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Comparison of numerical methods and metaheuristic optimization algorithms for estimating parameters for wind energy potential assessment in low wind regions

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A B S T R A C T

Recently, with energy crises and environmental problems becoming increasingly obvious, the utilization of wind power has become a big concern. Meanwhile, the inconsistent relationship between China's economy and wind energy potential distribution has caused inevitable difficulties in transportation of wind power and even in grid integration. Therefore, the establishment of electrical power system integrated with local-used low-speed wind power has got considerable attention.

Weibull, Rayleigh, Gamma and Lognormal probability distributions are evaluated. Then three numerical methods (NMs) - method of moment (MM), maximum likelihood estimation (MLE), and least squares method (LSM), are applied to get parameter estimation in the these distributions. Additionally, another three comparison metaheuristic optimization algorithms (MOAs), including bat algorithm (BA), cuckoo search algorithm (CS) and particle swarm optimization (PSO) are employed as comparison methods to tune the optimal parameters.

Experimental results conclude that in this case MOAs perform better than NMs. Moreover, BA-Weibull, CS-Weibull, and PSO-Weibull with only a slight difference outperform all of the other distributions. Specifically, BA-Weibull and PSO-Weibull are only slightly superior to CS-Weibull. The average wind power density, the effective wind power density, the available factor and the capacity factor of wind turbine are considered as key determinant factors in assessing the low-speed wind energy potential, which are directly influenced by the parameters in Weibull model. Moreover, the wind potential assessment in the low-speed wind areas can provide an essential technique support for further investment and development, even for further wind farm construction and economy evaluation. Consequently, accurate parameter estimation is of great importance in low speed wind energy resource assessment.

1. Introduction

With global economy and urbanization developing more and more rapidly, the world demands more and more energy, which results in gradually declining reserves of primary energy resources, and sharply increasing threat of energy crises and environmental problems around the world. Recently, the situation of global climate change is getting increasingly serious, of which global warming has the most prevalent adverse effect on the environment. With rising concerns related to the gradual shortage of conventional fossil fuels, as well as the global climate change, along with the urgent of global energy conservation and emission reduction, governments are taking steps to develop green renewable and clean sustainable energy resources throughout the world [1].

Wind energy, which is clean, renewable, and without greenhouse effect, has become an alternative and renewable energy to fossil fuels

Abbreviations: PDF, probability density function; NM, numerical methods; MOA, metaheuristic optimization algorithm; MEP, maximum entropy principle; MCP, Measure-Correlate-Predict; GWF, Gamma–Weibull function; MTN, mixture truncated normal function; GM, graphical method; MM, method of moment; EM, empirical method; LSM, least–squares method; MLE, maximum likelihood estimation; MMLE, modified maximum likelihood estimation method; EPF, energy pattern factor method; EEM, equivalent energy method; PSO, particle swarm optimization; CS, cuckoo search; SA, simulated annealing; GA, genetic algorithm; ACA, ant colony algorithm; BA, bat algorithm; DE, differential evolution approach; GEV, generalized extreme value distribution; CDF, cumulative distribution function; SSE, sum of squared errors; ECDF, experienced cumulative distribution function; R^2, the coefficient of determination; *RMSE*, root mean square error; K–S test, Kolmogorov–Smirnov test; AF, availability factor, CF, capacity factor

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[2]. In recent years, wind power, due to its lowest adverse impacts on environment and its sustainability, has become one of the most promising renewable energy sources with the most extensively utilization world widely [3,4]. And at present, with the technology of domestic and international wind power generation growing relatively maturely and reliably, wind power industry is of strategic importance to the society's sustainable development and has become an important aspect to the world's new energy industry development [5,6]. In recent years, wind power industry is expanding significantly throughout the world in the development and utilization of new energy sources [7,8]. Wind energy is gradually becoming one of the most promising renewable energy resources, and it will continue to lead the development of the world's new energy industries [9,10].

According to the Global Wind Report 2014 released by the Global Wind Energy Council on February 2015 [11], statistics show that by the end of 2014, the global total cumulative installed wind power capacity reached 369.553 GW (1 GW=10^9 W) and the world's new installations were 51.477 GW, which increased by about 16.188 GW compared with that of 2013. However, the world's new installed wind power capacity in 2013 hit the lowest point among the recent five years, with a capacity of 35.289 GW, which indicated that the annual wind power market dropped by almost 10 GW compared to 2012. China's total cumulative wind power installations in 2014 were 114.763 GW, accounting for 31% of the global wind energy market, ranking the first in the world, which exceeded the United States (65.879 GW) by 48.857 GW (13.2%); the new installed capacity was 23.351 GW, with a largest share of 45.2% of the global. China has become the leading of wind energy market, and will continue to lead the development of the world's wind power industry.

