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Optimal scheduling of interconnected micro energy grids with multiple fuel options

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ABSTRACT

Micro Energy Grid (MEG) represents a natural step in the evolution to smart grids. In future, distribution system will operate according to interconnected micro energy grids. In MEG, both operational cost and emissions are, mainly, dependent on the types of distributed energy resources (DERs) used. Using DERs with multiple fuel options can reduce the generation costs and increase the reliability in power systems. This paper presents an approach to interconnected MEGs generation scheduling with multiple fuel options. The scheduling approach determines the optimal outputs of DERs on the basis of multi-objective genetic algorithm (GA) optimization compromising between the operational cost and emission of the entire interconnected MEGs system. DERs operate within their respective capacity limits and economically satisfy both electrical and heat demands. The global economic scheduling scheme coordinates power transactions among MEGs and between each MEG and the main electrical grid. Results show that power sharing among MEGs and between each MEG and the main electrical grid can reduce the total operational cost and emissions of the entire interconnected MEGs system.

1. Introduction

Future distribution systems are composed of interconnected MEGs, which can be regarded as relatively small-scale localized energy networks with loads, control systems and sets of energy resources such as generators and energy storage devices [1,2]. MEG is widely recognized as an alternative generating system which can compete with traditional centralized electricity plant [3]. MEG paradigms represent a natural step in the evolution to smart grids as they facilitate the implementation of smart technology for the optimal monitoring and management of a power system [4]. MEG depends mainly on local energy resources with minimum energy transmission from/to remote regions. Hence, energy loss, capital and running cost of a transmission network and the risk of energy supply failure are minimized.

Recently, power utilities increased the penetration level of DERs. This penetration level has been mainly driven by environmental awareness, intention to diversifying the nature of energy resources, improving reliability, power quality, and economics of a system [5]. In an electrical power system, it is always purposed to achieve high operating efficiency to produce cheap electricity [6,7]. Using DERs with multiple fuel options is one of the candidate solutions to reduce the generation costs and to increase the reliability in power systems [6,7]. In such power systems, the minimum generation cost is achieved via selecting the most economic fuel types. Another candidate effective solution is to connect multiple generation areas/MEGs. Each of these areas can be a city, province, or a country in a distinct geographical location with its own regional energy resources such as wind, solar, and natural gas availability. Therefore, the potential benefits of power sharing can be maximized as the balance between generation and load can be achieved through power exchanging among interconnected MEGs in a way that the total cost of power generation in each MEG and the total cost of power exchanging between MEGs and the main electrical grid be optimized. For instance, DERs based on gas engines and micro turbines represent a reliable solution generally for countries that have an access to natural gas [8]. As an example, according to Canadian Association of Petroleum Producers, Canada is the world's fifth-largest producer of natural gas and has enough natural gas reserves to

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meet national energy demand for the upcoming 300 years [9]. Thus, gas-power technologies are drawing the attention of energy planners and policy makers to ensure optimum utilization of natural gas for robust energy supply in Canada.

A single MEG can generate and distribute energy within its localized area. Thus, the intermittent generated power by renewable-based energy resources (i.e., wind and solar) may cause variations in the output power, voltage, and frequency. Additionally, at occurrence of unavailability and/or failure for one or more of the local generators in a single MEG which operates in islanded mode, the single MEG will not be secured enough to meet its load demand due to limited energy generation capability. In such cases, the single MEG will be forced to apply load shedding to ensure supply–demand balance which is inconvenient and economically undesirable as it causes interruption to customers' operation. To overcome these challenges, the interconnection of MEGs can be implemented in neighboring locations to exchange power with each other and to improve the security of supply. Improved reliability, high penetration of renewable energy, and improved generation efficiency can be achieved using interconnected MEGs. Interconnecting MEGs has several benefits such as: (1) better utilization of assets, optimization, and efficient operation; (2) allows for accommodation of all generation and storage options; (3) supply of energy quality as a great need of today's industry; (4) robust operation against attacks and natural disasters; and (5) introduction of new services, products, and markets.

The management of energy flows is a challenge in interconnected MEGs. MEGs in different locations have different distributed energy sources, renewable generations, and local load profiles. Hence, through trading energy with each other, interconnected MEGs can exploit the diversities of supply and demand patterns, and improve their operational performance. For example, a micro energy grid with surplus generated energy can trade with its neighboring MEGs with deficit power supplies for mutual benefits. Therefore, in an interconnected MEGs system, MEGs not only coordinate their local energy resources and demands, but also conduct energy trading with each other and with the main grid. Each MEG aims to optimize its own performance in terms of minimizing its operating cost and/or gas emissions through energy trading.

From a MEG energy management point of view, the economic scheduling of DERs is a crucial task. For getting the optimal benefits from DERs available in MEGs, an appropriate scheduling strategy for power sharing is required. In literature, a great deal of research has been conducted to offer optimal scheduling of DERs in a day-ahead market [1,3,5,10–21]. Ref. [1] proposed a hierarchical framework to realize an economic generation schedule of MEGs. Their work was limited to the total cost objective and did not include the greenhouse gas emissions. Ref. [3] focused on evaluating different optimal output sets of DERs on the basis of multi-objective optimization compromising between fuel cost and emission. Authors in [5] aimed to reduce the fuel consumption rate of DERs in a MEG. However, greenhouse gas emissions and maintenance costs were not included. In [10] an algorithm to find the optimal types, sizes, and placement of DERs in a MEG was proposed. The objective considered was to minimize the capital and operational costs, but they did not consider emissions in their work. An optimization algorithm for optimal dispatching of DERs and storage systems in an islanded MEG was proposed in [11]. The objective was to minimize the overall operating cost and emission.

Ref. [12] proposed an optimal power dispatch formulation using real-time measurements to enhance the performance of online energy scheduling in a microgrid considering renewable energy, grid power trade, and demand response. DERs were optimally scheduled in terms of reduction in fuel and emission costs and voltage deviation. They did not, however, consider heat demand in their work. In Ref. [13], a cost minimization problem was formulated to schedule energy generations for microgrids equipped with renewable sources and combined heat and power (CHP) generators. Their work was limited to the total cost objective and did not include the greenhouse gas emissions. Authors in [14] studied the optimal energy management of microgrids including renewable energy sources, plug-in hybrid electric vehicles, and storage devices using Monte Carlo simulation to determine the optimal economic operation with minimum cost. They did not, however, consider heat demand and emissions in their work.

