The Selection of Optimal Structure for Stand-alone Micro-grid Based on Modeling and Optimization of Distributed Generators

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ABSTRACT The configuration programming of Distributed Generators (DGs) in a micro-grid (MG) through the achievement of multi-objective is an inevitable and primary issue ahead of micro-grid’s construction. The motivation of this paper is to select the most suitable catalog of MG from DC micro-grid (DC-MG), AC micro-grid (AC-MG) and hybrid MG by means of uncertainties’ models and corresponding DGs’ configurations. The DGs in all catalogs of MG are composed of wind turbine (WT), photovoltaic (PV), biomass generation (BG) and battery energy storage (BES) system. In terms of uncertainties’ models, the proposed mathematical models are combined with multifarious scenarios which are considered the uncertainties of variations in solar irradiance and wind speed, temperature and the load demand. Particularly, this paper also proposes differences about allocations and sizes of all the equipments based on the assumed specific structure for each catalog of MG. Then, the non-dominated sorting genetic algorithm III (NSGA-III) is utilized by MATLAB working platform to compute the multi-objective functions associating with the minimized system cost, the loss of power supply probability (LPSP), and the greenhouse gas (GHG) emissions for each catalog of MG. Finally, the results and comparisons demonstrate that the AC-MG is the optimal catalog for study case, which has superiorities of economy and reliability. Although the DC-MG has lower GHG emissions, the AC-MG is the optimal choice after the comprehensive comparisons and analyses depended on three objectives.

INDEX TERMS Distributed Generators (DGs), DC micro-grid (DC-MG), AC micro-grid (AC-MG), hybrid micro-grid, the non-dominated sorting genetic algorithm III (NSGA-III)

I. INTRODUCTION

The primary issue of setting up a micro-grid (MG) is to determine the sizes of distributed generations (DGs) in a MG. A reliable stand-alone MG makes the most of RE resources (wind, PV, hydro [1], biomass [2], geothermal, ocean wave) which show the advantages such as power supply reliability, less of GHG emission and system cost [3-5]. Nonetheless, these advantages become kinds of contradictory force when to seek the multi-objective optimal configuration of DGs in a MG. Based on the contradictions, many latest research considered different uncertainties such as variations in solar irradiance, wind speed and load demand to survey the optimal allocations of DGs in an AC-MG, DC-MG or hybrid MG. However, it is quite under researched that the role of different catalogs of MG in DGs’ configurations of MG.

In the last decade, many efforts have been dedicated to the optimization problems of DGs in MGs [6], [7], [8], [9]. The authors in [10] made use of a refined energy resources management (ERM) system to carried out a DC-MG comprised of PV, micro-turbine, fuel cell, diesel generator, battery system, and load profiles over four seasons of the year. Based on the sizing analysis of DGs in MG, [11], [12], [13] proposed an optimal sizing approach with comprehensive consideration to find optimal allocations of PV, WT and battery system in a DC-MG. The NSGA-II algorithm was used to find solutions for a multi-objective problem to minimize the generation cost and to minimize the battery life loss in an AC Island microgrid which consists of wind, PV, diesel generators, and lead–acid batteries [14]. Das et al. [15] proposed a computationally efficient near optimal control approach to
tackle the problem of optimizing battery energy storage systems (BESS) with other power supply units in islanded AC-MGs, they achieved the minimum daily operational cost. Reference [16] presented an improved Levy-Harmony algorithm with the aid of Levy flight and a triangular aggregation model for a multi-objective optimization scheme of island AC-MGs sizing. Moreover, some researches dealt with the sizing problem of the hybrid MG system that consists of multiple resources [17], [18], [19]. Reference [20] carried out a parallel approach combining both PSO and multi-

### NOMENCLATURE

#### A. ABBREVIATIONS

| Abbr.  | Description                             |
|--------|-----------------------------------------|
| AC-MG  | AC micro-grid                            |
| BES    | Battery Storage System                   |
| BG     | Biomass generator                        |
| DC-MG  | DC micro-grid                            |
| DGs    | Distributed generators                   |
| GHG    | Greenhouse gas                           |
| IGD    | Inverted Generational Distance           |
| LPSP   | Loss of power supply probability.        |
| MG     | Micro-grid                               |
| NSGA-III | Non-dominated sorting genetic algorithm III |
| PV     | Photovoltaic                             |
| RE     | Renewable energy                         |
| SOC    | State of charge value of the i\(^{th}\) battery |
| WT     | Wind turbine                             |
| CIGS   | Copper indium gallium selenium           |

#### B. PARAMETERS

- \( b_{bio} \): Specific propellant consumption
- \( b_{fuel} \): Fuel consumption rate
- \( C_{BES} \): Investment cost of BES
- \( C_{BG} \): Investment cost of BG
- \( C_{br} \): Cost of breaker
- \( C_{ca} \): Cost of AC cable
- \( C_{cd} \): Cost of DC cable
- \( C_{co} \): Cost of converters,
- \( C_{PV} \): Investment cost of PV system
- \( C_{WT} \): Investment cost of wind turbines
- \( f_{PV} \): Factor reflecting shading
- \( G_{STC} \): Solar irradiation under Standard Test Condition
- \( L \): Transport distances from all garbage stations to biomass power generation station
- \( LHV_{fuel} \): Low calorific value of fuel
- \( l \): Lifetime of DGs
- \( P_{ca} \): Rated capacities of AC cables
- \( P_{dc} \): Rated capacities of DC cables
- \( P_{co} \): Rated capacity of converters
- \( P_{r} \): Rated power of WT
- \( P_{STC} \): Rated power of the PV
- \( P_{TL}(t) \): Power for transmission lines
- \( T_{STC} \): Temperature under Standard Test Condition
- \( r \): Discount rate
- \( v_{ci} \): Cut-in wind speed
- \( v_{oc} \): Cut-off wind speed
- \( v_{r} \): Rated wind speed
- \( \eta_{c} \): Charging efficiencies of the battery
- \( \eta_{d} \): Discharging efficiencies of the battery

#### C. VARIABLES

- \( B_{fuel} \): Annual fuel consumption
- \( C_{DE} \): Acquisition cost and installation cost of DGs, cables and power electronic devices
- \( C_{BG} \): Investment cost of DGs
- \( C_{EQ} \): Investment cost of cables and power electronic devices
- \( C_{OM} \): Operation and maintenance cost
- \( C_{OM(DG)} \): Operation and maintenance costs of DGs
- \( C_{OM(EQ)} \): Operation and maintenance costs of equipment
- \( C_{RE} \): Replacement cost of BES and converters
- \( C_{RE(BES)} \): Replacement cost of BES
- \( C_{RE(co)} \): Replacement cost of converter
- \( C_{Y} \): Minimums of the system cost
- \( C_{TR} \): Fuel transportation fee
- \( c \): Capital recovery factor
- \( E_{env} \): Annual air pollution
- \( G(t) \): Real solar irradiation
- \( h_{BG} \): Annual service hours of biomass generator
- \( I_{av} \): Average daily data of illumination intensity
- \( I_{cc} \): Duration and frequency of cloud coverage
- \( I_{rand} \): Time period of the appearance and disappearance of daily light in different seasons
- \( L_{c} \): Length of DC cable or AC cable
- \( N_{PV(i)} \): Number of i\(^{th}\) PV module
- \( N_{WT(i)} \): Number of i\(^{th}\) wind turbine
- \( P_{BES} \): Output power of BES
- \( P_{BG} \): Output power of BG
- \( P_{C} \): Charging powers of BES
- \( P_{DG} \): Total output power of DGs
- \( P_{d} \): Discharging power of BES
- \( P_{day} \): Daily load of residents
- \( P_{e} \): Extra output power in the micro-grid
- \( P_{L} \): Load demand the power required for the load
- \( P_{PV(i)} \): Output power of PV system
- \( P_{WT} \): Actual power of a WT turbine
- \( P_{year} \): Annual average daily load
- \( P_{light} \): Load of street lamp
- \( P_{sun} \): Wind speed of gradient
- \( P_{sun,rand} \): The maximum of wind speed at night
- \( P_{gust} \): Wind speed of gusts
- \( P_{grad} \): Wind speed of gradient
- \( P_{rand} \): Random wind speed
- \( P_{DG} \): Capacity of each DG of each cycle
- \( OP \): Probability of occurrence
- \( Y \): Transportation price
- \( \Delta T_{BG} \): Average of annual operation hours of BG

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dimensional sensitivity analysis to design the storage optimal sizing in a real island hybrid renewable MG. Also, in order to get an effective integration of DGs within MGs and higher micro-grid performance, reference [21] developed PSO to optimize the control gains of D-FACTS controllers. It was obvious that most of studies focus on the DGs’ configuration optimization in settled AC-MG, DC-MG or hybrid MG.