After entering the 21st century, China has increased financial investment in wind energy development and utilization, thus the wind power industry is expanding quite rapidly. In just ten years, China is already leading the global wind power industry with government encouragement and financial investment. The total installed capacity of China in 2014 has increased by 25.54% compared with 91412 MW in 2013, with a growth of 45.15% in new installed capacity. In recent years, some progress in the transmission for local wind power has accelerated China's wind farm construction. China's wind power industry has experienced rapid development; furthermore, the expansion of wind energy industry has encountered many problems and potential challenges in the current large-scale wind power development in China.

With the development of large-scale wind power, nowadays, it has inevitably met with the predicament of wind power online, which will restrict the development of global wind power industry. The predicament of wind power online and insufficient capacity of wind power consumption in the local regions have aroused a great impact and become the most important factors affecting wind power industry, which often lead to increasingly serious phenomenon of "abandoning the wind". Inner Mongolia, Hebei, Gansu and Liaoning in China, with largest installed capacity but poor consumption capacity of wind power, have no choice but to abandon the wind, thus they have to face the serious losses caused by "abandoning the wind". We almost lose 16.2 TWh electricity of wind power because of "abandoning the wind" in 2013 throughout China. The situation can trigger terrible negative effect, which can not only cut down the investments and incomes of wind power, but also restrict the development of wind power industry in the long run.

"Abandoning the wind" is mainly caused by the local inability in consuming large-scale wind power, whereas the fundamental reason is the uneven distribution of wind resources and electricity markets. These problems limit the development and have become the global common concerns faced by the wind power industry, consequently, they need to be researched and resolved in urgent.

At present, wind farm construction are mainly located in those areas with high wind speed, namely areas with high-quality and abundant wind energy resources. The Northwest China, North and Northeast China, and southeast coastal areas are rich in high-quality wind energy resources, where the wind speed from 7 to 25 m/s could be utilized. Because of the regional imbalance of China's economic development, the economy in the regions with abundant wind energy is generally less developed, thus, large-scale wind power cannot be consumed, often resulting in difficulties of wind power grid integration, difficulties of transportation, and serious phenomenon of "abandoning the wind". Therefore, the development of low-speed wind power has gradually risen to concern.

Meanwhile, in the process of designing and planning wind energy project, an accurate assessment of the wind resource potential is essential, which is not only particularly important for the entire wind farm construction and operation, but also the key to obtaining investment income in the future.

Therefore, in order to find out the best location of the wind farms and wind turbines, the study of wind speed probability distribution is critical in the siting process. Wind speed is always viewed as a random variable, to determine the potential of wind energy resources in the region, the statistical analysis of wind speed is required.

It is obvious that wind power occupies an important position in the future Chinese power matrix as well as the energy construction. In recent years, the assessment of wind energy resources has become a heated topic of great interest for researchers, which can provide a necessary and scientific reference for project planning and site choosing in wind farm constructions, thus the realization of accurate wind energy resource assessment is urgently expected [12]. Once the wind speed probability density function (PDF) is derived, the wind power density (i.e. wind resource potential) can be easily calculated by integrating. And consequently, the study of wind speed distributions has become a big concern in the field of wind resource assessment [13–15].

With difficulties of wind power grid integration, difficulties of transportation, and serious phenomenon of "abandoning the wind", so the investigation and development of low-speed wind power in the areas with more developed economy but with less abundant wind resources has become inevitable. It will continue to be one of the biggest drivers for new energy industry development, particularly for wind power generation with low-speed wind. There is comparatively little wind energy investment in low-speed wind areas, which will become a worldwide focus especially under the urgent of energy conservation and emission reduction.

In this paper, four PDFs (including the two-parameter Weibull, Rayleigh, two-parameter Gamma and Lognormal) are employed to wind speed distribution modeling. To obtain accurate parameters of the PDFs, three numerical methods (NMs) and three metaheuristic optimization algorithms (MOAs) are adopted and compared. Thus the four wind speed distribution models are determined. Then the fitting performance of these four distribution models is evaluated according to the goodness-of-fit. In addition, the optimal function in modeling the wind speed distribution is chosen to assess the low-speed wind energy of this area.

The rest of this paper is organized as follows: Section 2 gives the definition of the low-speed wind power and its advantages. Section 3 presents a review on wind speed probability distribution models and a review on parameter estimation methods. A brief description of the study area is presented and wind speed data in the hub height are extrapolated in Section 4. Theory of the two-parameter Weibull, Rayleigh, two-parameter Gamma and Lognormal functions are overviewed in Section 5. In Section 6, three numerical methods and three metaheuristic optimization algorithms are introduced. Section 7 gives goodness-of-fit as the final evaluation criteria. Section 8 presents the final estimating parameter estimating results of the probability distribution models. Then the performances of these PDFs are compared under three evaluation criteria introduced in Section 7. The optimal PDF selected in Section 8 is applied to the wind energy assessment in