Sizing a 100% renewable energy based power supply system based on multi-objective optimization

1st Bei Li
College of Chemistry and Environmental Engineering
Shenzhen University
Shenzhen, China
bei.li@szu.edu.cn

2nd Robin Roche
FEMTO-ST, FCLAB
Univ. Bourgogne Franche-Comté, UTBM, CNRS
Belfort, France
robin.roche@utbm.fr

***Abstract*—Nowadays, large amounts of renewable energy have been installed around the world, and building a zero carbon emission energy supply system has been put on the agenda. Then, how to size the zero carbon emission energy system to achieve cost-effective is an essential problem. In this paper, we build a 100% renewable energy based generating station and microgrid clusters to supply the load demands. Three objectives are considered, namely, minimizing the total cost, minimizing the total exchanged energy, and maximizing the installed PV panels. Genetic algorithm is adopted to solve the problem. The simulation results show that: 1) the hydrogen storage operates as the core device to build the 100% renewable energy based power supply system; 2) when the investment cost is decreasing, the total exchanged energy is increasing, and the installed PV panels are decreasing; when the PV panels are decreasing, the total exchanged energy is decreasing; 3) the volume of the hydrogen tanks in generating station is larger than that in microgrids, because it needs to cover the demands from microgrids.**

***Index Terms*—zero carbon emission, cost-effective, multi-objective, microgrid, hydrogen storage.**

I. INTRODUCTION

Nowadays, renewable energy has been installed widely around the world. Based on the renewable energy generation, current energy supply system is increasingly changing to low carbon emissions system, and in the future, achieving zero carbon emission energy system is the ultimate goal [1]. In addition, photovoltaics have been verified as an effective way to reduce greenhouse gas emission in Europe union [2]. In the generation side, large amounts of renewable energy resources are integrated with storage systems to form zero carbon emission generating station. In the customer side, large numbers of microgrids are built to absorb local renewable energy and reduce buying costs from utility grids. The zero carbon emission generating station and microgrid clusters can be seen in Fig. 1.

The generating station and the microgrids are different. Generating station is often located in remote areas which has abundant renewable energy resources, and a large capacity of renewable energy is installed. Microgrid is often located in customer side, and due to the geographical limitation, limited renewable energy might be installed.

