

# Optimal Configuration of Off-grid Hybrid Renewable Energy System with PV/Wind/Hydrogen/Cooling

Leijiao Ge<sup>✉</sup>, Senior Member, IEEE, Member, CSEE, Jiaheng Liu, Student Member, IEEE, Member, CSEE, Zhongguan Wang, Member, IEEE, Member, CSEE, and Muhammad Umer Rafiq, Member, CSEE

**Abstract**—Hydrogen storage and ice storage are promising, environmentally friendly energy storage technologies. However, there are few investigations on the optimal configuration of hybrid renewable energy systems (HRES) for remote off-grid areas with localized scenarios. This paper proposes a new optimal configuration of an off-grid PV/wind/hydrogen/cooling system. Given three performance indices for evaluating HRES, i.e., the levelized cost of energy (LCOE), the loss of power supply possibility (LPSP), and the power curtailment rate (PCR), we use the  $\varepsilon$ -constraint method that formulates LCOE as the objective, while LPSP and PCR serve as constraints. Furthermore, to solve the optimal size of HRES, an improved salp swarm algorithm (ISSA) is proposed. The simulation results show that for an off-grid remote community, the LCOE, LPSP, and PCR of the optimal HRES configuration can achieve \$0.31/kWh, 5.00%, and 7.23%, respectively. The comparison of different systems illustrates that adding ice storage in the HRES with hydrogen storage will decrease the LCOE by 27.12%. In addition, compared with other heuristic algorithms, such as SSA, ISSA offers the configuration with the minimum LCOE. The hydrogen-ice storage system is economically significant to off-grid areas with cooling load demand, and the proposed ISSA has excellent accuracy.

**Index Terms**—Hybrid renewable energy systems, hydrogen storage, ice storage, improved salp swarm algorithm, off-grid.

## I. INTRODUCTION

WHILE most of the increasing power demands around the world have been served by interconnected power grids, many remote areas are unable to connect to the grid due to the harsh environment and high transmission costs [1]. Diesel power generators, with their high flexibility, have been the main power supply mode in off-grid areas [2]. However, in recent years, the price of diesel and the cost of transportation

have been on the rise, rendering it a less economical option [3]. The harsh remote environment can often restrict or disrupt fuel supply, and the carbon emission also comes with high environmental costs as the world is progressing toward clean and efficient renewable energy [4]. These challenges require alternative supplies to meet the demand of remote communities that have equal rights to access reliable energy [5]. Meanwhile, it is notable that many remote areas are rich in natural renewable resources, an ideal condition for the adoption of off-grid hybrid renewable energy systems (HRESs), which integrate various distributed renewable energy generation from, e.g., solar, wind, and biomass energy, to locally supply the energy demand in these remote areas [6].

However, due to the intermittence and volatility of renewable energy, the power supply and demand in off-grid areas are difficult to balance [7]. The installation of energy storage devices is beneficial for both reliability and cost-effectiveness, as they can store excessive energy at high generation and release it in the event of a power shortage [8]. While battery-based energy storage has been a popular choice, studies have pointed out that most of them still have insufficient energy density and lifespan as a reliable long-term solution for the off-grid communities [9][10].

There are many mature energy storage technologies, such as pumped storage [11], compressed air [12], supercapacitors [13], and hydrogen [14], [15]. Hydrogen energy storage has a much higher energy density, suitable for long-term storage capacity [16]. A hydrogen storage system mainly includes the electrolyzer, the fuel cell [17], and the hydrogen tank. The electrolyzer and fuel cell are pollution-free during the manufacturing and operation stages [18]. Zhang *et al.* [19] compared an off-grid PV/WT/battery system with a PV/WT/hydrogen storage system, and, through a detailed analysis of costs and advantages, this study suggested that hydrogen storage will gradually become the predominant solution with the reduction of hydrogen storage costs. Moghaddam *et al.* [20] optimized a PV/WT/fuel cell/hydrogen hybrid system to minimize the total net present value (TNPC) in northwest Iran, with the loss of energy expected (LOEE), and LOLE as the constraints. However, the above research only considers hydrogen as energy storage and does not consider that the slow hydrogen charging and discharging speed will affect the system performance. Xu *et al.* [21] pointed out in their recent study that combining

Manuscript received October 7, 2021; revised December 27, 2021; accepted February 20, 2022. Date of online publication August 18, 2022; date of current version May 16, 2025. This work was supported by National Key R&D Program of China (No.2018YFB1500800), National Natural Science Foundation of China (No. 51807134), Science and Technology Project of State Grid Corporation, and State Key Laboratory of Power System and Generation Equipment (SKLD21KM10).

L. J. Ge (ORCID: <https://orcid.org/0000-0001-6310-6986>), J. H. Liu, Z. G. Wang (corresponding author, email: [wang\\_zg@tju.edu.cn](mailto:wang_zg@tju.edu.cn)), and M. U. Rafiq are with the Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China.

DOI: 10.17775/CSEEJPES.2021.07430

hydrogen storage systems with other storage systems, such as batteries, is of great significance for improving the slow charging and discharging speed of hydrogen storage systems. Therefore, combining the hydrogen storage system with other storage systems is a promising approach for an energy storage method.

Many off-grid areas, which are rich in renewable resources, are also hot spots [22], where cooling systems, such as air-conditioning for resorts, hotels, and refrigerated food warehouses, pose a considerably higher demand for energy throughout the year [23]. Cooling water, ice [24], and other cold thermal energy storage operations, such as storage media, have been widely used for these cooling systems. Arcuri *et al.* Reference [25] studied the technical-economic aspects of Brazil's ice storage technology and found that in areas with hot climates, ice storage technology has higher economic benefits. Sepehri *et al.* [26] analyzed the energy and emissions of ice storage in the western U.S. and found that ice energy storage reduces the energy consumption for many U.S. cities. However, the above references only focus on ice storage for the optimized configuration of off-grid HRES, which does not consider the combination of power storage and cold storage. Luerssen *et al.* Reference [27] studied the cooling systems of battery and cold storage in Singapore offices, hotels, and cold storage warehouses using TRNSYS software. This study emphasized that cold storage has great potential for applications in systems that require a greater shift of energy. Another study by this author [28] analyzed the life cycle cost of seven system configurations, including PV, diesel generator, battery, and ice storage components in the Riau Islands, Indonesia. This study showed that adding PV and additional batteries to diesel generators can reduce the life cycle costs of PV-powered cooling systems. However, the environmental impact of diesel fuel and batteries was not considered in the study.

As mentioned earlier, hydrogen and ice storage have unique advantages and are widely used in HRES. Hydrogen has the advantages of high energy efficiency and no pollution. When there is a great demand for cooling loads in off-grid areas, a large amount of loss will inevitably occur in the conversion process of hydrogen-power-cooling. Ice storage can directly provide cooling load, omitting the step of converting hydrogen into cooling, which can solve the problem of low hydrogen utilization efficiency. As far as the authors know, in previous research, the off-grid HRES optimization configuration of the hydrogen-ice storage system has rarely been investigated. Therefore, this paper aims to identify an optimal configuration method for an off-grid HRES with PV/wind/hydrogen/cooling. The main contributions of this paper are as follows.

1) In comparison to the previous studies on the optimal configuration of the off-grid HRES, the optimal configuration of the hydrogen-ice hybrid storage system is rarely investigated. Therefore, in this paper, an optimal configuration method is proposed to identify the size of the PV system, WT system, hydrogen storage, chiller, and ice storage capacity. On the premise of ensuring reliability and reducing renewable energy abandonment, the economic optimal configuration of PV/wind/hydrogen/cooling is solved.

2) In the off-grid HRES with a hydrogen-ice storage system, the types of loads that need to be considered are power and cooling load, which are different from studies that only considered one type of load. Given that the previously mentioned operating strategies do not simultaneously consider power-cooling load, we propose a new operation strategy for the hydrogen-ice storage system.

3) We consider the salp swarm algorithm (SSA) [29] to configure off-grid HRES. Although SSA has excellent optimization performance in the existing heuristic algorithms, the leader and follower mechanisms still cause the algorithm to fall into a local optimum. Therefore, an improved salp swarm algorithm (ISSA) is proposed to enhance the effect of the off-grid HRES optimization.

4) We apply the proposed method to solve the off-grid HRES optimal configuration in Yinchuan, Ningxia, China. This case study of the optimal configuration is based on actual resource data in a local meteorological observatory (longitude 106.2, latitude 38.47). The simulation results of the case show that the hydrogen-ice storage system LCOE is reduced by \$0.083/kWh, or 27.12% in percentage terms, compared with only using a hydrogen storage system.

The rest of the paper is organized as follows: In Section II, the component model of the system is introduced. In Section III, the objective function and constraint conditions of HRES are introduced, and the operation strategy of HRES in this paper is formulated. In Section IV, the ISSA algorithm is proposed. A case study is carried out in Section V. Section VI concludes the paper.

## II. DESCRIPTION OF THE HRES SYSTEM

### A. Overview of HRES

The simplified scheme of off-grid HRES is shown in Fig. 1, including PV, WT, electrolyzer [30], fuel cell [31], hydrogen tank, electrical chiller (Vapor Compression Refrigeration, VCR), and ice tank. The technology of the electrolyzer, and hydrogen tank is consistent with the references mentioned above. It is worth noting that according to the research of Sanaya *et al.* [32], the use of absorption chillers in certain weather conditions, such as ambient temperature, will be restricted. In contrast, VCR is a better solution for providing cooling load. Therefore, VCR was chosen as the cooler of HRES in this paper, while ice storage, cold water storage, and other refrigerants have the same properties. Therefore, the method in this paper can be extended to the case of more cold storage media.