Various algorithms are the main method when DGs are organized into MG with reasonable capacity and remarkable energy regulation ability. Certain traditional AI algorithms such as Particle Swarm Optimization (PSO) [18], [22] [23], Genetic Algorithm (GA) [24], [25], [26] artificial bee colony algorithm (ABC) [27], [28] and ant colony [29] were used for optimization problem with different objectives. The traditional AI algorithms were employed in the early studies and improved in recent years, some studies made comparisons of traditional versions and the improved. The improved particle swarm optimization (IPSO) [30], [31], modified ABC algorithm [32] and improved GA algorithm [33], [34] were proved that have better convergence and excellent dynamic performance than those original visions. For instance, Bao et al. [35] proposed an IPSO algorithm with two improvements for solving the coordinated scheduling of day-ahead cooling load and electricity in MG. One improvement was added the mandatory correction to enhance the algorithm performance. The other one used solution occupation strategy and the size decrease method of near-zero points, which contributed to avoid the pre-maturity and showed the superior performance than original PSO. Moreover, some researches combined two or more algorithms for achieving higher efficiency of optimization in MGs. In [36], the GA algorithm was programmed to look for optimal scheduling of the sources of energy in a grid-connected micro-grid whereas parameters were optimized by Simulated Annealing (SA) method for the optimal scheduling of the sources of energy in a grid-connected micro-grid. In [37], the artificial neural network (ANN) was utilized to evaluate the demand response, meanwhile, the issues of economic dispatch which evaluate the generation, storage and responsive load offers were solved by bacterial foraging optimization algorithm (BFOA). However, only one or two objective functions were taken into account for the most above researches. Factually, recent researches gradually considered multi-objective for the sake of various purposes. In order to solve the constrained multi-objective problem, a modified version of GA called Non-dominated Sorting Genetic Algorithm (NSGA) was proposed, and recent evolutionary versions named NSGA-II [38] and NSGA-III [39], [40] were widely used in optimal scheduling of micro-grid. It was proved that NSGA-III outperforms NSGA-II at working out the multi-objective optimization with three or more objective functions [41], [42]. The NSGA-III was used for optimization of DGs in a micro-grid [43], [44] to work out the multi-objective functions such as minimum consumption costs, the minimized inconvenience caused by consumers, the rebound peak occurrence and minimized pollutant emission. Due to the good performance of multi-objective problem, this paper chooses NSGA-III for solving optimal issue of configuration in MGs.

Furthermore, the duration, time interval (time step length) and simulation methods of data such as wind speed, solar irradiation, temperature and load demand were the main uncertainties for most researches of micro-grid configurations. In [32], an approach combined artificial neural network with a Markov chain (ANN-MC) was used to predict 600 data points of the load demand and power generation of WT and PV during the 24 hours. References [27], [45] determined the WT and PV power values in hourly during the 24 hours period, and these values were based on the historical data or Predicted data. The authors in [17] showed the historical hourly profile of load and environmental conditions containing the temperature, wind speed and solar radiation during a year. In [10], the unit power of WT, PV and the micro-grid’s load curve were considered for a given day in each season of the year. After that, some efforts were focused on the forecasting for those uncertainties. The study in [46] forecasted average wind speed and loads from 17:05 to 18:05 within a day, the forecasted data was obtained from the prediction algorithm and a Real-Time Digital Simulator based on digital-analog hybrid simulation platform [47]. The study in [48] developed a deep recurrent neural network with long short-term memory units (DRNN-LSTM) model to forecast residential hourly PV power output power and load over short-term horizon respectively. It achieved total costs reduction and system reliability improvement. The mathematical probabilistic models were popular to describe uncertainties as well. In [49], the load demand and solar irradiance were modeled as hourly statistics in a day within one season based on the location’s three years of hourly historical data, and the data of solar irradiance was generated by a Beta-probability distribution function (PDF) while the normal PDF was used for the uncertain load demand. This mathematical models contributed to a hybrid systems with minimum power losses. Similarly, the method of PDF was employed in [50] [51], Weibull PDF, normal PDF and Beta PDF were utilized for modelling the uncertainties of the wind speed, load demand and solar irradiance respectively. A set of scenarios is obtained by a combination of these uncertainties for minimizing the expected power losses.

From the previous surveys, these papers do great works in many aspects of the DGs’ configuration management, especially in the improvements of algorithm and uncertainties of the output power of the DGs and load demand. However, differ catalog of MG brings some uncertainties that impact on the configuration accuracy of DGs by multi-objective optimal scheduling method, which are considered less. Furthermore, some studies use historical and predicted data in early and most build mathematical models to design solar irradiation, wind speed and loads. These forms of expression are a bit of onefold to describe these uncertainties from diversification. To address this issue, the main innovation points in this article are aware of the following: firstly, this article gives in-depth
analysis of the uncertainties arisen from differ catalogs of MG such as allocation of all the equipments and the prices of converters. Secondly, this paper generates a set of scenarios for solar irradiation, wind speed and loads, and these scenarios are simulated by mathematical models and smaller time step, which are benefit for reflecting the randomness.

The motivation of this paper is to select the most suitable catalog of MG and corresponding optimal capacity size of each DG. On the contrary, it proves that optimization of DGs is the factor which affects the selection of the catalog of MG. The main contributions are as follows:

1) This paper proves that the catalogs of MGs affect the optimal capacity configurations of DGs in a MG. There is little research to substantiate the point. It reminds designers that the uncertainties brought from catalogs of MG should be considered simultaneously with the construction of MG.

2) Many new uncertainties are taken into account when to calculate the optimal configuration of DGs in differ catalog of MG, this conduce to acquire accurate optimal results.

3) Most of previous works dealt with problems of DGs’ configuration after the catalog of MG had been set in advance. Compared with previous works, this paper is not only obtain the optimal configuration of DG as most researches, specifically, it also indicates the most suitable catalog of MG. This prevents the negligence that if researchers calculate the optimal configuration of DG in settled AC-MG, whereas the optimal configuration of DG in hybrid MG are better than that under all setting objective functions, unless the AC-MG is obligatory for the project.

This paper is organized as follows: Section II gives a brief introduction of three kinds of micro-grids. In Section III, the output of DGs and BES are modeled. Multi-objective function and constraints are collated in Section IV. Section V shows and provides the NSGA-III algorithm and operating strategy. Section VI shows meteorological models, load model, relative devices and parameters setting. Section VII and VIII show results analysis and conclusions.

II. THE STRUCTURE OF MICRO-GRIDS

A. DC MICRO-GRID

The alternators are connected to the DC-bus via converters, whereas the AC loads are obtained power from the DC-bus by AC/DC converters. The DC generators and DC loads are connected to the DC-bus via the DC/DC converters. The DC micro-grid has advantages of simple control, lower line loss, it also avoids problems such as frequency, reactive power and phase.

B. AC MICRO-GRID

The DC generators produced direct current into the AC-bus through the DC/AC converters. The AC loads get power from the AC bus by AC/DC converters. AC generators and AC loads transfer the energy by transformers [52]. Most power electronic devices assembled in AC-MG have a more competitive price such as transformers because of mature technologies. However, the shortcomings of an AC micro-grid mainly focus on high line loss, harmonic problem and control technology.

C. HYBRID MICRO-GRID

A hybrid micro-grid is composed of an AC-MG and a DC-MG, the AC-MG and DC-MG are connected by bidirectional
converters [36]. Two bidirectional converters is designed in hybrid MG, this guarantees the power transmission and load uninterrupted power supply between DC-MG and AC-MG in case either of them get out of order. The hybrid MG has the characteristics of lower loss, high efficiency, and strong flexibility, whereas it develops other issues such as expensive bidirectional converter [53].

The main differences of the three MGs' structures are significant factors to impact the catalog selection of MG from DC-MG, AC-MG, and hybrid MG. The differences are concluded as follows:

1) Bus and electric wire. Each type of micro-grid makes use of different category, voltage classes and length with regards to bus and electric wire, which has an effect on capacity configuration optimization of a micro-grid related to the system cost and line loss.

2) Convertors. The choice of convertor is related to the types of current, voltage classes and capacities of connections including DGs, bus and load at the two ends of the convertor. Therefore, the category, number, capacity and relevant cost of convertors have relationships with the optimization results such as the system cost of capacity configuration optimization.

3) DGs. The capacity and numbers of DGs could be different in each type of micro-grid, which affect the total cost and stability of a micro-grid. If the thermal power generation is installed in a micro-grid, the GHG emissions is influenced by the capacity and numbers of thermal power generation. Furthermore, the replacement, operational and maintenance cost of BES have a reducing trend as the technologies matured, the relative parameters are taken into account in this paper.

Thus, the category of micro-grid is an essential selection for capacity configuration optimization of a micro-grid.

III. THE MODELS OF DGS

A. OUTPUT POWER OF WT

The power output of a wind turbine is described by a piecewise function as follows [7]:

\[
P_{WT}(t) = \begin{cases} 
0 & 0 \leq v(t) \leq v_{ci} \\
P_r & v_{ci} \leq v(t) \leq v_r \\
P_r & v_r \leq v(t) \leq v_{oc} \\
0 & v(t) \geq v_{oc} 
\end{cases}
\]  

(1)

where \( v \) is the actual wind speed at time \( t \), \( v_{ci} \), \( v_r \), and \( v_{oc} \) represent the cut-in speed, rated wind speed, and cut-off speed separately, \( P_r \) denotes the rated power of wind turbine, \( P_{WT} \) is the actual power of a WT.

B. OUTPUT POWER OF PV

The maximum power point tracking device (MPPT) is assumed to install in PV system for seeking the maximum of solar energy. The output power of the PV system can be described as [54]:

\[
P_{PV}(t) = f_{PV}P_{STC}G(t)\frac{G(t)}{STC} \left[1 + k(T_{cell}(t) - T_{STC})\right]
\]

(2)

where \( T_{cell}(t) = T(t) + aG(t)(1 + \beta(t))(1 - \gamma v(t)) \)

(3)

\( P_{PV}(t) \) is the output power of PV at time \( t \), \( f_{PV} \) is the factor reflecting shading which is set as 0.9 in this paper, \( P_{STC} \) represents the rated power of the PV, \( G_{STC} \) and \( T_{STC} \) denote solar irradiation and temperature under Standard Test Condition, separately, and the value of \( T_{STC} \) normally is 25°C, \( G(t) \) and \( T(t) \) are real solar irradiation and temperature on panels, respectively, \( k \) is the temperature coefficient, and \( k = -0.0047°C, T(t) \) and \( v(t) \) represent ambient temperatures and wind speed at time \( t \) respectively.

