Web-based Tool for Preliminary Assessment of Wind Power Plant Design

Daniela Borissova[1] and Ivan Mustakerov[1]

[1] Department of Information Processes and Decision Support Systems
Institute of Information and Communication Technologies – BAS
Sofia – 1113, Bulgaria
dborissova@iit.bas.bg, mustakerov@iit.bas.bg

Abstract. Designing of reliable and cost-effective industrial wind power plant is a prerequisite for the effective use of wind power as an alternative resource. The design of a wind power plant includes the determination of type, number and layout of wind turbines for given site area. Preliminary assessment of design project will decrease the possibility of costly errors at practical realization of the project. A Web-based tool for preliminary assessment of wind power plant design project is described. An original algorithm with two branches ("iterative" and "intelligent") is at the core of this application. The proposed tool can be used to simulate and evaluate different wind power plant design projects by preliminary estimation of energy output and associated costs. The applicability of the described tool is demonstrated by real data for wind turbines and parameters of the wind site.

Keywords: wind power plant, design assessment algorithm, web-based tool architecture.

1 Introduction

Designing a wind power plant (WPP) is a complex and iterative process. It includes choice of turbines and definition of proper layout conforming to terrain and wind climate of a site while ensuring maximum of extracted power and optimizing the economic performance. The first step in building of a WPP is choosing a location with enough wind resources. Special wind speed maps are helpful to identify a region with suitable wind resources. The important questions are how much power the site can produce considers costs. It is needed also to take into consideration special concerns of the WPP location, such as road access, potential noise impacts, flickering shadows from the blades, and cultural issues etc. [1]. A number of mathematical approaches are available to facilitate the wind farm design process. Most of them deal with genetic algorithms for optimizing wind turbines placement [2-6]. Greedy heuristic methodology [7, 8] and swarm optimization [9] of the positions of turbines are proposed as better alternatives to genetic algorithms. Another approach for wind turbines optimal placement is the usage of exact optimization methods as mixed-integer programming

[10]. An economic optimization model for the high level system design and unit commitment of a microgrid is developed in [11]. A combinatorial optimization approach is proposed recently by the authors [12, 13] for wind farm optimal layout in respect of minimum cost per unit energy produced. An adequacy evaluation of wind farms is crucial in system planning to determine appropriate generating resources to meet the expected total demand [14]. Several forecast systems based on artificial neural networks are developed to predict power production of a wind farm in different time horizons [15]. Adopting an integrated macro perspective when evaluating and building wind farms is important for wind power development [16]. Despite the intelligence and sophistication of these approaches, human intervention may still be required during the design process, to come up with better layout designs than automatically generated [17].

It is extremely important that WPP be designed in such a way so as to minimize wake, turbulence, and other associated effects as much as possible. Design constraints dictate a certain minimum distance between the turbines, to minimize the impact each turbine has on the other turbines' power production capacity. The separation distances required between turbines depends mainly on the wind direction and turbine rotor diameter and there exist some practical recommendations that can be used [2, 10, 18]. Before settling on any brand of turbine, the potential turbines' production that turbine manufacturers claim are to be compared. The rated energy output of wind turbine, annual energy output can be estimated as *kilowatt per hours* where the turbines load is should be taken. Using different model will ensure estimation of turbine energy (kWh = kilowatt-hours) production based on site specifics and wind resources.

In the paper, a Web application for preliminary assessment of WPP about the installed power, number of turbines, separation distances between them and costs are presented.

