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OPTIMIZING THE WIND POWER GENERATION COST IN THE GULF OF KHAMBHAT OF INDIA USING ARTIFICIAL INTELLIGENCE TECHNIQUES

Prasun Bhattacharjee

Dr. Somenath Bhattacharya

Abstract

Even though India currently possesses the fourth-biggest installed wind power generation competence in the world, it needs to evolve faster to satiate the mounting energy demand of its developing financial system while curbing the subsequent greenhouse gas discharge for accomplishing its Paris Agreement pledges. Offshore wind power generation opportunities can play a pivotal role to achieve the remarkable goal set by the Government of India of establishing 140 GW wind power generation capability by 2030 at the same time evade land procurement disputes. The current paper focuses on the cost optimization of offshore wind power generation in the Gulf of Khambhat of India using artificial intelligence-assisted approaches. Genetic Algorithm and Binary Particle Swarm Optimization technique have been employed concurrently for five layouts with similar area of 1 km^2 but different aspect ratios. The experimentation outcomes verify the dependency of cost of energy with the layout aspect ratio and the better suitability of the Genetic Algorithm technique in minimizing the offshore wind power generation cost for all layout configurations compared with the Binary Particle Swarm Optimization.

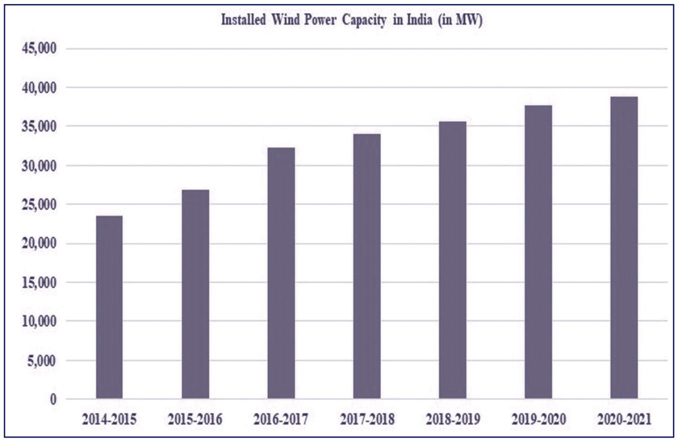
***Keywords:** Offshore Wind Power, Cost Optimization, Artificial Intelligence, Genetic Algorithm, Binary Particle Swarm Optimization, Gulf of Khambhat, Layout Aspect Ratio*

INTRODUCTION

Being the third biggest power-consuming nation, India has a vast competence to restraint global climate change (Enerdata, n.d.). As India is currently the second-most populous country on the planet, it is immensely vital for India to apply more renewable resources to boost its emerging financial system with a more environment-responsive approach (Kumar, Balasubramaniyan, Padmanaban, & Holm-Nielsen, 2019). The Government of India has asserted a remarkable aim of installing 60 GW Wind Power Generation (WPG) competency by 2022 to cope up with the fiscal growth of the country while complying with its emission cut commitments made following the Paris agreement of 2016 (Sharma & Sinha, 2019). The National Institute of Wind Energy (NIWE) has previously confirmed the wind power potential of 302 GW at 100 m for India (Sitharthan, Swaminathan, & Parthasarathy, 2018). As of 31 January 2021, India holds 10.3% of its 377260.67 MW whole installed capability from WPG farms (Ministry of Power, Government of India).

One of the most tempting attributes of WPG in India is that the Levelized Cost of Electricity (LCOE) is almost 35% lesser than most of the coal-fired power plants and this is expected to further decline by 7% by 2022 (Global Wind Energy Council). As the costly soil assets necessitated for onshore WPG farms are steadily turning out to be the main constriction, offshore WPG proposes a conceivable substitute (Ministry of New and Renewable Energy). Although offshore WPG is comparatively costlier, there are intrinsic advantages like abundant airstream, better air density, and velocity, superior load parameter, and possesses no terrain procurement disputes (Hevia-Koch & Klinge Jacobsen, 2019).

