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Multiobjective Generation Portfolio of Hybrid Energy Generating Station for Mobile Emergency Power Supplies

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***Abstract*—This paper proposes a mixed generation portfolio model of hybrid energy generating station (HEGS) for standby emergency power supply (EPS). The HEGS functions as a mobile and transportable reserve power source for critical loads in case of electricity outages. In the proposed model, various renewable and non-renewable energy sources with different mobility, energy density and power density characteristics are integrated to form a sufficient and reliable hybrid energy EPS system, and the uncertainties of demand load, wind speed, solar radiation intensity, as well as solar cell temperature are modeled as interval numbers to formulate the optimal sizing problem of HEGS under uncertainty into a deterministic combinatorial optimization model. Furthermore, the multiobjective generation portfolio model of EPS configuration is also designed to generate Pareto frontier between implementation cost reduction and mobility improvement. Four generic evaluation metrics are formulated to evaluate the resulting generation-mix schemes of HEGS with case study demonstrated the effectiveness and superiority of the proposed model.**

***Index Terms*—Hybrid energy system, mobile microgrid, optimal sizing, renewable energy, emergency power supply.**

I. Introduction

ELECTRIC power grid is one of the most important infrastructures as many facilities, like hospitals, bank systems, telecommunications, and waterworks, rely on its safe and reliable operation. Abrupt power blackouts will lead to not only inconveniences but also economic losses. The emergency power supply (EPS) system is an independent standalone generating installation to provide electricity supply for the critical load in case of loss of power supply, and enhance the power grid resilience for prevention of load interruptions and protection of life and property from the consequences of electricity outages [1]. The mobile electric power station, usually with all the generating equipment installed on a transport vehicle, can serve as the primary energy source for uninterruptible EPS or off-grid electricity services [2]. Most mobile generating stations are of the thermal fossil-fuel types, such as diesel engine (DE) and gas turbine (GT), due to their reliable performance and compact structures. Nevertheless, generating by means of burning of fossil fuel derivatives would result in atmospheric emissions and noise pollution [3]. Besides, its dependence on the fuel resources could be fatal in EPS with the lack of adequate fuel supply during natural disasters. In recent years, with the advancement of renewable generation and energy storage technologies, various alternative energy sources have great potential for use in mobile EPS during power outages so as to improve the resiliency of electricity grid [4]-[6].

The current state-of-the-art on vehicle-mounted generating stations designed for transportable EPS mostly adopt single-fuel generating units [2], and further investigations on flexible multi-fueled supply of mobile engine generators have been presented in [7]-[10]. So far, the generating stations for emergency and maintenance backup are typically fueled by diesel. However, with the surge in fossil fuel prices and increasing environmental concerns, the procurement of thermal standby generators generally does not prioritize fuel efficiency. Also, in-depth analysis results on hybrid energy system (HES) from National Renewable Energy Laboratory have confirmed that renewable and stored energy sources can effectively support energy security and resiliency of electricity system, and allow the diesel-fueled generator to sustain a greater length of time [6]. Consequently, various hybrid alternative energy and energy storage techniques, including photovoltaic (PV) and wind turbine generation (WTG) [7]-[9], nuclear energy [10], and lead acid battery [9], etc., have paved the way for mobile hybrid energy generating stations (HEGSs) as backup EPS systems [8].

The energy generation portfolio and optimum sizing of each single component in the HEGSs are important for the techno-economic feasibility of standby EPS [11]. The optimal sizing of HES is a highly constrained, nonlinear, and discrete combinatorial optimization problem involving the determination on the best set of compatible energy sources and their capacities [12]. The existing optimal sizing models of HES configuration mostly focus on the standalone off-grid Microgrid to minimize the investment cost while satisfying the requirement of power supply reliability [11]-[15]. However, the extension of these sizing optimization models to the mobile HEGS for various performances including mobility enhancement is still a very involved query. On the other hand, there is volatility and randomness in the power productions from PV and WTG. In order to efficiently and economically utilize the alternative renewables, the optimum design of mobile energy mix system becomes an important issue with increased complexity due to the nonlinear

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characteristics of various types of power sources, uncertain renewable generations and emergency load demand [7]-[10].

In this paper, an optimal generation portfolio model of PV-wind-diesel-gas energy mix with batteries storage (BS) is developed for the mobile EPS system. The proposed optimization model aims to yield the best configuration of HEGS based on hybrid energy complementarities so as to optimize the implementation cost and transportable mobility. Furthermore, the uncertainties of renewable energy sources and load demand are modeled as interval numbers such that the optimal sizing of diverse energy sources in HEGS can be formulated as a multiobjective, interval, and combinatorial optimization problem. Results obtained from a representative case study are then evaluated and benchmarked on various performance metrics, including energy and power density, to confirm the effectiveness and superiority of the proposed approach.

II. HEGS Architectures

In order to provide sufficient and reliable energy supply for critical loads with hundreds of kilowatts under emergency conditions, fossil-fuel-powered generators are indispensable pieces of components in the EPS system. On the other hand, alternative energy sources with batteries storage are well-suited for the kilowatt-level demand due to their self-sufficiency and emission-free characteristics [16]. Hence, a diversified energy mix of HEGS can take full advantage of the complementarities among renewable and non-renewable energies to address the efficiency, reliability, emissions, and economical limitations of single conventional energy source.

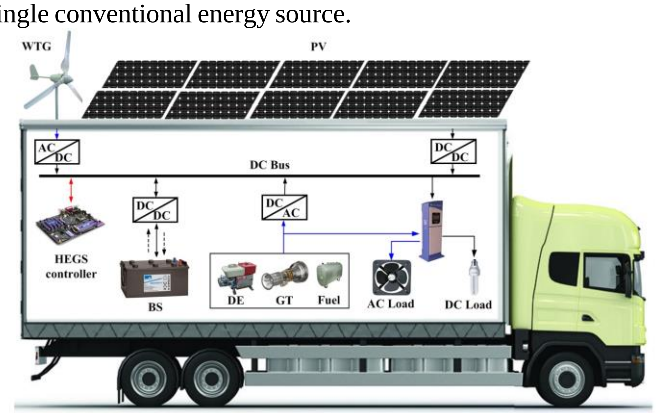


Fig. 1 System architecture of a typical mobile HEGS

In this study, the basic components in generation portfolio of HEGS consist of PV array, WTG, battery bank, DE and GT generators, fuel storage tanks, AC/DC, DC/DC and DC/AC converters, controller, and other accessory devices. A typical schematic diagram of mobile HEGS architecture is shown in Fig.1. In the mobile HEGS architecture, the PV panels and wind turbine are connected to a DC bus by the DC/DC and AC/DC converters with maximum power point tracking controllers [6], and the battery bank is also connected to the DC bus through a bidirectional DC/DC converter in a concentrated location so as to store the excess energy from PV and WTG. The DC bus can be transformed to supply electricity for AC load via the DC/AC inverter, and DE and GT are used as the main backup EPS to provide emergency electricity directly to the AC electrical load. The power generated by mobile EPS can provide the demanded energy for the local load, and can also be grid-integrated into the utility grid using a step-up transformer. The automatic monitoring and control can be implemented with the HEGS controller to regulate the generation outputs of power sources for load following operation, and ensure the optimum state-of-charge level of batteries storage. The renewable and non-renewable energy sources work together to satisfy the emergency load demand. Once the wind and solar energy generations are abundant, the excess power would be stored in the BS until it is fully charged. When the renewable energy sources are insufficient, the batteries with DE and GT will release energy to meet the load requirements.