Ref. [15] proposed an optimal market-based scheduling model for a microgrid participating in the electricity distribution market. Three terms have been included in the objective function: the operation cost, the load curtailment cost, and the deviation cost. The operation cost was the cost of power production, startup, and shut down costs of DER units. The load curtailment cost was defined as the value of lost load times the amount of load curtailment. The deviation cost was the penalty imposed on the microgrid in case the microgrid schedule deviates from the power transfer assigned by the Distribution Market Operator. They did not, however, consider heat demand and emissions in their work. In Ref. [16], a stochastic operation scheduling scheme was proposed to minimize carbon emissions and generation fuel costs while mitigating the impact of the intermittence of renewable energy. They did not, however, consider heat demand in their work.

Authors in [17] detailed an approach for the optimal scheduling of microgrids including datacenters, electric vehicles, and DER units. Several objectives were considered: (1) the first objective related to the minimization of the grid node's voltage deviation from its nominal value; (2) the second objective was aimed at improving the energy efficiency of the grid by minimizing power losses; (3) the third objective was aimed at guaranteeing secure operation of the grid by minimizing the security margin; (4) the fourth objective was aimed at reducing the cost of the energy imported from the upstream grid; and (5) the fifth objective has been hypothesized aimed at leveling the active power at the interconnection bus. A weight was associated to each objective, then, weighted sum method was applied to determine a solution. They did not, however, consider heat demand and emissions in their work. Authors in Ref. [18] proposed an online optimal operation approach for combined cooling, heating, and power microgrids based on model predictive control with feedback correction to compensate for prediction error. The objective considered was to minimize the total cost, but they did not consider emissions in their work.

The work reported in Refs. [1,3,5,10–18] covered only single MEG. The objective of interconnected-MEGs economic dispatch problem with multiple fuel options; is to determine the output powers of DERs to be economically generated for each MEG and transferred power to other MEGs in order to displace their generation and to/from the main electrical grid. In [19] the economic operation of interconnected-MEGs was formulated as an optimization problem. A probabilistic modeling of both DERs and load demand at each MEG was applied to determine the optimal economic operation with minimum cost. They did not, however, consider heat demand and emissions in their work. Authors in [20] proposed a hierarchical outage management scheme to enhance the resilience of a smart distribution system comprised of multiple interconnected microgrids against unexpected disaster events. The microgrids schedule their available DERs in the first stage using a model-predictive-control-based algorithm. Then, in the second stage, Distribution System Operator coordinates the possible power transfers among microgrids and utilizes the unused capacities for feeding the unserved loads in the first stage. The objective considered was to minimize the total cost, but they did not consider heat demand and emissions in their work. In Ref. [21], a comprehensive real-time interactive energy management system framework for the utility and multiple interconnected microgrids was proposed. The introduced distributed economic dispatch strategy can be configured in systems with multiple microgrids interconnection having different owners. The objective considered was to minimize the total cost, but they did not consider heat demand and emissions in their work.

Scheduling problem is aimed at minimizing the operational costs and the environmental impact while the demand is covered. The review of the literature shows that most of the published work has studied a single MEG based on the consideration of the electricity demand only. However, the multiple interconnected MEGs studies with considering both of the electricity and head demands are limited in the literature. Therefore, the goal of the work presented in this paper is to propose an economical generation scheduling of interconnected-MEGs with multiple fuel options in a manner that will include:

- Electrical and heat demands with their hourly variation during the day.
- Economic objective (total operational cost) and environmental objective (CO_2 emissions).
- Different types of DERs units (natural gas turbines (NGTs), natural gas fuel cells (NGFCs), hydrogen gas fuel cells (H_2FCs), biomass, wind, and photovoltaic) which are the most commonly used types.

The remainder of this paper is organized as follows: Section 2 presents the MEG. Section 3 presents the modeling of DER units. The problem formulation is explained in Section 4. Sections 5 and 6 detail the test results, and Section 7 presents the conclusions.

2. Micro energy grid

Different from traditional electric distribution systems, which only supply electrical loads, both electrical and heat loads may exist in MEGs due to the implementation of combined heat and power (CHP) units. CHP units generate electricity and heat simultaneously.

MEG can provide reliable and qualified power and heat to its customers at an economical cost. MEG can operate in a grid-connected mode where energy resources interact with the main electrical grid, or in an islanding mode where the MEG feeds its local loads without the use of the main electrical grid. MEG provides means to integrate generation, storage, and loads. Furthermore, MEG is used to integrate electricity, gas, and thermal grids [22–24]. Advantages of MEGs include:

- *High penetration of renewable energy sources*: MEGs facilitate a successful integration of massive amounts of DERs and renewable energy sources. Furthermore, to better adopt their intermittent and weather-dependent nature, energy storage devices such as batteries, heat buffers, and plug-in electric vehicles (PEVs) can be integrated in MEGs.
- *Energy loss reduction*: due to the proximity between local generators and loads, MEGs can significantly reduce the energy losses in electrical and heat transmission/distribution lines.
- *Reliability improvement*: as MEGs can operate in islanded mode if there is a fault in the main electrical grid, the negative impact of outages in the upstream electric power network can be reduced, hence, system reliability can be improved.
- *Enhancement of energy management*: as the local generators and loads are managed in a coordinated way, the electric and heat power can be better shared among the local customers.
- *Benefits to the main electrical grid*: by efficient energy management of MEGs, the imported energy from the main electrical grid can be reduced, which relieves power distribution/transmission line congestions. Furthermore, MEGs can provide ancillary services such as frequency regulation, participating on the day-ahead and balancing market, providing system support during low operational security, and improving voltage quality.

This paper presents an economic generation scheduling algorithm for interconnected-MEGs in order to determine the optimal output powers of DERs to be generated for each MEG and transferred power among MEGs and between each MEG and the main electrical grid. The performance of MEGs is evaluated from the economical (total operational cost) and environmental (carbon dioxide emission) viewpoints. Fig. 1 shows the energy flow schematic of an interconnected-MEGs system. The load of each MEG is heat and electricity, where heat load can be used for space heating, cooking, bathing, showers, washing, and laundry purposes, etc. [2]. Natural gas turbines, natural gas fuel cells, hydrogen gas fuel cells, and biomass generators are all CHP generators. The electrical load is mainly met by DERs while surplus/deficient electricity can be sold to/ purchased from other MEGs and/or the main electrical grid. The heat load is met by CHP generators together with a natural gas-fired boiler.

3. Modeling of DER units

In this paper, the considered types of DERs are natural gas turbines (NGTs), natural gas fuel cells (NGFCs), hydrogen gas fuel cells (H_2FCs), biomass, wind, and solar generators. Other DER types can be included and modeled with similar approaches. DER models describe gas fuel consumption, CO_2 emission, and total operational cost.

3.1. Natural gas turbines (NGTs)

Natural gas is one of the leading fuel options for DERs due to [25]: (1) extensive natural gas supply infrastructure, short construction times, and low initial investment costs which makes it attractive in a deregulated market; and (2) environmental benefits as burning natural gas emits less harmful emissions compared to other fossil fuels such as coal and oil. This type of DERs is typically favored for meeting peak loads, as the turbines can quickly achieve full generation capability.