Figure 1: WPG Capacity in India from Financial Year 2014- 2015 to 2020-2021



LITERATURE REVIEW

In 2011, the possibility of offshore WPG in the southernmost part of mainland India was measured with ENVISAT Advanced Synthetic Aperture Radar satellite images gathered from 2002 to 2011 (Hasager, Bingöl, Badger, Karagali, & Sreevalsan, 2011). A comprehensive literature review was carried out for assisting the development of the much-needed policy framework before the implementation of the first offshore wind farm project in India (Mani & Dhingra, 2013). Mani Murali et. al. discussed the probable locations for offshore WPG and their economic viability (Mani Murali, Vidya, Modi, & Jaya Kumar, 2014). In 2015, a comparative analysis of various policy frameworks regarding the offshore WPG in the United Kingdom, the United States of America, and India has been presented (Kota, Bayne,

& Nimmagadda, 2015). In the following year, another study has been executed to estimate the offshore WPG capacity of India using the OSCAT satellite data of 2012-'13 (Nagababu, Simha R, Naidu, Kachhwaha, & Savsani, 2016). Re-analysis data collected between 2001 and 2014 in addition to relating data of bathymetry have been utilized for evaluating the WPG competence in the Economic Exclusive Zone of India with the consideration of marine ecological situations (Nagababu, Kachhwaha, Naidu, & Savsani, 2017). Assessment of the offshore WPG capability and optimization of the LCOE for the wind farm in the Indian shore area has been attempted through General Algebraic Modeling Language (Singh & Kumar S.M., 2018). In 2020, Moth Flame Optimization was employed for the measurement of both onshore and offshore WPG competence in India (R, K, Raju, Madurai Elavarasan, & Mihet-Popa, 2020). In the same year, a larger offshore WPG setup for the western coast of Gujrat has been assessed with climate study and LCOE has been predicted (Kumar, Stallard, & Stansby, 2020). The optimization of WPG cost for Indian offshore sites needs more attention to assist the green transition of the Indian electricity generation sector. As the problem of WPG cost optimization necessitates extremely complicated computational effort, Artificial Intelligence (AI) can facilitate in such a multifaceted scenario. AI techniques have been already applied in diverse fields of engineering due to their robustness, adaptability, and rapidity with exemplary success (Jana & Bhattacharjee, 2017) (Duggirala, Jana, Shesu, & Bhattacharjee, 2018).

The Facilitating Offshore Wind in India (FOWIND) venture in alliance with the Ministry of New and Renewable Energy (MNRE) and the NIWE introduced Light Detection and Ranging (LiDAR) evaluation for confirming the WPG capability at the eight well-defined regions on the shores of Tamil Nadu and Gujarat of India (Charles Rajesh Kumar, et al., 2020). Detailed data regarding the characteristic of offshore airstream has been acquired by a LiDAR positioned close to the Gulf of Khambhat for the period between November 2017 and June 2018 (Hasager, et al., 2008).

The present study aims for optimizing the WPG cost in the Gulf of Khambhat of India using bio-inspired AI techniques named Genetic Algorithm (GA) and Binary Particle Swarm Optimization (BPSO) with varying layout aspect ratios.

PROBLEM FORMULATION

The wind energy captured by a WT is expressed as per Eq. (1).

$$P = \frac{1}{2}\rho A \vartheta^3 C_p \cos\theta \qquad (1)$$

where P is the kinetic energy absorbed by the WT, ρ denotes the density of air, A stands for the swept area, v is the incoming wind speed, C_p represents the power and θ is the yaw error (Wu & Wang, 2012).