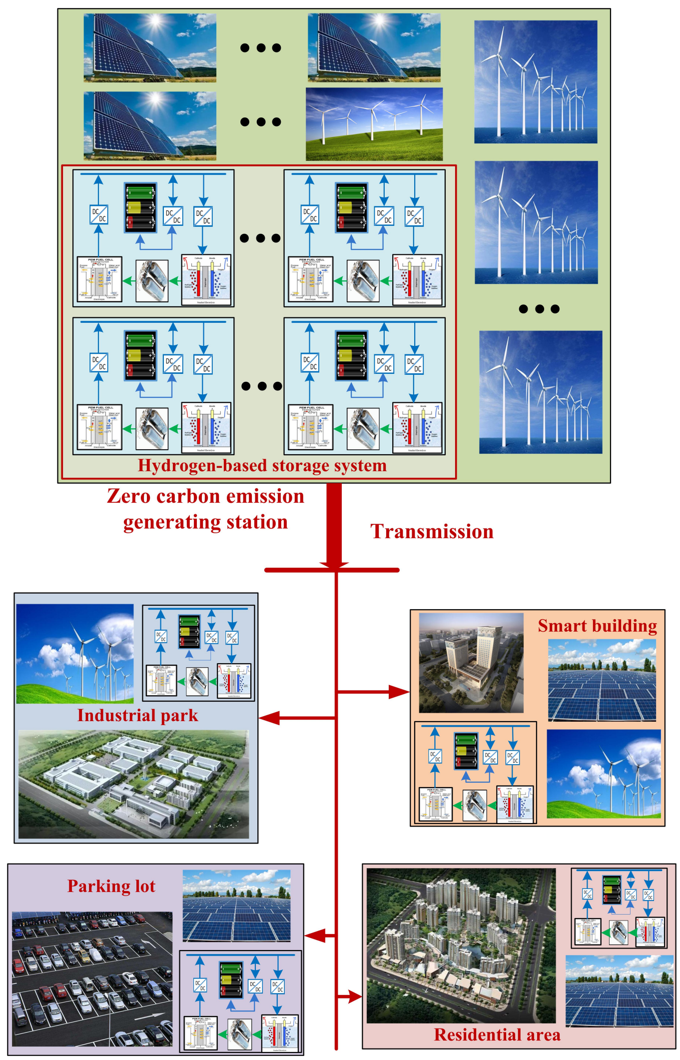

Fig. 1. Zero carbon emission generating station and microgrid clusters.

In fact, due to the intermittent and uncertainty of the renewable energy resources, energy storage system is a necessary component [3]. In general, hydrogen storage system has high

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energy density, medium power density; battery has medium energy and power density [3]. Then, a combined hydrogen and battery storage system is a better choice to respond to renewable energy uncertainty. This is because the energy and power density will be always in a high level. In this paper, the combined hydrogen and battery storage system is deployed to build the generating station and microgrids, and the structure can be seen in Fig. 2. In the hydrogen storage system, fuel cell uses H_2 to produce electricity and heat; electrolyzer uses electricity to produce H_2; H_2 is stored in hydrogen tanks.

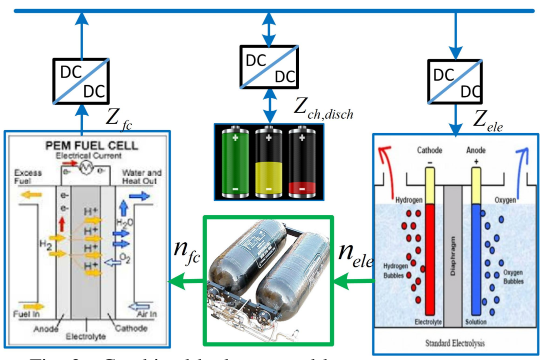

Fig. 2. Combined hydrogen and battery storage system.

Then how to size the above zero carbon emission energy system to achieve cost-effective is an essential problem [4]. On the one hand, we can install a large capacity of renewable energy resources and storage system, which can certainly satisfy the load demands, but the total investment cost is not economical. On the other hand, if we satisfy the economical budget (namely, install limited capacity of renewable energy), the total load demands may not be supplied, where a load shedding concern may happen. So, the sizing of such system should consider both the investment cost and operation efficiency.

Authors in [4] review the optimization sizing methods for energy storage systems, in which the different methods can be divided into four categories: probabilistic, analytical, artificial intelligence and hybrid methods. Among them, the artificial intelligence method can give a reasonable sizing values with limited searching time, but be with probabilities to converge to the local optimums [4]. And artificial intelligence technique is popular used in various researches.

In this paper, we focus on sizing a zero carbon emission energy system. Several objective functions are considered, including minimizing the total investment cost and operation cost, minimizing the exchanged energy, and maximizing the installed renewable energy. It is actually a multi-objective optimal sizing problem.

