NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL OF CIVIL ENGINEERING

DEPARTMENT OF STRUCTURAL ENGINEERING

STATICS AND ASEISMIC RESCEARCH LABORATORY

Life-cycle cost analysis of a wind park

MASTER THESIS

MARIA K. PAIDA

SUPERVISOR: NIKOS D. LAGAROS, LECTURER AT N.T.U.A.

Athens, October 2012

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Abstract

The purpose of this dissertation is to perform a life cycle cost analysis of a wind farm and to develop a life cycle cost model. Firstly, some references are made to the renewable energy and its mainstream forms are described briefly. Moreover, the main aspects of wind parks are mentioned: the factors that determine their construction location, the kind of the wind park (onshore-offshore), their environmental impact. Furthermore, the concept of life-cycle cost analysis is analyzed both as a significant process which can be used as an assessment tool generally and how it can be used in terms of the wind farm's design. Finally, an application of life-cycle cost analysis is performed by examining a particular wind park in Cyprus, with known characteristics (number and position of wind turbine, wind potential etc). Two case studies are examined for the same wind park, assuming different tower heights and different initial costs of each wind turbine. After, having evaluated the life cycle cost of each type of wind turbine for three wind hazard levels, through the process which is analytically described below, the life-cycle cost as well as the total cost of the wind park is estimated.

Key words

Lice-cycle cost analysis, wind park, wind hazard level

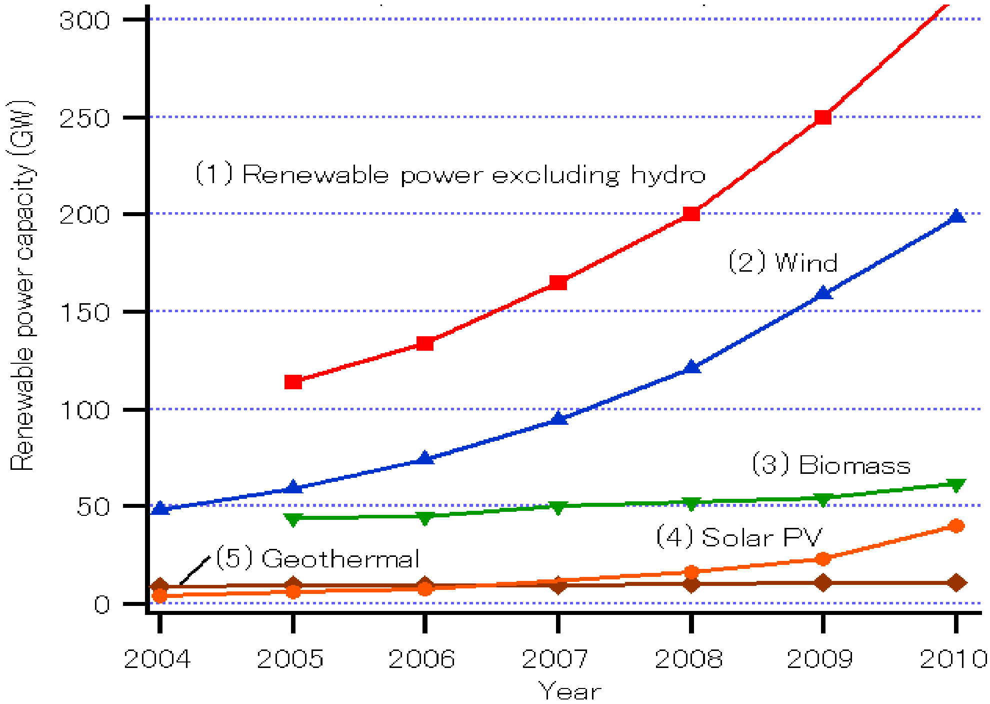
1. Introduction

Renewable energy sources (RES) or mild forms of energy are forms of exploitable energy derived from natural processes, such as the solar radiation, the movement of water, the wind and geothermal energy. There are two factors that make these forms of energy renewable. Firstly, their exploitation does not require active processes, such as pumping, combustion or extraction, which are required for the exploitation of the traditional energy sources. However, existing flows of energy are used. Additionally, these forms of energy do not release carbon dioxide, hydrocarbons and radioactive waste in the environment. These are the reasons why, they are characterized as mild or ‘clean’ energy sources. Renewable energy sources are considered to be a possible solution to the energy problem, namely the depletion of fossil fuel reserves. In the U.S.A. 6% of energy consumption derives from renewable sources, while in the European Union, about 25% of the consumed energy.

The advantages of renewable energy sources include the fact that they are environmentally friendly, without processing them to release residues and wastes. Moreover, they are inexhaustible, unlike fossil fuels and the equipment, which they require is simple in construction, maintenance and have a long life. Renewable energy can contribute to energy independence of small countries, since they may produce energy according to the needs of the local population, eliminating the need for huge power plants and transportation of produced energy over long distances.

On the other hand, the main disadvantage of the renewable energy sources is the low rate of return, about 30%, which makes the implementation cost in large areas of land high enough. Therefore, renewable energy sources cannot be used to meet the needs of large urban centers and mainly they have been used until now as additional sources of energy. The main factors, which determine the supply and efficiency of renewable energy sources are the season of year, the latitude and climate of a region. Finally, another disadvantage which refers specifically to wind turbines is that they alter the landscape, cause noise and bird deaths. However, with the evolution of technology and the appropriate selection of the installation area (e.g. offshore), many of these problems have been partially solved.

Mainstream forms of renewable energy are solar energy, hydropower, biomass, biofuel, geothermal energy and wind power. Renewable energy replaces conventional fossil fuels in four main areas: electricity generation, heating and cooling, motor fuels, and rural (off-grid) energy services. The following chart indicates the global renewable power capacity until 2010 excluding hydropower.

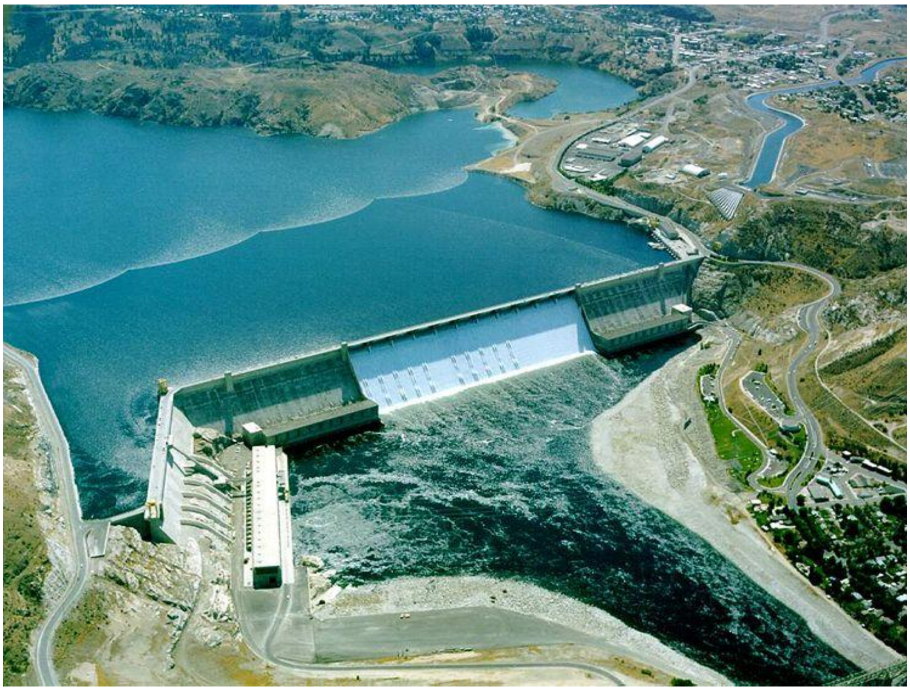


1.1 Global renewable power capacity until 2010

Solar energy derives from the sum through solar radiation. Solar technologies are mainly identified as passive or active solar systems according to the way the capture, convert and distribute solar energy. Passive solar techniques refer generally to the bioclimatic design of a building: the orientation, the chosen material etc. Active solar systems refer to the use of photovoltaic panels and solar thermal collectors. The main solar applications include heating and cooling, hot water, solar cooking etc.

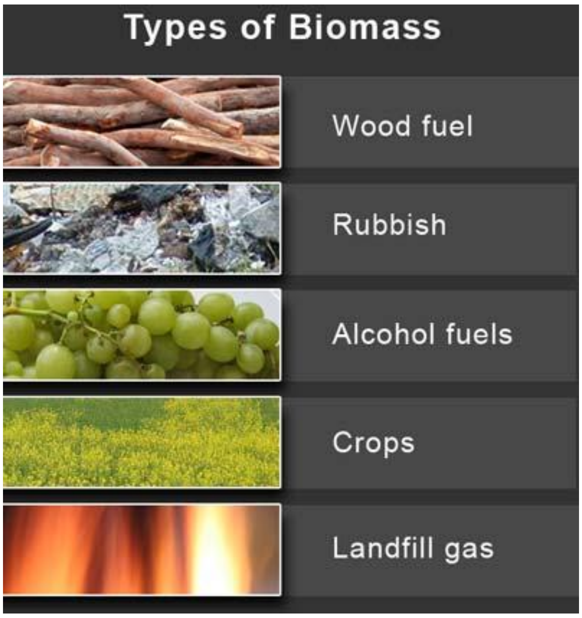
1.2 Solar cells for energy production

Energy from flowing water can be utilized, as water is 800 times denser than air and it yields appreciable amounts of energy even with slow stream water. Hydropower was used for irrigation and operation of various mechanical devices (watermills, textile mills etc) since ancient times. Since 20th century water power is used in association with the production of hydro-electric power. Some of the forms of hydropower are the hydroelectric energy produced by large-scale hydroelectric dams, the Micro hydro systems usually used as remote-area power suppliers and the Run-of-the-river hydroelectricity systems from the rivers' kinetic energy. Hydropower production varies from year to year, depending on precipitation.



1.3 Hydroelectric dam

Biomass is biological material from organisms, which is used either directly or converted into other energy products. It is based on carbon, hydrogen and oxygen and biomass energy derives from garbage, wood, waste, landfill gases and alcohol fuels. Initially, biomass is considered to be plant matter used to produce electricity with steam turbines or generate heat by direct combustion. However, biomass can even include plant and animal matter that can be converted into fibers or other industrial chemicals. The best approaches for using biomass vary from region to region according to the local requirements, climate, soils and geography.

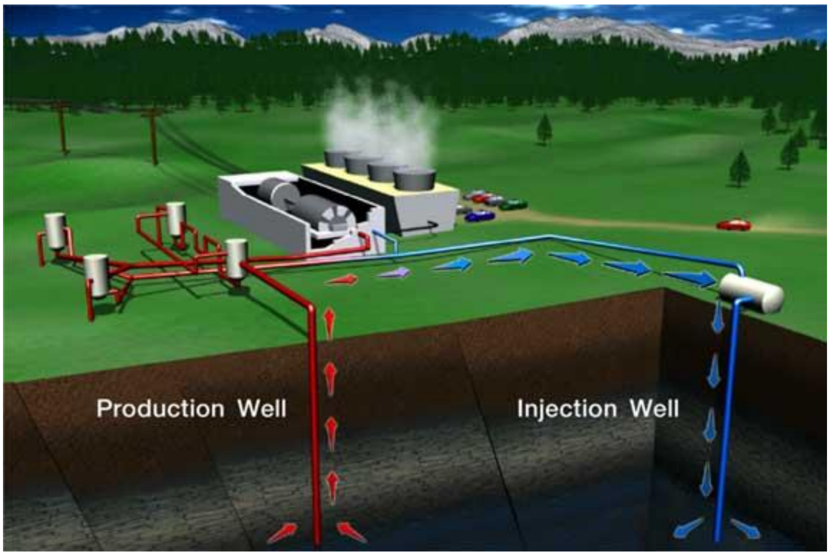


1.4 Types of biomass

Biofuel is a type of fuel whose energy derives from biological carbon fixation. Biofuels include fuels derived from biomass conversion, solid biomass, liquid fuels and various biogases. Biofuels are gaining increased public and scientific attention, because of the oil price hikes, the need for increased energy independence, and concern about greenhouse gas emissions from fossil fuels. The first generation biofuels include bioalcohols, biodiesel, green diesel, vegetable oil etc. Some second generation biofuels are under development such as Cellulosic ethanol, biohydrogen, biomethanol etc. Biofuels provided 2.7% of the world's transport fuel in 2010 and there is the potential to meet more than 25% of world’s demand for transportation fuel by 2050.

1.5 Production of biofuel from plants

Geothermal energy is thermal energy generated and stored in the Earth and it derives from the original formation of the planet (20%) and from radioactive decay of minerals (80%). The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, causes a continuous conduction of thermal energy from the core to the surface. Geothermal power is cost effective, reliable, sustainable, and environmentally friendly and it is used widely for various applications, such as home heating. Although, the cost of producing geothermal power has decreased by 25% during the last twenty years, its implementation is still limited due to the high cost of the exploitation.