\( \alpha, \beta, \gamma \) are experimental parameters, which are 0.0138, 0.031 and 0.042 respectively.

C. BIOMASS GENERATION SYSTEM

The relationship of fuel consumption and the capacity of BG is shown as:

\[
P_{BG} = \frac{b_{fuel}}{f_{fuel}} \frac{t}{\Delta T}
\]

(4)

where \( P_{BG} \) represents output power of BG, \( b_{fuel} \) is the annual fuel consumption rate in ton/year, \( b_{fuel} \) is fuel consumption rate in kg/kWh, \( \Delta T \) is annual operating hours in hour.

D. BATTERY ENERGY STORAGE SYSTEM

The battery absorbs or releases electrical energy when the excess electrical energy or insufficient power exists in the micro-grid. Meanwhile, the BES system in a micro-grid is capable of keeping the power balance, load leveling, and peak shaving. The state of BES is expressed as State-of-Charge (SOC), and it is calculated as [55]:

\[
\begin{align*}
\text{Discharge:} \quad \text{SOC}(t + \Delta t) &= \text{SOC}(t) - \Delta t \cdot P_d(t)/E_{STC} \cdot \eta_d \\
\text{Charge:} \quad \text{SOC}(t + \Delta t) &= \text{SOC}(t) + \Delta t \cdot \eta_c \cdot P_c(t)/E_{STC}
\end{align*}
\]

(5)

where \( \text{SOC}(t) \) is the SOC in the battery at time \( t \), \( \Delta t \) is time steps, \( P_c(t) \) and \( P_d(t) \) are charging and discharging powers separately, \( \eta_c \) and \( \eta_d \) are charging and discharging efficiencies of the battery.

IV. OBJECTIVE FUNCTIONS AND CONSTRAINTS

A. OBJECTIVE FUNCTIONS

In this paper, the multi-objective function is determined by the minimums of the system cost \( C_G \), greenhouse gas (GHG) emissions \( C_{GHG} \) and Loss of Power Supply Probability \( (LPSP) \). The congregated multi-objective function is shown as:

\[
F(X) = \min[C_G, C_{GHG}, LPSP]^T
\]

(6)

1) THE SYSTEM COST OF MICRO-GRID

The system cost of micro-grid \( C_G \) should make mention of capital recovery factor \( c \) which associates with discount rate \( r \) and lifetime \( l \) of DGs or other equipment [31].

\[
c = \frac{r(1+r)^l}{(1+r)^l-1}
\]

(7)

The system cost of micro-grid includes acquisition cost and installation cost \( C_{DE} \), operation and maintenance cost \( C_{OM} \),...
replacement cost $C_{DE}$ and transportation cost of fuel $C_{TR}$ is calculated using following equations:

$$C_T = \min \sum [C_{DE} + C_{OM} + C_{RE} + C_{TR}]$$

(8)

$C_{DE}$ is nonrecurring investments which includes the purchase cost and installation cost of wind turbines, PV system, BES, BG, cables and relevant power electronic devices. $C_{DE}$ is expressed as the following equations:

$$C_{DE} = C_{DG} + C_{EQ}$$

(9)

where $C_{DG} = c \cdot \sum (C_{WT} + C_{PV} + C_{BG} + C_{BES}) \eta_{ij,} P_{max}^{i,j}$

(10)

and $C_{EQ} = c \cdot \left[ \sum_{\Delta t=0}^{n} (C_{CA} + C_{CD}) L_i + \sum_{i}^{n} (C_{BR} + C_{CO}) \eta_{i} P_{max}^{i} \right]$.

(11)

where $C_{DG}$ and $C_{EQ}$ are investment cost of DGs and equipment investment cost separately, $C_{WT}$, $C_{PV}$, $C_{BG}$ and $C_{BES}$ are the investment cost of wind turbines, PV system, BG and BES, $C_{CA}$ and $C_{CD}$ indicate the investment of AC cable and DC cable in the micro-grid, $C_{BR}$ and $C_{CO}$ are cost of breaker and converters, respectively. $\eta_{ij}$ is the number of each DG, $i$ is the $i$th type of DGs, $j$ denotes the $j$th type in the same DG, for example, the number of the second type of PV is written as $n_{PV,2}$ or $n_{L,2}$. $i$ and $j$ also represent the positions in a matrix, $\eta_{i}$ is the maximum capacity of the $i$th equipment such as $P_{WT,1}^{max}$ and $P_{PV,2}^{max}$. $L_i$ is the length of DC cable or AC cable.

This paper adopts the capital recovery factor to calculate the $C_{OM}$, $C_{RE}$ and $C_{TR}$ in every year. $C_{OM}$ is made up of the operation and maintenance costs of DGs $C_{OM(DG)}$ and equipment $C_{OM(EQ)}$, which is shown as follows:

$$C_{OM} = c \cdot (C_{OM(DG)} + C_{OM(EQ)})$$

(12)

where

$$C_{OM(DG)} = c \cdot \int_{0}^{T} [k_{WT} P_{WT}(t) + k_{PV} P_{PV}(t) + k_{BG} P_{BG}(t) + k_{BES} P_{BES}(t)] dt$$

(13)

$$C_{OM(EQ)} = c \cdot \int_{0}^{T} [k_{CA} P_{CA}(t) + k_{CD} P_{CD}(t) + k_{CO} P_{CO}(t)] dt$$

(14)

where $k_{WT}$, $k_{PV}$, $k_{BG}$, $k_{BES}$, $k_{CA}$, $k_{CD}$ and $k_{CO}$ demonstrate the coefficients of operational and maintenance cost of WT, PV, BG, BES, AC cable, DC cable and converters, $P_{CA}(t)$ and $P_{CD}(t)$ and $P_{CO}(t)$ are the rated capacities of AC cables and DC cables separately, $P_{CO}(t)$ represents the rated capacity of converters.

Replacement cost is the investment which is used for changing DGs or equipment when DGs or equipment are damaged during the life-cycle of the micro-grid. Generally, the lifetime of BES and converters are usually less than 20 years [56]. Therefore, the system needs to consider the replacement of them for guarantying system normal operation during the whole lifetime. $C_{RE}$ can be formulated as [44]:

$$C_{RE} = (C_{RE(BES)} + C_{RE(CO)}) \sum_{k=1}^{n_k} k_{k} \left[ \sum_{l=0}^{n_k} \left( \frac{1+i_{k,l}}{1+i_{k,l}} \right) \right]$$

(15)

where $C_{RE}$ denotes the total replacement cost including BES and converters, $C_{RE(BES)}$ and $C_{RE(CO)}$ are the replacement cost of BES and converters separately, $k_{k}$ is the cost coefficient of the $k$th battery, $k_{0}$ is the number of types of battery in BES system, $i_{k,l}$ and $i_{k,q}$ are the annual increase rate of replacement costs and the rate of cost reduction caused by technological innovation, respectively, $n_{k}$ is the lifetime of the $k$th energy storage device.

$C_{TR}$ is caused by fuel transport from all garbage stations to biomass power generation station. It relates to annual fuel consumption ($B_{fuel}$), transportation price ($Y$) and transport distances ($L$).

$$C_{TR} = B_{fuel} Y L$$

(16)

where $B_{fuel}$ is shown as [57]:

$$B_{fuel} = b_{bio} \int_{0}^{T} P_{BG}(t) dt = b_{bio} P_{BG} h_{BG}$$

(17)

where $b_{bio}$ is specific propellant consumption in kg/kWh, $h_{BG}$ represents the annual service hours of biomass generator in hour.

2) LOSS OF POWER PROBABILITY

The LPSP reflects the reliability of the micro-grid system. That ensuring the DGs power meets the load demand is the main purpose of the micro-grid system. The lower LPSP indicates that the power supply of DGs in the micro-grid is much more able to satisfy the loads’ need. The expression of LPSP is as follows [17]:

$$LPSP = \min \left[ \frac{\sum_{t=1}^{T} P_{DG}(t)-P_{L}(t)}{\sum_{t=1}^{T} P_{L}(t)} \right]$$

(18)

where $P_{DG}(t)$ is the total output power of $P_{WT}(t)$, $P_{PV}(t)$, $P_{BG}$ and $P_{BES}(t)$. $P_{BES}(t)$ is the output power of BES, $P_{L}$ denotes the load demand.

3) ANNUAL AIR POLLUTION

The air pollutions are mainly emitted by BG, and the pollutants include: $CO_2$, $CO$, $SO_2$, $NO_x$ and dust. Meanwhile, the amounts of pollutants are proportional to the output power of BG and the operating time [45].

$$E_{env} = \min \left[ \Delta T_{BG} \sum_{i \in K} v_{i} P_{BG}(t) \right]$$

(19)

where $v_{i}$ is the amount of $i$th pollutant in kg/kWh, $K$ is the species number of pollutants, $\Delta T_{BG}$ is the average of annual operation hours of BG.