In fact, papers using multi-objective algorithm to optimal design renewable energy based microgrids have also been published. Authors in [5] address the optimal design of the biomass supply chain system. And analytic hierarchy process is adopted to firstly decide the candidate location of biogas facilities. Then a multi-objective mixed integer linear programming model (namely, maximize the profit, and minimize total distance between poultry farms and biogas facilities) is presented to determine the biogas facility capacities. In [6], authors adopt multi-objective self-adaptive differential evolution algorithm to size a hybrid microgrid system. Loss of power supply probability and cost of electricity are adopted as the two objective functions. In [7], authors present an optimal sizing for stand-alone hybrid microgrid. Two objective functions, i.e., loss of load probability and seasonal loss of load probability ratio are considered. In [8], authors adopt a multi-objective genetic algorithm to size the microgrid with hybrid storage system. Discrete Fourier transform is used to split energy to battery and supercapacitor. Total costs of electricity and loss of power supply probability two objective functions are deployed. In [9], authors optimally size a renewable hybrid power plant with storage. Multi-objective particle swarm optimization is used to minimize two objective functions, i.e., the annualized cost of system and the amount of energy imported from non renewable sources. In [10], authors present a multi-objective optimal design for typical rural microgrids in developing countries. Non-dominated sorting genetic algorithm (NSGA-II) is adopted, where there are two objective functions: net present value and modified internal rate of return are considered. In [11], authors present an optimal design of the integration of a hybrid CCHP system into a commercial building. Firstly, genetic algorithm is adopted to optimize three objective functions separately, namely, annual operating cost ratio, primary energy saving ratio and carbon emission reduction ratio. Then, an analytic hierarchy process is used to choose the best answer. In [12], authors present a method to determine the best combination of technologies in district buildings. Three objective functions (i.e., net present value, low carbon emissions, and low energy bill) are transferred to a single weighted function based on entropy weight method. In [13], authors present a planning model for a wind/hydrogen based hybrid microgrid system. Genetic algorithm is adopted to minimize system cost and wind curtailment rate.

However, the above papers all study the sizing of microgrids, and they did not consider the 100% renewable energy based generating station, which is used to supply energy to microgrids. With the extended microgrids and 100% renewable energy based generating station, a new zero carbon emission energy system can be built.

A. Contributions

In our previous paper, we studied the sizing of the full electric microgrid [14] and multi-energy supply microgrid [15], but they are single-objective optimization. In this paper, we build a zero carbon emission generating station and microgrid clusters using multi-objective optimization to achieve three goals: minimizing total cost, minimizing exchanged energy, and maximizing installed renewable energy. Compare to previous works, the contribution of this paper can be concluded as follows:

- First, a zero carbon emission energy supply system (100% renewable energy based generating station and microgrid clusters) is built;

- Second, three objective functions (minimizing total cost, minimizing exchanged energy, and maximizing installed renewable energy) are considered, and NSGA-II is adopted to obtain the optimal results;
- Last, it can be seen that the volume of the hydrogen tanks in generating station is larger than that in microgrids. Because it needs to cover the exchanged energy from microgrids. In addition, due to the geographical location of the generating station, the sizing value of PV number is larger than that in microgrids.

The remainder of this paper is organized as follows. Section II describes the operation of hydrogen-based storage system, and Section III the sizing method based on genetic algorithm. Section IV the simulation results. Finally, Section V concludes the paper.

II. Operation of hydrogen-based storage system

In the generating station and microgrid, the core device is the hydrogen-based storage system, which is used to respond to renewable energy intermittent. In fact, there are two common methods to operate the hybrid storage system, namely, rule-based strategy and optimization strategy. With different strategies, the operation of the storage is significantly different. Here, we adopt the basic rule-based strategy to control the operation of the hydrogen-based storage. More advanced operation strategies are out the scope of this paper, and will be further studied in the future.

The operation rules are set as follows:

Algorithm 1 Rule-based strategy

Input PV P_{PV} and load demand P_{load} dataset;
for $t = 1 : T$ **do**
  if $P_{PV} > P_{load}$ **then**
    firstly stored in hydrogen storage system, considering sizing limitations: $P_{hy}^{ch} < P_{hy}^{ch,max} (= P_{ele})$, $V_{H_2} < V_{tanks}$;
    secondly stored in battery storage, considering sizing limitations: $P_{ba}^{ch} < P_{ba}^{ch,max}$;
    if $P_{PV} > P_{load} + P_{hy}^{ch,max} + P_{ba}^{ch,max}$ **then**
      curtail the remaining surplus energy P_{curt};
  else $P_{PV} < P_{load}$
    firstly utilize the hydrogen storage system, considering sizing limitations: $P_{hy}^{dis} < P_{hy}^{dis,max} (= P_{fc})$, $V_{H_2} < V_{tanks}$;
    secondly use battery storage system, considering sizing limitations: $P_{ba}^{dis} < P_{ba}^{dis,max}$;
    if $P_{PV} + P_{hy}^{dis,max} + P_{ba}^{dis,max} < P_{load}$ **then**
      the remaining load demands are shed P_{ls};
  t=t+1;
Output: P_{curt}, P_{ls};

