentioned, the objective function of this model is the maximum delivered energy of the selected wind power plant projects. Results are introduced in a table to summarize the findings. After exhibition of results for each scenario according to various different parameter values, an overall evaluation is provided in the next section.

Sensitivity parameters used in these scenarios are the Φ values and the overall budget. The values for the rest of remaining parameter are same with the values presented previously in input data section.

5.2.1. Model A-II Scenario 1 Results

Sensitivity parameters used in this scenario are set as 5% for Φ, and 200 million Euro for the overall budget. This scenario represents the most conservative case which results in the minimum capacity allocation for wind power plants and in the minimum budget for connection lines. As can be seen in Table 5.7, there are 164 wind power plants are selected, while 96 substations are deployed to connect these wind power plants connect to the network. Almost two third of the connection lines (111) are at high voltage level. Total delivered energy of all plants is about 2150 MW.

Table 5.7. Results of 1st Scenario for Model A-II

Outputs	Values
# of Wind Power Plants to be Invested in	164
# of Substations that Plants will Connect	99
# of High Voltage Level Connections	111
# of Medium Voltage Level Connections	53

Table 5.7. Results of 1st Scenario for Model A-II (cont.)

Total Connection Cost	190792175 (€)
Total Revenue	131899320 (€)
Total Installed Capacity	5285 (MW)
Total Delivered Power	2151 (MW)

5.2.2. Model A-II Scenario 2 Results

Sensitivity parameters used in this scenario are set as 5% for Φ, and 300 million Euros for the overall budget. In this scenario, wind power capacity allocation rate is same with the rate of the previous scenario, while there is an increase in the overall budget. As can be seen in Table 5.8, 164 wind power plants are selected, while 97 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has remained same (111). Total delivered energy of all plants is about 2150 MW.

Table 5.8. Results of 2nd Scenario for Model A-II

Outputs	**Values**
# of Wind Power Plants to be Invested in	164
# of Substations that Plants will Connect	97
# of High Voltage Level Connections	111
# of Medium Voltage Level Connections	53
Total Connection Cost	193148585 (€)
Total Revenue	131899320 (€)
Total Installed Capacity	5285 (MW)
Total Delivered Power	2151 (MW)

5.2.3. Model A-II Scenario 3 Results

Sensitivity parameters used in this scenario are set as 8% for Φ, and 200 million Euros for the overall budget. In this scenario, while wind power capacity allocation rate at the substations is moderate, budget for all connection lines is low. As can be seen in Table 5.9, 186 wind power plants are selected, while 112 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has significantly increased (to 125). There is a big increase in total delivered energy of wind power plants which is about 3600 MW. This value is significantly higher than that of the base scenario.

Table 5.9. Results of 3rd Scenario for Model A-II

Outputs	**Values**
# of Wind Power Plants to be Invested in	186
# of Substations that Plants will Connect	112
# of High Voltage Level Connections	125
# of Medium Voltage Level Connections	61
Total Connection Cost	199989800 (€)
Total Revenue	219770880 (€)
Total Installed Capacity	8695 (MW)
Total Delivered Power	3584 (MW)

5.2.4. Model A-II Scenario 4 Results

Sensitivity parameters used in this scenario are set as 8% for Φ, and 300 million Euros for the overall budget. In this scenario, while wind power capacity allocation rate at the substations is moderate, total budget for all connection lines is high. As can be seen in Table 5.10, 222 wind power plants are selected, while 116 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has significantly increased (to 149) compared to previous scenario. Total delivered energy of wind power plants has slightly increased to 3641 MW. This value is significantly higher than that of the base scenario.

Table 5.10. Results of 4th Scenario for Model A-II

Outputs	**Values**
# of Wind Power Plants to be Invested in	222
# of Substations that Plants will Connect	116
# of High Voltage Level Connections	149
# of Medium Voltage Level Connections	73
Total Connection Cost	273422395 (€)
Total Revenue	223266120 (€)
Total Installed Capacity	8828 (MW)
Total Delivered Power	3641 (MW)

5.2.5. Model A-II Scenario 5 Results

Sensitivity parameters used in this scenario are set as 12% for Φ, and 200 million Euros for the overall budget. In this scenario, while wind power capacity allocation rate at the substations is at its highest level, budget for all connection lines is low. As can be seen in Table 5.11, 195 wind power plants are selected, while 110 substations are deployed to connect these wind power plants to the network. Number of high voltage connections has significantly decreased (to 141) compared to previous scenario. There is a big increase in the total delivered power (5100 MW) of wind power plants, compared to the values of both the previous scenario (3640 MW) and the base scenario (2150 MW).

Table 5.11. Results of 5th Scenario for Model A-II

Outputs	Values
# of Wind Power Plants to be Invested in	195
# of Substations that Plants will Connect	110
# of High Voltage Level Connections	141
# of Medium Voltage Level Connections	54
Total Connection Cost	199978695 (€)
Total Revenue	315246120 (€)
Total Installed Capacity	12432 (MW)
Total Delivered Power	5141 (MW)

5.2.6. Model A-II Scenario 6 Results

Sensitivity parameters used in this scenario are set as 12% for Φ, and 300 million Euro for the overall budget. This scenario represents the most relaxed case which results in the maximum capacity allocation for wind power plants and in the maximum budget for connection lines. As can be seen in Table 5.12, 255 wind power plants are selected, while 119 substations are deployed to connect these wind power plants to the network. Almost two third of the connection lines (171) are at high voltage level. Total delivered power of wind power plants has reached its maximum value which is about 5400 MW. Note that, the number of connections at high and medium voltage levels, along with the other results reaches their maximum values in this scenario, as expected.

Table 5.12. Results of 6th Scenario for Model A-II

Outputs	Values
# of Wind Power Plants to be Invested in	255
# of Substations that Plants will Connect	119
# of High Voltage Level Connections	171
# of Medium Voltage Level Connections	84
Total Connection Cost	299788860 (€)
Total Revenue	329043120 (€)
Total Installed Capacity	12877 (MW)
Total Delivered Power	5365 (MW)

5.2.7. Analysis of the Model A-II

It can be observed that, when wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments does not have any significant effect on total installed capacity and total delivered capacity. Similarly, as can be seen in Figure 5.5, when the allocation percentage is set at 8%, change in the total budget does not affect total installed capacity and total delivered power. On the other hand, when the capacity allocation rate is 12%, an increase in the total budget slightly affect total installed capacity of selected wind power plants.

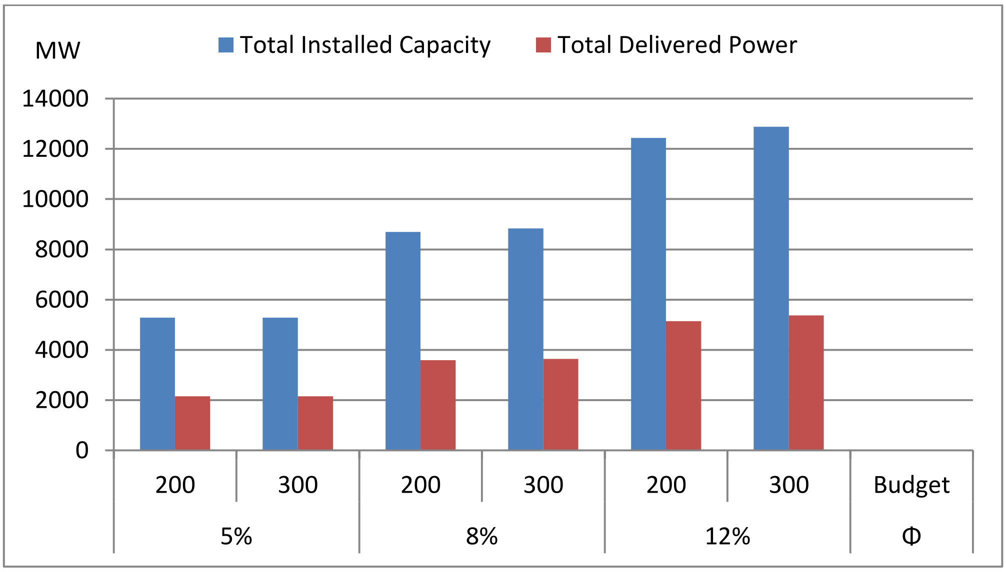


Figure 5.5. Total Installed Capacity and Total Delivered Power for the Model A-II

From a different point of view, when total budget is considered alone, there is a significant response to the capacity allocation rate. Fixing the total budget at 300 million Euro versus 200 million Euro, an increase in wind power capacity allocation rate has significant impact on the total installed capacity and total delivered power. There is about 60% increase in the value of installed capacity at the expansion of allocation percentage from 5% to 8%. As expected, total delivered power and total installed capacity reach their maximum values at 300 million Euro budget and 12% allocation rate.

Figure 5.6 displays number of wind power projects selected and substations which connect these plants into the network. When wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments has no significant effect on the number of wind power projects selected and substations. Similarly, when the allocation percentage is set at 8%, change in the total budget does not affect the number of wind power plants and substations. On the other hand, when the capacity allocation rate is 12%, an increase in the total budget slightly affects both the number of wind power plants selected and substations which connect these plants to the network.

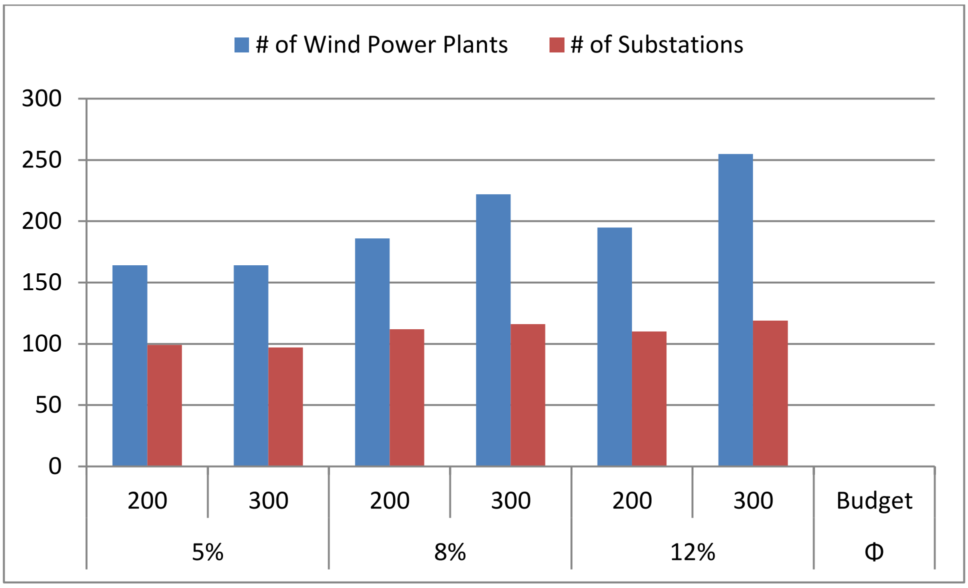


Figure 5.6. Number of Substations and Wind Power Plants for the Model A-II

When total budget is considered alone, there is a significant response in number of selected wind power plants to capacity allocation rate. Fixing the total budget at 200 million Euro, an increase in wind power capacity allocation rate from 5% to 8% then to 12%, leads to 13% and 19% increase in the number of wind power plants selected, respectively. When the total budget is 300 million euro, an increase in wind power capacity allocation rate from 5% to 8% then to 12%, leads to 35% and 55% increase in the number of WPP selected, respectively.

According to the Figure 5.7, when wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments has no significant effect on the number of connections at high voltage level. On the other hand, when the allocation percentage is set at 8%, a change in the total budget leads to an increase about 20% in number of connections both at high and medium voltage levels. Similarly, when the capacity allocation rate is 12%, an increase in the total budget leads to 21% and 55% increase in the number of connections at high and medium voltage levels respectively.

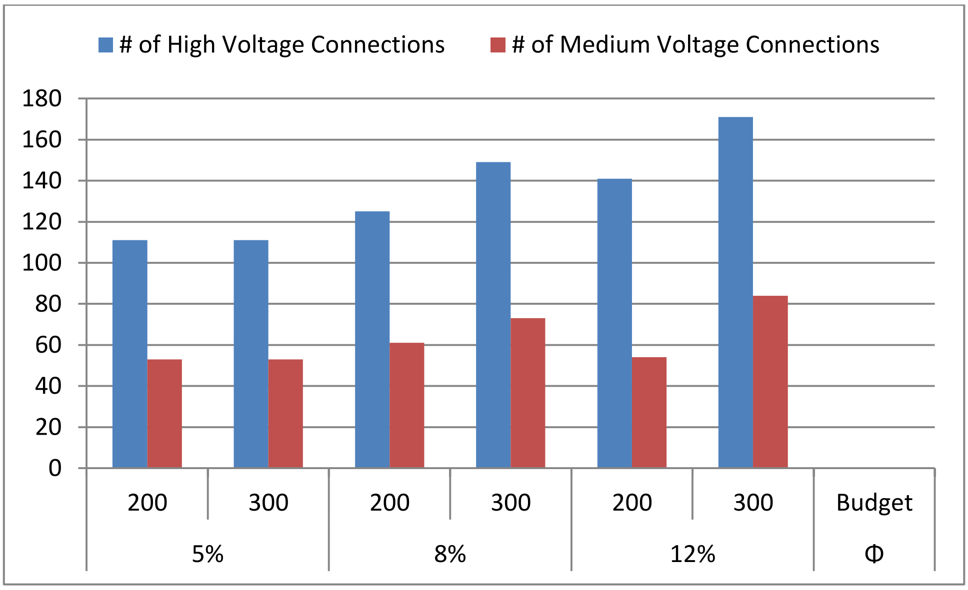


Figure 5.7. Number of Connections at High and Medium Voltage Level for the Model A-II

From a different point of view, fixing total budget at 200 million Euro, an increase in wind power capacity allocation rate from 5% to 12% adds 30 more connections to the network at high voltage level. Moreover, under the 200 million Euro overall budget limit, the number of connections at medium level slightly drops when wind power allocation rate increase from 8% to 12%. On the other hand, when the total budget is 300 million euro, increase in number of connections at high voltage level is more significant with 60 more connections to the network. As expected, the number of wind power plants selected and substations which connect these plants to the network reach their highest values at 300 million Euro budget and 12% wind power capacity allocation rate.

As it can be seen in the Figure 5.8, when wind power capacity allocation rate at the substations is 5%, total budget assigned for connection line investments has no effect on total connection cost and total revenue. On the other hand, when the allocation percentage is set at 8%, change in the total budget has a major impact on total connection cost and minor impact on total revenue. Similarly, when the capacity allocation rate is 12%, an increase in the total budget significantly affects total connection cost, while it slightly affects total revenue. Total revenue exceeds total cost for the scenarios where wind power capacity allocation rate is set as 12%. Another case where total revenue is greater than total cost is scenarios where allocation rate is 8% and total budget is 200 million Euro.