### B. Modeling of PV Panels

The output of PV panels  $P_o^{PV}(t)$  at time  $t$  is described as follows:

$$P_o^{PV}(t) = P_s I_{pv}(t) [1 + \alpha(T_{pv}(t) - T_s)] F_d \quad (1)$$

$$T_{pv}(t) = T_{amb}(t) + \left[ \frac{T_{NOC,a} - T_{NOC,c}}{G} \right] [I_{pv}(t)] \quad (2)$$

where  $P_s$  is the rated power of the PV panel,  $I_{pv}(t)$  is the solar radiation density at time  $t$ ,  $F_d$  is the derating factor,  $\alpha$  is the temperature coefficient,  $T_{pv}(t)$  is the temperature of the

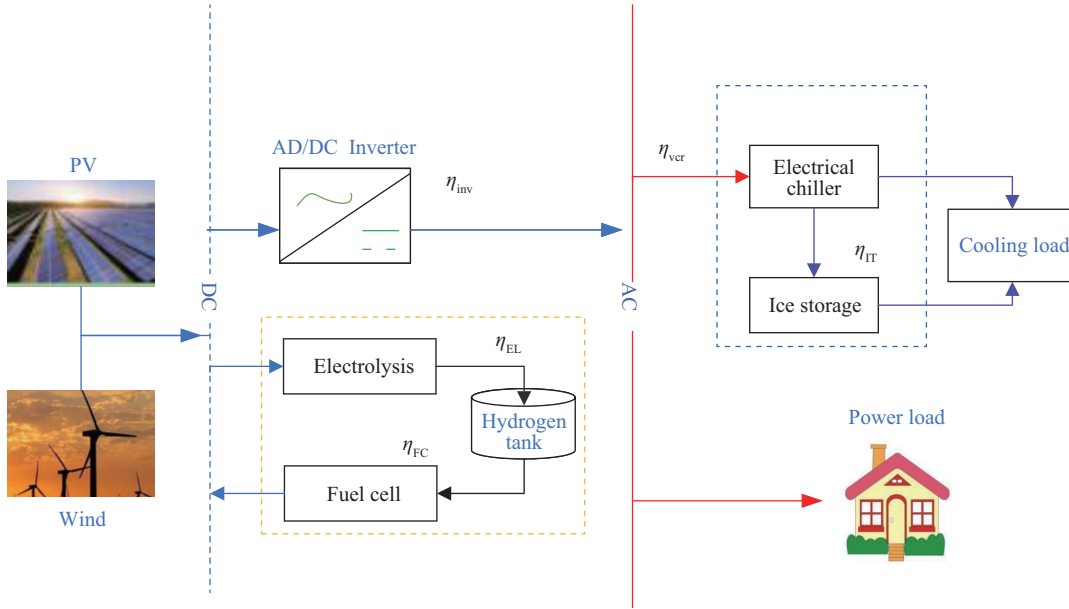


Fig. 1. The simplified scheme of off-grid HRES.

PV panel, and  $T_S$  shows the ambient temperature at standard conditions.  $T_{\text{NOC},a}$  represents the nominal operation temperature of the cell.  $T_{\text{NOC},c}$  is the nominal operation temperature of ambience,  $G$  is the radiation intensity at nominal operation temperature. Table I shows the parameters of the PV panels.

### C. Modeling of Wind Turbines

According to the cut-in wind speed, cut-out wind speed, and rated wind speed, the power output  $P_{\text{WT}}(t)$  of the three parts is calculated as follows [8]:

$$P_{\text{WT}}(t) = \begin{cases} 0 & v(t) \leq v_{\text{in}} \text{ or } v(t) > v_{\text{out}} \\ P_r & \frac{v(t)-v_{\text{in}}}{v_r-v_{\text{in}}}, v_{\text{in}} \leq v(t) \leq v_r \\ P_r & v_{\text{in}} \leq v(t) \leq v_r \end{cases} \quad (3)$$

where  $P_r$  is the rated power of the wind turbine,  $v(t)$  is the actual wind speed at time  $t$ ,  $v_{\text{in}}$ ,  $v_{\text{out}}$ , and  $v_r$  represent the cut-in wind speed, cut-out wind speed, and rated wind speed, respectively. Table II shows the parameters of wind turbines.

### D. Modeling of Hydrogen Energy Storage System

The storage capacity of the hydrogen energy storage system in charged and discharged states is described as follows [21].

charging:

$$\begin{cases} S_{\text{OC,HT}}(t) = S_{\text{OC,HT}}(t-1) + \eta_{\text{EL}} \cdot P_{\text{EL}}(t) \cdot \rho \\ P_{\text{EL}}(t) = P_g(t) - P_L(t)/\eta_{\text{inv}} \end{cases} \quad (4)$$

discharging:

$$\begin{cases} S_{\text{OC,HT}}(t) = S_{\text{OC,HT}}(t-1) - P_{\text{FC}}(t)/\eta_{\text{FC}}\eta \\ P_{\text{FC}}(t) = P_L(t)/\eta_{\text{inv}} - P_g(t) \end{cases} \quad (5)$$

where  $S_{\text{OC,HT}}(t)$  and  $S_{\text{OC,HT}}(t-1)$  respectively represent the hydrogen capacity of the hydrogen storage tank at time  $t$  and  $t-1$ ;  $P_{\text{EL}}(t)$  is the power of electrolyzer components at time  $t$ ,  $P_{\text{FC}}(t)$  is the power of fuel cell components at time  $t$ ;  $P_L(t)$  is the power load demand at time  $t$ ,  $P_g(t)$  is the power

TABLE I  
PARAMETERS OF THE PV PANELS [33]

| Parameters                                                       | Values                |
|------------------------------------------------------------------|-----------------------|
| Output power ( $P_s$ )                                           | 325 W                 |
| Derating factor ( $F_d$ )                                        | 80 %                  |
| Temperature coefficient at standard conditions ( $\alpha$ )      | -0.005                |
| Ambient temperature ( $T_S$ )                                    | 25°C                  |
| Nominal operation temperature of the cell ( $T_{\text{NOC},a}$ ) | 45°C                  |
| Nominal operation temperature of ambience ( $T_{\text{NOC},c}$ ) | 20°C                  |
| Radiation intensity at nominal operation temperature ( $G$ )     | 0.8 kW/m <sup>2</sup> |

TABLE II  
PARAMETERS OF THE WIND TURBINE

| Parameters                         | Values |
|------------------------------------|--------|
| Rated capacity ( $P_r$ )           | 10 KW  |
| Rated speed ( $v_r$ )              | 11 m/s |
| Cut-in speed ( $v_{\text{in}}$ )   | 2 m/s  |
| Cut-out speed ( $v_{\text{out}}$ ) | 25 m/s |

of renewable energy at time  $t$ ,  $\eta_{\text{inv}}$  is the inverter efficiency, and  $\eta_{\text{EL}}$  is the charging efficiency of the electrolyzer,  $\eta_{\text{FC}}$  is the discharge efficiency of the fuel cell,  $\rho$  is the hydrogen production efficiency per kilowatt of electricity, and  $\eta$  is the electricity produced per cubic meter of hydrogen. The value of  $\rho$  is 0.28 m<sup>3</sup>/KWh and  $\eta$  is 1.55 KWh/m<sup>3</sup> [21].

### E. Modeling of the Electrical Chiller and Ice Tank

The electric chiller of the HRES primarily refers to the VCR, which provides the necessary output power for the cooling load, as follows:

$$P_{\text{vcr}}(t) = \eta_{\text{vcr}} P_g(t) \quad (6)$$

where  $P_{\text{vcr}}(t)$  is the power of the electric refrigerator at time  $t$ , and  $\eta_{\text{vcr}}$  is the efficiency of the electric refrigerator.

The storage capacity of the ice tank in charged and discharged states is described as follows:

charging:

$$\begin{cases} S_{OC,IT}(t) = S_{OC,IT}(t-1) + P_{IT,ch}(t)\eta_{IT,chr} \\ P_{IT,ch}(t) = P_g(t)\eta_{inv}\eta_{vcr} - P_{IL}(t) \end{cases} \quad (7)$$

discharging:

$$\begin{cases} S_{OC,IT}(t) = S_{OC,IT}(t-1) - P_{IT,dis}(t)/\eta_{IT,dis} \\ P_{IT,dis}(t) = P_{IL}(t) - P_g(t)\eta_{inv}\eta_{vcr} \end{cases} \quad (8)$$

where  $S_{OC,IT}(t)$  and  $S_{OC,IT}(t-1)$  respectively represent the energy in the ice tank at time  $t$  and  $t-1$ , and  $P_{IT,ch}(t)$  is the charging power of the ice tank.  $\eta_{IT,chr}$  is the charging efficiency of the ice tank.  $\eta_{IT,dis}$  is the discharge efficiency of the ice tank.  $P_{IT,dis}(t)$  is the discharge power of ice tank, and  $P_{IL}(t)$  is the cooling load demand at time  $t$ . Table III shows the efficiency of HRES components.

TABLE III  
PARAMETERS FOR EFFICIENCIES

| Parameters                                             | Values |
|--------------------------------------------------------|--------|
| Inverter efficiency ( $\eta_{inv}$ )                   | 97%    |
| Electrolyzer charging efficiency ( $\eta_{EL}$ )       | 60%    |
| Fuel cell efficiency ( $\eta_{FC}$ )                   | 75%    |
| Electrical chiller efficiency ( $\eta_{vcr}$ )         | 80%    |
| Ice storage charging efficiency ( $\eta_{IT,chr}$ )    | 85%    |
| Ice storage discharging efficiency ( $\eta_{IT,dis}$ ) | 75%    |

### III. OPTIMAL CONFIGURATION OF HRES

The paper considers the Levelized cost of electricity (LCOE), Loss of power supply possibility (LPSP), and Power curtailment rate (PCR) as the techno-economic evaluation criteria of HRES.

