WIND FARM LAYOUT OPTIMIZATION USING COMBINED AREA DIMENSIONS AND DEFINITE POINT SELECTION TECHNIQUES

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To My beloved parents, and my daughters Hania and Tayyiba for their enduring love, sacrifice, patience, encouragement and best wishes.

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ABSTRACT

The current wind turbines are the biggest rotating machines on earth, operating in the lowest part of the earth boundary layer. The layout scheme of wind farms is a challenging job to researchers having many design objectives and constraints due to the multiple wake phenomenon. The far wake effect is more prominent in wind farm layout design problems than the near wake effect. At present, wind energy industry is facing major design constraints in boosting power output. Most of the existing approaches focused only on the positioning of the wind turbines within the wind farms. They did not consider the effect of the shape of wind farm area on power output. This research proposes a novel method to find the optimized dimensions of the wind farm shape where maximum area could face the free stream velocity. This is achieved by developing an area dimension method which rotates the wind farms up to 180 degree. Afterward, a novel method called Definite Point Selection (DPS) is developed to place the turbines in order to operate at their maximum efficiency, while providing the obligatory space between adjacent turbines for operation safety. The positions within the wind farm facing zero wake effect can be identified by using DPS method. It is observed that the combined area dimension and DPS techniques are more effective than the previous approaches. Jensen's wake model is used to calculate the wake effects among wind turbines as existing literatures illustrate that the Jensen's far wake model is a good choice acceptably for the solution of layout problem. A wind farm of 2 km x 2 km area is divided into 10 x 10 cells for case study. Three different wind scenarios i.e. constant wind speed with uniform direction (Case 1), uniform wind speed with variable direction for equal probability of occurrence (Case 2) and variable wind speed with variable direction for unequal probability of occurrence (Case 3) are considered for the application of proposed methods. The proposed layouts are simulated to place different number of wind turbines in all wind scenarios. The optimized layout operates with efficiency of 99.15%, 96.9% and 93.9% for Case 1, Case 2 and Case 3 respectively. Results show that power output of the wind farm by using the same area in different dimension has increased even with identical number of wind turbines. The proposed method is useful for onshore as well as offshore wind farms.

ABSTRAK

Turbin angin semasa adalah mesin berputar terbesar di dunia, yang beroperasi di kawasan paling rendah di lapisan sempadan bumi. Skim susun atur ladang angin adalah satu pekerjaan yang mencabar untuk para penyelidik yang mempunyai objektif reka bentuk banyak dan kekangan akibat fenomena berbilang keracak. Kesan keracak yang jauh ini adalah lebih menonjol dalam ladang angin masalah reka bentuk susun atur daripada kesan keracak yang dekat. Pada masa ini, industri tenaga angin sedang menghadapi kekangan reka bentuk utama dalam meningkatkan kuasa keluaran. Kebanyakan pendekatan yang sedia ada hanya memberi tumpuan kepada usaha membangunkan turbin angin dalam ladang angin. Mereka tidak mengambil kira kesan bentuk kawasan ladang angin pada kuasa keluaran. Penyelidikan ini mencadangkan satu kaedah baru untuk mencari dimensi optimum bentuk ladang angin di mana kawasan maksimum boleh menghadapi halaju arus bebas. Ini dicapai dengan membangunkan satu kaedah dimensi kawasan yang berputar ladang-ladang angin sehingga 180 darjah. Selepas itu, satu kaedah baru dipanggil Pemilihan Titik Tentu (DPS) dibangunkan untuk meletakkan turbin untuk beroperasi pada kecekapan maksimum, manakala menyediakan ruang yang wajib antara turbin bersebelahan untuk keselamatan operasi. Kedudukam dalam ladang angin menghadapi kesan keracak sifar boleh dikenal pasti dengan menggunakan kaedah DPS. Adalah diperhatikan bahawa kawasan dimensi gabungan dan teknik DPS adalah lebih berkesan daripada pendekatan yang sebelumnya. Model keracak Jensen digunakan untuk mengira kesan keracak antara turbin angin sebagai literatur menggambarkan bahawa model keracak jauh Jensen adalah pilihan yang baik boleh diterima bagi penyelesaian masalah susun atur. Sebuah ladang angin di kawasan 2 km x 2 km dibahagikan kepada 10 x 10 sel-sel untuk kajian kes. Tiga senario angin yang berbeza iaitu kelajuan angin yang berterusan dengan hala tuju seragam (Kes 1), kelajuan angin seragam dengan arah ubah untuk kebarangkalian kejadian yang sama (Kes 2) dan kelajuan angin berubah-ubah dengan arah ubah untuk kebarangkalian kejadian yang tidak sama (Kes 3) dipertimbangkan untuk penggunaan kaedah dicadangkan. Susun atur yang dicadangkan adalah simulasi untuk meletakkan beberapa jenis turbin angin dalam semua senario angin. Susun atur dioptimumkan beroperasi dengan kecekapan 99.15%, 96.9% dan 93.9% untuk Kes 1, Kes 2 dan Kes 3 masing-masing. Hasil kajian menunjukkan bahawa kuasa keluaran ladang angin dengan menggunakan kawasan yang sama dalam dimensi yang berbeza telah meningkat walaupun jumlah nombor turbin angin adalah sama. Kaedah yang dicadangkan adalah berguna untuk daratan dan juga untuk ladang angin luar pesisir.