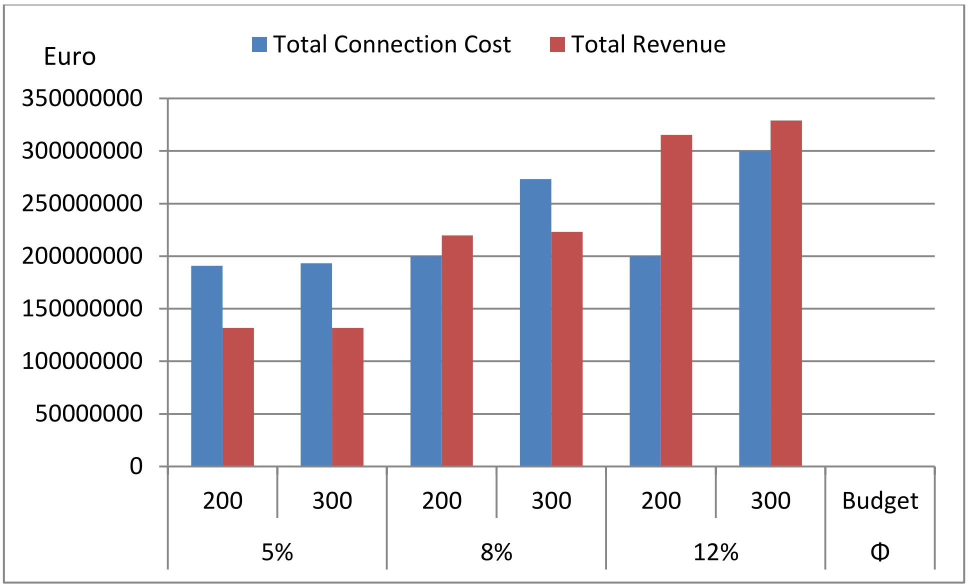


Figure 5.8. Total Connection Cost for the Model A-II

Furthermore, fixing total budget at 200 million Euro, an increase in wind power capacity allocation rate significantly affects total revenue, while it slightly affects total connection cost. On the other hand, when total budget is set as 300 million, wind power capacity allocation rate has a more significant impact on total connection cost. It is observed that total connection cost is limited by the total budget for the scenarios where the total budget is set as 200 million Euro.

Similar to results obtained in the Model A-I, number of wind power plants with installed capacity more than 100MW is 7 for the first two scenarios. Then, it jumps to 15 and 12 for the next two scenarios since capacity allocation rate for wind power plants in substations increases from 5% to 8%. Then, number of wind power plants with installed capacity more than 100 MW becomes 28 and 22 for the last two scenarios respectively. Again, although last scenario has highest values for capacity allocation rate and total budget, there is a decrease in number of wind power plants with over 100 MW installed capacity.

The number of selected WPP in different scenarios of Model A-II varies from 164 to 255. Only 73 wind power plants are common for all scenarios of Model A-II. In order to see the different WPP selected in Model A-I and Model A-II, Figure 5.9 shows the WPP selected in all scenarios of Model A-I versus the WPP selected in all scenarios of Model A-II. 8 of the WPP selected in all scenarios of Model A-I are not among the set of WPP selected in all scenarios of Model A-II. On the other hand, there are 58 WPP that are common for both Model A-I and Model A-II which maximizes the installed capacity and delivered power respectively. This might mean that WPP selected in both Model A-I and Model A-II have high installed capacity and high efficiency rates. However, as it is seen from the map, 4 of WPP selected in Model A-I are far from the coast of Turkey while all of the WPP selected in Model A-II are located on coast or west part of Turkey.

Figure 5.9. The Difference of WPP selections of Model A-I and Model A-II

5.3. Analysis of the Results of the Maximum Profit / Minimum Cost Model (Model B)

In this section, the results of the second model, Model B, are analyzed. As mentioned, the objective of this model is the maximum profit and minimum connection cost of the selected wind power plant projects. Results are introduced in a table in order to summarize the findings. After exhibition of results for each scenario according to various different parameter values, an overall evaluation is provided in the next section.

Sensitivity parameters used in these scenarios are the β and α values, Φ, and the minimum required installed power, R_{min}. The values for the rest of remaining parameter are same with the values presented previously in the input data section.

5.3.1. Model B Scenario 1 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 5% for Φ, and 3000 MW for R_{min}. This scenario represents the most conservative case which results in the minimum capacity allocation rate and in the minimum required energy from wind power plants. Weighting coefficients (1 for β, and 0 for α) indicates that only revenues from accepted projects are to be considered in the objective function. As can be seen in Table 5.13, 163 wind power plants are selected, while 98 substations are deployed to connect the selected wind power plants to the network. Almost two third of the connection lines (111) are at high voltage level. Total delivered power of plants is 2075 MW and total installed capacity is about 5250 MW.

Table 5.13. Results of 1st Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	163
# of Substations that Plants will Connect	98
# of High Voltage Level Connections	111
# of Medium Voltage Level Connections	52
Total Connection Cost	202443420 (€)
Total Revenue	127239000 (€)
Total Installed Capacity	5244 (MW)
Total Delivered Power	2075 (MW)

5.3.2. Model B Scenario 2 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 5% for Φ, and 3000 MW for R_{min}. In this scenario, wind power capacity allocation rate and minimum required energy from WPP are low. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.14, 65 wind power plants are selected, while 51 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 55) compared to base scenario (111). Total delivered power of plants is about 1350 MW and total installed capacity is about 3500 MW.

Table 5.14. Results of 2nd Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	65
# of Substations that Plants will Connect	51
# of High Voltage Level Connections	55
# of Medium Voltage Level Connections	10
Total Connection Cost	61445655 (€)
Total Revenue	83517840 (€)
Total Installed Capacity	3469 (MW)
Total Delivered Power	1362 (MW)

5.3.3. Model B Scenario 3 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 5% for Φ, and 3000 MW for R_{min}. In this scenario, wind power capacity allocation rate and minimum required energy from WPP are the lowest. Weighting coefficients (0.2 for β, and 0.8 for α) indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.15, 51 wind power plants are selected, while 40 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased to 42 from 111 in the base scenario. Total delivered energy of plants (1150 MW) and total installed capacity (3000 MW) has also significantly decreases when compared to base scenario where total delivered energy is 2075 MW and total installed capacity is 5250 MW. Note that the high weight assigned to connection costs has reduced the total installed capacity to its minimum.

Table 5.15. Results of 3rd Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	51
# of Substations that Plants will Connect	40
# of High Voltage Level Connections	42
# of Medium Voltage Level Connections	9
Total Connection Cost	50391445 (€)
Total Revenue	71131200 (€)
Total Installed Capacity	3000 (MW)
Total Delivered Power	1160 (MW)

5.3.4. Model B Scenario 4 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 5% for Φ, and 3000 MW for R_{min}. In this scenario, wind power capacity allocation rate and minimum required energy from WPP are low. Only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.16, 48 wind power plants are selected, while 37 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 38 from 111) when compared to base scenario. Total delivered power of plants is about 1185 MW and total installed capacity is about 3000 MW.

Table 5.16. Results of 4th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	48
# of Substations that Plants will Connect	37
# of High Voltage Level Connections	38
# of Medium Voltage Level Connections	10
Total Connection Cost	32056395 (€)
Total Revenue	72664200 (€)
Total Installed Capacity	3002 (MW)
Total Delivered Power	1185 (MW)

5.3.5. Model B Scenario 5 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 5% for Φ, and 4000 MW for R_{min}. In this scenario, wind power capacity allocation rate is low, while minimum required energy from WPP is at medium level. Only revenues from accepted projects are considered in the objective function. As can be seen in Table 5.17, 163 wind power plants are selected, while 98 substations are deployed to connect the selected wind power plants to the network. Number of connection lines (111) at high voltage level is the same with the number in the base scenario. Total delivered power of plants is about 2075 MW and total installed capacity is 5244 MW.

Table 5.17. Results of 5th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	163
# of Substations that Plants will Connect	98
# of High Voltage Level Connections	111
# of Medium Voltage Level Connections	52
Total Connection Cost	202443420 (€)
Total Revenue	127177680 (€)
Total Installed Capacity	5244 (MW)
Total Delivered Power	2074 (MW)

5.3.6. Model B Scenario 6 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 5% for Φ, and 4000 MW for R_{min}. In this scenario, wind power capacity allocation rate is low while minimum required energy from WPP is at medium level. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.18, 79 wind power plants are selected, while 59 substations are deployed to connect the selected wind power plants to the network. The number of high voltage connections has significantly decreased (to 66 from 111) when compared to base scenario. Total delivered power of plants is about 1550 MW and total installed capacity is about 4000 MW. Note that even 50% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement. However, since the minimum requirement in this (and in the following 2) scenarios is medium, the overall acceptance performance is comparable to the Model A scenarios' results.

Table 5.18. Results of 6th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	79
# of Substations that Plants will Connect	59
# of High Voltage Level Connections	66
# of Medium Voltage Level Connections	13
Total Connection Cost	76067775 (€)
Total Revenue	95720520 (€)
Total Installed Capacity	4003 (MW)
Total Delivered Power	1561 (MW)

5.3.7. Model B Scenario 7 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 5% for Φ, and 4000 MW for R_{min}. In this scenario, wind power capacity allocation rate is low while minimum required energy from WPP is at medium level. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.19, 79 wind power plants are selected, while 60 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 65 from 111) when compared to base scenario. Total delivered power of plants is about 1550 MW and total installed capacity is 4000 MW. Note that 80% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement.

Table 5.19. Results of 7th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	79
# of Substations that Plants will Connect	60
# of High Voltage Level Connections	65
# of Medium Voltage Level Connections	14
Total Connection Cost	74875680 (€)
Total Revenue	94984680 (€)

Table 5.19. Results of 7th Scenario for Model B (cont.)

Total Installed Capacity	4000 (MW)
Total Delivered Power	1549 (MW)

5.3.8. Model B Scenario 8 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 5% for Φ, and 4000 MW for R_{min}. In this scenario, wind power capacity allocation rate is low while minimum required energy from WPP is at medium level. Only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.20, 76 wind power plants are selected, while 59 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 61 from 111) when compared to base scenario. Total delivered power of plants is about 1550 MW and total installed capacity is 4000 MW.

Table 5.20. Results of 8th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	76
# of Substations that Plants will Connect	59
# of High Voltage Level Connections	61
# of Medium Voltage Level Connections	15
Total Connection Cost	56974710 (€)
Total Revenue	95904480 (€)
Total Installed Capacity	4000 (MW)
Total Delivered Power	1564 (MW)

5.3.9. Model B Scenario 9 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 5% for Φ, and 5000 MW for R_{min}. In this scenario, while wind power capacity allocation rate is low, minimum required energy from WPP is high. Only revenues from accepted projects are considered in the objective function. As can be seen in Table 5.21, 165 wind power plants are selected, while 98 substations are deployed to connect the selected wind power plants to the network. Almost two third of the connection lines (112) are at high voltage level.

Total delivered power of plants is about 2075 MW and total installed capacity is about 5250 MW.

Table 5.21. Results of 9th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	165
# of Substations that Plants will Connect	98
# of High Voltage Level Connections	112
# of Medium Voltage Level Connections	53
Total Connection Cost	202530160 (€)
Total Revenue	127300320 (€)
Total Installed Capacity	5246 (MW)
Total Delivered Power	2076 (MW)

5.3.10. Model B Scenario 10 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 5% for Φ, and 5000 MW for R_{min}. In this scenario, while wind power capacity allocation rate is low, minimum required energy from WPP is high. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.22, 122 wind power plants are selected, while 86 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 92 from 111) when compared to base scenario. Total delivered energy of plants is about 1950 MW and total installed capacity is 5000 MW which implies a slight decrease when compared to total delivered energy (2075 MW) and total installed capacity (5250 MW) of the base scenario. Note that even 50% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement. However, since the minimum requirement in this (and the following 2) scenarios is large, the overall acceptance performance is comparable to the Model A scenarios' results.

Table 5.22. Results of 10th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	122
# of Substations that Plants will Connect	86

Table 5.22. Results of 10th Scenario for Model B (cont.)

# of High Voltage Level Connections	92
# of Medium Voltage Level Connections	30
Total Connection Cost	123299935 (€)
Total Revenue	119144760 (€)
Total Installed Capacity	5000 (MW)
Total Delivered Power	1943 (MW)

5.3.11. Model B Scenario 11 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 5% for Φ, and 5000 MW for R_{min}. In this scenario while wind power capacity allocation rate is low, minimum required energy from WPP is high. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.23, 119 wind power plants are selected, while 85 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has slightly increased (to 93). Total delivered power of plants is about 1900 MW and total installed capacity is about 5000 MW.

Table 5.23. Results of 11th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	119
# of Substations that Plants will Connect	85
# of High Voltage Level Connections	93
# of Medium Voltage Level Connections	26
Total Connection Cost	122467645 (€)
Total Revenue	118347600 (€)
Total Installed Capacity	5001 (MW)
Total Delivered Power	1930 (MW)

5.3.12. Model B Scenario 12 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 5% for Φ, and 5000 MW for R_{min}. In this scenario while wind power capacity allocation rate is low, minimum required energy from WPP is high. Only connection costs of accepted projects are to be considered in the objective function. As can be seen in Table 5.24, 113 wind power plants are selected, while 83 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has slightly decreased (to 88 from 111) when compared to base scenario. Total delivered power of plants is about 1900 MW and total installed capacity is about 5000 MW.

Table 5.24. Results of 12th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	113
# of Substations that Plants will Connect	83
# of High Voltage Level Connections	88
# of Medium Voltage Level Connections	25
Total Connection Cost	103992210 (€)
Total Revenue	118286280 (€)
Total Installed Capacity	5000 (MW)
Total Delivered Power	1929 (MW)

5.3.13. Model B Scenario 13 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 8% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is moderate. Only revenues from accepted projects are to be considered in the objective function. As can be seen in Table 5.25, 211 wind power plants are selected, while 115 substations are deployed to connect the selected wind power plants to the network. Number of connection lines at high voltage level is 143. Total delivered power of plants is about 3550 MW and total installed capacity is about 8700 MW.

Table 5.25. Results of 13th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	211
# of Substations that Plants will Connect	115
# of High Voltage Level Connections	143
# of Medium Voltage Level Connections	68
Total Connection Cost	265817575 (€)

Table 5.25. Results of 13th Scenario for Model B (cont.)

Total Revenue	217747320 (€)
Total Installed Capacity	8732 (MW)
Total Delivered Power	3551 (MW)

5.3.14. Model B Scenario 14 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 8% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is moderate. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.26, 99 wind power plants are selected, while 71 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 79 from 111) compared to base scenario. Total delivered power of plants is about 2600 MW and total installed capacity is about 6400 MW. Note that, although total installed capacity remains at its minimum requirement in the previous scenarios where revenues and connection cost have equal importance in the objective function, total installed capacity in this scenario has not reached to its minimum requirement level. Note that, although 50% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement in the 9th scenario, total installed capacity in this scenario has not reached to its minimum requirement level.

Table 5.26. Results of 14th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	99
# of Substations that Plants will Connect	71
# of High Voltage Level Connections	79
# of Medium Voltage Level Connections	20
Total Connection Cost	91217105 (€)
Total Revenue	158205600 (€)
Total Installed Capacity	6394 (MW)
Total Delivered Power	2580 (MW)

5.3.15. Model B Scenario 15 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 8% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is moderate. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.27, 36 wind power plants are selected, while 26 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 29 from 111) when compared to base scenario. Total delivered power of plants is about 1200 MW and total installed capacity is 3000 MW. Note that 80% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement.

Table 5.27. Results of 15th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	36
# of Substations that Plants will Connect	26
# of High Voltage Level Connections	29
# of Medium Voltage Level Connections	7
Total Connection Cost	38388000 (€)
Total Revenue	74565120 (€)
Total Installed Capacity	3003 (MW)
Total Delivered Power	1216 (MW)

5.3.16. Model B Scenario 16 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 8% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is moderate. Weighting coefficients indicates that only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.28, 28 wind power plants are selected, while 24 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 28 from 111) when compared to base scenario. Total delivered power of plants is about 1250 MW and total installed capacity is 3000

MW. Note that, the 80% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement.

Table 5.28. Results of 16th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	28
# of Substations that Plants will Connect	24
# of High Voltage Level Connections	28
# of Medium Voltage Level Connections	8
Total Connection Cost	15326985 (€)
Total Revenue	77447160 (€)
Total Installed Capacity	3000 (MW)
Total Delivered Power	1263 (MW)

5.3.17. Model B Scenario 17 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 8% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP and wind power capacity allocation rate are moderate. Only revenues from accepted projects are to be considered in the objective function. As can be seen in Table 5.29, 217 wind power plants are selected, while 116 substations are deployed to connect the selected wind power plants to the network. Number of connection lines at high voltage level is 149. Total delivered power of plants is about 3550 MW and total installed capacity is about 8800 MW.