1.6 Energy production from geothermy

Finally, wind power, which the renewable energy sources that this master thesis deals with, is the conversion of wind energy into a useful form of energy: wind turbines to produce electricity, windmills for mechanical power, wind pumps for water pumping. Unlike fossil fuels, energy power is renewable, clean and plentiful and it does not produce greenhouse gas emissions. Moreover, wind is widely distributed and the construction of wind parks requires limited land. The environmental effects of the exploitation of wind power are not as severe as those from the energy produced by fossil fuels.

Several hundred individual wind turbines, which are connected to the electric power transmission network, form large offshore or onshore wind parks. Although, offshore wind farms can take advantage of more frequent and powerful winds than are available to land-based installations and they have less visual impact on the landscape, their construction costs, which are considerably higher, is a factor that affects its installation. On the other hand, onshore wind facilities harness winds at higher altitudes, which are stronger and more consistent, through the appropriate tower height, while small wind parks are used to provide electricity to isolated locations.

In the 1980s, the United States pioneered in wind farms and in 1997 German installed capacity surpassed the U.S.A. Between 2000 and 2006, world wind generation capacity more than quadrupled, doubling about every three years. Since 2008 China has been rapidly expanding its wind installations and until 2010 China became the world leader. Since the end of 2011, worldwide there are now many wind turbines operating, with a total nameplate capacity of 238,351 MW which corresponds to the 2.5% of worldwide electricity usage. Several countries have already achieved relatively high levels of penetration, which is the fraction of energy produced by wind compared with the total available generation capacity e.g. 28% of stationary (grid) electricity production in Denmark, 19% in Portugal, 16% in Spain, 14% in Ireland, and 8% in Germany.

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2. Wind Parks

2.1 Wind energy

Wind energy is the kinetic energy of a blowing air stream. The total wind energy can be estimated through the following relationship:

$$E = \frac{1}{2}mu^2 = \frac{1}{2}(Aut\rho)u^2 = \frac{1}{2}At\rho u^3$$

where

A the examined area, perpendicular to the wind direction

t the time duration

ρ the air density

u the wind velocity

Aut the volume of air passing

Autρ the mass m passing per unit time

Power is the quotient of energy per unit time:

$$P = \frac{E}{t} = \frac{1}{2}(A\rho)u^3$$

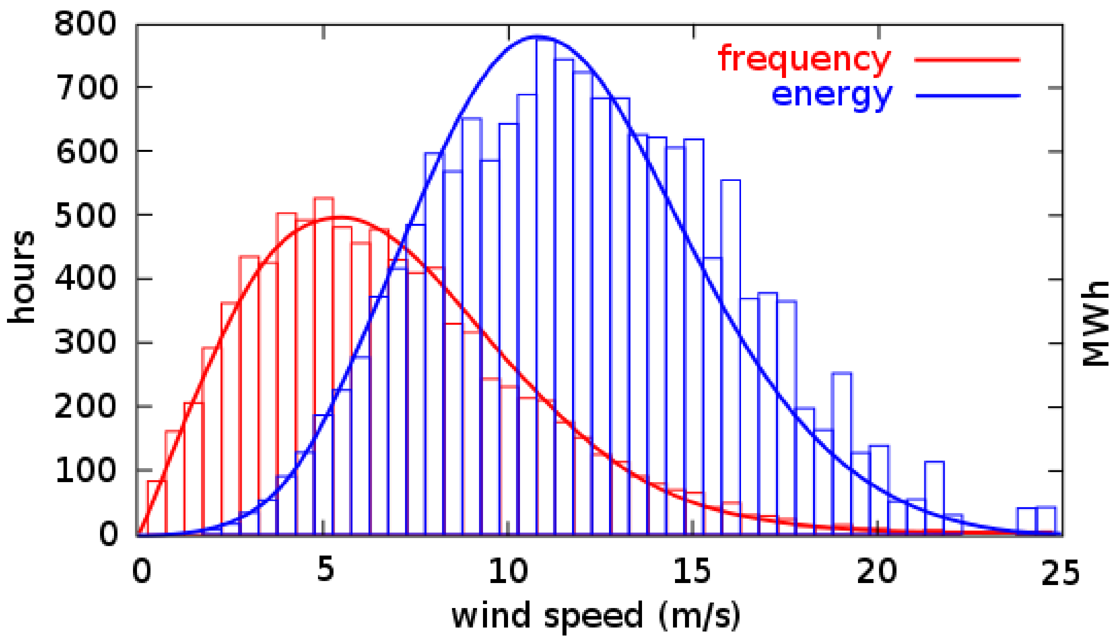
where

A the surface of the wind generator (rotor area)

Wind power is proportional to the third power of the wind velocity, as it is indicated by the above relationship. In that way, even a small increase in the wind speed leads to higher increase in the wind power produced. For example, doubling of the wind speed causes eight times higher wind power.

The surface of the Earth is heated unequally by the sun. The solar radiation depends on the topology of the area, the angle of incidence of the sun's rays at the earth surface according to the latitude and time of day, the existence or not of large water bodies. This absorbed heat energy from the earth's surface and the difference between it and the heat energy absorbed by oceans, which heat up and cool down slower due to water's high thermal capacity, creates a moving air mass. This air mass is warmed by the absorbed solar energy and moves upwards, as the warm air is denser than cool air. So, areas with higher and lower pressure are formed, causing strong pressure differentials. Since wind movement is affected by areas with high and low pressure, these pressure differentials and the rotation of the Earth cause the wind turbulence.

The wind velocity varies in time and area, making mean values of wind speed, wind direction etc insufficient to predict the amount of wind energy that a wind turbine could exploit in a particular area. A considerably high volume of statistical data should be taken into account in order to determine these magnitudes, which usually is extremely difficult to find them. In these cases, probability distribution functions are often fit to the observed data in order to predict the frequency of the wind speeds and wind direction in a particular area, where a wind farm may be constructed. The Weibull distribution function is considered to be that one which best illustrates the real distribution of hourly wind velocities.

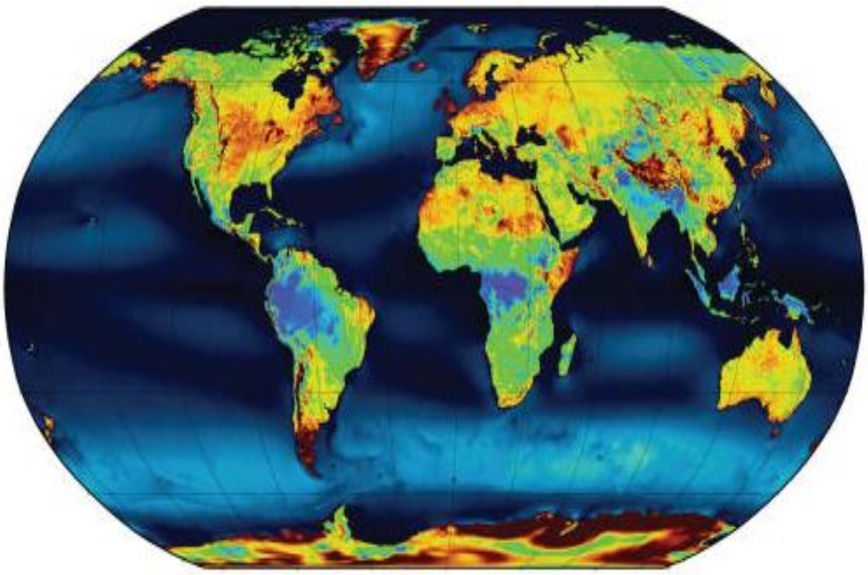


2.1 Weibull distribution function for wind speed

2.2 Design of wind parks

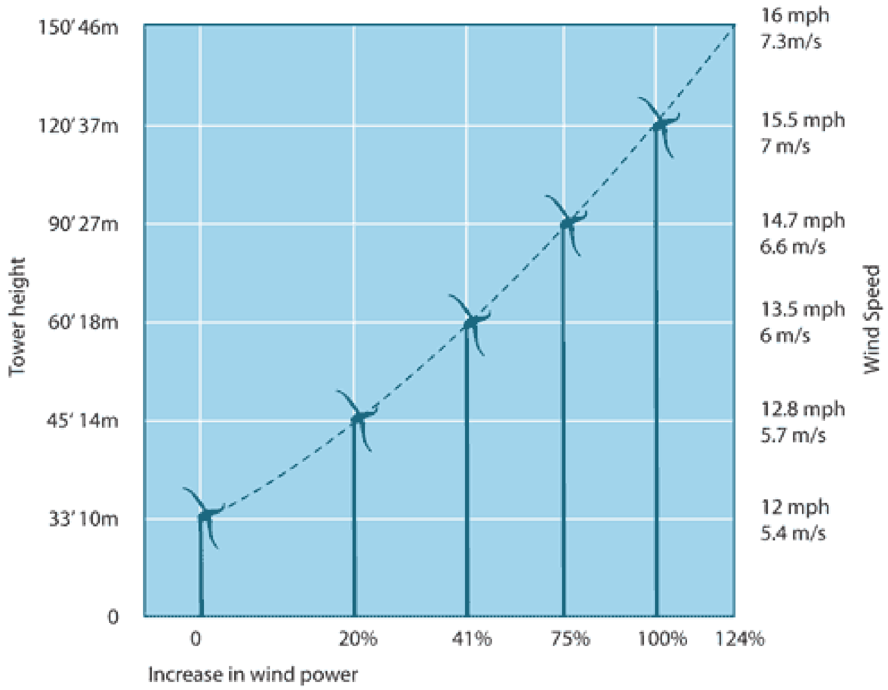
A large wind farm may consist of several hundred individual wind turbines, and cover an extended area of hundreds of square miles. Wind generators should be located in definite distances, which usually should be greater than 50 m or four times the diameter of the rotor. The most crucial factor for choosing the site potential for a wind farm is the high wind potential, which is estimated after having calculated the wind speed and wind frequency in detail. Another important factor of turbine sitting is the available access to local demand or transmission capacity. An ideal location would have a near constant flow of non-turbulent wind throughout the year, with a minimum likelihood of sudden powerful bursts of wind.

The wind potential of a region (mean value of wind velocity, the orientation of the wind, frequency of wind data) derives usually from a wind atlas and is validated with wind measurements. Investing on a wind farm construction project and determining the accurate potential site of it require both historical meteorological wind data and precise measurement of accurate data for wind velocity and direction, as meteorological wind data alone is usually not sufficient. The local winds are usually measured for more than one year using radars placed at the top of guyed towers, which are constructed for this purpose. After having recorded detailed measurements of the wind speed and its direction, local wind maps are designed.



2.2 Global wind map at 80 m

Usually, the wind speed is measured at a relative height of 10 m from the ground surface. However, as the influence of drag reduces at higher altitudes, the wind velocity increases with altitude dramatically. This increase depends on the topography, the upwind barriers (e.g. buildings, trees) and the surface roughness. Consequently, as the altitude of a turbine increases, the expected wind velocity increases, resulting in increased produced power. Generally, a wind speed of 4.5 m/s or greater is required for economic wind energy production. Typically, the increase of wind speeds with increasing height follows a wind profile model, which indicates that wind velocity rises incrementally to the seventh root of altitude. For example, doubling the altitude of a wind generator increases the expected wind velocities by 10% and the expected power by 34%.



2.3 Influence of height on the wind speed

The construction of wind farms requires the design and installation of a collection system and a substation. The individual wind generators are connected via a communication network with a medium voltage power collection system (usually 34.5 KV). Then, this medium-voltage electrical current increases its voltage at the substation with a transformer in order to be connected to the high voltage transmission system.

From the financial point of view, expect from the technical part, the design of a wind park results from the balance between two conflicting economic factors: the decrease of the installation and operation costs and the increase of profits derived from the sale of the produced energy.

The total cost of the construction and operation of a wind farm is of particular concern in both academic level as well as in industry. The main factors that affect the total cost include: the installation cost, the cost of operation and maintenance (O&M), the cost of electricity production. The installation cost includes the purchase cost of the wind turbine, the design, the construction and the connection of the wind turbines to the grid. Generally it is observed that the cost of installation and operation and maintenance cost are about 95% of total cost.

Generally, the production of wind power requires a high capital investment, while it has low ongoing costs. As the wind generator technology develops by using more sustainable materials for the blades and the tower, by improving the turbine performance and increasing the power generation efficiency, costs of wind power production are decreasing.

2.3 Wind parks in the world

A wind park consists of a number of wind turbines, which are located in a specified region, and its objective is to produce large amounts of electric energy. A wind farm can be placed both onshore and offshore. A large wind park is a group of numerous wind turbines and occupies an extended area, which might exceed some hundreds of square miles.

Generally, the site of a wind farm is carefully chosen according to the desirable wind potential of a region. Ideally, a location has as far as possible a constant flow of non-turbulent wind over the year, with a limited likelihood of sudden forceful bursts of wind. Furthermore, another important reason for choosing a particular turbine sitting is the easy access to transmission capacity or local demands.

