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A cost-efficient based cooperative model for reliable energy management of networked micro grids within a smart island

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Energy hub;
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Abstract. This paper mainly focuses on investigating a stochastic energy management approach to enhance reliability of the networked microgrids within a smart island. In this regard, a networked microgrid is considered in the smart island, which is integrated with a multi-Energy Hub (multi-EH) system aiming to simultaneously support the electrical, thermal, and water demands of the island, isolated from the main grid. The objective function is organized as the cost of operation and reliability of the networked microgrid and is solved using a modified bat algorithm. The uncertainty of stochastic parameters is modelled using the 2-m point estimate method, which has notable advantages in terms of accuracy and simplicity of implementation. Different scenarios are considered both in critical and normal conditions to evaluate the performance of the studied model. Both GAMS and MATLAB software's were employed to study the proposed model. The proposed model improved the reliability of the networked microgrid system and results reveal that the proposed cooperative approach could decrease total operation and investment cost of the networked microgrid by 13%.

1. Introduction

Nowadaysthe increase of renewable energy sources and high-efficiency Distributed Energy Resources (DERs) has introduced a new chapter in the power systems. In modern power systems, the generation has become smaller in scale and became closer to the consumption level, which has formed the concept of microgrids. Microgrids are a new type of power system consisting of DERs, Energy Storage (ES) devices, and electrical loads that can be connected to the upstream grid and work in parallel with the main grid and act as an island [1,2]. The use of microgrids provides many benefits, including the following:

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- Reducing the production of harmful environmental pollutants,
- Increasing the power quality and reliability,
- Increasing the variety of fuel consumption,
- Reducing investment risk,
- Electricity supply of rural and remote areas, and
- Reducing energy loss in transmission lines [3,4].

The optimal consumption of microgrids is essential for better use of production units. Microgrid operation strategies are fundamentally different from the conventional power systems. The use of ES systems such as batteries, flywheels, and controlled loads has complicated the management and operation of microgrids. Besides, the simultaneous production of heat and electricity havebolded the problem and more importantly, the random characteristics of renewable energy sources such as photovoltaic panels (PVs), Wind Turbines (WTs), and tidal turbines have further complicated the issue [5]. Specific optimization methods to solve the problem depend on the accuracy of the input variables. Therefore, an error in predicting random input variables will lead to unreliable solutions. However, there are several random variables in the problem of energy management and operation of microgrids [6]. For example, the price of power in the market and the amount of load required by consumers are among these uncertain data. Therefore, the strength of conventional optimization methods should be reviewed in the new context and methodsof operation in the presence of uncertainty should be renewed in such that they can minimize the risks associated with the design and operation of the microgrid [7,8]. Some classification of optimization methods can be done based on single-objective or multi-objective functions. For example, in the field of energy management of microgrids, minimization of costs and emissions or their simultaneous optimization can be considered in the studies. However, the answers to the optimization methods are reliable if the optimization methods consider the modelling of uncertainties [9,10]. In [11], the Particle Swarm Otimization (PSO) is used to minimize microgrid costs with controllable loads and ES devices. This function pursues the goal of minimizing cost, pollution and satisfying problem constraints [12]. In [13], the function of the central controller is described in the microgrids. In [14], the optimal design of a hybrid solar-wind system is pursued in both islanded and grid-connected applications. A novel method for determining the size of a grid-connected hybrid solar system based on fuzzy logic and multi-objective optimization is introduced in [15]. In the optimization process in [15], both economic and technical goals are considered. Also, in [16], a model is presented for the optimization problem of operation, including solar cells, and batteries. Same approach is pursued in [17] in which authors presented a modified bat algorithm for energy management of a microgrid encompassed with DG units such as PV, WT, and fuel cell and storage systems. Elgamal et al. [18] proposed an energy management system for a grid connect microgrid and represented a rule base-assisted improved bat algorithm for their optimization. Also, in [19] an enhanced version of bat algorithm is provided in which authors claimed that their modification actions improved the searching ability of the bats in the algorithm.

Recently, the concept of networked microgridshas attracted the attention of many researchers. Researchers stated that it would be receiving a boost if microgrids can interconnect with the goal of increasing reliability, flexibility, and efficiency of the systems, and supply the demands more efficiently [20]. Some recent activities regarding the networked microgrid systems can be exploited here. Harmon et al. [21] represented a communication platform based on cloud theory to deploy an effective energy management framework for the networked microgrids. In [22], a computational multi-objective optimization approach pursued to use the benefits of DGs for improving the resiliency of a networked microgrid. In [23], the energy management of a networked microgrid formed as a risk aversion problem, aiming to decrease the risks of considering the uncertainties associated with some DG units. A robust-based distributed approach is represented in [24] to execute proper operation management among different microgrids which are connected and controlled by a unique operator. The same approach is based on the Alternating Direction Method of Multipliers (ADMM) and pursued in [25] to represent the energy exchange mechanism between networked AC/DC microgrids. In [26], the authors investigated the energy exchange between microgrids, interconnected together using a bi-level linear programming approach considering the demand response problem.

Cooperative models for energy management of microgrids are also investigated in some literatures. In [27], a cooperative energy management procedure is represented for networked microgrid systems according to the canonical coalition games method. Day-ahead operation of networked microgrids is handled using an algorithm based on the Distributed Model Predictive Control (DMPC) method in [28]. Same viewpoint was followed in [29] wherein networked microgrids utilized a DMPC-based algorithm for resource sharing between microgrids.

It should be pointed out that today the power networks are facing with different types of loads, including electrical, thermal, gas, and water demands. Aiming to support the other types of demands, the Energy Hub (EH) is a promising option that comprises different energy converting equipment and can support different types of energy demands. The solution to such a problem is to use a concept called the EH, which was first proposed by Geidl et al. [30]. They have defined the EH as a super-node in power systems that receives various energy carriers such as electricity and gas asan input. The general framework of the EH is defined in such a way that different energy carriers can be consumed, stored, and converted to each other [31]. The EH model has recently experienced significant improvements. In [32–34], authors perused a comprehensive, intelligent and capable-to-control model of the EH so called Smart Energy Hub (SEH). In [35], the domestic EH procedure is investigated in the smart grid in which communication devices are implemented and their mathematical models are also provided for household appliances. In [36], the author addressed integrating renewable sources with virtual power plants and the EH. Ref. [37] focuses on the operation of DER-based multi-carrier energy systems in an islanded mode. Table 1 summarizes some of the main relevant references and their solution methods.

Looking over the above explanations, this paper is aimed to propose an effective energy management approach in a smart island. The smart island refers to an area that is isolated from the main grid and demands of which need to be supplied in a local manner [38]. Due to the easy access of such an area to the sea, the water demand can be supplied by the seawater through desalination units. Aiming to serve different energy demands of the island, this paper represents a networked microgrid system integrated with a multi-Energy Hub (multi-EH) system within the smart island to benefit from the potential of renewable energy sources to serve the electrical, thermal, and water demands of the island [39].

For more clarification, the main contributions and characteristics of this paper concerning prior publications are stated as follows:

- An effective model is represented for networked microgrid system with multi-EH system in an isolated smart island. The proposed model is an incorporated energy management scheme in which the networked microgrid and the multi-EH systems are able to transact energy to satisfy the network's obligations and provide different energy carriers including thermal, electrical, and water to make the energy management problem more effective and comprehensive;
- Enhancing the reliability of the studied networked microgrid in different critical scenarios utilizing the potential of multi-EH which collaboratively operates with renewable energy sources including PV, WT, and tidal units and easy access to the seawater in such area;
- The uncertainties associated with the energy management problem, including the wind speed, sunlight, thermal, electrical, and water demands of the multi-EH system is also a matter of concern in this paper which are modelled using the 2-m point estimate method (2-m PEM), which is a fast and easy-to-model approach.

The rest of the paper is organized as follows. The mathematical formulations are provided in Section 2. Section 3 represents the solution process. Section 4 exploits stochastic modelling based on the 2-m PEM. The performance effectiveness of the work is evaluated in Section 5, and Section 6 represents the conclusion part.