Table 5.29. Results of 17th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	217
# of Substations that Plants will Connect	116
# of High Voltage Level Connections	149
# of Medium Voltage Level Connections	68
Total Connection Cost	273961230 (€)
Total Revenue	218176560 (€)
Total Installed Capacity	8773 (MW)
Total Delivered Power	3558 (MW)

5.3.18. Model B Scenario 18 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 8% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP and wind power capacity allocation rate are moderate. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.30, 99 wind power plants are selected, while 71 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 79). Total delivered power of plants is about 2600 MW and total installed capacity is about 6400 MW. Note that even 80% weight given to connection costs has not forced the total installed capacity to remain at its minimum requirement in this scenario.

Table 5.30. Results of 18th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	99
# of Substations that Plants will Connect	71
# of High Voltage Level Connections	79
# of Medium Voltage Level Connections	20
Total Connection Cost	91217105 (€)
Total Revenue	158205600 (€)
Total Installed Capacity	6394 (MW)
Total Delivered Power	2580 (MW)

5.3.19. Model B Scenario 19 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 8% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP and wind power capacity allocation rate are moderate. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.31, 54 wind power plants are selected, while 37 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 40 from 111) when compared to base scenario. Total delivered power of plants is about 1600 MW and total installed capacity is 4000 MW. In this case the 80% weight given to connection costs has forced the total installed capacity to remain at its minimum requirement.

Table 5.31. Results of 19th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	54
# of Substations that Plants will Connect	37
# of High Voltage Level Connections	40
# of Medium Voltage Level Connections	14
Total Connection Cost	48907575 (€)
Total Revenue	99154440 (€)
Total Installed Capacity	4003 (MW)
Total Delivered Power	1617 (MW)

5.3.20. Model B Scenario 20 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 8% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP and wind power capacity allocation rate are moderate. Only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.32, 42 wind power plants are selected, while 34 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 30 from 111) compared to base scenario. Total delivered power of plants is about 1650 MW and total installed capacity is 4000 MW.

Table 5.32. Results of 20th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	42
# of Substations that Plants will Connect	34
# of High Voltage Level Connections	30
# of Medium Voltage Level Connections	12
Total Connection Cost	26687815 (€)
Total Revenue	101545920 (€)
Total Installed Capacity	4003 (MW)
Total Delivered Power	1656 (MW)

5.3.21. Model B Scenario 21 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 8% for Φ, and 5000 MW for R_{min}. In this scenario wind power capacity allocation rate is moderate while minimum required energy from WPP is high. Only revenues from accepted projects are considered in the objective function. As can be seen in Table 5.33, 217 wind power plants are selected, while 116 substations are deployed to connect the selected wind power plants to the network. Almost two third of the connection lines (149) are at high voltage level. Total delivered power of plants is about 3550 MW and total installed capacity is about 8800 MW.

Table 5.33. Results of 21st Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	217
# of Substations that Plants will Connect	116
# of High Voltage Level Connections	149
# of Medium Voltage Level Connections	68
Total Connection Cost	273961230 (€)
Total Revenue	218176560 (€)
Total Installed Capacity	8773 (MW)
Total Delivered Power	3558 (MW)

5.3.22. Model B Scenario 22 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 8% for Φ, and 5000 MW for R_{min}. In this scenario wind power capacity allocation rate is moderate, minimum required energy from WPP is high. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.34, 99 wind power plants are selected, while 71 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 79). Total delivered power of plants is about 2600 MW and total installed capacity is about 6400 MW.

Table 5.34. Results of 22nd Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	99
# of Substations that Plants will Connect	71
# of High Voltage Level Connections	79
# of Medium Voltage Level Connections	20
Total Connection Cost	91217105 (€)
Total Revenue	158205600 (€)
Total Installed Capacity	6394 (MW)
Total Delivered Power	2580 (MW)

5.3.23. Model B Scenario 23 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 8% for Φ, and 5000 MW for R_{min}. In this scenario wind power capacity allocation rate is moderate while minimum required energy from WPP is high. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.35, 119 wind power plants are selected, while 85 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has slightly increased (to 93). Total delivered power of plants is about 1900 MW and total installed capacity is about 5000 MW.

Table 5.35. Results of 23rd Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	68
# of Substations that Plants will Connect	49
# of High Voltage Level Connections	53
# of Medium Voltage Level Connections	15
Total Connection Cost	61905115 (€)
Total Revenue	122701320 (€)
Total Installed Capacity	5001 (MW)
Total Delivered Power	2001 (MW)

5.3.24. Model B Scenario 24 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 8% for Φ, and 5000 MW for R_{min}. In this scenario wind power capacity allocation rate is moderate while minimum required energy from WPP is high. Only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.36, 57 wind power plants are selected, while 48 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 43). Total delivered power of plants is about 2050 MW and total installed capacity is about 5000 MW.

Table 5.36. Results of 24th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	57
# of Substations that Plants will Connect	48
# of High Voltage Level Connections	43
# of Medium Voltage Level Connections	14
Total Connection Cost	40717525 (€)
Total Revenue	125399400 (€)
Total Installed Capacity	5002 (MW)
Total Delivered Power	2045 (MW)

5.3.25. Model B Scenario 25 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 12% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is high. Only revenues from accepted projects are considered in the objective function. As can be seen in Table 5.37, 259 wind power plants are selected, while 117 substations are deployed to connect the selected wind power plants to the network. Number of connection lines at high voltage level is 182. Total delivered power of plants is about 5250 MW and total installed capacity is about 12800 MW. Note that 100% weight given to revenues along with the high wind power capacity allocation rate has led the total installed capacity to increase above 12000 MW values.

Table 5.37. Results of 25th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	259
# of Substations that Plants will Connect	117
# of High Voltage Level Connections	182
# of Medium Voltage Level Connections	77
Total Connection Cost	332511170 (€)
Total Revenue	321194160 (€)
Total Installed Capacity	12813 (MW)
Total Delivered Power	5238 (MW)

5.3.26. Model B Scenario 26 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 12% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is high. Revenues from accepted projects and connection cost of these projects are to be considered equally in the objective function. As can be seen in Table 5.38, 132 wind power plants are selected, while 84 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 109). Total delivered power of plants is about 4200 MW and total installed capacity is about 10350 MW.

Table 5.38. Results of 26th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	132
# of Substations that Plants will Connect	84
# of High Voltage Level Connections	109
# of Medium Voltage Level Connections	23
Total Connection Cost	126721140 (€)
Total Revenue	258954360 (€)
Total Installed Capacity	10342 (MW)
Total Delivered Power	4223 (MW)

5.3.27. Model B Scenario 27 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 12% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is high. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.39, 45 wind power plants are selected, while 32 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 37). Total delivered power of plants is about 1850 MW and total installed capacity is 4450 MW. Note that, although 80% weight is given to connection costs, the total installed capacity remains significantly above its minimum requirement since Φ is set as 12%.

Table 5.39. Results of 27th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	45
# of Substations that Plants will Connect	32
# of High Voltage Level Connections	37
# of Medium Voltage Level Connections	8
Total Connection Cost	44152300 (€)
Total Revenue	112890120 (€)
Total Installed Capacity	4448 (MW)
Total Delivered Power	1841 (MW)

5.3.28. Model B Scenario 28 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 12% for Φ, and 3000 MW for R_{min}. In this scenario, while minimum required energy from WPP is low, wind power capacity allocation rate is high. Only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.40, 22 wind power plants are selected, while 21 substations are deployed to connect the selected wind power plants to the network. Note that, number of connections at high voltage level and medium voltage level has decreased their minimum values (16 and 6) in this scenario. Total delivered power of plants is 1275 MW and total installed capacity is about 3000 MW. Also note that although wind power capacity allocation rate is set as 12%, since 100% weight is given to connection costs, total installed capacity has remained at its minimum requirement.

Table 5.40. Results of 28th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	22
# of Substations that Plants will Connect	21
# of High Voltage Level Connections	16
# of Medium Voltage Level Connections	6
Total Connection Cost	9719810 (€)
Total Revenue	78183000 (€)
Total Installed Capacity	3003 (MW)
Total Delivered Power	1275 (MW)

5.3.29. Model B Scenario 29 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 12% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP is moderate while wind power capacity allocation rate is high. Only revenues from accepted projects are considered in the objective function. As can be seen in Table 5.41, 267 wind power plants are selected, while 117 substations are deployed to connect the selected wind power plants to the network. Number of connection lines at high voltage level is 190. Total delivered power of plants is about 5250 MW and total installed capacity is about 12800 MW. Note that the result of this scenario is very similar to those of the 25th scenario since the R_{min} constraint is a nonbinding constraint in both scenarios.

Table 5.41. Results of 29th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	267
# of Substations that Plants will Connect	117
# of High Voltage Level Connections	190
# of Medium Voltage Level Connections	77
Total Connection Cost	345271865 (€)
Total Revenue	322727160 (€)
Total Installed Capacity	12842 (MW)
Total Delivered Power	5263 (MW)

5.3.30. Model B Scenario 30 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 12% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP is moderate while wind power capacity allocation rate is high. Revenues from accepted projects and connection cost of these projects are considered equally in the objective function. As can be seen in Table 5.42, 132 wind power plants are selected, while 84 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 109). Total delivered power of plants is about 4200 MW and total installed capacity is about 10350 MW. Note that results of this scenario are the same with the results of 26th scenarios since R_{min} is a nonbinding constraint in both scenarios.

Table 5.42. Results of 30th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	132
# of Substations that Plants will Connect	84
# of High Voltage Level Connections	109
# of Medium Voltage Level Connections	23
Total Connection Cost	126721140 (€)
Total Revenue	258954360 (€)
Total Installed Capacity	10342 (MW)
Total Delivered Power	4223 (MW)

5.3.31. Model B Scenario 31 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 12% for Φ, and 4000 MW for R_{min}. In this scenario, minimum required energy from WPP is moderate while wind power capacity allocation rate is high. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.43, 45 wind power plants are selected, while 32 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 37). Total delivered power of plants is about 1850 MW and total installed capacity is about 4450

MW. Note that, this scenario has also same results with 27th scenario, since R_{min} constraint is nonbinding in this scenario.

Table 5.43. Results of 31th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	45
# of Substations that Plants will Connect	32
# of High Voltage Level Connections	37
# of Medium Voltage Level Connections	8
Total Connection Cost	44152300 (€)
Total Revenue	112890120 (€)
Total Installed Capacity	4448 (MW)
Total Delivered Power	1841 (MW)

5.3.32. Model B Scenario 32 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 12% for Φ, and 4000 MW for R_{min}. In this scenario, while minimum required energy from WPP is moderate while wind power capacity allocation rate is high. Only connection costs of accepted projects are considered in the objective function. As can be seen in Table 5.44, 28 wind power plants are selected, while 24 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 21 from 111) compared to base scenario. Total delivered power of plants is 1680 MW and total installed capacity is about 4000 MW.

Table 5.44. Results of 32nd Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	28
# of Substations that Plants will Connect	24
# of High Voltage Level Connections	21
# of Medium Voltage Level Connections	7
Total Connection Cost	15936540 (€)
Total Revenue	103017600 (€)
Total Installed Capacity	4004 (MW)
Total Delivered Power	1680 (MW)

5.3.33. Model B Scenario 33 Results

Sensitivity parameters used in this scenario are set as 1 for β, 0 for α, 12% for Φ, and 5000 MW for R_{min}. This scenario represents the most relaxed case which results in the maximum capacity allocation for wind power plants and in the maximum budget for connection lines. Only revenues from accepted projects are to be considered in the objective function. As can be seen in Table 5.45, 263 wind power plants are selected, while 117 substations are deployed to connect the selected wind power plants to the network. Number of connection lines at high and medium voltage level reaches their maximum values which is 186 and 77 respectively. Total delivered power of plants is about 5250 MW and total installed capacity is about 12800 MW. Also note that this scenario has similar results with the 29^{th} scenario since R_{min} constraint is nonbinding in both scenarios.

Table 5.45. Results of 33^{rd} Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	263
# of Substations that Plants will Connect	117
# of High Voltage Level Connections	186
# of Medium Voltage Level Connections	77
Total Connection Cost	343309945 (€)
Total Revenue	322297920 (€)
Total Installed Capacity	12835 (MW)
Total Delivered Power	5256 (MW)

5.3.34. Model B Scenario 34 Results

Sensitivity parameters used in this scenario are set as 0.5 for β, 0.5 for α, 12% for Φ, and 5000 MW for R_{min}. In this scenario, wind power capacity allocation rate and minimum required energy from WPP are high. Revenues from accepted projects and connection cost of these projects are to be considered equally in the objective function. As can be seen in Table 5.46, 132 wind power plants are selected, while 84 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 109). Total delivered power of plants is about 4200 MW and total installed capacity is about 10350 MW. This scenario has results similar to those of 30^{th} scenario, since R_{min} constraint is nonbinding in both scenarios.

Table 5.46. Results of 34th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	132
# of Substations that Plants will Connect	84
# of High Voltage Level Connections	109
# of Medium Voltage Level Connections	23
Total Connection Cost	126721140 (€)
Total Revenue	258954360 (€)
Total Installed Capacity	10342 (MW)
Total Delivered Power	4223 (MW)

5.3.35. Model B Scenario 35 Results

Sensitivity parameters used in this scenario are set as 0.2 for β, 0.8 for α, 12% for Φ, and 5000 MW for R_{min}. In this scenario, wind power capacity allocation rate and minimum required energy from WPP are high. Weighting coefficients indicates that connection cost of accepted projects has higher impact than revenues of these projects in the objective function. As can be seen in Table 5.47, 52 wind power plants are selected, while 37 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections has significantly decreased (to 43 from 111) compared to base scenario. Total delivered power of plants is about 2050 MW and total installed capacity is about 5000 MW.

Table 5.47. Results of 35th Scenario for Model B

Outputs	Values
# of Wind Power Plants to be Invested in	52
# of Substations that Plants will Connect	37
# of High Voltage Level Connections	43
# of Medium Voltage Level Connections	9
Total Connection Cost	48049425 (€)
Total Revenue	126625800 (€)
Total Installed Capacity	5017 (MW)
Total Delivered Power	2065 (MW)

5.3.36. Model B Scenario 36 Results

Sensitivity parameters used in this scenario are set as 0 for β, 1 for α, 12% for Φ, and 5000 MW for R_{min}. In this scenario, wind power capacity allocation rate and minimum required energy from WPP are high. Only connection costs of accepted projects are to be considered in the objective function. As can be seen in Table 5.48, 39 wind power plants are selected, while 31 substations are deployed to connect the selected wind power plants to the network. Number of high voltage connections is 30. Total delivered power of plants is about 2100 MW and total installed capacity is about 5000 MW.

Table 5.48. Results of 36th Scenario for Model B

Outputs	**Values**
# of Wind Power Plants to be Invested in	39
# of Substations that Plants will Connect	31
# of High Voltage Level Connections	30
# of Medium Voltage Level Connections	9
Total Connection Cost	23735030 (€)
Total Revenue	128036160 (€)
Total Installed Capacity	5000 (MW)
Total Delivered Power	2088 (MW)

5.3.37. Analysis of Model B

It can be observed that, when weighting coefficient α is set as 1, R_{min} becomes the most significant factor affecting the value of total installed capacity and total delivered power. As an expected result of cost minimization, high weight given to connection costs force the total installed capacity to remain at its minimum requirement which is defined by R_{min}. On the other hand, in the scenarios where α is set as 0, the optimization model maximizes the revenues from wind power plants, which drives total installed capacity up. Therefore, R_{min} becomes a nonbinding parameter and it has no effect on total installed capacity in such cases. Furthermore, in the scenarios where α is set as 0.5 or 0.8, effect of R_{min} on total installed capacity changes according to values of wind power capacity allocation rate, Φ.