There are two kinds of wind parks: onshore wind parks and offshore wind parks, which both have their advantages and disadvantages. Generally, the installation of onshore wind turbines in mountainous or hilly regions is done on ridgelines at least three kilometers from the nearest shoreline. In that way, the topographic acceleration as the wind accelerates over the ridge is neutralized and the additional, gained wind velocity increases the produced wind energy. Moreover, the design distances between the wind turbines of an onshore wind park have to be large, so the land between them can be used for various purposes, such as agricultural.

2.4 Onshore wind park

The world's first wind farm was constructed on Crotched Mountain in southern New Hampshire, USA, in December 1980. After that, plenty of wind farms started to be installed around the world. The most of the largest onshore wind parks operate in the USA and China. China has several wind power bases of great size, such as the Gansu Wind Farm of more than 5000 MW installed. The second largest wind farm in the world is the Alta Wind Energy Center in California at 1020 MW. However, there are other large onshore wind parks which are under construction, such as Shepherds Flat Wind Farm (845 MW) in Oregon, United States.

Offshore wind parks are those constructed in large bodies of water to produce electricity. The average wind velocity is considered to be much higher over open seas, because of the low water surface roughness, which is the property that offshore wind parks try to exploit. Therefore, these installations benefit of the more frequent and powerful winds that are available in these locations and are not blocked by obstacles, such as hills and mountains.

The installation and operation of offshore wind parks require service vessels with availability higher than 80% of time in order to offer sufficient amortization of the wind generators, as well as special fast service vehicles, responsible for installation and maintenance. The initial installation, operation and maintenance costs of offshore wind farms are significantly higher than that of an onshore wind farm. Specifically, since 2011 offshore wind farms were at least 3 times more expensive than onshore wind farms of the same nominal power. However, these costs are expected to fall as the industry expands. Finally, offshore wind generators are much less obtrusive, as their apparent size and noise is mitigated, and have less aesthetic impact on the landscape than land based projects.

2.5 Offshore wind park

The leader in offshore wind energy is Europe with the first offshore wind farm installed in Denmark in 1991. Until 2010, there were about 40 installed offshore wind parks constructed in Denmark, United Kingdom, Belgium. Currently, there are many large offshore wind farms under construction including: The London Array (1000 MW), BARD Offshore 1 (400 MW), Sheringham Shoal Offshore Wind Farm (317 MW), Lincs Wind Farm, (270 MW), Greater Gabbard wind farm (500 MW).

London Array offshore wind park

3. Life cycle cost analysis

3.1 Introduction

Life-cycle cost analysis is used to evaluate the total cost of an object (product, structure etc) required in order to keep it for its lifetime, in its initial condition. As in other scientific areas, life cycle cost analysis is a significant process which can be used as an assessment tool in the field of structural engineering. Having examined the structural response of a structure, the life cycle cost could be a tool for comparing in economic terms its impact on the structural system and its performance with other alternatives.

The life-cycle cost of a structure consists of the sum of the present value of all the costs, which may derive during its lifetime: construction and installation costs, maintenance and operations costs, management costs. Life-cycle cost analysis usually refers to the risk related to natural phenomena (e.g. wind, earthquake) and to the worsening of a structure's performance due to these phenomena. Finally, life-cycle cost analysis takes into consideration all the possible losses due to expected or unexpected events during the examined structure's lifetime and due to insufficient structural performance.

Incremental structural, dynamic analysis is considered to be an analysis process for obtaining satisfactory estimates of the structural performance and it is an appropriate method to be embedded into the life-cycle cost analysis procedure. Through this method, possible damage and structural losses are taken into account for a reliable estimation of life-cycle cost. In this project, pushover analysis was applied with respect to the maximum drift. The life-cycle cost is generally estimated taking into consideration the damage repair cost, the cost of loss of contents, the loss of rental cost, the income loss cost, the cost of injuries and the cost of human fatalities.

The basic principles of life-cycle cost analysis derive from economic theories, which have been implemented in many projects, such industrial and commercial projects, energy and water conservation projects, transportation projects etc. Even in construction projects, life-cycle cost analysis is applied effectively in order to being used as a structural performance criterion for the possible future damages. Moreover, this method is considered to be significant as a decision making tool for cost-effective investments in construction.

3.2 Literature survey

The life-cycle cost analysis (LCCA) principles are based on economic theories, and have been used as decision-support tools in industrial and commercial projects. LCCA is mainly implemented to energy and water conservation projects as well as transportation projects, including highways, bridges, and pavements. When it comes to building structures, the application of LCCA is considered particularly important in the case of retrofitted/deteriorating structures. Especially in the case of steel and reinforced concrete building structures in seismic regions, LCCA is applied as a structural performance criterion for taking into account future damages due to earthquakes. Furthermore, it is also used as a decision making tool for the most cost-effective solution related to the construction of building structures in seismic regions.

In early 1960s LCCA was applied in the commercial area in the design of products considering the total cost of developing, producing, using and retiring. The introduction of LCCA was made in the field of infrastructures as an absolute investment assessment tool. In particular, in early 1980s it was used in USA as an appraisal tool for the total cost of ownership over the lifespan of an asset (Arditi et al., 1996, Asiedu et al., 1998). Later, in view of large losses due to extreme hazards, like earthquakes and hurricanes, there was a need for new design procedures of facilities that could lead to life protection and reduction of damage and economical impact of such hazards to an acceptable level (Wen & Kang, 2001a). In this context LCCA was introduced in the field of constructions as a complex investment appraisal tool incorporating a structural performance criterion (Sanchez-Silva & Rackwitz, 2004).

A considerable amount of work has been done in estimating losses due to earthquakes. In particular in the work by Beck et al. (2003) a measure, to be incorporated into the seismic risk assessment framework for economic decision-making of buildings, was introduced, denoted as the probable frequent loss, which is defined as the mean loss resulting from shaking with 10% exceedance probability in 5 years. Liu et al. (2003) presented a two-objective optimization procedure for designing steel moment resisting frame buildings within a performance-based seismic design framework, where initial material and lifetime seismic damage costs are treated as two separate objectives. In the work by Sanchez-Silva and Rackwitz (2004) it is concluded that structures should be optimal with respect to economic investment, benefits derived from their use, expected consequences in case of failure and the degree of protection to human life. Lagaros et al. (2006) have adopted the limit state cost in order to compare descriptive and performance based design procedures. Frangopol and Liu (2007) reviewed the recent development of life-cycle maintenance and management planning for deteriorating civil infrastructure with emphasis on bridges. Kappos and Dimitrakopoulos (2008) implemented decision making tools, namely cost-benefit and life-cycle cost analyses, in order to examine the feasibility of strengthening reinforced concrete buildings. A probabilistic framework to estimate long-term earthquake-induced economical loss for wood frame structures was proposed and demonstrated in the work by Pei and Van De Lindt (2009).

Moreover the LCCA is used lately in the framework of a cost optimization problem. In general, it is introduced in the formulation of the problem optimization procedure as an objective function. Among others, in the work by Wen and Kang (2001a and 2001b) building design criteria are developed to protect life and to reduce damage and loss to an acceptable level for this purpose a minimization problem of the total life-cycle cost is considered. Sarma and Adeli (2002) addressed the life-cycle optimization of steel structures, solving a four criteria optimization problem. Their study is based on a detailed breakdown of all factors that influence the life-cycle cost of steel structures. Khajehpour and Griersson (2003) investigated the trade-off between life-cycle profitability and load-path safety for a high-rise office building. Takahashi et al. (2004) presented a decision methodology for the management of seismic risk of a building. The decision criterion aims at minimizing the expected life-cycle cost, including the initial cost of the design and the expected cost of damage due to future earthquakes. Liu et al. (2005) proposed a multiobjective structural optimization formulation where the present capital investment and the future seismic risk are treated simultaneously as separate objectives. In the work by Rackwitz et al. (2005) an appropriate objective function for cost-benefit analyses based on a renewal model is established while various renewal models for deteriorating structures including multiple failure modes are examined.

3.3 Calculation of the life-cycle cost

The total cost of a structure (C_{tot}) refers either to the total life period of a structure or to the residual life period of an existing structure. According to Wen & Kang (2001a), the total cost of a structure is a function of the design vector s and time:

$$C_{tot}(t, s) = C_{in}(s) + C_{lc}(t, s)$$

where

C_{in} initial cost of a new or existing structure

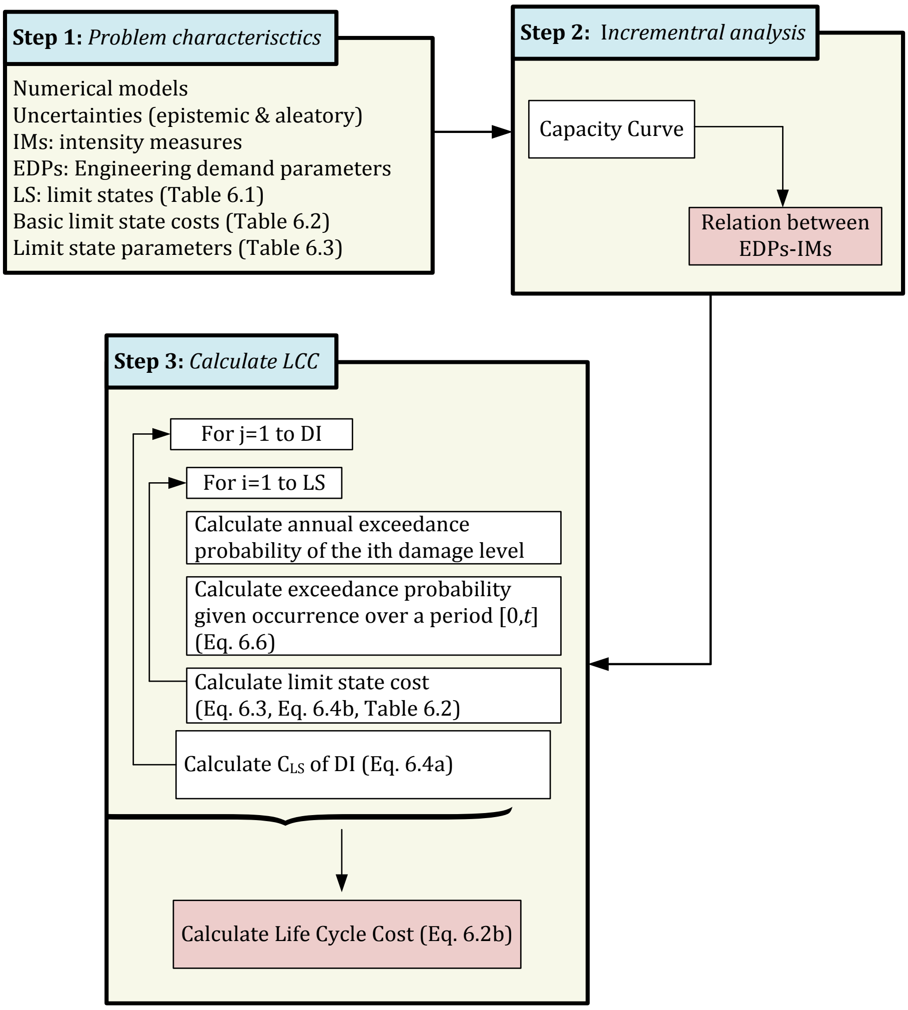
C_{lc} present value of the life-cycle cost

t time period

s design vector considering the design loads, the material, the structural system etc

The initial cost C_{in} refers to the total construction cost, which includes the cost for the materials (concrete, steel, reinforcement etc), the labour cost and the non-structural component cost. In addition, life-cycle cost C_{lc} refers to the potential, future costs from unexpected or expected phenomena (earthquakes, hurricanes, winds) that may occur during the design life period of a new or existing structure. It should be emphasized that the present value of the C_{lc} is estimated in order to be added to the initial cost, taking into account the compounding of money.

Firstly, in order to compute the C_{lc} of a structure, the limit states should be defined. These are structural damage states which correspond to particular damage indices, individually determined for each type of structure. In that way, it can be estimated the Clc through the quantification of the occurred damage from an external factor. Life-cycle cost analysis may refer both to structural and non-structural damage. The maximum inter-storey drift (θ) is considered to be the most satisfactory response factor, which describes the structural performance and possible structural damage, corresponding to the different limit states.