A. Energy Mix of Mobile Generating Station

1) Photovoltaics: Solar power is one of the most promising renewable energy with potential for transportable generation. Mobile PV panels enable a versatile and flexible use of solar energy with a variety of configurations from 10W to 40kW [17]. During the inclement weather or other catastrophic situations, the fuel transportations may not be available in the impacted regions, and deploying PV panels in combination with energy storage or auxiliary generating sources can offer electricity to critical facilities, so as to contribute the system resiliency during and after grid outages. On the other hand, although the initial capital costs for PV manufacturing are relatively expensive, the influences of these costs can be greatly reduced by the length of equipment depreciation period [16]. Therefore, with the advantages of scalable size, light weight, no fuel requirement, economic benefit and convenient installation, the solar PV cells can be incorporated into the HEGS.

2) Wind turbine: Wind power is another inexhaustible renewable energy resource utilized in the HEGS. The complementary intermittencies of PV-wind energy system allow improving the system reliability and efficiency with more economic and environmental returns, as more wind power can often be generated in cloudy days and at night time without solar irradiance so as to overcome the weakness of PV panels. Furthermore, the solar-wind renewable system can be coupled with the generators fueled by diesel, natural gas, or gasoline to provide emergency electricity to facilitate the extension of fuel supplies during power blackouts [18]. Previous studies in [7]-[9] have demonstrated the technical feasibility and efficiency to integrate WTG into small-scale mobile HESs, and the mobile wind turbines have also been applied in the trailer-mounted hybrid renewable energy supply systems for military use [8].

3) Batteries: Batteries storage is vital for HEGS to alleviate the randomness and fluctuations of renewable power generations in order to improve energy utilization and sustain an uninterruptable supply for end-users [15]. Storage of the solar-wind power in excess of the load demand makes it accessible for later release once there are inadequate solar irradiation and wind speed, and it also allows higher penetrations of renewable energy sources to be incorporated through smoothening power outputs and time shifting generated electricity for load following as well as increasing hosting capacities [19]. Various types of storage batteries, including lead-acid, Li-ion and NiMH, have been developed and widely used for HES applications. In this paper, the lead-acid battery is adopted in HEGSs because of its efficient rechargeability, cost effectiveness, and good life cycle advantages [19].

4) Micro gas turbine and diesel engine: The hybrid energy system of mobile EPS should include diesel (DE) or gas (GT) generators due to their lower installation costs than renewable energy. In the HEGS, DE and GT have fast startup capabilities, high reliability of fuel storage and durability for load changes, and thus are usually used as the essential reserve power [2], [20]. The backup fuel tanks are also required for refueling the DEs and GTs to prolong the service cycle of the EPS. In general, the initial installation cost, maintenance cost as well as fuel cost of the diesel-powered generators are quite low, while GTs can work with relatively low emission, high mobility and efficient power density. Therefore, the proposed HEGS with natural gas and diesel generators can provide stable and long-sustained emergency power supplies for the hundred-kW level facilities or residential communities [21].

B. Evaluation Criteria for HEGS

The selection of evaluation criteria is necessary for designing and analyzing HEGS. The following four evaluation metrics are crucial to assess the performance and efficiency of the hybrid energy generation system for mobile EPS.

1) Power density metrics: Power density metrics of HEGS, including volumetric power density ρ_{V} and gravimetric power density ρ_{G}, refer to the time rate of energy released from mobile EPS per unit volume or per unit weight [22]. The generating station with high power density indicates its loading capacity to accommodate the large power-consuming demand. Here, the power density metrics of the HEGS can be typically expressed in kW/m^3 or kW/kg, as follows,

$$\begin{cases} \rho_{\mathrm{V}} = \dfrac{P_S}{v_{\mathrm{PV}} + v_{\mathrm{WTG}} + v_{\mathrm{BS}} + v_{\mathrm{DE}} + v_{\mathrm{GT}} + v_{\mathrm{fuel}}} \\ \rho_{\mathrm{G}} = \dfrac{P_S}{m_{\mathrm{PV}} + m_{\mathrm{WTG}} + m_{\mathrm{BS}} + m_{\mathrm{DE}} + m_{\mathrm{GT}} + m_{\mathrm{fuel}}} \\ P_S = P_{\mathrm{PV}} + P_{\mathrm{WTG}} + P_{\mathrm{BS}} + P_{\mathrm{DE}} + P_{\mathrm{GT}} \end{cases} \tag{1}$$

where P_S is the maximum power output of the mobile HEGS; P_{PV}, P_{WTG}, P_{BS}, P_{DE}, and P_{GT} are the power capacities of PV panels, WTGs, BS, DEs and GTs, respectively; v_{PV}, v_{WTG}, v_{BS}, v_{DE}, v_{GT}, and v_{Fuel} represent the volume of PV cells, WTGs, BS, DEs, GTs, and fuel tanks, respectively; m_{PV}, m_{WTG}, m_{BS}, m_{DE}, m_{GT}, and m_{Fuel} represent the mass of PV cells, WTGs, BS, DEs, GTs, and fuel tanks, respectively.

2) Energy density metrics: Energy density is the amount of available energy stored in a given system per unit mass or volume [22]. In the mobile EPS applications, the energy density relates to both of the volume and the mass of the HEGS facility, and thus the energy density of a hybrid energy system indicates the amount of energy capable of exerting and transport in comparison to its size and mass. Consequently, the volumetric and gravimetric energy density metrics of HEGS, ε_{V} and ε_{G}, are formulated to express the amount of onboard energy per unit volume or per unit weight in the transportable hybrid energy station, typically expressed in kWh/m^3 or kWh/kg,

$$\begin{cases} \varepsilon_{\mathrm{V}} = \dfrac{E_S}{v_{\mathrm{PV}} + v_{\mathrm{WTG}} + v_{\mathrm{BS}} + v_{\mathrm{DE}} + v_{\mathrm{GT}} + v_{\mathrm{fuel}}} \\ \varepsilon_{\mathrm{G}} = \dfrac{E_S}{m_{\mathrm{PV}} + m_{\mathrm{WTG}} + m_{\mathrm{BS}} + m_{\mathrm{DE}} + m_{\mathrm{GT}} + m_{\mathrm{fuel}}} \\ E_S = T_{\mathrm{E}} P_{\mathrm{PV}} + T_{\mathrm{E}} P_{\mathrm{WTG}} + E_{\mathrm{BS}} + \eta_{\mathrm{DE}} E_{\mathrm{DE}} + \eta_{\mathrm{GT}} E_{\mathrm{GT}} \end{cases} \tag{2}$$

where E_{S} indicates the estimated energy that could be released from the HEGS; E_{BS}, E_{DE}, and E_{GT} denote the transportable energy capacity in the BS, DEs and GTs, respectively; η_{DE} and η_{GT} denote the average energy conversion efficiency of DEs and GTs, respectively. Here, the transported energy in DE or GT is determined by the amount of extractable electrical energy from the fuels in the generator tank and backup fuel tanks, while the battery energy capacity is the maximum amount of energy which can be released from the BS. Moreover, the energy capacity of PV or WTG is defined as the electrical energy generated with the rated power for the expected running time of mobile EPS T_{E}.

III. The Proposed HEGS Model

Here, the stochastic renewable generation model with interval uncertainty is formulated, and an intuitive multiobjective optimal sizing method is further proposed to determine the numbers and capacities of battery banks, WTGs, PVs, diesel and gas generators with fuel storage tanks for the HEGS so as to minimize total cost and enhance the energy mobility. The model objectives of implementation cost reduction and mobility enhancement are always conflicting and competing, and the improved mobility of HEGS indicates high energy and power density of the integrated hybrid energy system with high investment cost [22]. Hence, the best compromise solution between the two contradictory objectives should be solved.

Moreover, it should be pointed out that the amount of fuel storage in the HEGS has significant influences on the energy supply capability and mobility performance. The total fuel storage capacity in the HEGS consists of the fuel prefilled in the fuel tanks of DEs and GTs as well as the backup fuel storage tanks of diesel and liquefied natural gas (LNG). The mobile EPS with the oversized fuel storage capacity can provide the sufficient fossil fuel for DEs and GTs, but it will increase the volume and weight burden of HEGS and thus degrade the maneuvering performance of EPS carrier. On the other hand, the undersized fuel storage can improve the mobility performance of EPS carrier, and may cause the fuel deficit and energy supply shortage issues.