When the generated PV power P_{PV} is larger than the load demands P_{load}, the surplus energy $P_{PV} - P_{load}$ is firstly stored in hydrogen storage system; if the hydrogen storage is full, then secondly stored in battery storage; if the two storages are all fully charged, the remaining surplus energy is curtailed. When the generated PV power P_{PV} is smaller than the load demands P_{load}, the shortage energy $P_{load} - P_{PV}$ is firstly supplied by hydrogen storage system; if the hydrogen storage is insufficient, battery storage system is secondly used; if the two storages are all used up, the remaining load demands are shed. Here, $P_{ba}^{ch,dis,max} = 0.9 \cdot C_{ba}$. P_{ele}, P_{fc}, V_{tanks} are the sizing values of fuel cell, electrolyzer, and tanks, respectively. The shed loads P_{ls} in microgrids are then supplied by generating station, and P_{ls} is the exchanged energy P_{ex}^{MGi} in each microgrid. In fact, there are many rule-based strategies, it depends on the storage conditions and user's goal. Here, we just show a reasonable operation strategy.

Based on the above storage system operation strategy, we can then develop the operation of the microgrid clusters and generating station, which is shown in the following:

Algorithm 2 Operation strategy of the whole system

Input PV P_{PV}^{base}, P_{PV}^{MG1}, $\cdots$, P_{PV}^{MGn} and load demand P_{load}^{base}, P_{load}^{MG1}, $\cdots$, P_{load}^{MGn}dataset;
for $t = 1 : T$ **do**
  for $i = 1 : n$ **do**
    MGn: run Algorithm 1$\leftarrow \{P_{PV}^{MGi}, P_{load}^{MGi}\}$;
    Obtain exchanged energy P_{ex}^{MGi} (namely, P_{ls});
  Calculate total exchanged energy $\sum_{i=1}^{n} P_{ex}^{MGi}$;
  generating station: run Algorithm 1$\leftarrow \{P_{PV}^{base}, P_{load}^{base} + \sum_{i=1}^{n} P_{ex}^{MGi}\}$;
  generating station: calculate curtailed power P_{curt}^{base} and load shedding P_{ls}^{base}; battery charging/discharging power $Z_{ch,dis}$, fuel cell/electrolyzer ON/OFF state $onoff_{fc,ele}$;
  t=t+1;
Output: $\sum_{i=1}^{n} P_{ex}^{MGi}$, P_{curt}^{base}, P_{ls}^{base}, $Z_{ch,dis}$, $onoff_{fc,ele}$;

P_{PV}^{base}, P_{PV}^{MGn} are the installed PV panels in generating station and microgrid n. Firstly, each microgrid runs the operation strategy based on Algorithm 1, and the exchanged energy P_{ex}^{MGi} with generating station can be obtained; then, the total exchanged energy $\sum_{i=1}^{n} P_{ex}^{MGi}$ are then submitted to generating station; thirdly, generating station runs its operation strategy based on Algorithm 1; at last, the curtailed power P_{curt}^{base}, load shedding P_{ls}^{base}, battery charging/discharging power $Z_{ch,dis}$, and fuel cell/electrolyzer ON/OFF state $onoff_{fc,ele}$ of the generating station are obtained.