A generalized DER model can be represented by the following equations:

$$f_{fue,i}(t) = \frac{P_i(t)}{\eta_{i,P}} \quad \forall t \in T,\ P_i(t) \leq P_{r,i},\ i \in G \tag{1}$$

$$H_i(t) = P_i(t)\frac{\eta_{i,H}}{\eta_{i,P}} \quad \forall t \in T,\ i \in G \tag{2}$$

$$E_i(t) = K_i\ P_i(t) \quad \forall t \in T,\ i \in G \tag{3}$$

where, G is the set of DERs; $f_{fue,i}$ is the consumed fuel by DER i at hour t; P_i is output power from DER i at hour t; T is set of hourly periods in the next day; $\eta_{i,P}$ power efficiency of DER i; $P_{r,i}$ rated power for DER i; H_i is the generated heat power from DER i at hour t; $\eta_{i,H}$ heat efficiency of DER i; E_i is the CO_2 emissions from DER i at hour t; and K_i is the carbon footprint for the energy produced by DER i in kg CO_2/kWhr.

3.2. Natural gas fuel cells (NGFCs)

A fuel cell converts the energy present in a fuel to electricity using an electro-chemical process. So, it extracts electricity from a fuel without going through a combustion process. Fuel cell requires

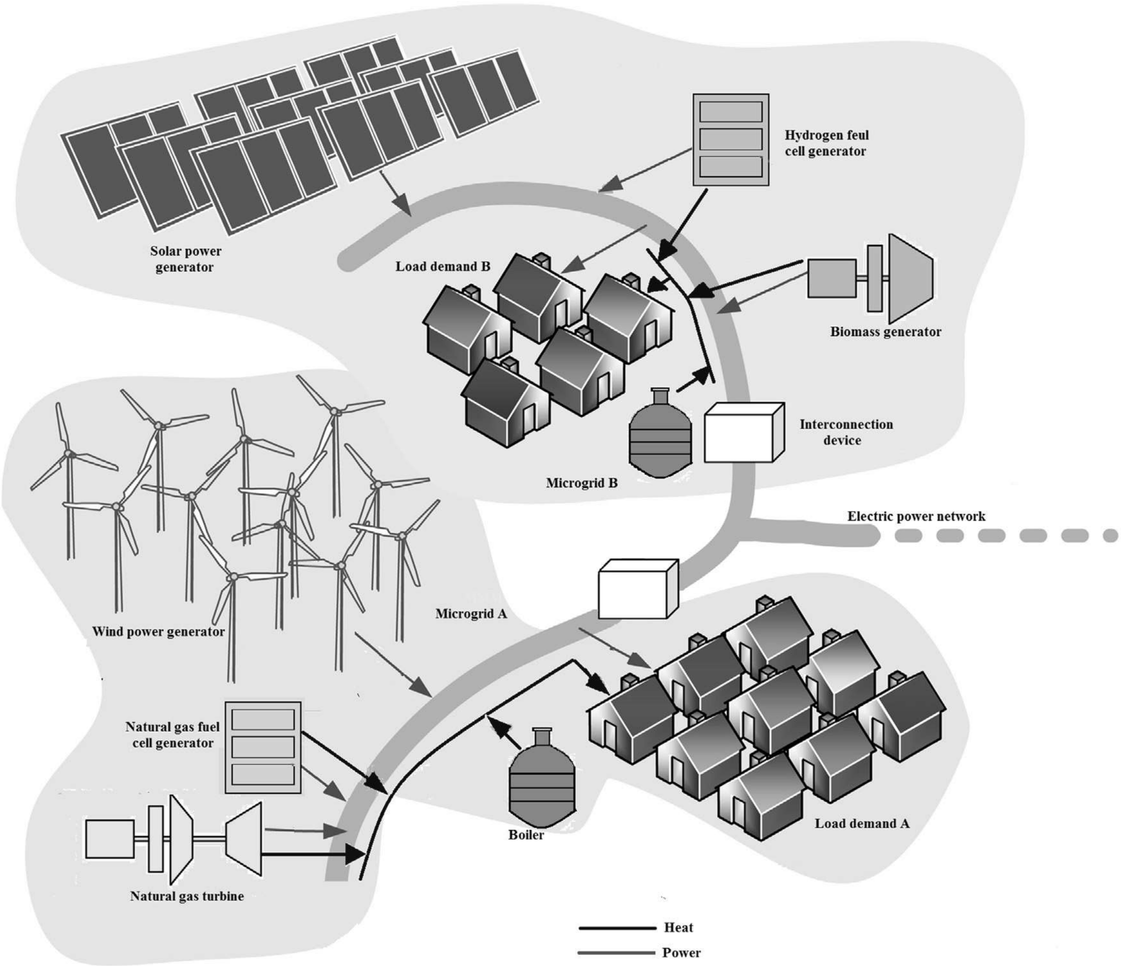

Fig. 1. Energy flow schematic of interconnected-MEGs system.

hydrogen as a fuel source. However, hydrogen can be produced from a readily available fuel source such as natural gas. Similar to NGTs, NGFC can be represented by Eqs. (1)–(3) using its own parameters (i.e., $i = NGFC$).

3.3. Hydrogen fuel cells (H_2FCs)

At presence of hydrogen fuel infrastructure, hydrogen gas fuel can be supplied to fuel cells. This results in a clean operation without CO_2 pollutants ($E_{H_2FC} = 0$ in Eq. (3)).

3.4. Biomass generators

Biomass has proven to be economically stable source of energy. Biomass fuels can be derived from wood, agricultural crops and other organic residues. Biomass energy is neutral in terms of carbon dioxide (CO_2) emissions as burning biomass fuels merely releases the CO_2 that plants absorbed over their life spans. Using biomass energy displaces fossil fuels and helps to slow the rate of climate changes. Typical applications for biomass energy are wood processing industries, district heating systems, and industries with a high process heat cooling demand [26].