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LIST OF ABBREVIATIONS

ACO	-	Ant Colony Optimization
AMPL	-	A Mathematical Programming Language
BPSO	-	Particle Swarm Optimization
CF	-	Capacity Factor
DPS	-	Definite Point Selection
DE	-	Differential Evolution
ENDOW	-	Efficient Development of Offshore Wind farm
EWTS	-	European Wind Turbine Standards
ECN	-	Energy research Centre of the Netherlands
EV	-	Eddy Vescosity
FlaP	-	Farm Layout Program
GA	-	Genetic Algorithm
GGA	-	Global Greedy Algorithm
MIL	-	Mixed Integer linear
NPC	-	Net Present Cost
NSE	-	Navier Stokes Equations
PSO	-	Particle Swarm Optimization
PEVM	-	Parabolic Eddy Viscosity Model
PBL	-	Planetary Boundary Layer
QIO	-	Quadratic Interpolation Optimization
RANS	-	Reynolds-averaged Navier Stokes
SA	-	Simulated Annealing
SE	-	Stochastic Evolution
Sim E	-	Simulated Evolution
TMSI	-	Turbine-site Matching Index
UO	-	University of Oldenburg
UPMW	-	Universidad Polytecnica de Madrid Wakefarm
WF	-	Wind farm
WT	-	Wind turbine
WFLO	-	Wind farm layout optimization

WAsP	-	Wind Atlas Analysis and Application Program
WINDOPS	-	Wind Online Performance Surveillance

LIST OF SYMBOLS

α	-	Wake decay constant
γ	-	Divergence angle
ρ	-	Air density
θ	-	Diagonal angle of area
ϕ	-	Rotational angle
u_o	-	Free stream wind velocity
u_1	-	Wake velocity at downward distance
D	-	Rotor diameter
z	-	Hub height
Z_0	-	Surface roughness
C_T	-	Thrust coefficient
A_{shadow}	-	Wake shadow cone
P_t	-	Totall energy produced
P_{rated}	-	Rated power output
C_t	-	Cost per annum
C_i	-	Installation cost
C_{ij}	-	Cost of cables
C_p	-	Power coefficient
A	-	Rotor swept area
t	-	Life time of project
R_w	-	Wake radius
r_d	-	downstream radius of wind turbine
r_r	-	Wake radius just behind of wind turbine
a	-	Axial induction factor
s	-	Wind sector
v_{co}	-	Cut out wind velocity
v_{ci}	-	Cut in wind velocity
N_t	-	Total number of wind turbines
c	-	Weibull scale parameter
k	-	Weibull shape parameter

p_v	-	Probability density function of wind
U_o	-	Free stream flow passing through disc
p_b	-	Pressure drop at point b
p_c	-	Pressure drop at point c
A_c	-	swept area of rotor disc
A_w	-	surface crossection of stream tube after disc
A_o	-	surface crossection of stream tube before disc
m_s	-	mass flux on the sides of stream tube
T	-	Thrust force
B_t	-	Payback period of wind farm
P_i	-	Total power of ith wind turbine
ICC	-	Normalized initial capacity cost

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Due to depletion of the fossil fuels, leading to acute scarcity of energy production from the conventional source, there is an upsurge in utilization of the non conventional energy resources like wind, biogas, solar etc [1]. One of the profligate developing sources of energy among sustainable and renewable is the wind energy source [2, 3]. Wind energy installation has experienced a tremendous increase in the past years. At the same time, related research activities have flourished in the past decade [4]. According to the Global Wind Energy Council 2015 Report [5], it has become the fastest growing energy source in the world with a steep increase in development from 2009 to date. Figure 1.1 shows the global installed wind capacity from 1997 to 2014. In 2004, the total world wide wind capacity was 14,781 MW but in 2014 the capacity became 51,477 MW [5].

Due to rapid development of wind turbine technology and increasing size of wind farm, 4 GW in construction now, 40 GW by 2020, and 150 GW by 2030 are planned to construct, meaning many large wind farms [6, 7]. Now wind power plays a significant role in the power production of developing countries as well as in developed countries [8–15]. This increasing demand for wind energy has given way to a shift from single turbine installation to multi megawatt installations consisting of a large number of clustered wind turbines called 'Wind Farms'. The main task of a wind farm is to get maximum possible power by using minimal area with less number of wind turbines [16, 17].