III. Sizing method based on genetic algorithm

Based on the above operation strategy of the whole system, we can then develop the sizing method. Here, we adopt the genetic algorithm (NSGA-II) to search for the best sizing values. The developed sizing algorithm can be seen as follows:

Genetic algorithm is an iterative search method based on biological evolution to find optimal solutions [13]. Firstly, genetic algorithm generates sizing values for each component. Then, based on the generated sizing values, operation of the whole system is executed, namely, run Algorithm 2. Based on the running output of Algorithm 2, the operation cost C_{op},

Algorithm 3 Developed sizing method

for $j = 1 : it^{max}$ **do**
  generate initial sizing values, generating station: N_{PV}^{base},P_{fc}^{base}, P_{ele}^{base}, V_{tanks}^{base}, C_{ba}^{base}; microgrids: N_{PV}^{MGi}, P_{fc}^{MGi}, P_{ele}^{MGi}, V_{tanks}^{MGi}, C_{ba}^{MGi}, $i = 1, \cdots, n$;
  run Algorithm 2;
  calculate operation cost C_{op}, investment cost C_{inv}, exchanged energy $P_{ex}^{total} = \sum_{i=1}^{n} P_{ex}^{MGi}$;
  three objective functions: $f_{fitness} = [C_{op} + C_{inv}, P_{ex}^{total}, N_{PV}^{total}]$;
  process NSGA-II operators;
  j=j+1;
Output: sizing values; objective function values $f_{fitness}$;

and exchanged energy P_{ex}^{total} can be calculated. In addition, based on the given sizing values, the investment cost C_{inv} and installed PV numbers N_{PV}^{total} can be also calculated. And the three objective functions form the fitness function $f_{fitness} = [C_{op} + C_{inv}, P_{ex}^{total}, N_{PV}^{total}]$. After that, based on the fitness function, process NSGA-II operators [8], the newly sizing values are updated. The sizing algorithm is repeatedly running until the stopping criteria is satisfied. Here, the stopping criteria is the maximum iteration number it^{max}.

The operation cost C_{op} is shown as follows:

$$\sum_{t=1}^{T} Ba_{op}(Z_{ch}(t) + Z_{dis}(t)) + Hy_{op}(onoff_{fc}(t) + onoff_{ele}(t)) + Hy_{st}(ST_{fc}(t) + ST_{ele}(t)) + \alpha P_{ls}(t) + \beta P_{curt}(t) \tag{1}$$

where T is the time horizon, here $T = 8760h$ represents one year; $Ba_{op} = \frac{B_{inv}}{B_{life}}$ is the battery utilization cost, B_{inv} is the battery investment cost, B_{life} is the battery lifetime; Z_{ch}, Z_{dis} are the charging and discharging power of battery; $Hy_{op} = \frac{fc,ele_{inv}}{fc,ele_{life}} + O\&m$ is the hydrogen storage utilization cost, fc, ele_{inv} is the fuel cell/electrolyzer investment cost, $O\&m$ is the operation and maintenance cost; $onoff_{fc,ele}$ are the ON/OFF state of fuel cell/electrolyzer; Hy_{st} is the start up cost of hydrogen storage; $ST_{fc,ele}$ are start up state of fuel cell/electrolyzer; α is the penalty cost of load shedding; P_{ls} is the load shedding; β is the penalty cost of curtailed renewable energy; P_{curt} is the curtailed power. Here, α and β are arbitrarily chosen as 10^{20}, in order to reduce load shedding and curtailed power. When the value of the objective function is larger than 10^{20}, it means that load shedding and curtailed power occur.

The investment cost C_{inv} is shown as follows:

$$\begin{aligned} C_{inv} =& PV_{inv}N_{PV} + fc_{inv}P_{fc} + ele_{inv}P_{ele} \\ &+ Tank_{inv}V_{tanks} + Ba_{inv}C_{ba} \end{aligned} \tag{2}$$

where PV_{inv}, $Tank_{inv}$ are the investment cost of PV panel and hydrogen tanks, respectively.