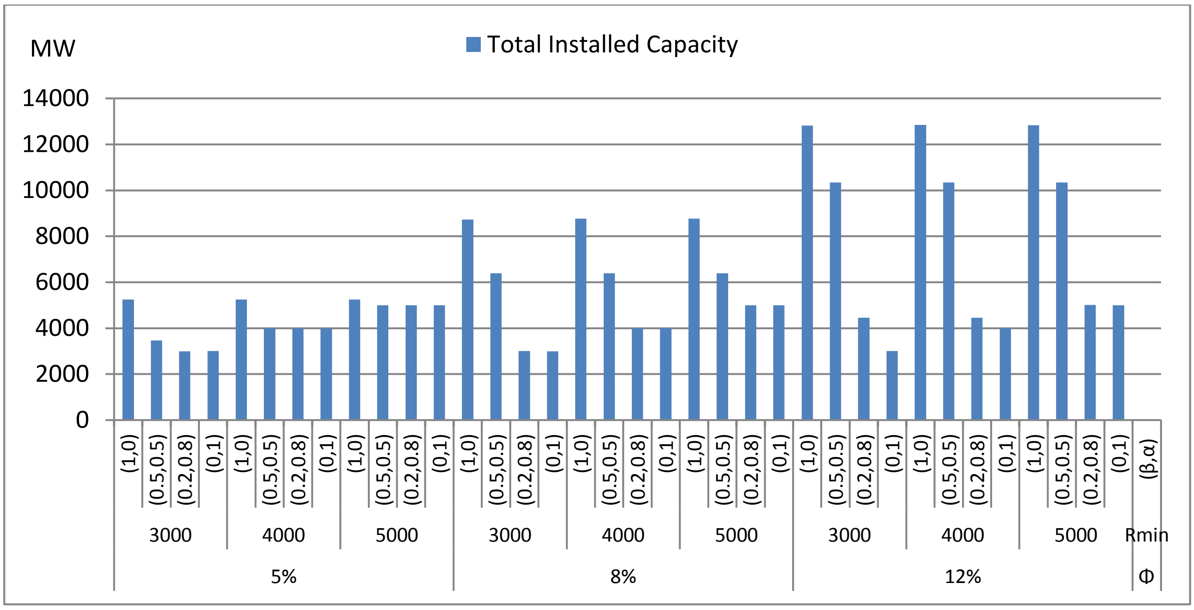


Figure 5.10. Total Installed Capacity for the Model B

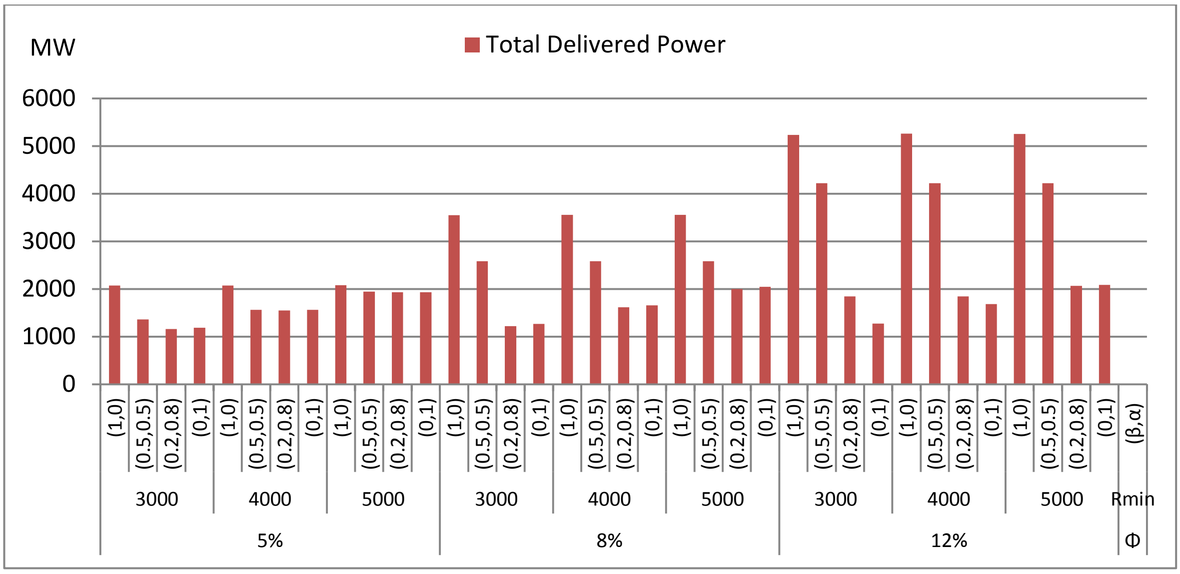


Figure 5.11. Total Delivered Power for the Model B

From a different point of view, as can be seen in Figure 5.10 and Figure 5.11, Φ has a significant effect on total installed capacity and total delivered energy especially in the scenarios where α is set as 0 or 0.5. When α is 0, changing the value of Φ from 5% to 8% and to 12% leads to about 70% and 145% increase in total installed capacity. Similarly, when α is 0.5, changing the value of Φ from 5% to 8% and to 12% leads to about 60% and 160% increase in total installed capacity. On the other hand, when α is set as 0.8, effect of

Φ on the total installed capacity and total delivered energy is limited. The reason behind this result is the fact that, the optimization model tends to decrease total installed capacity due to high weight assigned to connection costs.

The analysis of the number of WPP and substations selected is also interesting. As can be seen in Figure 5.12, when weighting coefficient α is set as 1, R_{min} becomes the most significant factor on the number of WPP and substations selected. High weight given to connection costs force the model to reach minimum connection cost which results in minimum number of WPP and substations selected. On the other hand, in the scenarios where α is set as 0, the optimization model increases the number of WPP and substations selected in order to maximize the revenues. In such cases, R_{min} becomes a nonbinding constraint. Similarly, in the scenarios where α is 0.5 and Φ is 8%, R_{min} has no effect on the number of WPP.

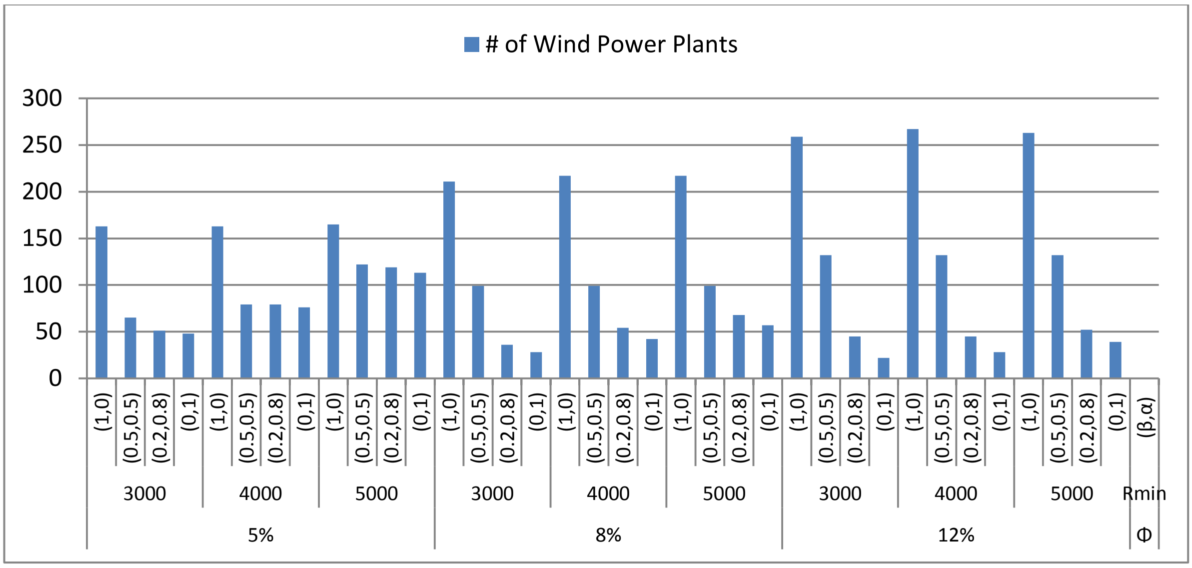


Figure 5.12. Number of Wind Power Plants for the Model B

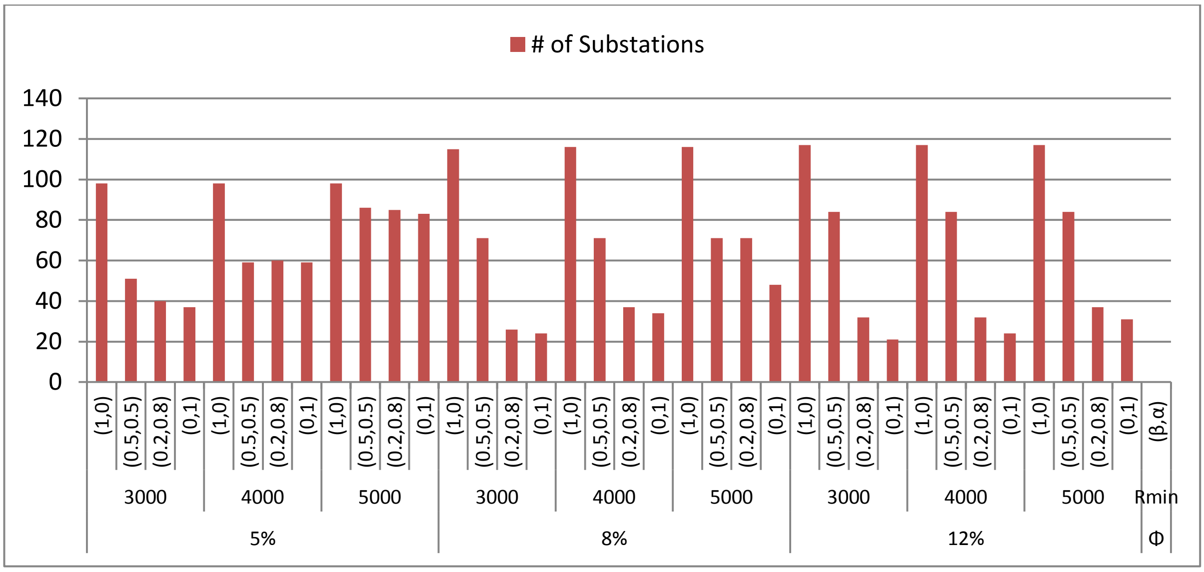


Figure 5.13. Number of Substations for the Model B

As it can be seen in Figure 5.12 and Figure 5.13, when R_{min} is set to 3000 MW, and weighting coefficients (β, α) in the objective function is set as (1, 0), there is a significant response in the number of WPP and substations selected to changes in wind power capacity allocation rate. Similarly, when R_{min} is 4000 MW and 5000 WM, wind power capacity allocation rate significantly affects number of wind power plants selected. It is seen that for the scenarios where weighting coefficients are set as (1, 0) or (0.5, 0.5), number of wind power plants selected increases as wind power capacity allocation rate increases. However, when weighting coefficients are set as (0.2, 0.8) or (0, 1), number of wind power plants selected decreases in most cases as wind power capacity allocation rate increases.

The scenario analysis results regarding high and medium voltage connections is also worthwhile to note. As can be seen in Figure 5.14 and Figure 5.15, R_{min} is one of the most significant factors that affect the number of connections at high voltage and medium voltage level when weighting coefficient α is set as 1. In the scenarios where 100% weight is given to connection costs, the optimization model decreases the number of connections as much as possible. In such cases, R_{min} becomes lower binding constraint. On the other hand, in the scenarios where α is set as 0, the optimization model maximizes the revenues from wind power plants which also increases number of high voltage level and medium voltage level connections. In these scenarios, R_{min} has no effect on number of connections.

However, when α is set as 0.5 or 0.8, effect of R_{min} on the number of connections changes according to values of wind power capacity allocation rate, Φ. When Φ is 5%, R_{min} changes the number of connections. On the other hand, it has no effect on high voltage level and medium voltage level connections when Φ is either 8% or 12%.

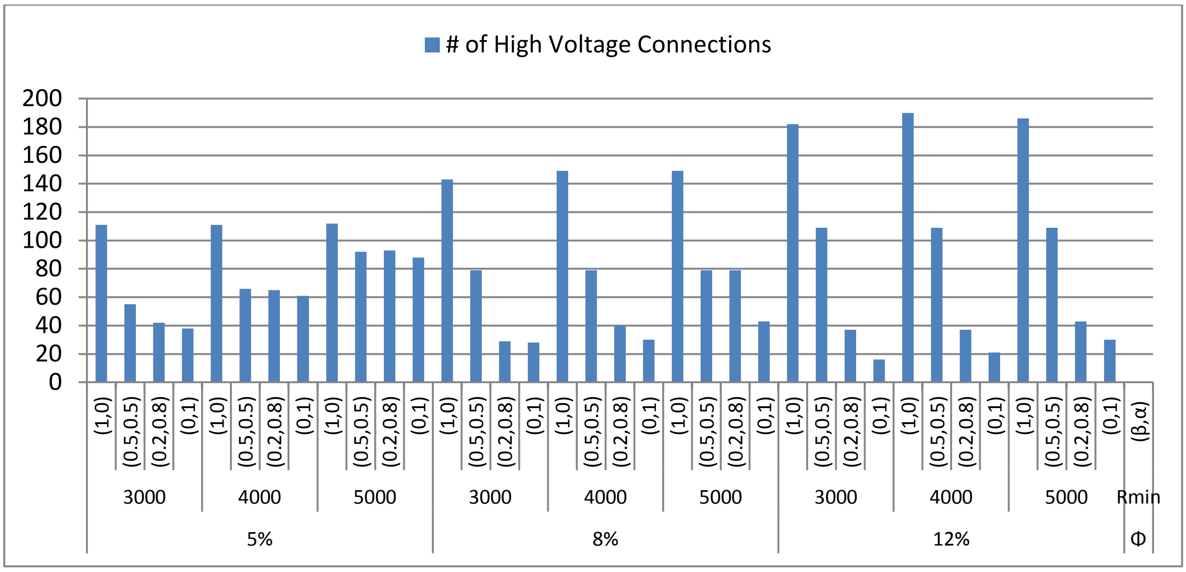


Figure 5.14. Number of Connections at High Voltage Level for the Model B

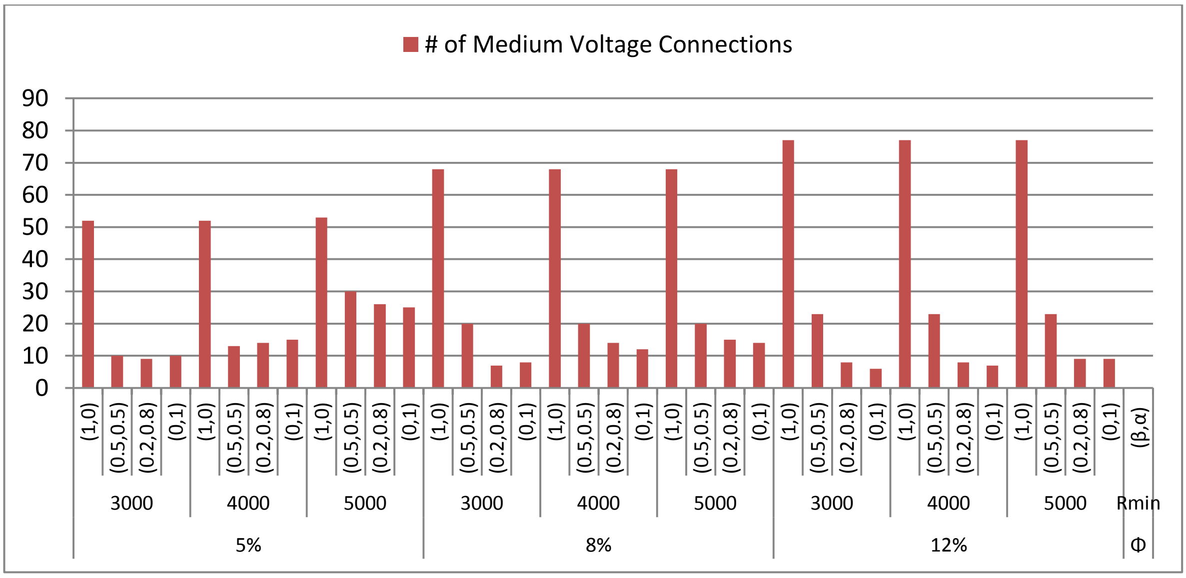


Figure 5.15. Number of Connections at Medium Voltage Level for the Model B

When number of connections at high and medium voltage level is analyzed from Φ point of view, it can be seen in Figure 5.14 and Figure 5.15 that Φ has a significant effect on number of connections in the scenarios where β is set as 1 or 0.5. When β is 1, changing the value of Φ from 5% to 8% and to 12% increases the number of connections at high voltage level about 35% and 70%. Similarly, when β is 0.5 and R_{min} is 3000 MW, changing the value of Φ from 5% to 8% and to 12% causes a 55% and 100% increase in high voltage level connections. However, when β is set as 0.2, Φ has a limited effect on the number of high voltage level and medium voltage level connections.