2. Mathematical modeling of the smart islands

This section investigates the mathematical formulation of the proposed smart island system (see Figure 1) As mentioned before, a networked microgrid is expanded across the island, which contains PV, WT, tidal, and multi-EH units. The total cost of the studied networked microgrid is made up of different terms and

Table 1. A brief comparison between references.

Reference	Method	Reliability	Uncertainty	EH/multi-EH	Networked microgrid
[14]	Modified krill herd algorithm	×	×	×	✓
[21]	Cloud-base framework	×	×	×	✓
[31]	Distributed approach	×	×	×	✓
[32]	MILP	×	✓	×	✓
[30]	MILP	×	✓	✓	×
[33]	ε-constraint method	×	✓	✓	×
[43]	θ-modified bat algorithm (SAIFI-SAIDI)	✓	✓	×	×
[46]	MILP (EENS)	✓	×	×	×
Proposed model	θ-modified bat algorithm	✓	✓	✓	✓

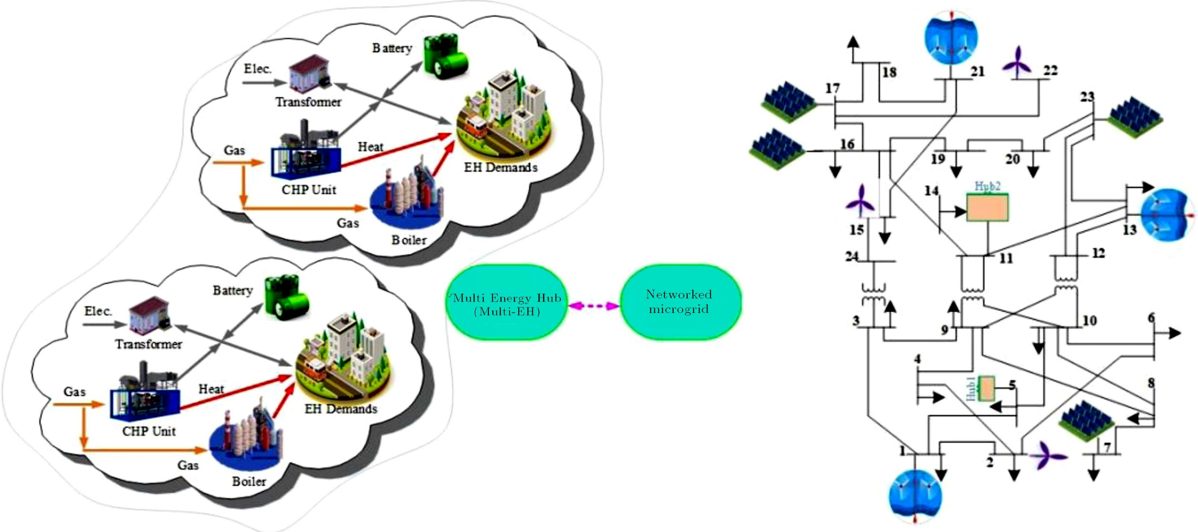


Figure 1. Illustrative representation of the smart island.

can be represented as follows:

$$C^{NETM}=\min\sum_{s}\sum_{i}\sum_{t}C_t^{PV}P_{s,i,t}^{PV}+C_t^{WT}P_{s,i,t}^{WT}$$
$$+C_t^{tidal}P_{s,i,t}^{tidal}+C^{NM}P_{s,i,t}^{NETM\_H}+ENS, \quad (1)$$

$$P_{s,i,t}^{PV}+P_{s,i,t}^{WT}+P_{s,i,t}^{tidal}+\sum_{j\in\Omega^j}P_{s,ij,t}+P_{s,i,t}^{NETM\_H}$$
$$=P_{i,t}^{l}-LS_{s,i,t}, \quad \forall t\in\Omega^T,\ \forall i\in\Omega^i,\ \forall s\in\Omega^s. \quad (2)$$

As can be seen, the main objective function of the proposed networked microgrid is provided in Eq. (1), which consists of five different terms, including the operation cost of the PV units, WT units, tidal units, cost of power transactions with the multi-EH, and the cost of ENS, respectively. As previously mentioned, the multi-EH and the networked microgrid system are able to transact energy in different hours of the day to satisfy network concerns. Hence, from the perspective of the networked microgrid, its transaction cost with multi-EH need to be minimized as well. This work is about to execute an energy management framework within the networked microgrid system, where minimizing the operating cost of each segment of which is essential. Eq. (2) describes the equation of power balance of the networked microgrid system, which guarantees the supplement of system's demands. This equation also comprised of different terms. The left-handed terms are the power transactions of PV, WT and tidal units, power injection through the lines [40,41], and the power transaction between the networked microgrid system and multi-EH.Such power transaction is bilateral, which means both parties can transact energy with each other. Additionally, the right-handed terms are the demand loads of the system and the load shedding. The proposed left-sided terms are expressed in detail in Eqs. (3)–(6):

$$P_{s,i,t}^{PV}=\frac{DNI\times E_{i,t}^{PV}}{G}\times(1-PV^{loss}),$$
$$\forall t\in\Omega^T,\ \forall i\in\Omega^i,\ \forall s\in\Omega^s, \quad (3)$$

$$P_{s,i,t}^{WT}=\begin{cases}0 & \leq WS_{i,t}\leq WS_{rated}\\ \frac{1}{2}\rho A(WS_{i,t})^3 & WS_{cutin}\leq WS_{i,t}\leq WS_{rated}\\ P_{rated}^{WT} & WS_{rated}\leq WS_{i,t}\end{cases}$$
$$\forall t\in\Omega^T,\quad \forall i\in\Omega^i,\quad \forall s\in\Omega^s, \quad (4)$$

$$P_{s,i,t}^{tidal}=\begin{cases}0 & 0\leq V_{i,t}\leq V_{rated}\\ 0.5\ H_{pc}\rho_s\ A_{tidal}\ V_{i,t}^3 & V_{cutin}\leq V_{i,t}\leq V_{rated}\\ P_{rated} & V_{rated}\leq V_{i,t}\end{cases}$$
$$\forall t\in\Omega^T,\quad \forall i\in\Omega^i,\quad \forall s\in\Omega^s, \quad (5)$$

$$ENS=\sum_{s,i,t}C^{ENS}PC_sLS_{s,i,t}, \quad (6)$$

$$LS_{s,i,t}\leq P_{i,t}^{l}, \quad \forall t\in\Omega^T,\ \forall i\in\Omega^i,\ \forall s\in\Omega^s, \quad (7)$$

$$P_{i,t}^{Batt}=P_{i,t}^{chg}-P_{i,t}^{disg} \quad \forall t\in\Omega^T,\ \forall i\in\Omega^i, \quad (8)$$

$$P^{\min}\delta_{i,t}\leq P_{i,t}^{Batt}\leq P^{\max}\delta_{i,t} \quad \forall t\in\Omega^T,\ \forall i\in\Omega^i, \quad (9)$$

$$E^{\min} \leq E_{i,t}^{Batt} \leq E^{\max} \quad \forall t \in \Omega^T, \ \forall i \in \Omega^i, \tag{10}$$

$$E_{i,t}^{Batt} = E_{i,t-1}^{Batt} + (P_{i,t}^{chg} - P_{i,t}^{disg})\eta^{Batt}$$
$$\forall t \in \Omega^T \ \forall i \in \Omega^i, \tag{11}$$

$$\delta_{i,t} = \delta c_{i,t} + \delta d_{i,t} \quad \forall t \in \Omega^T, \ \forall i \in \Omega^i. \tag{12}$$

Eq. (3) defines the output power of the PV units. As can be seen, the generated power directly depends on the sun irradiation DNI and the loss of the PV cells, and inversely relates to the solar radiation G [42]. The output power of the WTs is represented in Eq. (4), which is related to the cubed of wind speed [43]. The power generation of the tidal units is expressed by Eq. (5), which explains that the output power is determined by the current speed of tidal ($V_{i,t}$). The tidal unit would generate no power, $P_{s,i,t}^{tidal}$ if its current speed is below the rated speed (V_{rated}). The tidal starts generating power when the current speed hits the cut-in speed (V_{cutin}) and is below the rated speed. If so, the output power would be the rated speed of the tidal unit [43]. Finally, the ENS equation is expressed by Eq. (6) and the load shedding value is limited by the Constraint (7) [42].