B. SYSTEM CONSTRAINTS

1) POWER BALANCE CONSTRAINT

The output power of DGs needs to matches the power of load and other requirements in the micro-grid. At the same time, the power balance is obliged to keep in a state of equilibrium during the whole life cycle of micro-grid [18]:

$$P_{L}(t) + P_{TL}(t) + P_{e}(t) = P_{WT}(t) + P_{PV}(t) + P_{BG}(t) + P_{BES}(t)$$

(20)

Where $P_{L}(t)$ is the power required for the load, $P_{e}(t)$ is the extra output power in the micro-grid, $P_{TL}(t)$ is the power for transmission lines which consists of DC cable and AC cable.

$$P_{TL}(t) = P_{CA}(t) + P_{CD}(t)$$

(21)

$$P_{e}(t) = P_{WT}(t) + P_{PV}(t) + P_{BG}(t) + P_{BES}(t) - P_{L}(t) - P_{TL}(t)$$

(22)

2) CONSTRAINTS OF WT

Technically, the power output and permissible number of WTs are limited by lower and upper limits [10]:

$$0 \leq N_{WT}(t) \leq N_{WT}(t)$$

(23)
\[ P_{WT}^{min}(i) \leq P_{WT}(i)(t) \leq P_{WT}^{max}(i) \]  
(24)

where \( N_{WT}(i) \) is the number of \( i \)th wind turbine, \( N_{WT}^{max}(i) \) represents the maximum number of \( i \)th wind turbine, \( P_{WT}^{min}(i) \) and \( P_{WT}^{max}(i) \) are the minimum and maximum output power of \( i \)th wind turbine, \( P_{WT}(i)(t) \) denotes the output power of \( i \)th wind turbine.

3) CONSTRAINTS OF PV [18]

\[ 0 \leq N_{PV}(i) \leq N_{PV}^{max}(i) \]  
(25)

\[ P_{PV}^{min}(i) \leq P_{PV}(i)(t) \leq P_{PV}^{max}(i) \]  
(26)

where \( N_{PV}(i) \) is the number of \( i \)th PV module, \( N_{PV}^{max}(i) \) represents the maximum number of \( i \)th PV module, \( P_{PV}^{min}(i) \) and \( P_{PV}^{max}(i) \) are the minimum and maximum output power of \( i \)th PV module, \( P_{PV}(i)(t) \) denotes the output power of \( i \)th PV module.

4) BES CONSTRAINTS [18]

\[ SOC_{ch,BES}^{min}(i) \leq SOC_{ch,BES}(i)(t) \leq SOC_{ch,BES}^{max}(i) \]  
(27)

\[ P_{ch,BES}(i)(t) \leq P_{ch,BES}^{max}(i) \]  
(28)

\[ P_{dis,BES}(i)(t) \leq P_{dis,BES}^{max}(i) \]  
(29)

where \( SOC_{i}(t) \) is the state of charge value of the \( i \)th battery, \( SOC_{min}^{ch} \) and \( SOC_{max}^{ch} \) are the minimum and maximum state of charge the \( i \)th battery, respectively, \( P_{ch,BES}(i)(t) \) and \( P_{dis,BES}(i)(t) \) indicate the charging and discharging power of \( i \)th battery, \( P_{ch,BES}^{max}(i) \) is the maximum capacity limit of the charging power in the \( i \)th battery, \( P_{dis,BES}^{max}(i) \) is the maximum capacity limit of the discharging power of \( i \)th battery. In this paper, the BES charges or discharges when \( SOC(t) \) is within certain ranges. When the SOC of the battery reaches the upper limit \( SOC_{max}^{ch} \), the battery would not be charged any more. On the contrary, the battery would not discharged if the SOC of the battery is lower than \( SOC_{min}^{ch} \). It is necessary to mention that charge and discharge power in an hour should no more than 20% of the capacity of battery.

5) CONSTRAINTS OF BG

The power output of BG should be between max and min boundaries, as follow [18]:

\[ P_{BG}^{min} \leq P_{BG}(t) \leq P_{BG}^{max} \]  
(30)

where \( P_{BG}^{min} \) and \( P_{BG}^{max} \) are the minimum and maximum output power of BG.

V. ALGORITHM, OPERATING STRATEGY AND PARAMETERS OF DGs

A. NSGA-III ALGORITHM

In this paper, the NSGA-III algorithm is used for handling multi-objective optimization problem. The NSGA-III has outstanding performance when it faces up to optimization problems composed of three or more objectives [43]. In particular, the diversity of candidate solutions is aided by a number of well-spread reference points which result in a very uniform distribution of Pareto solutions in the search space, even when the number of objectives is large [40]. The flowchart of the NSGA-III algorithm is shown in Figure 4.

The number of individuals in the population is set as 200. However, 190 non-dominated optimal solutions and corresponding optimal schemes can be obtained after 200 iterations because of recursive method. The NSGA-III is used to calculate the optimal capacities' schemes of DGs in the three types' micro-grid.

B. THE OPERATING STRATEGY

The operating strategy of isolated micro-grids is as follows:

**Step1:** The BG stops running when the output power of RE meets the load demand. If the SOC of BES is less than \( SOC_{max}^{ch} \) as well as the excess power in the micro-grid is less than the maximum charging power \( P_{ch,BES}^{max} \), the BES gets on charging.

**Step2:** When the excess power in micro-grid exceeds \( P_{ch,BES}^{max} \) of the BES or the SOC of BES is greater than \( SOC_{max}^{ch} \), the BES rejects to charge. Meanwhile, the WTs or PVs get power reduction.

**Step3:** When the RE could not meet the load demand and \( P_{BG}^{min} \leq P_{L} - P_{WT} - P_{PV} \leq P_{BG}^{max} \), the BG turns on but the BES does not charge and discharge.

**Step4:** If \( P_{BG}^{min} \leq P_{L} - P_{WT} - P_{PV} \leq P_{BG}^{max} \) and SOC of BES is less than \( SOC_{max}^{ch} \), and the value of \( (P_{BG}^{min} - P_{L} + P_{WT} + P_{PV}) \) is less than \( P_{max}^{ch,BES} \), the BG starts on with \( P_{BG}^{max} \), and BES is charged.

**Step5:** If the output power of BG is lower than \( P_{BG}^{min} \) but BES does not satisfy the charging conditions, the RE power generation will have a power reduction and the output power of BG is \( P_{BG}^{min} \).

**Step6:** When the output power of BG is at \( P_{BG}^{max} \), however, the output power of the RE and BG still cannot satisfy the load demand, the BES discharges if the BES meets the discharge conditions.

**Step7:** When the output power of BG is at \( P_{BG}^{max} \), however, the output power of the RE and BG still cannot satisfy the load demand. If the SOC of BES is less than \( SOC_{max}^{ch} \), and the
the maximum of wind speed at night, \( P_L - P_{WT} - P_{PV} \) is larger than \( P_{dis,BES}^{max} \), the BES discharges with \( P_{dis,BES}^{max} \) at this moment. Meanwhile, LPSP is recorded.

**Step8:** When the output power of BG is at \( P_{BG}^{max} \), however, the output power of the RE and BG still cannot satisfy the load demand. If the SOC of BES and the value of \( (P_L - P_{WT} - P_{PV} - P_{dis,BES}^{max}) \) are larger than \( SOC^{max} \) and \( P_{dis,BES}^{max} \) respectively, the algorithm records the LPSP directly.

**VI. CASE STUDY**

The Kongtong Island of 37°56’ north latitude and 121°52’ east longitude. The Kongtong Island is located in the east of China and 10 kilometers away from the mainland, which is rich in wind and light but electricity.

In this paper, the history data of wind speed, temperature, and illumination intensity on Kongtong Island are get from NASA data station. These historical data are daily average, and cannot reflect the characteristics of randomness, intermittent and mutability. Therefore, this paper establishes environmental uncertainties based on history data by MATLAB. The time step and duration of data are set as 0.1 hour and 8,760 hours separately, which are better to restore the real fluctuation and benefit to the accuracy of optimal results. Besides, the uncertainties of devices are also described in this section.

**A. WIND SPEED**

The model of wind speed is divided into two parts, deterministic wind speed and nondeterministic wind speed. The deterministic wind speed is depended on historical wind speed data (\( V_{a\nu} \)) which is shown in Figure 5(a). It describes the distribution trend of wind resources in a year. The nondeterministic wind speed including gust, gradient wind, random wind and day-night wind speed differences are designed in the random wind speed.

Normally, the wind speed at night is higher than that during the day. The differences in wind speed between day and night (\( V_{dn} \)) is shown in Figure 5 (b). it is formulated as [58]:

\[
V_{dn} = \begin{cases} 
0, & t < t_{dn1} \text{or } t > t_{dn2} + t_{dn4} \\
V_{dn,rand} + \frac{t-t_{dn1}}{t_{dn2}-t_{dn1}}, & t_{dn1} \leq t \leq t_{dn2} \\
V_{dn,rand}, & t_{dn2} < t \leq t_{dn2} + t_{dn3} \\
V_{dn,rand} - \frac{t-t_{dn3}}{t_{dn4}-t_{dn3}}, & t_{dn3} \leq t \leq t_{dn4} 
\end{cases} 
\]

(31)

where \( V_{dn} \) represents the wind speed of gradient, \( V_{dn,rand} \) is the maximum of wind speed at night, \( t_{dn1} \) represents the beginning of night wind, \( t_{dn2} \) represents the ending of night wind, \( t_{dn3} \) is the period of night wind, \( t_{dn4} \) represents the ending of night wind.

The gusts are shown in Figure 5(c) and formulated as [58]:

\[
V_{gust} = \begin{cases} 
V_{gust,max}, & t < t_{g1} \\
\frac{1}{2} \left[ 1 - \cos \left( 2\pi \frac{t-t_{g1}}{t_{gust}} \right) \right], & t_{g1} \leq t \leq t_{g1} + T_{gust} \\
0, & t_{g1} + T_{gust} \leq t 
\end{cases} 
\]

(32)

where \( V_{gust} \) is the wind speed of gusts, \( V_{gust,max} \) is the maximum of gusts, \( t_{g1} \) represents the beginning of the gusts, \( t_{gust} \) is the period of gusts.