Wind farms can remain cost-effective through competent management of the Cost of Energy (CoE). The objective of this study is to minimize the CoE which was formulated in the 22nd Genetic and Evolutionary Computation Conference held in 2015. The cost function can be estimated according to Eq. (2).

$$\mathrm{CoE} = \left[\frac{\left\{\left(C_t N + C_s \mathrm{floor}\left(\frac{N}{m}\right)\right)\left(\frac{2}{3}+\frac{1}{3}e^{-0.00174N^2}\right)\right\} + (C_{om}N)}{(1-(1+r)^{-y})/r} * \frac{1}{8760*P}\right] + \frac{0.1}{N} \qquad (2)$$

where C_t is the price of a WT. C_s stands for the expenses for a sub-station. N is the number of WTs and m is the number of WT per sub-station. C_{om} is the yearly operational and maintenance charge. r is the rate of interest. y is the operational life.

This work followed the values of the constants of the cost function considered in the 22nd Genetic and Evolutionary Computation Conference (Wilson, et al., 2018). The final term (0.1/N) rewards the layouts with a superior WT count to raise the WPG.

The wind flow pattern observed in the Gulf of Khambhat is shown in Table 1.

Table 1: Yearly Wind Flow Pattern for the Gulf of Khambhat (R, K, Raju, Madurai Elavarasan, & Mihet-Popa, 2020)

Direction	Least Wind Speed (m/s)	Highest Wind Speed (m/s)	Wind Occurrence (%)
N	0.37	15.05	10.17
NNE	0.40	17.98	11.07
NE	0.42	18.12	5.82
ENE	0.47	20.21	3.72
E	0.41	22.99	2.92
ESE	0.44	20.27	2.93
SE	0.41	16.95	4.07
SSE	0.43	15.74	3.53
S	0.47	14.05	4.66
SSW	0.30	18.17	13.05
SW	0.48	20.39	15.80
WSW	0.49	18.74	8.75
W	0.35	14.06	3.24
WNW	0.68	11.82	2.86
NW	0.41	16.42	3.08
NNW	0.61	13.84	4.25

GENETIC ALGORITHM

Genetic Algorithm (GA) is a bio-inspired metaheuristic search procedure to propose resolutions for optimization challenges to emulate the progression of ecological choice as projected by Turing to demonstrate a 'learning machine' approximating the idea of evolution (Turing, 1950).

GA has been engaged in various engineering domains for solving single as well as multi-criteria decision-making problems (Jana & Bhattacharjee, 2017). GA can be presented as follows.

Table 2: Genetic Algorithm (Jana & Bhattacharjee, 2017)

Arrange the factors like population size, iteration number, chances for crossover, and mutation.
Compute the aptness of each chromosome.
Set the population randomly.
Calculate the aptness of each chromosome.
Set off the arithmetic crossover process
Choose a number arbitrarily within 0 and 1. If it is less than the chance of crossover, choose the parental chromosome for the crossover method.
Perform crossover between the parents.
Examine the viability of the offspring.
If the offspring is feasible, then integrate them into the recent population.
Start the mutation process
Choose a number arbitrarily within 0 and 1. If it is less than the chance of mutation, pick the chromosome for the mutation method.
Mutate the chromosomes.
Validate the fresh chromosome.
If the created chromosome is feasible, integrate it into the recent population.
Test the aptness of the fresh entities created through crossover and mutation methods.
Pick out the most excellent result following the decision maker's predilection.

BINARY PARTICLE SWARM OPTIMIZATION (BPSO)

Particle Swarm Optimization (PSO) is an AI-assisted searching procedure that impersonates the societal deeds of a swarm of bees by corresponding the communication associated with the all-inclusive and restricted optimum resolutions (Duggirala, Jana, Shesu, & Bhattacharjee, 2018).

The BPSO is a modified form of PSO that counts all particles as strings of bits. The site of a 'particle' is modified by switching between 0 and 1 depending upon the velocity (Liu, Mei, & Li, 2016) The velocity v_{ij} applicable for the jth bit of ith particle can be expressed as per Eq. (3),

$$v_{ij} = wv_{ij} + c_1 r_{1j}\left(q_{ij} - y_{ij}\right) + c_2 r_{2j}\left(h_j - y_{ij}\right) \quad (3)$$

Where w indicates the inertia weight. w is calculated as per Eq. (4).

$$w = w_{high} - \left(w_{high} - w_{low}\right)\frac{k}{k_{high}} \quad (4)$$

Where w_{high} and w_{low} are the extreme bounds of inertia weight. k represents the existing count of reiteration and k_{high} is the supreme count of reiteration. c_1 and c_2 are acceleration factors. r_{1j} and r_{2j} are arbitrarily chosen factors within the boundary of 0 and 1. q_{ij} stands for the jth bit of the distinct finest site of the ith particle. h_j denotes the jth bit of the collective finest site.