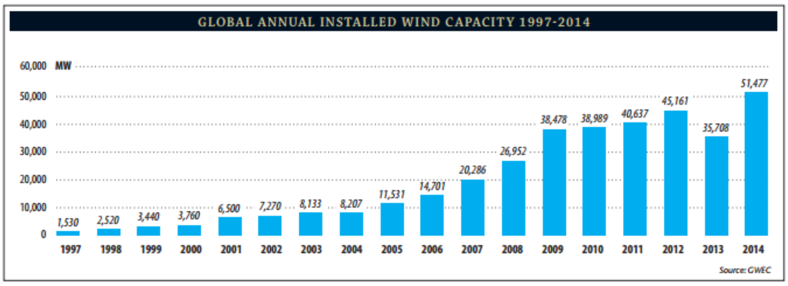

Figure 1.1: Global Annual Installed Capacity from 1996 to 2014 [5]

1.2 Problem statement

The problems can be formulated into three points.

- The wind farm area dimension is a crucial parameter that is not mentioned by wind energy community. In other words, except the relative positions of the wind turbines in the installation site, the boundaries of the installation area also affect the overall electricity production. In literature an unavailability of wind farm area dimension model has been observed.
- Careful planning of the geometrical arrangement of wind turbines in the wind farm can minimize the wake effects and increase the farm efficiency in terms of power production. However, the question, "where to install the turbines", is not a trivial one. The wind flow inside the farm (evolution of wakes) depends on the wind speed and direction, as well as on the wind turbine specifications.
- Wind direction varies with time making it challenging to arrange turbines in a manner such that they can escape, wakes of upstream turbines for a majority of their operational time. At the same time, the determination of the wind farm output for a given layout is also not straight forward, since wake effects, wind variations and turbine responses need to be carefully considered. Advanced numerical methodologies are, therefore, necessary to optimize the arrangement of turbines in the wind farm, a process more commonly known as Wind Farm Layout Optimization (WFLO).

1.3 Research objectives

The objectives of this research are:

1. To model wind farm area dimension which ensures the maximum width of wind farm perpendicular to the mean wind direction and investigate its effect on the total output power of a wind farm.
2. To develop a new technique named 'Definite Point Selection (DPS)' which identify the zero wake effect points within the wind farm. The DPS is based on an idea of installing the wind turbines in a form of group, while no one turbine laying in the wake of other wind turbine.
3. To explore the validation of the DPS algorithm applying it on different wind scenarios with varying number of wind turbines installation and verify by comparing with previous relative research work.

1.4 Significance of research

The present research offers a paradigm move in wind farm layout optimization problem. A momentous research work has been done (and is on-going) in the wind farm design literature. However, the most researches in this field focused only the placement of wind turbine within some given boundaries of the wind farm. In contrast, present research introduces the new concept of two level optimization. First, to identify and analyze the impact of land area and land shape on the optimization of wind farm layout, an area dimension method is proposed to get the optimal area dimension of wind farm. This can provide novel insights into the role of farm land shape in the wind farm layout design. Second to explore the zero wake effect points within the wind farm area for wind turbine placement. For this, a novel method called Definite Point Selection (DPS) is developed to place the turbines in order to operate their maxima, while provided the obligatory space between adjacent turbines for operation safety. The implementation of such novel concepts present significant modelling and design challenges that have been appropriately addressed in this research. In addition, this research takes three different type of wind scenarios, constant wind speed with constant direction, variable wind speed with variable wind direction for equal probability of occurrence and variable wind speed with wind direction for unequal probability of occurrences. In order to explore the effectiveness of the developed techniques 'wind farm area dimension and DPS algorithm', these techniques are applied on each wind scenario with varying number of wind turbines installation and are validated by comparing the outcomes with previous relative research work.

1.5 Scope of study

In order to achieve the objective of the research, the scope of research will be carried out: The total area of wind farm is fixed which is equal to $2\,km \times 2\,km$ and divided into cells of same size for wind turbine installation. This dimension is chosen based on the benchmark in the literature for comparative study purposes. This type of discrete siting is convenient for the realization of optimal method. As the wind turbine type matters, only horizontal axis are considered, and all having same rotor radius, hub height and power curve characteristics. It is also assumed that the turbine nacelle is fully controlled and can move the rotor towards the wind direction. The obligatory distance between wind turbines in the columns and rows is accepted to be around five rotor diameters (5D), the wind farm area is discretized by equal number of cells. The layout is simulated to work on different wind farm layouts for the maximum power output. It seems good to understand the impact of multiple shadowing of turbines on one another in the farm in different wind conditions. The proposed layout technique is equally valid for onshore as well as offshore wind farms.

1.6 Organization of thesis

This thesis is organized into five chapters, namely the introduction, literature review, research methodology, results and discussion, and conclusion and future recommendations.

Chapter 1 provides information on the background of study, problem statement, objectives and scope of research.

Chapter 2 analyzes the status of wake effect in wind farm, discusses its significance on the energy yield and structure of the problem will be defined. This chapter also reviews the optimization methods used in Wind Farm Layout Optimization (WFLO). The important finding from the previous work will be used as a guideline in this research.

