Layout optimization of offshore wind farms for electricity and clean hydrogen production

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ABSTRACT

In several countries, energy planners have analyzed wind energy expansion in the sea to, e.g., diversify their electricity generation matrix. For example, in Brazil, 700 GW of offshore wind energy can be used to generate electricity. However, offshore wind projects have high costs related to capital expenditures and operating expenses. One way to reduce these costs is to evaluate the production of electrical energy and clean hydrogen. Thus, this work presents an optimization model to determine the optimal layout of offshore wind farms, minimizing capital expenditures and operating expenses. Such a model is formulated as a mixed-integer nonlinear optimization problem. This model is applied to determine the layout of 30 offshore wind turbines to be connected to a 220 kV substation at sea. The optimal configuration of the offshore wind farm is found using two metaheuristics and an optimization solver to ensure the best solution to the problem. The results of this model can help energy sector planners and agents in each country to use offshore potential energy better, meeting demands for electricity and clean hydrogen.

Keywords: Clean Hydrogen, Layout, Reconfiguration, Optimization, Wind Farm Offshore.

Introduction

The global demand for sustainable energy solutions has motivated energy planners in various countries to explore the expansion of offshore wind energy as a viable option for diversifying their electricity generation matrix [1]. In particular, countries like Brazil have recognized the immense potential of offshore wind, with an impressive capacity of around 700 GW, which promises to contribute significantly to their energy transition goals [2]. However, the implementation of offshore wind projects faces economic challenges due to high capital expenditures and operating expenses. To address these economic concerns and enhance the viability of offshore wind farms, researchers have focused on developing innovative optimization models that aim to minimize costs while maximizing energy output [3]. To deal with the challenge of economic viability and enhance commercial feasibility, several works have investigated the co-production of clean hydrogen as an auxiliary benefit of offshore wind energy generation. This approach not only provides a potential revenue stream but also aims at allowing the hydrogen production and storage systems to balance the electricity grid and facilitate the maximum utilization of offshore wind energy [4].

Thus, aiming to make offshore wind farms more attractive, the authors in [5] developed an algorithm based on clustering, minimum spanning tree, and firefly optimization, which can significantly decrease the total length of cables and its costs in the design phase of the project and, consequently, minimize the associated power losses. The optimized collection grid led to a 4.5 % cost reduction and a 6.4 % decrease in energy losses compared to the current layout of the floating offshore wind farm (FOWF). This optimization also incorporated dynamic power cables, factoring in their acquisition and installation expenses for connecting floating wind turbines [6].

The objective of this work is to introduce an innovative mathematical model for optimizing offshore wind farms consisting of wind turbines connected to one substation. The model addresses the complex challenge of simultaneously meeting electricity demand and producing clean hydrogen while adhering to a radial system configuration with connecting and fixed lines. It must also adhere to voltage

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limits and active/reactive generation constraints, resulting in a complex mixed-integer nonlinear optimization problem. To tackle these challenges, we employ the Flower Pollination Algorithm (FPA) algorithm [7], along with KNITRO commercial optimization solver. This integration enhances the model's effectiveness in finding optimal solutions for the intricate radial wind farm system with multiple generators and clean hydrogen production while meeting primary constraints. By considering these unique constraints, our model aims to optimize offshore wind farm layouts, contributing to renewable energy optimization and a sustainable energy future.

Problem Formulation

A. Objective Function

The objective function of the offshore wind farm optimization model is designed to minimize annual electrical losses and optimizes both CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) while seeking the optimal layout.

$$MinZ = \mu\,(losses) + CAPEX + OPEX \tag{1}$$

$$losses = \sum_{km\in\Omega_{lf}} [g_{km}(V_k^2 + V_m^2 - 2V_kV_m cos\theta_{km})] + \sum_{ij\in\Omega_{lc}} [g_{ij}(V_i^2 + V_j^2 - 2V_iV_j cos\theta_{ij})]y_{ij} \tag{2}$$

$$OPEX = -6.349\times10^8 \cdot P_{\text{WT}}^{0.187} + 2.595\times10^{-19}\cdot e^{0.830D} + 8.413\times10^5\cdot P_{\text{WF}} + 9.506\times10^8 \tag{3}$$

$$CAPEX = -1.485\times10^{11}\cdot P_{\text{WT}}^{0.001} + 2.353\times10^6\cdot\text{WD} + 2.530\times10^6\cdot D + 2.451\times10^6\cdot P_{\text{WF}} + 1.487\times10^{11} \tag{4}$$