As expected, the discussed parameter changes have a major impact on revenues and costs. It can be observed in Figure 5.16 and Figure 5.17 that, when weighting coefficient α is set as 1, R_{min} plays a significant role on the values of total connection cost and total revenue. As an expected result of cost minimization, high weight given to connection costs force the optimization to reach its minimum connection cost. This also brings down the total revenues. On the other hand, in the scenarios where β is set as 1, the optimization model maximizes the revenues. In such scenarios, R_{min} has no significant effect on total connection cost and total revenues since it becomes a nonbinding parameter. Furthermore, in the scenarios where α is set as 0.5 or 0.8, effect of R_{min} on total connection cost and total revenues is limited. It changes according to values of wind power capacity allocation rate, Φ.

Another observation is that Φ has a significant effect on total connection cost and total revenue especially in the scenarios where α is set as 0 or 0.5. In scenarios where model maximizes the revenues, Φ becomes an upper binding parameter which defines the maximum allowable wind power connection capacity at substations. When α is 0, changing the value of Φ from 5% to 8% and to 12% leads to about 75% and 160% increase in total revenue. Note that maximizing total revenue also leads to an increase in total connection cost. However, when α is 0.5, total connection cost does not only depend on Φ but also value of R_{min}. On the other hand, when α is set as 0.8, effect of Φ on the total connection cost and total revenue is limited. Also note that lowest cost/revenue value is achieved when α is set as 1.

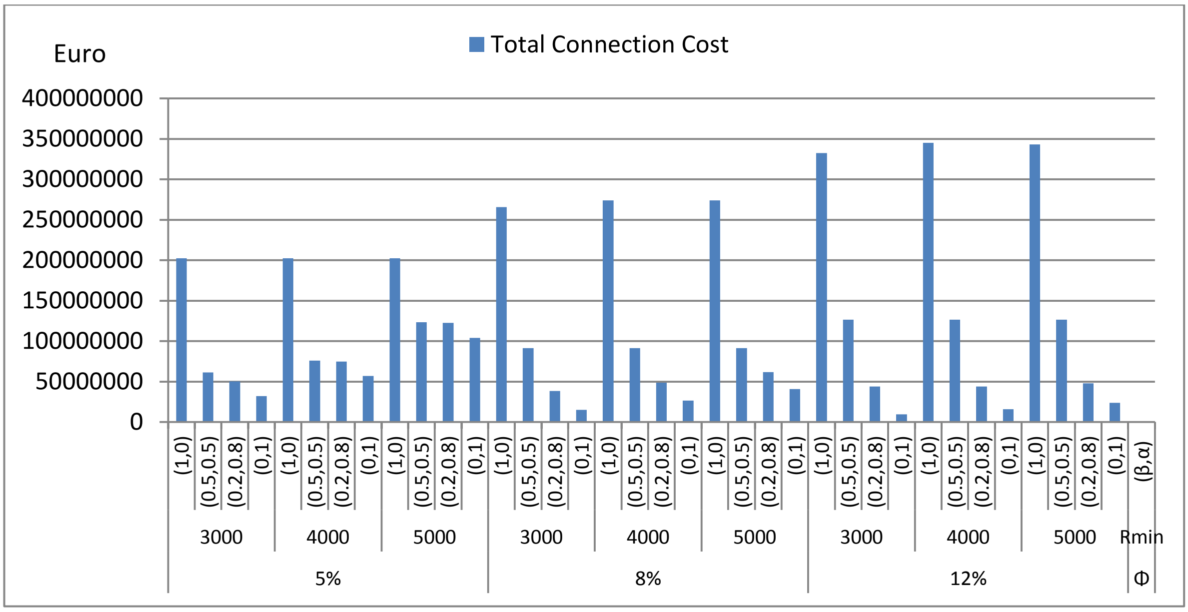


Figure 5.16. Total Connection Cost for the Model B

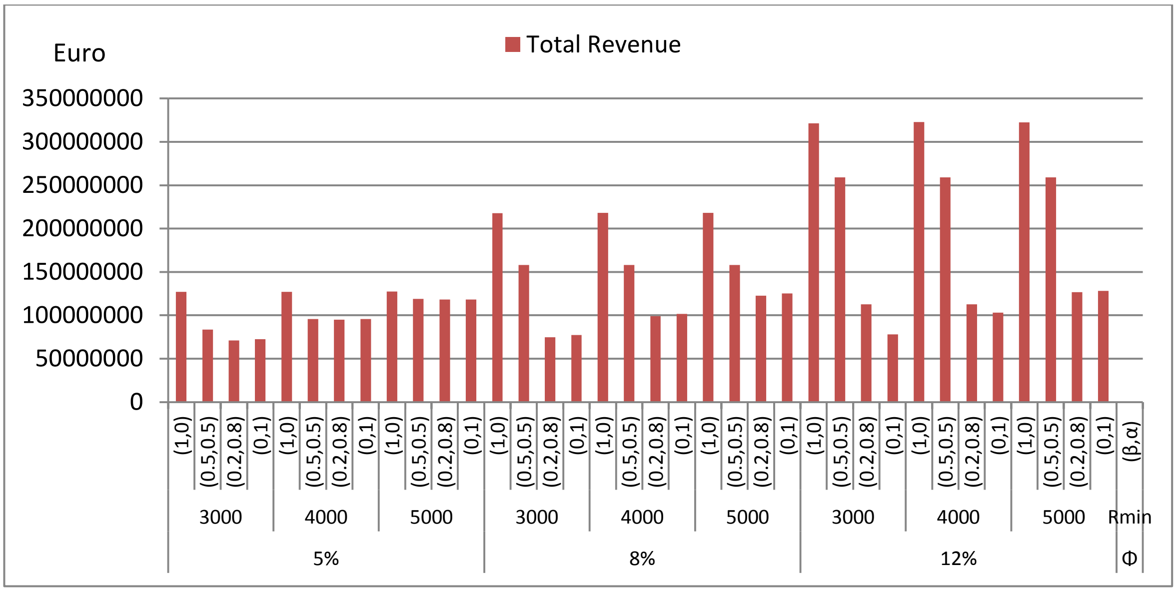


Figure 5.17. Total Revenue for the Model B

Another important point about results is the number of WPP with over 100 MW installed capacity. It can be seen from Figure 5.18 that wind power capacity allocation rate is the main factor which changes this number. When wind power capacity allocation rate is set as 5%, neither weighting coefficients nor R_{min} are effective on selection of wind power plants with over 100 MW installed capacity. However, this number more than doubles from 5 to 12 for the scenarios where wind power capacity allocation rate is 8%. The reason behind this increase is the expansion of substation capacity. On the other hand, when wind power capacity allocation rate increases to 12%, weighting coefficients appear to affect this number significantly. In these scenarios, there is plenty of available capacity for wind power plants. Therefore, when β is greater than α, model maximizes the number of wind power plant connections as much as possible which also results in increasing the number of WPP with installed capacity over 100 MW.

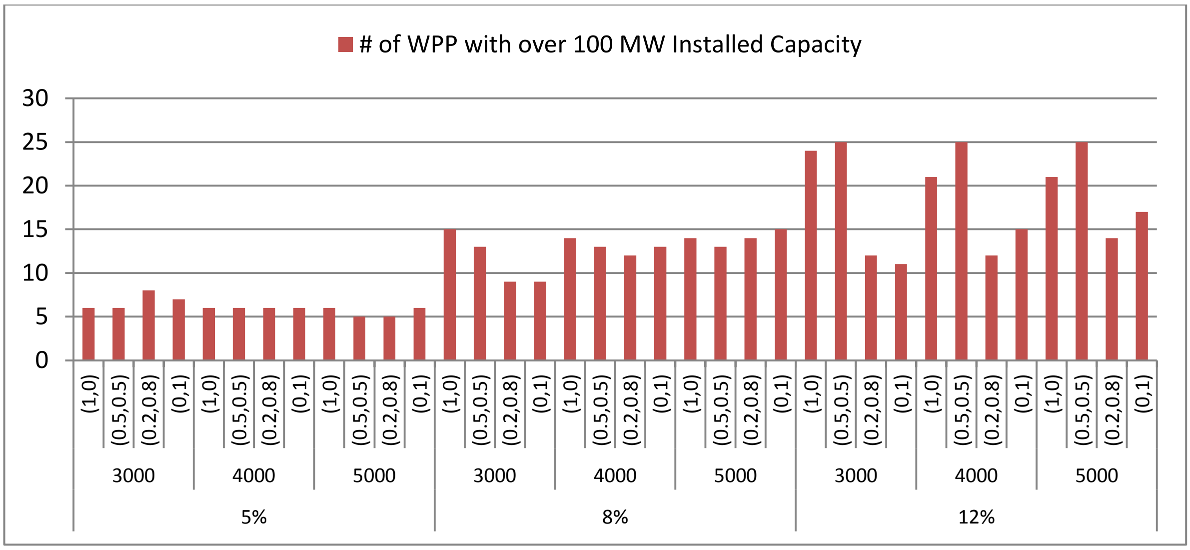


Figure 5.18. WPP with over 100 MW Installed Capacity for the Model B

It is also interesting to see WPP selected in all scenarios of Model B where α is 1. In this manner, it is possible to observe WPP that strictly minimizes the cost. The number of selected WPP in Model B when α is 1 varies from 22 to 113. 8 of them are selected in at least 8 scenarios. Figure 5.19 shows the locations of these WPP.

Figure 5.19. WPP Selected in at least 8 scenarios of Model B under α=1 restriction

On the other hand, there are 122 WPP selected in all scenarios of Model B when the β value is 1. Range of the number of selected WPP in these scenarios varies from 163 to 267. It is seen that average connection distance for WPP selected under α=1 restriction is 6.6 km. This value increases to 14.7 km when β is 1. It is also important to note that the average revenue of WPP selected in the cost minimization case is 1701000 Euro/WPP. As expected, this value increase to 2315000 for WPP selected in all scenarios of Model B when β is 1.

6. CONCLUSION AND FUTURE RESEARCH

In this study, a series of binary programming optimization models are developed in order to evaluate a set of new wind power project proposals for possible acceptance to be integrated to the existing grid. In these models, decision variables are the individual specific wind power plant project proposals, substations through which accepted projects are to be connected to the network and voltage level of such connections. The first submodel maximizes total installed capacity of wind power plants selected, while the second submodel maximizes total energy delivered to the network. The last model maximizes a linear combination of total revenue and total connection cost of accepted wind power plant projects. These optimization models are aimed to provide decision makers a practical tool for the evaluation of new wind power plant projects.

In this study, a specific case in Turkey is evaluated as an application of the developed models. Regulations governing the selection process are defined based on the literature review and interviews with national electricity experts. These regulations are used as constraints in the optimization models. Input data is obtained from the project pool which is provided by TEİAŞ and EPDK. On the other hand, information gathered via interviews with electricity experts and authorities are used to compensate the missing data in the optimization models.

In these models, wind power plants, voltage level of connection lines and substations which connect these plants to the network are defined according to a number of constraints such as substation constraints, connection line constraints, cost constraints and connection rule constraints. In order to better support the evaluation of wind power projects, various scenarios are developed by using different values of parameters. Parameters used in scenarios include wind power capacity allocation rate (at the substations), total budget allowed for connection lines, minimum required energy from wind power plants and weighting coefficients (for cost and revenue) in the objective function.

Analyses of scenarios are accomplished based on some critical indicator values obtained from the results. These indicators calculated for each scenario includes number of wind power plants selected, number of substations which connect these power plants to the network, number of connections at high and medium voltage levels, total installed capacity, total delivered energy, total connection cost and finally total revenue.

It is observed that, there is a significant effect of sensitivity parameters on the results of different scenarios. First of all, wind power capacity allocation rate is one of the most significant parameters which define allowable maximum value of total installed capacity of selected wind power plants. When there is sufficient budget, total installed capacity is seriously limited by wind power capacity allocation rate. Therefore, it also effects total delivered power, total connection cost and total revenue.

Secondly, it is observed that in scenarios associated with connection cost minimization, minimum required energy is one of the important parameters which affect the indicator values significantly. Especially for the scenarios where weighting coefficients are set as (0, 1), which minimizes total connection cost, R_{min} sets a binding lower bound for total installed capacity.

Thirdly, it is observed that total budget has a significant effect on installed capacity, accepted projects an connection points, via total cost limitations. Most drastic impact of the total budget is seen on the results of scenarios where wind power capacity allocation rate is set at high values. In these scenarios, total budget operates as an upper bound for the total connection cost. Therefore, it also limits the number of wind power plants selected.

Fourthly, weighting coefficients plays a significant role on indicatior values. Especially for the optimization model (Model B) which maximizes a linear combination of total revenue and total connection cost, weighting coefficients which define the importance of total connection cost and total revenue, highly influence installed capacity, accepted projects and connection points.

Finally, it is seen that, these optimization models and scenarios provide projection for number of connections at high and medium voltage levels. It is seen that connections at high voltage level are preferred to connections at medium voltage level. Furthermore, these optimization models have the flexibility such that decision makers can change weighting coefficients in the objective function of Model B in order to obtain solutions for various cases.

6.1. Future Research

In this study, wind power plants are selected based on the information provided by the authorities. For further work, accuracy of the connection cost for two different voltage levels may be improved. In the developed models, connection costs are fixed for two different voltage levels. However, connection line cable specifications may be selected by the optimization models for more advanced decision making. It is known that geographical conditions play a significant role on the connection line costs. Therefore, locations of the wind power plants may be taken into account when computing the connection cost per kilometer in future studies.

In this study, in order to define bid values by wind power plants, a fixed value of domestic production is assumed for all wind power plants. However, if more information about wind power plants is provided, they may also be evaluated according to, not only their distances to connection points or installed capacity, but also other specifications such as the technology of the wind turbines, domestic products to be used in the plant, their effects on environments and so on. These improvements may provide a more realistic and environment friendly decision making.

In the revenue maximization model, weighting coefficients in the objective function, (the β and α values), are considered as a linear combination of total revenue and total cost. In addition to cost and revenue, wind power plants have various positive and negative impacts on environment when compared with conventional plants. These contributions can be added to objective function by using a different coefficient. On the other hand, the β parameter may be interpreted (and valued) so as to reflect the general “public good” associated with a unit of installed capacity.

In the developed models, if the wind power connection capacity at substations is not enough, the project is not accepted. However, it is known that authorities may ask for a capacity decrease in order to connection to the network. Therefore, if the models may be developed in that respect, more wind power plants may be connected to the network. Besides, authorities have different priorities when making decision about wind power plant selection. Some of the assumptions might be modified to make the study more realistic for different countries or for different cases.