Chapter 3 aims to focus the wind farm modelling which includes cost model, wake model, power and efficiency modelling. In this chapter, the novel methods of influence of wind farm area on power yield and Definite Point Selection (DPS) for wind turbine positioning are proposed. This chapter also presents the implementation of the proposed methodology in different wind scenario.

Chapter 4 discusses and compares the results of proposed research finding with the previous work for three wind scenarios; constant wind speed with uniform direction, uniform wind speed with variable direction and variable wind speed with variable direction.

Chapter 5 concludes the discussion of the work undertaken and highlights the contributions of this research. Several suggestions are recommended for possible directions of future work.

REFERENCES

1. Raheem, A., Hassan, M. Y. and Shakoor, R. Pecuniary Optimization of Biomass/Wind Hybrid Renewable System. *Proceedings of the 1st Int. e-Conf. on Energies, 14-31 Mrach 2014*, 2014. 01(Sciforum Electronic Conference Series c006): 1–10. doi:10.3390/ece-1-c006. URL http://www.sciforum.net/conference/ece-1/paper/2333/download/manuscript.pdf.

2. Perveen, R., Kishor, N. and Mohanty, S. R. Off-shore wind farm development: Present status and challenges. *Renewable and Sustainable Energy Reviews*, 2014. 29: 780–792.

3. Khan, S. A. and Rehman, S. Iterative non-deterministic algorithms in on-shore wind farm design: A brief survey. *Renewable and Sustainable Energy Reviews*, 2013. 19: 370–384. ISSN 13640321. doi:10.1016/j.rser.2012.11.040. URL http://linkinghub.elsevier.com/retrieve/pii/S1364032112006521.

4. Agency, I. E. International Energy Agency WIND 2012 Annual Report @ONLINE, 2012. URL http://www.ieawind.org/AnnualReportsPDF/2012/.

5. wind energy council, G. Global Wind Report Annual Market update 2015 @ONLINE, 2015. URL http://www.gwec.net/wp-content/uploads/2015/06/Annualreport2015LowRes.pdf.

6. Manwell, J. F., McGowan, J. G. and Rogers, A. L. *Wind energy explained: theory, design and application*. John Wiley & Sons. 2010.

7. Hau, E. and Von Renouard, H. *Wind turbines: fundamentals, technologies, application, economics*. Springer Science & Business Media. 2013.

8. Kinab, E. and Elkhoury, M. Renewable energy use in Lebanon: Barriers and solutions. *Renewable and Sustainable Energy Reviews*, 2012. 16(7): 4422–4431.

9. Stambouli, A. B., Khiat, Z., Flazi, S. and Kitamura, Y. A review on the renewable energy development in Algeria: Current perspective, energy

scenario and sustainability issues. *Renewable and Sustainable Energy Reviews*, 2012. 16(7): 4445–4460.

10. Saidur, R., Islam, M., Rahim, N. and Solangi, K. A review on global wind energy policy. *Renewable and Sustainable Energy Reviews*, 2010. 14(7): 1744–1762.

11. Sahu, B. K., Hiloidhari, M. and Baruah, D. Global trend in wind power with special focus on the top five wind power producing countries. *Renewable and Sustainable Energy Reviews*, 2013. 19: 348–359.

12. Abanda, F. Renewable energy sources in Cameroon: Potentials, benefits and enabling environment. *Renewable and Sustainable Energy Reviews*, 2012. 16(7): 4557–4562.

13. Komarov, D., Stupar, S., Simonović, A. and Stanojević, M. Prospects of wind energy sector development in Serbia with relevant regulatory framework overview. *Renewable and Sustainable Energy Reviews*, 2012. 16(5): 2618–2630.

14. Li, H., Xie, M. and Zhang, T. Promote the development of renewable energy: A review and empirical study of wind power in China. *Renewable and Sustainable Energy Reviews*, 2013. 22: 101–107.

15. Jervase, J. A. and Al-Lawati, A. M. Wind energy potential assessment for the Sultanate of Oman. *Renewable and Sustainable Energy Reviews*, 2012. 16(3): 1496–1507.

16. Youcef Ettoumi, F., Adane, A. E. H., Benzaoui, M. L. and Bouzergui, N. Comparative simulation of wind park design and siting in Algeria. *Renewable Energy*, 2008. 33(10): 2333–2338.

17. Mustakerov, I. and Borissova, D. Wind turbines type and number choice using combinatorial optimization. *Renewable Energy*, 2010. 35(9): 1887–1894.

18. Froude, R. On the part played in propulsion by differences of fluid pressure. *Transactions of the Institute of Naval Architects*, 1889. 30: 390–405.

19. A Complete Online Guide for Mechanical Engineer. URL http://www.mechanicalengineeringblog.com/1782-introductiontowindturbine/windturbinedesign/windturbinetechnology/.