It is worth noting that the PV units, Tidal units, and WT units are comprised of two parts including their main renewable resources and their relevant storage systems which are modelled in Eqs. (8)-(12). Eq. (8) indicates the injection/consumption power of the storage systems and could be charged or discharged at t. Eq. (9) describes the restriction on charging or discharging power of the storage systems due to the technical limitation of the storage systems. The same goes for Constraint (10) which forces the energy level of the storage systems to be within their maximum and minimum values. Eq. (11) represents the hourly energy level of the storage systems and defines the hourly energy level of the batteries after each power charging or discharging. Finally, Eq. (12) assures that the charging/discharging will not happen at the same time. In this regard, $\delta c_{i,t}$ and $\delta d_{i,t}$ are binary variables that define the charging or discharging status of the batteries, respectively.

The multi-EH system comprises two EH systems, located on two different buses of the networked microgrid and these EHs are assumed to have the same structure in the energy management process. It is worth mentioning that these EHs are interconnected through the graph of the networked microgrid, which can be seen in Eq. (2). In the following, the formulation related to the energy management framework of each EH is provided. The multi-EH system is another section of the networked microgrid, the formulation of which is exploited in the following. Firstly, it should be mentioned that the CHP, boiler unit, and battery are the main parts of the EH unit. The objective function and constraints of the multi-EH system provided as follows:

$$cost^{M-EH} = \min$$
$$\sum_{t\in\Omega^t} \begin{pmatrix} P_t^C C_{CHP} + P_t^{boi} C_{boi} - P_t^{bat} C_{bat} + \\ W_t^G C_{water} - C_H \sum\limits_{s\in\Omega^s} P_{s,t}^{NETM\_H} \end{pmatrix}. \tag{13}$$

Objective functions in multi-EH layers:

1. *Electrical layer*

$$P_t^E + P_t^{Des} + \eta_e^T \sum_{s\in\Omega^s} P_{s,t}^{NETM\_H} = \eta_{chp}^{GtoE} P_t^C$$
$$+P_t^{bat} + \eta_{boi}^{GtoE} P_t^{boi} \quad \forall t \in \Omega^T, \tag{14}$$

$$\underline{P}_t^{EH} \leq \sum_s P_{s,t}^{NETM\_H} \leq \bar{P}_t^{EH} \qquad \forall t \in \Omega^T, \tag{15}$$

$$\underline{Eb}^{bat} \leq Eb_t^{bat} \leq \overline{Eb}^{bat} \quad \forall t \in \Omega^T, \tag{16}$$

$$Eb_t^{bat} = \left(1 - ES_e^{loss}\right) Eb_{t-1}^{bat} + P_t^{bat} \quad \forall t \in \Omega^T, \tag{17}$$

$$\frac{1}{\eta_e} \underline{P}^{bat} \leq P_t^{bat} \leq \frac{1}{\eta_e} \bar{P}^{bat} \quad \forall t \in \Omega^T. \tag{18}$$

2. *Heat layer*

$$P_t^{Heat} = \eta_{chp}^{GtoH} P_t^C + \eta_{boi}^{GtoH} P_t^{boi} \quad \forall t \in \Omega^T, \tag{19}$$

$$P_t^{Gas} = P_t^C + P_t^{boi} \quad \forall t \in \Omega^T, \tag{20}$$

$$\eta_e^T \left(\sum_s P_{s,t}^{NETM\_H} \right) \leq Cap^{Tr} \quad \forall t \in \Omega^T, \tag{21}$$

$$\eta_{chp}^{GtoH} P_t^C \leq Cap^{CHP} \quad \forall t \in \Omega^T, \tag{22}$$

$$\eta_{boi}^{GtoH} P_t^{boi} \leq Cap^{Boi} \quad \forall t \in \Omega^T. \tag{23}$$

3. *Water layer*

$$V_t^{ST} = V_{t-1}^{ST} + W_t^{OD} + W_t^G - W_t^{Out} \quad \forall t \in \Omega^T, \tag{24}$$

$$V_t^{DT} = V_{t-1}^{DT} + W_t^{ID} - W_t^{OD} \quad \forall t \in \Omega^T, \tag{25}$$

$$\underline{W}^{ID}.I_t^D \leq W_t^{ID} \leq \bar{W}^{ID}.I_t^D \quad \forall t \in \Omega^T, \tag{26}$$

$$P_t^{Des} = W_t^{ID}.CF^{Des} \qquad \forall t \in \Omega^T, \tag{27}$$

$$C^{Total} = C^{NETM} + cost^{M-EH}. \tag{28}$$

Eq. (13) indicates the objective function of the multi-EH system which consists of five different terms including the operation costs of CHP, boiler, and ES system, cost of water consumption from the grid, and cost of power transaction between the networked microgrid system and multi-EH, respectively. For more clarification, the constraints are partitioned based on the layers of the multi-EH. The constraints associated with the electrical layer are expressed in Eqs. (14)–(18), the thermal constraints are provided in Eqs. (19)–(23), and the constraints related to the water layer are stated in Eqs. (24)–(27). In the electrical layer, Eq. (14) indicates the electrical power balance equation of the multi-EH [5]. The left-sided terms are the electrical demand of the multi-EH (P_t^E), the desalination unit power consumption, P_t^{Des} and the power injection of the multi-EH unit to the networked microgrid system $P_{s,t}^{NETM\text{-}H}$, respectively. The right-sided terms are the output power of the CHP unit, P_t^C power exchange of the ES system, P_t^{bat} and output power of the boiler, P_t^{boi} respectively. Constraint (15) indicates that the power transaction between multi-Hub and networked microgrid system need to be restricted within its allowable ranges [44]. Constraints (16)–(18) are associated with the charging/discharging power of the ES unit. Constraints (19)–(23) represent the heating layer of the multi-EH. In (19), the heat balance equation is provided, which assures that the heat demand of the multi-Hub will be served. Eq. (20) defines the total gas consumed by CHP and boiler units to generate power, which is supported through the network. Also, Constraints (21)–(23) express that the output power of multi-Hub, CHP, and boiler units are not allowed to exceed their transformers capacities.

Finally, the constraints related to the water layer need to be explained, which are represented in Eqs. (24)–(27). In Eq. (24), the water balancing equation is presented. Some explanations are needed here. The water layer is defined to support the water demand of the smart island including the water usage of residential, commercial, industrial units. In the related formulations, the summation of the usages is defined by W_t^{out}. Two ways are available to support the water demand of the smart island, W_t^{out}, including the water of the grid (W_t^G) and the output of the desalination unit (W_t^{OD}). The water of both of these sources is poured into a water tank; the capacity of which is indicated by V_t^{ST}, preceded by pouring the desalinated water coming out from the desalinated unit into the desalination tank, where its capacity is defined by V_t^{DT} and Constraint (25) describes this process. Constraint (26) restricts the sea water's volume which comes into the desalination unit. The desalination unit consumes power to handle the whole process which is defined in the problem by Eq. (27). And finally,

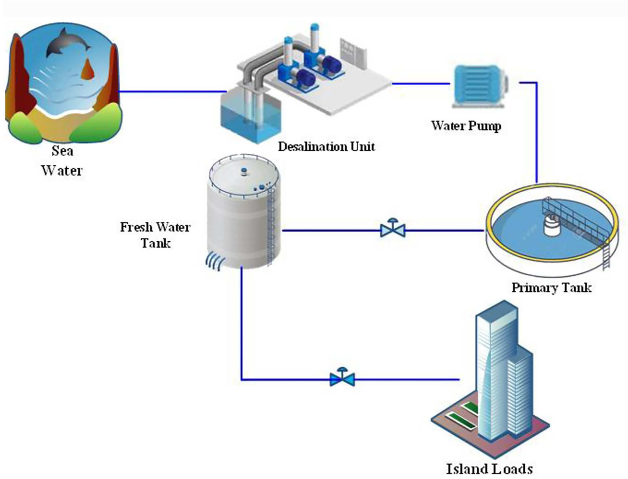


Figure 2. Illustrative representation of the smart island water supplement system.

