

Economic optimization for configuration and sizing of micro integrated energy systems

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Abstract Based on analysis of construction and operation of micro integrated energy systems (MIES), this paper presents economic optimization for their configuration and sizing. After presenting typical models for MIES, a residential community MIES is developed by analyzing residential direct energy consumption within a general design procedure. Integrating with available current technologies and local resources, the systematic design considers a prime mover, fed by natural gas, with wind power, photovoltaic generation, and two storage devices serving thermal energy and power to satisfy cooling, heating and electricity demands. Control strategies for MIES also are

presented in this study. Multi-objective formulas are obtained by analyzing annual cost and dumped renewable energy to achieve optimal coordination of energy supply and demand. According to historical load data and the probability distribution of distributed generation output, clustering methods based on *K*-means and discretization methods are employed to obtain typical scenarios representative of uncertainties. The modified non-dominated sorting genetic algorithm is applied to find the Pareto frontier of the constructed multi-objective formulas. In addition, aiming to explore the Pareto frontier, the dumped energy cost ratio is defined to check the energy balance in different MIES designs and provide decision support for the investors. Finally, simulations and comparison show the appropriateness of the developed model and the applicability of the adopted optimization algorithm.

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1 Introduction

Environmental pollution and energy crisis have caused extensive concern all over the world during the past decades [1]. There is a growing attention of efficient energy conversion and clean energy utilization. As a result, renewable energy sources (RES) such as solar energy, wind energy, hydro energy, and tidal energy, have obtained international attention for the characteristics such as green, clean, inexhaustible energy resource. However, due to the inherent intermittency of RES, it is difficult to supply load using them alone [2, 3]. Comprehensive use of these resources to provide different services simultaneously, such as power, heating, and cooling, represents an

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important energy balance challenge, with the potential to improve the penetration of RES as well as assure high efficiency of energy use [4–6].

Existing integration technologies are able to support the safe and stable operation of small-scale RES, but have difficulty to assure that of large-scale RES due to drawbacks such as small storage capacity, imperfect communication and control devices, and low levels of automatic energy management [7, 8]. This context is never an easy thing to change in a short time, which can result in delayed adoption of RES. Furthermore, decreasing RES costs and policies encouraging clean energy motivate demand for RESs among small investors or customers [9]. Therefore, integration of different energy sources is an important near-term challenge for RES adoption [10].

Not only as a new technology but also due to its diverse research fields and different historical approaches, the concept of micro integrated energy systems (MIES) is not uniform over the world. Its research design and analysis is mainly based on previous studies guided by local circumstances. The foundation of the research covers several areas including microgrids [11], combined heat and power (CHP) generation, combined cooling heating and power (CCHP) systems [5, 12], smart grids [13–15], energy internet [10], and other distributed energy technologies. At present, technical studies and design theory for CHP and CCHP are relatively comprehensive and mature, while the researches on smart grids, microgrids and energy internet have made substantial progress. All these have laid a solid foundation for the development of MIES.

More encouragingly, micro-CHP, which can be taken as a special case of MIES, has been researched recently in some European countries. By comparing different configurations of micro-CHP systems, [16] quantified the behavior of integrated hybrid solar thermal, photovoltaic (PV), and micro-CHP systems. Based on linear programming techniques, [17] addressed the optimal sizing of hybrid micro-CHP to satisfy the energy demand in dwellings. In order to design superior integrated systems, [18] reviewed the existing design options for heating systems incorporating fuel cell micro-CHP in dwellings, motivating a new methodology considering all possible interconnections of plant. [19] explored the potential overall benefit of integrating a resistor for storage heating, which acts as a power sink when needed, presenting a cost-minimizing control strategy for a residential micro-CHP system. Considering fuel cell output compared to user thermal and electrical demand, [12] employed four operational modes to evaluate the system behavior under both for the electrical-led and thermal-led operation in single-family buildings. To fulfill domestic user energy demand and reduce the primary energy

consumption, [20] investigated the potential to integrate a solid oxide fuel cell prime mover and ZEBRA batteries by comparing alternative micro-CHP technologies. By considering two heat-led operational strategies, [21] addressed the economic optimization of a micro-CHP system during the cold season for multi-apartment housing. The four different micro-CHP systems are analyzed in [22] to evaluate the effect of heat dumping on economic performance and emission of pollutants. To investigate various designs of a district heating pipe network, [23] constructed an objective formula to minimize the annual total energy consumption and costs so as to arrive at the optimal flow rate and supply temperature operating strategy. To achieve comprehensive use of solar energy, [24] designed and constructed an integrated solar house with solar PV system, direct-gain solar system and an advanced building envelope (e.g. Low-E glass window, flat-opening airtight door, double-layer polyurethane insulation wall, etc.) to perform an experimental study of solar energy, energy efficiency and energy balance.

Compared with foreign countries, domestic research for MIES is still in its infancy. The existing distributed energy system has problems such as low efficiency of energy supply, disharmony of cooling-heating-power loads, and unplanned impacts on the power system [25–27], even though it has played a positive role in efficient use of energy. This suggests that planning cooling-heating-power cogeneration has the potential to produce a locally optimized configuration and also to contribute to an optimal operation strategy for the power system. In addition, for the large global population living in high-rise, densely populated residential areas, MIES developed on the basis of the energy cascade utilization principle [25–27] are very appropriate. They can produce great economic and social benefit when developed and operated at scale.