20. Moskalenko, N. and Rudion, K. Study of Wake Effects for Offshore Wind Farm Planning. 2010.

21. Jensen, N. O. *A note on wind generator interaction*. RISO-M-2411, RISO National Laboratory, Denmark. 1983.

22. Katic, I., Højstrup, J. and Jensen, N. A simple model for cluster efficiency. 1986.

23. Ishihara, T., Yamaguchi, A. and Fujino, Y. Development of a new wake model based on a wind tunnel experiment. *Global Wind Power*, 2004.

24. Frandsen, S., Barthelmie, R., Pryor, S., Rathmann, O., Larsen, S., Højstrup, J. and Thøgersen, M. Analytical modelling of wind speed deficit in large offshore wind farms. *Wind Energy*, 2006. 9(1-2): 39–53.

25. S. Lissaman, P. Energy effectiveness of arbitrary arrays of wind turbines. *Journal of Energy*, 1979. 3(6): 323–328.

26. Manwell, J., McGowan, J. and Rogers, A. Wind characteristics and resources. *Wind Energy Explained: Theory, Design and Application*, 2002: 21–82.

27. Bastankhah, M. and Porté-Agel, F. A new analytical model for wind-turbine wakes. *Renewable Energy*, 2014. 70(1): 116–123.

28. Ainslie, J. F. Calculating the flowfield in the wake of wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics*, 1988. 27(1): 213–224.

29. Crespo, A. and Hernández, J. Numerical modelling of the flow field in a wind turbine wake. *Proceedings of the 3rd Joint ASCE/ASME Mechanics Conference*. 1989. 121–127.

30. Crespo, A. and Hernández, J. Parabolic and Elliptic Models of Wind-Turbine Wakes, Application to the Interaction between Different Wakes and Turbines. *Phoenics Journal of Computational Fluid Dynamics and Its Applications*, 1991. 4: 104–127.

31. Schepers, J. *ENDOW: Validation and improvement of ECN's wake model*. Energy research Centre of the Netherlands ECN. 2003.

32. Schepers, J. and Van der Pijl, S. Improved modelling of wake aerodynamics and assessment of new farm control strategies. *Journal of Physics: Conference Series*. IOP Publishing. 2007, vol. 75. 012039.

33. Van der Pijl, S. and Schepers, J. Improvements of the WAKEFARM wake model. *Energy research*, 2006: 2.

34. Crasto, G. and Gravdahl, A. R. CFD wake modeling using a porous disc. *European Wind Energy Conference & Exhibition*. 2008.

35. Werle, M. A new analytical model for wind turbine wakes. *Report No. FD*,

2008. 200801.

36. Vermeer, L., Sø rensen, J. and Crespo, a. Wind turbine wake aerodynamics. *Progress in Aerospace Sciences*, 2003. 39(6-7): 467–510. ISSN 03760421. doi:10.1016/S0376-0421(03)00078-2. URL http://linkinghub.elsevier.com/retrieve/pii/S0376042103000782.

37. VanLuvanee, D. R. Investigation of Observed and Modelled Wake Effects at Horns Rev Using WindPro. *Report, Technical University of Denmark, MEK Department, Fluid Mechanics Section, Denmark*, 2006.

38. Sørensen, T., Thøgersen, M. L., Nielsen, P. and Jernesvej, N. Adapting and calibration of existing wake models to meet the conditions inside offshore wind farms. *EMD International A/S. Aalborg*, 2008.

39. Renkema, D. J. Validation of wind turbine wake models. *Master of Science Thesis, Delft University of Technology*, 2007.

40. Wilcox, D. C. *Turbulence modeling for CFD*. vol. 2. DCW industries La Canada. 1998.

41. Aytun Ozturk, U. and Norman, B. A. Heuristic methods for wind energy conversion system positioning. *Electric Power Systems Research*, 2004. 70(3): 179–185.

42. Guillén, F. B. Development of a design tool for offshore wind farm layout optimization. *Technische Universiteit Delft, Eindhoven, The Netherlands, Master of Science Thesis*, 2010.

43. Holland, J. H. *Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence.* U Michigan Press. 1975.

44. Goldberg, D. E. and Holland, J. H. Genetic algorithms and machine learning. *Machine learning*, 1988. 3(2): 95–99.

45. Kirkpatrick, S. Optimization by simulated annealing: Quantitative studies. *Journal of statistical physics*, 1984. 34(5-6): 975–986.

46. Nahar, S., Sahni, S. and Shragowitz, E. Simulated annealing and combinatorial optimization. *proceedings of the 23rd ACM/IEEE Design Automation Conference*. IEEE Press. 1986. 293–299.

47. Storn, R. and Price, K. Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces. *Journal of global optimization*, 1997. 11(4): 341–359.

48. King, R.-M. and Banerjee, P. Optimization by simulated evolution with

applications to standard cell placement. *Design Automation Conference, 1990. Proceedings., 27th ACM/IEEE*. IEEE. 1990. 20–25.