The transfer operator which can be utilized to revise the bit value is explained as per Eq. (5).

$$s\left(v_{ij}\right) = \frac{1}{1+e^{-v_{ij}}} \quad (5)$$

The bit value is renewed following Eq. (6).

$$x_{ij} = \begin{cases} 1, & \text{if rand()} \le s(v_{ij}) \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

Where rand() is a function that arbitrarily creates a fractional value varying between 0 and 1 (Liu, Mei, & Li, 2016).

The BPSO algorithm is accessible in Table 3, where existing sites, distinct finest sites, collective finest sites are indicated as $\mathbf{y_i} = (y_{i1}, \ldots\ldots, y_{in})$, $\mathbf{q_i} = (q_{i1}, \ldots\ldots, q_{in})$ and $\mathbf{h} = (h_1, \ldots\ldots, h_n)$ correspondingly.

Table 3: BPSO Algorithm

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Arbitrarily produce a primary populace;
Arbitrarily produce the elementary velocities within the bounds.
iterate
for i = 1 to Populace Limit do
if $f(\mathbf{y}_i) < f(\mathbf{q}_i)$ then $\mathbf{q}_i = \mathbf{y}_i$;
if $f(\mathbf{q}_i) < f(\mathbf{h})$ then $\mathbf{h} = \mathbf{q}_i$;
end
  for i = 1 to Populace Limit do
  for j = 1 to Particle Bit Limit do
        Estimate w with Eq. (4);
        Amend velocity as per Eq. (3);
        Modify position with Eq. (5) and Eq. (6);
     end
  end
until Finishing norms are accomplished
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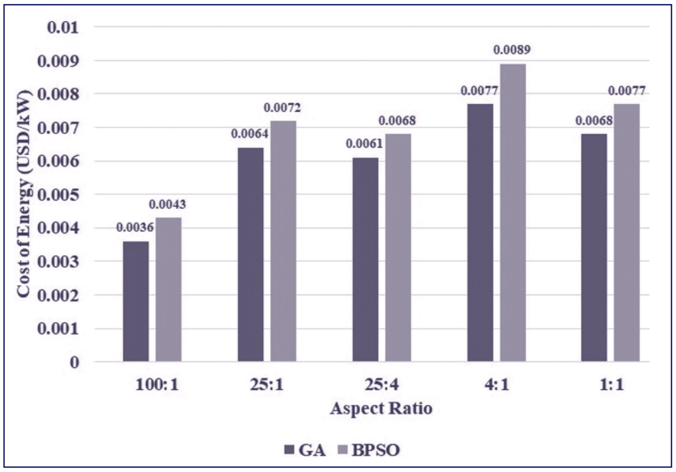
RESULTS AND DISCUSSIONS

1.5 MW WT of diameter 77 m has been engaged for the current experimentation. To decrease the wake loss consequence, the space between the two closest WTs has been maintained as 4 times the WT diameter. The cut-in wind speed for the WT has been deemed as 3.5 m/s while the cut-off wind speed for the considered WT is 20 m/s to prevent possible damages. In the current study, population size and iteration limit have been counted as 20 and 50 respectively.

A total layout area of 1000000 m^2 has been considered for offshore WPG. In the present experimental setup, aspect ratios of 100:1, 25:1, 25:4, 4:1, and 1:1 have been taken into account for assessing their effect on minimum WPG cost in the Gulf of Khambhat of India.

