Capacity optimization of renewable energy microgrid considering hydropower cogeneration

Lijun Fan* and Jiedong Cui
School of Mechanical Engineering, TianGong University, Tianjin, China
*Corresponding author e-mail: fanlijun0613@163.com

Abstract. This paper proposes a renewable energy system based on photovoltaic power generation, wind power generation and solar thermal power generation, combining thermal power plants with low-temperature multi-effect distillation. Through the electric heater and the thermal storage system photovoltaic and wind power will spare capacity in the form of heat energy, at the same time by thermal power generation system to maintain the stability of the power supply, run under constant output scheduling policy, to the levelling of the smallest energy cost and the design of power rate of maximum satisfaction as the goal, using multi-objective particle swarm optimization (PSO) algorithm to find the best combination of capacity, this system is established. At the same time, combined with low-temperature multi-effect distillation, compared with reverse osmosis seawater desalination cost is lower, reduce energy consumption, has a good application prospect.

1. Introduction
In today's world, electricity is generated mainly from fossil fuels. To reduce the impact of fossil fuels on the environment, use cleaner energy sources. Solar and wind energy are abundant clean energy sources, however, in the absence of complementary power generation systems or/and energy storage systems (ESS) [1], it can lead to unreliable power generation systems. Therefore, a combination of multiple renewable energy (RE) technologies is needed to improve the efficiency of the system.

Wahib Khiari et al. proposed a solution combining wind energy, solar energy and reverse osmosis seawater desalination [2]. The combination of photovoltaic and wind power can improve system efficiency, but in the absence of complementary power generation system or energy storage system, hybrid power generation system is still inefficient [3]. Therefore, it is necessary to provide an energy supply that can continuously output power to support load demand [4]. Combining different renewable energy and energy storage systems can improve system stability. Thermal power plants (CSPS) with thermal energy storage systems operate stably under intermittent solar energy. Therefore, it has attracted the attention of many scholars and is very attractive for combined power generation and desalination plants. Multi-effect distillation uses low-temperature steam as a heat source and is the only commercially proven technology that can operate under partial load conditions so far.

In this paper, CSP is combined with wind power and photovoltaic power generation to reduce the impact of conventional energy on the environment and improve the stability of the system. The low temperature exhaust steam of steam turbine is used as the heat source of low temperature multi-effect distillation and the cost of water production is reduced. Use reverse osmosis equipment to produce water
together. The system runs under the scheduling strategy of constant output, and takes the satisfaction rate of design power and LCOE (leveling energy cost) as optimization objectives, and adopts multi-objective particle swarm optimization algorithm to optimize capacity.

2. Configuration of microgrid system for combined hydropower generation

2.1. Overall structure

![System configuration diagram.](image)

**Figure 1.** System configuration diagram.

2.2. System description.
The system configuration is shown in Fig 1. Wind power, photovoltaic power station, and thermal field is the main energy source, EH is used to reduce the time limit of power wind power and photovoltaic power station, TES system to store heat from heat field and EH, the two work together to enhance the stability of wind farms and photovoltaic power station, reduce volatility, enables the system to try to keep in the design of power under the external power supply. Multieffect distillation is combined with a steam turbine, using the exhaust steam from the turbine as the driving steam. Because multi-effect distillation is combined with CSP, the minimum power of CSP is 40% of the design specification.

3. Mathematical modeling of system components

3.1. Wind turbine model

The hourly power output of the wind turbine is obtained through the equation [5]:

\[
P_w(t) = \begin{cases} 
0 & 0 \leq V < V_{cut-in} \text{ and } V > V_{cut-out} \\
0 & V_{cut-in} \leq V < V_r \\
V_r \leq V \leq V_{cut-out} 
\end{cases}
\]

(1)

Where: \( V_{cut-in} \) is the cut wind speed; \( V_{cut-out} \) is the cutting wind speed; \( V_r \) is rated speed of wind turbine.