Considering problems existing in traditional distributed energy supply systems and energy situation in China, this paper presents the structure and operating mechanism of MIES, giving typical models. Taking a residential community-type of MIES as an example, the general procedure of designing MIES is specified by analyzing the structure of residential direct energy consumption in North China and integrating with availability of current technology and local resources. Subsequently, multi-objective formulas are developed by analyzing annual cost and dumped renewable energy to achieve optimal coordination of energy supply and demand. The non-dominated sorting genetic algorithm (NSGA-II) is used to find Pareto frontier of the constructed formulas. Simulations are carried out by adopting scenarios analysis technique to deal with uncertainties involving load and renewable distributed generation (DG). The results are presented and discussed.



2 Generic descriptions of the envisaged comprehensive MIES

The advent of modern information and communication technology offers excellent controllability for different engineering applications [28, 29]. Meanwhile, energy conversion devices exhibiting excellent controllability are evolving rapidly [29, 30]. Here a MIES refers to a self-organized and small smart system capable of achieving generation, transformation, transmission, storage and distribution of different forms of energy (heating, cooling, and electricity) which is typically installed on users' premises. Through increasing the connectivity of different forms of energy, analyzing their complementarity, and coordinating energy requirements of the user, an MIES can realize security, energy savings, high efficiency, low carbon emissions, cascade utilization and environmental protection.

2.1 Structure of MIES

The structure of MIES will change with the user's demand and local available resources. Generally speaking, a MIES is usually equipped with distributed energy supply devices including dispatched energy (e.g. gas generation, internal combustion engine) and non-dispatched energy (e.g. wind power, PV plant), storage devices (flywheel, electrochemical cells, heat storage), energy transforming devices (electric water heater, chiller), control systems (local control and central control devices, energy management, network management), energy bus (electric line, heat line), communication control bus, and loads (electric, heating, cooling). The generic configuration of the studied MIES is shown in Fig. 1. A successful MIES has the following fundamental characteristics.

- 1) Highly automated: it requires interoperation and automation capabilities for all processes including energy generation, transformation, distribution, and consumption. Thus, information and communication technology and interaction strategies are necessary.
- 2) Localizable: the localization properties refer that it usually meets all energy requirements using locally available natural resources. Only in an emergency can standby or deployed energy be obtained.
- 3) Highly efficient: to make full use of various resources, an energy structure suited to cascade utilization should be designed to arrive at high efficiency.
- 4) Environmental friendly: it supplies energy in an environmentally friendly way, using RES like wind, PV, and tidal energy, as much as possible.
- 5) Reliable: MIES must assure reliable and secure grid operation as their highest priority, consistently with the expectation of large power systems.
- 6) Economical: characteristics of localization can reduce loss and save human and non-human resources, which will decrease the capital and operating costs.

2.2 Operation mode of MIES

Based on the aforementioned concept, MIES are dominated by running in stand-alone mode, while interconnected operation is a supplement. MIES in stand-alone mode generally require dynamic balancing of energy production and energy consumption. Interconnected operation of MIES refers to connection into larger networks, or other MIES, when there is insufficient or surplus supply from local energy.

In order to enable operation of MIES, coordination and interoperation among multiple sources and loads is required. As a result, operational data are anticipated to flow among different equipment. Therefore, an advanced energy management center (AEMC) needs be developed to manage information exchange between equipment according to an interaction strategy. The size, capacity and communication network of an AEMC depend on the size, type and location of energy production and consumption. An AEMC is responsible only for data communication and energy dispatch and transformation in its own area to avoid overlapping responsibilities. Meanwhile, communication between AEMCs is also necessary to arrive at the dynamic balance of whole system. Accordingly, communication in MIES is divided into internal and external communications. Internal communication refers to interactive activities between an AEMC and internal units including load, source, and storage devices. External communication means interaction between an AEMC and another AEMC

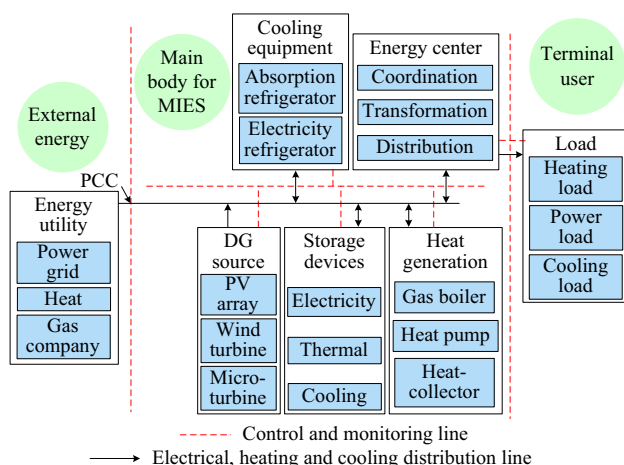


Fig. 1 Generic configuration of MIES

in the area, exchanging information with external systems for the purpose of the combined operation of MIES.

Correspondingly, operational control of MIES is classified into central control, energy station control and distributed/local control. The central control uses an advanced central control unit, which is supported by information and communication technologies like the “internet of things”, to implement optimization and integration of energy, achieve two-way of energy management and coordinate MIES operation according to local load requirements, energy production, and electrical system events. The tasks of central control is concerned with the sampling of state variables, provision of logic and control information for energy station control, management of the operation mode, maximization of operational efficiency across multiple MIES and minimization of emissions and losses. Energy station control is able to communicate with the central control and the distributed/local control system. Besides realizing information exchange with the energy station control system, the tasks of the distributed control are to manage energy production based on the local conditions to assure reliability, security, stability, while trying to maximize the use of RES.