A. Economic Objective

Without loss of generality, the economic objective is to minimize the annual total implementation cost of HEGS, $C(\boldsymbol{x})$, including annualized capital cost, operation and maintenance cost (O&M), fuel cost and environmental cost, as follows,

$$\min C(\boldsymbol{x}) = \sum_{i=1}^{N} (C_{\mathrm{CAP},i} x_i + C_{\mathrm{OM},i} x_i + C_{\mathrm{FC},i} x_i + C_{\mathrm{EC},i} x_i) \tag{3}$$

where N is the number of types of components in HEGS, including different power sources and backup fuel tanks; $\boldsymbol{x} = [x_1, \ldots, x_i, \ldots, x_N]$ is the decision vector representing a configuration solution to be optimized, and x_i denotes the number of component i; $C_{\mathrm{CAP},i}$, $C_{\mathrm{OM},i}$, $C_{\mathrm{FC},i}$ and $C_{\mathrm{EC},i}$ represent the annualized capital cost, annual O&M cost, annual fuel cost, and annual environmental cost of the ith component, respectively.

1) Annualized capital cost: The annualized cost of capital investment for each component in HEGS, including PV cells, WTGs, BS, DEs, GTs, and backup fuel tanks has taken into account the total implementation cost [23], and it can be calculated as,

$$C_{\mathrm{CAP},i}=C_{\mathrm{TCP},i}\frac{r(1+r)^{Y_{\mathrm{p}}}}{(1+r)^{Y_{\mathrm{p}}}-1} \quad (4)$$

where r is the annual real interest rate; $C_{\mathrm{TCP},i}$ is the total capital cost of the ith component, and Y_{p} denotes the planning year horizon.

2) Operation and maintenance cost: The annual O&M cost of the ith type of power source is shown as follows,

$$C_{\mathrm{OM},i}=K_{\mathrm{OM},i}P_i \quad (5)$$

where $K_{\mathrm{OM},i}$, expressed in \$/kW, is the annual O&M cost coefficient of the ith power source [24], and P_i represents the rated power capacity of the ith power source.

3) Fuel cost: The annual fuel cost of diesel or gas for the ith power source can be obtained as follows,

$$C_{\mathrm{FC},i}=K_{\mathrm{FC},i}P_iT_{\mathrm{A}} \quad (6)$$

where $K_{\mathrm{FC},i}$ is the annual fuel cost coefficient for the ith power source [24], and T_{A} is the annual operational time of EPS during the electricity outages in the studied region.

4) Environmental cost: Economic penalty to pollutant emission imposed on the fossil-fuel generators is an effective subsidiary measure to promote the practice of environmental protection. Various pollutant effects on the environment has been quantitatively analyzed and evaluated in [24], and the environmental cost of the ith power source can be formulated as,

$$C_{\mathrm{EC},i}=\sum_{k=1}^{K} f_{k,i}P_iT_{\mathrm{A}}(F_k+F_k') \quad (7)$$

where K is the number of pollutant types from the HEGS; $f_{k,i}$, F_k, and F_k' represent emission factor, environmental value, and penalty cost caused by the kth type of pollutant, respectively.

B. Mobility Objective

Mobile EPS plays a crucial role in the contingency plan to restore electricity service in emergencies for critical facilities, and the HEGS should be available on site as soon as possible to mitigate the consequences of a power disruption. Hence, the maneuvering performance is an important objective of EPS configuration model considering the vehicle's payload capacity and traffic lane restrictions. The mobility objective involves the definition of a dimensional weight which has been widely used in the commercial freight transportation, and it is a calculation of theoretical weight of a transportable object [25]. In this paper, a novel volumetric weight is proposed to define this theoretical weight as the total mass of the power sources with fuel storage tanks in the mobile EPS, when this mass is greater than the weight with a specified minimum density chosen by the freight carrier. If the total volume of power sources with backup fuel storage is large and dominant in the mobility objective, the volume of EPS should be taken into account in the mobility calculation of volumetric weight measure. Consequently, the mobility objective of the proposed model, $M(\boldsymbol{x})$, can be formulated as,

$$\min M(\boldsymbol{x})=\begin{cases}\sum_{i=1}^{N}x_im_i & (\sum_{i=1}^{N}x_im_i\geq\sum_{i=1}^{N}\zeta x_iv_i)\\ \sum_{i=1}^{N}x_im_i+\tau\sum_{i=1}^{N}x_iv_i & (\sum_{i=1}^{N}x_im_i<\sum_{i=1}^{N}\zeta x_iv_i)\end{cases} \quad (8)$$

where m_i and v_i are the mass and volume of the ith component in the HEGS, respectively; τ and ζ are volumetric shipping factor and the specified density coefficient for the dimensional weight. Here, the volume of a power source is determined by its length, width and height in meters using the longest point of each side, and the bulges or misshaped sides should also be considered. The smaller value of M means the HEGS with higher mobility to provide customers with fast recovery of electricity supply for resiliency, and the higher energy and power density metrics would also be expected.

C. Interval Uncertain Model of HEGS

1) Interval modelling of renewable generations: In the HEGS, the volatility and intermittency always accompany the renewable energy sources due to weather variability. In this paper, the uncertainties on wind speed, solar radiation intensity, solar cell temperature, and load demand are formulated as the interval numbers to model the renewable generation outputs as well as the emergency power demand. Based on the elementary operations of interval arithmetic [26], the output power curves of PV module and WTG can be transformed into the following interval models [12],

$$\begin{aligned}&G_{\mathrm{ING}}^{\mathrm{I}}=[G_{\mathrm{ING,L}},G_{\mathrm{ING,U}}],\quad T_{\mathrm{C}}^{\mathrm{I}}=[T_{\mathrm{C,L}},T_{\mathrm{C,U}}]\\ &P_{\mathrm{P}}^{\mathrm{I}}=\begin{bmatrix}\frac{P_{\mathrm{PV}}}{G_{\mathrm{STC}}}(G_{\mathrm{ING,L}}+\alpha_{\mathrm{T}}G_{\mathrm{ING,L}}T_{\mathrm{C,L}}-\alpha_{\mathrm{T}}G_{\mathrm{ING,U}}T_{\mathrm{R}}),\\ \frac{P_{\mathrm{PV}}}{G_{\mathrm{STC}}}(G_{\mathrm{ING,U}}+\alpha_{\mathrm{T}}G_{\mathrm{ING,U}}T_{\mathrm{C,U}}-\alpha_{\mathrm{T}}G_{\mathrm{ING,L}}T_{\mathrm{R}})\end{bmatrix}\end{aligned} \quad (9)$$

where $P_{\mathrm{P}}^{\mathrm{I}}$ represents the interval generation output of PV array; $G_{\mathrm{ING}}^{\mathrm{I}}$ and G_{STC} denote the interval of incident irradiance and the irradiance at standard test condition 1000 W/m^2, respectively; α_{T} is the temperature coefficient of power; T_{R} is the reference rated temperature; $T_{\mathrm{C}}^{\mathrm{I}}$ is the interval of PV temperature; $G_{\mathrm{ING,L}}$ and $G_{\mathrm{ING,U}}$, $T_{\mathrm{C,L}}$ and $T_{\mathrm{C,U}}$ are the lower and upper bounds of the irradiance and cell temperature interval, respectively.