49. Turner, S., Romero, D., Zhang, P., Amon, C. and Chan, T. A new mathematical programming approach to optimize wind farm layouts. *Renewable Energy*, 2014. 63: 674–680. ISSN 09601481. doi:10.1016/j.renene.2013.10.023. URL http://linkinghub.elsevier.com/retrieve/pii/S0960148113005545.

50. Crespo, A., Hernandez, J. and Frandsen, S. Survey of modelling methods for wind turbine wakes and wind farms. *Wind energy*, 1999. 2(1): 1–24.

51. Snel, H. Review of the present status of rotor aerodynamics. *Wind Energy*, 1998. 1(s 1): 46–69.

52. Snel, H. Review of aerodynamics for wind turbines. *Wind Energy*, 2003. 6(3): 203–211.

53. Hansen, M. O. L., Sørensen, J. N., Voutsinas, S., Sørensen, N. and Madsen, H. A. State of the art in wind turbine aerodynamics and aeroelasticity. *Progress in aerospace sciences*, 2006. 42(4): 285–330.

54. Sanderse, B., Van der Pijl, S. and Koren, B. Review of computational fluid dynamics for wind turbine wake aerodynamics. *Wind Energy*, 2011. 14(February): 799–819. doi:10.1002/we.458.

55. Sanderse, B. Aerodynamics of wind turbine wakes. *Energy Research Center of the Netherlands (ECN), ECN-E–09-016, Petten, The Netherlands, Tech. Rep*, 2009.

56. Barthelmie, R., Larsen, G., Frandsen, S., Folkerts, L., Rados, K., Pryor, S., Lange, B. and Schepers, G. Comparison of wake model simulations with offshore wind turbine wake profiles measured by sodar. *Journal of Atmospheric and Oceanic Technology*, 2006. 23(7): 888–901.

57. Wilcox, D. A. Simulation of transition with a two-equation turbulence model. *AIAA journal*, 1994. 32(2): 247–255.

58. Menter, F. Influence of freestream values on k-omega turbulence model predictions. *AIAA journal*, 1992. 30(6): 1657–1659.

59. Larsen, G. C. *A simple wake calculation procedure*. RisÃž-M- 2760, RisÃž National Laboratory. 1988.

60. Renkema, D. J. Validation of wind turbine wake models. *Master of Science Thesis, Delft University of Technology*, 2007.

61. Larsen, G. C., Højstrup, J. and Aagaard Madsen, H. Wind fields in wakes.

1996 European Wind Energy Conference and Exhibition. 1996. 764–768.

62. Gaumond, M., Réthoré, P.-E., Bechmann, A., Ott, S., Larsen, G. C., Peña, A. and Hansen, K. S. Benchmarking of wind turbine wake models in large offshore wind farms. *Proceedings of the Science of Making Torque from Wind Conference*. 2012.

63. Frandsen, S. T. *et al. Turbulence and turbulence-generated structural loading in wind turbine clusters*. Risø National Laboratory. 2007.

64. Rathmann, O., Barthelmie, R. and Frandsen, S. Turbine wake model for wind resource software. *European Wind Energy Conference*. 2006.

65. Tong, W., Chowdhury, S., Zhang, J. and Messac, A. Impact of different wake models on the estimation of wind farm power generation. *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, American Institute of Aeronautics and Astronautics*. 2012.

66. Barthelmie, R., Larsen, G., Pryor, S., Jørgensen, H., Bergström, H., Schlez, W., Rados, K., Lange, B., Vølund, P., Neckelmann, S. *et al.* ENDOW (efficient development of offshore wind farms): modelling wake and boundary layer interactions. *Wind Energy*, 2004. 7(3): 225–245.

67. Lange, B., Waldl, H.-P., Guerrero, A. G., Heinemann, D. and Barthelmie, R. J. Modelling of offshore wind turbine wakes with the wind farm program FLaP. *Wind Energy*, 2003. 6(1): 87–104.

68. WindFarmer, G. Wind Farm Design Software: Theory Manual, 2010.

69. Brower, M. and Robinson, N. The openWind deep-array wake model: development and validation. USA: AWS Truepower; 2010.

70. Schlez, W. and Neubert, A. New developments in large wind farm modelling. *Proceedings of the European Wind Energy Conference*. 2009.

71. Ammara, I., Leclerc, C. and Masson, C. A viscous three-dimensional differential/actuator-disk method for the aerodynamic analysis of wind farms. *Transactions-American Society of Mechanical Engineers Journal of Solar Energy Engineering*, 2002. 124(4): 345–356.

72. Mikkelsen, R. *Actuator disc methods applied to wind turbines*. Ph.D. Thesis. Technical University of Denmark. 2003.

73. Troldborg, N., Sørensen, J. N. and Mikkelsen, R. Numerical simulations of wakes of wind turbines in wind farms. *Technical University of Denmark*, 2006.