Eq. (28) represents the total objective function of the problem which needs to be minimized and includes the operation costs of networked microgrid and multi-EH. It is assumed that both of these systems are operated and controlled by a single and unique system operator of the smart island. Figure 2 illustrates the water supplement system of the smart island.

3. Optimization algorithm

This section is dedicated to the optimization method for solving the studied model. In this regard, an appropriate θ-modified bat algorithm is applied to handle the energy management problem. The bat algorithm is an evolutionary-based optimization method that is inspired by the behaviour of bats. Some pre-descriptions are needed to figure out how the algorithm works and finds the optimal solution. Suppose a group of bat animals fly in a free space where each one, indicated with Bat_r, has its velocity of vel_r and propagates a signal with a frequency of $freq_r$ and loudness of $loud_r$ which alters automatically with the rate of R_r. The bats use this approach to fly toward their desired target. At first, a random population of bats is generated and the objective function is defined for each bat. After that, the population is updated as follows:

$$Bat_r^{new} = Bat_r^{old} + vel_r^{new} \qquad \forall r \in \Omega^r, \tag{29}$$

$$vel_r^{new} = vel_r^{old} + freq_r(Bat_{glob} - Bat_r) \quad \forall r \in \Omega^r. \tag{30}$$

Another movement procedure is also executed in the method by generating a random value κ. If the random value is more extensive than R_r, a new movement for the bats is applied as follows:

$$Bat_r^{new} = Bat_r^{old} + \tau loud_{MV}^{old} \qquad \forall r \in \Omega^r. \tag{31}$$

In case of having a κ smaller than the R_r, a new bat will be produced if the following conditions hold:

$$\begin{array}{r}\kappa < loud_r\\ F(B_r) < F(Bat_{glob})\end{array} \quad (32)$$

By doing so, the loudness and rate parameters are updated iteratively during the process by the following equations:

$$loud_r^{new} = \delta loud_r^{old} \qquad \forall r \in \Omega^r, \quad (33)$$

$$R_r^{It+1} = R_r^0 \left[1 - \exp(\sigma \times It)\right]$$

$$\forall r \in \Omega^r. \quad (34)$$

A modification procedure is represented in this paper to enhance the effectiveness of the proposed algorithm. In this approach, the bats' search ability is represented in the polar coordinates, which accordingly improves the accuracy and solution speed. In this regard, repositioning of the bats is calculated using the phase angle of the bats and Eqs. (29)–(31) are updated as follows:

$$\Upsilon_r^{new} = \Upsilon_r^{old} + vel_r^{new} \qquad \forall r \in \Omega^r, \quad (35)$$

$$vel_r^{new} = vel_r^{old} + freq_r \left(\Upsilon_{glob} - \Upsilon_r\right)$$

$$\forall r \in \Omega^r, \quad (36)$$

$$\Upsilon_r^{new} = \Upsilon_r^{old} + \tau loud_{MV}^{old}, \qquad \forall r \in \Omega^r, \quad (37)$$

where Υ_r^{old} is assumed to be between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$ and $\Upsilon_r \epsilon \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$. Additionally, each one of the generated bats needs to be transformed into the Cartesian coordinates as follows:

$$Bat_r = \frac{Bat_{\max} - Bat_{\min}}{2} \sin(\Upsilon_r) + \frac{Bat_{\max} + Bat_{\min}}{2}. \quad (38)$$

This paper also uses the two-stage modification framework of the bat algorithm similar to the one represented in [40]. Figure 3 illustrates the steps of the bat algorithm.

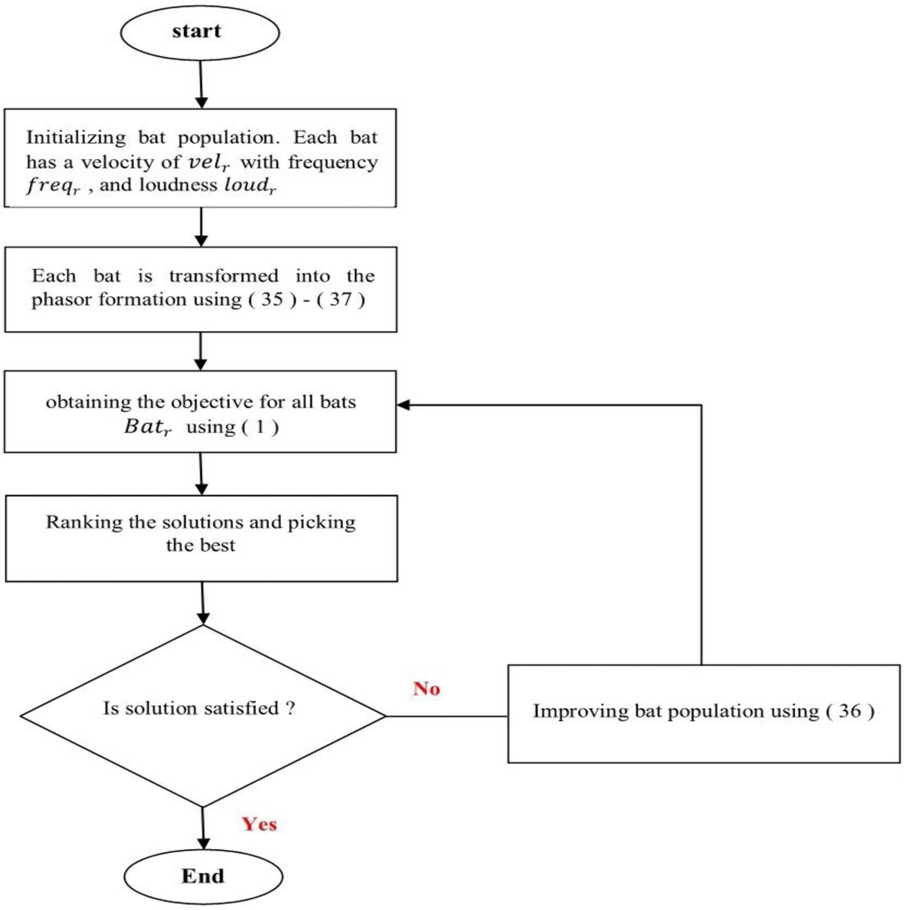


Figure 3. Illustration of the proposed bat algorithm.

4. Stochastic modelling based On 2-M PEM

For the last few years, researchers have ongoingly attempted to deal with the stochastic inherent of some of the main parameters in the power system. Along with the ever-growing development of technology and the advent of renewable energy sources, stochastic modelling has become prominent for making the operation management frameworks more efficient and reliable. Hence, such an issue will make the decision-making challenging and has sparked more attention than before. Malekpour et al. [45] investigated different methods for stochastic modelling. They pointed out that the approximate methods are less computationally challenging and require preliminary data of random variables for modelling. The 2-m PEM is an effective and fast uncertainty modelling method that falls into the category of approximate methods. This paper attempts to capture the uncertainty associated with some of the main stochastic factors of the modelling, including the wind speed, sunlight, thermal, electrical, and water demands of the multi-EH system and tidal current speed. In the following, the mathematical modelling of the 2-m PEM method is provided.