$$\begin{aligned}&w^{\mathrm{I}}=[w_{\mathrm{L}},w_{\mathrm{U}}]\\ &P_{\mathrm{W}}^{\mathrm{I}}=\begin{cases}0, & (w_{\mathrm{U}}\leq w_{\mathrm{C}}\text{ or }w_{\mathrm{L}}\geq w_{\mathrm{F}})\\ \left[0,P_{\mathrm{WTG}}\frac{w_{\mathrm{U}}-w_{\mathrm{C}}}{w_{\mathrm{R}}-w_{\mathrm{C}}}\right], & (w_{\mathrm{L}}\leq w_{\mathrm{C}}\text{ and }w_{\mathrm{C}}\leq w_{\mathrm{U}}\leq w_{\mathrm{R}})\\ \left[P_{\mathrm{WTG}}\frac{w_{\mathrm{L}}-w_{\mathrm{C}}}{w_{\mathrm{R}}-w_{\mathrm{C}}},P_{\mathrm{WTG}}\frac{w_{\mathrm{U}}-w_{\mathrm{C}}}{w_{\mathrm{R}}-w_{\mathrm{C}}}\right], & (w_{\mathrm{L}}\geq w_{\mathrm{C}}\text{ and }w_{\mathrm{U}}\leq w_{\mathrm{R}})\\ \left[P_{\mathrm{WTG}}\frac{w_{\mathrm{L}}-w_{\mathrm{C}}}{w_{\mathrm{R}}-w_{\mathrm{C}}},P_{\mathrm{WTG}}\right], & (w_{\mathrm{C}}\leq w_{\mathrm{L}}\leq w_{\mathrm{R}}\text{ and }w_{\mathrm{R}}\leq w_{\mathrm{U}}\leq w_{\mathrm{F}})\\ P_{\mathrm{WTG}}, & (w_{\mathrm{L}}\geq w_{\mathrm{R}}\text{ and }w_{\mathrm{U}}\leq w_{\mathrm{F}})\end{cases}\end{aligned} \quad (10)$$

where w^{I} and $P_{\mathrm{W}}^{\mathrm{I}}$ represent the intervals of wind speed and WTG output; w_{R}, w_{C}, and w_{F} are the rated wind speed, the cut-in wind speed and the cut-off wind speed, respectively; w_{L} and w_{U} denote the lower and upper bounds of the wind speed interval in a selected region, respectively.

2) Interval optimization model: With the interval power models of PV, WTG, and load, the proposed uncertain optimal sizing problem of HEGS can be formulated as a multiobjective, interval, and combinatorial optimization model, as follows,

$$\begin{aligned} &\min \ \{C(\boldsymbol{x}),\ M(\boldsymbol{x})\} \\ &\text{s.t.}\ \ \boldsymbol{x} = [x_1,\ x_2,\ ...,\ x_i,\ ...,\ x_N],\quad x_i \in \mathbb{N}^{\circ} \\ &\qquad \Lambda = \{w,\ G_{\mathrm{ING}},\ T_{\mathrm{C}},\ P_{\mathrm{D}}\} \\ &\qquad w \in w^{\mathrm{I}} = [w_{\mathrm{L}},\ w_{\mathrm{U}}],\quad G_{\mathrm{ING}} \in G_{\mathrm{ING}}^{\mathrm{I}} = [G_{\mathrm{ING,L}},\ G_{\mathrm{ING,U}}] \\ &\qquad T_{\mathrm{C}} \in T_{\mathrm{C}}^{\mathrm{I}} = [T_{\mathrm{C,L}},\ T_{\mathrm{C,U}}],\quad P_{\mathrm{D}} \in P_{\mathrm{D}}^{\mathrm{I}} = [P_{\mathrm{D,L}},\ P_{\mathrm{D,U}}] \\ &\qquad \psi(g_j(x,\Lambda) \ge D_j^{\mathrm{I}}) \ge \lambda_j,\quad (j=1,2,...,J) \\ &\qquad D_j^{\mathrm{I}} = [D_{j,\mathrm{L}},\ D_{j,\mathrm{U}}] \end{aligned} \tag{11}$$

where Λ represents the set of interval random state variables in the model; $\mathbb{N}^{\circ}$ refers to the set of nonnegative integers; $P_{\mathrm{D,L}}$ and $P_{\mathrm{D,U}}$ are the lower and upper bounds of the interval load demand $P_{\mathrm{D}}^{\mathrm{I}}$, respectively; g_j represents the jth model constraint, and J is the number of constraints; $D_{j,\mathrm{L}}, D_{j,\mathrm{U}}]$ denotes the allowable interval number of the jth interval constraint; $\psi(g_j(x,\Lambda) \ge D_j^{\mathrm{I}})$ indicates the possibility degree of the jth interval constraint; λ_j is a predetermined possibility degree level to express the extent of constraint satisfaction [26].

D. Model Constraints

1) Power generation constraint: The mobile EPS should be designed to offer standby power for different consumers in case of electricity outages, and thus the total generation output of the HEGS should be not less than the interval load demand, $P_{\mathrm{D}}^{\mathrm{I}}$, in the target region, as follows,

$$P_S^{\mathrm{I}} \ge P_{\mathrm{D}}^{\mathrm{I}} \tag{12}$$

where the generation interval of HEGS, P_S^{I}, can be calculated as,

$$\begin{aligned} &P_S^{\mathrm{I}} = P_{\mathrm{PV}}^{\mathrm{I}} + P_{\mathrm{WTG}}^{\mathrm{I}} + P_{\mathrm{BS}} + P_{\mathrm{DE}} + P_{\mathrm{GT}} \\ &P_{\mathrm{PV}}^{\mathrm{I}} = \sum_{i=1}^{N_{\mathrm{PV}}} P_{\mathrm{P},i}^{\mathrm{I}} x_{\mathrm{PV},i},\quad P_{\mathrm{WTG}}^{\mathrm{I}} = \sum_{i=1}^{N_{\mathrm{WTG}}} P_{\mathrm{W},i}^{\mathrm{I}} x_{\mathrm{WTG},i} \\ &P_{\mathrm{BS}} = \sum_{i=1}^{N_{\mathrm{BS}}} P_{\mathrm{BS},i} x_{\mathrm{BS},i},\ P_{\mathrm{DE}} = \sum_{i=1}^{N_{\mathrm{DE}}} P_{\mathrm{DE},i} x_{\mathrm{DE},i},\ P_{\mathrm{GT}} = \sum_{i=1}^{N_{\mathrm{GT}}} P_{\mathrm{GT},i} x_{\mathrm{GT},i} \end{aligned} \tag{13}$$

where $P_{\mathrm{P},i}^{\mathrm{I}}$, and $P_{\mathrm{W},i}^{\mathrm{I}}$, which can be obtained with (9) and (10), represent the power output intervals of the ith type of PV and WTG, respectively; $P_{\mathrm{BS},i}$, $P_{\mathrm{DE},i}$ and $P_{\mathrm{GT},i}$ are the rated power capacities of the ith type of BS, DE and GT, respectively; $x_{\mathrm{PV},i}$, $x_{\mathrm{WTG},i}$, $x_{\mathrm{BS},i}$, $x_{\mathrm{DE},i}$ and $x_{\mathrm{GT},i}$ are the components of decision solution to indicate the numbers of the ith type of PV, WTG, BS, DE and GT, respectively; N_{PV}, N_{WTG}, N_{BS}, N_{DE} and N_{GT} denote the numbers of types of PV, WTG, BS, DE and GT, respectively.

2) Energy constraint: In order to provide sufficient and uninterruptable emergency energy, the mobile EPS should be capable of energizing the important loads for a certain number of hours before electricity restoration, as follows,

$$E_S \ge P_{\mathrm{D,U}} T_{\mathrm{E}} \tag{14}$$

where T_{E} is the expected running time of EPS, which is determined by the historical power outage data in the selected region [21]; $P_{\mathrm{D,U}}$ denotes the upper bound of the emergency load interval. Also, the amount of available energy capacity of HEGS, E_S, can be calculated from (2).

3) Volumetric and gravimetric constraints: Due to the space and weight restriction of the freight carrier, the volume and mass of each type of power source in the HEGS should be limited, and the total volume and weight of hybrid power sources with fuel storage tanks should also be not excess the limits of EPS transport carrier, as follows,

$$\begin{cases} \sum_{i=1}^{N} v_i \cdot x_i \le v_{\max} \\ \sum_{i=1}^{N} m_i \cdot x_i \le m_{\max} \end{cases} \tag{15}$$

where $v_{\max}$ and $m_{\max}$ represent the maximum volume and mass limits of the EPS transport carrier, respectively.