Figure 2: Optimized WPG Cost for the Gulf of Khambhat



The optimization outcomes of GA and BPSO for 5 different layout aspect ratios have been presented in Fig. 2. The solutions demonstrate the apprehensible impact of aspect ratio for comparable layout areas. The comparative analysis shows that GA is more competent in optimizing the WPG cost for the Gulf of Khambhat compared with BPSO. The most optimal WPG cost that could have been achieved is 0.0036 USD/kW for the layout with an aspect ratio of 100:1 (length x width: 10000 m x 100 m) using GA.

CONCLUSION

Optimization of offshore WPG cost for the Gulf of Khambhat in India has been attempted in the current research work. GA and BPSO have been engaged concurrently for 5 dissimilar layout aspect ratios with equal area of 1km^2. The experimentation results clearly show the dependability of WPG cost on layout aspect ratio and better competence of GA in finding the most optimal WPG cost over BPSO. This study will set off inventive opportunities for optimizing the WPG cost for both offshore and onshore sites with variable layout configurations. Other CoE functions related to different market conditions may be employed too in near future for a better understanding of their profitability.

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REFERENCES

1. *Charles Rajesh Kumar, J., Vinod Kumar, D., Baskar, D., Mary Arunsi, B., Jenova, R., & Majid, M. (2020), "Offshore wind energy status, challenges, opportunities, environmental impacts, occupational health, and safety management in India", Energy & Environment, p. 0958305X2094648.*

2. *Duggirala, A., Jana, R., Shesu, R., & Bhattacharjee, P. (2018), "Design optimization of deep groove ball bearings using crowding distance particle swarm optimization", Sādhanā, Vol. 43, No. 1.*

3. *Enerdata. (n.d.), "Electricity Production", Retrieved July 23, 2021, from Global Energy Statistical Yearbook 2021: https://yearbook.enerdata.net/electricity/world-electricity-production-statistics.html*

4. *Global Wind Energy Council. (n.d.), "India Wind Outlook Towards 2022: Looking beyond headwinds", Retrieved July 23, 2021, from GWEC: https://gwec.net/india-wind-outlook-towards-2022-looking-beyond-headwinds/*

5. *Hasager, C., Bingöl, F., Badger, M., Karagali, I., & Sreevalsan, E. (2011), "Offshore Wind Potential in South India from Synthetic Aperture Radar", Information Service Department Risø National Laboratory for Sustainable Energy Technical University of Denmark, Retrieved July 21, 2021, from https://www.osti.gov/etdeweb/servlets/purl/1045515*

6. *Hasager, C., Pena, A., Christiansen, M., Astrup, P., Nielsen, M., Monaldo, F., Thompson, D., & Nielsen, P. (2008), "Remote Sensing Observation Used in Offshore Wind Energy", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Vol. 1, No. 1, pp. 67–79.*

7. *Hevia-Koch, P., & Klinge Jacobsen, H. (2019), "Comparing offshore and onshore wind development considering acceptance costs", Energy Policy, Vol. 125, pp. 9–19.*

8. *Jana, R., & Bhattacharjee, P. (2017), "A multi-objective genetic algorithm for design optimisation of simple and double harmonic motion cams", International Journal of Design Engineering, Vol. 7, No. 2, pp. 77-91.*

9. *Kota, S., Bayne, S., & Nimmagadda, S. (2015), "Offshore wind energy: A comparative analysis of UK, USA and India", Renewable and Sustainable Energy Reviews, Vol. 41, pp. 685–694.*

10. *Kumar, M. B., Balasubramaniyan, S., Padmanaban, S., & Holm-Nielsen, J. B. (2019), "Wind Energy Potential Assessment by Weibull Parameter Estimation Using Multiverse Optimization Method: A Case Study of Tirumala Region in India", Energies, Vol. 12, No. 11, p. 2158.*

11. *Kumar, R., Stallard, T., & Stansby, P. (2020), "Large-scale offshore wind energy installation in northwest India: Assessment of wind resource using Weather Research and Forecasting and levelized cost of energy", Wind Energy, Vol. 24, No. 2, pp. 174–192.*