Suppose a nonlinear function that bears the basic mathematical equations of the system and links the input parameters with the output variables. This function can be represented as follows:

$$\boldsymbol{A} = \Psi(\boldsymbol{B}), \tag{39}$$

where $\boldsymbol{A}$ is the vector of output variables and $\boldsymbol{B}$ is the vector of input parameters. The 2-m PEM method starts with assigning a probability density function to each random variable $b_i, i = 1, \cdots, m$. After that, two points called concentration points including $b_{i,1}$ and $b_{i,2}$ are replaced with b_i which can be calculated as follows:

$$\begin{cases} b_{i,r} = \mu_{b_i} + \xi_{i,r}\sigma_{b_i} \\ \xi_{i,r} = \lambda_{i,3}/2 + (-1)^{3-k}\sqrt{m - \left(\lambda_{i,3}^2/2\right)^2} \\ \qquad r = 1, 2; \quad i = 1, ..., m \\ \lambda_{i,3} = E\left[(b_i - \mu_{b_i})^3\right] / (\sigma_{b_i})^3 \end{cases} \tag{40}$$

Where E indicates the expected value. After obtaining the $b_{i,1}$ and $b_{i,2}$ concentration points, the studied probabilistic problem needs to be calculated for each point. Aiming to attain the final answer, two weighting factors are assigned to the concentration points to determine the impact of calculated points on the final solution. These two factors are represented as follows:

$$\begin{cases} \omega_{i,1} = -\frac{1}{m}\left(\frac{\xi_{i,2}}{\xi_{i,1} - \xi_{i,2}}\right) \\ \\ \omega_{i,2} = +\frac{1}{m}\left(\frac{\xi_{i,1}}{\xi_{i,1} - \xi_{i,2}}\right) \end{cases} \quad i = 1, ..., m \tag{41}$$

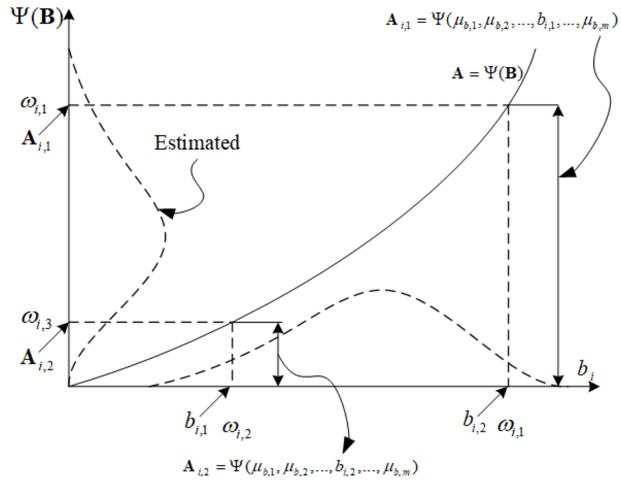


Figure 4. Illustration of 2m PEM [45].

After evaluating the weighting factors, the standard deviation and expected value of the objective function can be calculated using the following equations:

$$\begin{cases} \sigma = \sqrt{var\left(\mathbf{A}_i\right)} = \sqrt{E\left(\mathbf{A}_i^2\right) - \left[E\left(\mathbf{A}_i\right)\right]^2} \\ \\ E\left(\mathbf{A}_i^j\right) = \sum\limits_{i=1}^{m}\sum\limits_{r=1}^{2} \\ \quad \left(\omega_{i,r} \times \mathbf{A}_i^j\left(\mu_{b_1}, \mu_{b_2}, \ldots, b_{i,r}, \ldots, \mu_{b_m}\right)\right). \end{cases} \tag{42}$$

The illustrative representation of the 2-m PEM method is depicted in Figure 4.

5. Simulation results

This section is dedicated to the performance analysis of the proposed networked microgrid model. The studied networked microgrid comprises renewable energy sources, including PV, WT, and tidal units [5], and EH [32]. This problem is analyzed on a 24-bus test system, drawn from [47]. The PV units are located at buses 7, 16, 17, 23 and the WTs are located at buses 2, 15, 22. Also, the tidal units are connected to buses 1, 13, 21, and the EHs including the EH1 and EH2 are connected to buses 5 and 11, respectively. The parameters related to the microgrid system and bat algorithm are drawn from Refs. [5] and [40], respectively.

Figure 5 illustrates the smart island's network. The WTs are assumed to be operated based on the wind speed [48]. Different case studies are represented to evaluate the work in different aspects and are provided as follows:

- Case I: Energy management analysis of the studied networked micro grid.
- Case II: Reliability analysis of the proposed networked microgrid.

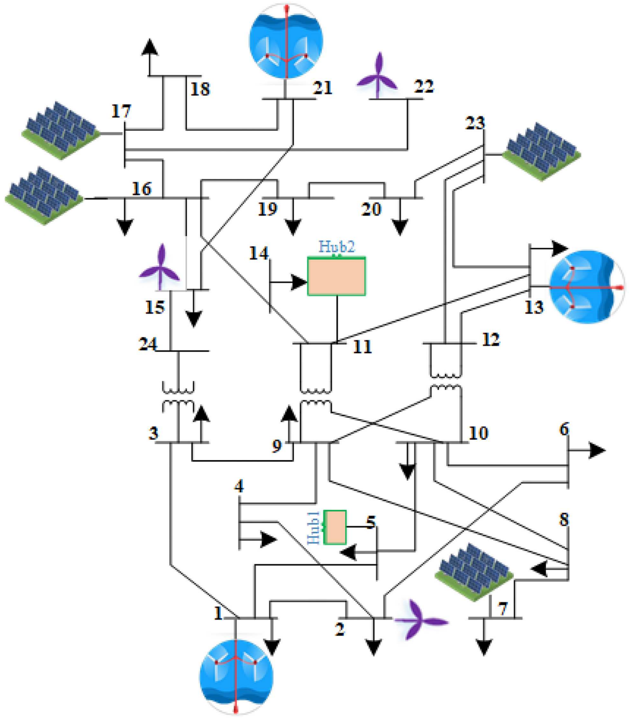


Figure 5. The illustration of the proposed network in the smart island.

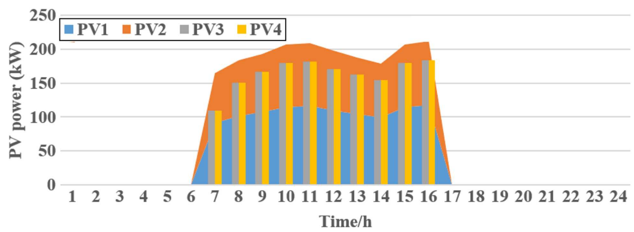


Figure 6. Hourly generated power of the PV units.

- Case III: Impact of uncertainties on the performance of the proposed networked microgrid system.

In the following, each one of the cases will be discussed in detail.

5.1. *Case I: Energy management analysis of the studied networked microgrid*

In this section, the energy management procedure within the studied networked microgrid system is presented. In the first case, it is meant to analyze the performance of the network microgrid, DG units (their output power) and EHs. The behavior of the units is explained in detail and the total operation and investment cost of networked microgrid and multi-hub system is proposed at the end. Each one of the units in the network is able to inject/draw power to/from the networked microgrid system.

The hourly output power of the PV units is illustrated in Figure 6. It is evident that the units started generating power from $t = 6$ until $t = 17$ during

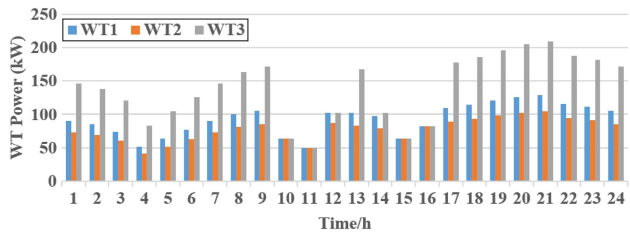


Figure 7. Hourly generated power of the WT units.

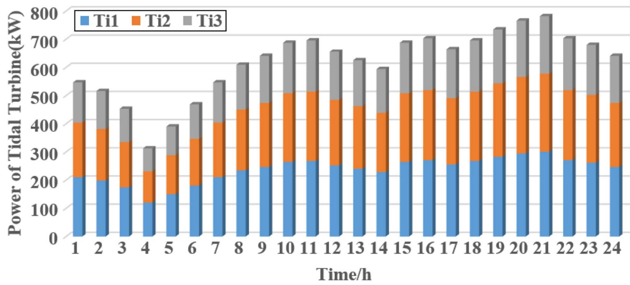


Figure 8. Hourly generated power of the tidal units.