3.5. Renewable energy sources

Renewable energy sources such as wind power and photovoltaic (PV) become a dominant choice in power systems because they are inexhaustible and nonpolluting. The integration of

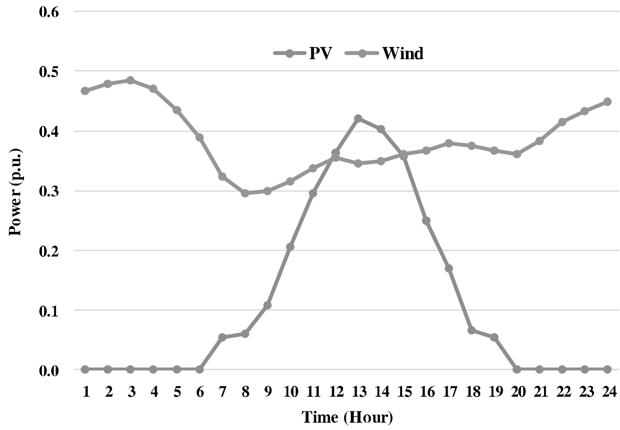

Fig. 2. Typical renewable power forecast.

renewable energy sources can increase reliability, reduce greenhouse gas emissions, and reduce energy losses for power systems [27,28]. Renewable energy sources are characterized as fluctuating power sources due to changes in wind speed and solar irradiance. The corresponding output power of wind and PV generators at each hour are calculated using forecasted wind speed/solar irradiance at the site and turbine power performance curve/PV module characteristics respectively [27]. Three years of historical wind speed and solar irradiance data are utilized for modeling the output power of the wind and PV DER units. Fig. 2 shows the wind and PV power forecast for a typical weekday in winter. For wind and PV generators, there are no fuel costs, and their operating and maintaining costs are considered in the model.

4. Interconnected-MEGs scheduling optimization

The interconnected-MEGs scheduling optimization problem is similar to the economic dispatch (ED) with traditional generation units. The purpose of the problem is to minimize the total operational cost and emissions considering equality and inequality constraints. This section explains the proposed problem formulation, where the following assumptions are considered:

- Renewable generators (wind and PV) are assumed to operate at unity power factor and their available power is directly injected into the network.
- No heat transfer is allowed between MEGs.

4.1. Objective (fitness) function

$$Minimize\ (OF_1, OF_2) \tag{4}$$

$$OF_1 = \sum_{t\in T}(C_{ope}(X_t) + C_{pur}(X_t) + C_{losses}(X_t)) \tag{5}$$

$$OF_2 = \sum_{t\in T}(E_{grid}(X_t) + E_{DER}(X_t) + E_{bo}(X_t)) \tag{6}$$

$$C_{ope}(X_t) = \sum_{i\in G}(C_{gas,i}\, f_{fue,i}(t) + C_{m,i}\, P_i(t) + C_{su,i}\, SU_i(t)) \quad \forall t \in T \tag{7}$$

$$C_{pur}(X_t) = \sum_{j\in n_{MG}}(C_{buy}(t)\ P_{buy,j}(t) - C_{sell}(t)\ P_{sell,j}(t) + H_{bo,j}(t)\ (C_{heat} + C_{m,bo})) \quad \forall t \in T \tag{8}$$

$$C_{losses}(X_t) = \sum_{j\in n_{MG}} C_{buy}(t)\, P_{losses,j}(t) \quad \forall t \in T \tag{9}$$

$$E_{grid}(t) = K_{grid}\, P_{grid+}(t) \quad \forall t \in T \tag{10}$$

$$E_{DER}(t) = \sum_{i\in G} E_i(t) \quad \forall t \in T \tag{11}$$

$$E_{bo}(t) = \sum_{j\in n_{MG}} K_{bo}\, H_{bo,j}(t) \quad \forall t \in T \tag{12}$$

where, $OF_1(cost)$ and $OF_2(emission)$ are the objectives required to be minimized; X_t is the decision variable vector at hour t; C_{ope} is the operational cost; C_{pur} is the energy purchase cost; C_{losses} is the energy losses cost; E_{grid} is the CO_2 emissions from the main grid; E_{DER} is the total CO_2 emissions from all DERs in the interconnected-MEGs system; E_{bo} is the CO_2 emissions from all boilers in the interconnected-MEGs system; $C_{gas,i}$ gas price required for DER i; $C_{m,i}$ maintenance cost of DER i; $C_{su,i}$ start-up cost of DER i; SU_i start-up status of DER i at hour t; n_{MG} total number of MEGs in the system; C_{buy}/C_{sell} buying/selling price of electricity at hour t; P_{grid+}/P_{grid-} power bought/sold from/to the main grid at hour t; $P_{buy,j}/P_{sell,j}$ power bought/sold by MEG j at hour t; C_{heat} heat price; $H_{bo,j}$ heat supplied by the boiler of MEG j at hour t; $C_{m,bo}$ maintenance cost of boilers; $P_{losses,j}$ is the energy losses of MEG j at hour t; K_{grid} is the carbon footprint for the energy purchased from the grid in kg CO_2/kWhr; and K_{bo} is the emission from the boiler in kg CO_2/kWhr.

4.2. Constraints

4.2.1. Power and heat balance constraints

$$\sum_{i\in G} P_i(t) + \sum_{j\in n_{MG}}(P_{buy,j}(t) - P_{sell,j}(t)) = \sum_{j\in n_{MG}}(P_{ld,j}(t) + P_{losses,j}(t)) \quad \forall t \in T \tag{13}$$

$$0 \le P_{grid+}(t),\ P_{grid-}(t) \le P_{grid,\max} \quad \forall t \in T \tag{14}$$

$$P_{i,\min} \le P_i(t) \le P_{i,\max} \quad \forall i \in G,\ t \in T \tag{15}$$

$$Q_{i,\min} \le Q_i(t) \le Q_{i,\max} \quad \forall i \in G,\ t \in T \tag{16}$$

$$\sum_{i\in G_j} H_i(t) + H_{bo,j}(t) \ge H_{ld,j} \quad \forall t \in T,\ j \in n_{MG} \tag{17}$$

where, $P_{ld,j}$ and $H_{ld,j}$ power and heat demand of MEG j at hour t; $P_{grid,\max}$ upper capacity of the main grid; $P_{i,\min}$ and $P_{i,\max}$ are lower and upper active power generation of DER i respectively; Q_i output reactive power from DER i at hour t; $Q_{i,\min}$ and $Q_{i,\max}$ are lower and upper reactive power generation of DER i respectively; G_j DERs of MEG j.

4.2.2. Voltage limits constraints

$$V_{\min} \le V_k(t) \le V_{\max} \quad \forall k \in N_{bus},\ t \in T \tag{18}$$

where, V_k voltage magnitude in p.u at bus k and hour t; N_{bus} total number of buses for the interconnected-MEGs system; $V_{\min}$ and $V_{\max}$ are the minimum and maximum voltage limits respectively (i.e., 0.9 and 1.05 p.u.).

4.2.3. Current limits constraints

$$I_{l,\min} \le I_l(t) \le I_{l,\max} \quad \forall l \in N_l,\ t \in T \tag{19}$$

where, I_l current magnitude flowing in line l during hour t; N_l total number of lines for the interconnected-MEGs system; $I_{l,\min}$ and $I_{l,\max}$ are the minimum and maximum current limits for line l.