4) Reliability constraint: In the mixed generation portfolio of HEGS, the power outputs of BSs, DEs and GTs are generally stable and controllable, while the volatile and intermittent renewable energy would increase the risk of power deficiency. In order to offer reliable and stable standby power for the important loads, the total generating capacity of controllable power sources should be not less than the minimum load demand,

$$P_{\mathrm{BS}} + P_{\mathrm{DE}} + P_{\mathrm{GT}} \ge P_{\mathrm{D,L}} \tag{16}$$

where $P_{\mathrm{D,L}}$ is the lower bound of the emergency load interval.

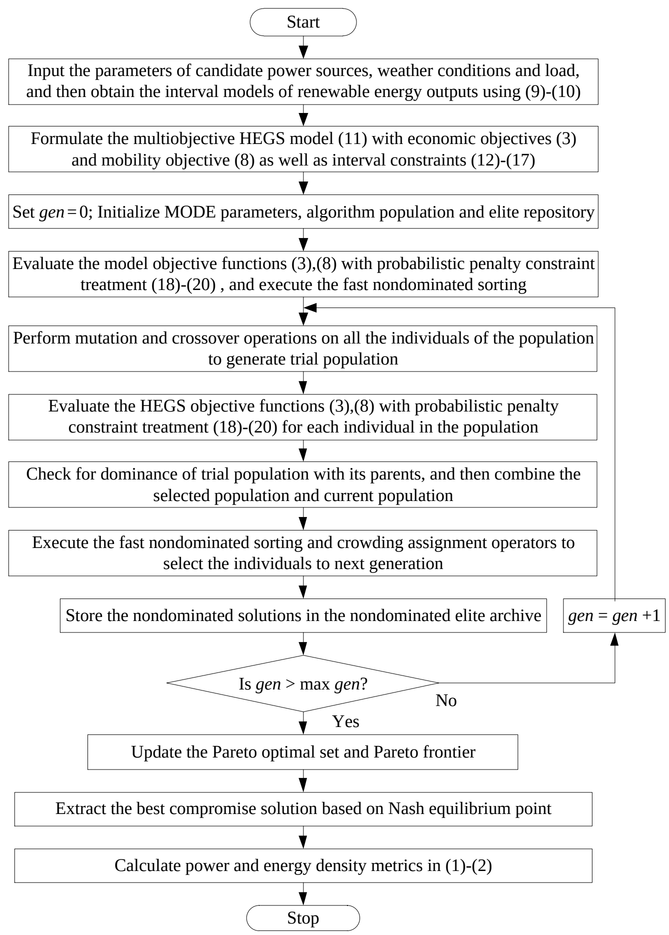


Fig. 2 Flowchart of MODE for multiobjective HEGS model

5) Battery capacity constraint: The sizing of battery banks in HEGS is important for stabilizing the power generations of PV and WTG so as to enhance the renewable energy utilization. Here, the total power rating of battery banks should be not less than a proportion of the total rated capacity of PVs and WTGs [27], as follows,

$$\begin{cases} P_{\mathrm{BS}} \ge \mu(P_{\mathrm{PV}} + P_{\mathrm{WTG}}) \\ P_{\mathrm{PV}} = \sum_{i=1}^{N_{\mathrm{PV}}} P_{\mathrm{PV},i} x_{\mathrm{PV},i},\quad P_{\mathrm{WTG}} = \sum_{i=1}^{N_{\mathrm{WTG}}} P_{\mathrm{WTG},i} x_{\mathrm{WTG},i} \end{cases} \tag{17}$$

where $P_{BS,i}$, $P_{PV,i}$ and $P_{WTG,i}$ are the rated power capacities of the ith type of BS, PV and WTG; μ is the proportion factor to indicate the required capacity of energy storage in the HEGS. A higher value of μ reveals a higher degree of intermittency and variability in the renewable generations, and thus a larger capacity of BS is required to mitigate the power outputs of HEGS.

E. Algorithm Framework

In this study, the proposed HEGS model is an interval nonlinear, multimodal, non-differential, and dual-objective Pareto optimization problem and is solved by the multiobjective differential evolution algorithm (MODE), which is a highly effective and classical method and has been widely utilized to solve the multiobjective optimization problem [28]. A flowchart of algorithm execution steps for the proposed multiobjective HEGS model is illustrated in Fig. 2.

IV. Case Study

A. System Data and Configuration

In this paper, a case study of the transportable EPS in Hohhot, China, is presented to validate the performance of the proposed mixed generation portfolio model. Based upon the data provided from the meteorological station and historical electricity outage information [12], the interval state variables in the studied region, including wind speed, solar radiation intensity and cell temperature, emergency loads, have been summarized in Table I. Besides, the pollutant emissions of thermal power sources and their environmental evaluation parameters are listed in Table II and III [24].

In this case study, through the analysis on system reliability and historic outages, the EPS configuration is designed with the expected uninterruptible running time of 8 hours. The annual running time of EPS, T_A, can be determined by the total average annual outage time of all the important loads in the target region [29], and it is set to 800 hours in this case. In addition, various characteristic parameters of the selected components are taken from literature [21], [24], [27], [29]-[31], as shown in Table I and IV, and hence the proposed sizing model of HEGS in (11) with parameter settings can be formulated.

The parameter settings are important to implement the proposed HEGS model. In the mobility objective, two parameters ζ and τ in (8) are determined by the HEGS carrier to calculate the dimensional weight. The ζ is a specified density threshold to indicate the transit-supportive theoretical weight of the freight carrier, and a larger ζ tends to ignore the volumes of EPS components in the piecewise mobility function. In the case study, ζ is set to 400kg/m^3 [2]. The volumetric shipping factor τ expresses the effects of volume on the EPS mobility performance. A smaller value of τ means the higher volumetric capacity of the transport vehicle carrier, while a larger one reveals the limited volume carrying capacity and road transport situation. Here, the factor τ is set to 100kg/m^3.

TABLE I
Parameter Settings of HEGS Model in the Case Study

Interval state variables	G^I_{ING} = [0.6, 1.2] kW/m^2		
	T^I_C = [20, 23] ℃		
	w^I = [5, 12] m/s		
	P^I_D = [0, 340] kW		
PV module	α_T = -0.48 %/ ℃	T_R = 25 ℃	
WTG module	w_C = 2.5m/s	w_R = 12m/s	w_F = 18m/s
BS module	μ = 0.6		
DE and GT modules	η_{DE} = 40%	η_{GT} = 35%	
Transport carrier	m_{max}= 7000kg	v_{max}= 22 m^3	
Economic objective	r = 6%	Y_p = 12.5	
Mobility objective	τ = 100 kg/m^3	ζ = 400 kg/m^3	
Interval optimal model	T_E = 8 hours	T_A = 800 hours	
	λ_j = 0.9 (j = 1, 2, …, J)		

TABLE II
Emission Characteristics of DE and GT

Power source	NO_x (10^{-3}kg/kWh)	CO_2 (10^{-3}kg/kWh)	CO (10^{-3}kg/kWh)	SO_2 (10^{-3}kg/kWh)
DE	4.330	232	2.32	0.464000
GT	0.619	184	0.170	0.000928

TABLE III
Environmental Value and Penalty of Pollutant Emissions

Coefficients	NO_x ($/kg)	CO_2 ($/kg)	CO ($/kg)	SO_2 ($/kg)
Environmental value	1.000	0.002875	0.125	0.750
Penalty	0.250	0.001250	0.020	0.125