2.3 Typical applications for MIES

Due to their intelligent, flexible, reliable, economic and efficient characteristics, the applications for MIES are many and their prospects are bright. They can serve families, communities, enterprises, governments and other organizations to improve reliability and obtain economic benefits, and also provide energy for remote rural areas, so as to realize rural electrification.

Typical models for MIES are classified into four types depending on the energy consumer: community, commercial, industrial and agricultural. Each model can be designed according to its location, user’s demands and available resources. In the following section, a community MIES is analyzed and designed in line with the consumption behavior among urban residents in North China. Others can use it as a reference case.

3 Optimal designs for community MIES

Considering civil requirements and the real natural resources while analyzing the characteristics of integrated complementary and currently available technology, here a community MIES are designed using the principles described above.

3.1 Structure for community MIES

Here the energy consumption and natural resources available are discussed, as the prerequisite for optimal MIES designs, and then some assumptions are described for community MIES in North China.

3.1.1 Analysis of residential direct energy consumption

Located in middle latitudes and influenced by monsoon circulation, North China has the characteristics of a warm temperate zone continental monsoon climate, with four distinct seasons, cold and long winters, and high temperatures during summer, sometimes with drought conditions. Precisely because of this, household direct energy mainly involves cooking, lighting, heating, and cooling. According to the China Energy Statistical Yearbook, residential energy consumption traditionally consists of coal, natural gas, coal gas, electricity, and liquefied petroleum gas [25]. However, along with the development of RES technology, the improvement of people’s living standards as well as the change of consumption patterns, residential direct energy consumption is shifting towards clean energy, through clean energy sources and highly-efficient energy use. Therefore, from the viewpoint of sustainable development, this paper assumes that residential direct energy consumption mainly consists of natural gas and electricity.

3.1.2 Structure of community MIES and assumptions

To meet this residential direct energy consumption with the resources available in the northern region, a community MIES is composed of heating equipment (gas boiler, electric heating), cooling devices (electric chiller), wind turbine (generating electricity), PV systems (generating electricity), cell (electricity storage and generation), tank (heating storage, cooling storage), energy conversion system (converting gas into electricity such as gas generator, electricity into heat like the electric heater, electricity into cooling like electric chiller, and heat into electricity such as heat engine) and some necessary accessories. The following assumptions are made for the economic optimization of residential MIES.

- 1) The operation of heating equipment, which is fed by renewable generation or natural gas, is limited to the cold season from November 15 to March 15.
- 2) The operation of cooling devices, which are fed by renewable generation, is limited to the hot season from May 20 to August 20.
- 3) The energy conversion system can rapidly and efficiently carry out energy transformation according



to energy production, energy consumption and the state of the storage device.

- 4) Electricity and gas are assumed to be in unlimited supply from the external system, but they are used only if renewable energy is insufficient to meet demand.
- 5) Storage devices have a maximum rate of charging and discharging.

3.2 Multi-objective formulas

From the residents, economic benefits are assumed to be the first priority alongside reliable and safe energy supply. Therefore, the objective formulas for community MIES are based on the annual investment cost, annual cost of energy purchased from public utilities, and annual energy dumped because these are direct and indirect measures of residential benefits. Balancing different energy costs to help investors make considered investment decisions in the light of their own specific situation, the multi-objective goal shown in (1) is applied.

$$\min C_{\text{sys}}, \min C_{\text{pur}}, \min E_{\text{dum}} \tag{1}$$

where C_{sys} is the annual investment cost; C_{pur} is the annual cost of energy purchased from public utilities; and E_{dum} is the energy dumped.

3.2.1 Annual investment cost

Residential investment is managed similarly to traditional power grid investment planning. The total annual cost includes the annual capital investment, which is a discounted amount based on the initial equipment investment and the planning horizon in years, and annual operation and maintenance cost. The total annual cost is calculated as follows:

$$\begin{aligned} C_{\text{sys}} &= C_{\text{inv}} + C_{\text{OM}} \\ &= \sum_{i=1}^{N_{\text{ene}}} f_{\text{ene}}^i E_i^{\text{rated}} C_i^{\text{fixed}} + \sum_{j=1}^{N_{\text{sto}}} f_{\text{sto}}^j E_j^{\text{rated}} C_j^{\text{fixed}} \\ &\quad + \sum_{k=1}^{N_{\text{tra}}} f_{\text{tra}}^k E_k^{\text{rated}} C_k^{\text{fixed}} + \sum_{p=1}^{N_{\text{tot}}} C_p^{\text{OM}} \end{aligned} \tag{2}$$

where C_{inv} is the annual capital investment, which is converted from the initial capital cost by a capital recovery factor; C_{OM} is the annual operation and maintenance cost; N_{ene} , N_{sto} and N_{tra} are the number of energy supply, storage, and transformation devices, respectively, in the MIES; N_{tot} is the sum of N_{ene} , N_{sto} and N_{tra} ; E_i^{rated} is the rated installed capacity from the i^{th} energy supply device; E_j^{rated} is the rated storage capacity from the j^{th} storage device;

E_k^{rated} is the rated transformation capacity from the k^{th} energy station; C^{fixed} is the total fixed investment cost; C_p^{OM} is the annual operation and maintenance cost for the p^{th} device; f_{ene}^i , f_{sto}^j and f_{tra}^k are the capital recovery factors for each investment year for energy supply, storage, and transformation devices, respectively.