#### A. Levelized Cost of Electricity (LCOE)

$L_{COE}$  represents the cost per kWh of power generation throughout the life cycle, which is described below [33]:

$$L_{COE} = \frac{C_{RF}T_{NPC}}{\sum_{t=1}^{8760} P_U(t)} \quad (9)$$

$$C_{RF} = \frac{r(1+r)^y}{(1+r)^y - 1} \quad (10)$$

where  $C_{RF}$  is the capital recovery rate.  $r$  is the interest rate.  $y$  is the lifetime of the life cycle,  $P_U(t)$  is the amount of electricity that HRES and load can match,  $T_{NPC}$  stands for the total net present cost of the project, which is described below.

$$T_{NPC} = N_{PC,PV} + N_{PC,WT} + N_{PC,vcr} + N_{PC,IT} + N_{PC,EL} + N_{PC,FC} + N_{PC,HT} \quad (11)$$

where  $N_{PC,PV}$  is the total cost of PV.  $N_{PC,WT}$  is the total cost of WT.  $N_{PC,vcr}$  is the total cost of electrical chiller,  $N_{PC,IT}$  is the total cost of ice tank,  $N_{PC,EL}$  is the total cost of electrolyzer,  $N_{PC,FC}$  is the total cost of fuel cells, and  $N_{PC,HT}$  is the total cost of hydrogen energy storage. Use electrolyzers as an example, then the net present cost of the electrolyzers ( $N_{PC,EL}$ ) can be expressed as follows. The total net present cost of other components is calculated in the same way as for the electrolyzer.

$$N_{PC,EL} = I_{EL} + O_{M,EL} + R_{EL} \quad (12)$$

$$I_{EL} = p_{EL} \times N_{EL} \quad (13)$$

$$O_{M,EL} = O_{m,EL} \times N_{EL} \times \sum_{n=1}^y \left( \frac{1}{1+r} \right)^n \quad (14)$$

$$R_{EL} = r_{EL} \times N_{EL} \times \sum_{n=Z, 2Z, \dots, 20} \left( \frac{1}{1+r} \right)^n \quad (15)$$

where  $N_{PC,EL}$  is the net present cost of the electrolyzers.  $I_{EL}$  indicates the investment cost of the electrolyzers.  $O_{M,EL}$  is the operation and maintenance cost of the electrolyzers.  $R_{EL}$  is the replacement cost of the electrolyzers.  $p_{EL}$  is the price of each electrolyzer.  $N_{EL}$  is the number of the electrolyzers.  $O_{m,EL}$  is the annual operation and maintenance cost of each of the electrolyzers.  $r_{EL}$  is the replacement cost for one time.  $Z$  indicates the lifetime of the electrolyzers. The economic parameters of the system components are described in Table IV. Among them, part of the parameters comes from literature [34], [35].

TABLE IV  
ECONOMIC PARAMETERS OF SYSTEM COMPONENTS

| Components    | Parameters              | Values       |
|---------------|-------------------------|--------------|
| PV            | Capital cost            | \$200        |
|               | O&M cost                | \$4/year     |
|               | Lifetime                | 20 years     |
| WT            | Capital cost            | \$4100       |
|               | O&M cost                | \$82.16/year |
|               | Lifetime                | 20 years     |
| Fuel cell     | Capital cost            | \$6000       |
|               | O&M cost                | \$120/year   |
|               | Replacement cost        | 5000         |
|               | Rated power             | 2 kW         |
|               | Lifetime                | 5 years      |
| Electrolyzer  | Capital cost            | \$4000       |
|               | O&M cost                | \$20/year    |
|               | Replacement cost        | \$3000       |
|               | Rated power             | 2 kW         |
|               | Lifetime                | 15 years     |
| Hydrogen tank | Capital cost            | \$3960       |
|               | O&M cost                | \$79.20/year |
|               | Rated power             | 6 m3         |
|               | Lifetime                | 20 years     |
| VCR           | Capital cost            | \$3180       |
|               | O&M cost                | \$159        |
|               | Replacement cost        | \$2200       |
|               | Rated power             | 2 kW         |
|               | Lifetime                | 5 years      |
| Ice tank      | Capital cost            | \$2320       |
|               | O&M cost                | \$116        |
|               | Rated capacity          | 6 kW         |
|               | Rated charging power    | 2 kW         |
|               | Rated discharging power | 2 kW         |
|               | Lifetime                | 5 years      |

#### B. Loss of Power Supply Possibility (LPSP)

1)  $L_{PSP}$  is the proportion of the unmet load demand to the total load demand of HRES, which can be calculated as follows:

$$L_{PSP} = \frac{\left( \sum_{t=1}^T \max\{P_L(t) + P_{IL}(t) - P_{WT}(t) - P_{PV}(t) - P_{IT}(t-1) - P_{HS}(t-1), 0\} \right)}{\sum_{t=1}^T (P_L(t) + P_{IL}(t))} \quad (16)$$

where  $P_{IT}(t-1)$  is the power of the ice tank at time  $t$ ;  $P_{HS}(t-1)$  is the hydrogen storage tank at time  $t$ .

2)  $P_{CR}$  represents the proportion of power curtailed to the total power generation of renewable energy, which can be calculated as follows [21]:

$$P_{CR} = \frac{\left( \sum_{t=1}^T \max\{P_{WT}(t) + P_{PV}(t) - P_L(t) - P_{IL}(t) - P_{HS,max} - P_{IT,max}, 0\} \right)}{\sum_{t=1}^T (P_{WT}(t) + P_{PV}(t))} \quad (17)$$

where  $P_{IT,max}$  is the maximum power of the ice tank,  $P_{HS,max}$  is the maximum hydrogen storage tank.

### C. Epsilon-constraint Method

The epsilon-constraint ( $\varepsilon$ -constraint) is an effective method for multi-objective optimization. A general multi-objective optimization problem can be described as [37][38]:

$$\begin{aligned} & \text{Min}(f_1(x), f_2(x), \dots, f_n(x)), x \in S \\ & \text{s.t. } g_i(x) \leq 0 \quad i = 1, \dots, p \\ & \quad h_j(x) = 0 \quad j = 1, \dots, q \\ & \quad lb \leq x \leq ub \end{aligned} \quad (18)$$

where  $f_i$  ( $i = 1, 2, \dots, n$ ) represents  $n$  conflicting objective functions;  $x$  is the decision variables;  $S$  is the feasible solution space.  $g_i(x) \leq 0$  and  $h_j(x) = 0$  are  $p$  equality constraints and  $q$  inequality constraints, respectively.  $lb$  and  $ub$  represent the upper and lower limits of decision variables, respectively.

Among multiple objectives, we can select one objective for optimization, and the remaining objectives are used as constraints for the selected objective [36]:

$$\begin{aligned} & \min\{f_j(x)\}, j \in \{1, \dots, k\}; f_i(x) \leq \varepsilon_i, \\ & \quad \forall i \in \{1, \dots, k\}, i \neq j; x \in S \end{aligned} \quad (19)$$

where  $f_j(x), j \in \{1, \dots, k\}$  is the optimized objective function;  $f_i(x) \leq \varepsilon_i, \forall i \in \{1, \dots, k\}$  is a constraint.  $\varepsilon$  represents the value that the objective function is not allowed to exceed.

To fully utilize the information of some individuals not in the solution space, we can set a decreasing degree of constraint violation  $\phi(x)$  [37]:

$$\phi(x) = \max\{\max_i\{0, g_i(x)\}, \max_j\{|h_j(x)|\}\} \quad (20)$$

The evaluation method of candidate solutions consists of the fitness function and constraint violation degree:

$$(f_1, \Phi_1) \leq (f_2, \Phi_2) \Leftrightarrow \begin{cases} f_1 \leq f_2, & \text{if } \Phi_1, \Phi_2 \leq \varepsilon \\ f_1 \leq f_2, & \text{if } \Phi_1 = \Phi_2 \\ \Phi_1 < \Phi_2, & \text{otherwise} \end{cases} \quad (21)$$

where  $f_1$  and  $f_2$  are the fitness function values of different objectives,  $\Phi_1$  and  $\Phi_2$  are the constraint violation degrees of  $f_1$  and  $f_2$ , respectively. In this paper,  $\varepsilon$  is decreased by:

$$\varepsilon = \varepsilon_0(1 - l/(M_{axiter}/4)) \quad (22)$$

where  $l$  is the current iteration number of the algorithm and  $M_{axiter}$  is the maximum iteration number, and  $\varepsilon_0$  represents the initial value of  $\varepsilon$ .

In this paper, LCOE is selected as the optimization target, while PCR and LPSP are the targets of constrained selection. The PV/WT/hydrogen/cooling energy system is modeled as a constrained integer programming problem, which can be described as follows:

$$\min[L_{COE}] \quad (23)$$

$$\text{s.t. } \begin{cases} l_{b,i} \leq x_i \leq u_{b,i} \\ x_i \in Z^+ \\ L_{PSP} \leq \varepsilon_1 \\ P_{CR} \leq \varepsilon_2 \end{cases} \quad (24)$$

where  $x_i$  represents the decision variable used in the HRES optimization process, that is, the number of off-grid HRES components, which can be defined as the following  $7 \times 1$  vector:

$$x_i = [N_{PV} \ N_{WT} \ N_{vcr} \ N_{IT} \ N_{HT} \ N_{FC} \ N_{EL}]^T \quad (25)$$

where  $N_{WT}$ ,  $N_{PV}$ ,  $N_{vcr}$ ,  $N_{IT}$ ,  $N_{HT}$ ,  $N_{FC}$ , and  $N_{EL}$  are the quantities of WT, PV, VCR, ice tank, hydrogen tank, fuel cell, and electrolyzer respectively.