3.2. Solar panel power generation model.
The output of photovoltaic panels depends on solar radiation and ambient temperature, and the output power of photovoltaic modules can be expressed as:

\[
P_{pv} = P_{stc} \cdot \frac{S}{S_{stc}} (1 + \varepsilon \cdot (T - T_{stc}))
\]

(2)
Where, $P_{PV}$ and $P_{STC}$ represent the actual photovoltaic power output and the maximum power output (STC) under standard STC conditions respectively; $S$ and $S_{STC}$ represent the actual solar radiation and STC radiation respectively; $T$ and $T_{STC}$ represent the ambient temperature and STC temperature $\varepsilon$ as temperature coefficients respectively.

### 3.3. Mathematical model of heat collection field.

\[
P_{sf}' = \eta_{sf} \cdot S_{sf} \cdot R_t
\]

\[
P_{sf}' = P_{TES}' + P_{PB}'
\]

The available solar thermal power in time period $T$ is expressed in the above equation, where $\eta_{sf}$ is the efficiency from radiation to heat, $S_{sf}$ is the total mirror area of the solar field, and $R_t$ is the average direct normal irradiation during the time period $T$ is the thermal power input into TES, and is the thermal power directly input into PB.

### 4. Fitness function

The system has two optimization objectives, one is to minimize the energy cost LCOE, and the other is to maximize the satisfaction rate $PS$ of the system design power, that is, to minimize the power loss probability. The decision variables are the capacity of photovoltaic power station, the capacity of wind farm, the area of heat collecting field and the capacity of TES.

The standardized energy cost is the ratio of the total cost of a power generation system to the total generation capacity over its life cycle.

\[
C_{IN} = C_w \cdot U_w + C_{PV} \cdot U_{PV} + C_{TES} \cdot U_{TES} + C_{PB} \cdot U_{PB} + C_{EH} \cdot U_{EH} + C_{MED} \cdot U_{MED} + C_{Rg} \cdot U_{Rg}
\]

\[
C_s = C_w \cdot U_w \cdot k_w + C_{PV} \cdot U_{PV} \cdot k_{PV} + C_{TES} \cdot U_{TES} \cdot k_{TES} + C_{PB} \cdot U_{PB} \cdot k_{PB} + C_{EH} \cdot U_{EH} \cdot k_{EH} + C_{sf} \cdot U_{sf} \cdot k_{sf}
\]

$C_{IN}$ represents the initial installation cost of the system proposed in this paper, $C_s$ Represents the maintenance cost of each part of the system, $C$ represents the installation volume of each part of the system, $U$ represents the unit cost, and $K$ represents the percentage of maintenance cost in the initial installation cost.

\[
LCOE = \frac{C_{IN} + \sum_{i=1}^{n} \frac{C_s}{(1+i)^n}}{E_w \cdot (1 - r_w)^n + E_{pg} \cdot (1 - r_{pg})^n + E_{pv} \cdot (1 - r_{pv})^n}
\]

In the formula, $R$ represents the attenuation rate of each part, $E$ represents the total power generation of each part in the first year of installation, $I$ is the discount rate, and $N$ is the expected life cycle of the system, which is 20 years in this paper.

\[
P_s = \sum_{t=1}^{8760} \frac{(E_w(t) \cdot l + E_{PV}(t) \cdot l + E_{PB}(t) \cdot l)}{E_{DE} \cdot 8760}
\]

The maximum satisfaction rate of the design power is expressed as the ratio of the sum of the electric quantity which is finally absorbed into the main AC line by each part after adjustment within a year and the design power. $E_w(t)$, $E_{PV}(t)$, $E_{PB}(t)$ respectively represent the power input to the main AC line by wind farm, photovoltaic power station and PB part after the regulation strategy of the system. $E_{DE}$ Represents the design work of the system. $T$ is the time interval, and is one hour.