2 Modeling and Assessment of Wind Power Plant Design

The variety of wind turbines types put a challenge to select the most appropriate turbine type. On the other hand, the wind turbines type selection reflects in the choice of turbines number and placement within given wind site area [13]. The energy output and investments costs are the most essential wind power plant design characteristics. The key factor that have to considered for accurate evaluation/estimation of investment cost of WPP, involve capital costs, operation and maintenance costs, generation costs with respect to wind availability and the economic lifetime of the total financial investment. Costs of wind turbines, transportation, civil works, road construction, installation, grid connection and development and engineering are the capital cost which comprises the major part of the total cost of the WPP [19]. The investment cost of WPP can be modeled taking into account only the number N of installed turbines. A generalized non-dimensional relation of total cost/year for entire WPP can be estimated as $costs = N\left(\frac{2}{3} + \frac{1}{3}e^{(-0.00174N^2)}\right)$ [2, 3]. The wind turbine energy produced per year can be calculated as it is described [2]. It can also be estimated approximately using some practically determined nominal power utilization coefficient η of the total wind power plant installed power [12]. For the goal of the current modeling, the WPP produced energy per year is estimated as $P = h_y \eta N P_{wt}$, where h_y is the number of the hours over the year, η is nominal power utilization coefficient of wind power plant (capacity factor), N is the number of turbines within WPP and P_{wt} is the wind turbine rated power.

The goal of the preliminary assessment of WPP design project is to define type, number and layout, and WPP energy output and costs. The wind site area is considered as a known by its dimensions. The effective use of wind site area requires building WPPs with as many wind turbines as it is possible. Spacing of wind turbines consider the wake losses by introducing of proper separation coefficients [2, 3]. Using these considerations, a mathematical model for preliminary assessment of WPP design project is described as:

$$C = N\left(\frac{2}{3} + \frac{1}{3}e^{\left(-0.00174N^2\right)}\right) \quad (1)$$

$$P = 8760\eta N P_{wt} \quad (2)$$

$$N = \left(\frac{L_x}{SD_x} + 1\right)\left(\frac{L_y}{SD_y} + 1\right) \quad (3)$$

$$SD_x = k_x D \quad (4)$$

$$SD_y = k_y D \quad (5)$$

$$k_x^{min} \leq k_x \leq k_x^{max}, k_x > 0 \quad (6)$$

$$k_y^{min} \leq k_y \leq k_y^{max}, k_y > 0 \quad (7)$$

where C are non-dimensional WPP costs per year [12], N is installed number of turbines, P_{wt} is wind turbine rated power, η is nominal power utilization coefficient (availability of wind over year), P is WPP energy output per year, L_x, L_y are WPP area dimensions, SD_x, SD_y are separation distances between turbines calculated by means of separation coefficients k_x and k_y and wind turbine diameter D. The separation coefficients are limited by boundaries $k_x^{min}, k_x^{max}, k_y^{min}$ *and* k_y^{max} which are defined according to the wind direction. The corresponding turbines layouts corresponding to two basic wind direction cases are illustrated on the Fig. 1 [13].

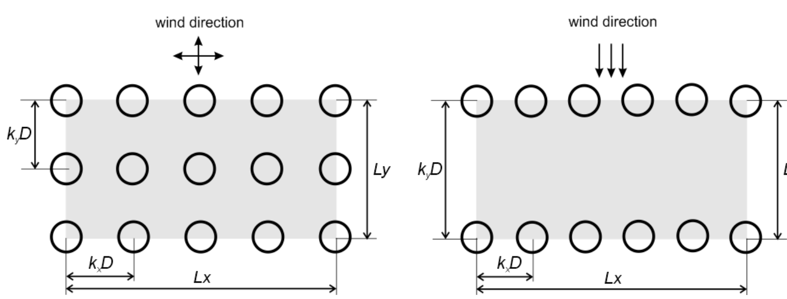

Fig. 1. WPP layout for: (a) *uniform* and (b) *predominant* wind direction

According to the wind resources, two basic layout designs of WPPs are investigated – for uniform and predominant wind direction. For the uniform wind direction case the separation coefficients are equal and are limited within boundaries $4.5 \le k_x = k_y \le 5.5$ while for the predominant wind direction they are defined by restrictions $1.5 \le k_x, \le 2.5$ and $7 \le k_y \le 9$.

3 Algorithm for Preliminary Assessment for Wind Power Plant Design Project

The proposed Web-based tool implements an algorithm composed of two basic branches: 1) iterative design and assessment, 2) intelligent design and assessment. The graphical representation of the algorithm is shown in Fig. 2.