4.3. Implementation of the genetic algorithm (GA)

In this paper, a GA has been applied in order to solve the generation scheduling problem based on the proposed formulation. GA is a search and optimization technique based on the mechanism of natural selection and natural genetics. It has been successfully applied to a wide range of real-world problems of significant complexity. GA operates on a population of chromosomes (i.e., strings or individuals). Each chromosome represents a possible solution to a problem and has a fitness value which is a measure of how good a solution it is to the particular problem. Starting with a randomly generated population of chromosomes, GA carries out a process of fitness based selection and recombination to produce a successor population (next generation). During recombination, parent chromosomes are selected and their genetic material is recombined to produce child chromosomes. As this process is iterated, a sequence of successive generations converges to the fitter solutions until some stopping criterion is reached. In this way, GA evolves a best solution to a given problem. As shown in Fig. 3, the algorithm includes the following steps [29]:

Step 1: Read the following information that has been input to the algorithm: MEG power and heat demands, parameters for calculating the operational cost and emission (i.e., fuel cost, DERs efficiencies, electricity and heat prices, etc.), population size, chromosome length, and maximum number of iterations (MI).

Step 2: Generate an initial population (Pop_0). As shown in Eq. (20), the chromosome length equals the total number of decision variables (optimal active and reactive output powers for each DER unit).

$$X_t = [P_1(t)\ P_2(t)\ \dots\ P_G(t)\ Q_1(t)\ Q_2(t)\ \dots\ Q_G(t)] \quad \forall t \in T. \tag{20}$$

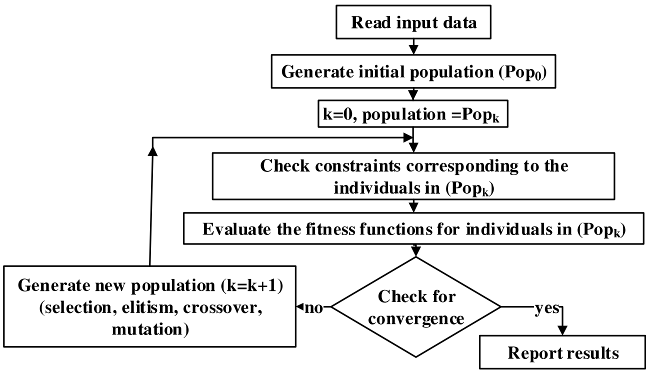

Fig. 3. Flow chart for GA-based generation scheduling algorithm.

Step 3: Check the constraints that correspond to the individuals in (Pop_0). Infeasible solutions are then removed from the solution space through the assignment of a large penalty cost.

Step 4: Evaluate the fitness functions for individuals in (Pop_0) using Eqs. (5) and (6). The population is then denoted by iteration number k (i.e., population = Pop_k).

Step 5: Generate a new population (Pop_{k+1}) through the application of the following operators to (Pop_k):

- Selection: GA uses fitness function values as a discriminator of the quality of solutions represented by different chromosomes in a population. The selection is designed to use these fitness values to guide the evolution of chromosomes by selective pressure. Chromosomes with higher (better) fitness should have a greater chance of selection than those with lower fitness (i.e., selective pressure towards more highly fit solutions). Selection is usually with replacement as highly fit chromosomes have a chance of being selected more than once or recombined with themselves. For example, Roulette Wheel (or fitness proportional) selection method allocates each chromosome a probability of being selected proportional to its relative fitness, which is its fitness as a proportion of the sum of fitnesses of all chromosomes in the population.
- Elitism: GA uses elitism to guarantee the presence of the best individuals of the current generation in the new one. Elitism involves copying a small proportion of the fittest candidates, unchanged, into the next generation. Thus, it has positive impact on performance by ensuring that GA does not waste time re-discovering previously discarded partial solutions. Candidate solutions that are preserved unchanged through elitism remain eligible for selection as parents when breeding the remainder of the next generation.
- Crossover: GA uses crossover for combining parts of two parents to produce children that contain some parts from both parents. Thus, the crossover operator represents the mixing of genetic material from two selected parent chromosomes to produce one or two child chromosomes. One commonly used crossover operator is one-point crossover. Then, child chromosomes are constructed from the characters of the first parent occurring before the crossover point and the characters of the second parent occurring after the crossover point. For two and multi-point crossover operations, a sequence of crossover points is chosen along the chromosome length and the child chromosomes are constructed from the allele values of the two parents, interchanging at each crossover point.
- Mutation: which applies random changes to a single chromosome to create a child. Mutation operators act on an individual chromosome to flip one or more allele values.

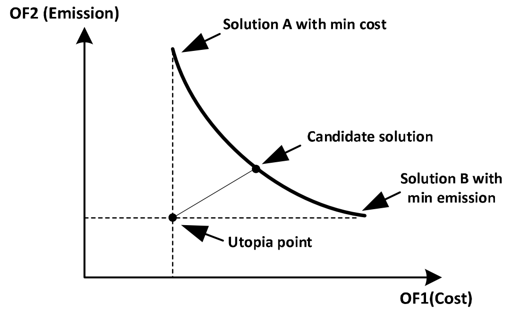

Fig. 4. Pareto-front for a bi-objective problem.

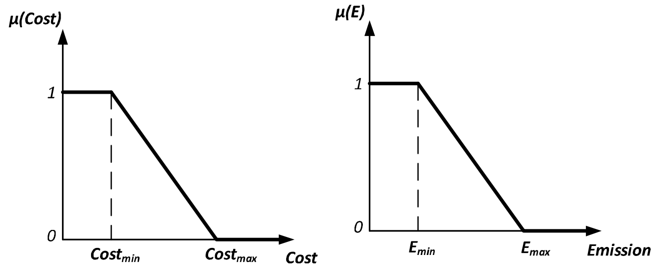

Fig. 5. Membership functions.

Step 6: Check the constraints of the distribution networks that correspond to the individuals in (Pop_{k+1}).

Step 7: Evaluate the fitness functions for the individuals in (Pop_{k+1}).

Step 8: Check for the termination condition. If the optimal pattern remains unchanged after a preset number of iterations or MI has been reached, go to step 9; otherwise go to step 5.

Step 9: Report the results.

4.4. Solution of the bi-objective scheduling problem

In this case both of the cost and emission objectives are considered to obtain a single suitable/compromised solution. The two objectives are contradicted as the optimal solutions of individual objectives are not the same. Thus, the problem is to balance between the two objectives for getting the best possible compromise. A weighted sum method can be applied to convert the bi-objective aspect of a problem to a single objective with a single evaluated value by using weighting factors. However, these weights are highly dependent on the system (i.e., weights depend on the importance of different objectives and on the scaling of objectives due to their differing values).