3.1 Flowchart of the life-cycle cost analysis

The estimation of the life-cycle cost C_{lc} includes the sum of the functions which correlate the costs according to particular damage indices with time, for all the damage indices used to quantify the stage of structural damage. Moreover, according to the damage index, each damage cost is a function of the sum of the defined limit state costs, as each damage index is quantified in n limit states.

$$C_{lc}(t,s) = \sum_{i=1}^{DI} C_{lc}^{i}(t,s)$$

$$C_{lc}^{DI}(t,s) = \sum_{i=1}^{n} f\left(C_{lc}^{i}, t, s\right)$$

The life-cycle cost Clc involves the cost of damage repair, the cost of loss of contents, the rental and income cost, the cost of injuries and the cost of human fatalities. The most challenging to determine is the two last costs: cost of injuries and the cost of human fatalities, for which many approaches and assumptions may be done. The estimation of the others lies in socio-economic criteria. The above cost components refer to the damage of the structural system. Generally, the limit state cost C_{lc} can be calculated from the following relationship for each damage state:

$$C_{lc}^{i} = C_{dam}^{i} + C_{con}^{i} + C_{ren}^{i} + C_{inc}^{i} + C_{inj}^{i} + C_{fat}^{i}$$

where

C_{dam}^{i} the damage repair cost

C_{con}^{i} the cost of loss of contents

C_{ren}^{i} the loss of rental cost

C_{inc}^{i} the income loss cost

C_{inj}^{i} the cost of injuries

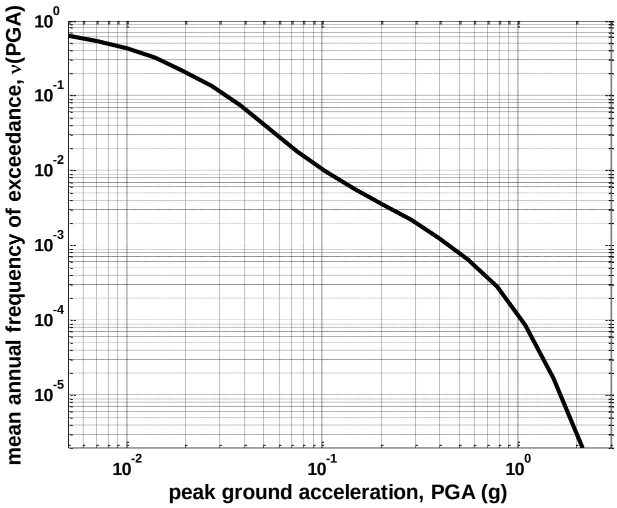
C_{fat}^{i} the cost of human fatalities

The implementation of the life-cycle cost analysis and the estimation of life-cycle cost require the evaluation of the structural performance in at least three hazard levels, which are determined according to the examined load case (earthquake, wind etc) and the examined structure. So, at least three pairs of annual probability of exceedance $\overline{P}_i$ and maximum value of the damage index are taken into consideration. The pairs $(\overline{P}_i - DI_i)$ are obtained from nonlinear static structural analysis or dynamic structural analysis and correspond to definite values of exceedance probabilities, which derive from the hazard curve of the examined phenomenon.

3.4 An implementation of the life cycle cost analysis framework

In this part, the already described procedure of life-cycle cost analysis is applied on a structure, analyzed with nonlinear static analysis. The limit state cost calculation procedure requires the assessment of the structural capacity in at least three hazard levels of increased intensity with the definition of at least three pairs of annual probability of exceedance $\overline{P}_i$ and maximum value of the damage index in questionDI_i. In this work the abscissa values of the $(\overline{P}_i - DI_i)$ pairs, corresponding to the maximum values of the damage index, are obtained either by means of nonlinear static or dynamic analysis procedure, while the ordinate values correspond to the annual probabilities of exceedance.

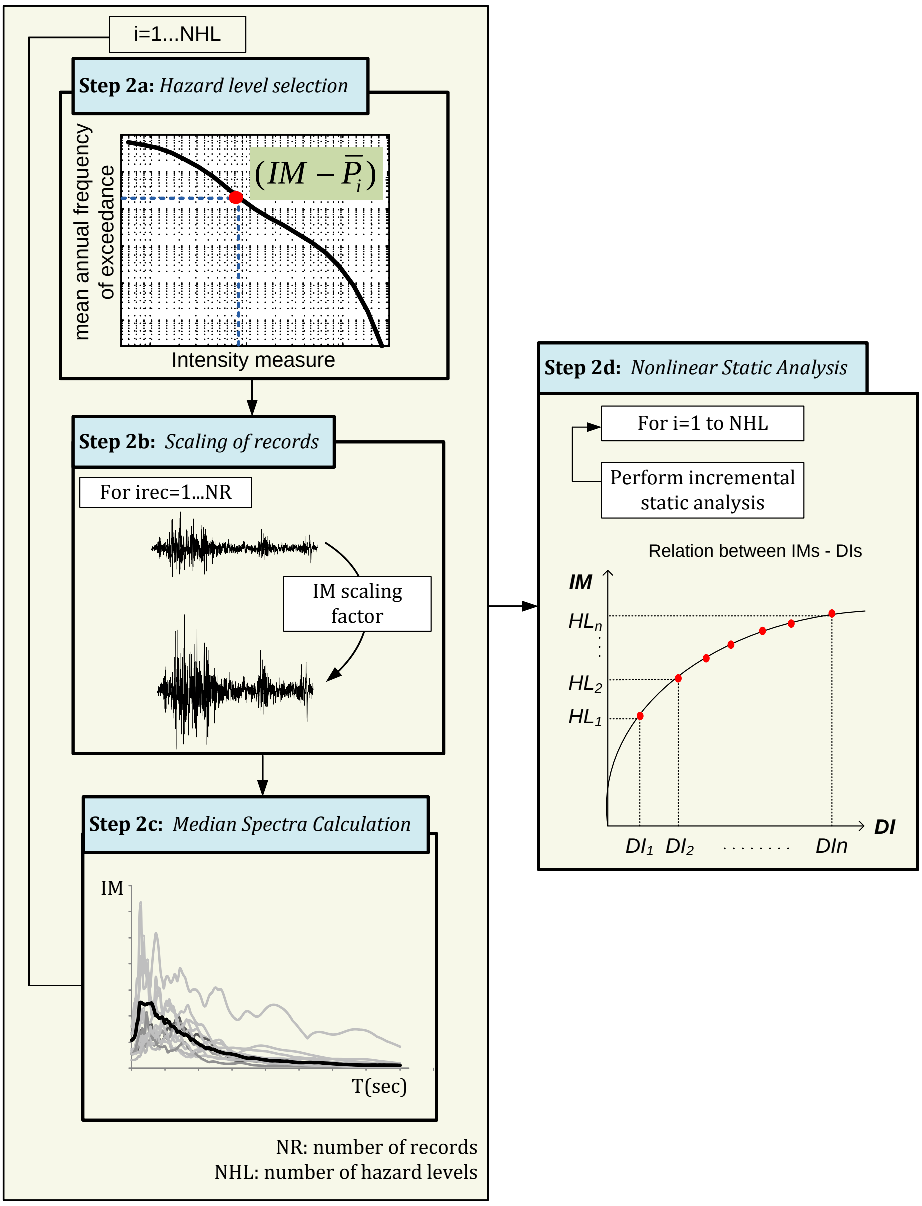
These probabilities correspond to discrete values of annual probabilities of exceedance obtained from a hazard curve, which describes the seismic risk of a region. An example of a hazard curve in the city of San Diego, California (Latitude (N) 32.7o, Longitude (W) -117.2o) is presented in the diagram below, which was obtained from the US Geological Survey. From this curve three or more pairs of the intensity measure and the corresponding annual probability of exceedance ($IM - \overline{P}_i$) can be derived, where the IM (intensity measure) will be applied to the structure in order to give the corresponding damage indices. In the case of nonlinear static analysis procedure the damage index considered is the maximum interstorey drift.



3.2 Hazard curve of the city of San Diego, California (Latitude (N) 32.7°, Longitude (W) -117.2°).

The implementation of results of a structural analysis in the life-cycle cost analysis procedure depends on the type of the analysis implemented (incremental nonlinear static or incremental nonlinear dynamic). Significant role in that step of the life-cycle cost analysis framework plays the selection procedure of the seismic actions.

Nonlinear static analysis is based on the assumption that the response of the structure is described by an equivalent single degree of freedom system with properties proportional to the first mode of the structure. For the implementation of nonlinear static analysis, a lateral load distribution that follows the fundamental mode is adopted. The analysis is terminated when 150% of the target displacement that correspond to the 2% in 50 years (2/50) hazard level is reached, or earlier if the structure has collapsed (FEMA-356, 2006).



3.3 Implementation of nonlinear static analysis procedure in LCCA framework

According to the capacity spectrum method, the capacity of a structural system to resist lateral forces is compared to the demand of an earthquake response spectrum and nonlinear static analysis procedure results with the calculation of the maximum interstorey drift (θ_i). In order to calculate the maximum interstorey drift in multiple hazard levels the corresponding earthquake response spectra are used. These spectra are the median ones of the selected seismic records when scaled to the corresponding hazard level based on the intensity measure used. Step 2 of the life-cycle cost analysis framework, as it is shown in figure 3.1, is presented in figure 3.3 corresponding to the case of nonlinear static analysis. Nonlinear static analysis is limited with regard to evaluation of the simultaneous response to ground shaking in different directions. To overcome this deficiency, the recommendation of FEMA-350 (2000) is employed where multidirectional excitation effects are accounted for by combining 100% of the response due to loading in the longitudinal direction with 30% of the response due to loading in the transverse direction, and vice versa. The worst of these two combinations in each hazard level is used in order to assess the structural performance in the corresponding performance levels.

3.5 Life-cycle cost model of wind parks

In order to estimate the life-cycle cost of a wind park in this master thesis, almost the same process is followed as described above. The total cost of a wind park is considered to be the sum of the total cost of each wind turbine that is located in the wind park. The total cost of the ith wind turbine is the sum of all the initial costs for construction (material, labor cost etc) and the present value of life-cycle cost according to the following relationship:

$$C_{tot}^{i}(t,s) = C_{in}^{i}(s) + C_{lc}^{i}(t,s)$$

$$C_{tot}^{wind\ park}(t,s) = \sum_{i=1}^{N} C_{tot}^{i}(t,s)$$

where

N the total number of the wind turbines

It was assumed that the most significant response factor, which describes efficiently the structural performance of a wind turbine, is the maximum drift (θ). It has been determined which drift ratio limit best corresponds to each limit state. Their relation, which was assumed in this master thesis, can be seen in the following matrix:

Limit State	Damage State	Wind Turbine Drift (%)
(I) - None	None	θ≤0.30
(II) - Slight	Slight	0.30< θ ≤0.36
(III) - Light	Light	0.36< θ ≤0.56
(IV) - Moderate	Moderate	0.56< θ ≤1.20
(V) - Heavy	Heavy	1.20< θ ≤3.00
(VI) - Major	Major	3.00< θ ≤8.0
(VII) - Collapsed	Destroyed	θ >8.0

3.4 Damage state drift ratio limits for a wind park

During the estimation of the life-cycle cost of each wind turbine, only the damage repair cost was taken into account. The effect of the cost of loss of contents, the rental and income cost, the cost of injuries and the cost of human fatalities were disregarded. The reason for this assumption was that wind turbines rarely work to produce electricity in strong winds, when the wind velocity is extremely high, limiting in that way the possibility of human injuries and fatalities. In addition, the area where a wind park is constructed and operates is non- residential. So, the equations of the life-cycle cost and the total cost of each wind turbine are:

$$C_{lc}^{i} = C_{dam}^{i}(t, s)$$

$$C_{tot}^{i}(t, s) = C_{in}^{i}(s) + C_{dam}^{i}(t, s)$$

The initial cost of a wind turbine is determined according to the type of the wind generator, its construction location etc and it is assumed to be constant in this master thesis.

For the evaluation of the life-cycle cost of a wind park, three hazard levels should be considered: the usual case, when the wind velocity's mean value is the most frequent, the rare case, when the wind velocity is quite high and the extreme case, when the wind speed exceeds far beyond the expected limits. For each of these three hazard levels, the annual exceedance probability should be estimated, in order to specify the three pairs $(\overline{P}_i - DI_i)$.