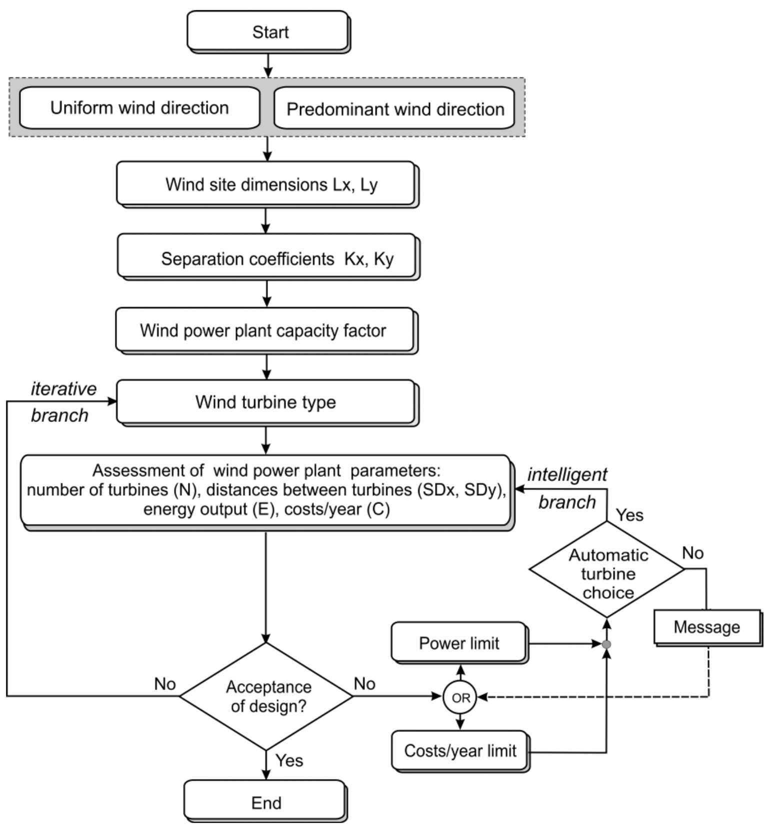

Fig. 2. Algorithm for preliminary assessment of project for WPP design

The algorithm execution starts with defining of wind direction – predominant or uniform. On the second stage the dimensions of WPP area are to be introduced. It is assumed that WPP shape is approximated to a rectangle with *width* and *length* dimensions that are known. Next, the value of the expected wind power utilization coefficient η is given. Then the algorithm splits into two branches – iterative and intelligent choice of wind turbines. By using the iterative branch, the WPP designer can make selection of particular wind turbine type. The formulae (1) – (7) are used to calculate number of turbines, separation distances between them, energy output and costs. If the user in not satisfied with some of the parameters of designed WPP he can choose other type of turbine and to repeat the design estimation. In this way he can iteratively simulate and estimate different design scenario. The other possibility is to switch to the use of intelligent branch of the algorithm. The intelligent branch allows setting up some preliminary requirements about the energy output or costs of designed WPP (not both in the same time). The main idea of intelligent branch is to find automatically a proper wind turbine type to satisfy given requirement. The algorithmic realization of the intelligent choice of turbine type is based on calculation of energy output or costs of each type of turbines for given site dimensions and wind direction. The resulting array for energy output/costs is sorted in ascending order and the corresponding to each array element WPP parameters (number and type of turbines, separation distances, costs/energy output) are calculated and loaded in adjacent arrays. Then a search for satisfying the given requirement is performed as it is shown in Fig. 3.