The gradient wind is shown in Figure 5(d) and formulated as:

\[
V_{grad} = \begin{cases} 
0, & t < t_{grad1} \text{or } t > t_{grad2} + t_{grad3} \\
V_{grad,max}, & t_{grad1} \leq t \leq t_{grad2} \\
V_{grad,max} - \frac{t-t_{grad1}}{t_{grad2} - t_{grad1}}, & t_{grad2} < t \leq t_{grad2} + t_{grad3} 
\end{cases} 
\]

(33)

\[
V_{rand} = V_{rand,max} \cdot R(-1,1) \cdot \cos (\omega_n t + \varphi_n) 
\]

(34)

where \( V_{rand} \) and \( V_{rand,max} \) are random wind and its maximum value, \( R(-1,1) \) denotes the random value between 0 and 1, \( \omega_n \) represents the average value of random wind, normally between 0.5 and 2rad/s, \( \varphi_n \) is the random value between 0 and \( 2\pi \).

The total wind speed (\( v(t) \)) is assembled by the whole scenarios, which is shown in Figure 5(f).

\[
v(t) = V_{gust} + V_{grad} + V_{rand} + V_{dn} + (V_{av} - 5rand) 
\]

(35)

**B. ILLUMINATION INTENSITY**

The photovoltaic power is based on the historical data of illumination intensity (\( I_{av} \)) shown in Figure 6(a). Besides, it also supplements some special situations such as cloud coverage and the duration of sunlight affected by the season.

The scenario of cloud coverage shows the duration and frequency of cloud coverage (\( I_{CC} \)), and it is described in Figure 6(b) and formulated as:
The temperature is introduced for precise calculation of PVs’ output power. The simulated temperature is a combination of historical data (Figure 7(a)) and changing trend of daily temperature (Figure 7(b)).

$$I_{cc} = \begin{cases} 0, & t < t_{cc1} \text{ or } t > t_{cc1} + \Delta t \\ 1, & t_{cc1} \leq t \leq t_{cc1} + \Delta t \end{cases}$$

where $t_{cc1}$ represents the beginning of cloud coverage, $\Delta t$ is the period of cloud coverage.

The duration of sunlight in different seasons (Figure 6(c)) shows the time period of the appearance and disappearance of daily sunlight in different seasons ($I_{rand}$). The equations is expressed as:

$$I_{rand} = \begin{cases} 0, & t < t_{rand1} \text{ or } t > t_{rand2} \\ 1, & t_{rand1} \leq t \leq t_{rand2} \end{cases}$$

where $t_{rand1}$ is the beginning of daytime illumination intensity, $t_{rand2}$ represents the ending of daytime illumination intensity.

The total illumination intensity ($G(t)$) is shown in Figure 6(d) and formulated as:

$$G(t) = (I_{av} - I_{cc} \ast I_{av}) \ast I_{rand}$$

C. TEMPERATURE

The temperature is introduced for precise calculation of PVs’ output power. The simulated temperature is a combination of historical data (Figure 7(a)) and changing trend of daily temperature (Figure 7(b)).

$$T_{day} = \frac{\text{Rand}(0,1)}{2} \left[ 1 - \cos \left( \frac{t-t_{day}}{\Delta t_{day}} \right) \right]$$

where $t_{day}$ represents the beginning of $T_{day}$, $\Delta T_{day}$ is the period of $T_{day}$.

D. LOAD MODEL

The load on Kongtong Island is divided into three scenarios: the annual average daily load of residents, daily load of residents and the load of street lamp. The annual average daily load ($P_{year}$) and daily load of residents ($P_{day}$) are historical data, which are shown in Figure 9(a) and 9(b).

The street lamps are turned on and off at different times in different seasons. The load of street lamp is calculated as:

$$R_{light} = \begin{cases} 0, & t < t_{light1} \text{ or } t > t_{light2} \\ 120, & t_{light1} \leq t \leq t_{light2} \end{cases}$$

where $t_{light1}$ is the beginning of street lamp, $t_{light2}$ represents the ending of street lamp.

The total load model $R_{total}(d, t)$ is expressed as:

$$R_{total}(d, t) = a \ast P_{year}(d) + b \ast P_{day}(t) + R_{light}$$

where $a$ and $b$ are the weights of the annual average load and daily load of residents, respectively, in addition, $a + b = 1$. $P_{year}$ is the annual average load of residents, $P_{day}$ indicates the daily load of residents, $d$ represents the $d$th day in a year, $t$ donated the of a day.

E. SELECTION AND PARAMETERS OF EQUIPMENTS

For the sake of better selection of DGs, this paper takes many types DGs into consideration. The parameters of different DG are significant information to affect the final result of populations. It is helpful when the designers cannot estimate the applicability of one type of DGs.

1) PHOTOVOLTAIC MATERIAL

Pe-Si cells have a slight advantage in price but the conversion efficiency is mediocre. Cs-Si cells have the highest conversion efficiency than the other two types, but the price is relatively higher. The thickness of CIGS thin-film solar cells is only $1\mu m$, which can be attached to the roof because of its good

| Photovoltaic material | Cost (¥/W) | Voltage(V)/Capacity(W) | conversion efficiency |
|-----------------------|------------|------------------------|-----------------------|
| Sc-Si Cell            | 2.80       | 36/300                 | 18%~25%               |
| Pe-Si cells           | 2.75       | 300                    | 14%~20%               |
| CIGS                  | 6          | 300                    | 10%                   |
toughness. The parameters of PV are listed in Table 1.

2) WIND TURBINES
The cost of a wind turbine increase with the growth of the capacity of wind turbine. Nevertheless, the unit costs of construction and transportation decrease with the increasing of capacity of wind turbine. Considering the difficulties in transport, the WTs larger than 500kW are not considered. The capacity of wind turbines and relevant technical parameters are listed in Table 2.

### Table 2. Parameters of wind turbines.

| Installed capacity | Cost /kW | carriage / incidental cost /kW | construction cost /kW | installation cost /kW |
|--------------------|----------|-------------------------------|-----------------------|----------------------|
| 110kW              | 12800    | 200                           | 13800                 | 800                  |
| 250kW              | 10500    | 200                           | 11500                 | 800                  |
| 330kW              | 10300    | 200                           | 11300                 | 800                  |
| 500kW              | 8500     | 200                           | 9500                  | 800                  |

3) BATTERIES
The lead-acid battery and ternary lithium battery’s relevant technical parameters are listed in Table 3.

### Table 3. Parameters of batteries.

| Battery                  | Cost /Wh | Density Wh/kg | deep discharge | cycles |
|--------------------------|----------|---------------|----------------|--------|
| lead-acid battery        | 0.8      | 28            | 0.4            | 700    |
| ternary lithium battery  | 2.7      | 165           | 0.2            | 3500   |

4) BIOMASS POWER GENERATION
The fuel cost is a significant factor of biomass power generation. The annual consumption of fuels is linearly associated to the capacity of BGs. According to the formula (4), the fuel consumption rate \( b_{\text{fuel}} \) is calculated as [57]:

\[
b_{\text{fuel}} = \frac{LHV_{\text{fuel}} \eta_e}{3600}
\]

where \( LHV_{\text{fuel}} \) is the low calorific value of fuel, \( LHV_{\text{fuel}} = 46600 \)kJ/kg, \( \eta_e \) represents generating efficiency in 44%.

The annual per capita waste output is about 440kg/year, and the number of residents on the island is around 1000. Thus, \( b_{\text{fuel}} \) and the annual consumption of biomass fuel are 1.78kg/kWh and 440t respectively.

The operation of BG results in GHG emissions. This paper utilizes a correction cost to assess the contamination caused by these emissions as shown in Table 4.

### Table 4. Parameters of biomass power generation.

| GHG            | SO₂ | NOₓ | CO₂ | CO | Dust |
|----------------|-----|-----|-----|----|------|
| Emmission g/kWh | 0.5 | 3   | 320 | 0.14| 2    |

5) POWER ELECTRONIC DEVICES
There are different types of power electronic devices installed in DC-MG, AC-MG and hybrid MG. The costs of these devices affect the total cost in different MG. Besides, the voltage level, amount and capacity of these devices also have effect on the economics and the result of the optimized configuration in different MGs. The price of the devices are shown in Table 5. Based on the structure models of AC-MG, DC-MG and MG, Table 6 shows the number of different electronic devices and lengths of cables in the three types of MG. These reflect the uncertainties in different structures of MG.