12. *Liu, J., Mei, Y., & Li, X. (2016), "An Analysis of the Inertia Weight Parameter for Binary Particle Swarm Optimization", IEEE Transactions on Evolutionary Computation, Vol. 20, No. 5, pp. 666–681.*

13. *Mani Murali, R., Vidya, P., Modi, P., & Jaya Kumar, S. (2014), "Site selection for offshore wind farms along the Indian coast", Indian Journal of Geo-Marine Sciences, Vol. 43, No. 7, pp. 1401-1406.*

14. *Mani, S., & Dhingra, T. (2013), "Offshore wind energy policy for India—Key factors to be considered", Energy Policy, Vol. 56, pp. 672–683.*

15. *Ministry of New and Renewable Energy. (n.d.), Retrieved July 21, 2021, from Offshore Wind: https://mnre.gov.in/wind/offshore-wind/*

16. *Ministry of Power, Government of India. (n.d.), "Renewable Generation Report", Retrieved July 23, 2021, from Central Electricity Authority: https://cea.nic.in/renewable-generation-report/?lang=en*

17. *Nagababu, G., Kachhwaha, S., Naidu, N., & Savsani, V. (2017), "Application of reanalysis data to estimate offshore wind potential in EEZ of India based on marine ecosystem considerations", Energy, Vol. 118, pp. 622–631.*

18. *Nagababu, G., Simha R, R., Naidu, N. K., Kachhwaha, S. S., & Savsani, V. (2016), "Application of OSCAT satellite data for offshore wind power", 5th International Conference on Advances in Energy Research (ICAER) 2015, Mumbai, Energy Procedia, Vol. 90, pp. 89-98.*

19. *R, K., K, U., Raju, K., Madurai Elavarasan, R., & Mihet-Popa, L. (2020), "An Assessment of Onshore and Offshore Wind Energy Potential in India Using Moth Flame Optimization", Energies, Vol. 13, No. 12, p. 3063.*

20. *Sharma, S., & Sinha, S. (2019), "Indian wind energy & its development-policies-barriers: An overview", Environmental and Sustainability Indicators, Vol. 1-2, p. 100003.*

21. *Singh, R., & Kumar S.M., A. (2018), "Estimation of Off Shore Wind Power Potential and Cost Optimization of Wind Farm in Indian Coastal Region by Using GAMS", 2018 International Conference on Current Trends Towards Converging Technologies (ICCTCT), 2018.*

22. *Sitharthan, R., Swaminathan, J., & Parthasarathy, T. (2018), "Exploration of Wind Energy in India: A Short Review", 2018 National Power Engineering Conference (NPEC), pp. 1-5, IEEE.*

23. *Turing, A. (1950), "I.—COMPUTING MACHINERY AND INTELLIGENCE", Mind, Vol. LIX, No. 236, pp. 433–460.*

24. *Wilson, D., Rodrigues, S., Segura, C., Loshchilov, I., Hutter, F., Buenfil, G., Kheiri, A., Keedwell, E., Ocampo-Pineda, M., Özcan, E., Peña, S. I. V., Goldman, B., Rionda, S. B., Hernández-Aguirre, A., Veeramachaneni, K., & Cussat-Blanc, S. (2018), "Evolutionary computation for wind farm layout optimization", Renewable Energy, Vol. 126, pp. 681-691.*

25. *Wu, Z., & Wang, H. (2012), "Research on Active Yaw Mechanism of Small Wind Turbines", Energy Procedia, Vol. 16, pp. 53–57.*

AUTHORS

Prasun Bhattacharjee, Ph.D. Scholar, Department of Mechanical, Engineering, Jadavpur University, 188, Raja S.C. Mallick Road, Kolkata – 700032, West Bengal.
E-mail: prasunbhatta@gmail.com

Dr. Somenath Bhattacharya, Associate Professor, Department of Mechanical Engineering, Jadavpur University, 188, Raja S.C. Mallick Road, Kolkata – 700032, West Bengal.
E-mail: snb_ju@yahoo.com

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