At last, the three objective functions can be described as:

$$f_1 = C_{op}^{base} + C_{inv}^{base} + \sum_{i=1}^{n}(C_{op}^{MGi} + C_{inv}^{MGi}) \tag{3}$$

$$f_2 = \sum_{i=1}^{n} P_{ex}^{MGi} \tag{4}$$

$$f_3 = N_{PV}^{base} + \sum_{i=1}^{n} N_{PV}^{MGi} \tag{5}$$

The multi-objective sizing problem can be represented as:

$$min f_1, min f_2, max f_3 \tag{6}$$

Namely, minimizing the operation and investment cost, minimizing the exchanged energy with generating station, maximizing the installed PV panels. It can be seen that when the investment cost is decreasing ($f_1 \downarrow$), the exchanged energy is increasing ($f_2 \uparrow$), and the installed PV panels are decreasing ($f_3 \downarrow$).

IV. SIMULATION RESULTS

Based on the above proposed multi-objective sizing algorithm, we then deploy a typical simulation case. In the case, four microgrids are considered, including industrial park microgrid, smart building microgrid, parking lot, and residential area microgrid. These four microgrids are supplied by a zero carbon emission generating station. Our goal is to find the best sizing value for each component to achieve the above three objective functions. The cost coefficients are presented in Tab. I.

TABLE I
PARAMETERS.

Parameters	Value	Parameters	Value
B_{inv}	470 €/kWh	fc_{life}	3000h
B_{life}	2000 cycles	ele_{inv}	3200€/kW
SOC_{min}	0.2	ele_{life}	3000h
SOC_{max}	0.9	$O\&m$	0.2€/h
fc_{inv}	4000€/kW		

The data is obtained from [14] [16]. One unit PV panel rated power is $10kW$. The solar radiation data profile in microgrids area is shown in Fig. 3. The load demands in generating station is presented in Fig. 4. Load demands in residential microgrid is presented in Fig. 5. Due to the page limitation, load demands in the other microgrids are not presented.

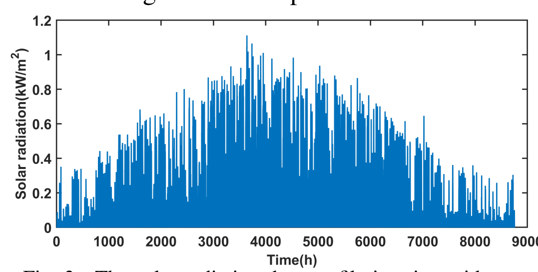

Fig. 3. The solar radiation data profile in microgrids area.

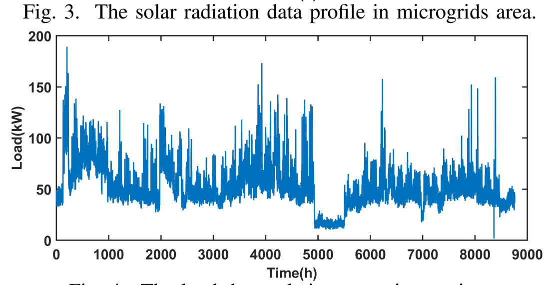

Fig. 4. The load demands in generating station.

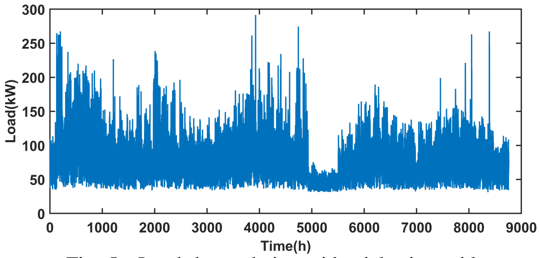

Fig. 5. Load demands in residential microgrid.

One simulation results based on genetic algorithm is shown in Fig. 6. The average time of one simulation running is about 1289 seconds. It can be seen that one objective function results (Total costs) in some candidates are larger than 10^{20}. Here, we should notice that if the operation costs are larger than 10^{20}, it means that load shedding or curtailed PV power happen, then we should abandon this candidate. In order to obtain possible candidates that no load shedding and curtailed power occur, we run large numbers of simulations. At last, the simulation results are presented in Fig. 7. Here, the installed PV numbers are negative values, because the third objective function is maximization, and we need to transfer it into the minimization using the negative operator. The simulation results did not show obvious Pareto fronts, because the candidate solutions are not enough, and more simulations should be done.