### Table 5. Parameters of electrical devices.

| Devices | substation /kW | converter station /kW | Breaker /device | Rectifier/Inverter /kW | transformer /device | Cable /m |
|---------|----------------|-----------------------|----------------|------------------------|---------------------|---------|
| AC      | 300            | 1,000                 | 20,000 (10kV)  | 800                    | 150,000 (10kV)      | 330     |
| DC      | 300            | 1,000                 | 40,000 (±10kV) | 800                    | 500,000 (±10kV)     | 130     |

### Table 6. The number of different electronic devices and length of cable in the micro-grid.

| Devices | AC Micro-grid | DC Micro-grid | Hybrid Micro-grid |
|---------|---------------|---------------|-------------------|
| Breaker(AC)| 1(BG)+NWT+3(Load)+1 (PV+BES) | 0 (PV+BES) | 1(BG)+NWT+2(AC Load)+1 (converter station) |
| Breaker(DC) | 0 (WT) +3(Loading)+1 (PV+BES) | 1(BG)+1 (PV+BES) | 1(DG Load)+1 (PV+BES) |
| Transformer (AC) | 1(BG)+NWT+3(Loading)+1 (PV+BES) | 1(BG)+NWT+2(AC Load) | 1(DG Load)+1 (PV+BES) |
| Transformer (DC) | 1(AC Load)+1 (PV+BES) | 0 (PV+BES) | 1(DG Load)+1 (PV+BES) |
| Rectifier | P_BG + NWT + PV + P_Dc,load | P_BG + NWT * WT | P_BG + NWT * WT |
| Inverter | P_BG + NWT + PV + N_PV | P_BG + NWT * WT | P_BG + NWT * WT |
| Bidirectional | N_BES * P_BES | Max(P_BG + NWT * WT, P_BG * N_PV * PV + N_BES) |
| Converter | 0 | 1000* (P_Ac/P_total) m | 1000* (P_Dc/P_total) m |
| AC Cable (10kV) | 1000m | 0 | 1000m |
| DC Cable (±10kV) | 0 | 1000m | 1000m |
where $P_{PV}$, $P_{WT}$, $P_{bes}$ and $P_{BG}$ are the matrices of capacities of PV, WT, BES and BG, respectively.

Some calculations involve the tensor product function of ‘kron’ in MATLAB software. This function is used to realize the product of different scale matrices. Taking the costs of DGs as an example:

$$C_{DG} = [C_{PV} \ C_{WT} \ C_{bes} \ C_{BG}]$$

where

$$C_{PV} = [C_{PV1} \ C_{PV2} \ C_{PV3} \ C_{PV4}]$$

$$C_{WT} = [C_{WT1} \ C_{WT2} \ C_{WT3} \ C_{WT4}]$$

$$C_{bes} = [C_{bes1} \ C_{bes2}]$$

$$C_n = \text{kron}(X_n \ P_{DG}) = [C_n^1 \ C_n^2 \ C_n^3 \ C_n^4]$$

where $C_{DG}$ is the matrix combined by the matrices $C_{PV}$, $C_{WT}$, $C_{bes}$, and $C_{BG}$ which are the unit costs of various types of DGs, $C_n$ is the total cost of DGs in each individual of population.

It is necessary to record the running time of different DGs during the operating cycle of a micro-grid. The running time of each DG is related to the probability of occurrence (OP) in every moment. The OP is recorded as true (1) when the DG is running (on). On the contrary, it is recorded as false (0) when the DG is stopped (off). The values in matrix OP are modified on the basis of OP_{ini}. The DGs’ annual OP_{ini} with 0.1 step is shown in Algorithm 1.

$$OP_{ini} = \begin{bmatrix}
T_{PV1}^1 & T_{PV2}^2 & \ldots & T_{PV87600}^87600 \\
T_{PV1}^1 & T_{PV2}^2 & \ldots & T_{PV87600}^87600 \\
T_{PV1}^1 & T_{PV2}^2 & \ldots & T_{PV87600}^87600 \\
T_{WT1}^1 & T_{WT2}^2 & \ldots & T_{WT87600}^87600 \\
\vdots & \vdots & \ddots & \vdots \\
T_{WT4}^1 & T_{WT4}^2 & \ldots & T_{WT87600}^87600 \\
T_{bes1}^1 & T_{bes1}^2 & \ldots & T_{bes1}^87600 \\
T_{bes2}^1 & T_{bes2}^2 & \ldots & T_{bes2}^87600 \\
T_{BG}^1 & T_{BG}^2 & \ldots & T_{BG}^87600 \\
\end{bmatrix}$$

where the elements in OP_{ini} denotes the probability of occurrence of each DG based on the meteorological model.

According to the operating strategy, the value of a DG in OP extracts the accordingly value in OP_{ini} when the operating state presented in OP_{ini} is same as the actual running status of DG, otherwise, it flips the accordingly value in OP_{ini} between 0 and 1. For example, when the value of WT2 in OP_{ini} is 1, whereas WT2 suffers power reduction and stop running, thus the value of WT2 in the OP will be flipped 1→0. The program flow of DGs’ annual OP with 0.1 step is shown in Algorithm 2.

The annual running time of each DG is determined by OP, the total output power of DGs and load demand. Taking BG as an example, the annual running time of BG in the program flow of running time is formulated as:

$$T_{BG} = 0.1 \times \sum_{t=0}^{87600} OP_{BG}$$

where $T_{BG}$ is the annual running time of BES in the whole year of a micro-grid at nth cycles, OP_{BG} is the operating probability of each step. The step is set as 0.1.

The calling function calculatetim() or calculatetimed() in Algorithm 2 not only returns the operating status of RE, but also calculates and updates the state of BES after charging and discharging.

There are three situations of BES with charging state. First, only one type of batteries satisfies the charging conditions. Second, both batteries meet the charging conditions. Thirdly, all the batteries do not satisfy the charging conditions. The programming process of charging of BES utilizes the ‘xor’ function in MATLAB to estimate charging conditions, which is shown in Algorithm 3.

The calling function calculatetim() is triggered while BES receives the signal for charging. This program assumes that the initial operating states of the two batteries in BES are keeping running and the values are set as 1 (true). When the battery satisfies the charging conditions, the value in OP extracts the corresponding value in OP_{ini} directly. Oppositely, the value of the in the OP is flipped from 1 to 0 when the battery does not satisfy the charging conditions. The SOC of the two batteries must be updated immediately at every moment. Specially, the function renewable limitation() is called when the output power of RE has a power reduction. Some RE stop running, and the values of these equipment in the OP are flipped 1→0.

The BES discharges as the total output of RE and BG are unable to meet the load demand. The discharging situation of BES is similar to the charging situation. When the BES meets the discharging conditions whereas it cannot meet the power shortage of the load totally. Therefore, using the ‘||’ function in MATLAB is for selecting the battery with discharge conditions. The aim of this method is to ensure the battery discharges as much as possible for reducing the power shortage of the load. At the same time, the program modifies the status values of BES in OP and calculates LPSP. Moreover, no LPSP exists in Step1 and Step2, which is recorded as 0. In Step3, the output of RE, BG and BES is unable to meet the load, hence LPSP > 0.

VII. SIMULATION RESULTS AND DISCUSSIONS

A. CONVERGENCE OF OPTIMAL VALUE

Hyper plane and normalization methods are utilized before the end of iteration during simulation. The values in hyper plane are contraction of actual values. Thus, following figures draw the plane with average values (Figure 10(a), (c), (e)) and maximum values (Figure 10(b), (d), (f)) instead of hyper plane for better observation of actual optimal values. The spots in following figures indicate the objective values reflected from the combination of population.

It can be seen from the simulation results in Figure 11 that better performance have obvious convergence on system cost and LPSP. The average values and maximum values are sort out in Table 7. Balancing the objective factors is fundamental to determine the combination of DGs. However, compared with the convergence of Cost and LPSP, Figure 11 and Table 7 show that the GHG emissions have weak shrinkage. In the three types of micro-grids, the distributions of optimal values have similar characteristics. As the second-
biggest power generation in the operating strategy of a micro-grid, BG is arranged to supply power when RE generations are with insufficient supply ability. Particularly, lot of costs of WT, PV and BES result in the larger per-unit cost of generating the electricity. Oppositely, the capacity of BG with lower power generation cost is increased. Therefore, the results of GHG are higher in some cases. Furthermore, the results of system cost and LPSP have better convergence because the proportional tailor-made combinations of RE power generation and BES.

**TABLE 7.** The average value and maximum value.

| Type of MG | Type of Hyperplane | Status | System Cost | GHG Emissions | LPSP |
|------------|--------------------|--------|-------------|---------------|------|
| DC         | Average            | Initial | 458.7       | 308           | 6884 |
|            |                    | Optimal | 175.86      | 208           | 1007 |
|            | Maximum            | Initial | 744.0       | 6239          | 127840 |
|            |                    | Optimal | 259.40      | 5510          | 17141 |
|            | Average            | Initial | 421.8       | 2594          | 60865 |
|            |                    | Optimal | 169.31      | 2485          | 9198 |
| AC         | Maximum            | Initial | 632.4       | 5572          | 112043 |
|            |                    | Optimal | 270.29      | 4910          | 15711 |
|            | Average            | Initial | 406.5       | 3066          | 63922 |
|            |                    | Optimal | 173.71      | 2442          | 12892 |
|            | Maximum            | Initial | 659.5       | 5538          | 126168 |
|            |                    | Optimal | 259.65      | 5432          | 19279 |

**B. RELATIONSHIPS BETWEEN OBJECTIVE FUNCTIONS**

Figures 11 shows the distributions of results of system cost and LPSP when the values of GHG emissions are set equal to specific value.

In Figures 11, it can be depicted that at the same GHG emissions, with the increase in the system cost, corresponding values of the LPSP decrease because the increase of system cost results in higher energy supplied by the DGs and lower possibility of power loss. Most results of system cost in the DC-MG focus between 400 and 500, whereas that in the AC-MG and hybrid MG mainly concentrate between 350 and 500. Moreover, some scattered results in DC micro-grid and hybrid micro-grid distribute far from the results group when the GHG emissions are situated in smaller values. Although these scattered results far away from the results groups, it demonstrates that the diversity of optimal results. Actually, a lesser value of GHG emissions implies that the energy generated by the BG is smaller, further, the utilization of household waste is smaller. Additionally, the BG has better stability of energy supply than that of PV and WT because of its operation unimpeded by environment, therefore, the higher
energy supplied by the BG contributes to the less LPSP. With the growth of GHG emissions, the number of results has distinct reduction in Figures 11. Meanwhile, system costs concentrate gradually as the GHG emissions increase, for example, most results of system cost in hybrid MG are between 350 and 500 when the GHG emissions are 1086. While the system costs shrink between 420 and 470 when the GHG emissions are 4346. Particularly, the concentration of system costs move down slightly. This is becauselarger capacity of BG is installed and the inputs of other DGs get smaller in MG when the GHG emissions increase, which the results of total system cost tend to similar.