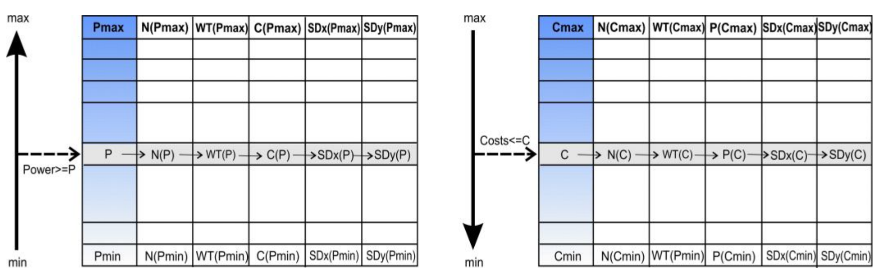

Fig. 3. Algorithmic realization of intelligent branch

If the given requirements cannot be satisfied a proper message is shown and new requirements are to be given.

4 Architecture of Web-based Tool for Assessment of Wind Power Plant Design

The described architecture is based on using of one of the most popular Internet application technologies – AJAX (Asynchronous JavaScript and XML) on the client-side [20]. The architecture of Web-based tool for preliminary assessment of WPP design is shown in Fig. 4.

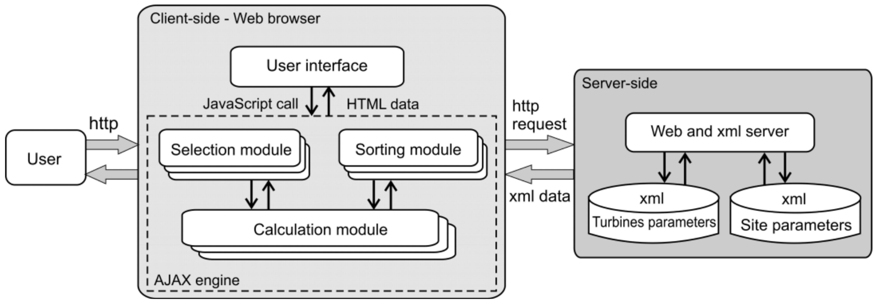

Fig. 4. Web-based application architecture

The main idea behind the architecture of the AJAX engine is to refresh information on the web page without reloading it [20]. In practice, AJAX engine is realized as JavaScript functions that are called whenever information needs to be requested from the server. When the AJAX engine receives the server response, it goes into action, parsing the data and making updates of the presented to the user information. Because this process involves transferring less information than the traditional web application model, user information updates are faster. The databases for wind turbines and their parameters, and all files of the web-based system for assessment of WPP are stored on the server-side as XML data-bases. The server-side code creates and serves the page and responds to the client asynchronous requests.

One of the essential problems when designing an interactive system is the creation of its graphical user interface (GUI). The principle used in the paper is based on the assumption that user interface should be as much intuitive as it is possible to facilitate the user. The developed GUI is shown in Fig. 5.

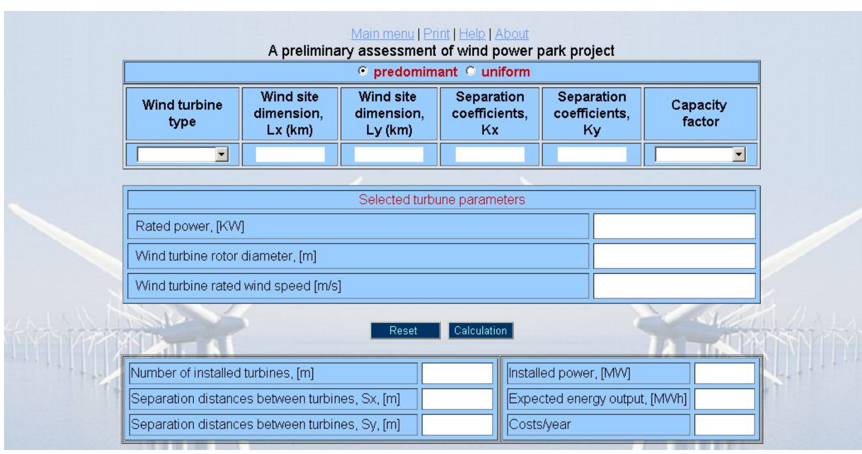

Fig. 5. Graphical user interface of the proposed Web application for WPP assessment