74. Seim, F. Validating kinematic wake models in complex terrain using CFD. 2015.

75. Jeon, S., Kim, B. and Huh, J. Comparison and verification of wake models in an onshore wind farm considering single wake condition of the 2 MW wind turbine. *Energy*, 2015. 93: 1769–1777.

76. Samorani, M. The wind farm layout optimization problem. *P. Pardalos Leeds School of Business, University of Colorado at Boulder*, 2010.

77. Gary, M. R. and Johnson, D. S. Computers and Intractability: A Guide to the Theory of NP-completeness, 1979.

78. Grady, S., Hussaini, M. and Abdullah, M. M. Placement of wind turbines using genetic algorithms. *Renewable Energy*, 2005. 30(2): 259–270.

79. Huang, H.-S. Distributed genetic algorithm for optimization of wind farm annual profits. *Intelligent Systems Applications to Power Systems, 2007. ISAP 2007. International Conference on*. IEEE. 2007. 1–6.

80. Kusiak, A. and Song, Z. Design of wind farm layout for maximum wind energy capture. *Renewable Energy*, 2010. 35(3): 685–694.

81. Mosetti, G., Poloni, C. and Diviacco, B. Optimization of wind turbine positioning in large windfarms by means of a genetic algorithm. *Journal of Wind Engineering and Industrial Aerodynamics*, 1994. 51(1): 105–116.

82. Rivas, R. A., Clausen, J., Hansen, K. S. and Jensen, L. E. Solving the turbine positioning problem for large offshore wind farms by simulated annealing. *Wind Engineering*, 2009. 33(3): 287–297.

83. Şişbot, S., Turgut, Ö., Tunç, M. and Çamdalı, Ü. Optimal positioning of wind turbines on Gökçeada using multi-objective genetic algorithm. *Wind Energy*, 2010. 13(4): 297–306.

84. Serrano González, J., Burgos Payán, M., Santos, J. M. R. and González-Longatt, F. A review and recent developments in the optimal wind-turbine micro-siting problem. *Renewable and Sustainable Energy Reviews*, 2014. 30: 133–144. ISSN 13640321. doi:10.1016/j.rser.2013.09.027. URL http://linkinghub.elsevier.com/retrieve/pii/S1364032113006989.

85. Kling, R. and Banerjee, P. ESP: Placement by simulated evolution. *IEEE Transactions on Computer-Aided Design*, 1989. 8(3): 245–256.

86. Colorni, D. M., Alberto and Maniezzo, V. Distributed optimization by ant colonies. *Proceedings of the first European conference on artificial*

Intelligence. Paris, France. 1991. 134–142.

87. Kennedy, J. and Eberhart, R. Particle swarm optimization. *Proceedings of ICNN'95 - International Conference on Neural Networks*, 1995. 4: 1942–1948. doi:10.1109/ICNN.1995.488968. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=488968.

88. Saab, Y. and Rao, V. An evolution-based approach to partitioning ASIC systems. *Proceedings of the 26th ACM/IEEE Design Automation Conference*. ACM. 1989. 767–770.

89. Saab, Y. G. and Rao, V. B. Combinatorial optimization by stochastic evolution. *Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on*, 1991. 10(4): 525–535.

90. Castro Mora, J., Calero Barón, J. M., Riquelme Santos, J. M. and Burgos Payán, M. An evolutive algorithm for wind farm optimal design. *Neurocomputing*, 2007. 70(16-18): 2651–2658. ISSN 09252312. doi:10.1016/j.neucom.2006.05.017. URL http://linkinghub.elsevier.com/retrieve/pii/S0925231207000914.

91. Marmidis, G., Lazarou, S. and Pyrgioti, E. Optimal placement of wind turbines in a wind park using Monte Carlo simulation. *Renewable energy*, 2008. 33(7): 1455–1460.

92. Ma, Y., Yang, H., Zhou, X., Li, J. and Wen, H. The dynamic modeling of wind farms considering wake effects and its optimal distribution. *2009 World Non-Grid-Connected Wind Power and Energy Conference*, 2009: 1–4. doi:10.1109/WNWEC.2009.5335828. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5335828.

93. Herbert-Acero, J.-F., Franco-Acevedo, J.-R., Valenzuela-Rendón, M. and Probst-Oleszewski, O. Linear wind farm layout optimization through computational intelligence. In: *MICAI 2009: Advances in Artificial Intelligence*. Springer. 692–703. 2009.

94. Emami, A. and Noghreh, P. New approach on optimization in placement of wind turbines within wind farm by genetic algorithms. *Renewable Energy*, 2010. 35(7): 1559–1564. ISSN 09601481. doi:10.1016/j.renene.2009.11.026. URL http://linkinghub.elsevier.com/retrieve/pii/S0960148109005023.

95. Rahmani, R., Khairuddin, A., Cherati, S. M. and Pesaran, H. A novel method for optimal placing wind turbines in a wind farm using particle swarm

optimization (PSO). *IPEC, 2010 Conference Proceedings*. IEEE. 2010. 134–139.