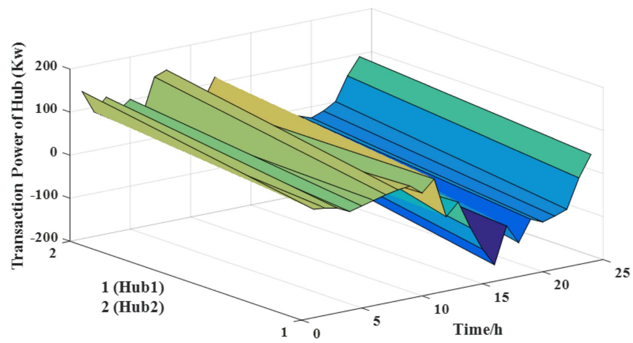


Figure 9. Hourly exchanged power of the EHs.

the middle of the day which is generally compatible with the behavior of PV units. Besides, the PV4 has shown more contribution in the output power of PV units compared to the others, where it hits the top at $t = 11$, which is about 210 KW. Figure 7 illustrates the hourly generated power of the WTs where they imitate the wind speed pattern. It can be seen that the WT3 has more significant share in the output power of WTs than the other units, especially after $t = 17$ where the units have much more potential to serve the demands ofthe system.

Figure 8 depicts the hourly generated power of tidal units. Tidal units 1 and 2 have more contributions to the generated power, especially during $t = 9-12$ and $t = 17 - 20$. As can be seen, the output power of the units starts at $t = 7$ and increases steadily until $t = 12$. The same goes for $t = 7 - 21$. However, the output power of tidal unit 1 overtakes that of tidal unit 2 at $t = 21$ and after that, it shows a faster downward trend. Figure 9 represents the power transaction of EHs with the networked microgrid system. The vertical axes 1 and 2 indicate the values of the transacted power of the

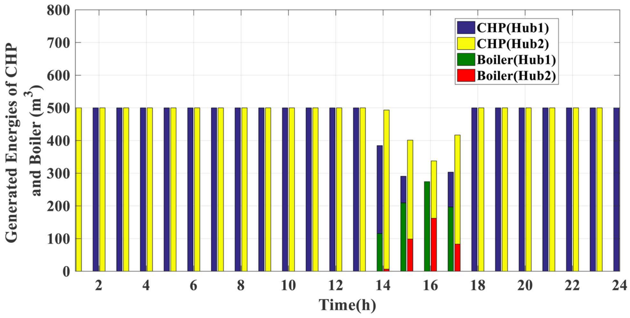


Figure 10. Hourly generated energies of the CHP and boiler units of both EHs.

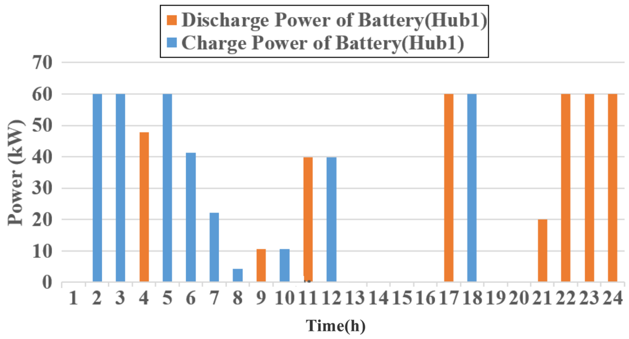


Figure 11. Hourly charge/discharge power of the storage of EH1.

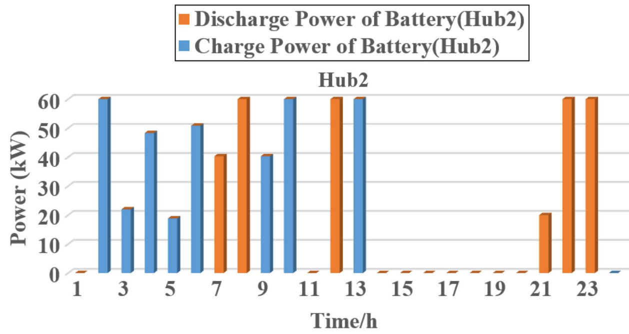


Figure 12. Hourly charge/discharge power of the storage of EH2.

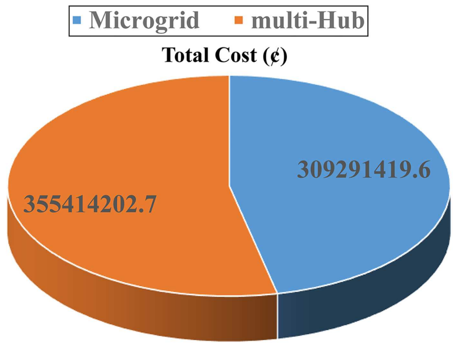


Figure 13. Total operation and investment cost of networked micro grid and multi-hub system.

EHs. It is worth mentioning that the positive values imply the transacted power from EHs to the network and the negative values express the power transaction from the network to the EHs. It can be seen that the system mostly prefers to buy energy from the EH1 due to the higher capacity for serving the loads. While the behavior completely changes after $t = 20$ and the transacted energy from the EHs to the network increases dramatically to support the demands of the system at the end of the day and nearly levels off at $t = 24$. Figure 10 illustrates the generated energies of the boiler and CHP units for both the EH1 and EH2. Same as previous, the vertical axes indicate the generated energy values throughout the 24-hour daily horizon. Some explanations need to be provided here. Firstly, it can be seen that the CHP units experienced two periods of stabilization including the $t = 1-13$ and $t = 18 - 24$ which implies the significant contribution of the CHP units in serving the system's loads. The system preferred to use the generated power of the boiler units at $t = 15$ compared to the CHP unit, which falls markedly after $t = 13$, due to two main reasons: (1) high demand loads in the middle of the day and (2) more beneficial price of the boiler which provides a cost-effective strategy for the system at this particular time of the day. Aiming to represent a more comprehensive view over the performance of the EHs, Figures 11 and 12 are provided, which depict the charging and discharging power of the storages of the EH1 and EH2. One can conclude that the storage units are more intended to be charged during off-peak load hours of the day and discharged during peak load hours, which can be seen mostly at the beginning and end of the day, respectively. The rapid increase of hub-to-network power transactions also confirms this fact in Figure 9 at the end of the day.

Figure 13 compares the total cost of operation and investment of the networked microgrid and multi-hub system. It can be said that the networked microgrid system has almost 13% higher cost than that of the multi-hub system.

5.2. *Case II: Reliability analysis of the proposed networked microgrid*

This section is about to assess the reliability of the studied model. In the second case, it was intended to analyze the reliability of the networked microgrid system when losing some critical lines. Two scenarios of failure considered where each scenario defines each failure. In this section the ENS cost is considered as a tool for reliability and it is tried to focus on the energy exchange between multi-EH and microgrid system during critical situation to improve the reliability of the network. Two different scenarios are considered for the evaluation including: (1) outage of lines 10 and 7, and (2) outage of lines 3 and 5. Figure 14 illustrates the power transaction between the networked microgrid and the EH. It should be

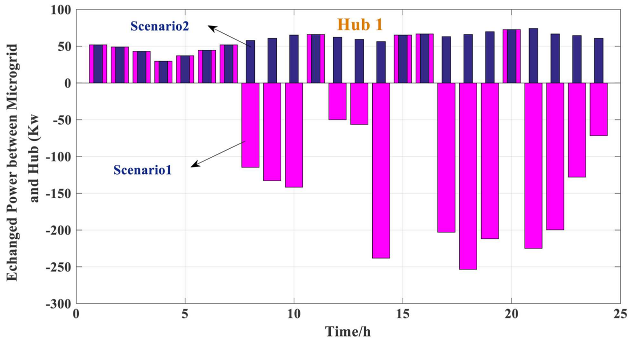


Figure 14. Hourly power transaction between EH1 and networked micro grid.