Each capital recovery factor f is defined as:

$$f = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{3}$$

where n denotes the project's lifetime and r is the applicable interest rate.

It is noted that the capital recovery factor of some devices like fuel cell or the electrolyzer cannot be directly obtained by (3) because these storage devices have a very short life span and sometimes they need to be replaced several times over the whole project's lifetime. Assuming that the lifetime of storage devices is five years and the project's lifetime is twenty years, then the capital recovery factor is replaced by (4) for these devices [31]. The calculation for other devices requiring replacement follows the same pattern.

$$f_{\text{rep}} = \sum_{h=0,5,10,15} \frac{1}{(1+r)^h} \tag{4}$$

3.2.2 Cost of energy purchased from public utility

In this study, energy is purchased from public utilities to satisfy customer's needs when the MIES can't supply sufficient energy. This arises due to the intermittent and random nature of renewable resources. Otherwise, an enormous storage capacity is necessary, which is not only uneconomical but also unfeasible using current technologies. Additionally, considering a stand-alone MIES, it is extremely important for the user to quantify the cost of energy purchased from public utilities. Therefore, minimizing this cost is taken as an independent optimization objective for investors in MIES. Purchased energy costs can be calculated as shown in (5).

$$C_{\text{pur}} = \sum_{b=1}^{N_{\text{sc}}^{\text{ins}}} \left(t_{\text{gas}}^b C_{\text{gas}} G_{\text{gas}}^b + t_{\text{pow}}^b C_{\text{pow}} P_{\text{pow}}^b \right) \tag{5}$$

where $N_{\text{sc}}^{\text{ins}}$ is the number of state annually when the MIES energy supply is smaller than users' energy demand; C_{gas} and C_{pow} are the gas price (¥/kWh) and the power price (¥/kWh) from public utilities, respectively; G_{gas}^b and P_{pow}^b are the gas volume and electrical energy from the utilities at the b^{th} state, respectively; t_{gas}^b and t_{pow}^b are the duration time of upstream gas boiler use and electricity use at the b^{th} state, respectively. When t_{gas}^b or t_{pow}^b is zero, the purchase doesn't happen.

3.2.3 Energy dumped

Due to the intermittent and random nature of RES, it sometimes happens that supply from RES is beyond the total sum of users' demands and the maximum charging rate of storage devices, so there is an energy surplus. Similarly, it also occurs that the total amount of RES and the maximized discharge capacity of storage devices are smaller than the users' demands, so there is an energy deficit. To deal with this there are several published solutions, for example, exporting/import energy to the grid [32, 33], using excess energy to produce hydrogen [34], keeping the energy balance by adding a dump load [32, 35] or shedding load [36, 37]. Taking into account the attendant technological challenges and avoiding increased costs, energy surplus is analyzed as dumped energy, while energy deficit is neglected due to the assumption of unlimited electricity and gas which can be converted into required energy by the energy station. In contrast to the investment cost, energy dumped is an indirect reflection of users' benefit as energy is wasted. The mathematical express for energy dumped is shown in (6).

$$E_{\text{dum}} = \sum_{s=1}^{N_{\text{sce}}^{\text{suf}}} t_s \left(\sum_{i=1}^{N_{\text{ene}}} E_{i,s}^{\text{ene}} - \sum_{m=1}^{N_{\text{req}}} E_{m,s}^{\text{req}} - \sum_{j=1}^{N_{\text{sto}}} E_{j,s}^{\text{max}} \right) \quad (6)$$

where $N_{\text{sce}}^{\text{suf}}$ denotes the number of annual energy dumped enumerated as distinct states; t_s is the duration of the s^{th} state; N_{req} is the number of user loads; $E_{i,s}^{\text{ene}}$ is the generation capacity from the i^{th} energy supply device at the s^{th} state; $E_{m,s}^{\text{req}}$ is the required load capacity for the m^{th} load at the s^{th} state; $E_{j,s}^{\text{max}}$ is the maximum storage charging capacity for the j^{th} storage device at the s^{th} state.

3.3 Constraints

Depending on the technology, load demand, energy supply, land availability and so on, the constraints included in the proposed optimization are as follows.

3.3.1 Energy balance

In view of the presented model for community MIES in the previous section, energy balance should be achieved through electrical load balance, heating load balance and cooling load balance at any time, i.e.,

$$(1 + \lambda_t^{\text{h}})H_t^{\text{dem}} + H_t^{\text{rel}} = \sum_{i=1}^{N_{\text{ene}}} H_t^i + \sum_{j=1}^{N_{\text{sto}}} H_t^j + \sum_{k=1}^{N_{\text{tra}}} H_t^k \quad (7)$$

$$(1 + \varphi_t^{\text{p}})P_t^{\text{dem}} + P_t^{\text{rel}} = \sum_{i=1}^{N_{\text{ene}}} P_t^i + \sum_{j=1}^{N_{\text{sto}}} P_t^j + \sum_{k=1}^{N_{\text{tra}}} P_t^k \quad (8)$$