In this work and as shown in Fig. 4, the compromised solution has been determined using a common method which is based on minimizing the distance between the candidate compromised solutions and an ideal solution called the utopia point [30]. The utopia point may be infeasible as it minimizes the two objectives simultaneously. The optimal solutions of individual objectives (i.e., OF_1 (cost) only and OF_2 (emission) only) are used to set the lower and upper bounds of the objectives. For example, the optimal solution of OF_1 sets the lower bound on the cost ($Cost_{\min}$) and the upper bound on emission ($E_{\max}$). On the other side, the optimal solution of OF_2 sets the upper bound on the cost ($Cost_{\max}$) and the lower bound on the emission ($E_{\min}$). Then, these lower and upper bounds can be used to characterize membership functions of the two objectives under consideration. As shown in Fig. 5, each membership function of an objective has a value ranging from 0 to 1 (i.e., 1 represents full desirability and 0 represents full undesirability). The membership functions of the OF_1 (cost) and

Table 1
Characteristics of DER units.

MG number	1 (33-bus MEG)				2 (69-bus MEG)			
DER type	CHP units			WT	CHP units			PV
	NGT1	NGT2	NGFC		Biomass1	Biomass2	H_2FC	
Size of DER in MW	2	1	1	0.5	2	1.5	0.5	0.5

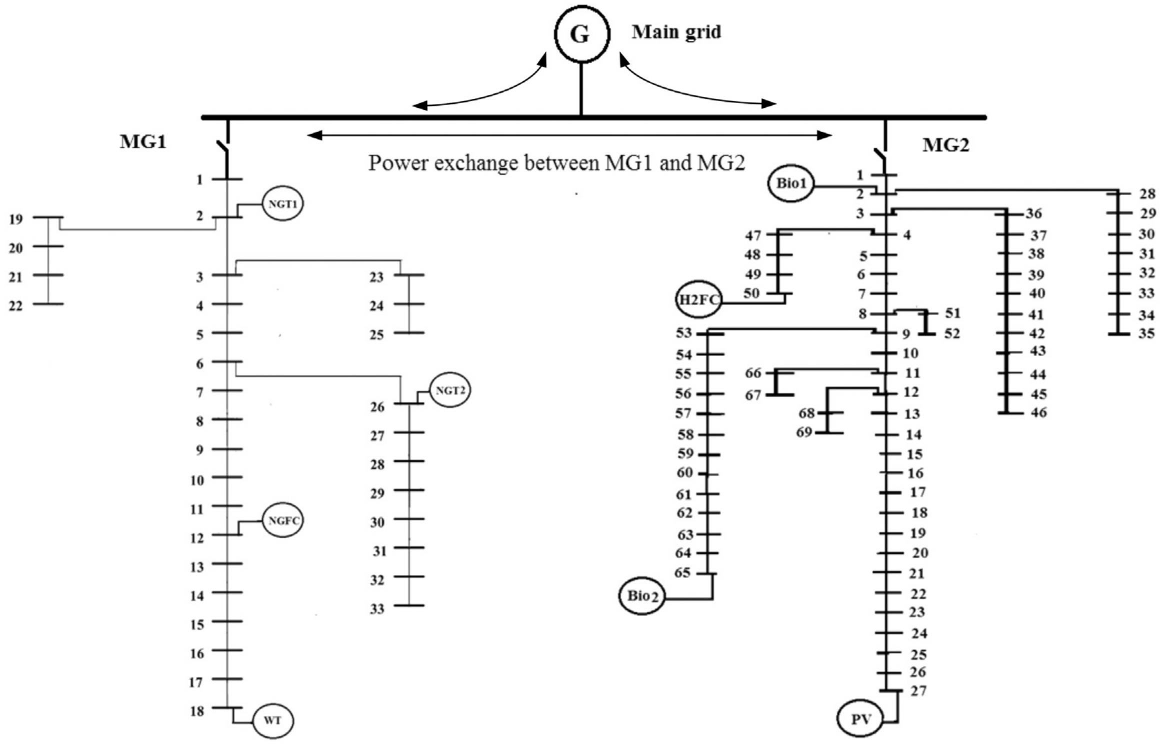

Fig. 6. Structure of a system with two interconnected MEGs.

OF_2 (emission) can be given as:

$$\mu(Cost) = \begin{cases} 1 & \forall Cost \leq Cost_{\min} \\ \dfrac{Cost_{\max} - Cost}{Cost_{\max} - Cost_{\min}} & \forall Cost_{\min} < Cost < Cost_{\max} \\ 0 & \forall Cost \geq Cost_{\max} \end{cases} \quad (21)$$

$$\mu(E) = \begin{cases} 1 & \forall E \leq E_{\min} \\ \dfrac{E_{\max} - E}{E_{\max} - E_{\min}} & \forall E_{\min} < E < E_{\max} \\ 0 & \forall E \geq E_{\max}. \end{cases} \quad (22)$$

Finally, the scheduling problem can be solved by minimizing the distance of the candidate solution to the ideal utopia point ($Cost_{\min}, E_{\min}$). The Euclidean distance of the candidate solution (Cost, Emission) to the utopia point can be given as:

$$\|S\| = \sqrt{(1 - \mu(Cost))^2 + (1 - \mu(E))^2}. \quad (23)$$

5. Case study

The proposed method has been applied to a 33-bus and 69-bus MEGs as shown in Fig. 6. Line data and typical bus data of the 33-bus MEG (MG1) are given in [31], and its total peak load is 4.37 MVA. Line data and typical bus data of the 69-bus MEG (MG2) are given in [31], and its total peak load is 4.66 MVA. The system voltage level is 12.66 kV for the 33-bus and for the 69-bus MEGs.

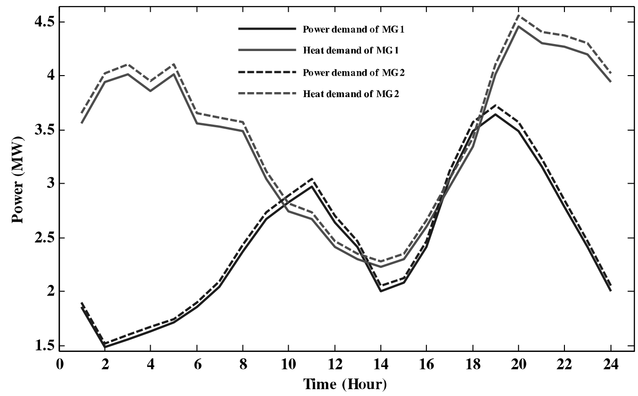

Fig. 7. Load demand for MEG1 and MEG2.

Fig. 7 shows power and heat demands for a typical weekday in winter of each MEG [1]. To consider the effect of power generation cost in each MEG and as shown in Table 1, it is assumed that the characteristics of DERs such as size and type are different.

Five different cases are presented in this work which are:

Case 1: Electrical and heat demands are completely supplied by the main grid and the boilers, respectively (no DERs included).

Case 2: All CHP units operate at full power and unity power factor throughout the whole day.