On the top of the main screen *radio buttons* are used to select the established for the WPP site wind direction as uniform or predominant direction. Then *drop-down lists* allow WPP designer to select the wind turbine type and site dimensions. Each selection is visualized by corresponding item parameters within relevant text fields. Then pressing of button "*Calculation*" activates defining of the parameters of WPP shown in appropriate text fields. In this way the preliminary design assessment via the iterative branch of the developed algorithm is accomplished. This sequence of actions can be repeated iteratively as many times as it is necessary. The intelligent branch of the proposed algorithm becomes effective when user enters some required value for the WPP energy output or costs in the corresponding text field. This requirement is processed by algorithm shown in Fig. 3 to define choice of proper wind turbine type that will satisfy the given preference. AJAX technology is used to collect and transfer the pure information that is needed by the server and to retrieve from the server some new information that can be integrated into the already loaded page. For example, when appropriate turbine is found its parameters are visualized and WPP parameters are calculated and shown. In case of entering of impossible requirement a proper message is shown.

5 Results and Discussions

To illustrate the applicability of the proposed application, real data of wind turbines are used as input data (Table 1) and WPP area with dimensions *4 km* x *4 km* are considered.

Table 1. Wind turbines parameters

No	Wind turbine type	Rotor diameter, m	Rated power, kW
1	Enercon E-33	33.00	330
2	Enercon E-44	44.00	900
3	Enercon E-48	48.00	800
4	Vestas V52	52.00	850
5	Enercon E-53	53.00	800
6	Vestas V60	60.00	850
7	Enercon E-70	70.00	2300
8	Vestas V80	80.00	2000
9	Enercon E-82	82.00	3000
10	Enercon E-92	92.00	2350
11	Vestas V100	100.00	2000
12	Enercon E-101	101.00	3050
13	Vestas V112	112.00	3300
14	Enercon E-115	115.00	2500
15	Enercon E-126	126.00	7580

Note: The data are taken from Internet: http://www.enercon.de/, http://www.vestas.com

5.1 Uniform Wind Direction

The choice of particular wind turbine under given uniform wind direction and wind power plant utilization factor of *30 %* when iterative branch of algorithm is used results in the estimation for the WPP project parameters shown in Table 2.

Table 2. Results of iterative branch execution for uniform wind direction

Selected wind turbine	Number of turbines	Separation distance, SDx=SDy,m	Installed power, MW	Expected power output, MWh/year	Costs
Enercon E-70	169 (13x13)	332.50	388.70	1021503.60	112.67
Vestas V112	64 (8x8)	571.20	211.20	555033.60	42.68

When intelligent branch of algorithm is used some upper limit about the costs or lower limit about the energy output should be given. In Table 3 are shown the results after execution of intelligent branch for two independent cases: energy output more than 900 000 MWh/year and costs less than 60.

Table 3. Results of intelligent branch execution for uniform wind direction

Selected wind turbine	Number of turbines	Separation distance, SDx=SDy,m	Installed power, MW	Expected energy output, MWh/year	Costs
		Expected energy output ≥ 900 000 MWh/year			
Enercon E-126	49 (7x7)	661.50	371.42	976091.76	32.92
		Costs ≤ 60			
Vestas V100	81 (9x9)	500.00	162.00	425736.00	54.00
Enercon E-101	81 (9x9)	499.95	247.05	649247.40	54.00

The first restriction (energy output more than 900 000 MWh/year) leads to choice of wind turbine “Enercon E-126” and the corresponding WPP parameters are: expected energy output of 976 091.76 MWh/year under 32.92 costs. Imposing the restriction of 60 for costs leads to two equivalent selections – wind turbine “Vestas V100” or “Enercon E-101”. For both turbines the costs are equal to 54, but with different expected energy output – 425 736 MWh/year if turbine “Vestas V100” is used and 649 247.40 MWh/year if the turbine is “Enercon E-101”. In this case, intuitively the choice of turbine leading to larger energy output is better choice but the final decision depends on the WPP designer.