The annual probabilities of exceedance are calculated efficiently, if the available statistical data are adequate. Accurate measurements should be taken for the wind velocity, its direction and frequency for some years. Especially for the estimation of the annual possibilities of exceedance for wind parks the Weibull distribution can be used, which describes the distribution of some natural phenomena quite well.

$$f(x, \lambda, k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}} & , x > 0 \\ 0 & , x < 0 \end{cases}$$

4. Application

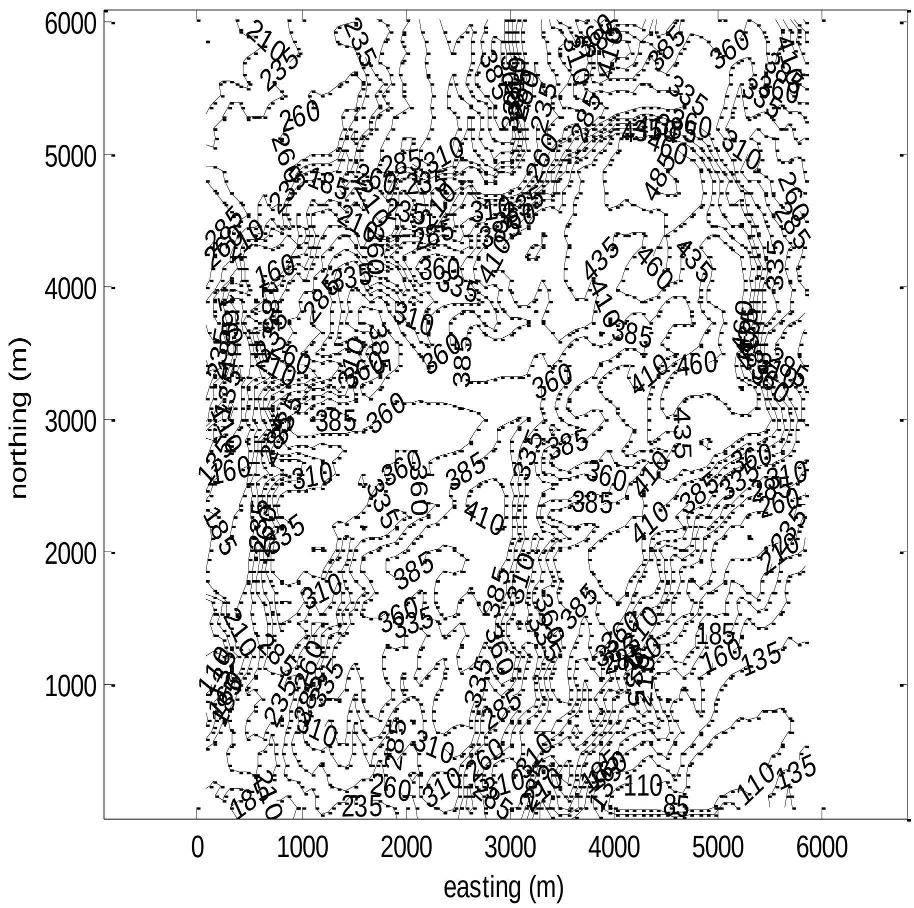
4.1 General description of the examined wind park

In order to estimate the total life-cycle cost of a wind park, it was chosen an onshore wind park in Paphos, Cyprus to be examined. It is located close to the town's airport, which was an auxiliary factor for gathering statistical data about the wind velocity, frequency and wind direction. The examined wind farm was installed in July 2010 and occupies an area of 16 square kilometers. It consists of 41 Vestas wind turbines with nominal power equal to 2 MW.

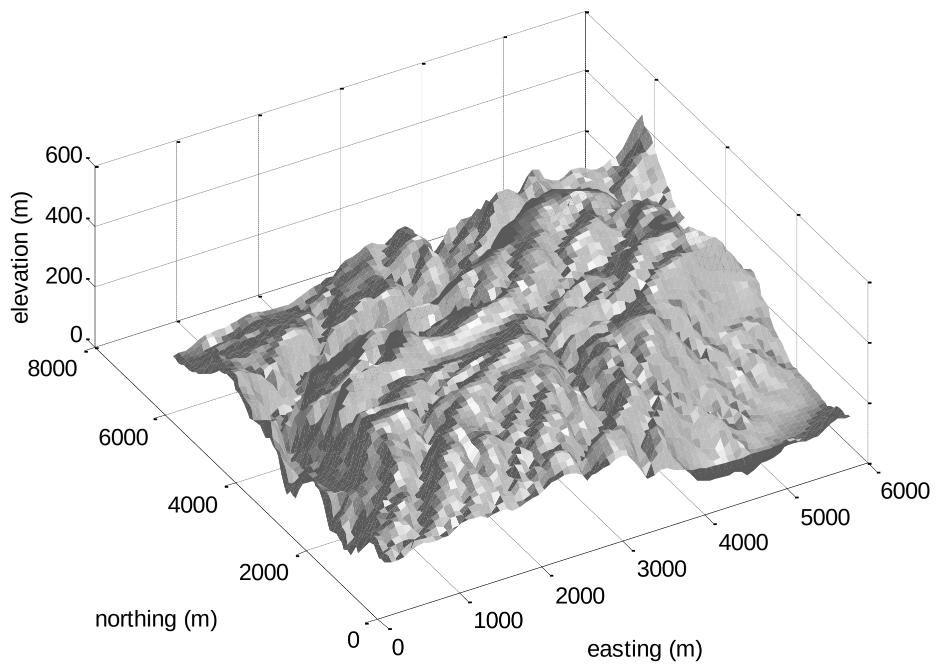
The coordinates of the construction location and the positions of the wind turbines are known. So, it was easy to examine the influence of topology and the terrain of the region on the wind velocity, wind load and as a result on the life-cycle cost of it. The analysis was performed with Matlab and the whole area was divided into 289 equal squares, as this was the maximum possible analysis of the wind speed stochastic fields. In each square the wind velocity is considered to be constant and equal to the wind speed developed at the centre of each square.

4.1 The wind park region in Paphos, Cyprus

4.2 The examined onshore wind park



4.3 The contour lines of the wind park



4.4 The terrain of the examined wind park produced by Matlab

4.2 Description and structural analysis of wind turbines

During this master thesis two types of wind turbines were examined with different technical and economical features. The first type of wind generator is has tower height equal to 80 m and rotor diameter equal to 90 m. As regards the tower of the construction, it is conical tubular with gradually decreasing diameter in relation to the height. The bottom diameter is considered to be 4.3 m and the top diameter equal to 2.95 m when H=80 m and equal to 2.60 m when H=100 m, and the thickness of the hollow circular cross section is equal to 0.07 m. The design material is steel S500.

The examined wind turbine has a rotor diameter is of 90 m with swept area of 6362 m^2. It has three rotor blades, each of which has length equal to 44 m. The blades are made of fibre glass reinforced epoxy and carbon fibres. Each blade consists of an inner beam encircled by two shells. The blades are designed for optimized output and minimized noise and light reflection.

The second type of wind turbine, which was examined, has the same technical aspects as above, except from the tower height, which is equal to 100 m. This assumption is made, in order to investigate how the tower height affects the structural performance of the wind generator, weather the higher wind speed can be better exploitable and how it influences the life-cycle cost of the wind park.

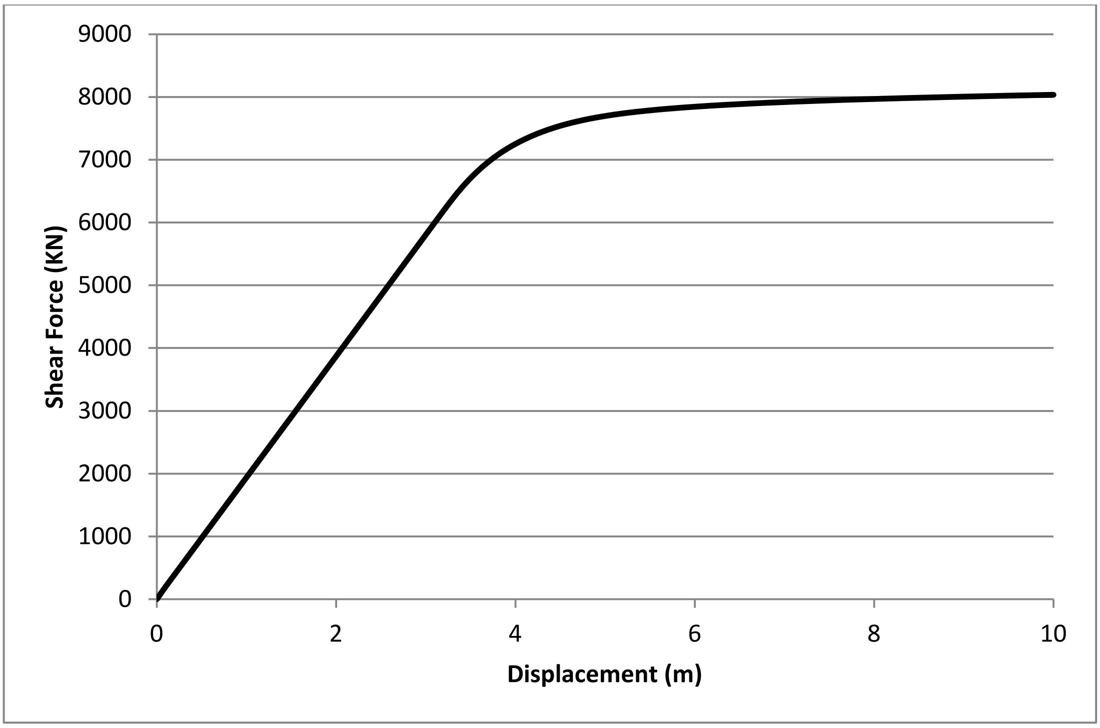
The structural analysis of the described wind turbine was carried out with the software 'Seismostruct'. For the structural analysis of the tower linear elements with hollow circular section were used, whose diameter reduces as the height increases. In order to achieve detailed and reliable results, the tower was divided into parts of 5 m height. Each part has a different diameter depending on the total height from the ground (z=0). Specifically, the diameter of each part is determined by the following relationship:

$$\mathrm{D} = 4.3 - 0.008\mathrm{z}, \text{where } \mathrm{z} = 0{,}5{,}10, \dots{,}80, \dots{,}100 \text{ m}$$

In the structural analysis, two types of loads are implemented: the static loads of the rotor's self weight and the wind load. It was assumed that the self weight of the rotor is about 800 KN and it is placed about 1 m from the tower. So, it was analyzed in a vertical load at the top of the tower equal to 800 KN and in a moment about 800 KNm. The wind load was simulated with a constant, horizontal load at the top of the pillar. The base of the wind turbine is considered to be embedded.

A pushover analysis is performed for the wind turbine's structural analysis, which purpose is to examine the loaded structure's behavior in relation with the implemented displacement. During this process, the structural model is being pushed using a predetermined, fixed side load, which is implemented incrementally. The pushover method provides information about the yielding point of a section and identifies the areas in which the inelastic deformation is expected to be large. The pushover analysis is based on the assumption that the response of a structure is associated with the response of an equivalent single-degree-of-freedom system with properties, which correspond to the first mode of the construction. The step of pushover analysis is determined, when the structure meets the initial step of the static analysis.

The pushover analysis resulted in the capacity curves for the two types of wind turbines, which are indicated in the graphs below. As it was expected, the maximum load that the wind turbine can resist in higher in the case, where the tower height is equal to 80 m.



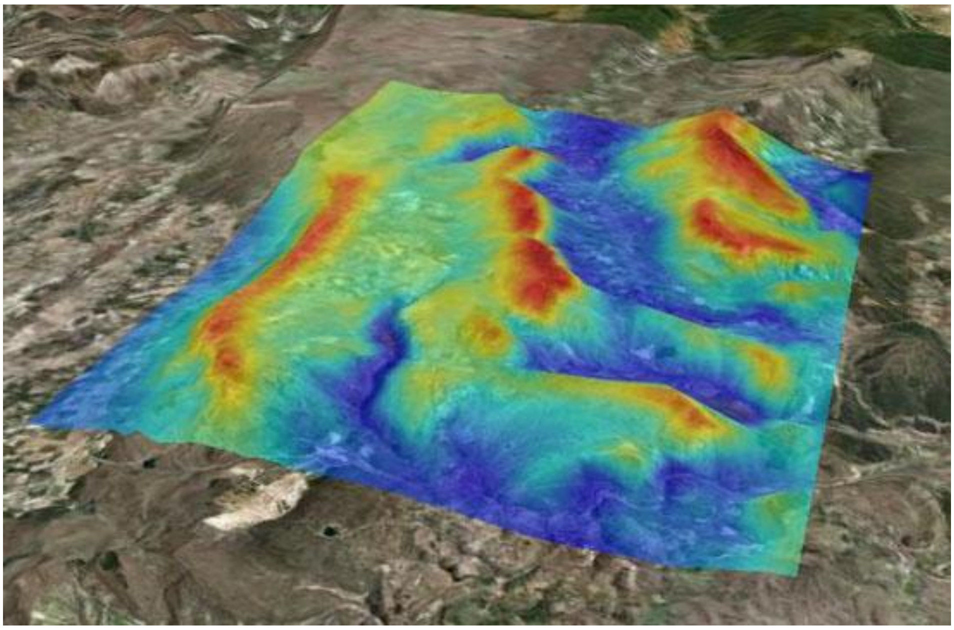
4.5 Capacity curve for tower height H=80 m

4.6 Capacity curve for tower height H=100 m

4.3 Stochastic fields of wind velocity

As it was mentioned in the third chapter, the wind park was examined for three hazard levels: the usual case, the rare case and the extreme case. For each of them, the distribution of the wind speed is taken into account in order to estimate its affect on the structural performance of each wind turbine. The first hazard level is determined by the statistical data that were available and provided by the airport's weather station. For the second hazard level, it was assumed that the mean value of wind velocity is equal to 25 m/s, which is something very rare for this specific region. For the last hazard level, the average wind speed developed in the wind park is considered to be equal to 36 m/s, which is extremely infrequent.