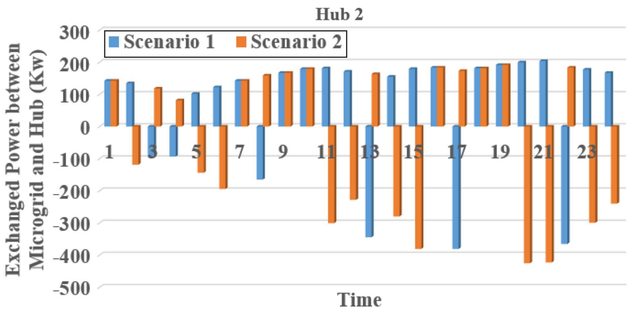
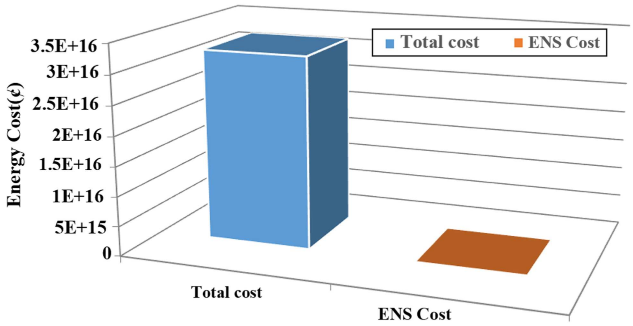


Figure 15. Hourly power transaction between EH2 and networked micro grid.

mentioned that the positive values indicate the power transaction from the EH to the networked microgrid. On the contrary, negative values define the energy flow from the networked microgrid to the EH. It can be said that in the first scenario, the system is more intended to draw power from the EH to support its demand since the networked microgrid is not able to do so. Such a tendency can also be seen in Figure 15, where it depicts the hourly power transaction of the EH with a networked microgrid system in both scenarios 1 and 2. In the second scenario, the EHs have consumed power from the network, aiming to support the system during high-price hours. Looking over these Figures 14 and 15, one can conclude that the performance of the EHs and the network immensely depends on the type of fault in the system, its consequences and the price of energy during the hours that the fault remains in the system. On the other hand, based on the intensity of the fault and its duration time, the price of energy (buy or sell) may alter and directly affects the performance of the agents.

Figure 16 shows the total ENS cost compared to the total operation cost of the networked microgrid in both scenarios. It should be mentioned that the ENS cost accounts the ENS cost of the system in both scenarios 1 and 2, which is about 3228204 and is a trivial value compared to the total cost of the system. Figure 17 shows the convergence curve of different optimization scenarios considered in this section.



	Total cost	ENS Cost
Series1	3.2282E+16	3228204.323

Figure 16. Comparison between total cost of the network and the ENS cost.

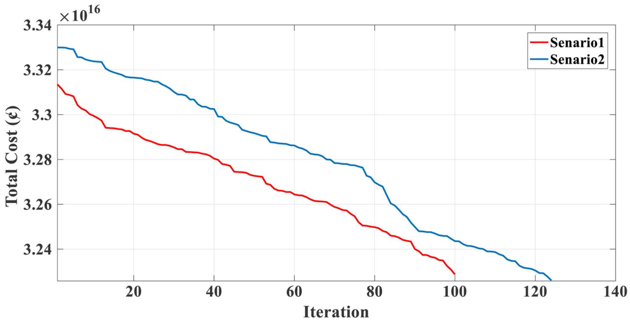


Figure 17. Convergence curve of different optimization scenarios.

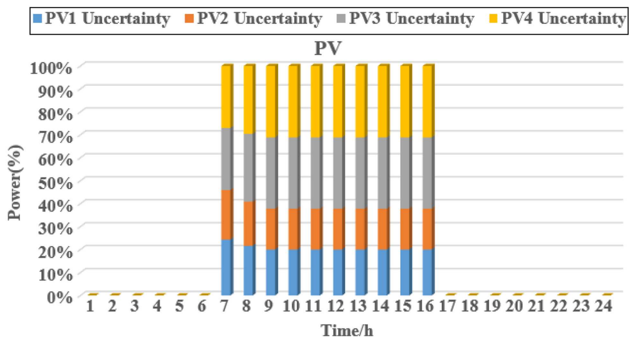


Figure 18. Hourly power transaction between EH2 and networked micro grid.

5.3. Case III: Impact of uncertainties on the performance of the proposed networked microgrid system

Aiming to show the performance of the studied model better, the system should be modeled in the stochastic environment as well. In the third case, the impact of uncertainty on the performance of the networked microgrid is analyzed, since the network is encompassed with renewable sources and their uncertainty on the performance of the system is un neglectable. The output powers of the units are provided in the stochastic environment. In this regard, Figure 18 depicts the tolerance percentage of the output power

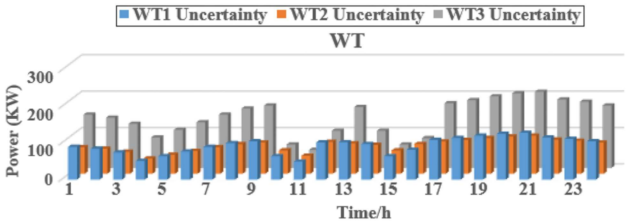


Figure 19. Power generation of the WTs considering the uncertainty.

of the PV units. It can be seen that the PV units 1, 2, 3, and 4 have shown nearly 19%, 16%, 31%, and 32% power tolerance in the stochastic environment, respectively. This shows that the output power of PV4 is the most affected term compared to the others. Figure 19 depicts the generated output power of the WTs in the stochastic environment.

Figure 19 shows the output power of the WT units considering the uncertainty factors of the system. It is worth mentioning that the uncertainty factors have caused the power units of the system to alter their output power aiming to support the uncertain demand of the system. To make it more straightforward, Figure 20 is depicted to represent the output power of tidal units in the stochastic environment. Comparing the peak values at $t = 21$ with that of the deterministic framework, it can be said that the uncertainty has caused units 1 and 2 to increase their output power by 10.77% and 13.31%, respectively. On the flip side, tidal unit 3 falls to 9.13% of the peak value of the deterministic condition. One can conclude that alternation of the output power of the units remarkably depends on the variation of the load demands in the uncertain environment and how the system decides to deal with it in the most cost-effective way.

Figure 21 shows a comparison between the cost function of the system in the stochastic environment and deterministic conditions. It can be said that about 3.12% additional cost is imposed on the system, highlighting the cost of forecasting errors of the system's uncertainties. Figure 22 shows the proposed model

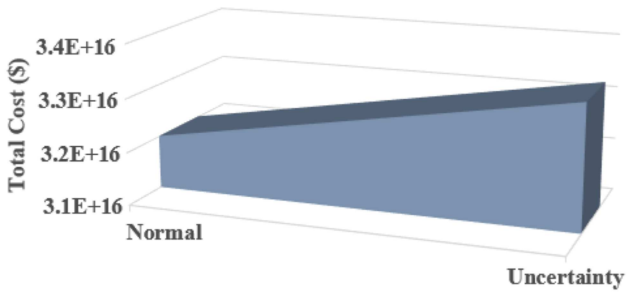


Figure 21. Comparison between stochastic and deterministic costs.

compared with the normal condition, where no transaction link exists between the multi-EH and networked microgridsystem. It shows that the proposed model could properly decrease the total cost of both units.

6. Conclusion

This paper tried to evaluate the reliability of a networked microgrid in a smart island, which is isolated from the main electrical grid, by providing effective stochastic energy management in the island. A networked microgridsystem assumed to be expanded across the island, which is responsible for supporting the demand loads of the island. The potential features of the smart island simplify a proper access to the seawater and provide the chance of using renewable energy sources such as tidal units. In this regard, different renewable energy sources are considered on the island including PV units, WT units, and tidal units. Also, it is necessary to propose an effective approach that could be able to supply different energy carriers. To do so, this paper suggested a networked microgrid system incorporated with a multi-EH system aiming to serve the proposed electrical, water and heat demands of the smart island. Furthermore, the reliability of the proposed system was improved by scheduling the exchanged energy between the networked microgrid and the multi-EH system in different scenarios of failure (such as the outages of lines). Additionally, the uncertainty associated with the wind speed, sun

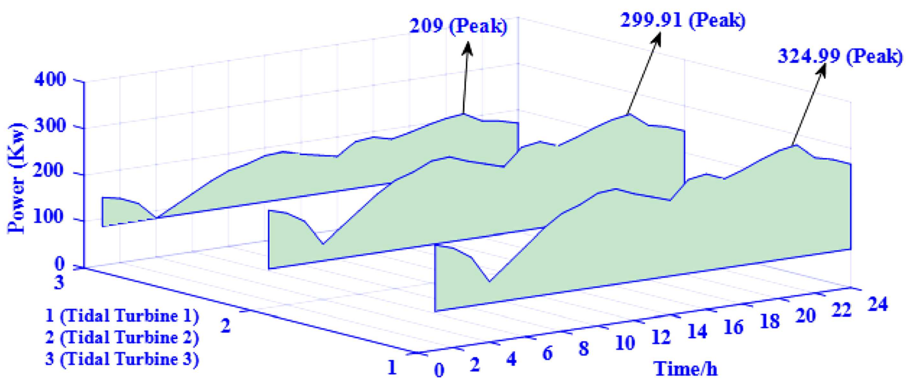


Figure 20. Generated output power of the tidal units considering the uncertainty.