### D. Other Constraints

Due to space constraints, the number of components in HRES is restricted as follows:

$$\begin{aligned} 0 & \leq N_{WT} \leq N_{WT,max} \\ 0 & \leq N_{PV} \leq N_{PV,max} \\ 0 & \leq N_{vcr} \leq N_{vcr,max} \\ 0 & \leq N_{IT} \leq N_{IT,max} \\ 0 & \leq N_{HT} \leq N_{HT,max} \\ 0 & \leq N_{FC} \leq N_{FC,max} \\ 0 & \leq N_{EL} \leq N_{EL,max} \end{aligned} \quad (26)$$

where  $N_{WT,max}$ ,  $N_{PV,max}$ ,  $N_{vcr,max}$ ,  $N_{IT,max}$ ,  $N_{HT,max}$ ,  $N_{FC,max}$ , and  $N_{EL,max}$  are the maximum quantities of WT, PV, VCR, ice tank, hydrogen tank, fuel cell, and electrolyzer, respectively.

To reduce the impact of the HRES power shortage on residents and the curtailment of wind and PV energy, referring to the parameters of [21], LPSP and PCR should be restricted as follows:

$$L_{PSP} \leq 5\% \quad (27)$$

$$P_{CR} \leq 10\% \quad (28)$$

The power constraints of the HRES components are as follows:

$$P_{EL} \leq P_{EL,max} \quad (29)$$

$$P_{FC} \leq P_{FC,max} \quad (30)$$

$$P_{vcr} \leq P_{vcr,max} \quad (31)$$

$$P_{IT,ch} \leq P_{IT,ch,max} \quad (32)$$

$$P_{IT,dis} \leq P_{IT,dis,max} \quad (33)$$

where  $P_{EL}$ ,  $P_{FC}$ , and  $P_{vcr}$  are the power of the electrolyzer, fuel cell, and VCR components, respectively.  $P_{EL,max}$ ,  $P_{FC,max}$ , and  $P_{vcr,max}$  are the maximum power of the electrolyzer, fuel cell, and VCR components, respectively,  $P_{IT,ch}$  and  $P_{IT,dis}$  are the input and output power of the ice tank, respectively.  $P_{IT,ch,max}$  and  $P_{IT,dis,max}$  are the maximum input power and maximum output power of the ice tank, respectively.

The capacity constraints of the HRES storage system are as follows:

$$0 \leq S_{OC,HT} \leq S_{OC,HT,max} \quad (34)$$

$$0 \leq S_{OC,IT} \leq S_{OC,IT,max} \quad (35)$$

where  $S_{OC,HT,max}$  and  $S_{OC,IT,max}$  are the maximum capacities of the hydrogen tank and ice tank, respectively.

#### E. Hybrid System Operation Strategies

The operation strategy determines the energy flow in the HRES and designing a reasonable operation strategy is the prerequisite for the optimal configuration of HRES. For the convenience of explanation, we divide HRES into two main operational cases: the state of charge of the entire system and the state of discharge of the entire system. The flowcharts of these two states are shown in Figs. 2 and 3, respectively.

### IV. IMPROVED SALP SWARM ALGORITHM

#### A. Salp Swarm Algorithm (SSA)

SSA is a metaheuristic algorithm proposed by Mirjalili in 2017, which is inspired by the swarming behavior of the salp swarm. The two-stage optimization mechanism of SSA mentioned above achieves a balance between exploration and exploitation. Therefore, the SSA is very suitable for the HRES optimal configuration model with the combination of multiple nonlinear components. The mathematical model is described as follows:

##### 1) Leader Update

The update of the leader's position is primarily related to the position of the food, which is described as follows:

$$x_j^1 = \begin{cases} F_j + c_1((u_{b,j} - l_{b,j})c_2 + lb_j) & c_3 \geq 0.5 \\ F_j - c_1((u_{b,j} - l_{b,j})c_2 + lb_j) & c_3 < 0.5 \end{cases} \quad (36)$$

where  $x_j^1$  is the position of the leader in the  $j$ -th dimension,  $F_j$  is the position of the food in the  $j$ -th dimension,  $ub_j$  and  $lb_j$  represent the upper and lower bounds of the  $j$ -th dimension,  $c_2$  and  $c_3$  are random numbers generated uniformly on  $[0, 1]$ ;  $c_1$  is a factor that balances exploration and exploitation, and is defined as follows:

$$c_1 = 2e^{-(\frac{4l}{L})^2} \quad (37)$$

where  $l$  is the current iteration and  $L$  is the maximum number of iterations.

##### B. Followers Update

The follower's position update is primarily related to his previous sage position, which is described as follows:

$$x_j^i = \frac{1}{2}at^2 + v_0t \quad (38)$$

where  $x_j^i$  is the position of the  $i$ -th follower salp in the  $j$ -th dimension,  $t$  is time,  $a$  is acceleration,  $v_0$  is the initial speed, and the calculation formula is  $v_0 = \frac{x - x_0}{t}$ .

Since the time  $t$  in optimization is an iteration in SSA, the difference between iterations is 1, considering the initial velocity  $v_0 = 0$ , the formula can be written as:

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \quad (39)$$

where  $x_j^i$  is the position of the  $i$ -th follower salp in the  $j$ -th dimension.

#### C. Improved Salp Swarm Algorithm

Although SSA has an excellent optimization performance, because the salp in the SSA group is affected by a single individual in both the leadership and following stages, if this individual is a local optimal solution, other salps in the population will fall into the local optimal solution. When dealing with the optimal configuration of HRES, it faces the challenge of low solution accuracy and poor stability. Therefore, this research improves the leader update and follower update strategies of SSA and adjusts its structure to make it more suitable for the optimal configuration of HRES in this paper.

##### 1) Improved Leader Update

The position update of the leader is influenced by the food position and a random operator, which causes SSA to have a good searching ability. However, this update method also means the leader has no chance to exchange information with other salps. Therefore, to strengthen the information transmission between the salp swarm and the leader, this paper proposes a new leader update strategy, which is described as follows:

$$x_j^1 = \begin{cases} F_j + c_1((u_{b,j} - l_{b,j})c_2 + lb_j)c_3 \geq 0.5, & c_4 \geq 0.5 \\ F_j + c_1(x_j^1 - X_{m,j})c_3 \geq 0.5, & c_4 < 0.5 \\ F_j - c_1((u_{b,j} - l_{b,j})c_2 + lb_j)c_3 < 0.5, & c_4 \geq 0.5 \\ F_j - c_1(x_j^1 - X_{m,j})c_3 < 0.5, & c_4 < 0.5 \end{cases} \quad (40)$$

where  $c_4$  is a random number generated uniformly on  $[0, 1]$ .  $X_{m,j}$  is the average position of the salp in the  $j$ -th dimension, described as follows:

$$X_m = \frac{1}{N} \sum_{i=1}^N X^i \quad (41)$$

where  $X_m$  is the average position of all salp in the salp swarm,  $X^i$  is the location of each salp in the salp swarm,  $N$  represents the population size of the salps.

##### 2) Improved Follower Position Update

The follower position update is influenced by the movement of the previous salp, which may cause the salp to be affected by a salp worse than its own. Therefore, this paper adopts the concept of weighting to improve the followers' development ability. When the position of the sea squirt is better than its position, it will increase the influence of the previous salp on its own position. Conversely, when the position of the previous one is worse than its position, the influence of the previous slap on the position movement is reduced. The new follower update strategy is:

$$x_j^i = wx_j^i + (1 - w)x_j^{i-1} \quad (42)$$

where  $w$  represents the weight of the influence of  $x_j^i$  and  $x_j^{i-1}$  on the salp:

$$w = \frac{f(x_j^i)}{f(x_j^i) + f(x_j^{i-1})} \quad (43)$$

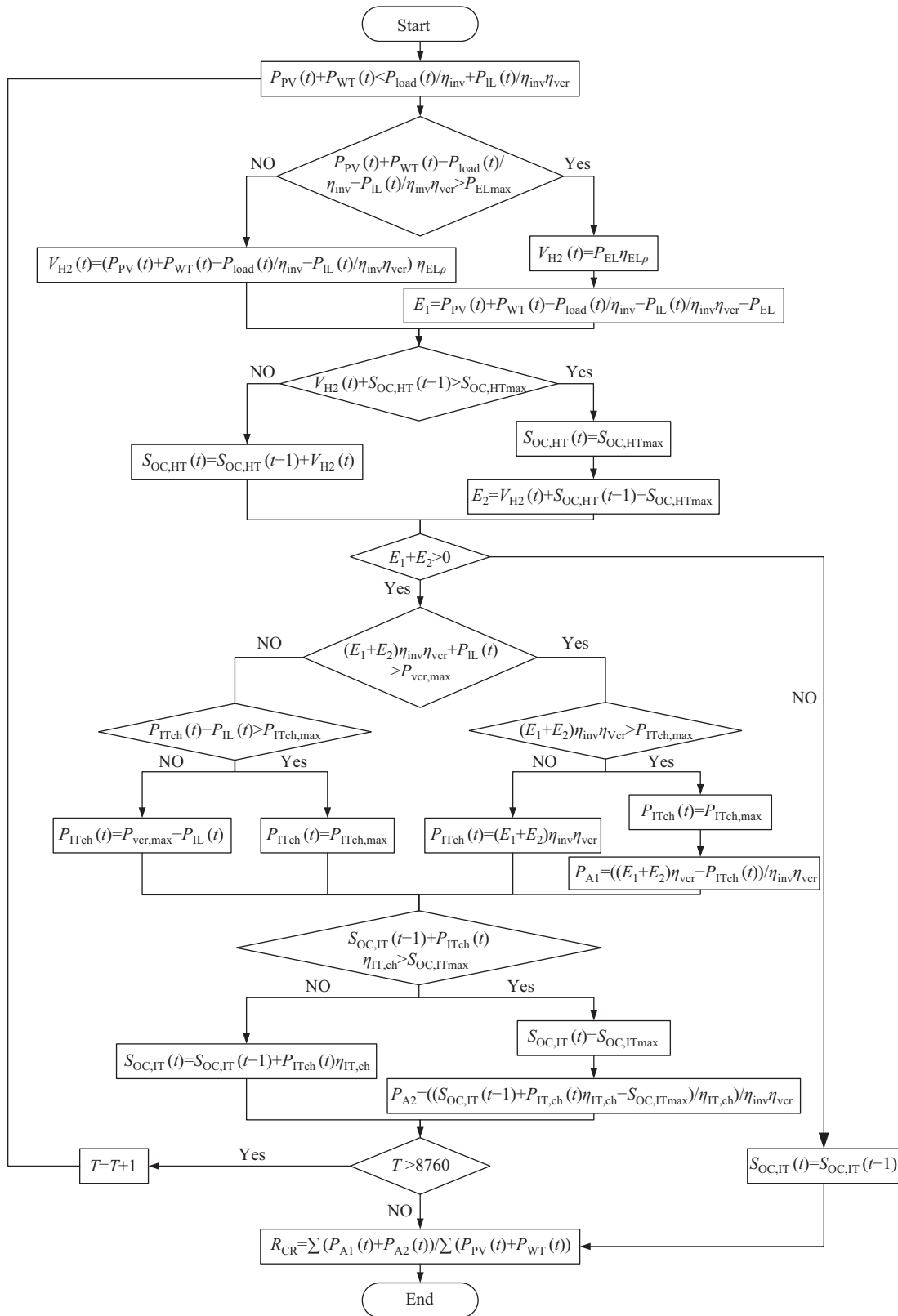


Fig. 2. The state of charge of the entire HRES.

where  $f(x_j^i)$  and  $f(x_j^{i-1})$  are the fitness of  $x_j^i$  and  $x_j^{i-1}$ , respectively.

### 3) Improved Algorithm Structure

Once all salp positions are updated in the traditional SSA

structure, SSA will evaluate all salp positions and find the optimum. If the best salp is better than the current food, then the position of the food will be replaced with the position of the best salp. Otherwise, the food position will not change.

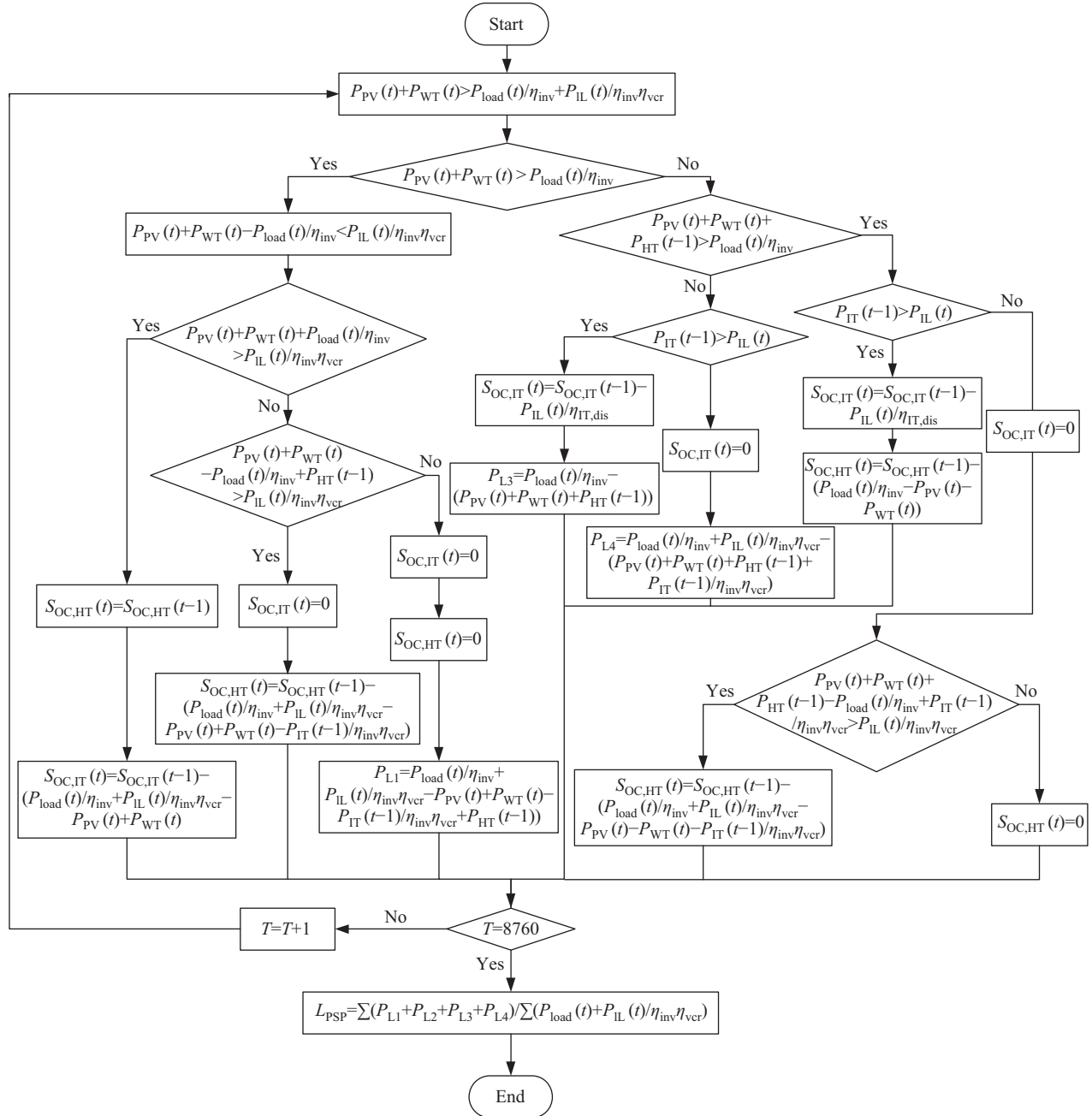


Fig. 3. The state of discharge of the entire HRES.

This paper proposes a new SSA algorithm structure, where each salp position will be evaluated after updating. If the fitness of the salp is better than the previous position, the position of the salp is unchanged; otherwise, the position of the salp is updated. Furthermore, if the fitness of the current salp is better than that of the food, the position of the food will be replaced by the position of the salp. Otherwise, the position of the food will not be changed.

## V. CASE STUDY

### A. Test Parameters

The proposed hybrid off-grid WT/PV/hydrogen/cooling system is applied to a remote community in Yinchuan, Ningxia,

China. Yinchuan is located in a temperate continental climate, and it is one of the regions with the most solar radiation and sunshine hours in China, which has abundant renewable resources. Fig. 4(a)–(c) shows the hourly meteorological data set in 2019 measured by a meteorological observatory in Yinchuan (longitude 106.2, latitude 38.47), including radiation intensity, wind speed, and temperature. The collection period of meteorological data is 1 hour. The annual average solar radiation in the area is 219.3 W/m<sup>2</sup>, the average wind speed is 3.49 m/s, and the average temperature is 9.87°C.

According to the local load demand in Yinchuan City, Ningxia Province, the power load and cooling load were simulated. The power and cooling load curves for one year are shown in Fig. 5. The power load data is measured in

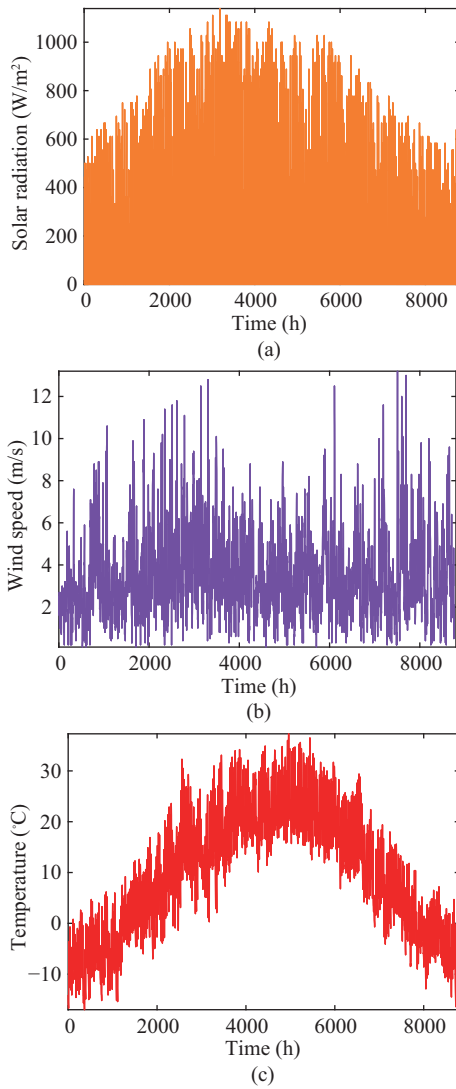


Fig. 4. Data of (a) hourly solar radiation, (b) hourly wind speed and (c) hourly temperature.