In order to take into account the random distribution of wind speed for the above three hazard levels, which could appear at the construction area of the wind park, fourteen different stochastic fields were produced in Matlab. Twelve of them refer to the usual case for the wind velocity for twelve possible directions per 30o, as the next two refer to the other hazard levels (25 m/s and 36 m/s) respectively. The stochastic fields have exactly the same dimensions as the plan view of the region, where the wind farm is located, and they were 'placed' directly on this. In that way, each possible position of any wind turbine corresponds to a value of the wind speed for each stochastic field.



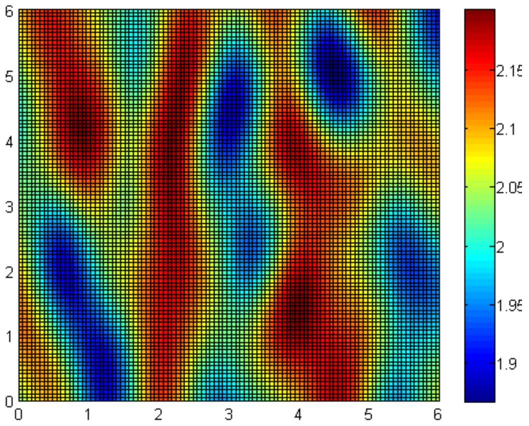
4.7 Adaptation of the stochastic field on the terrain

During the production of the stochastic fields, the topography of the examined area was taken into account. They were produced according to the normal (or Gaussian) distribution:

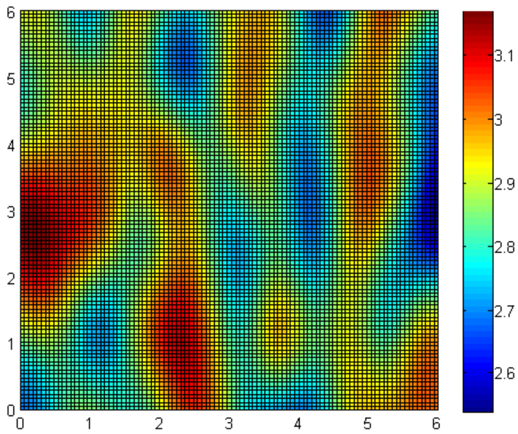
$$f(x, \mu, \sigma 2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\chi=\mu}{\sigma}\right)^2}$$

μ the mean or expectation value

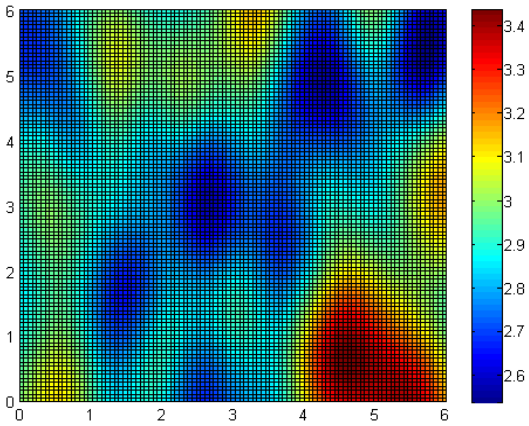
σ the standard deviation



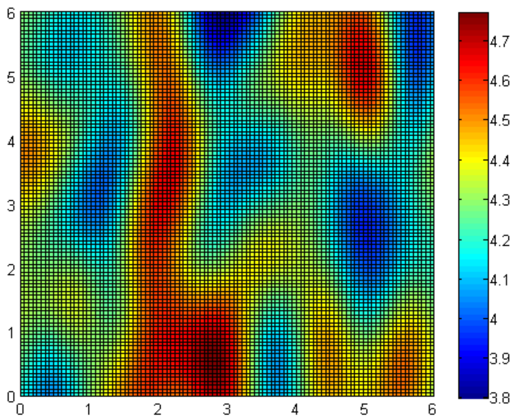
4.8 Stochastic field for wind direction 0°



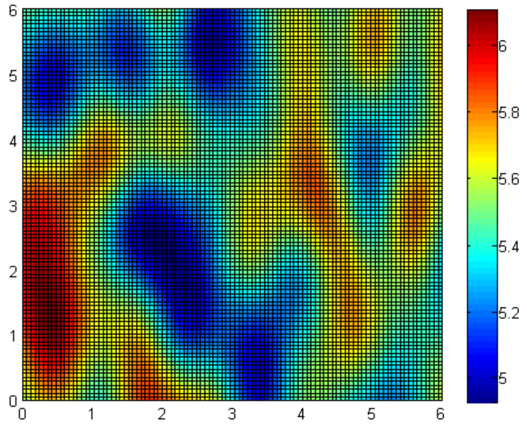
4.9 Stochastic field for wind direction 30°



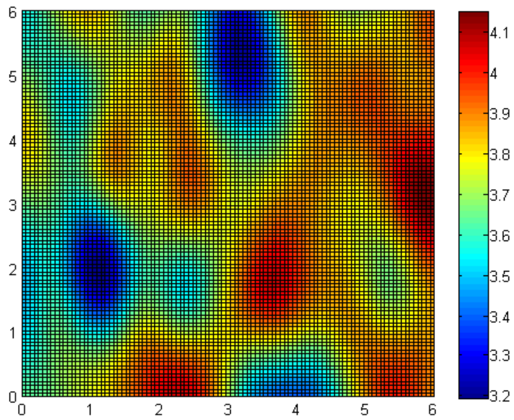
4.10 Stochastic field for wind direction 60°



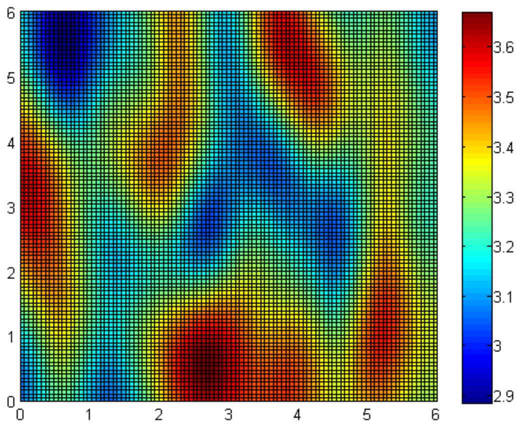
4.11 Stochastic field for wind direction 90°



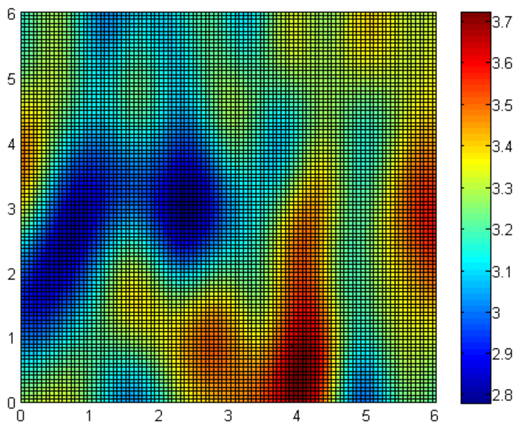
4.12 Stochastic field for wind direction 120°



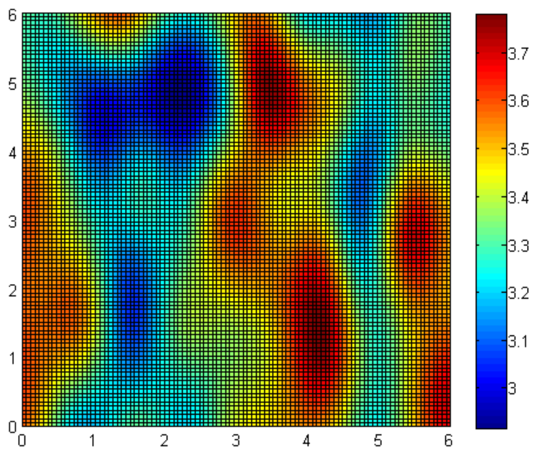
4.13 Stochastic field for wind direction 150°



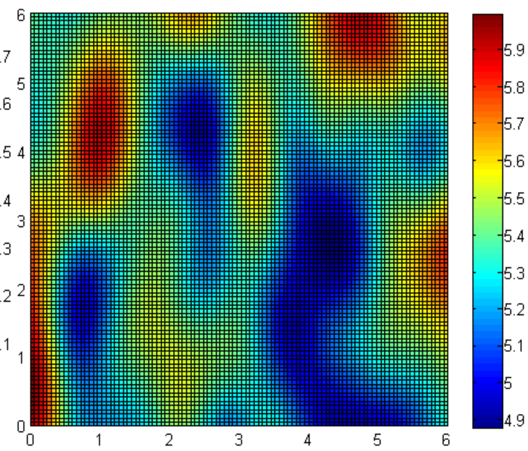
4.14 Stochastic field for wind direction 180°



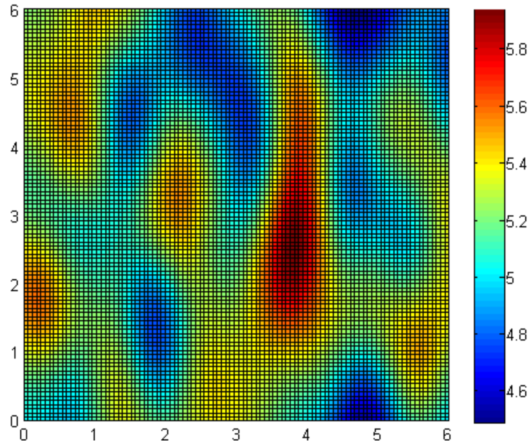
4.15 Stochastic field for wind direction 210°



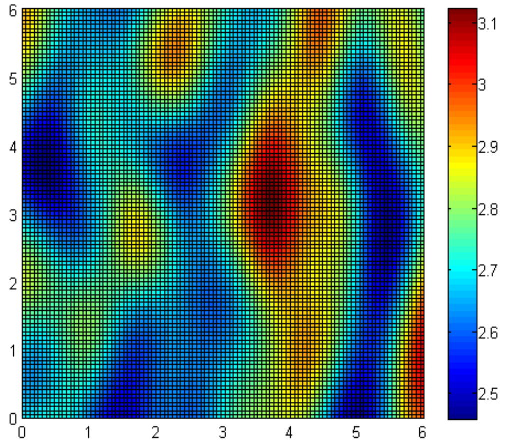
4.16 Stochastic field for wind direction 240°



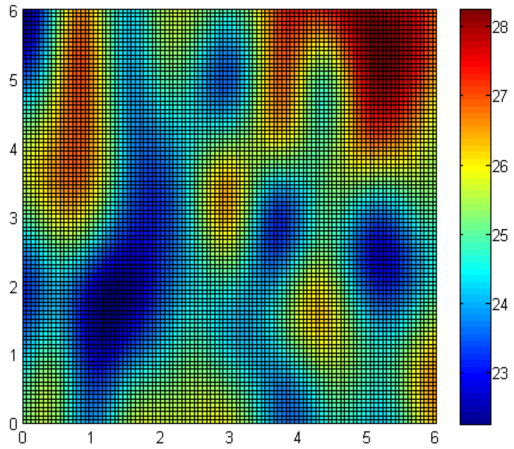
4.17 Stochastic field for wind direction 270°



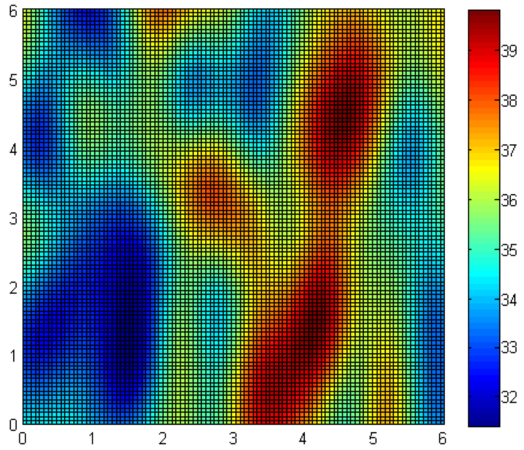
4.18 Stochastic field for wind direction 300°



4.19 Stochastic field for wind direction 330°



4.20 Stochastic field for average wind speed 25 m/s



4.21 Stochastic field for average wind speed 36 m/s

4.4 Estimation of wind velocity

The calculation of the wind speed at the top of each wind turbine is a determining factor in order to calculate the wind load. Usually, the wind speed is measured at a reference height about 10 m from the ground surface. Below, the wind velocity at the desirable height is calculated through the following formula:

$$\bar{U}(h) = \bar{U}_g \cdot \frac{\ln\frac{h}{z_o}}{\ln\frac{h_{ref}}{z_o}}$$

where

$\bar{U}(h)$ wind speed at height h (m/s)

$\bar{U}_g$ the average wind speed at the reference height href (m/s)

h_{ref} the reference height, usually equal to 10 m

z_o the roughness length (m)

For this particular wind park, which is examined, it is assumed that the construction region is a countryside area, without tall buildings and dense vegetation. So, the roughness length zo is considered to be equal to 0.01. Generally, the roughness length takes values according to the follow matrix.