TABLE IV
Model Parameters of Candidate Components in the HEGS

HEGS components	Component type	Mass (kg)	Volume (m^3)	Initial capital cost ($/kW)	O&M cost ($/kW/year)	Unit fuel cost ($/kWh)	Environmental cost ($/kWh)	Energy capacity (kWh)
PV	MSX-83	1.21	0.02663	1500	14.3	0	0	0.664
WTG	WT-1	34	0.3179	2709	5.7	0	0	8
	WT-10	545	2.2311	2690	5.7	0	0	80
BS	LA-2.5	63	0.02909375	1350	7.0	0	0	2.25
DE	DE-K-15	960	2.112	2257	26.5	0.162	0.007112	241.54
	DE-K-30	980	2.112	1290	26.5	0.162	0.007112	483.07
	DE-K-60	1100	3.542	864	26.5	0.149	0.007112	890.88
	DE-K-105	2100	6.006	800	26.5	0.144	0.007112	1505.28
	DE-K-200	2800	8.0272	750	26.5	0.145	0.007112	2880
GT	MTL-C-30	605	2.052	1333	119.0	0.045	0.001558	501.12
	MTL-C-65	958	3.0436	1218	119.0	0.045	0.001558	1085.76
Backup fuel tank	Diesel	45.6	0.035	30.3	/	/	/	375.67
	LNG	31.6	0.035	13.44	/	/	/	204.64

The proportion factor, $0 < \mu < 1$, indicates the requirement of BS capacity ratings to mitigate the stochastic generations of PVs and WTGs for the energy supply reliability. In general, the BS power ratings in the range from 50% to 60% of the corresponding rated capacity of renewable energy can ensure a significant power supply reliability of HEGS [27]. Therefore, parameter μ is set to 0.6. Besides, the possibility degree level, $0 < \lambda < 1$, is used to adjust the feasible field of the interval constraint in (12)-(13). A larger value of λ will make the corresponding inequality constraint more strictly for satisfactory reliability, while a smaller one allows the constraint to be violated at a certain extent. In this study, a relatively larger possibility degree of 0.9 is selected due to the important reliability of EPS.

B. Comparative Results and Analysis

Here, three multiobjective optimization algorithms, including non-dominated sorting genetic algorithm II (NSGA-II) [32], strength Pareto evolutionary algorithm II (SPEA-II) [33], and MODE [28], were implemented to solve the proposed sizing problem of mobile HEGS, as these algorithms have been widely adopted to solve various multiobjective optimization problems with fast convergence and powerful solution searching capability. The parameter settings of three algorithms have been heuristically well-tuned through a number of comparative studies and simulations. Thus, on all the optimization runs, the population size and maximum number of iterations are set to 100 and 500, respectively. Also, the mutation and crossover factors in the algorithms are set to 0.5 and 0.9, respectively [33], [34]. With the probabilistic constraint treatment, the proposed interval sizing model (11) can be transformed into a deterministic combinatorial optimization problem, and the penalty function technique is further applied to handle the problem constraints (12)-(17). The details of the penalty function based interval constraint treatment technique [35] can be found in the Appendix.

The three algorithms were performed with the software platform of Matlab R2010a, and ten independent runs of each algorithm were implemented on a personal computer with 4-GHz Intel Core i7 CPU and 8GB RAM. The ten nondominated sets of solutions from each algorithm were then combined and sorted by the dominance comparisons to yield the resulting Pareto frontier of each multiobjective algorithm, respectively, as shown in Fig. 3. The comparative frontiers indicate that MODE is well-distributed and dispersedly covered the entire trade-off surface of NSGA-II and SPEA-II.

Four typical performance metrics, including inverted generational distance (IGD) [36], diversity metric [32], average computation time, and variance of the computation time, are adopted to measure and compare the solution performance of Pareto frontiers obtained from different algorithms. The first is the IGD used as the convergence indicator [36], and the smaller values of IGD indicate the superior performance of algorithms. Secondly, the distribution and diversity of Pareto front solutions can be assessed by diversity metric [32]. Finally, the average and variance computation time are used to measure the algorithm computational efficiency and stability. A comparison among various performance results obtained with different algorithms is summarized in Table V. The resulting statistics demonstrated that, MODE can outperform other algorithms and provides satisfactory performance on IGD, diversity metric, average computation time per run as well as variance of computation time. In addition, the ultimate goal of any Pareto-based algorithm is to identify a unique solution with the best compromise among multiple objectives. Table V presents the economic and mobility objective values of the best solutions resulted from the three algorithms, and it is confirmed that the obtained Pareto frontier with MODE can provide a reasonable bargaining solution for the HEGS configuration problem. Meanwhile, it can also be found from Table V and Fig. 3 that MODE can provide more Pareto solutions with HEGS designer, demonstrating its superiority on solving the proposed sizing problem of mobile EPS.

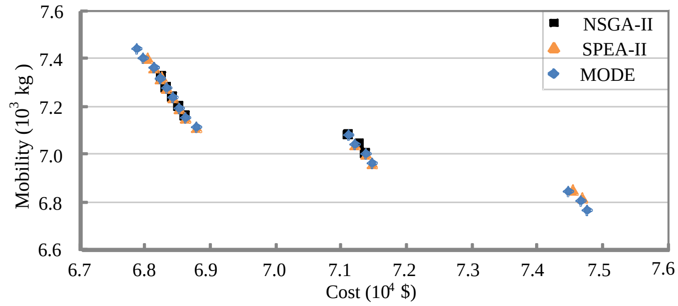


Fig. 3 Pareto frontiers of multiobjective HEGS with different algorithms

TABLE V
COMPARISONS OF PERFORMANCE RESULTS WITH DIFFERENCE ALGORITHMS

Performance metric	MODE	NSGA-II	SPEA-II
IGD	**0.0062**	0.0433	0.0147
Diversity metric	**1.1548**	1.7298	1.6064
Average computation time	**19.50**	19.91	19.99
Variance of the run time	**2.047**	2.052	2.060
Economic objective	68793.92	**68625.92**	68793.92
Mobility objective	**7114.83**	7155.77	7114.83
Number of Pareto solutions	**16**	8	13

For in-depth investigation of the effectiveness of the mixed generation portfolio and optimal sizing method, three schemes are considered for comparative analysis, as follows,

1) Scheme 1: The PV-WTG-DE-GT-BS energy mix is adopted;
2) Scheme 2: A hybrid of DEs and GTs is considered;
3) Scheme 3: Only the DEs are used for EPS configuration.

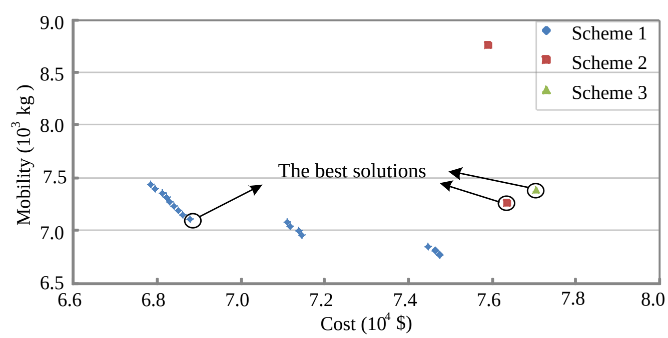


Fig. 4 Pareto-optimal frontiers resulted from schemes 1-3

The three sizing optimization models of schemes 1-3 were implemented with MODE to obtain the Pareto-optimal frontiers, as plotted in Fig. 4. It can be found that, compared with schemes 2 and 3, scheme 1 performs well with the better maneuvering and economic objectives, and this demonstrates the superior performance of renewable energy to improve the mobility and cost of the HEGS. With the Pareto-optimal set in

Fig. 4, an equilibrium-based decision making mechanism in [34] was adopted to identify the best compromise solution for each scheme. The optimized number and capacity of each EPS component from the best solutions of schemes 1-3 are listed in Table VI, and the comparative performance metrics of the three best solutions are also tabulated in Table VII. It is quite evident that the proposed scheme can outperform schemes 2 and 3 on the implementation cost, mobility, environmental consequence, and gravimetric energy density, which further confirms the advantages of the hybrid generation portfolio of mobile EPS.