Ningxia Province, China, and standardized to meet the needs of off-grid communities. The average electric load after being standardized is 27.023 KW. The cooling load data, with an average of 13.147 KW, is based on the local temperature from the simulation.

### B. System Optimization by ISSA

The optimal design of HRES with PV/WT/hydrogen/cooling systems in remote areas considers the input of wind energy and solar energy, storage capacity for hydrogen/ice storage, and load consumption. The main purpose of the  $\varepsilon$ -constraint and ISSA method is to select the optimal variables to minimize LCOE. We set the lifetime of the HRES to 20 years and the interest rate to 5%. The quantity constraints of PV/WT/ hydrogen/electrical chiller/ice storage are: 920, 100, 182, 154, 168, 115, and 108, respectively. The minimum number of all components is 0. The population size of ISSA in this paper is 30, and the maximum number of iterations is 150. The algorithm parameters of ISSA are consistent with those of traditional SSA.

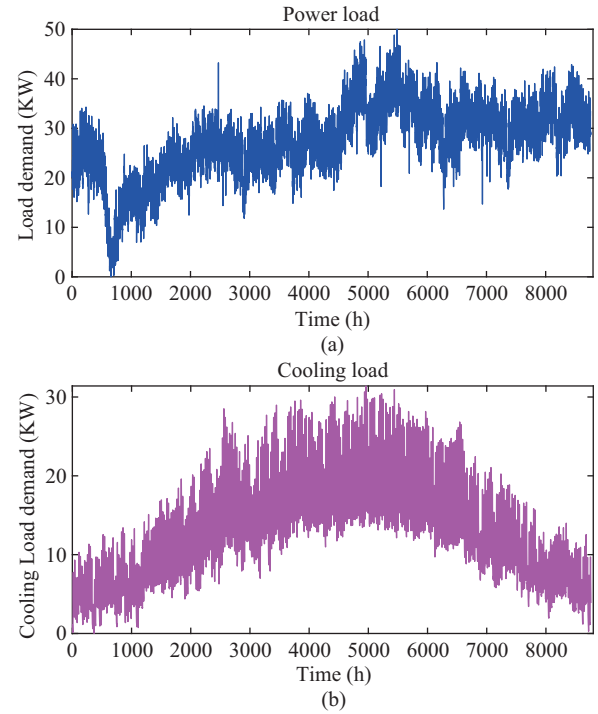


Fig. 5. Profile of (a) aggregated hourly power load and (b) aggregated hourly cooling load.

The simulation results show that the optimal system consists of 255.125 kW PV, 780 kW WT, 32 kW electrolyzer, 40 kW fuel cell, 198 m<sup>3</sup> hydrogen tank, 36 kW VCR, and 180 kWh ice tank. In this optimal configuration of HRES, the economic results for the simulation are shown in Table V. To illustrate the importance of hydrogen-ice storage to the PV/WT/Hydrogen/cooling system, the HRES with hydrogen storage alone [21] and with hydrogen-ice storage are shown in Table VI. Compared with the hydrogen storage system, the TNPC of the hydrogen-ice storage system has decreased by  $\$3,784 \times 10^5$ , or 27.12% in percentage terms, and its LCOE has decreased by  $\$0.083/\text{kWh}$ , or 27.12% in percentage terms. The results indicate that hydrogen-ice storage is conducive to

TABLE V  
THE ECONOMICAL RESULTS FOR THE SIMULATION-BASED ON US\$

| Item          | N   | I (\$)  | OM (\$) | R (\$) | NPC (\$) |
|---------------|-----|---------|---------|--------|----------|
| PV            | 785 | 157,000 | 39,131  | 0      | 196,131  |
| WT            | 78  | 319,800 | 79,864  | 0      | 399,664  |
| hydrogen tank | 33  | 130,680 | 32,571  | 0      | 163,251  |
| electrolyzer  | 16  | 64,000  | 39,879  | 90,166 | 158,154  |
| fuel cell     | 20  | 120,000 | 29,909  | 48,102 | 198,011  |
| VCR           | 18  | 57,240  | 35,667  | 74,387 | 167,294  |
| ice tank      | 30  | 69,600  | 43,368  | 0      | 112,968  |

TABLE VI  
RESULTS OBTAINED BY THE ISSA FOR PV/WT/HYDROGEN/COOLING SYSTEM WITH AND WITHOUT ICE TANK

| System type                  | TNPC ( $10^6$ \$) | LCOE (\$/kWh) | LPSP (%) | PCR (%) |
|------------------------------|-------------------|---------------|----------|---------|
| Hydrogen-ice storage system  | 1.3955            | 0.3061        | 4.9998   | 7.2329  |
| Hydrogen storage system [21] | 1.7739            | 0.3891        | 4.9992   | 0.4216  |

the economic improvement of the HRES.

The reasons for reducing LCOE in off-grid areas by cold energy storage are as follows. The off-grid area has a hot climate and requires a lot of cooling load. If only hydrogen is used to store energy, there will be energy loss in transforming electricity into cold. Cold storage can be directly provided to the cooling load. The process of converting hydrogen into power and converting power into cold is not needed, thus improving the energy utilization efficiency. Therefore, under the condition of the exact cost and component parameters, the LCOE of an off-grid system using hydrogen/cold storage is smaller.

### C. Discussion of Evaluation Criteria

To illustrate the seasonal changes in the evaluation criteria, the changes in LPSP and PCR throughout the year are illustrated in Fig. 6. In summer (4,320 h–5,760 h), the load demand is high, and the energy of renewable energy is insufficient to support the increased load demand. Consequently, the power shortage is relatively large, and less energy is curtailed. In spring and winter, a significant amount of renewable energy is curtailed without power shortages. In the autumn (5,833 h–8,016 h), shortages and curtailments of energy occur alternately as load demand is lower than that in summer. As the autumn climate changes significantly and renewable energy power generation is affected by the climate, it is prone to power shortages and power curtailment.

### D. Algorithm Analysis

In order to verify the effectiveness of the proposed method, the simulation results of the ISSA are compared with SSA, particle swarm optimization (PSO) [39], Harris Hawks optimization (HHO) [40], and the Sine Cosine Algorithm (SCA) [41]. In PSO, inertia weight  $w = 0.5$ , learning factor  $c_1 = 2$ , and learning factor  $c_2 = 2$ . For fairness, the optimization parameters in the remaining algorithms are consistent with the original literature. To guarantee the fairness of algorithm verification, each algorithm is independently run 30 times. The population size of all algorithms is 30, and the maximum number of iterations is 150.

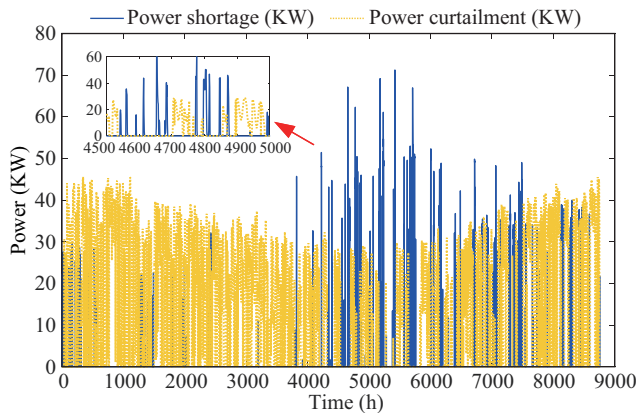


Fig. 6. Simulated hourly power shortage and power curtailment.

Table VII shows the simulation results of the ISSA and other comparison algorithms. The results of the case show that the

TABLE VII  
ALGORITHM COMPARISON

| Algorithm     | ISSA   | SSA    | PSO    | HHO    | SCA    |
|---------------|--------|--------|--------|--------|--------|
| mean (\$/kWh) | 0.3143 | 0.3304 | 0.3431 | 0.4602 | 0.3914 |
| std           | 0.0100 | 0.0178 | 0.0343 | 0.0969 | 0.0399 |
| mean-t (s)    | 43.03  | 43.10  | 42.68  | 90.77  | 41.99  |

system ICOE is reduced by 4.8%, 8.40%, 31.7%, and 19.7% compared with the SSA, PSO, HHO, and SCA, which proves the effectiveness of the method proposed in this paper. Among them, HHO has poor applicability to the HRES optimization design problem (mean = 0.4520, std = 0.0719). ISSA is the optimal HRES optimization solution with the minimum LCOE (mean = 0.3143). In addition, the results obtained by ISSA are the most stable (std = 0.0100). This means that the improvement of SSA is effective, making SSA more suitable for the optimal design of HRES.

Furthermore, SCA (41.99 s) has the shortest time among all the algorithms. Except for HHO, which runs for a long time (90.77 s), there is little difference in the execution time of the other algorithms. It is worth noting that the average running time of the proposed improved ISSA (43.03 s) is not much different from that of SSA (43.10 s). This is because only the mathematical model of salps' movement was reconstructed, and the algorithm structure was adjusted. The number of evaluations of the objective was not increased, so there is no significant difference in the solution time of the algorithm.