Case 3: Interconnected-MEGs generation scheduling for minimum cost (OF_1 only is included as shown in Eq. (5)).

Table 2
Parameters for calculating corresponding costs and environmental attributes of the interconnected-MEG system.

Parameter	Value	Parameter	Value
$\eta_{NGT,P}$	37% [33]	$\eta_{NGT,H}$	48% [33]
$\eta_{NGFC,P}$	33.9% [34]	$\eta_{NGFC,H}$	46% [34]
$\eta_{H_2FC,P}$	40%	$\eta_{H_2FC,H}$	50%
$\eta_{biomass,P}$	28.5% [26]	$\eta_{biomass,H}$	64.2% [26]
K_{grid}	143 $kgCO_2/MWh$ [35]	K_{NGT}	201.6 $kgCO_2/MWh$ [36]
K_{boiler}	201.6 $kgCO_2/MWh$ [36]	K_{NGFC}	366.1 $kgCO_2/MWh$ [37]
$K_{biomass}$	3 $kgCO_2/MWh$ [38]	C_{NG}	20.5 \$/MWh [1]
C_{heat}	25.6 \$/MWh [1]	$C_{biomass}$	63 \$/MWh [38]
C_{H_2FC}	60.01 \$/MWh [39]	$C_{m,NGT}$	0.003 \$/kWh [33]
C_{m,H_2FC}	0.034 \$/kWh [33]	$C_{m,NGFC}$	0.034 \$/kWh [33]
$C_{m,boiler}$	0.003 \$/kWh [33]	$C_{m,biomass}$	0.012 \$/kWh [38]
$C_{m,WT}$	0.01 \$/kWh [1]	$C_{m,PV}$	0.01 \$/kWh [1]
$C_{SU,NGT}$	0.47 \$ [1]	$C_{SU,biomass}$	0.47 \$ [1]
$C_{SU,NGFC}$	0.15 \$ [1]	C_{SU,H_2FC}	0.15 \$ [1]
Time of use	Off-peak1 (00–08)	Peak (08–20)	Off-peak2 (20–24)
C_{buy} (\$/kWh)	0.08 [1]	0.16 [1]	0.12 [1]
C_{sell} (\$/kWh)	0.04 [1]	0.08 [1]	0.06 [1]

Table 3
Results of the studied cases.

Case	Total cost (\$)	Total CO_2 emissions (kg)	MEG1					MEG2					Vmin (p.u)	Vmax (p.u)
			DERs generated energy		Boiler heat (MWh)	Electricity trade[a] (MWh)		DERs generated energy		Boiler heat (MWh)	Electricity trade (MWh)			
			Electricity (MWh)	Heat (MWh)		From or to MG2	From or to main grid	Electricity (MWh)	Heat (MWh)		From or to MG1	From or to main grid		
1	21 771.68	50 972.79	0	0	81.81	0	60.74	0	0	83.73	0	62.34	0.9112	1.0000
2	24 237.70	23 553.60	100.62	125.97	0	0	−40.59	97.41	204.22	0	0	−35.87	0.9534	1.0339
3	13 969.71	31 973.56	77.68	94.90	0.29	−17.71	−0.75	17.96	31.07	52.67	17.71	25.53	0.9251	1.0055
4	17 782.3	13 733.07	66.52	80.32	1.50	0.001	5.09 −12.20	62.22	125.33	0	−0.001	−1.428	0.9443	1.0298
5	15 396.61	20 358.17	71.66	87.02	1.08	−8.74	0.96 −4.61	39.65	78.12	16.08	8.74	12.19	0.9506	1.0055

[a] Positive values for purchased and negative values for sold electricity.

Case 4: Interconnected-MEGs generation scheduling for minimum emissions (OF_2 only is included as shown in Eq. (6)).

Case 5: Interconnected-MEGs generation scheduling for compromised solution between cost and emission.

Table 2 presents the parameters used for calculating various costs and emissions in the simulation study. As the proposed method is generic; the number of MEGs, profile of heat and electricity demands, and values of different parameters can be easily adjusted according to the MEGs under study and the local distribution company. The following factors were taken into consideration:

- The GA parameters applied were population size: 50; crossover rate: 0.8; mutation rate: 0.05; MI: 150; selection type: roulette wheel; and crossover type: two points.
- A distribution system power flow program based on the backward/forward sweep method was used in order to obtain the simulation results [32] (i.e., to check voltage and current constraints limits and to calculate power losses).

6. Results and discussions

The outcomes of the scheduling problem for a 24 h period are shown in Table 3.

6.1. Case 1: base case results

In this case, the electrical and heat loads are completely supplied by the main grid and the boilers, respectively. The total daily operational cost of the interconnected-MEGs system is \$21,771.68. Furthermore the total amount of CO_2 emissions is 50,972.79 kg. These results are totally system dependent and significant differences can occur for other systems. As shown in Table 3, case 1 provides the highest CO_2 emissions compared to other cases. As shown in Table 3, in case 1 the electricity and heat generations are balanced with electricity and heat demands. This is because each MEG purchases electricity and heat from the main grid and boiler according to its electrical and heat load.

6.2. Results of case 2

In this case, all CHP units operate at full power and unity power factor throughout the whole day. The total daily operational cost of the interconnected-MEGs system is \$24,237.70. Furthermore the total amount of CO_2 emissions is 23,553.60 kg. By comparing these results with the base case, the total daily operational cost is increased by 11.33%, and the total CO_2 emissions decreased by 53.79%. From these results it is obvious that CHP units have a significant effect in reducing the CO_2 emissions compared to the natural gas fired boiler. As shown in Table 3, in case 2 the electricity and heat generations are higher than electricity and heat demands. This is because all CHP units operate at their full capacity during the whole day.

6.3. Results of case 3

As shown in Table 3, case 3 represents the minimum cost solution, the system cost is reduced by 35.84%; on the other hand,

Table 4
Results of the studied cases (scenario of same utility/owner of all MEGs).