TABLE VI
BEST CONFIGURATION SOLUTIONS OF SCHEMES 1-3

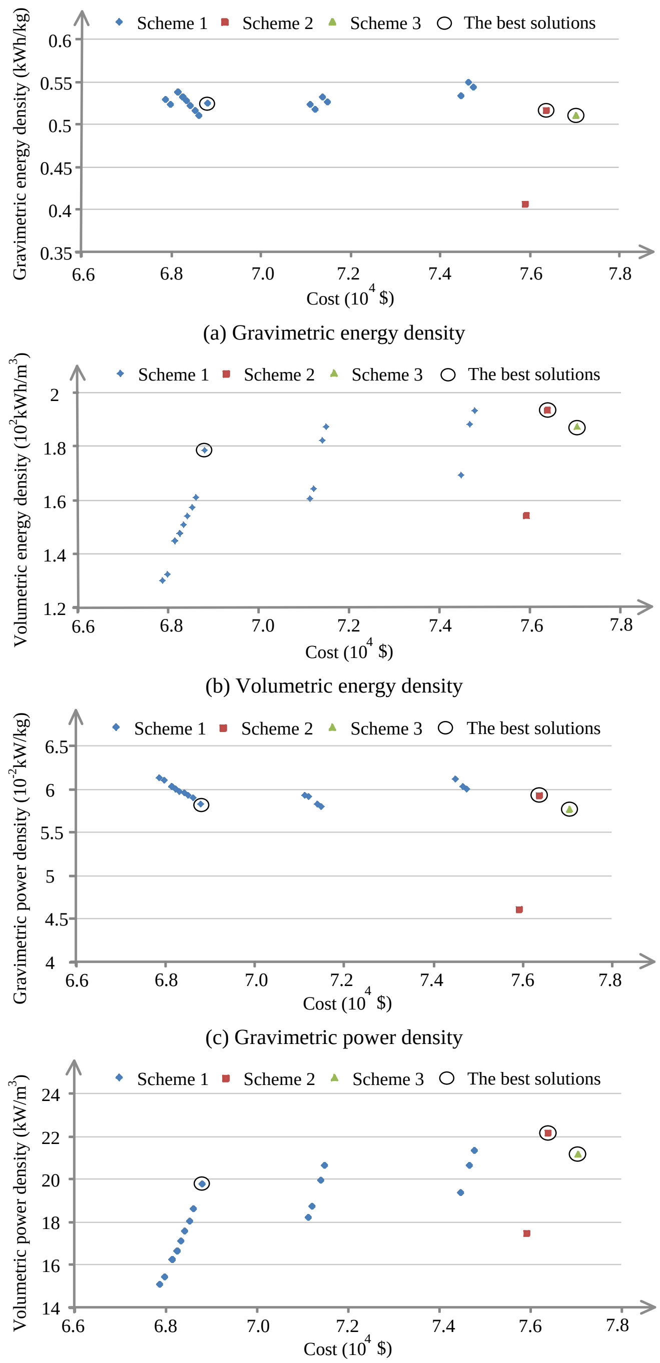
Scheme	PV (kW)	WTG (kW)	DE (kW)	GT (kW)	BS (kW)	Diesel (L)
1	463×0.083	0	1×200	0	30×2.5	9×35
2	0	0	1×60+1×200	1×65	0	9×35
3	0	0	2×60+1×200	0	0	7×35

Highlights from the results can be summarized as follows:

1) Though the initial cost of renewable generation with energy storage does require high investment, it is still cheap to maintain and operate with zero emission and fuel consumption, and shows to be highly cost-effective compared to fossil-fuel power sources.
2) Due to the poor mobility performance of WTGs, wind energy may not be suitable for transportation, and thus is not included in the final best solution of scheme 1.
3) With the mobility definition in (8), the PV panels exhibit the best transportable performance with high power density in comparison with other power sources, and thus can effectively enhance the mobility objective of HEGS.
4) Since the volumes of PVs and BS are relatively larger than other power sources, the volumetric energy density and power density of the best solution in scheme 1 are slightly lower.
5) In schemes 2 and 3, only a few configuration solutions without versatile energy portfolio were obtained. Also, it can be found from Fig. 4 and Table VII that the performance metrics of hybrid diesel-gas multi-fueled EPS are better than the single-fueled DEs.

C. Performance Analysis and Discussions

In this study, a dimensional weight measure considering both volume and weight of the transportable EPS has been proposed in (8), and then used to evaluate the integrated mobility objective of the sizing model. Moreover, four evaluation metrics have been formulated in (1) and (2) from different perspectives to assess the energy and power transport capacity of the HEGS. Fig. 5 plots the power density and energy density metrics in relation to the cost with schemes 1-3 in Fig. 4. It can be found that the proposed scheme can provide the best overall performance with satisfactory evaluation metrics for mobile EPS. The integration of mobile renewables and batteries in scheme 1 can improve the gravimetric power and energy density metrics with lower fuel consumption and environmental emissions, while the volumetric power and energy density in schemes 2 and 3 are slightly higher than scheme 1 due to the larger space occupied by PV panels and battery banks. On the other hand, scheme 1 can offer much more posteriori candidate solutions with diverse generation mix, including a variety of low-cost configuration options.



(a) Gravimetric energy density

(b) Volumetric energy density

(c) Gravimetric power density

(d) Volumetric power density

Fig. 5 Four evaluation metrics with respect to cost from schemes 1-3

The obtained generation portfolios with schemes 1-3 were further applied to provide electricity supply for a given residential community in northern China, and the solar radiation intensity and cell temperature, as well as the emergency load data were taken from [12]. The maximum power point tracking [6] is utilized to determine the PV generation outputs, and the BS is used to smooth out the variability and intermittency of PV power. Also, the power outputs of DEs and GTs in the mobile EPS are scheduled based on the economic generation dispatch [34]. The power generation outputs of hybrid power sources in the three schemes are plotted in Fig. 6. It can be found that, compared with schemes 2 and 3, the proposed HEGS in scheme 1 can effectively sustain the reliable electricity supply for a greater length of period without power inadequacy. Furthermore, from the comparative simulations, scheme 1 is performed with lower fuel consumption and environmental emissions. Compared with the scheme 2, the fuel cost from electricity supply can decline by 25.30% with scheme 1, while the environmental cost can decrease by 16.72%. With respect to the scheme 3, the reductions on fuel cost and environmental cost from electricity supply are 14.46% and 16.52% with the proposed scheme, respectively. Therefore, it can then be concluded that the proposed mixed generation portfolio scheme can effectively improve the resiliency of power supply system during and after grid outages while ensuring superior performances on economic cost and energy mobility.

TABLE VII
PERFORMANCE EVALUATION RESULTS OF THE BEST SOLUTIONS FROM OPTIMIZATION SCHEMES 1-3

Scheme	Cost ($)	Mobility (kg)	Gravimetric energy density (kWh/kg)	Volumetric energy density (kWh/m^3)	Gravimetric power density (kW/kg)	Volumetric power density (kW/m^3)	Environmental cost ($)
1	**68793.92**	**7114.83**	**0.526**	178.689	0.0582	19.781	**1137.920**
2	76378.47	7264.38	0.517	**193.644**	**0.0592**	**22.194**	1560.312
3	77039.55	7379.95	0.511	187.866	0.0576	21.176	1820.672