5.2 Predominant Wind Direction

The influence of predominant wind direction on the parameters of designed WPP for execution of iterative branch of algorithm is shown in Table 4 and for intelligent branch execution – in Table 5.

Table 4. Results of iterative branch execution for predominant wind direction

Selected wind turbine	Number of turbines	Separation distance, SDx, m	Separation distance, SDy, m	Installed power, MW	Expected energy output, MWh/year	Costs
Enercon E-70	240 (30x8)	140	560	552.00	1450656.00	160.00
Vestas V112	95 (19x5)	224	896	313.50	823878.00	63.33

Table 5. Results of intelligent branch execution for predominat wind direction

Selected wind turbine	Number of turbines	Separation distance, SDx,m	Separation distance, SDy,m	Installed power, MW	Expected energy output, MWh/year	Costs
			Expected energy output ≥ 900 000 MWh/year			
Vestas V80	182 (26x7)	160	640	364.00	956592.00	121.33
			Costs ≤ 60			
Enercon E-126	85 (17x5)	252	1008	644.30	1693220.40	56.67

The first restriction (energy output more than 900 000 MWh/year) leads to choice of wind turbine "Vestas V80" and expected energy output is 956 592 MWh/year with 121.33 costs. The second restriction of costs less than 60 leads to selection of wind turbine "Enercon E-126" and the expected energy output is 1 693 220.40 MWh/year with 56.67 costs.

6 Conclusion

The design of reliable and cost-effective industrial wind power plant is a prerequisite for the effective use of wind power as an alternative resource. Of great importance is the evaluation of WPP potential on early designing stage. To have successful design on this stage some estimates about the type, number and layout of wind turbines in relation to the best utilization of the available wind power capacity have to be done. For the goal is developed a Web application for preliminary assessment of wind power plant design by calculating the basic WPP parameters: number of turbines of particular type, separation distances between turbines and their layout, installed power, expected energy output over the year and associated costs. The Web application is based on mathematical model that is implemented in an algorithm for preliminary assessment of the WPP project. The algorithm is composed of two basic components: 1) component for iterative design and assessment, 2) component for intelligent design and assessment.

The iterative branch of algorithm allows choice of wind turbine of particular type and automatic calculation of the WPP parameters. If these parameters do not satisfy the WPP designer he can choose another type of turbine and to compare the corresponding parameters. This iterative process can be repeated as many times as it is needed to support making proper design decision.

The intelligent branch of algorithm allows setting of a value for minimum energy output or for maximum eligible costs. Then the choice of wind turbine type and other

WPP parameters (number of turbines, separation distances and layout, installed power, expected energy output and associated costs) are calculated automatically (by pressing of a button in main menu) and are shown to the user. If the user is not satisfied or the given requirement is infeasible, he may set other requirement and repeat the calculations. The user can switch whenever he wants between the two branches of the algorithm and in this way he can simulate different scenarios for designing of WPP.

The described Web application is based on XHTML, JavaScript, XML and AJAX technology using. The AJAX technology using avoids reloading the same HTML form or page if a part of it should be actualized, reduces the network traffic and increases the user acceptance. The Web based application is tested with real data of 15 different wind turbines' types toward 2 scenarios – for uniform and predominant wind directions for given WPP area. The test results proved the applicability of the proposed approach for building and using of Web application for preliminary assessment of wind power plant design. Future development of this approach would be inclusion of optimization module to determine the optimal toward certain criteria choice of WPP parameters.

Acknowledgments. The research work reported in the paper is partly supported by the project AComIn "*Advanced Computing for Innovation*", grant 316087, funded by the FP7 Capacity Programme (Research Potential of Convergence Regions).