96. Saavedra-Moreno, B., Salcedo-Sanz, S., Paniagua-Tineo, a., Prieto, L. and Portilla-Figueras, a. Seeding evolutionary algorithms with heuristics for optimal wind turbines positioning in wind farms. *Renewable Energy*, 2011. 36(11): 2838–2844. ISSN 09601481. doi:10.1016/j.renene.2011.04.018. URL http://linkinghub.elsevier.com/retrieve/pii/S096014811100190X.

97. Mittal, A. *Optimization of the layout of large wind farms using a genetic algorithm*. Ph.D. Thesis. Case Western Reserve University. 2010.

98. Eroğlu, Y. and Seçkiner, S. U. Design of wind farm layout using ant colony algorithm. *Renewable Energy*, 2012. 44: 53–62.

99. Chen, Y., Li, H., Jin, K. and Song, Q. Wind farm layout optimization using genetic algorithm with different hub height wind turbines. *Energy Conversion and Management*, 2013. 70: 56–65. ISSN 01968904. doi:10.1016/j.enconman.2013.02.007. URL http://linkinghub.elsevier.com/retrieve/pii/S0196890413000873.

100. Chen, X. and Li, Y. An improved stochastic PSO with high exploration ability. *Proc. IEEE Swarm Intell. Symp*. May. 2006. 228–235.

101. Chen, Y., Li, H., Jin, K. and Song, Q. Wind farm layout optimization using genetic algorithm with different hub height wind turbines. *Energy Conversion and Management*, 2013. 70: 56–65.

102. Pookpunt, S. and Ongsakul, W. Optimal placement of wind turbines within wind farm using binary particle swarm optimization with time-varying acceleration coefficients. *Renewable Energy*, 2013. 55: 266–276. ISSN 09601481. doi:10.1016/j.renene.2012.12.005. URL http://linkinghub.elsevier.com/retrieve/pii/S0960148112007604.

103. Weng, W., Taylor, P. A. and Walmsley, J. L. Guidelines for airflow over complex terrain: model developments. *Journal of Wind Engineering and Industrial Aerodynamics*, 2000. 86(2): 169–186.

104. Han, X., Guo, J. and Wang, P. Adequacy study of a wind farm considering terrain and wake effect. *IET generation, transmission & distribution*, 2012. 6(10): 1001–1008.

105. Han, X., Qu, Y., Wang, P. and Yang, J. Four-dimensional wind speed model for adequacy assessment of power systems with wind farms. *Power Systems,*

IEEE Transactions on, 2013. 28(3): 2978–2985.

106. Song, M., Chen, K., Zhang, X. and Wang, J. The lazy greedy algorithm for power optimization of wind turbine positioning on complex terrain. *Energy*, 2015. 80: 567–574.

107. Song, M., Chen, K., Zhang, X. and Wang, J. Optimization of wind turbine micro-siting for reducing the sensitivity of power generation to wind direction. *Renewable Energy*, 2016. 85: 57–65.

108. Xie, K., Yang, H., Hu, B. and Li, C. Optimal layout of a wind farm considering multiple wind directions. *Probabilistic Methods Applied to Power Systems (PMAPS), 2014 International Conference on*, 2014: 1–6.

109. Mittal, P., Kulkarni, K. and Mitra, K. A novel hybrid optimization methodology to optimize the total number and placement of wind turbines. *Renewable Energy*, 2016. 86: 133–147.

110. Wan, C., Wang, J., Yang, G. and Zhang, X. Optimal micro-siting of wind farms by particle swarm optimization. In: *Advances in swarm intelligence*. Springer. 198–205. 2010.

111. Rajper, S. and Amin, I. J. Optimization of wind turbine micrositing: A comparative study. *Renewable and Sustainable Energy Reviews*, 2012. 16(8): 5485–5492. ISSN 13640321. doi:10.1016/j.rser.2012.06.014. URL http://linkinghub.elsevier.com/retrieve/pii/S1364032112004017.

112. Betz, A. *Introduction to the theory of flow machines*. Elsevier. 2014.

113. González-Longatt, F., Wall, P. and Terzija, V. Wake effect in wind farm performance: Steady-state and dynamic behavior. *Renewable Energy*, 2012. 39(1): 329–338. ISSN 09601481. doi:10.1016/j.renene.2011.08.053. URL http://linkinghub.elsevier.com/retrieve/pii/S0960148111005155.

114. Gao, X., Yang, H. and Lu, L. Study on offshore wind power potential and wind farm optimization in Hong Kong. *Applied Energy*, 2014. 130: 519–531.

115. Mortensen, N. G., Landberg, L., Troen, I. and Lundtang Petersen, E. Wind atlas analysis and application program (WAsP). 1993.

116. Maor, E. *The Pythagorean theorem: a 4,000-year history*. Princeton University Press. 2007.

117. Abernethy, R. B. *The new Weibull handbook*. RB Abernethy. 1996.