$$(1 + \beta_t^{\text{p}})F_t^{\text{dem}} + F_t^{\text{rel}} = \sum_{i=1}^{N_{\text{ene}}} F_t^i + \sum_{j=1}^{N_{\text{sto}}} F_t^j + \sum_{k=1}^{N_{\text{tra}}} F_t^k \quad (9)$$

where H_t^{dem} , P_t^{dem} and F_t^{dem} denote the total heating load demand, electric load demand and cooling load at the t^{th} time interval; λ_t^{h} , φ_t^{p} and β_t^{p} are the pipe/line loss coefficient corresponding to total heating load demand, electric load demand and cooling load demand; H_t^{rel} , P_t^{rel} and F_t^{rel} are the waste heating, electrical and cooling capacity at the t^{th} time interval, respectively; H_t^i , P_t^i , F_t^i , H_t^j , P_t^j , F_t^j , H_t^k , P_t^k , F_t^k are heating, electrical and cooling power from energy supply, storage and transformation devices at the t^{th} time interval, respectively.

3.3.2 Fuel cell constraint

According to the characteristics and lifetime of fuel cells, their constraint should consider capacity and the depth of charge/discharge [32], which is shown in (10).

$$(1 - C_{\text{DoD}})C_{\text{rate}} \leq C_t \leq C_{\text{rate}} \quad (10)$$

where C_t is the state of charge at time t ; C_{rate} is nominal capacity of cell; and C_{DoD} is the depth of discharge of cell.

3.3.3 Storage constraint

Seeking an economical notation and noting that both cooling and heating are related to temperature, it is assumed that a single representation can be used for both heating and cooling storage. The storage capacity should satisfy the following constraint:

$$S^{\text{min}} \leq S^t \leq S^{\text{max}} \quad (11)$$

where S^t is the state of charge of heat storage at time t ; S^{min} and S^{max} are the allowed minimum and maximum storage capacities, respectively.

3.3.4 Distributed generation physical limits

Considering land availability, a maximum power constraint should be applied to any renewable DG, i.e.,

$$0 \leq P_{\text{DG}}^i \leq P_i^{\text{max}} \quad (12)$$

where P_{DG}^i and P_i^{max} are the actual and allowed maximum installed capacity of the i^{th} renewable DG.



4 Optimization and simulation for a numerical example

To demonstrate performance of the presented economic optimization model, the optimization method and some input parameters are described, and simulations are carried out and analyzed.

4.1 Multi-objective formulas

Obviously, the presented planning model in Sect. 3 is a constrained multi-objective optimization problem with uncertain factors such as loads, wind and solar energy resources. Based on available historical data, the *K*-means clustering method is employed to obtain the scenarios of load uncertainties, while a discretization method is used to get states of DGs including wind turbine and PV array outputs. In addition, considering the wide and successful application of NSGA-II in power system optimization [38–40], the application of NSGA-II presented in [38] is adopted to solve the constructed multi-objective formulas. The flow chart is shown in Fig. 2. Some details for NSGA-II can be found in [38], while a general description of the optimisation process follows.

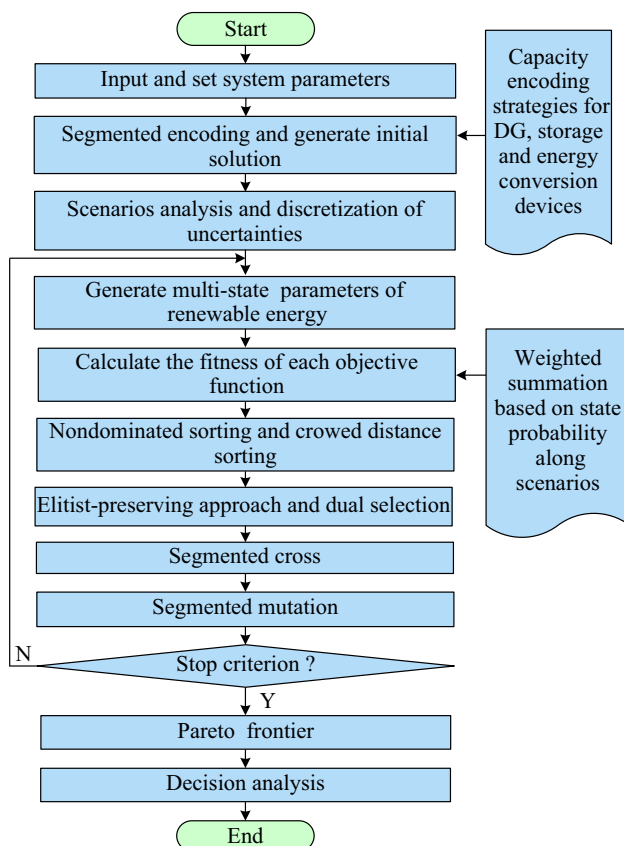


Fig. 2 Flow chart of multi-objective optimization method

4.1.1 Scenario analysis for load uncertainties

Scenario analysis has been widely applied to deal with uncertainties and to avoid deficiencies of Monte Carlo methods such as over many training samples, long training time and slow convergence rate [41], particularly for distribution network planning which must deal with many uncertainties. Selecting reasonable scenarios is important to achieve useful results from optimized planning. Using accumulated historical load data, the *K*-means clustering method is applied to obtain typical scenarios.

The basic algorithm of the *K*-means clustering method is as follows.

Step 1: Use historical data samples to select the *K* initial clustering centers.