References

1. Lima, F., Ferreira, P., Vieira, F.: Strategic Impact Management of Wind Power Projects. Renew. & Sustain. Energy Rev. 25, 277–290 (2013)
2. Marmidis, G., Lazarou, S., Pyrgioti, E.: Optimal Placement of Wind Turbines in a Wind Park using Monte Carlo Simulation. Renew. Energy. 33, 1455–1460 (2008)
3. Grady, S.A., Hussaini, M.Y., Abdullah, M.M.: Placement of Wind Turbines using Genetic Algorithms. Renew. Energy 30, 259–270 (2005).
4. Wan, C., Wang, J., Yang, G., Li, X., Zhang, X.: Optimal Micro-Siting of Wind Turbines by Genetic Algorithms based on Improved Wind and Turbine Models. In: 48th IEEE Conf. on Decis. & Control and 28th Chinese Control Conf., Shanghai, China, 2009, pp. 5092–5096. (2009)
5. Santos, J. R., Payan, M.B., Calero, J., Mora, J. C.: An Evolutive Algorithm for Wind Farm Optimal Design. Neurocomputing 70, 2651-2658(2007).
6. González, J.S., Rodriguez, A.G.G., Mora, J.C., Santos, J.R., Payan, M.B.: Optimization of Wind Farm Turbines Layout using an Evolutive Algorithm. Renew. Energy 35, 1671–1681 (2010).
7. Ozturk, U.A.: Heuristic Methods for Wind Energy Conversion System Positioning. Electr. Power Syst. Res. 70, 179–185 (2004).
8. Elkinton, C. N., Manwell, J. F., McGowan, J. G.: Offshore Wind Farm Layout Optimization (OWFLO) Project: An Introduction. In: Copenhagen offshore wind conference. Copenhagen, Denmark, (2005).

9. Wan, C., Wang, J., Yang, G., Zhang, X.: Optimal Micro-Siting of Wind Farms by Particle Swarm Optimization. In: Advances in swarm intelligence, Berlin, Heidelberg, pp. 198–205 (2010)
10. Donovan, S.: Wind Farm Optimization. In: 40th Annual Conf. of Operations Research Society, Wellington, New Zealand, pp. 196–205 (2005)
11. Hawkes, A. D., Leach, M.A.: Modelling High Level System Design and Unit Commitment for a Microgrid. Appl. Energy 86, 1253–1265 (2009)
12. Mustakerov, I., Borissova, D.: Wind Turbines Type and Number Choice using Combinatorial Optimization. Renew. Energy 35, 1887–1894 (2010)
13. Mustakerov, I., Borissova, D.: Wind Park Layout Design using Combinatorial Optimization, in: I. Al-Bahadly (Ed.), Wind Turbines, InTech, pp. 403–424 (2011)
14. Mabel, M. C., Edwin Raj, R., Fernandez, E.: Adequacy Evaluation of Wind Power Generation Systems. Energy 35, 5217–5222 (2010)
15. De Giorgi, M.G., Ficarella, A., Tarantino, M.: Assessment of the Benefits of Numerical Weather Predictions in Wind Power Forecasting based on Statistical Methods. Energy 36, 3968–3978 (2011)
16. Sperling, K., Hvelplund, F., Vad Mathiesen. B.: Evaluation of Wind Power Planning in Denmark – Towards an Integrated Perspective. Energy 35, 5443–5454 (2010)
17. Khan, S.A., Rehman, Sh.: Iterative Non-Deterministic Algorithms in On-Shore Wind Farm Design: A brief survey. Renew. & Sustain. Energy Rev. 19, 370–384 (2013)
18. Mosetti, G., Poloni, C., Diviacco, B.: Optimization of Wind Turbine Positioning in Large Windfarms by means of a Genetic Algorithm. J. Wind. Eng. Ind. Aerod. 51, 105–116 (1994)
19. Shafiullah, G.M., Amanullah, M.T.O, Shawkat Ali, A.B.M., Wolfs, P.: Potential Challenges of Integrating Large-scale Wind Energy into the Power Grid–A Review. Renew. & Sustain. Energy Rev. 20, 306–321 (2013)
20. Hertel, M., Aspects of AJAX, 2007, `http://www.mathertel.de/AJAX/AJAXeBook.aspx`.