The fitness function of multi-objective optimization of this system is
\[
\min = \begin{cases} 
F_1 = LCOE(C_{(1)}, C_{(2)}, C_{(3)}, C_{(4)}) \\
F_2 = -P_s(C_{(1)}, C_{(2)}, C_{(3)}, C_{(4)}) 
\end{cases}
\] (8)

\(C_{(1)}, C_{(2)}, C_{(3)}, C_{(4)}\) Respectively represent the installation capacity of photovoltaic power station, the installation capacity of wind farm, the area of heat collecting field and the capacity of TES. The range of values for each variable is as follows

\[
\begin{align*}
C_{(1)}^{\text{min}} & \leq C_{(1)} \leq C_{(1)}^{\text{max}} \\
C_{(2)}^{\text{min}} & \leq C_{(2)} \leq C_{(2)}^{\text{max}} \\
C_{(3)}^{\text{min}} & \leq C_{(3)} \leq C_{(3)}^{\text{max}} \\
C_{(4)}^{\text{min}} & \leq C_{(4)} \leq C_{(4)}^{\text{max}}
\end{align*}
\] (9)

5. Case study

5.1. Data preparation

The system needs to be rich in solar energy and wind energy, so it needs low-latitude areas. At the same time, the source of seawater for desalination is considered to meet the daily water demand of nearby residents and at the same time, the excess electricity is transferred to the power grid. Masira Island (20.7° N/58.9° E) in Oman, a Mediterranean country, was selected for analysis. The weather data is shown in Fig 2-4.

5.2. Optimization results

The figure above depicts Pareto front for multi-objective optimization. The Pareto frontier helps decision makers select optimal solutions from optimal solution sets. The Pareto front can be divided into four regions. From point E to point D, \(P_s\) increases from 0.8036 to 0.8831, while LCOE increases only slightly by 0.0082$/kWh, so improving \(P_s\) is cost-effective. From point D to point C, this region shows a relatively moderate increment with the increase of LCOE, and this region is always considered to be the optimal Pareto region because the points in this region have relatively good comprehensive performance. From point C to point B, \(P_s\) increases slightly from 0.9776 to 1, but LCOE increases greatly, which is 0.0281$/kWh. From point B to point A, \(P_s\) equals 1, and increasing the installation quantity will only increase the cost.

Fig 2. DNI  
Fig 3. Wind speed  
Fig 4. GHI and temperature
5.3. Result analysis

From the perspective of power generation system, it is necessary to provide external power under the design power under the condition of smooth operation of the system as far as possible. Therefore, this paper analyzes the system under the condition of maximum PS, and selects the maximum satisfaction rate point B in the figure. The installed capacity of each part is shown in Table 1.

| System       | CPV (KW) | Cw (KW) | Cs (m²) | CTES (h) | LCOE ($/KWh) | Ps |
|--------------|----------|---------|---------|----------|--------------|----|
| PV-WIND-CSP  | 3978.3   | 3700.6  | 4000    | 64.4     | 0.1890       | 1  |

The heat source of multi-effect distillation is from the exhaust steam discharged by the steam turbine, so the water yield of multi effect distillation can be obtained according to the power output of CSP, as shown in Fig 6.

The red line in the Fig 6 shows the daily water demand of the island. It can be seen that the water yield of multi effect distillation is not enough to meet people's daily water demand, so the reverse osmosis equipment needs to be connected to produce water.

In this system, the LCOE is 0.1890$/kWh, which can calculate the power consumption and power cost of RO equipment. Ignoring the heat source cost, the water production cost can be calculated as 0.6375$/t from the equipment cost and maintenance cost. If the power cost in this system is considered without Med, the water production cost is 1.2421$/t. The cost was reduced by 48.7%.
6. Conclusion
This paper proposes a 100% renewable energy generation system that considers hydropower cogeneration. The system consists of wind farm, photovoltaic power station, CSP system, electric heater, multi-effect distillation and reverse osmosis equipment. The optimization objective of the system is to minimize the leveling energy cost and maximize the satisfaction rate of design power. The capacity optimization is solved by multi-objective particle swarm optimization algorithm, and the solution collective is in Pareto front. Through the comparison of three different combination forms, it is found that under the condition of high satisfaction rate, the system proposed in this paper has good economy, and the cost of water production is 48.7% lower than that of using reverse osmosis equipment. Therefore, the proposed system has a good application under the concept of future cost reduction and sustainable development.

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