Step 2: Assign each sample into the neighboring cluster using the principle of minimum-in-cluster-distance.

Step 3: Take the sample mean in each cluster as a new clustering center. The *i*th clustering center can be calculated by:

$$\bar{x}_i = \frac{1}{M} \sum_{j=1}^M x_{i,j} \quad i = 1, 2, \dots, k \quad (13)$$

where *M* is the number of samples in the *i*th clustering center.

Step 4: Repeat Step 2 and Step 3, until the clustering centers converge to fixed positions.

Step 5: Obtain duration time of each scenarios according sample falling in constant clustering center.

4.1.2 State analysis for wind power and PV array

Taking into account insufficiency of current information for DGs in North China due to their recent application, both wind turbine generator (WTG) output and PV generator output are taken as random variables, while other types of DG are assumed to work at the rated output at any time. A discretization method based on confidence intervals is applied to get their typical states. The detailed description includes following three steps:

Step 1: Determine the upper and lower bounds for discretization intervals from a given confidence level and a given total number of discretization intervals.

Step 2: Take the mean value and cumulative probability for each interval as a typical scenario. The equations are shown in (14) and (15).

$$\bar{x}_t = \frac{x_t + x_{t+1}}{2} \quad (14)$$

$$\psi_t = \int_{x_t}^{x_{t+1}} f(x) dx = F(x_{t+1}) - F(x_t) \quad (15)$$

where x_t and x_{t+1} are the upper and lower bounds of the t^{th} time interval, respectively; ψ_t is the cumulative probability of the t^{th} time interval; $F(\cdot)$ and $f(\cdot)$ are the cumulative probability density function and the probability density function, respectively.

Step 3: Normalize to ensure that the sum of probabilities is equal to 1. The probability of t^{th} time interval is shown in (16).

$$\bar{\psi}_t = \frac{\psi_t}{\sum_{t=1}^{M_d} \psi_t} \tag{16}$$

where $\bar{\psi}_t$ is the probability of the t^{th} time interval; M_d is the total number of intervals.

4.2 System parameter description

From aforementioned structure and operation mechanism of MIES, the energy transformation system plays a very important role in both improving energy efficiency and decreasing cost. High efficiency in use of variable energy sources necessarily results in cost increase. On the contrary, achieving low cost can encourage resource waste, which doesn't fulfil the purpose of improving energy efficiency. In addition, as an emerging technology, parameters for the energy station aren't available. Based on these regards, the capacities of devices comprising the energy transformation system, which determine the annual cost of the system, are taken as decision variables besides the wind installation capacity, PV installation capacity, fuel cell size and the size of heat storage tank. Some input parameters for the simulation are described in the following sections.

4.2.1 Parameters of loads and DGs

Load includes heating load, electrical load and cooling load. North China has the advantage of existing load information, so historical data for recent three years are

used. For heating load, historical data representing the winter heating season from November 15 to March 15 are chosen. For cooling load, historical data representing the period of summer heat from June 1 to September 1 are selected. For electrical load, historical data representing the whole year are selected.

Here the output of wind and PV generators is calculated by (17) and (18) [42, 43].

$$P_w = \begin{cases} \frac{P_r(v - V_i)}{V_r - V_i} & V_i \leq v < V_r \\ P_r & V_r \leq v \leq V_o \\ 0 & v > V_o \text{ or } v < V_i \end{cases} \tag{17}$$

$$P_{PV} = P_{\max} \zeta \tag{18}$$

where the wind speed v for WTGs is taken to follow a Weibull distribution; supposing that the cut-in wind speed $V_i = 4$ m/s, the rated wind speed $V_r = 14$ m/s, and the cut-out wind speed $V_o = 25$ m/s, the shape parameter and the scale parameter of Weibull distribution are 2 and 8 m/s, respectively; P_{PV} and P_{\max} are PV output power and peak power, respectively. The variability caused by sunny days, cloudy days and rainy days is modelled using the output efficiency ζ of PV, which is taken to be a truncated normal distribution with mean $U_{16} = 0.4$ p.u., standard deviation $\sigma = 0.01$, lower 10% and upper 60%.

4.2.2 Parameters of investment and maintenance for different devices

RES DG includes wind generation and PV generation, while storage devices include fuel cells and heat storage tanks. Considering that not all the energy transformation technologies are currently available, assumed information is used, estimated according to known examples of the conversion technologies (gas boilers, electric heating, electric chillers, thermoelectric generators and communication facilities). Their parameters are given in Table 1 [44].

Table 1 Lifetime and cost for different devices

DG type	Lifetime (year)	Cost of investment (¥/kW)	Cost of replacement (¥/kW)	Cost of operation and maintenance (¥/(kW·year))
Wind	20	8000	9750	260
PV array	25	6500	7800	195
Fuel cell	12	1923	7800	390
Tank	30	4500	4500	0
Electric heating	12	1000	1000	0
Electric chiller	10	8000	8000	20
Gas boiler	20	1000	1000	0
Thermoelectric generator	20	5000	5000	0



4.2.3 Other parameters for optimization

Regarding NSGA-II parameters, the genetic algorithm operators are 0.9 for the selection rate, 0.9 for the crossover rate and 0.05 for the mutation rate, with population size of 80 and maximum iterations of 100. The gas price is 0.213 ¥/kWh (2.1 ¥/m³) [6]. The power price is 0.55 ¥/kWh. The conversion efficiency among energy forms is listed in Table 2 [45, 46]. The planning horizon is 20 years. The interest rate is 2.75%. The heat loss coefficient λ_t^h is 10%, while power loss coefficient φ_t^p is 8%. For a unit fuel cell, C_{rate} is 45 kW, C_{DoD} is 90%. To quantify some factors depending on local conditions, like geographical position, investment costs, equipment performance, and technical limitations, it was assumed that the maximum installed capacity for WTGs, PV array, fuel cell, tank, electric heating, electric chiller, gas boiler, thermoelectric generator are 100, 60, 40, 50, 60, 50, 80, 60 kW, respectively.