Case	Total cost ($)	Total CO_2 emissions (kg)	MG1					MG2					Vmin (p.u)	Vmax (p.u)
			DERs generated energy		Boiler heat (MWh)	Electricity trade[a] (MWh)		DERs generated energy		Boiler heat (MWh)	Electricity trade (MWh)			
			Electricity (MWh)	Heat (MWh)		From or to MG2	From or to main grid	Electricity (MWh)	Heat (MWh)		From or to MG1	From or to main grid		
3	12 302.73	34 021.88	92.37	114.81	0.14	−32.69	−0.40	14.89	25.95	57.79	32.69	13.71	0.9239	1.0266
4	17 919.97	13 104.29	66.21	79.91	1.90	4.84	0.74	64.96	133.14	0	1.96	−1.25	0.9468	1.0194
						−1.96	−10.24				−4.84			
5	14 288.36	20 395.03	78.10	95.48	0.33	−15.13	−3.71	36.67	73.40	18.46	15.13	8.82	0.9495	1.0128

[a] Positive values for purchased and negative values for sold electricity.

the system emissions are reduced by 37.27%. The cost of generated power by each DER at each MEG is different. Based on the DER types and the parameters given in Table 2, the cost of generated power in MG1 is lower than MG2. As a result and as shown in Table 3, MG1 generates higher amount of electricity compared to MG2. Also, MG1 covers its local load and sells large amount of electricity to MG2 (17.71 MWh) and to the grid (0.75 MWh) over the day to maximize its revenue. This is because MG1 has two NGT units and natural gas turbines are superior to other types (NGFCs, H_2FCs, Biomass) in reducing the cost as they are cheaper in terms of their operation and maintenance costs.

6.4. Results of case 4

As shown in Table 3, case 4 represents the minimum emission solution with a 73.06% reduction in emissions, while the system cost is reduced by 18.32%. The carbon footprint for energy generated by each DER at each MEG is different. Based on the DER types and the parameters given in Table 2, the CO_2 emissions for generated power in MG2 is lower than MG1. As a result and as shown in Table 3, MG2 generates high amount of electricity. Also, MG2 covers its local load and sells large amount of electricity to the grid (1.428 MWh) and to MG1 (0.001 MWh) over the day to minimize the total CO_2 emissions for the entire system. This is because MG2 has two biomass units, one H_2FC unit, and one PV unit which are superior to other types (NGTs and NGFCs) in reducing the CO_2 emissions as they are clean and have environmental friendly nature.

6.5. Results of case 5

For utilities who interested in reducing both cost and emissions; case 5 provides the compromised solution. The system cost is reduced by 29.28%; on the other hand, the system emissions are reduced by 60.06%. As shown in Table 3, the head demand is mainly supplied by the DER units with a minor participation from the natural gas-fired boilers. The scheduling results for the compromised solution are provided in Figs. 8 and 9.

6.6. Results of case 3, case 4, and case 5 (scenario of same utility/owner of all MEGs)

In this part, the results of cases 3, 4, and 5 are repeated without considering the selling/buying prices for power transactions among MEGs (i.e., only cost of DERs fuel, maintenance and startup, cost of boilers heat, and cost of electricity trade with the main grid are considered). This can be considered as a typical scenario for interconnected-MEGs which owned/operated by the same local distribution company (LDC). Therefore, the main goal from LDC point of view is to find the optimal DERs scheduling in order to maximize its benefits and minimize CO_2 emissions. The details of the scheduling problem for a 24 h period are shown in Table 4.

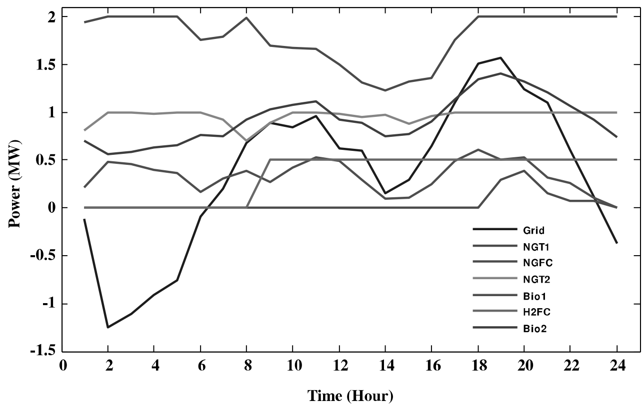

Fig. 8. Planned power generation of DERs and exchanged power with the main grid for case 5.

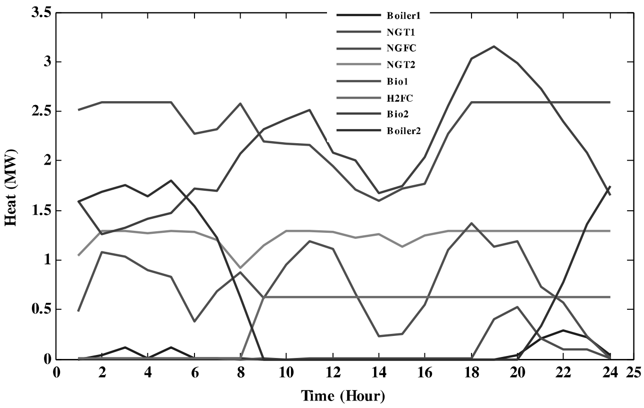

Fig. 9. Planned heat generation of DERs and boilers for case 5.

As shown in Table 4, power transactions between MG1 and MG2 have been increased in all cases 3, 4, and 5. The flow of power from a MEG to the other one depends on the objective to be considered. For example, in case 3 (Table 4) the power transaction from MG1 to MG2 is increased to be 32.69 MWh compared to 17.71 MWh for the same case in Table 3. As a result, significant improvements have been gotten compared to the similar cases in Table 3. For example, the cost in case 3 (Table 4) has decreased by 11.93% compared by case 3 (Table 3). Similarly, the CO_2 emissions in case 4 (Table 4) has decreased by 4.58% compared by case 4 (Table 3). Finally, the cost in case 5 (Table 4) has decreased by 7.20% compared by case 5 (Table 3) and the emissions have minor change.

7. Conclusion

In this paper, an optimization algorithm is proposed to schedule interconnected-MEGs system in an optimal manner. A two-objective problem is developed to determine the optimal DERs output during each hour of a day to minimize the operational cost and the CO_2 gas emissions. Simulation results show that the proposed method is effective to offer an optimal generation scheduling plan of DERs with multiple fuel options. Through the presented analysis, it has been shown that MEGs can support operations as local and community resources. Furthermore, the proposed method is efficient to operate the interconnected-MEGs system from the perspectives of economy and environment. The results illustrate the trade-off relationship between the carbon emission and the total operational cost. Cheap and/or clean DERs are always arranged in priority. The results showed that natural gas turbines are superior to fuel cells and biomass generators in reducing the cost objective. Also, hydrogen based fuel cells and biomass generators are superior to natural gas turbines and natural gas based fuel cells in reducing the gas emissions. The economic analysis indicates that the presence of DERs can lead to savings of the total operational cost, reduction in emissions, and enhance the voltage profile. Furthermore, the power sharing among multi-area and multi-fuel sources with the main electrical grid can amplify the benefits. The benefits of the proposed interconnected-MEGs scheduling algorithm can be summarized as follows: (1) it allows operating the interconnected-MEGs system in a cost effective, secure, and high quality manner; (2) the procedure is effective in the presence of a number of DER units which can cooperate to achieve optimal operation; and (3) the multi-objective approach seems the most suitable to handle complexity in modern power grids as it avoids unfavorable grid operation.

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