In this context, the symbol μ represents the levelized cost of energy, term $losses$ represents the losses of the offshore wind farm, where Ω_{lf} represents the set of fixed lines, g_{km} denotes the conductance between buses k and m, and θ_{km} represents the difference between angle of bus k and bus m. Additionally, V_k and V_m indicate the voltage magnitude at buses k and m, respectively. Moreover, the notation Ω_{lc} represents the set of candidate lines. In this situation, g_{ij} represents the conductance between buses i and j, and θ_{ij} represents the difference between angle of bus i and bus j. The voltage magnitudes at buses i and j are denoted as V_i and V_j, respectively. Then we have the term y_{ij}, which is our decision variable and takes binary values 0 and 1, 0 indicating that the candidate line is open and 1 indicating that the candidate line is closed.

The terms $CAPEX$ and $OPEX$ have an important role in the economic evaluation of an offshore wind farm. $CAPEX$ refers to the capital costs associated with the construction of the wind farm, while $OPEX$ represents the annual operating costs, both of which are dependent on the wind turbine power (P_{WT}), distance to the coast (D), water depth (WD), and wind farm power (P_{WF}) [8].

B. Power Flow Constraint

The formulation of power flow equations holds paramount significance in the comprehensive analysis and design of electrical systems. These equations serve as the foundation for determining active and reactive power flows across transmission lines, being instrumental in assessing the behavior and stability of electrical grids.

$$PG_k - PD_k = V_k \sum_{m\in k} V_m(G_{km}cos\theta_{km} + B_{km}sin\theta_{km}) + V_i \sum_{j\in i} V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \tag{5}$$

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$$QG_k - QD_k = V_k \sum_{m \in k} V_m (G_{km} sin\theta_{km} + B_{km} cos\theta_{km}) + V_i \sum_{j \in i} V_j (G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij}) \quad (6)$$

where PG_k and QG_k represent active and reactive power generation, while PD_k, and QD_k stand for active and reactive power demand, respectively. Similarly, equations (7), (8) and (9) represents the constraints for the limit of generated active power, generated reactive power, and voltage, respectively [9].

$$P_G^{min} \leq P_G(V, \theta) \leq P_G^{max} \quad (7)$$

$$Q_G^{min} \leq Q_G(V, \theta) \leq Q_G^{max} \quad (8)$$

$$V^{min} \leq V_i \leq V^{max} \quad (9)$$

C. Radiality Restriction

The radiality constraint for connecting offshore wind plants is defined by equation.

$$|\Omega_{lf}| + \sum_{i,j \in \Omega_{lc}} y_{ij} = |\Omega_b| - 1 \quad (10)$$

where $|\Omega_{lf}|$ represents the number of fixed lines and $|\Omega_b|$ are the number of buses in the offshore wind farm.

D. Hydrogen Production

Clean hydrogen production is a crucial aspect in the context of sustainable energy generation. According to [10], the production of hydrogen from renewable sources, such as wind energy, can play an essential role in transitioning to a more efficient and environmentally friendly energy matrix.

$$W_{H_2,\text{prac}}(t) = \frac{D_{H_2} \times 1 \text{ hour}}{E_{elec}} \eta_{\text{conv}} [\text{kg/hour}] \quad (11)$$

where $W_{H_2,\text{prac}}(t)$ represents the practical hourly hydrogen production capacity, D_{H_2} represents the demand to be met for clean hydrogen production, E_{elec} is the electricity consumed for electrolyzing one unit of hydrogen (MWh/kg), and η_{conv} is the conversion efficiency.

Solution Techniques

The proposed strategy involves solving the same problem using two independent approaches: the Flower Pollination Algorithm (FPA) and the solver KNITRO.