4.3 Simulation results

4.3.1 Scenarios simulation of uncertainties

The scenario simulation was performed on MATLAB version 2014a. Load scenarios were developed on the basis of the K-means algorithm. The total number of scenarios modelled was 12 and the values per scenario for heating load, cooling load and electric load are shown in Fig. 3 for power and Fig. 4 for scenario duration.

The output power for WTGs and PV generators were discretized to 8 values, expressed as a relative output with respect to the maximum output power, each with a probability of occurrence. For WTGs and PV array, the relative outputs and their probabilities were shown in Table 3.

4.3.2 Optimization results

The optimization was also carried on MATLAB 2014a. Pareto-front solutions are shown in Fig. 5, which was obtained at the 11th iteration. Table 4 lists objective values for some Pareto-front solutions. The objective function values for 4 scenarios are graphed in Fig. 6.

Table 2 Conversion efficiency among energy forms

Type	Conversion efficiency (%)
From electricity to cooling	310
From electricity to heating	85
From heat to electricity	45
From gas to heating	80

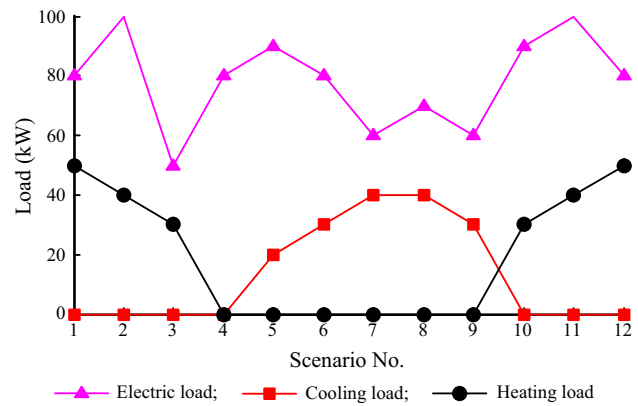


Fig. 3 Load parameters for different scenarios

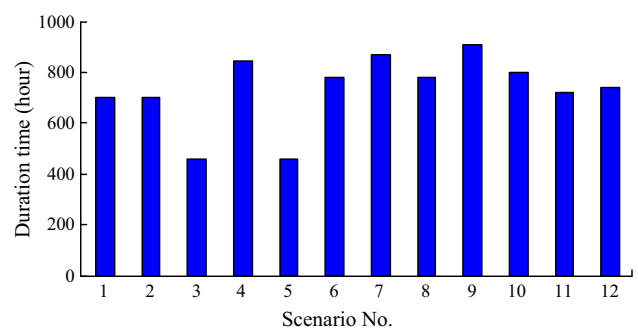


Fig. 4 Duration time of different scenarios

Table 3 Output and probability for WTGs and PV array

No.	WTGs		PV array	
	Output (p.u.)	Probability (%)	Output (p.u.)	Probability (%)
1	0.0501	10	0.0571	60
2	0.1197	20	0.1370	50
3	0.1094	40	0.5091	40
4	0.2090	50	0.1484	30
5	0.2213	60	0.0776	20
6	0.1531	80	0.0399	10
7	0.1001	90	0.0251	5
8	0.0374	100	0.0057	0

Simultaneously, simulations using CPLEX software tools have been carried out to verify the validity of the proposed optimization method. A large number of simulations showed that the convergence of NSGA-II is very rapid. Compared with the simulation results of CPLEX software, the maximal relative errors of simulation is less than 2%. This shows that NSGA-II is well suited to solving this multi-objective optimization problem. From Figs. 5 and 6 and Table 3, it can be seen that there is no solution