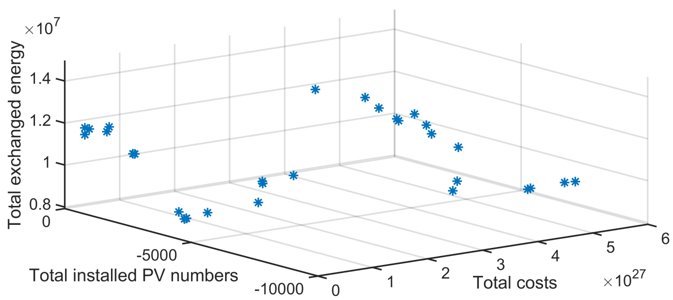

Fig. 6. One simulation results based on genetic algorithm.

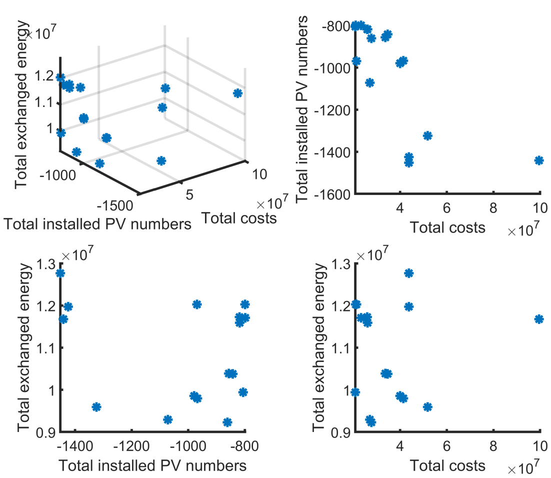

Fig. 7. Simulation results.

We then adopt the scatter plot to present the relationship between each sizing component, which can be seen in Fig. 8. It can be seen that the values of the components are falling in a respectful range, which means the sizing results are effective.

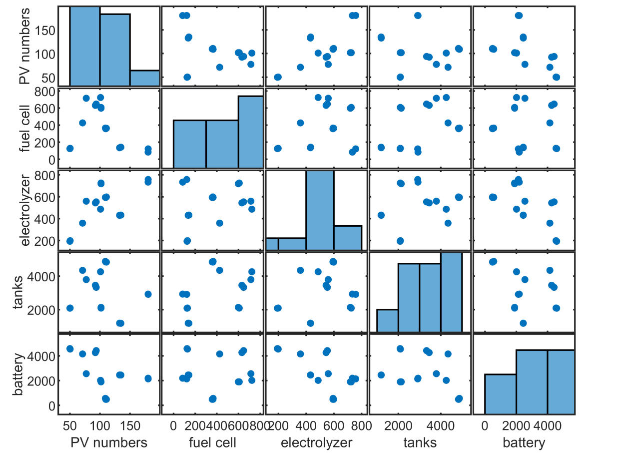

Fig. 8. Scatter plot to present the relationship between each sizing component.

A. Results analysis

We choose one candidate solution from Fig. 7 as an example, and analyse the sizing results. The chosen sizing solution is presented in Tab. II.

TABLE II
ONE CANDIDATE SOLUTION.

Variables	PV numbers	fuel cell $[kW]$	electrolyzer $[kW]$	hydrogen tanks $[N.m^3]$	battery $[kWh]$
Generating station	500	5191	14362	28138	1284
Residential	111	363	598	4834	484
Parking lot	78	323	451	2670	4494
Industrial	57	28	754	4950	4011
Smart building	55	377	306	4980	4679

Pie plot is adopted to show the sizing results of residential, parking lot, industrial, and smart building microgrid in Fig. 9. It can be seen that the volume of tanks and the capacity of battery are the important constituent parts of the microgrid.