Terrain category	z_o (m)	z_{min}(m)
0 Sea or costal area exposed to the open sea	0,003	1
I Lakes or flat and horizontal area with negligible vegetation and without obstacles	0,01	1
II Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0,05	2
III Area with regular cover of vegetation or buildings or with isolates obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0,3	5
IV Area in which at least 15% of the surface is covered with buildings and their average height exceeds 15 m	1,0	10

4.22 Roughness length according to the terrain category

The above stochastic fields are also produced at a reference height of 10 m (h_{ref}) and they indicate so the average wind velocity at this height for twelve different directions per 30^o. According to the wind turbine height and the above formulae, the wind velocity at the top of each wind turbine is calculated.

4.5 Density of atmospheric air

The density of the atmospheric air affects the wind load which develops at the top of each wind turbine. It is a function of the atmospheric pressure and the temperature and decreases with increasing height.

The density of the air at the sea surface, when the temperature is about 20oC and the atmospheric pressure 101.6 KPa, is:

$$d_o = 1{,}225\ \mathrm{kg/m^3}$$

The change in pressure with respect to height is expressed by the following relationship:

$$p = 101325 \cdot (1 - 2.2557 \cdot 10^{-5} \cdot h)^{5.25588}$$

where

p the air pressure (Pa)

h the height from the sea surface (m)

$$d = d_o \cdot \frac{288{,}15}{T} \cdot \frac{p}{101325}$$

Where

d_o the density of atmospheric air at the sea surface (kgr/m^3)

p the air pressure (Pa)

T the temperature (K=273+Co)

4.6 Wind Load

At the top of each wind generator develops different wind velocity, which depends on the altitude, on the pillar height and the value of wind potential in this specific region. Having assumed the wind speed at the height of the wind turbine's rotor, the operating load of wind is specified for the three examined wind hazard levels according to the following formula:

$$F_w = \frac{1}{2} \cdot C_d \cdot d \cdot A \cdot \bar{U}^2(h)$$

F_w wind load at the height of the wind turbine (N)

C_d drag coefficient ($C_d = 0.9$)

d air density at the wind turbine's height ($kgr\ /m^3$)

A swept area (m2)

$\overline{U}(h)$ wind velocity at the top of wind turbine (m/s)

4.7 Displacements of wind turbines

In this project, three different wind hazard levels were investigated: the usual wind velocity according to the statistical measurements for one year, the rare wind velocity of 25 m/s and the extreme wind velocity of 36 m/s as mentioned above.

Having known the wind load at the top of each wind generator for every direction and wind speed, through the capacity curve it is easy to calculate the displacement, which corresponds to this particular wind load for each direction and each of the above three cases. Concerning the usual wind velocity, which is calculated for twelve directions per 30^o, the corresponding displacement is considered to be the median value for the twelve displacements derived from the capacity curve for each direction. The same process was implemented for both the rare (25 m/s) and the extreme case (36 m/s) for each wind turbine. However, in the cases which the developed wind loads were larger than the maximum resistance loads indicated by the capacity curves, it was assumed that the value of the displacement was large and equal to 10 m.

For example, the wind load one of the wind turbines is F_{wind}=240 KN for wind direction 120^o. Through the capacity curve and linear interpolation, we indentify the developed displacement of 0.12 m.

4.8 Probabilities of exceedance

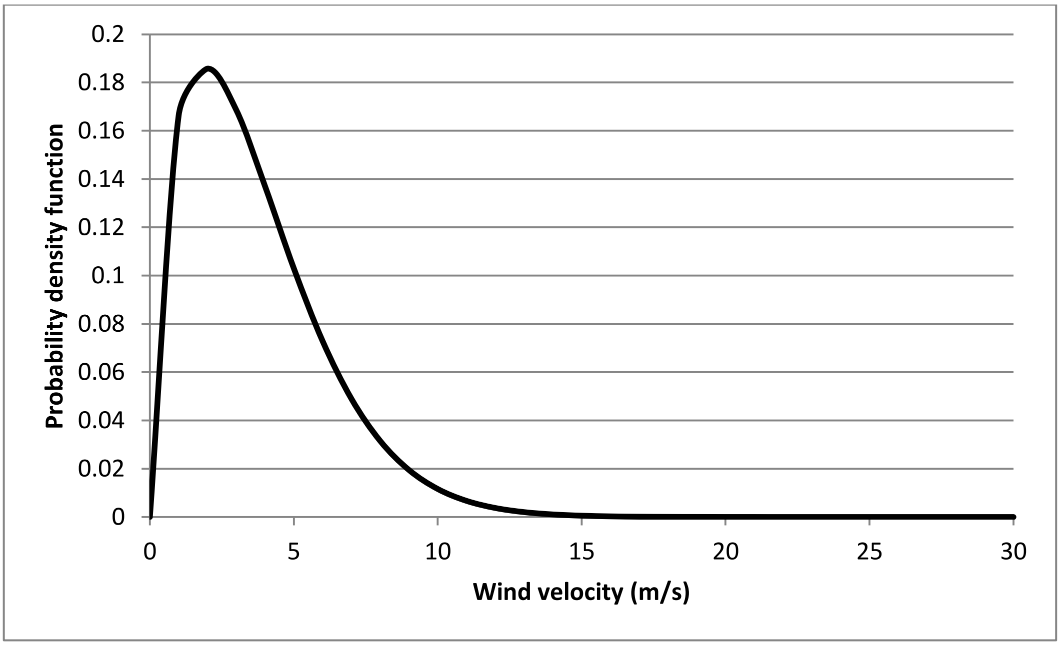
In this part, the annual exceedance probabilities of the three limit states are calculated. The annual exceedance probability for the usual case is obtained using the Weibull distribution.

Weibull distribution is a continuous probability distribution. The probability density function of a Weibull random variable x is:

$$f(x, \lambda, k) = \begin{Bmatrix} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k} & , x > 0 \\ 0 & , x < 0 \end{Bmatrix}$$

The parameters k and λ are positive and are the shape parameter and the scale parameter respectively. It was assumed that the scale parameter k is equal to 2, so that the Weibull distribution approximates the Rayleigh distribution. The scale parameter determines the mean value of the wind speed. The Weibull distribution is applied in several cases, such as in reliability engineering and failure analysis, in industrial engineering and

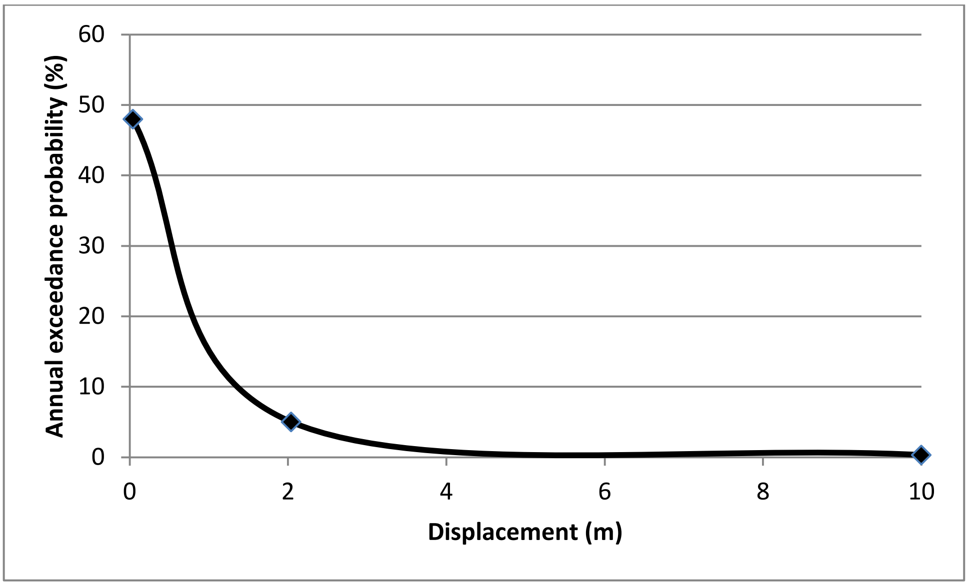
The following chart indicates how the distribution of the probability density function changes according to the wind velocity. The curve has been calculated for the limited statistical data that were available.



4.23 Weibull distribution for the wind velocity

Considering the rare and extreme wind potential, the annual exceedance probabilities could be also calculated through the Weibull distribution function. However, the obtained statistical data refer to a period of only one year. It is assumed that this approximation would not lead to reliable results. So, these probabilities were calculated assuming recurrence interval periods about 2500 years and 6000 years respectively. As a result, the annual probability of exceedance for the rare case with a wind speed potential of 25 m/s is about 0.04 % and the annual probability of exceedance for the extreme case with a wind speed potential of 36 m/s is 0.0167 %.

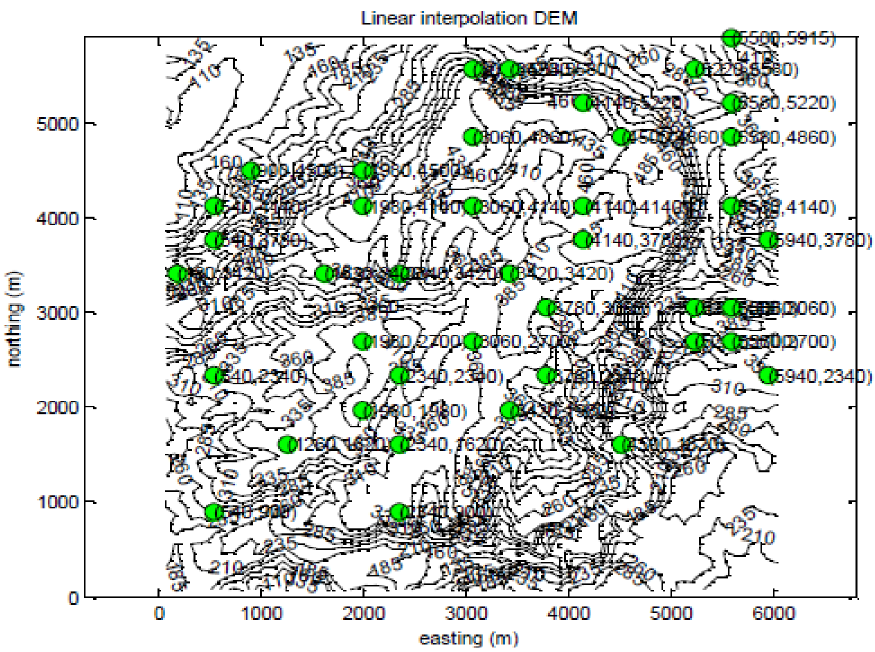
Taking into account the three limit states (usual, rare, extreme), the corresponding displacements have been calculated, as well as the respective annual exceedance probabilities for every wind turbine. For each of them, these three pairs of annual probabilities of exceedance and maximum drift build the (P-d) fitted curves, at it is indicated approximately below for the first wind turbine.



4.24 $(\overline{P}_i - \theta_{max,i})$ pairs and fitted curve

4.9 First test case

In this part, it is described the first test case which was examined. It is assumed that the wind park consists of 41 wind turbines of the same type, those with tower height H=80 m. The positions of the wind turbines in the wind park are shown below.