### E. Sensitivity Analysis

To verify the effect of the parameters on the results, we present the sensitivity analysis of the proposed HRES in this subsection. Table VIII shows the system optimization configuration results, in which the changes of electrical load are  $\pm 5\%$ ,  $\pm 10\%$ , and  $\pm 20\%$ , respectively. When the load change is  $+20\%$ , the HRES has the highest LCOE (\$0.3170/kWh) and TNPC ( $1.6231 \times 10^6$ ). When the load change is  $-20\%$ , the HRES has the lowest LCOE (\$0.2970/kWh) and TNPC ( $1.1879 \times 10^6$ ). It is seen that the reduction of electrical load results in decreases for both LCOE and TNPC, while TNPC is more sensitive to changes in the electrical load than LCOE. For example, compared with the surplus load (%) = 20%, when the residual load (%) = 0, the LCOE decreases by 3.56%, while NPC decreases by 16.31%.

TABLE VIII  
THE LOAD VARIATIONS ON THE SYSTEM

| The surplus load (%) | LCOE (\$/kWh) | NPC (\$ $10^6$ ) |
|----------------------|---------------|------------------|
| 20                   | 0.3170        | 1.6231           |
| 10                   | 0.3150        | 1.5245           |
| 5                    | 0.3078        | 1.4468           |
| 0                    | 0.3061        | 1.3955           |
| -5                   | 0.3021        | 1.3349           |
| -10                  | 0.2990        | 1.2794           |
| -20                  | 0.2970        | 1.1879           |

The optimization configuration results of the system where the cooling load changes are  $\pm 10\%$ ,  $\pm 20\%$ , and  $\pm 40\%$  are shown in Table IX. Unlike power load, if the cooling load ratio increases, although the TNPC of HRES will increase, the

TABLE IX  
THE COOLING LOAD VARIATIONS ON THE SYSTEM

| The surplus cooling load (%) | LCOE (\$/kWh) | NPC (\$ 10 <sup>6</sup> ) |
|------------------------------|---------------|---------------------------|
| 40                           | 0.2957        | 1.5560                    |
| 20                           | 0.2961        | 1.4539                    |
| 10                           | 0.3036        | 1.4374                    |
| 0                            | 0.3061        | 1.3955                    |
| -10                          | 0.3150        | 1.3807                    |
| -20                          | 0.3244        | 1.3651                    |
| -40                          | 0.3310        | 1.2766                    |

LCOE of HRES will decrease. When the cooling load change = 40%, the HRES has the lowest LCOE (\$0.2957/kWh) and the highest TNPC (\$1.6231 × 10<sup>6</sup>). When the surplus cooling change is -40%, the HRES has the highest LCOE (\$0.3310/kWh) and lowest TNPC (\$1.6231 × 10<sup>6</sup>). This is because the change of cooling load has little effect on the number of components, but it increases the matching energy between HRES and total load, which leads to the increase in LCOE. This means that we can increase the LCOE by increasing the proportion of the cooling load in the project.

To illustrate the relationship between load changes and LCOE changes, the changes of LCOE when the power and cooling load increase or decrease by a certain percentage are shown in Fig. 7. When the load increases or decreases by the same proportion, the LCOE may not follow linearly. For instance, a 10% decrease in cooling load has a more significant impact on LCOE than a 10% increase. Since both the power and energy storage capacity of components have upper limits, the energy that can meet the load is not linear, which further indicates that the capacity configuration cost of energy storage components does not increase linearly with the load. Therefore, when the cooling load decreases, the

TNPC of the system changes less, the cooling load satisfied by the system decreases significantly, and the final result is an increase in LCOE. For the changes in power load, when the load changes are between 10% and 20%, the increase in load has a greater impact on LCOE than the decrease in load. On the other hand, when the load changes by 5%, the decrease in load has a greater impact on LCOE than the increase in load. This result is also caused by the limitations mentioned above for component power and energy storage capacity.

## VI. CONCLUSION

In this paper, we have carried out the optimal configuration of an off-grid WT/PV/hydrogen/cooling system. The research uses three evaluation criteria, including the LCOE, LSPS, and PCR of the HRES. By using the ISSA and  $\varepsilon$ -constraint method with constraint violation degree, the HRES with the LCOE of \$0.3061/kWh, the LPSP of 5.00%, the PCR of 7.23% can be obtained, which consists of 255.125 kW PV panels, 780 kW wind turbines, 32 kW electrolyzers 40 kW fuel cells, 198 m<sup>3</sup> hydrogen storage tanks, 36 kW vapor compression refrigeration and 180 kWh ice tanks. For HRES with hydrogen-ice storage, the following conclusions can be obtained.

1) The TNPC and LCOE of the HRES with hybrid hydrogen/ice storage are lower than those of HRES with only hydrogen storage. Therefore, for off-grid PV/WT/Hydrogen/cooling systems, the increase in ice storage helps to improve the economics of this HRES.

2) The optimization results of the proposed ISSA are compared with those based on SSA, PSO, HHO, and SCA, which proves that the ISSA has the highest accuracy and stability.

3) TNPC is more sensitive to power and cooling load changes than LCOE.

4) When the power load changes, the LCOE of the HRES has the same changing trend. However, when the cooling load changes, the changing trend of the LCOE is opposite to the changing trend of the cooling load. This shows that the increased cooling load ratio of HRES with hydrogen/ice storage can help reduce the LCOE.

In this paper, the efficiency of the energy conversion equipment is simplified to a constant. However, in actual system operations, with system input and output variations, all the configurations are working under off-design conditions. The efficiency of off-grid HRES devices will change with variations of input and output and environmental factors (such as temperature). Therefore, in a future study, we will further analyze the optimal configuration of off-grid PV/wind/hydrogen/cooling systems, considering the energy conversion devices working under off-design conditions.

## REFERENCES

- [1] J. Hazelton, A. Bruce, and I. MacGill, "A review of the potential benefits and risks of photovoltaic hybrid mini-grid systems," *Renewable Energy*, vol. 67, pp. 222–229, Jul. 2014.
- [2] S. B. Silva, M. M. Severino, and M. A. G. de Oliveira, "A stand-alone hybrid photovoltaic, fuel cell and battery system: a case study of Tocantins, Brazil," *Renewable Energy*, vol. 57, pp. 384–389, Sep. 2013.

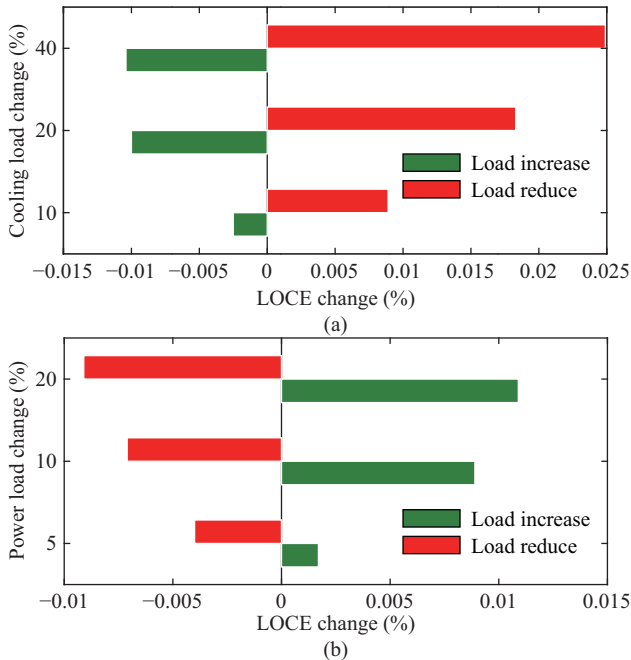


Fig. 7. Sensitivity analysis of changes in power and cooling load to LCOE. (a) Sensitivity analysis of changes in cooling load to LCOE. (b) Sensitivity analysis of changes in power load to LCOE.