C. INVERTED GENERATIONAL DISTANCE

Inverted Generational Distance (IGD) is an evaluation index with comprehensive performance. It calculates the sum of minimum distances between each point on the real Pareto frontier and the sets of individuals obtained by the algorithm, so that it evaluates the convergence performance and distribution performance of algorithm. The smaller the value of IGD, the better the comprehensive performance of the algorithm. The function of IGD is expressed as [40]:

$$ IGD(P, Q) = \frac{\sum_{v \in P} d(v, Q)}{|P|} $$  \hspace{1cm} (53)

where $P$ is the sets of individuals distributed on the real Pareto surface, $|P|$ is the number of individuals, $Q$ is the sets of optimal Pareto solution obtained by the algorithm, $d(v, Q)$ represents the minimum Euclidean distance from individual $v$ in $P$ to population $Q$.

| Type of MG | AC | DC | Hybrid |
|------------|----|----|--------|
| IGD        | 8718.293 | 9254.966 | 9659.24 |

In Table 8, the value of IGD is smallest in the AC micro-grid, which is approximately 8718. However, the IGD is largest in the hybrid micro-grid, which is about 9659. Therefore, the optimal simulation solutions in the AC-MG show the best convergence performance, but the optimal simulation solutions of the hybrid micro-grid underachieved in convergence performance. At the same time, the simulation solutions in the DC-MG perform mediocre. In addition, the results of IGD are proved in Table 7, the system cost, LPSP and GHG of AC-MG have obviously low values than other kinks of MGs.

D. COMPARATIVE ANALYSIS

In order to make comparisons between the sets of objective functions of different DGs combinations in DC-MG, AC-MG and hybrid MG, Figure 12 shows the solutions in different colour.

Most solutions of objective functions in AC-MG are lower than that for DC-MG and hybrid MG. The reason is that the significant equipments applied to AC-MG have long history of development, and they have developed into a mature technology. The prices of those equipments are less than that for the DC-MG and hybrid MG. Solutions of objective functions in the hybrid MG are slightly lower than DC-MG and some are interlaced, which means these solutions in the DC-MG and hybrid MG might have similar system cost, LPSP and capacity of BG. Although part of the hybrid MG is composed of AC-MG with lower system cost, the system cost of the hybrid MG keeps higher because of the expensive bidirectional converters. Figure 12 also confirms that the AC-MG has the excellent convergence performance with the lowest IGD.

An obvious limitation of this simulation is that the number of population can not be set as large as possible, which reduces some potential solutions with special characteristics. In order to extend the solution space, surface fitting model is emulated by using acquired combinations in the DC-MG, AC-MG and hybrid micro-grid, which is shown in Figure 13.
Figure 13 and indicates the relationship of overlaps with different colors. Figure 14 is separated with six areas by different colors. Differ areas denotes the different overlapping relationships of LPSP between the DC-MG, AC-MG and hybrid MG at the same GHG emissions and system cost. It can be observed that the overlaps have no change when system costs are around 300 and GHG emissions are about 0. Slight change appears as the GHG emissions achieve approximately 7000. Especially, lots of changes arise in the middle of the pattern and the end of GHG emissions. Accordingly, Table 9 indicates the relationships in different areas.

![Figure 14. The top view of Figure 13.](image)

| Area | Overlap in LPSP |
|------|-----------------|
| A    | hybrid micro-grid > DC micro-grid > AC micro-grid |
| B    | DC micro-grid > hybrid micro-grid > AC micro-grid |
| C    | DC micro-grid > hybrid micro-grid > hybrid micro-grid |
| D    | hybrid micro-grid > AC micro-grid > DC micro-grid |
| E    | AC micro-grid > hybrid micro-grid > DC micro-grid |
| F    | AC micro-grid > DC micro-grid > hybrid micro-grid |

Factually, most solutions are distributed in area a, b and c, and f. Therefore, the solutions in area a, b and c are the primary choice for selection suitable solutions when the LPSP as low as possible. In order to find property and typical combination of DGs in AC-MG, DC-MG and hybrid MG, we mapped Figure 12 into Figure 13, and find the lower points in the three-objective space. Comparisons based upon system cost, GHG emissions and LPSP, nine possible solutions chose from the solution space are tabulated in Table 10. The corresponding optimal capacities of PV, WT, BES, and BG are list in Table 11.

| Case No. | Typ of Micro-grid | System cost<sub>kWh</sub> | GHG emissions<sub>kWh</sub> | LPSP<sub>%</sub> area |
|----------|-------------------|-----------------------------|-----------------------------|----------------------|
| 1        | AC                | 632.44                      | 3482.42                     | 6665.88              |
| 2        | AC                | 366.3                       | 2089.45                     | 14147.19             |
| 3        | AC                | 441.59                      | 696.48                      | 8272.33              |
| 4        | DC                | 561.3                       | 2496                        | 6923                 |
| 5        | DC                | 415.9                       | 1248                        | 12471                |
| 6        | DC                | 513.1                       | 6239                        | 7390                 |
| 7        | hybrid            | 494.82                      | 1086.47                     | 8224.66              |
| 8        | hybrid            | 458.44                      | 4345.9                      | 8866.07              |
| 9        | hybrid            | 376.4                       | 2172.95                     | 15532.49             |

In Table 10, system cost is minimum in Case 2 and maximum in Case 1, as can be seen in Table 11 that the installed capacities of DGs in AC-MG of Case 1 are greater than that of other cases, this enhances the total system cost in Case 1. However, the capacities of most DGs in Case 2 are lower than other cases, which decreases the cost of power electronic devices in Case 2. In Table 10, the values of GHG emissions are smaller in Case 3 and Case 7, whilst they are larger in Case 6 and Case 8, and moderate for other Cases. Table 11 shows that only one BG machine is utilized in Cases 3 and 7, there is the reason that these cases represent lower GHG emissions. While Case 6 installs largest capacity of BG among the 9 cases. Although the Case 8 only has 20kW of BG, the explanation is that the BG in Case 8 has with longer operating time. Additionally, Table 10 shows that LPSPs are highest for Cases 2 and 9 whereas lower for Case 4 and Case 6, and lowest for Case 1, because the installed capacities of DGs in Case 1, 4 and 6 are higher than that of other cases (Table 11).

As the optimal solution is determined based upon the mentioned objectives, Table 10 clearly shows that Case 3 is the optimal choice. Although the system costs are lower in Case 2 and Case 9, they are not be selected due to the relatively higher insufficient power supply. The LPSPs of Case 2 and Case 9 are around 70% and 87% larger than that of Case 3 respectively. Case 1 has largest system cost and GHG emissions which are about 43.2% and 5 times greater than that of other cases. Case 9 have the smallest GHG emissions which are about 43.2% and 5 times great than that of other cases. Case 9 and Case 1 have the heighest insufficient power supply. The LPSPs of Case 2 and Case 9 are around 70% and 87% larger than that of Case 3 respectively. Case 1 has largest system cost and GHG emissions which are about 43.2% and 5 times greater than that of other cases. Case 9 have the smallest GHG emissions which are about 43.2% and 5 times great than that of other cases. Case 9 and Case 6 are 16.3% and 10.7% less than Case 3, but the system costs in Case 1, 4 and 6 are 27.1% and 16.2% larger than that in Case 1, 4 and 6, and lowest for Case 1, because the installed capacities of DGs in Case 1, 4 and 6 are higher than that of other cases (Table 11).

As the optimal solution is determined based upon the mentioned objectives, Table 10 clearly shows that Case 3 is the optimal choice. Although the system costs are lower in Case 2 and Case 9, they are not be selected due to the relatively higher insufficient power supply. The LPSPs of Case 2 and Case 9 are around 70% and 87% larger than that of Case 3 respectively. Case 1 has largest system cost and GHG emissions which are about 43.2% and 5 times greater than Case 3 separately. Moreover, the LPSPs in Case 4 and Case 6 are 16.3% and 10.7% less than Case 3, but the system costs in Case 4 and Case 6 are 27.1% and 16.2% larger than that in Case 3, and the GHG emissions in Case 4 and Case 6 are

![Table 10. The value of 9 cases.](image)

| Case No. | PV1 kW | PV2 kW | PV3 kW | WT1 kW | WT2 kW | WT3 kW | WT4 kW | BES1 kWh | BES2 kWh | BG kW |
|----------|--------|--------|--------|--------|--------|--------|--------|----------|----------|-------|
| 1        | 0      | 0      | 77.1   | 220    | 750    | 1320   | 1000   | 0.48     | 66       | 50    |
| 2        | 0      | 0      | 75.3   | 110    | 250    | 330    | 1000   | 18.84    | 0        | 30    |
| 3        | 0      | 0      | 72.9   | 110    | 500    | 1320   | 1000   | 0.48     | 0        | 10    |
| 4        | 0.3    | 0.3    | 91.5   | 110    | 1000   | 1320   | 1000   | 0.48     | 0        | 40    |
| 5        | 0.3    | 0.3    | 91.2   | 110    | 250    | 660    | 1000   | 1.2      | 0        | 20    |
| 6        | 0.3    | 0.3    | 69     | 110    | 250    | 1320   | 1000   | 0.24     | 38       | 100   |
| 7        | 0.3    | 0      | 72.3   | 110    | 250    | 330    | 1000   | 0.48     | 0        | 10    |
| 8        | 117.6  | 18.6   | 373.5  | 110    | 500    | 330    | 1000   | 0.48     | 0        | 20    |
| 9        | 0.3    | 0      | 108.3  | 110    | 250    | 330    | 1000   | 0.48     | 104      | 20    |
around 3 times larger and 9 times than that in Case 3. Compared with Case 3, Case 5’s system cost has less system cost, but the values of GHG emissions and LPSP in Case 5 are quieter than Case 3 which are 1.8 times and 50.8% higher than Case 3.