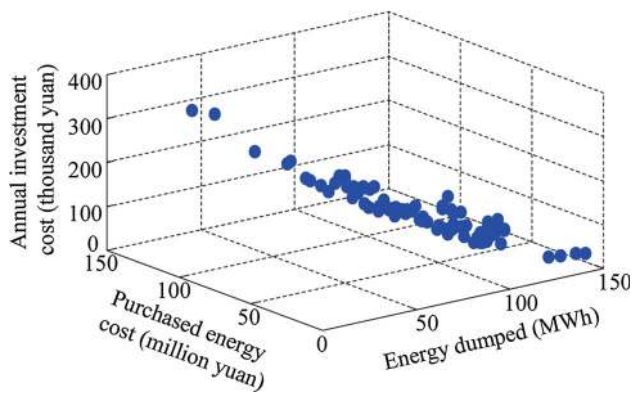


Fig. 5 Objective function values for Pareto-front solutions

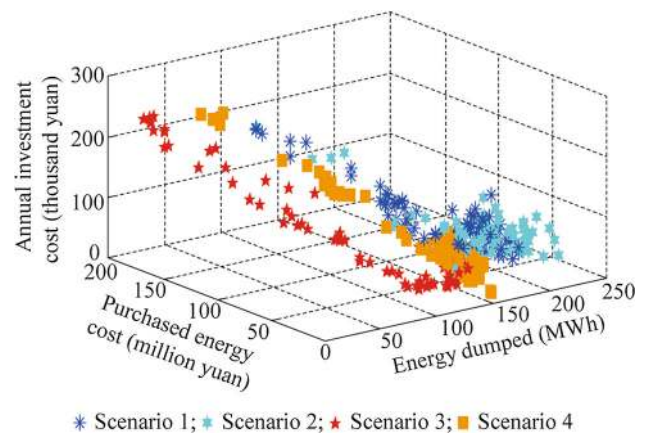


Fig. 6 Objective function values for different scenarios

Table 4 Some Pareto-front solutions and their objective function values

No.	Objective function value (kW)								Energy dumped (MWh)	Purchased energy cost (million yuan)	Annual investment cost (thousand yuan)
	WTGs	PV	Cell	Tank	Electric heating	Electric chiller	Gas boiler	Thermoelectric generator			
1	80	10	35	27	40	32	57	41	63.89	90.35	100.939
2	19	55	4	28	37	5	42	51	44.77	92.68	107.800
3	28	33	1	20	45	35	75	1	317.53	86.92	108.840
4	80	30	8	29	24	40	71	9	654.16	85.76	116.210
5	63	30	24	3	42	1	44	0	317.53	86.91	119.730
6	89	54	35	32	6	33	34	16	112108.31	30.98	287.100
7	33	10	15	23	13	34	73	0	93654.94	32.08	251.280
8	46	23	16	2	0	42	75	0	7.48	95.09	144.720
9	55	5	17	15	0	18	80	0	78166.99	36.75	234.070
10	34	26	22	12	43	20	38	0	47859.84	40.33	231.900
11	51	4	20	16	22	46	26	0	41299.76	44.23	203.320
12	46	39	23	38	29	33	32	55	67427.38	34.71	271.960
13	78	20	5	31	10	3	44	24	19628.20	57.99	171.400
14	78	54	8	6	5	9	60	3	5785.75	63.94	173.140
15	68	1	6	1	27	23	64	0	14486.12	65.91	146.880
16	46	15	2	34	39	49	47	47	243.44	86.26	168.470

simultaneously satisfying minimal investment, minimal energy dumped and minimal purchased energy cost.

From Fig. 6, the results are very different in various scenarios. Therefore, selecting a classification method for scenarios plays a very important role to the scientific merit and the practical effectiveness of the optimization results.

4.3.3 Decision analysis based on energy dump

In order to check energy use in different MIES designs and provide decision support for the investor, the energy dump cost ratio is defined in (19).

$$\eta_{dum} = \frac{E_{dum}C_{pow}}{C_{sys} + C_{pur}} \tag{19}$$

where η_{dum} is the energy dump cost ratio of an MIES. Using the data in Table 4, the energy dump cost ratio is graphed against scenario number in Fig. 7.

From Fig. 7, the energy dump cost ratio is various under different MIES structures. The higher energy dump cost ratio shows the lower energy utilization of the MIES, while the lower energy dump cost ratio represents a higher energy utilization of the MIES. The highest energy dump cost ratio is 2.5, which shows that energy use efficiency in MIES No. 9 is rather low. Therefore, higher energy dump cost ratios should be avoided if possible for a standalone MIES, because the dumped energy cannot be used by other customers.



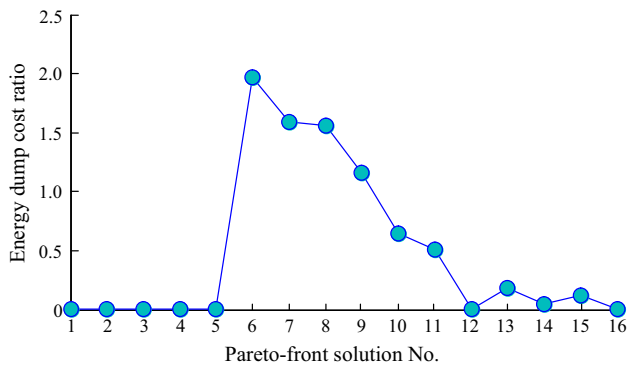


Fig. 7 Energy dump cost ratio under different MIES structures

5 Conclusion

The comprehensive application of energy is an extremely complex project. In this paper, the structure, operational mechanism and typical performance for MIES are presented. By presenting the procedure of constructing community MIES, a general framework for designing MIES is obtained. This study also proposes a multi-objective optimization for community MIES planning. The proposed multi-objective formulas can comprehensively represent MIES's economic performance by taking into account into annual investment and energy dumped under uncertainty. Application of the NSGA-II optimization algorithm can not only obtain Pareto frontier solutions, which can provide flexible selection schemes for a designer, but also manage the conflict between multiple objectives. A large number of simulations show the proposed methodology is feasible and reliable. The proposed planning design for MIES is versatile and flexible, that is, it is appropriate to plan community MIES and it can be extended to develop comprehensive energy applications for other industries. The constructed economic optimization formulas consider all aspects of costs, so the results can provide real economic guidance for DG investors. In addition, the primary role of renewable energy in this study is obviously beneficial to environmental protection, which implies tremendous social and environmental benefits.

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