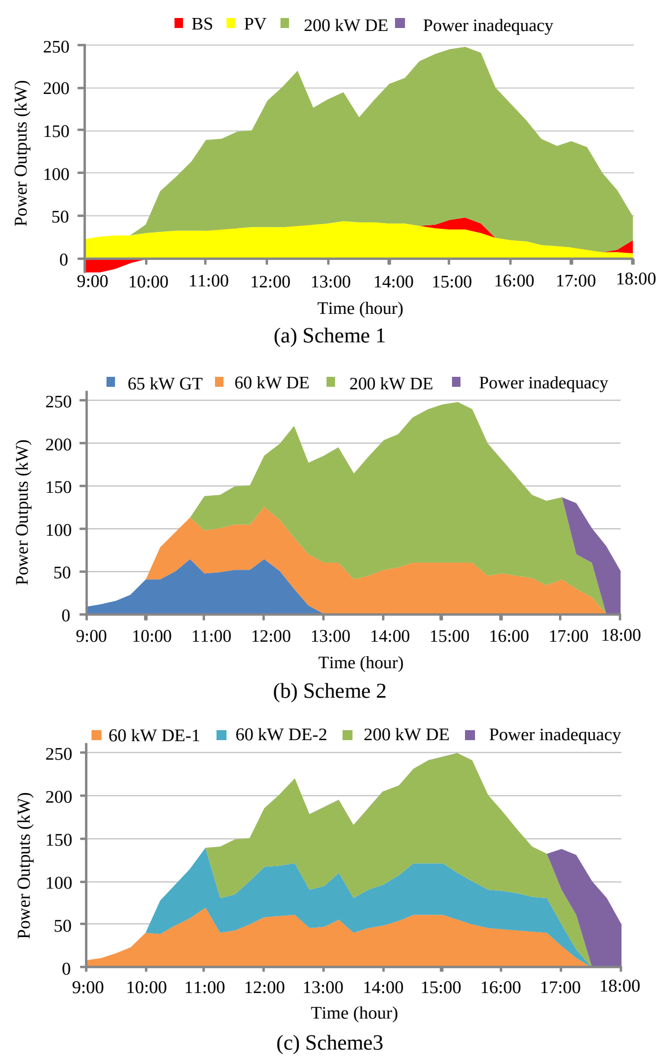


Fig. 6 Power outputs of hybrid power sources in schemes 1-3

V. CONCLUSION

In this paper, a hybrid energy supply model is investigated for the generation portfolio of mobile EPS system, and a novel multiobjective sizing method is proposed to configure the optimum number and capacity of each generating component in the HEGS. The main improvements and contributions of the proposed approach are as follows: 1) A novel biobjective sizing model is presented based on hybrid energy complementarities for the implementation cost reduction and mobility enhancement of mobile EPS; 2) A dimensional weight measure is proposed to evaluate the mobility performance of the HEGS, and the amount of backup fuel storage in the mobile EPS has also been fully considered and optimized to improve the energy mobility; 3) Four generic evaluation metrics are formulated to characterize and assess the configuration performance of the obtained HEGS.

The comparative simulations have been further implemented among three configuration schemes. The results demonstrate the superiority of the proposed HEGS on implementation cost and mobility with low emission and fuel consumption. In addition, with respect to the evaluation criteria of mobile EPS, the proposed optimum sizing scheme of hybrid energy portfolio can provide satisfactory performance on power density and energy density, and would also contribute to the resilience improvement of smart grid.

APPENDIX

Here, a penalty function based probabilistic constraint treatment technique is used to cope with the interval uncertain constraints in the proposed model (11), and the possibility degree of constraint satisfaction is adopted for the comparison of intervals. For two interval random variables A^{I} and B^{I}, the possibility degree, $\psi_{A^{\mathrm{I}}\geq B^{\mathrm{I}}}$, can be formulated based on six possible relations between two intervals, as follows,

$$\psi_{A^{\mathrm{I}}\geq B^{\mathrm{I}}}=\begin{cases}1, & A_{\mathrm{L}}\geq B_{\mathrm{U}}\\ \dfrac{A_{\mathrm{U}}-B_{\mathrm{U}}}{A_{\mathrm{U}}-A_{\mathrm{L}}}+\dfrac{B_{\mathrm{U}}-A_{\mathrm{L}}}{A_{\mathrm{U}}-A_{\mathrm{L}}}\cdot\dfrac{A_{\mathrm{L}}-B_{\mathrm{L}}}{B_{\mathrm{U}}-B_{\mathrm{L}}} & \\ +\,0.5\cdot\dfrac{B_{\mathrm{U}}-A_{\mathrm{L}}}{A_{\mathrm{U}}-A_{\mathrm{L}}}\cdot\dfrac{B_{\mathrm{R}}-A_{\mathrm{L}}}{B_{\mathrm{U}}-B_{\mathrm{L}}}, & B_{\mathrm{L}}\leq A_{\mathrm{L}}<B_{\mathrm{U}}\leq A_{\mathrm{U}}\\ \dfrac{A_{\mathrm{U}}-B_{\mathrm{U}}}{A_{\mathrm{U}}-A_{\mathrm{L}}}+0.5\cdot\dfrac{B_{\mathrm{U}}-B_{\mathrm{L}}}{A_{\mathrm{U}}-A_{\mathrm{L}}}, & A_{\mathrm{L}}<B_{\mathrm{L}}<B_{\mathrm{U}}\leq A_{\mathrm{U}}\\ 0.5\cdot\dfrac{A_{\mathrm{U}}-B_{\mathrm{L}}}{A_{\mathrm{U}}-A_{\mathrm{L}}}\cdot\dfrac{A_{\mathrm{R}}-B_{\mathrm{L}}}{B_{\mathrm{U}}-B_{\mathrm{L}}}, & A_{\mathrm{L}}<B_{\mathrm{L}}\leq A_{\mathrm{U}}<B_{\mathrm{U}}\\ \dfrac{A_{\mathrm{L}}-B_{\mathrm{L}}}{B_{\mathrm{U}}-B_{\mathrm{L}}}+0.5\cdot\dfrac{A_{\mathrm{U}}-A_{\mathrm{L}}}{B_{\mathrm{U}}-B_{\mathrm{L}}}, & B_{\mathrm{L}}\leq A_{\mathrm{L}}<A_{\mathrm{U}}<B_{\mathrm{U}}\\ 0, & A_{\mathrm{U}}<B_{\mathrm{L}}\end{cases}\tag{18}$$

where A_L and A_U, B_L and B_U represent the lower and upper bounds of intervals A^I and B^I, respectively. With the possibility degree in (18), the penalty function φ can then be formulated by a measure of the comparison of the possibility degree and predetermined level λ_j, and it can be expressed as following form,

$$\begin{aligned}&\varphi[\psi(g_j(x,\Lambda)\geq D_j^I)-\lambda_j]\\&\quad=(\max(0,-(\psi(g_j(x,\Lambda)\geq D_j^I)-\lambda_j)))^2\end{aligned} \tag{19}$$

Hence, the interval constraint treatment in (18) and penalty function in (19) can be used to transform the constrained interval optimization problem in (11) into an unconstrained deterministic problem. Thus, the penalty function multiplied by a scale factor is added to the objective functions (3) and (8), as follows,

$$\begin{cases}\min C = C(\boldsymbol{x})+\sigma\sum_{j=1}^{J}\varphi[\psi(g_j(x,\Lambda)\geq D_j^I)-\lambda_j]\\ \min M = M(\boldsymbol{x})+\sigma\sum_{j=1}^{J}\varphi[\psi(g_j(x,\Lambda)\geq D_j^I)-\lambda_j]\end{cases} \tag{20}$$

where σ is the penalty factor which is usually specified as a large value. The penalty function method may work quite well for the multiobjective interval optimization problems. If the value of penalty function φ is too small, an infeasible solution may not be penalized enough, and thus an infeasible solution would be resulted and evolved in the algorithm optimization process. On the other hand, a feasible solution is very likely to be found if φ is large, but the solution optimization performance would be limited. In this study, the penalty factors have been heuristically well-tuned through a number of comparative simulation tests, and then set to 10,000. Consequently, the penalty function value is zero when the possibility degree is equal or greater than the prespecified possibility degree λ_j; Otherwise, the penalty value is positive and the large scale factor can force the solution of the unconstrained problem to converge to the optimal solution of the original interval constrained problem.

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