Through the four ways of analysis including extremum and average value, IGD, the surface fitting model and comparation, we found that AC-MG is the most suitable microgrid structure in this location. And then, a relatively reasonable DG capacity allocation of AC-MG comes out. Therefore, it is certain that this method can achieve the purpose we proposed that finding the befitting structure of MG and corresponding combination of DGs that less other works mentioned.

VIII. CONCLUSION
This paper used the case study of Kongtong island to select suitable type of islanded micro-grid from DC-MG, AC-MG and hybrid MG, and find an associated DGs’ configuration. This investigation is primarily depended upon multiple important objectives associated with a micro-grid system including system cost minimization, less greenhouse gases (GHG) emissions, and higher reliability. In order to improve the accuracy of simulation results, the proposed method estimated uncertainties in residential power demand, solar irradiation, temperature and wind speed data. In a micro-grid, the DGs are comprised of wind turbine (WT), solar photovoltaic (PV), battery energy storage (BES) system and biomass power generation (BG). The uncertainties caused by power electronic devices are considered for calculating accurate system cost of each kind of micro-grid. The NHGA-III algorithm is applied for the multi-objective problem. It has been also observed that the AC-MG is the optimal choice for Kongtong Island with multiple analysis including the advantages extremum and average values, IGD, the surface fitting model and comparation. Moreover, it is also accompanied by the optimal combinations of DGs. The case study confirms that these uncertainties and multiple analysis methods can be considered in other places where the people plan to construct a micro-grid. These uncertainties and analysis methods are beneficial to achieve an accurate combination of DGs in a MG.

It has two problems during our researching. Firstly, the NSGA-III algorithm has complex computational process and spent long time to compute on MATLAB platform. Secondly, the nine cases are chosen by authors’ observation and subjectivity. For future work, the author will take into account more comprehensive factors such as land area, Direct Normal Irradiance (DNI) or Diffuse Horizontal Irradiance (DHI) of PV system, and improve the NSGA-III algorithm to enhance the performance in more complex simulation environments. In addition, the evaluation method of results should be improved in next work for selecting the suitable micro-grid structure and DGs’ configuration.

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APPENDIX

Algorithm 1: DGs’ annual OP_{inv} with 0.1 step
read: PV Wind N_{PV} N_{WT} N_{bes}
for t=1:8760/0.1
if PV(t)>0
    OP_{PV}(t,1)=1;
else
    OP_{PV}(t,1)=0;
end
if (Wind(t)>=2.8) && (Wind(t)<=25)
    OP_{WT}(t,1)=1;
else
    OP_{WT}(t,1)=0;
end
OP_{PV_total}=repmat(OP_{PV},N_{PV},1);
OP_{WT_total}=[OP_{WT}(1,:),repmat(OP_{WT}(2,:),N_{WT}-1,1)];
OP_{bes}=ones(1,size([0.1:8760,2]));
OP_{bes_total}=[repmat(OP_{bes},N_{bes}-1,1);
OP_{BG}=ones(1,size([0.1:8760,2]));
OP_{BG_total}=repmat(OP_{BG},N_{BG},1);
OP_{ind}=[OP_{PV_total};OP_{WT_total};OP_{bes_total};OP_{BG_total}];
end

Algorithm 2: running time of each DGs
for n=1:N
read: SOC1(t) SOC2(t) P_{max}, P_{min}, N_{PV}, N_{WT}, PV, Temp
calculate: P_{PV}(t), P_{WT}(t), P_{bes}(t), P_{BG}(t)
\[ P_{ren}(t) = P_{PV}(t) + P_{WT}(t) \]
if P_{ren}(t) > P_{load}(t)
    \[ \Delta P = P_{ren}(t) - P_{load}(t) \]
    \[ [T_{PV,on},T_{WT,on},T_{bes,on},T_{BG,on}] = \text{calculatedtime()} \]
end
update: SOC1(t) SOC2(t)
\[ T_{BG,on} = \text{false} \]
\[ P_{vac}(t) = 0 \]
elseif \( P_{ren}(t) < P_{load}(t) \) && \( P_{ren}(t) + P_{BG}(t) > P_{load}(t) \)
if \( P_{ren}(t) + P_{min} < P_{load}(t) \) && \( P_{ren}(t) + P_{min} > P_{load}(t) \)
update: SOC1(t) SOC2(t)
\[ OP(N_{PV}+N_{WT}+1,t) = \text{false} \]
\[ T_{PV,on} = \text{OP}(1:N_{PV},t') \]
end
\[ T_{WT,on} = \text{OP}(N_{PV}+1:N_{PV}+N_{WT},t') \]
\[ T_{bes,on} = \text{OP}(N_{PV}+N_{WT}+1:N_{PV}+N_{WT}+N_{bes},t') \]
elseif \( P_{ren}(t) + P_{max} > P_{load}(t) \)
\[ [T_{PV,on},T_{WT,on},T_{bes,on}] = \text{calculatedtime()} \]
end

update: SOC1(t) SOC2(t)
\[ T_{BG,on} = \text{true} \]
\[ P_{vac}(t) = 0 \]
elseif \( P_{ren}(t) + P_{BG}^\text{max} < P_{load}(t) \)
\[ [T_{PV,on},T_{WT,on},T_{bes,on},P_{vac}](t) = \text{calculatedtime()} \]
update: SOC1(t) SOC2(t)
\[ T_{BG,on} = \text{true} \]
end
\[ T_{on} = [T_{PV,on},T_{WT,on},T_{bes,on},T_{BG,on}] \]
\[ \text{LPSP}(t) = P_{vac}(t)/P_{load}(t) \]
if t==8760/0.1
\[ T_{total}(n,:) = \text{sum}(T_{on}) \]
\[ \text{LPSP}(n,:) = \text{sum}(\text{LPSP}) \]
end

Algorithm 3: charging process of BES
\[ [T_{PV,on},T_{WT,on},T_{bes,on}]=[\text{calculatedtime()} \]
read: P_{bes1}(n) P_{bes2}(n) P_{ch} N_{PV} N_{WT} N_{bes} SOC1(t) SOC2(t)
\[ \text{elseif}(SOC1(t) <= SOC1(t) + \Delta P(t) < P_{bes1}(n)*P_{ch}) \]
\[ SOC2(t) <= SOC2(t) + \Delta P(t)*P_{bes2}(t)/0.9 \]
\[ OP(N_{PV} + N_{WT} + 2,t) = \text{true} \]
end
elseif \( SOC1(t) <= SOC1(t) + \Delta P(t) < P_{bes1}(n)*P_{ch} \)
\[ SOC1(t+1) = SOC1(t) + 0.1\Delta P(t)*P_{bes1}(n)/0.7 \]
end
\[ SOPC(t+1) = SOPC(t) + 0.1\Delta P(t)*P_{bes1}(n)/0.7 \]
end
\[ SOPC(t+1) = SOPC(t) + 0.1\Delta P(t)*P_{bes1}(n)/0.7 \]
end
\[ T_{bes,on} = \text{OP}(N_{PV} + N_{WT} + 1:N_{PV} + N_{WT} + N_{bes},t') \]
\[ T_{PV,on} = \text{OP}(1:N_{PV},t') \]
\[ T_{WT,on} = \text{OP}(N_{PV} + 1:N_{PV} + N_{WT},t') \]
\[ T_{bes,on} = \text{OP}(N_{PV} + N_{WT} + 1:N_{PV} + N_{WT} + N_{bes},t') \]
\[ T_{PV,on} = \text{OP}(1:N_{PV},t') \]
\[ T_{WT,on} = \text{OP}(N_{PV} + 1:N_{PV} + N_{WT},t') \]
\[ T_{bes,on} = \text{OP}(N_{PV} + N_{WT} + 1:N_{PV} + N_{WT} + N_{bes},t') \]
else
update: SOC1(t) SOC2(t)
\[ P(N_{PV} + N_{WT} + 1,t) = \text{true} \]
\[ OP(N_{PV} + N_{WT} + 2,t) = \text{true} \]
\[ T_{PV,on} = \text{OP}(1:N_{PV},t') \]
\[ T_{WT,on} = \text{OP}(N_{PV} + 1:N_{PV} + N_{WT},t') \]
\[ T_{bes,on} = \text{OP}(N_{PV} + N_{WT} + 1:N_{PV} + N_{WT} + N_{bes},t') \]
else
update: SOC1(t) SOC2(t)
\[ OP(N_{PV} + N_{WT} + 1,t) = \text{false} \]
\[ OP(N_{PV} + N_{WT} + 2,t) = \text{false} \]
\[ T_{bes,on} = \text{OP}(N_{PV} + N_{WT} + 1:N_{PV} + N_{WT} + N_{bes},t') \]
\[ [T_{PV,on},T_{WT,on}]=\text{renewablelimitation()} \]
end