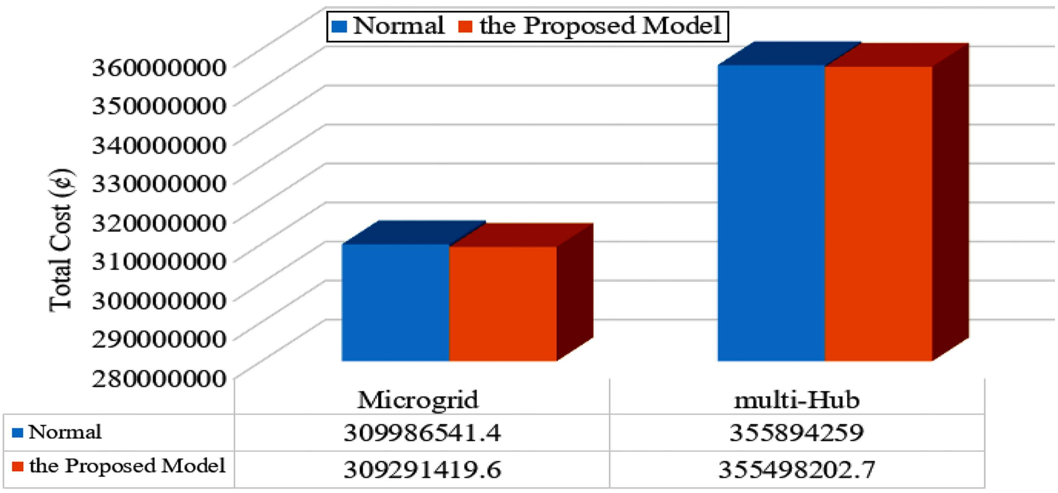


Figure 22. Comparison between the normal case (no transaction between multi-EH and networked micro grid) and the proposed model.

irradiation, and thermal, electrical, and water demands of the multi-EH system was modelled using 2-m PEM which has shown outstanding advantages including the accuracy and implementation speed. By using an effective θ-modified bat algorithm the problem solved and different scenarios were considered to prove the effectiveness of the work. All in all, the proposed optimization solution could handle the energy management of the smart island, the ENS, and total cost of the system was obtained with the minimum number of iterations. Also, the multi-Hub system was effective as a proper option in serving the demands of the system during both normal and critical conditions and improved the reliability of the system. In addition, an analysis was carried out and indicated that the energy transaction scheme between the networked microgrid system and the multi-EH could effectively decrease their total operation and investment cost. Some studies including the investigation of DC and hybrid microgrids and their decentralized energy negotiation can be considered as future works.

Nomenclature

Ω^r/r	Set/indices of bats, $\Omega^r=\{1,...,r\}$.
Ω^t/t	Set/indices of time, $\Omega^t=\{1,...,24\}$.
Ω^i/i	Set/indices of units, $\Omega^i=\{1,...,i\}$.
Ω^s/s	Set/indices of scenarios, $\Omega^s=\{1,...,s\}$.

Constants

$\eta_e^T, \eta_{chp}^{GtoE}$,	Efficiencies of transformer passing electricity, gas-to-electricity conversion of CHP.
η_{boi}^{GtoE},	Gas-to-electricity conversion of the boiler.
η_{chp}^{GtoH},	Gas to heat conversion of CHP.
η_{boi}^{GtoH},	Gas-to-heat conversion of boiler.
η_e	Battery energy exchange.
$\overline{P}_t^{EH}, \underline{P}_t^{EH}$	The maximum and minimum multi-EH power transaction, respectively.
$\overline{B}^{bat}, \underline{B}^{bat}$	The maximum and minimum energy level of the battery, respectively.
$\overline{P}^{bat}, \underline{P}^{bat}$	The maximum and minimum power exchange of the battery, respectively.
$E^{\max/\min}$,	Maximum/minimum energy level,
$P^{\max/\min}$	Maximum/minimum power charging discharging of the batteries of renewable energy sources, respectively.
η^{Batt}	Efficiency of batteries of renewable energy sources, respectively.
$\overline{W}^{ID}, \underline{W}^{ID}$	The maximum and minimum input water of the desalination unit, respectively.
Cap^{Tr}, Cap^{CHP}, Cap^{Boi}	Nominal capacities of the transformer, CHP, and boiler units, respectively
DNI, G, PV^{loss}	Direct normal irradiation, solar radiation and power loss of PV, respectively.
$\rho, A, WS_{i,t}$	Wind density, area of rotor blades, and wind speed, respectively.
$H_{pc}, \rho_s, A_{tidal}$	The power capture coefficient, seawater density and swept area of the turbine blades, respectively.

ES_e^{loss}	The loss efficiency of energy storage system.
CF^{Des}	The energy coefficient of desalination system (KW/Lit).
$Bat_{\max/\min}$	Minimum and maximum limited value of the bat.
α	Random value between [0, 1].

Variables

C^{NETM},	Operation costs of the networked microgrid system.
C_t^{PV},	PVs, WTs, tidal units, and
C_t^{WT},	cost of power transaction
C_t^{tidal},	from multi-EH system to the networked microgrid and
C^{NM}, ENS,	total ENS cost, respectively.
C^{ENS}	Costs of ENS,
$cost^{M-EH}$,	multi-EH system,
C_{CHP},	CHP,
C_{boi},	boiler,
C_{bat},	energy storage system,
C_{water},	water supply system,
C_H	power transaction from networked microgrid to the multi-EH system, respectively.
$P_{s,i,t}^{PV}$,	Power generation of PVs,
$P_{s,i,t}^{WT}$,	Power generation of WTs,
$P_{s,i,t}^{tidal}$,	tidal units,
$P_{s,t}^{NETM\_H}$,	power transaction to/from multi-EH system to/from networked microgrid,
$P_{s,ij,t}, P_{i,t}^l$	power injection through the lines, and electrical demands of the networked microgrid, respectively.
$P_{i,t}^{Batt}, P_{i,t}^{chg}$,	Power exchange, charging power
$P_{i,t}^{disg}, E_{i,t}^{Batt}$	Discharging power and energy level of the batteries of renewable energy sources, respectively.
$\delta c_{i,t}, \delta d_{i,t}$	Binary variables that define charging and discharging status of the batteries of renewable energy sources, respectively.
$LS_{s,i,t}, PC_s$	Load shedding and the probability of each critical scenario, respectively.
$P_t^C, P_t^{boi}, P_t^{bat}$,	CHP input gas power, boiler input gas power power exchange of the energy storage system
P_t^E, P_t^{Des},	electrical demand of the multi-EH system consumption of desalination unit,
P_t^{Heat}, P_t^{Gas}	the power thermal demand of the multi-EH, and gas demand of the multi-EH, respectively.
V_t^{ST},	Secondary tank water volume
W_t^{OD},	desalination unit output water
W_t^G,	consumed water from the grid
W_t^{Out},	secondary tank output water
V_t^{DT},	desalination unit water volume
W_t^{ID},	desalination unit input water
I_t^D	binary variable, respectively.
Eb_t^{bat}	The Energy level of the battery,
$E_{i,t}^{PV}$	Energy of PV,
$V_{i,t}$	Tidal current speed,
Bat_{glob}	Global solution related to the optimization method,
l_{MV}^{old}	Loudness means value of all bats,
δ, σ	Constant parameters of bat algorithm,
τ	Random value between [−1, 1].

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