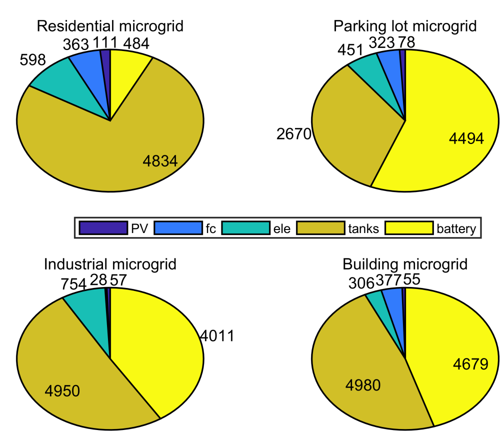

Fig. 9. The sizing results for residential, parking lot, industrial, and smart building microgrid.

The sizing for generating stations can be seen in Fig. 10, where "fc" represents fuel cell, "ele" represents electrolyzer, "tanks" represents hydrogen tanks. Compared with microgrids, it can be seen that the volume of the hydrogen tanks in generating station is six times larger than that in microgrids. In addition, large numbers of PV panels can be installed, because the generating station is located far away from city centre, thus a plenty of lands can be utilized.

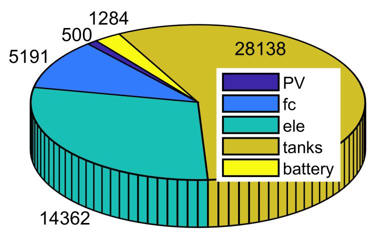

Fig. 10. The sizing for generating station.

At last, based on the above candidate sizing results, we run the operation of the whole system for one year. And the changes of the levels of the hydrogen in different parts can be seen in Fig. 11. It shows that at the end of the current year, the hydrogen in residential microgrid is used up; in addition, the volume of the hydrogen at the end of the year is less than the volume of the hydrogen at the beginning of the year. This means that along the whole year, the produced hydrogen is less than the consumed hydrogen, and the extra hydrogen should be charged in each part for preparing the next year operation.

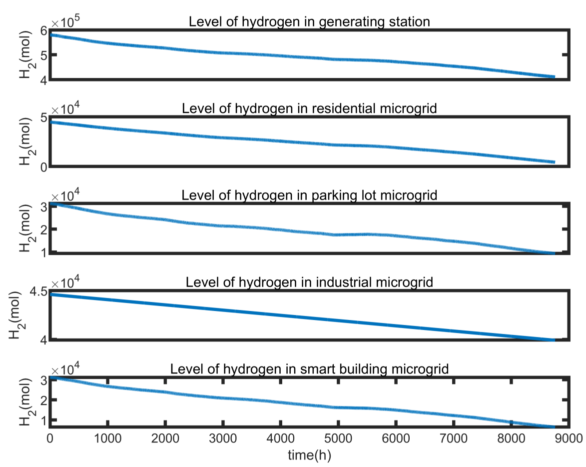

Fig. 11. Changes of the levels of the hydrogen in different parts.

V. Conclusion

In this paper, we have developed a zero carbon emission generating station and microgrid clusters, to achieve a zero carbon emission energy supply system. In order to consider different aspects, a multi-objective optimization is adopted to achieve three goals simultaneously, namely, minimizing total cost, minimizing total exchanged energy, and maximizing installed PV panels. The simulation results show several insights. 1) It is a reasonable idea to build the zero carbon emission generating station to supply energy to microgrids. The core device is the hydrogen-based storage system. The scatter distribution shows that the sizing values are all in a respectful range. 2) When the investment cost is decreasing, the total exchanged energy is increasing, and the installed PV panels are decreasing; when the PV panels are decreasing, the total exchanged energy is decreasing. 3) The volume of the hydrogen tanks in generating station is larger than that in microgrids, because it needs to cover the exchanged energy from microgrids.

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