A. Flower Pollination Algorithm

The Flower Pollination Algorithm (FPA), originally developed by Xin-She Yang in 2012, is based on the behavior of flowers in nature [7]. From a biological evolution standpoint, the purpose of flower pollination is the optimal reproduction of plants in terms of numbers, as well as the survival of the fittest. In the Global Pollination stage, flower pollen is carried by pollinators such as insects and birds, represented in 12.

$$X_i^{t+1} = X_i^t + L(X_i^t - g_*) \quad (12)$$

where X_i^{t+1} stands for flower i during iteration t, the best flower from the entire group of flowers at iteration t is denoted as g_*. Also, $L > 0$ is the Lévy flight step size, which indicates the pollination strength and this step size is determined from a Lévy distribution. The efficient motion of L is influenced by Lévy flight, a pattern similar to how insects move across both short and long distances. The model effectively follows this movement pattern as described in (13).

$$L \backsim \frac{\lambda \Gamma(\lambda) \sin(\pi \lambda /2)}{\pi} \frac{1}{\mathcal{S}^{1+\lambda}} \tag{13}$$

where $\Gamma(\lambda)$ is the standard gamma function, whose distribution is valid for large steps $\mathcal{S} > 0$. In most simulations, $\lambda = 1.5$ has been adopted. Equation (14) represent the local pollination and can be represented as:

$$X_i^{t+1} = X_i^t + \varepsilon(X_j^t - X_k^t) \tag{14}$$

where ε parameter enforces local pollination between two randomly chosen flowers within [0, 1]. Moreover X_j^t and X_k^t are flowers obtained from different but similar species obtained from the solution set.

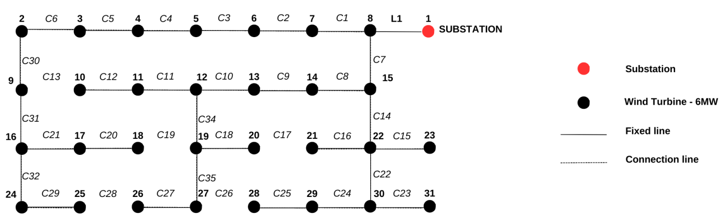
Results

The model proposed in this paper is applied to a system of 30 wind turbines, each with a capacity of 6 MW, adapted from [11] at a 220 kV voltage level with a distance D to the coast of 36 km and water depth WD of 26 km. We utilized the KNITRO solver and the FPA metaheuristic with a population size of 80 flowers $('N')$ to effectively explore the solution space. Additionally, we set a maximum of 100 iterations $iter_{max}$ to control the FPA algorithm's stopping criterion.

For the KNITRO solver, the obtained results show a CAPEX and OPEX of \$639.646 million and \$260.226 million, respectively, along with electrical losses of about 0.038 MW. In contrast, the FPA metaheuristic yielded CAPEX and OPEX costs of approximately \$640.378 million and \$260.714 million, respectively, with electrical losses of roughly 0.0504 MW. The difference between the KNITRO solver technique and FPA resides in the fact that some wind turbines do not reach their maximum power generation capacity. Moreover, our model demonstrates that we can produce 1562.4 kg/h of clean hydrogen with a 100 MW generation capacity. These results highlight the effectiveness of our model in planning offshore wind farms, indicating a promising future for clean energy and hydrogen production. Figure 1, illustrates the design of the offshore wind farm consisting of 30 wind turbines and 1 substation. This system encompasses a fixed line and 35 candidate lines that interconnect the offshore wind turbines.

During the model implementation, it was prominently highlighted that as the complexity of the problem increased, both the solver and the metaheuristics failed to find a solution, KNITRO was effective up to a dimension of 37 candidate lines, while FPA worked effectively up to a dimension of 47 candidate lines. This challenge was primarily attributed to the exponential growth of the problem in terms of dimensions and variables. The simulations carried out using a computer with an Intel® Core™ i7 CPU @ 1.8 GHz processor, with 4 GB of RAM and Windows 10 Home - 64-bit operating system.

Figure 1: Optimized Wind Farm Layout



Conclusion

In this study, we have presented a mathematical model for optimizing offshore wind farms with the goal of reducing capital costs, operational costs, losses, and meeting a demand for clean hydrogen

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production. The proposed model was solved using the FPA algorithm and the KNITRO solver. Thus, in order to provide information for offshore wind farm planning, an optimization model for offshore wind farms with a clean hydrogen demand was presented. Finally, this study can emphasize the importance of concessionaire companies in efficiently planning and making offshore wind generation systems viable.

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