In this model, wind power plants are selected based on a discrete case. It is seen that total budget available significantly affects the results of the models. Therefore, dynamic programming modeling approach may be deployed in modified versions of the current models. Through this approach time phasing of budget allocation and project selection decisions can be accomplished on a longer time horizon, which would better represent the actual selection process.

APPENDIX A: INPUT DATA FOR MODELS

A.1. Data Related With Wind Power Plants

Table A.1. Wind Power Projects and Related Data

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
1	54	44	1470208	33	8	40	196224
2	50	41	1241730	34	12	40	294336
3	90	39	2168888	35	7	40	176602
4	3	25	4599	36	36	40	883008
5	172	38	4007875	37	69	43	1819364
6	9	44	248223	38	924	46	26063453
7	394	44	10630435	39	345	45	9519930
8	720	40	17660160	40	93	46	2623270
9	952	45	26269488	41	150	53	4874940
10	20	40	49056	42	99	48	2913926
11	150	44	4047120	43	126	43	3322318
12	120	40	2943360	44	153	43	4034243
13	10	40	244054	45	51	46	1438567
14	20	33	404712	46	1167	46	32917802
15	3	30	55188	47	1068	42	27505699
16	2	34	41698	48	1605	46	45272556
17	15	40	36792	49	888	46	25047994
18	850	46	23976120	50	60	45	1655640
19	500	48	14716800	51	15	25	22995
20	800	45	22075200	52	9	25	13797
21	975	38	22719060	53	60	25	9198
22	1512	46	42649286	54	1	36	1766
23	300	42	7726320	55	23	40	573955
24	180	44	4856544	56	595	40	14594160
25	210	44	5665968	57	50	37	1134420
26	16	30	294336	58	50	36	1103760
27	390	42	10044216	59	50	41	1257060
28	726	42	18697694	60	60	37	1361304
29	108	45	29801520	61	8	36	176602
30	288	42	7417267	62	50	46	1398096
31	108	48	3178829	63	2	35	34339
32	3	48	88300800	64	106	37	2385471

Table A.2. Wind Power Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
65	5	46	13981	102	58	45	1586655
66	50	44	1333710	103	12	35	257544
67	21	42	540842	104	10	37	226884
68	70	37	1588188	105	18	38	419429
69	50	35	1073100	106	30	38	699048
70	100	35	2146200	107	40	44	1079232
71	50	35	1073100	108	20	45	55188
72	30	40	73584	109	13	46	35259
73	100	37	2268840	110	20	42	515088
74	73	38	1689366	111	16	45	444263
75	30	32	579474	112	76	40	1861675
76	12	37	273732	113	60	38	1398096
77	2	31	37405	114	55	42	1416492
78	46	38	1071874	115	55	37	1247862
79	40	40	983573	116	45	39	1064301
80	75	44	2023560	117	55	38	1286248
81	90	38	2097144	118	51	50	1551396
82	10	35	218912	119	51	38	1188382
83	70	42	1802808	120	36	37	816782
84	150	44	4047120	121	60	42	1545264
85	14	46	38195	122	30	42	772632
86	120	44	3237696	123	20	47	576408
87	4	37	90754	124	20	47	576408
88	25	45	68985	125	200	41	5028240
89	70	40	1716960	126	500	44	13490400
90	32	45	883008	127	50	35	1073100
91	20	35	42924	128	90	37	2041956
92	40	37	895272	129	18	40	441504
93	63	40	1533000	130	30	45	825796
94	24	39	573955	131	51	42	1313474
95	62	39	1482718	132	27	40	662256
96	759	40	18616752	133	23	41	565677
97	3	39	71744	134	55	42	1416492
98	10	35	21462	135	30	42	764722
99	30	44	805745	136	32	42	824141
100	15	42	386316	137	65	40	1589414
101	46	40	1128288	138	72	42	1854317

Table A.3. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
139	30	41	754236	176	124	38	2864306
140	31	40	765274	177	80	36	1763563
141	15	44	404712	178	122	31	2305657
142	34	38	777231	179	48	38	1125541
143	18	40	441504	180	78	33	1569767
144	30	42	781462	181	34	39	821026
145	300	42	7726320	182	118	36	2601256
146	48	43	1252461	183	82	27	1377235
147	200	35	4292400	184	74	36	1631296
148	150	38	3495240	185	64	36	1410851
149	100	45	2759400	186	70	33	1396318
150	50	45	1379700	187	48	31	907144
151	100	40	2452800	188	48	34	991029
152	150	40	3679200	189	156	33	3111794
153	6	38	13981	190	30	43	792316
154	8	30	13797	191	30	44	817334
155	6	35	128772	192	10	43	265025
156	60	43	1563660	193	8	44	20254
157	24	39	573955	194	60	39	1434888
158	30	40	73584	195	40	36	883008
159	27	40	662256	196	20	35	42924
160	27	35	579474	197	39	35	837018
161	15	35	32193	198	90	36	1986768
162	63	40	1545264	199	25	38	58254
163	42	39	1004422	200	75	38	1747620
164	54	41	1347691	201	41	38	943715
165	43	39	1033119	202	60	37	1361304
166	58	39	1377492	203	90	37	2041956
167	25	40	6132	204	111	40	2722608
168	5	39	10872	205	225	39	5380830
169	60	40	1471680	206	3	23	42311
170	98	35	2091858	207	75	49	2231895
171	60	41	1511783	208	20	47	570276
172	146	39	3525581	209	43	44	1138344
173	434	28	7432389	210	20	43	523918
174	158	30	2930789	211	21	37	476456
175	64	29	1119654	212	15	38	349524

Table A.4. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
213	70	38	1631112	250	72	44	1942618
214	104	41	2614685	251	72	40	1766016
215	36	40	883008	252	88	40	2158464
216	152	42	3914669	253	24	41	603389
217	24	42	618106	254	26	43	685558
218	100	42	2575440	255	14	43	369146
219	184	40	4513152	256	28	42	721123
220	26	42	669614	257	32	40	784896
221	21	36	467442	258	50	37	1134420
222	30	44	816782	259	40	42	1030176
223	21	40	515088	260	72	40	1766016
224	14	47	389075	261	13	31	243318
225	93	38	2167049	262	10	30	191318
226	50	35	1073100	263	11	35	240374
227	10	38	233016	264	12	30	220752
228	10	40	24528	265	13	33	259016
229	10	40	24528	266	13	38	29826
230	9	35	193158	267	13	35	274714
231	50	39	1186542	268	16	41	402259
232	50	40	1235598	269	24	41	603389
233	30	44	805745	270	20	42	515088
234	30	42	764722	271	30	38	699048
235	30	42	764722	272	60	38	1398096
236	30	42	764722	273	28	37	631519
237	32	40	789802	274	28	36	610946
238	50	36	1103760	275	25	45	69169
239	10	38	233016	276	45	44	1215240
240	60	42	1545264	277	43	44	1157630
241	44	44	1187155	278	38	47	1071337
242	220	46	6205584	279	16	40	392448
243	15	46	42310800	280	10	35	214007
244	200	40	4905600	281	10	30	176602
245	54	40	1324512	282	10	30	176602
246	88	40	2158464	283	260	41	6536712
247	80	40	1962240	284	44	41	1106213
248	100	41	2514120	285	44	41	1106213
249	72	41	1810166	286	84	42	2163370

Table A.5. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
287	70	44	1888656	324	120	41	3016944
288	50	40	1226400	325	85	49	2562318
289	264	44	7122931	326	123	40	3016944
290	150	40	3679200	327	120	40	2943360
291	204	46	5754269	328	90	35	1931580
292	300	40	7358400	329	20	40	49056
293	134	40	3286752	330	20	40	49056
294	112	40	2747136	331	28	42	721123
295	68	39	1614249	332	20	44	539616
296	65	40	1594320	333	30	40	73584
297	72	38	1677715	334	10	41	251412
298	70	40	1716960	335	5	40	12264
299	150	40	3679200	336	135	35	2897370
300	20	41	502824	337	75	35	1609650
301	100	42	2575440	338	240	42	6181056
302	100	41	2514120	339	72	44	1942618
303	20	40	49056	340	26	40	637728
304	20	44	539616	341	20	44	539616
305	20	42	515088	342	20	40	49056
306	20	40	49056	343	20	43	527352
307	20	42	515088	344	264	40	6475392
308	500	40	12264000	345	320	40	7848960
309	100	41	2514120	346	300	42	7726320
310	150	44	4047120	347	500	46	14103600
311	20	43	527352	348	30	50	92164
312	20	41	502824	349	315	37	7146846
313	20	40	49056	350	65	42	1674036
314	350	42	9014040	351	40	40	98112
315	28	44	741972	352	145	41	3645474
316	200	37	4537680	353	70	45	1948750
317	83	49	2455084	354	235	42	6052284
318	88	38	2066018	355	73	40	1778280
319	48	38	1137314	356	138	41	3456915
320	25	37	574838	357	90	37	2041956
321	68	46	1891983	358	50	38	1165080
322	51	41	1282201	359	78	42	1995966
323	51	44	1376021	360	70	40	1716960

Table A.5. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
361	95	42	2446668	398	268	40	6573504
362	80	38	1864128	399	316	46	8913475
363	28	40	67452	400	38	42	978667
364	66	38	1537906	401	106	46	2989963
365	150	39	3550428	402	60	42	1545264
366	191	51	5966927	403	428	42	11022883
367	80	54	2647479	404	500	42	12877200
368	156	42	4017686	405	456	42	11744006
369	82	43	2162143	406	372	44	10036858
370	318	41	7994902	407	418	48	12303245
371	51	43	1344748	408	324	48	9536486
372	45	38	1048572	409	970	44	26171376
373	20	38	463947	410	16	46	452296
374	24	39	573514	411	24	44	643124
375	24	52	763949	412	60	37	1342908
376	9	47	257838	413	36	39	860933
377	9	47	260653	414	50	44	1333710
378	9	48	26711	415	120	43	3164112
379	15	38	340731	416	42	34	87565
380	17	38	396127	417	42	40	1030176
381	15	36	332968	418	72	40	1766016
382	30	70	1281281	419	54	33	1092722
383	50	40	1250119	420	60	33	1214136
384	19	40	460682	421	54	31	1026497
385	29	39	708504	422	11	42	278148
386	78	35	1674036	423	11	44	291393
387	30	35	64386	424	11	44	291393
388	40	39	944328	425	18	34	374175
389	45	37	1020978	426	75	42	1931580
390	30	36	662256	427	51	39	1219655
391	210	44	5665968	428	45	37	1026497
392	38	35	793328	429	50	41	1247862
393	138	42	3554107	430	66	32	1291031
394	66	38	1537906	431	50	38	1168146
395	396	40	9713088	432	51	39	1210273
396	276	44	7446701	433	99	39	2391848
397	230	44	6205584	434	50	41	1247862

Table A.6. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
435	42	34	87565	472	48	35	1030176
436	39	39	923111	473	87	35	1867194
437	50	47	1450218	474	80	41	2011296
438	51	46	1422931	475	50	44	1356742
439	51	36	1113326	476	51	33	1022634
440	42	38	968365	477	50	36	1100694
441	30	40	73768	478	50	32	993384
442	30	38	693529	479	50	55	1670970
443	75	41	1876392	480	50	41	1260126
444	50	35	1066968	481	50	41	1250928
445	50	42	1278522	482	30	40	734
446	18	34	370863	483	25	39	59787
447	51	35	1094562	484	48	41	1206778
448	22	35	47729	485	26	37	589898
449	110	37	2472790	486	88	29	1547619
450	334	38	7803215	487	53	35	1126755
451	69	35	1480878	488	30	38	699048
452	42	35	901404	489	252	46	7108214
453	150	35	3219300	490	182	44	4910506
454	122	44	3291658	491	148	46	4174666
455	600	43	15820560	492	664	43	17508086
456	24	35	520975	493	51	36	1125835
457	210	44	5665968	494	117	44	3156754
458	380	43	10019688	495	60	42	1526868
459	220	46	6205584	496	117	47	3336115
460	40	40	98112	497	120	45	3311280
461	12	40	294336	498	30	40	73584
462	208	46	5867098	499	45	38	1048572
463	20	40	49056	500	93	35	1995966
464	40	35	85848	501	78	35	1674036
465	50	36	1103760	502	159	35	3412458
466	75	35	1609650	503	105	35	2253510
467	57	35	1223334	504	39	47	1116821
468	75	35	1609650	505	30	51	930838
469	96	35	2060352	506	20	35	42924
470	12	40	294336	507	30	40	73584
471	174	35	3734388	508	45	40	1103760

Table A.6. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
509	25	36	55188	546	5	38	116508
510	24	38	559238	547	11	38	256318
511	63	40	1533000	548	16	38	372826
512	20	42	515088	549	12	37	272261
513	40	36	883008	550	2	38	41943
514	30	39	717444	551	150	40	3679200
515	35	33	708246	552	60	45	1655640
516	48	40	1177344	553	260	42	6696144
517	50	39	1195740	554	44	45	1214136
518	24	38	559238	555	2	37	34033
519	30	39	713765	556	68	40	1667904
520	23	38	533116	557	42	40	1030176
521	30	40	737496	558	10	33	202356
522	45	45	1241730	559	10	36	220752
523	10	45	27594	560	30	49	901404
524	50	42	1287720	561	45	35	96579
525	150	41	3771180	562	10	30	18396
526	100	41	2514120	563	10	30	18396
527	100	40	2452800	564	30	35	64386
528	15	43	395514	565	50	35	1073100
529	15	44	404712	566	150	36	3311280
530	30	42	777415	567	50	36	1103760
531	38	45	1034775	568	40	45	1106213
532	44	37	984799	569	50	36	1103760
533	40	42	1020365	570	50	36	1103760
534	76	49	2269576	571	50	35	1073100
535	1	41	25141200	572	50	36	1103760
536	24	32	45875	573	50	36	1103760
537	60	35	1287720	574	50	36	1103760
538	80	40	1954391	575	50	35	1073100
539	83	41	2074149	576	10	30	18396
540	40	49	1201872	577	10	30	18396
541	7	25	103478	578	50	36	1103760
542	9	25	13797	579	3	38	69905
543	19	25	287438	580	30	40	73584
544	11	40	264902	581	51	38	1194207
545	13	38	302921	582	30	38	699048

Table A.7. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
583	120	40	2936002	620	2	36	4415
584	50	44	1349040	621	2	36	4415
585	300	39	7137648	622	2	36	4415
586	126	41	3160065	623	114	35	2446668
587	50	42	1287720	624	63	35	1352106
588	50	40	1226400	625	120	35	2575440
589	5	45	136866	626	30	42	772632
590	3	40	73584	627	50	41	1257060
591	600	50	18396000	628	72	38	1677715
592	500	42	12877200	629	9	37	204196
593	250	39	6009360	630	36	30	662256
594	600	50	18396000	631	10	40	24528
595	45	42	1158948	632	20	38	466032
596	15	39	360562	633	50	35	1073100
597	29	42	749968	634	100	35	2146200
598	32	41	783835	635	100	35	2146200
599	10	38	230686	636	50	35	1073100
600	39	36	860933	637	100	35	2146200
601	18	36	397354	638	50	35	1073100
602	38	37	850815	639	50	35	1073100
603	15	49	447943	640	50	35	1073100
604	165	42	4249476	641	50	35	1073100
605	45	37	1020978	642	50	35	1073100
606	24	35	515088	643	50	35	1073100
607	60	35	1287720	644	500	35	10731000
608	40	37	914894	645	500	35	10731000
609	75	32	1471680	646	100	35	2146200
610	50	42	1275456	647	50	35	1073100
611	30	40	73584	648	50	35	1073100
612	60	38	1413181	649	100	35	2146200
613	39	56	1337794	650	50	35	1073100
614	90	55	3027614	651	50	35	1073100
615	78	49	2334563	652	50	35	1073100
616	60	41	1522821	653	50	35	1073100
617	72	60	2658296	654	50	35	1073100
618	75	52	2374004	655	50	35	1073100
619	60	54	1970212	656	50	35	1073100

Table A.8. Wind Power Plant Projects and Related Data (cont.)

Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)	Project #	Power Capacity (MW)	Efficiency (%)	Bid Value (€)
657	100	35	2146200	668	50	35	1073100
658	50	35	1073100	669	500	35	10731000
659	50	35	1073100	670	500	35	10731000
660	50	35	1073100	671	50	35	1073100
661	50	35	1073100	672	50	35	1073100
662	50	35	1073100	673	15	35	32193
663	50	35	1073100	674	18	37	408391
664	50	35	1073100	675	19	47	538941
665	100	35	2146200	676	15	35	32193
666	500	35	10731000	677	8	32	156979
667	100	35	2146200				

APPENDIX B: PROGRAMMING CODES IN C++

B.1. C++ Codes of Model A-I

```
#include <stdlib.h>
#include <math.h>
#include <stdio.h>
#include <string.h>

int nof_plants;
int nof_substations;
int nof_ends;
double *production_cap;
double *efficiency;
double *biddingval;
double **distance;
double **shortcycle_cap;
double *unitcost;
double *loss_coef;
double *voltage_out_level;
double *eff;
double *bid;
double per_parameter;
double weight_conn_cost;
double weight_bid_value;
double allocation_percentage;
double max_loss;
double max_total_loss;
double max_cost;
double max_total_cost;

void preparedata();
void write_model_max_energy();

int main(){
    preparedata();
    write_model_max_energy();
   // getchar();
    return 0;
}


void preparedata()
{
     FILE *inp;
     int i,j,nofdistance,temp1,temp2,k;

     inp=fopen("inputmodelA1.txt","r");
     fscanf(inp, "%d", &nof_plants);
     fscanf(inp, "%d", &nof_substations);
     fscanf(inp, "%d", &nof_ends);

     production_cap=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
         fscanf(inp, "%lf", &production_cap[i]);
```

```
        // printf("%f\t",production_cap[i]);
     }

     shortcycle_cap=new double*[nof_substations+1];

     for(j=1;j<=nof_substations;j++){
        shortcycle_cap[j]=new double[nof_ends+1];
        for(k=1;k<=nof_ends;k++)
              fscanf(inp, "%lf", &shortcycle_cap[j][k]);
     }

     unitcost=new double[nof_ends+1];
     for(i=1;i<=nof_ends;i++){
         fscanf(inp, "%lf", &unitcost[i]);
     }

     distance=new double*[nof_plants+1];
     for(i=1;i<=nof_plants;i++){
          distance[i]=new double[nof_substations+1];
     }

     for(i=1;i<=nof_plants;i++)
         for(j=1;j<=nof_substations;j++)
                distance[i][j]=-1;

     fscanf(inp, "%d", &nofdistance);
     for(i=1;i<=nofdistance;i++){
         fscanf(inp, "%d",&temp1);
         fscanf(inp, "%d",&temp2);
         fscanf(inp, "%lf",&distance[temp1][temp2]);
         printf("%f\t",distance[temp1][temp2]);
     }

     efficiency=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
         fscanf(inp, "%lf", &efficiency[i]);
     }

     biddingval=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
    //     fscanf(inp, "%lf", &biddingval[i]);
     }

     loss_coef=new double[nof_ends+1];
     for(i=1;i<=nof_ends;i++){
         fscanf(inp, "%lf", &loss_coef[i]);
     }

      fscanf(inp, "%lf", &allocation_percentage);
      fscanf(inp, "%lf", &max_loss);
      fscanf(inp, "%lf", &max_total_loss);
      fscanf(inp, "%lf", &max_cost);
      fscanf(inp, "%lf", &max_total_cost);
    // printf("%d\t%d",nof_plants,nof_substations);

     fclose(inp);
}
```

```
     void write_model_max_energy()
     {
          FILE *f11;
          int i,j,k;

          f11 = fopen("modelA1.lp","w");
          fprintf(f11, "MAX\n");

          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11, "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                   }            }       }   }
        fprintf(f11, "\nSUBJECT TO\n");


        //Substation Constraints:
        for(j=1;j<=nof_substations;j++){
            for(k=1;k<=nof_ends;k++){
                for(i=1;i<=nof_plants;i++){
                    if(distance[i][j]>0){
                        fprintf(f11, "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                    } }
                fprintf(f11,
"<=%.4f\n",shortcycle_cap[j][k]*allocation_percentage);
            }   }
        //end of Substation Constraints:


         //United Substation Constraints:
         for(k=1;k<=nof_ends;k++)    {
             for(j=1;j<=nof_substations;j++)        {
                 if(j == 13 || j == 17 || j == 25 || j == 58 || j == 67
|| j == 79 || j == 124 || j == 155  )           {
                     for(int t=1; t<4; t++)               {
                        for(i=1;i<=nof_plants;i++)                    {
                            if(distance[i][j]>0)                        {
                                fprintf(f11, "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                            }                   }
                        j++;                }
                     j--;
                     fprintf(f11,
"<=%.4f\n",shortcycle_cap[j][k]*allocation_percentage);
                 }       }    }
     //end of United Substation Constraints:

   //Connection Line Constraints:
        //each
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11, "%.6fX_i%d_j%d_k%d<=%.6f\n",
production_cap[i]*loss_coef[k]*distance[i][j],i,j,k,max_loss);
                    }            }       }   }
```

```
        //total
          for(i=1;i<=nof_plants;i++){
             for(j=1;j<=nof_substations;j++){
                 if(distance[i][j]>0){
                     for(k=1;k<=nof_ends;k++){
                         fprintf(f11, "+%.6fX_i%d_j%d_k%d",
pow(production_cap[i],2)*loss_coef[k]*distance[i][j],i,j,k);
                     }            }       }   }
        for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11, "-%.4fX_i%d_j%d_k%d",
production_cap[i]*max_total_loss,i,j,k);
                    }            }       }   }
        fprintf(f11, "<=0\n");
        //end of Connection Line Constraints:


         //Cost Constraints:
        //each
          for(i=1;i<=nof_plants;i++){
             for(j=1;j<=nof_substations;j++){
                 if(distance[i][j]>0){
                     for(k=1;k<=nof_ends;k++){
                         fprintf(f11, "%.6fX_i%d_j%d_k%d<=%.6f\n",
unitcost[k]*distance[i][j],i,j,k,max_cost);
                     }            }       }   }

        //total
          for(i=1;i<=nof_plants;i++){
             for(j=1;j<=nof_substations;j++){
                 if(distance[i][j]>0){
                     for(k=1;k<=nof_ends;k++){
                         fprintf(f11, "+%.6fX_i%d_j%d_k%d",
unitcost[k]*distance[i][j],i,j,k);
                     }            }       }   }

        fprintf(f11, "<=%.6f\n",max_total_cost);
        //end of Cost Constraints:

          //50MW and 10MW constraint
         for(i=1;i<=nof_plants;i++)    {
             for(j=1;j<=nof_substations;j++)       {
                 if(distance[i][j]>0)          {
                    if(production_cap[i]>=50)              {
                       fprintf(f11, "+X_i%d_j%d_k%d",i,j,1);
                    }else if(production_cap[i]<=10)
                    {
                       fprintf(f11, "+X_i%d_j%d_k%d",i,j,2);
                    }      }       }
             if(production_cap[i]>=50 || production_cap[i]<=10)
fprintf(f11, "<=0\n");
        }
        //end of 50MW and 10MW constraint

        //only one end
         for(i=1;i<=nof_plants;i++){
             for(j=1;j<=nof_substations;j++){
```

```
            if(distance[i][j]>0){
                for(k=1;k<=nof_ends;k++){
                    fprintf(f11, "+X_i%d_j%d_k%d",i,j,k);
                }           }       }
        fprintf(f11, "<=1\n");
    }
    //end of only one end

    fprintf(f11, "BIN\n");
     for(i=1;i<=nof_plants;i++){
        for(j=1;j<=nof_substations;j++){
            if(distance[i][j]>0){
                for(k=1;k<=nof_ends;k++){
                    fprintf(f11, "X_i%d_j%d_k%d\n",i,j,k);
                }           }       }   }

    fprintf(f11, "END");
    fclose(f11);}
```

B.2. C++ Codes of Model A-II

```
#include <stdlib.h>
#include <math.h>
#include <stdio.h>
#include <string.h>

int nof_plants;
int nof_substations;
int nof_ends;
double *production_cap; // Wi
double *efficiency; //Ei
double *biddingval;  //Bi
double **distance;   //Dij
double **shortcycle_cap;   //Sjk
double *unitcost;   //Ck
double *loss_coef;   //Fk
double *voltage_out_level;
double *eff;
double *bid;
double per_parameter;
double weight_conn_cost;  //Alfa
double weight_bid_value;  //Beta
double allocation_percentage; // Phi
double max_loss;  //Lmax
double max_total_loss;  //ToLmax
double max_cost;     //Cmax
double max_total_cost;   //ToCmax

void preparedata();
void write_model_max_energy();

int main(){
    preparedata();
    write_model_max_energy();
   // getchar();
    return 0;
}
```

```
void preparedata()
{
     FILE *inp;
     int i,j,nofdistance,temp1,temp2,k;

     inp=fopen("inputmodelA2.txt","r");
     fscanf(inp, "%d", &nof_plants);
     fscanf(inp, "%d", &nof_substations);
     fscanf(inp, "%d", &nof_ends);

     production_cap=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
         fscanf(inp, "%lf", &production_cap[i]);
        // printf("%f\t",production_cap[i]);
     }

     shortcycle_cap=new double*[nof_substations+1];

     for(j=1;j<=nof_substations;j++){
        shortcycle_cap[j]=new double[nof_ends+1];
        for(k=1;k<=nof_ends;k++)
              fscanf(inp, "%lf", &shortcycle_cap[j][k]);
     }

     unitcost=new double[nof_ends+1];
     for(i=1;i<=nof_ends;i++){
         fscanf(inp, "%lf", &unitcost[i]);
     }

     distance=new double*[nof_plants+1];
     for(i=1;i<=nof_plants;i++){
          distance[i]=new double[nof_substations+1];
     }

     for(i=1;i<=nof_plants;i++)
         for(j=1;j<=nof_substations;j++)
                distance[i][j]=-1;

     fscanf(inp, "%d", &nofdistance);
     for(i=1;i<=nofdistance;i++){
         fscanf(inp, "%d",&temp1);
         fscanf(inp, "%d",&temp2);
         fscanf(inp, "%lf",&distance[temp1][temp2]);
         printf("%f\t",distance[temp1][temp2]);
     }

     efficiency=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
         fscanf(inp, "%lf", &efficiency[i]);
     }

     biddingval=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
    //     fscanf(inp, "%lf", &biddingval[i]);
           fscanf(inp, "%lf", &biddingval[i]);
     }
```

```
          loss_coef=new double[nof_ends+1];
          for(i=1;i<=nof_ends;i++){
              fscanf(inp, "%lf", &loss_coef[i]);
          }

           fscanf(inp, "%lf", &allocation_percentage);
           fscanf(inp, "%lf", &max_loss);
           fscanf(inp, "%lf", &max_total_loss);
           fscanf(inp, "%lf", &max_cost);
           fscanf(inp, "%lf", &max_total_cost);
         // printf("%d\t%d",nof_plants,nof_substations);

          fclose(inp);
     }


     void write_model_max_energy()
     {
          FILE *f11;
          int i,j,k;

          f11 = fopen("modelA2.lp","w");
          fprintf(f11, "MAX\n");

          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                       fprintf(f11,                  "+%.6fX_i%d_j%d_k%d",
efficiency[i]*production_cap[i],i,j,k);
                    }           }       }   }
        fprintf(f11, "\nSUBJECT TO\n");


        //Substation Constraints:
        for(j=1;j<=nof_substations;j++){
            for(k=1;k<=nof_ends;k++){
                for(i=1;i<=nof_plants;i++){
                    if(distance[i][j]>0){
                        fprintf(f11,                "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                    }           }
                fprintf(f11,
"<=%.4f\n",shortcycle_cap[j][k]*allocation_percentage);
            }   }
        //end of Substation Constraints:


         //United Substation Constraints:
         for(k=1;k<=nof_ends;k++)    {
             for(j=1;j<=nof_substations;j++)        {
                 if(j == 13 || j == 17 || j == 25 || j == 58 || j == 67
|| j == 79 || j == 124 || j == 155  )            {
                     for(int t=1; t<4; t++)                {
                        for(i=1;i<=nof_plants;i++)                    {
                            if(distance[i][j]>0)                     {
                                fprintf(f11,        "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                            }                   }
```

```
                        j++;
                     }
                     j--;
                     fprintf(f11,
"<=%.4f\n",shortcycle_cap[j][k]*allocation_percentage);
     } } }
     //end of United Substation Constraints:

       //Connection Line Constraints:
        //each
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,          "%.6fX_i%d_j%d_k%d<=%.6f\n",
production_cap[i]*loss_coef[k]*distance[i][j],i,j,k,max_loss);
                    } }  }  }

        //total
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,                 "+%.6fX_i%d_j%d_k%d",
pow(production_cap[i],2)*loss_coef[k]*distance[i][j],i,j,k);
                    }   }   }  }

        for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,                 "-%.4fX_i%d_j%d_k%d",
production_cap[i]*max_total_loss,i,j,k);
                    }    }    }  }
        fprintf(f11, "<=0\n");
        //end of Connection Line Constraints:


         //Cost Constraints:
        //each
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,          "%.6fX_i%d_j%d_k%d<=%.6f\n",
unitcost[k]*distance[i][j],i,j,k,max_cost);
                    }      }    } }

        //total
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,                 "+%.6fX_i%d_j%d_k%d",
unitcost[k]*distance[i][j],i,j,k);
                    }       }      }  }

        fprintf(f11, "<=%.6f\n",max_total_cost);

        //end of Cost Constraints:
```

```
          //50MW and 10MW constraint
         for(i=1;i<=nof_plants;i++)    {
            for(j=1;j<=nof_substations;j++)       {
                if(distance[i][j]>0)           {
                   if(production_cap[i]>=50)                {
                      fprintf(f11, "+X_i%d_j%d_k%d",i,j,1);
                   }else if(production_cap[i]<=10)                {
                      fprintf(f11, "+X_i%d_j%d_k%d",i,j,2);
                   }      }     }
            if(production_cap[i]>=50       ||      production_cap[i]<=10)
fprintf(f11, "<=0\n");


        }
        //end of 50MW and 10MW constraint

        //only one end
         for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11, "+X_i%d_j%d_k%d",i,j,k);
                    }      }      }
            fprintf(f11, "<=1\n");
        }
        //end of only one end

        fprintf(f11, "BIN\n");
         for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11, "X_i%d_j%d_k%d\n",i,j,k);
                    }       }    }  }
        fprintf(f11, "END");

        fclose(f11);
     }
```