4.25 Positions of the wind turbines in the wind park

Having given the technical features of the wind turbines and the stochastic fields of the wind velocity for each wind hazard level, the wind speed is estimated which corresponds to the relevant stochastic field at measurement height equal to h_{ref}=10 m. Subsequently, these values are discounted to the wind velocity at the rotor height of each turbine according to their installation altitude through the following relationship:

$$\overline{U}(h) = \overline{U}_g \cdot \frac{\ln\frac{h}{z_o}}{\ln\frac{h_{ref}}{z_o}}$$

where

$\overline{U}(h)$ wind speed at height h for each wind turbine (m/s)

$\overline{U}_g$ the average wind speed estimated from the corresponding stochastic field (m/s)

h_{ref} = 10 m

z_o = 0.01 m

Having calculated the wind speed at the top of each wind turbine for each wind hazard level, the air pressure and air density are impaired according to:

$$p = 101325 \cdot (1 - 2.2557 \cdot 10^{-5} \cdot h)^{5.25588}$$

$$d = d_o \cdot \frac{288{,}15}{T} \cdot \frac{p}{101325}$$

where

h the altitude of each wind turbine (m)

d_o = 1.225 kg/m3

T = 293 K (20o C+273=293 K)

The wind load at the top of all wind turbines for each case is calculated through the next formulae:

$$F_w = \frac{1}{2} \cdot C_d \cdot d \cdot A \cdot \overline{U}^2(h)$$

where

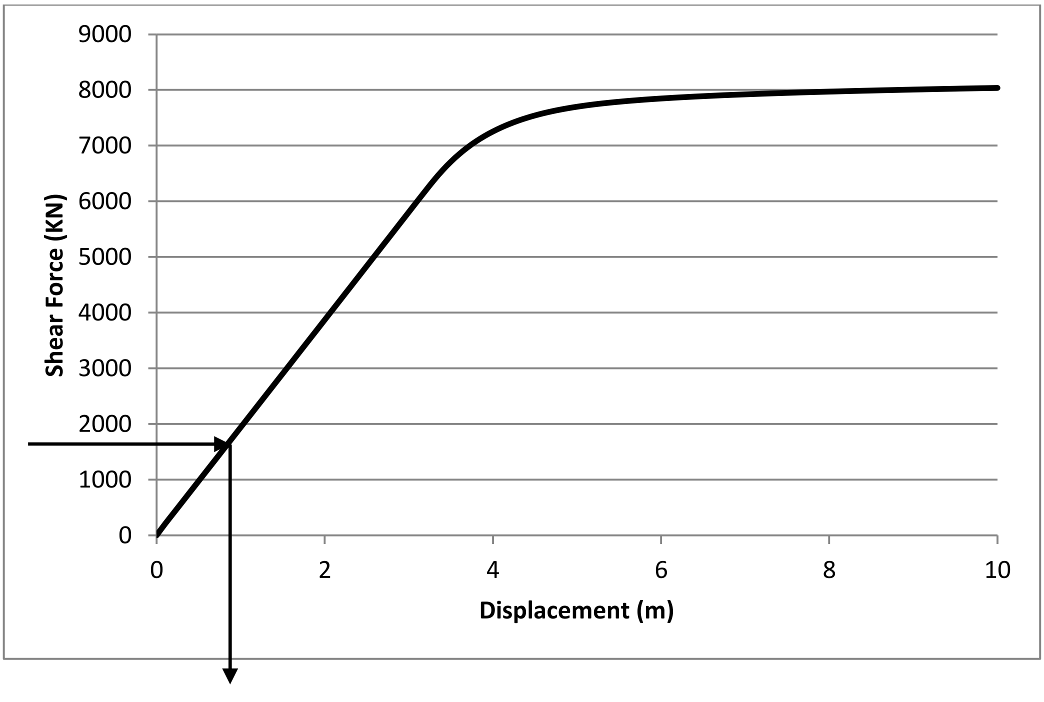
C_d = 0.9

d air density calculated as described

A = 6362 m2

$\overline{U}(h)$ wind velocity at the top of each wind turbine

Furthermore, the displacements which correspond to each wind load calculated by the above relationship are estimated through performing linear interpolation in the capacity curve of the first type of wind turbines, which are examined in this part.



4.26 Linear interpolation in the capacity curve (H=80 m)

For the first wind hazard level, while twelve different values for the wind load are calculated, each one for each wind direction per 30^o, the displacement taken into account is the median value of these. For the other two hazard levels, the displacements are estimated as described. However, it is considered more accurate to compare not just the displacement, but the drift of a construction. That is why, the developed displacements are divided by the tower height in order to calculate drift θ.

$$\theta = \frac{\text{displacement (m)}}{\text{H (m)}}$$

The next step of the life-cycle cost analysis procedure is the determination for each of wind hazard levels, the annual exceedance probability, in order to specify the three pairs $(\overline{P}_i - DI_i)$. For the first wind hazard level, the annual probability of exceedance is calculated through the Weibull distribution:

$$f(x, \lambda, k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}}, x > 0$$

Where

k = 2, the shape parameter

λ = 4.5, the scale parameter specified by the statistical data for wind speed

For the other wind hazard levels the annual exceedance probabilities have not been estimated by the Weibull distribution due to the lack of efficient statistical information. It is assumed that they have recurrence interval periods about 2500 years and 6000 years respectively. As a result, the annual exceedance probability for wind velocity equal to 25 m/s is 0.04 % and for wind velocity equal to 36 m/s, 0.0167 %. For each hazard level, for every wind turbine of the examined wind park the three pairs of annual exceedance probabilities and damage indices are formed.

So as to calculate the life-cycle cost of the each wind turbine, the initial installation cost of this type of wind turbines should be defined. It is assumed equal to 1,800,000 Euros. For each wind generator, the life-cycle cost is considered to be a function only of the damage repair cost, ignoring the cost of loss of contents, the rental and income cost, the cost of injuries and the cost of human fatalities.

$$C_{lc}^{i} = C_{dam}^{i}(t, s)$$

The damage repair cost is estimated assuming that it is a percentage of the initial installation cost of each wind turbine according to corresponding limit state of the damage index. The next matrix indicates this relationship between the drift of the wind turbine and the percentage of the initial cost. The total life-cycle cost of the wind park is the sum of the life-cycle costs of all wind turbines.

$$C_{lc}^{wind\ park}(t,s) = \sum_{i=1}^{N} C_{lc}^{i}(t,s)$$

where

N the total number of the wind turbines

Limit State	Wind Turbine Drift (%)	Percentage of the initial cost (%)
(I) - None	θ≤0.30	0
(II) - Slight	0.30< θ ≤0.36	0.5
(III) - Light	0.36< θ ≤0.56	5.0
(IV) - Moderate	0.56< θ ≤1.20	20
(V) - Heavy	1.20< θ ≤3.00	45
(VI) - Major	3.00< θ ≤8.0	80
(VII) - Collapsed	θ >8.0	100

4.27 Damage index and damage repair cost according to the limit state

Consequently, the life cycle of the wind turbine resulted equal to

$$C_{lc}^{wind\ park}(t,s) = 4{,}363{,}300 \text{ Euros}$$

The initial cost of the wind park is the sum of the initial installation costs of the wind turbines:

$$C_{initial}^{wind\ park}(s) = \sum_{i=1}^{N} C_{initial}^{i}(s) = N \cdot C_{initial}^{i}(s) = 41 \cdot 1{,}800{,}00 = 73{,}800{,}000 \text{ Euros}$$

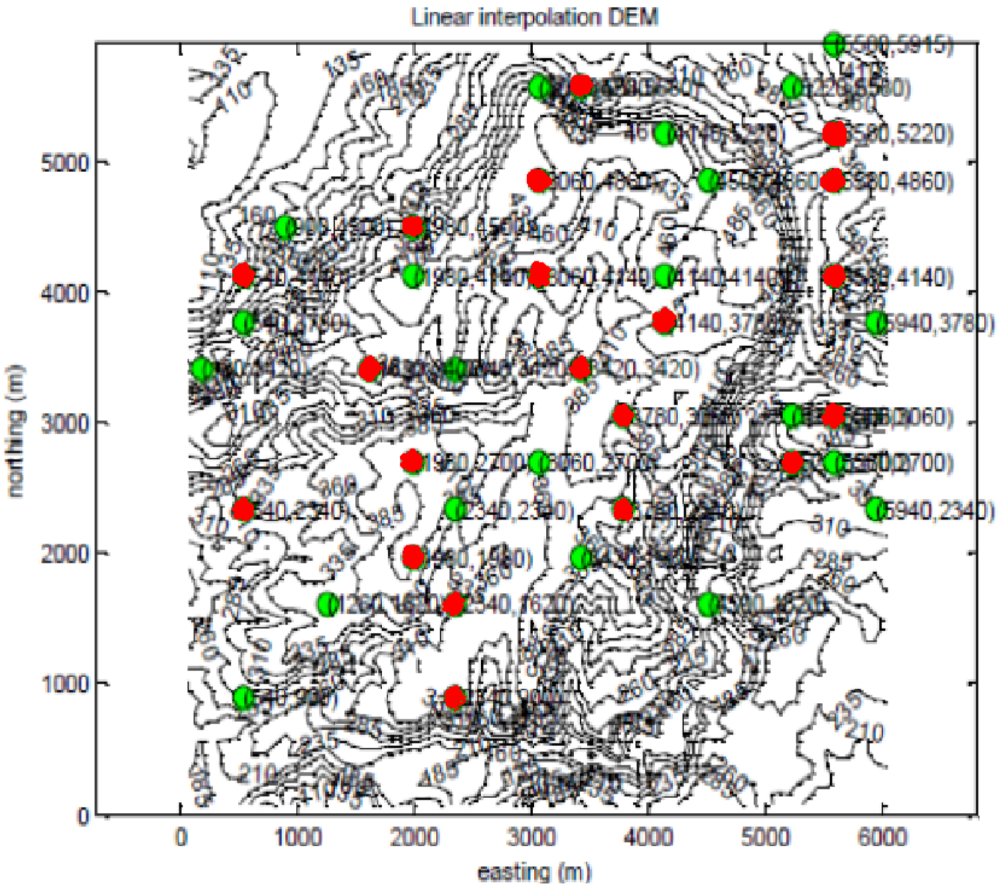
Finally the total cost of the wind park is the sum of the initial cost and the life-cycle cost:

$$C_{total}^{wind\ park}(s,t) = C_{initial}^{wind\ park}(s) + C_{lc}^{wind\ park}(t,s)$$

$$C_{total}^{wind\ park}(s,t) = 73{,}800{,}000 + 4{,}363{,}300 = 78{,}163{,}300 \text{ Euros}$$

4.10 Second test case

In the second test case, it is examined the same wind park consisting of the same number of wind turbines, but of two different types of them. In this case twenty one of them are 80 m high and the remaining 20 are 100 m high. The positions of the second type of wind generators were chosen randomly and they are illustrated with the red color on the next map:



4.28 Positions of wind turbines with height 80 m (green) and height 100 m (red)

In order to estimate the life-cycle cost of the wind park, the same process described as above is implemented for the two typed of wind turbines. The wind velocity at the top of the wind turbines, as well as the air density, are calculated. Consequently, the wind load for each wind turbine and the displacements which correspond to the relevant capacity curve for each one of the three wind hazard levels are evaluated. The three required pairs $(\overline{P}_i - DI_i)$ are determined, as the annual exceedance probabilities are the same as in the first test case.

4.29 Linear interpolation in the capacity curve for wind turbines with height 100 m

While the initial installation cost of the first type (H=80 m) was assumed equal to 1,800,000 Euros, the initial installation cost of the second type of wind turbines (H=100 m) is 2,000,000 Euros. The analysis reached the following results

$$C_{lc}^{wind\ park}(t,s) = \sum_{i=1}^{N} C_{lc}^{i}(t,s) = 7{,}892{,}300 \text{ Euros}$$

$$C_{initial}^{wind\ park}(s) = \sum_{i=1}^{N1} C_{initial}^{i}(s) + \sum_{j=1}^{N2} C_{initial}^{j}(s) = N_1 \cdot C_{initial}^{i}(s) + N_2 \cdot C_{initial}^{j}(s)$$

where

N_1 the number of the wind turbines with height 80 m

N_2 the number of the wind turbines with height 100 m

$$C_{initial}^{wind\ park}(s) = 21 \cdot 1{,}800{,}000 + 20 \cdot 2{,}000{,}000 = 77{,}800{,}000 \text{ Euros}$$

$$C_{total}^{wind\ park}(s,t) = C_{initial}^{wind\ park}(s) + C_{lc}^{wind\ park}(t,s)$$

$$C_{total}^{wind\ park}(s,t) = 77{,}800{,}000 + 7{,}892{,}300 = 85{,}692{,}300 \text{ Euros}$$

5. Conclusions-Observations

Due to the global shift to renewable energy, high volume of research has been conducted on how to achieve maximum performance, while minimizing the production costs. Many useful tools have been developed for this purpose depending on the investment, on the type of the renewable source of energy etc. The present master thesis concentrated on the wind energy and on developing a useful tool for assessing the investment for the construction and operation of a wind park.

The study was based on the use of the life-cycle cost analysis procedure. The analysis performed was focused on the evaluation of a wind park from the engineering point of view. The cost of buying or renting land, the financing of the whole investment (loans etc), the interest rates resulted from the compounding of money and the selling price from the produced energy were not taken into account. In order to estimate the life-cycle cost of the wind park only the initial installation cost of each wind turbine and the damage repair cost were taken into consideration.

Life-cycle cost analysis was proved to be a valuable assessment tool in order to evaluate an investment for its lifetime, like the construction of a wind park. As the number of the examined parameters involved in the calculation procedure of the life-cycle cost increases, the accuracy and reliability of the estimation of life-cycle cost increase too.

Concerning the comparison between the two test cases, the results were similar as expected. The wind park, examined in the second test case and consists of two types of wind turbines, resulted to have a higher life-cycle cost and higher total cost. This result derives from both structural and economical reasons. Firstly, in the second test case the wind park consists of twenty wind turbines, whose height is equal to 100 m. As is resulted from the capacity curve of those wind turbines, the maximum resistant wind load is lower than the first one, which leads to higher displacements and higher life-cycle cost. In addition, the fact that the initial installation cost of the second type of wind turbines is higher, the initial cost of the wind park in the second test case is higher. Consequently, the total cost in the second test case is higher.

Finally, it can be concluded that the choice of evaluating the investment of a wind park through the process of life-cycle cost analysis was successful. The life-cycle cost analysis could also be proposed to be implemented in various applications, even on large and small buildings. Life-cycle cost analysis, as an economic evaluation technique, could contribute to making the right decisions about construction or improvements to a facility.

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