- [3] F. Tooryan, H. HassanzadehFard, E. R. Collins, S. S. Jin, and B. Ramezani, "Optimization and energy management of distributed energy resources for a hybrid residential microgrid," *Journal of Energy Storage*, vol. 30, pp. 101556, Aug. 2020.
- [4] Y. Kalinci, "Alternative energy scenarios for Bozcaada island, Turkey," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 468–480, May 2015.
- [5] B. Robertson, J. Bekker, and B. Buckham, "Renewable integration for remote communities: comparative allowable cost analyses for hydro, solar and wave energy," *Applied Energy*, vol. 264, pp. 114677, Apr. 2020.
- [6] M. T. Ma, J. Chen, X. Ma, et al., "Multi-objective optimal configuration of off-grid residential hybrid renewable energy system based on hypervolume-improved Non-dominated Sorting Genetic Algorithm III," *International Journal of Hydrogen Energy*, vol. 87, pp. 277–289, 2024.
- [7] T. Ma and M. S. Javed, "Integrated sizing of hybrid PV-wind-battery system for remote island considering the saturation of each renewable energy resource," *Energy Conversion and Management*, vol. 182, pp. 178–190, Feb. 2019.
- [8] M. R. Elkadeem, S. R. Wang, S. W. Sharshir, and E. G. Atia, "Feasibility analysis and techno-economic design of grid-isolated hybrid renewable energy system for electrification of agriculture and irrigation area: a case study in Dongola, Sudan," *Energy Conversion and Management*, vol. 196, pp. 1453–1478, Sep. 2019.
- [9] G. Cau, D. Cocco, M. Petrollese, S. K. Kær, and C. Milan, "Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system," *Energy Conversion and Management*, vol. 87, pp. 820–831, Nov. 2014.
- [10] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, "The future cost of electrical energy storage based on experience rates," *Nature Energy*, vol. 2, pp. 17110, Jul. 2017.
- [11] S. Emmanouil, E. I. Nikolopoulos, B. François, C. Brown, and E. N. Anagnostou, "Evaluating existing water supply reservoirs as small-scale pumped hydroelectric storage options – A case study in Connecticut," *Energy*, vol. 226, pp. 120354, Jul. 2021.
- [12] H. L. Fu, Q. He, J. T. Song, X. P. Shi, Y. P. Hao, D. M. Du, and W. Y. Liu, "Thermodynamic of a novel advanced adiabatic compressed air energy storage system with variable pressure ratio coupled organic rankine cycle," *Energy*, vol. 227, pp. 120411, Jul. 2021.
- [13] Z. S. Jiang, S. L. Zhai, M. Z. Huang, P. Songsiririthigul, S. H. Aung, T. Z. Oo, M. Luo, and F. M. Chen, "3D carbon nanocones/metallic MoS<sub>2</sub> nanosheet electrodes toward flexible supercapacitors for wearable electronics," *Energy*, vol. 227, pp. 120419, Jul. 2021.
- [14] Y. H. Song, M. Shahidehpour, S. Rahman, N. Brandon, K. Strunz, J. Lin, "Utilization of energy storage and hydrogen in power and energy systems: Viewpoints from five aspects," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 1, pp. 1–7, Jan. 2023.
- [15] N. S. Attemene, K. S. Agbli, S. Fofana, and D. Hissel, "Optimal sizing of a wind, fuel cell, electrolyzer, battery and supercapacitor system for off-grid applications," *International Journal of Hydrogen Energy*, vol. 45, no. 8, pp. 5512–5525, Feb. 2020.
- [16] M. Baumann, M. Weil, J. F. Peters, N. Chibeles-Martins, and A. B. Moniz, "A review of multi-criteria decision making approaches for evaluating energy storage systems for grid applications," *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 516–534, Jun. 2019.
- [17] Q. Li, T. H. Wang, S. H. Li, W. R. Chen, H. Liu, E. Breaz, and F. Gao, "Online extremum seeking-based optimized energy management strategy for hybrid electric tram considering fuel cell degradation," *Applied Energy*, vol. 285, pp. 116505, Mar. 2021.
- [18] M. S. Guney and Y. Tepe, "Classification and assessment of energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 1187–1197, Aug. 2017.
- [19] Y. S. Zhang, Q. S. Hua, L. Sun, and Q. Liu, "Life cycle optimization of renewable energy systems configuration with hybrid battery/hydrogen storage: a comparative study," *Journal of Energy Storage*, vol. 30, pp. 101470, Aug. 2020.
- [20] M. J. Hadidian Moghaddam, A. Kalam, S. A. Nowdeh, A. Ahmadi, M. Babanezhad, and S. Saha, "Optimal sizing and energy management of stand-alone hybrid photovoltaic/wind system based on hydrogen storage considering LOEE and LOLE reliability indices using flower pollination algorithm," *Renewable Energy*, vol. 135, pp. 1412–1434, May 2019.
- [21] C. B. Xu, Y. M. Ke, Y. B. Li, H. Chu, and Y. N. Wu, "Data-driven configuration optimization of an off-grid wind/PV/hydrogen system based on modified NSGA-II and CRITIC-TOPSIS," *Energy Conversion and Management*, vol. 215, pp. 112892, Jul. 2020.
- [22] B. Kılıç, "Energetic comparison of wind energy storage with ice making cycle versus mini-hydrogen economy cycle in off-grid district cooling," *International Journal of Hydrogen Energy*, vol. 42, no. 28, pp. 17571–17582, Jul. 2017.
- [23] C. Luerksen, H. Verbois, O. Gandhi, T. Reindl, C. Sekhar, and D. Cheong, "Global sensitivity and uncertainty analysis of the levelised cost of storage (LCOS) for solar-PV-powered cooling," *Applied Energy*, vol. 286, pp. 116533, Mar. 2021.
- [24] M. J. Sebzali and P. A. Rubini, "The impact of using chilled water storage systems on the performance of air cooled chillers in Kuwait," *Energy and Buildings*, vol. 39, no. 8, pp. 975–984, Aug. 2007.
- [25] B. Arcuri, C. Spataru, and M. Barrett, "Evaluation of ice thermal energy storage (ITES) for commercial buildings in cities in Brazil," *Sustainable Cities and Society*, vol. 29, pp. 178–192, Feb. 2017.
- [26] A. Sepehri and B. Nelson, "Energy and emissions analysis of ice thermal energy storage in the western US," *Energy and Buildings*, vol. 202, pp. 109393, Nov. 2019.
- [27] C. Luerksen, O. Gandhi, T. Reindl, C. Sekhar, and D. Cheong, "Levelised Cost of Storage (LCOS) for solar-PV-powered cooling in the tropics," *Applied Energy*, vol. 242, pp. 640–654, May 2019.
- [28] C. Luerksen, O. Gandhi, T. Reindl, C. Sekhar, and D. Cheong, "Life cycle cost analysis (LCCA) of PV-powered cooling systems with thermal energy and battery storage for off-grid applications," *Applied Energy*, vol. 273, pp. 115145, Sep. 2020.
- [29] B. Yang, L. E. Zhong, X. S. Zhang, H. C. Shu, T. Yu, H. F. Li, L. Jiang, and L. M. Sun, "Novel bio-inspired memetic salp swarm algorithm and application to MPPT for PV systems considering partial shading condition," *Journal of Cleaner Production*, vol. 215, pp. 1203–1222, Apr. 2019.
- [30] G. S. Pan, W. Gu, X. G. Chen, Y. P. Lu, and S. H. Zhang, "Cooperative electricity-hydrogen trading model for optimizing low-carbon travel using Nash bargaining theory," *CSEE Journal of Power and Energy Systems*, vol. 10, no. 6, pp. 2577–2586, Nov. 2024.
- [31] D. J. Zhao, M. Zhou, J. X. Wang, T. C. Zhang, G. Y. Li, and H. H. Zhang, "Dispatching fuel-cell hybrid electric vehicles toward transportation and energy systems integration," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 4, pp. 1540–1550, Jul. 2023.
- [32] S. Sanaye and N. Khakpaay, "Thermo-economic multi-objective optimization of an innovative cascaded organic Rankine cycle heat recovery and power generation system integrated with gas engine and ice thermal energy storage," *Journal of Energy Storage*, vol. 32, pp. 101697, Dec. 2020.
- [33] M. Baneshi and F. Hadianfard, "Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions," *Energy Conversion and Management*, vol. 127, pp. 233–244, Nov. 2016.
- [34] M. Gharibi and A. Askarzadeh, "Size and power exchange optimization of a grid-connected diesel generator-photovoltaic-fuel cell hybrid energy system considering reliability, cost and renewability," *International Journal of Hydrogen Energy*, vol. 44, no. 47, pp. 25428–25441, Oct. 2019.
- [35] A. C. Duman and Ö. Güler, "Techno-economic analysis of off-grid PV/wind/fuel cell hybrid system combinations with a comparison of regularly and seasonally occupied households," *Sustainable Cities and Society*, vol. 42, pp. 107–126, Oct. 2018.
- [36] K. Khalili-Damghani, A. R. Abtahi, and M. Tavana, "A new multi-objective particle swarm optimization method for solving reliability redundancy allocation problems," *Reliability Engineering & System Safety*, vol. 111, pp. 58–75, Mar. 2013.
- [37] S. Z. Martinez and C. A. C. Coello, "A multi-objective evolutionary algorithm based on decomposition for constrained multi-objective optimization," in *2014 IEEE Congress on Evolutionary Computation (CEC)*, 2014, pp. 429–436.
- [38] M. A. Ashraf, Z. L. Liu, A. Alizadeh, S. Nojavan, K. Jermisittiparsert, and D. Q. Zhang, "Designing an optimized configuration for a hybrid PV/Diesel/Battery Energy System based on metaheuristics: a case study on Gobi Desert," *Journal of Cleaner Production*, vol. 270, pp. 122467, Oct. 2020.
- [39] L. J. Ge, Y. L. Li, J. Yan, Y. Q. Wang, and N. Zhang, "Short-term load prediction of integrated energy system with wavelet neural network model based on improved particle swarm optimization and chaos optimization algorithm," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 6, pp. 1490–1499, Nov. 2021.
- [40] L. J. Ge, J. H. Liu, J. Yan, and M. Umer Rafiq, "Improved Harris hawks optimization for configuration of PV intelligent edge terminals," *IEEE Transactions on Sustainable Computing*, vol. 7, no. 3, pp. 631–643, Jul./Sep. 2022, doi: 10.1109/TSUSC.2021.3125016.
- [41] S. Mirjalili, "SCA: a sine cosine algorithm for solving optimization problems," *Knowledge-Based Systems*, vol. 96, pp. 120–133, Mar. 2016.



**Leijiao Ge** received a Ph.D. degree in Electrical Engineering from Tianjin University, Tianjin, China, in 2016. He is currently an Associate Professor in the School of Electrical and Information Engineering at Tianjin University. His main research interests are smart distribution network, cloud computing and big data.



**Zhongguan Wang** received B.S. and Ph.D. degrees from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 2014 and 2019, respectively. He is currently an Associate Professor at the School of Electrical and Information Engineering, Tianjin University, Tianjin, China. His current research interests include the operation of renewable power generation and active distribution system energy management.



**Jiaheng Liu** received an M.S. degree in Electrical Engineering from Tianjin University, Tianjin, China, in 2023. He is currently working at the Material Branch of State Grid Liaoning Electric Power Co., Ltd, Shenyang, Liaoning, China. His main research interests are smart distribution networks, microgrids, and renewable energy systems.



**Muhammad Umer Rafiq** received a B.S. degree from the University of Engineering and Technology, Lahore, Pakistan. He is currently studying for an M.S. degree at Tianjin University, China. His research areas are renewable energy management, energy optimization, and the smart grid.