B.3. C++ Codes of Model B

```
#include <stdlib.h>
#include <math.h>
#include <stdio.h>
#include <string.h>

int nof_plants;
int nof_substations;
int nof_ends;
double *production_cap; // Wi
double *efficiency; //Ei
double *biddingval;  //Bi
double **distance;   //Dij
double **shortcycle_cap;   //Sjk
double *unitcost;   //Ck
double *loss_coef;   //Fk
double *voltage_out_level;
```

```
double *eff;
double *bid;
double per_parameter;
double weight_conn_cost;  //Alfa
double weight_bid_value;  //Beta
double allocation_percentage; // Phi
double max_loss;  //Lmax
double max_total_loss;  //ToLmax
double max_cost;     //Cmax
double max_total_cost;   //ToCmax

void preparedata();
void write_model_max_energy();

int main(){
    preparedata();
    write_model_max_energy();
   // getchar();
    return 0;
}


void preparedata()
{
     FILE *inp;
     int i,j,nofdistance,temp1,temp2,k;

     inp=fopen("inputmodelB1.txt","r");
     fscanf(inp, "%d", &nof_plants);
     fscanf(inp, "%d", &nof_substations);
     fscanf(inp, "%d", &nof_ends);

     production_cap=new double[nof_plants+1];

     for(i=1;i<=nof_plants;i++){
         fscanf(inp, "%lf", &production_cap[i]);
        // printf("%f\t",production_cap[i]);
     }

     shortcycle_cap=new double*[nof_substations+1];

     for(j=1;j<=nof_substations;j++)
     {
        shortcycle_cap[j]=new double[nof_ends+1];
        for(k=1;k<=nof_ends;k++)
              fscanf(inp, "%lf", &shortcycle_cap[j][k]);
     }

     unitcost=new double[nof_ends+1];
     for(i=1;i<=nof_ends;i++){
         fscanf(inp, "%lf", &unitcost[i]);
     }

     distance=new double*[nof_plants+1];
     for(i=1;i<=nof_plants;i++){
          distance[i]=new double[nof_substations+1];
     }

     for(i=1;i<=nof_plants;i++)
         for(j=1;j<=nof_substations;j++)
```

```
                    distance[i][j]=-1;

          fscanf(inp, "%d", &nofdistance);
          for(i=1;i<=nofdistance;i++){
              fscanf(inp, "%d",&temp1);
              fscanf(inp, "%d",&temp2);
              fscanf(inp, "%lf",&distance[temp1][temp2]);
              printf("%f\t",distance[temp1][temp2]);
          }

          efficiency=new double[nof_plants+1];

          for(i=1;i<=nof_plants;i++){
              fscanf(inp, "%lf", &efficiency[i]);
          }

          biddingval=new double[nof_plants+1];

          for(i=1;i<=nof_plants;i++){
         //     fscanf(inp, "%lf", &biddingval[i]);
                fscanf(inp, "%lf", &biddingval[i]);
          }

          loss_coef=new double[nof_ends+1];
          for(i=1;i<=nof_ends;i++){
              fscanf(inp, "%lf", &loss_coef[i]);
          }

           fscanf(inp, "%lf", &allocation_percentage);
           fscanf(inp, "%lf", &max_loss);
           fscanf(inp, "%lf", &max_total_loss);
           fscanf(inp, "%lf", &max_cost);
           fscanf(inp, "%lf", &max_total_cost);
         // printf("%d\t%d",nof_plants,nof_substations);

          fclose(inp);
     }


     void write_model_max_energy()
     {
          FILE *f11;
          int i,j,k;

          f11 = fopen("modelB1.lp","w");
          fprintf(f11, "MAX\n");
     for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                       fprintf(f11,
"+%.2fX_i%d_j%d_k%d",0*biddingval[i],i,j,k);
                    }           }       }   }

          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                       fprintf(f11,                                   "-
%.2fX_i%d_j%d_k%d",1*unitcost[k]*distance[i][j],i,j,k);
```

```
                    }           }       }   }
        fprintf(f11, "\nSUBJECT TO\n");


        //Substation Constraints:
        for(j=1;j<=nof_substations;j++){
            for(k=1;k<=nof_ends;k++){
                for(i=1;i<=nof_plants;i++){
                    if(distance[i][j]>0){
                        fprintf(f11,                "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                    }           }
                fprintf(f11,
"<=%.4f\n",shortcycle_cap[j][k]*allocation_percentage);
            }   }
        //end of Substation Constraints:


         //United Substation Constraints:
         for(k=1;k<=nof_ends;k++)    {
             for(j=1;j<=nof_substations;j++)        {
                 if(j == 13 || j == 17 || j == 25 || j == 58 || j == 67
|| j == 79 || j == 124 || j == 155  )            {
                     for(int t=1; t<4; t++)                {
                        for(i=1;i<=nof_plants;i++)                   {
                            if(distance[i][j]>0)                       {
                                fprintf(f11,        "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                            }                   }
                        j++;
                     }
                     j--;
                     fprintf(f11,
"<=%.4f\n",shortcycle_cap[j][k]*allocation_percentage);
                 }        }    }
     //end of United Substation Constraints:
        //Connection Line Constraints:
        //each
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,         "%.6fX_i%d_j%d_k%d<=%.6f\n",
production_cap[i]*loss_coef[k]*distance[i][j],i,j,k,max_loss);
                    }           }       }   }

        //total
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,                "+%.6fX_i%d_j%d_k%d",
pow(production_cap[i],2)*loss_coef[k]*distance[i][j],i,j,k);
                    }           }       }   }
        for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,                "-%.4fX_i%d_j%d_k%d",
production_cap[i]*max_total_loss,i,j,k);
```

```
                    }           }       }   }
        fprintf(f11, "<=0\n");
        //end of Connection Line Constraints:

              //Cost Constraints:
        //each
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,          "%.6fX_i%d_j%d_k%d<=%.6f\n",
unitcost[k]*distance[i][j],i,j,k,max_cost);
                    }           }       }   }


        //end of Cost Constraints:


         //Required Capacity Constraint:

        //Rmin
          for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11,                 "+%.2fX_i%d_j%d_k%d",
production_cap[i],i,j,k);
                    }           }       }   }
        fprintf(f11, ">=5000\n");

        //end of Required Capacity Constraint

          //50MW and 10MW constraint
         for(i=1;i<=nof_plants;i++)    {
            for(j=1;j<=nof_substations;j++)        {
                if(distance[i][j]>0)            {
                   if(production_cap[i]>=50)                {
                      fprintf(f11, "+X_i%d_j%d_k%d",i,j,1);
                   }else if(production_cap[i]<=10)                {
                      fprintf(f11, "+X_i%d_j%d_k%d",i,j,2);
                   }            }       }
            if(production_cap[i]>=50       ||       production_cap[i]<=10)
fprintf(f11, "<=0\n");


        }
        //end of 50MW and 10MW constraint

        //only one end
         for(i=1;i<=nof_plants;i++){
            for(j=1;j<=nof_substations;j++){
                if(distance[i][j]>0){
                    for(k=1;k<=nof_ends;k++){
                        fprintf(f11, "+X_i%d_j%d_k%d",i,j,k);
                    }           }       }
            fprintf(f11, "<=1\n");
        }
        //end of only one end

        fprintf(f11, "BIN\n");
```

```
    for(i=1;i<=nof_plants;i++){
       for(j=1;j<=nof_substations;j++){
           if(distance[i][j]>0){
               for(k=1;k<=nof_ends;k++){
                   fprintf(f11, "X_i%d_j%d_k%d\n",i,j,k);
               }           }       }   }
   fprintf(f11, "END");

   fclose(f11);

}
```

REFERENCES

1 Kasım RES Başvuruları, 2010, http://www.energydanismanlik.com/tr/haberler/s/62, accessed at 05, 2012.

Alboyacı, B., B., Dursun, 2008, "Grid Connection Requirements for wind Turbine Systems in selected Countries Comparison to Turkey", *Electrical Power Quality & Utilization* , 1-15.

Altuntaşoğlu, Z. T., 2011, *Rüzgar Enerjisi Konusunda Mevcut Durum*, http://www.nukte.org/node/997, accessed at 06, 2012.

Bushnell, J., Y. Chen, 2009, http://www.econ.iastate.edu/sites/default/files/publications/papers/paper_13131.pdf , accessed at 06, 2012.

Chowdhury, S., J. Zhang, A. Messac, L. Castillo, 2011, "Unrestricted wind farm layout optimization (UWFLO): Investigating key factors influencing the maximum power generation", *Renewable Energy*, Vol. 38, No. 1, pp. 16-30.

Cristina L. Archer, M. Z., 2005, *Evaluation of global wind power*, http://www.stanford.edu/group/efmh/winds/global_winds.html, accessed at 05, 2012.

Cullen, J. A., 2011, http://www.u.arizona.edu/~jcullen/Documents/dynamic%20response.pdf, accessed at 01, 2012.

Department of Energy, 2012, *What is Renewable Energy*, http://www.renewableenergyworld.com/rea/tech/home, accessed at 06, 2011.

Electric Current, 2008, http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elecur.html, accessed at 05, 2011.

Electric Frequency - Hertz, 2010, http://international-electrical-supplies.com/electric-frequency.html, accessed at 08, 2011.

Electric Power and Transmission and Distribution Forum, 2005, http://www.eng-tips.com/viewthread.cfm?qid=139432, accessed at 02, 2012.

Electric power, 2011, http://en.wikipedia.org/wiki/Electric_power, accessed at 08, 2011.

Electrical Grid, 2011, http://en.wikipedia.org/wiki/Electrical_grid, accessed at 07, 2011.

Electrical Substation, 2011, http://en.wikipedia.org/wiki/Electrical_substation, accessed at 07, 2011.

Electrical Substation, 2012, http://en.wikipedia.org/wiki/Electrical_substation, accessed at 07, 2012.

Electricity Market Grid Regulation, 2003, http://www.ongurergan.av.tr/en-EN/articles.html, accessed at 07, 2010.

Emami, A., P. Noghreh, 2009, "New approach on optimization in placement of wind turbines within wind farm by genetic algorithms", *Renewable Energy*, Vol. 35, No. 7, pp. 1559–1564.

Enerji Piyasası Düzenleme Kurumu, 2005, *Yenilenebilir Enerji Kaynaklarının Elektrik Enerjisi Üretimi Amaçlı Kullanımına İlişkin Kanun*, http://www.mevzuat.adalet.gov.tr/html/1477.html, accessed at 06, 2011.

Enertürk Haberler, 2010, http://www.enerturk.com.tr/TR/news_detail.asp?newID=104&newTitle=R%FCzgar%20enerjisi%20Bakan%20ile%20EPDK'y%FD%20birbirine%20d%FC%FE%FCrd%FC, accessed at 06, 2012.

Eroglu, Y., S. U. Seçkiner, 2012, "Design of wind farm layout using ant colony algorithm", *Renewable Energy*, Vol. 44, pp. 53-62.

EU Offshore, 2011, http://www.gwec.net/index.php?id=172, accessed at 05 2012.

European Wind Energy Association, 2012, *The European offshore wind industry key 2011 trends and statistics* . http://www.ewea.org/index.php?id=1861, accessed at 05, 2012.

Glossary, 2012, http://www.ackenergy.org/GLOSSARY.html, accessed at 06, 2012.

Gonzalez, J. S., A. G. Rodriguez, J. C. Mora, J. R. Santos, M. B. Payan, 2010, "Optimization of wind farm turbines layout using an evolutive algorithm", *Renewable Energy*, Vol. 35, No. 8, pp. 1671–1681.

Hau, E., 2006, *Wind Turbines: Fundamentals, Tehcnologies, Application, Economics*, New York, Springer.

Ibrahim, H., M. Ghandourb, M. Dimitrovaa, A. Ilincac , J. Perrond, 2011, "Integration of Wind Energy into Electricity Systems: Technical Challenges and Actual Solutions", *Energy Procedia*, Vol. 6, pp. 815-824.

Ituarte-Villarreal, C. M., J. F. Espiritu, 2011, "Optimization of wind turbine placement using a viral based optimization algorithm", *Procedia*, Vol. 6, pp. 469–474.

Kahn, E., 2010, "Wind Integration Studies: Optimization vs. Simulation", *The Electricity Journal*, Vol. 23, No. 9, pp. 51-64.

Kaya, T., C. Kahraman, 2010, "Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul", *Energy*, Vol. 35, No.6, pp. 2517–2527.

Le, N. A., S. C. Bhattacharyya, 2011, "Integration of wind power into the British system in 2020", *Energy*, Vol. 36, No. 10, pp. 5975-5983.

Liu, S., J. Zhang, W. Liu, Y. Qian, 2012, "A Comprehensive Decision-Making Method for Wind Power Integration Projects Based on Improved Fuzzy AHP", *Energy Procedia*, Vol. 14, pp. 937 – 942.

Mevlüt Akdeniz, E. B., 2009, *Türkiye Elektrik İletim Sisteminde Rüzgar Santrali Bağlantıları.* http://www.dektmk.org.tr/pdf/enerji_kongresi_11/114.pdf, accessed at 05 2012.

Mills, A., A. Phadke, R. Wiser, 2010, *Exploration of Resource and Transmission Expansion Decisions in the Western Renewable Energy Zone Initiative,* http://eetd.lbl.gov/ea/ems/reports/lbnl-3077e.pdf, accessed at 06 2012.

Mills, A., R. Wiser, K. Porter, 2011, "The cost of transmission for wind energy in the United States: A review of transmission planning studies", *Renewable and Sustainable Energy Reviews*, Vol 16. No. 1, pp. 1-19.

Renewable Energy, 2011, http://en.wikipedia.org/wiki/Renewable_energy, accessed at 06 2011.

RES Bağlanabilir Kapasiteleri, 2010, http://www.teias.gov.tr/KAPAS%C4%B0TELER.pdf, accessed at 05 2012.

Resmi Gazete, 2005, *Yenilenebilir Enerji Kaynaklarının Elektrik Enerjisi Üretimi Amaçlı Kullanımına İlişkin Kanun,* http://www.ttgv.org.tr/tr/yenilenebilir-enerji-kaynaklarinin-elektrik-enerjisi-uretimi-amacli-kullanimina-iliskin-kanunda-degisiklik-yapilmasina-dair-kanun, accessed at 05 2012.

Saavedra-Moreno, B., S. Salcedo-Sanz, A. Paniagua-Tineo, L. Prieto, A. Portilla-Figueras, 2011, "Seeding evolutionary algorithms with heuristics for optimal wind turbines positioning in wind farms", *Renewable Energy*, pp. 2838-2844.

Short Circuit Power, 2004, http://www.designers.schneider-electric.ru/Attachments/ed/guide/mv_partner_b12_short_circuit_power.pdf, accessed at 08 2011.

TEİAŞ Supply Reliability and Quality Regulation of the Electrical Transmission Systems, 2010, www.teias.gov.tr/Yonetmelikler/supply.doc, accessed at 09 2011.

Turkish News Agency, 2010, *Turkey.* Ankara: Ertem Basım Ldt. Şti.

Turkuvaz Gazete Dergi Basım A.Ş., 2010, *Elektrik,* http://www.globalenerji.com.tr/hab-23000202-141,35@2300.html, accessed at 06 2012.

Türkiye Elektrik İletim Anonim Şirketi, 2010, *2011-2015 Dönemi Stratejik Plan.* http://www.teias.gov.tr/TEIAS_Strtj_2011.pdf, accessed at 03 2012.

Ucoz, R., 2011, *Flickr,* http://www.flickr.com/photos/68143365@N08/6314755854/, accessed at 05, 2012.

Urban Wind Turbines, 2011, http://www.urbanwind.net/pdf/technological_analysis.pdf, accessed at 08 2011.

Utility Frequency, 2011, http://en.wikipedia.org/wiki/Utility_frequency, accessed at 08 2011.

Voltage, 2011, http://en.wikipedia.org/wiki/Voltage, accessed at 08 2011.

Wind Energy Contracting, Capabilities & Solutions, 2012, http://www.emacontracting.com/?page=wec_capabilities_solutions, accessed at 04 2010.

Wind Energy Potential in Turkey, 2012, http://www.geni.org/globalenergy/library/renewable-energy-resources/world/middle-east/wind-middleeast/wind-turkey.shtml, accessed at 02 2012.

Wind Power Plant, 2011, http://www.daviddarling.info/encyclopedia/W/AE_wind_power_plant.html, accessed at 07 2011.

World Energy Consumption, 2007, http://www.solcomhouse.com/worldenergy.htm, accessed at 07 2011.

World Energy Demand and Economic Outlook., 2010, http://www.eia.gov/oiaf/ieo/world.html, accessed at 07 2011.

World Wind Energy Association, 2011, http://www.wwindea.org/home/index.php, accessed at 07 2011.

ZRD Muhendislik, 2010, http://www.zrd.com.tr/TR, accessed at 06 2012.