Energy 118 (2017) 827–839

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy management in microgrid based on the multi objective stochastic programming incorporating portable renewable energy resource as demand response option

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ARTICLE INFO

Article history:
Received 30 April 2016
Received in revised form
30 August 2016
Accepted 26 October 2016
Available online 2 November 2016

Keywords:
Augmented Epsilon-constraint method
Microgrid
Multi objective programming
Portable renewable energy resource
Stochastic programming

ABSTRACT

Renewable energy resources are often known as cost-effective and lucrative resources and have been widely developed due to environmental-economic issues. Renewable energy utilization even in small scale (e.g., microgrid networks) has attracted significant attention. Energy management in microgrid can be carried out based on the generating side management or demand side management. In this paper, portable renewable energy resource are modeled and included in microgrid energy management as a demand response option. Utilizing such resources could supply the load when microgrid cannot serve the demand. This paper addresses energy management and scheduling in microgrid including thermal and electrical loads, renewable energy sources (solar and wind), CHP, conventional energy sources (boiler and micro turbine), energy storage systems (thermal and electrical ones), and portable renewable energy resource (PRER). Operational cost of microgrid and air pollution are considered as objective functions. Uncertainties related to the parameters are incorporated to make a stochastic programming. The proposed problem is expressed as a constrained, multi-objective, linear, and mixed-integer programing. Augmented Epsilon-constraint method is used to solve the problem. Final results and calculations are achieved using GAMS24.1.3/CPLEX12.5.1. Simulation results demonstrate the viability and effectiveness of the proposed method in microgrid energy management.

1. Introduction

Energy management of microgrid is one of most important aspects in microgrid operation. This management can be generally classified into two categories: first, generation side management and second, demand side management. Most of the previous studies have worked on generation side management and some others have studies the demand side management [1,2]. Demand side management programs are offered to modify consumer demand for energy. In such programs, rather than increasing electricity generation to meet the demand, demand side management programs motivate consumers to decrease their consumption of energy [3]. Demand response programs are the other similar programs that are designed to modify consumer demand for power. Demand response programs encourage consumers to make temporary (short-term) reductions in their energy demand in response to a signal from the network operator. Normally, demand response schedules are in the range of 1–4 h. Demand response programs designed in electrical networks can be classified into two types, reliability-based (or load-response) and market-based programs [4]. Reliability-based programs suggest customers with economic motivations such as lower electricity prices or special bill credits to modify or change their demand for energy. Reliability-based programs are mainly classified into three sub-categories: Direct load control, interruptible programs, and curtailable load programs [4]. In direct load-control programs, network operator is allowed to turn off the consumers' loads by remote control switches during periods of peak demand. In interruptible programs, large commercial and industrial customers are considered. These large scale consumers either have back-up generations that can supple their loads or their operation process can be shut down during short-term periods to satisfy the load demand reduction requirements. In curtailable load programs, the consumers reduce their consumed energy upon notice from the network operator. The targeted load size of customers is the key difference between interruptible and curtailable programs. Where, curtailable programs mainly have a

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http://dx.doi.org/10.1016/j.energy.2016.10.113
0360-5442/

Nomenclature

Symbols, indexes and parameters

A	Wind generator blade area (m^2)
A'	Wind generator blade area for portable WT (m^2)
$C_{CHP}\,(t)$	Total cost of CHP at time t ($)
$C_{PV}\,(t)$	Total cost of PV at time t ($)
$C_{Boiler}\,(t)$	Total cost of boiler at time t ($)
$C_{MT}\,(t)$	Total cost of MT at time t ($)
$C_{Wind}\,(t)$	Total cost of WT at time t ($)
$C_{ES}\,(t)$	Total cost of ES at time t ($)
$C_{TS}\,(t)$	Total cost of TS at time t ($)
$C_{Buy}\,(t)$	Cost of buying at time t ($)
$C_{Sell}\,(t)$	Cost of selling at time t ($)
$C_{M\text{-}CHP}$	Maintenance cost of CHP ($)
$C_{OP\text{-}CHP}$	Operation cost of CHP ($/kWh)
$C_{OP\text{-}WT}$	WT operation cost ($/kWh)
$C_{OP\text{-}PV}$	PV operation cost ($/kWh)
$C_{CONS\text{-}WT}$	WT constant cost ($)
$C_{CONS\text{-}PV}$	PV constant cost ($)
$C_{M\text{-}Boiler}$	Maintenance cost of boiler ($)
$C_{OP\text{-}Boiler}$	Operation cost of boiler ($/kWh)
$C_{M\text{-}MT}$	Maintenance cost of MT ($)
$C_{OP\text{-}MT}$	Operation cost of MT ($/kWh)
$C_{M\text{-}ES}$	ES maintenance cost ($)
C_{Sell}	Cost of selling ($)
C_{Buy}	Cost of buying ($)
C_{Fuel}	Cost of fuel ($)
$C_{OP\text{-}ES}$	ES operation cost ($/kWh)
$C_{OP\text{-}TS}$	TS operation cost ($/kWh)
$C_{M\text{-}TS}$	TS maintenance cost ($)
$DR_{REV}(t)$	Demand response revenue ($)
$E_{LD}\,(t)$	Electrical load demand at time t (kW)
$E_S\,(t)$	Electrical storage energy at time t (kWh)
EM_{CHP}	Emission of CHP (kg)
EM_{MT}	Emission of MT (kg)
EM_{Boiler}	Emission of boiler (kg)
EM_{MG}	Emission of main grid (kg)
EF_{CHP}	Emission factor of CHP (kg/Mwah)
EF_{MT}	Emission factor of MT (kg/Mwah)
EF_{Boiler}	Emission factor of boiler (kg/Mwah)
EF_{MG}	Emission factor of main grid (kg/Mwah)
E_S^{max}	Maximum electrical storage energy (kWh)
E_S^{min}	Minimum electrical storage energy (kWh)
$F\,(Cost)$	Total cost of microgrid ($)
$F\,(Emission)$	Total pollution of microgrid (kg)
$GT\,(t)$	Solar radiation on tilted module plane (kW/m2) of PV at time t
GT_{NOCT}	Solar radiation in NOCT (normal operating cell temperature) (kW/m^2)
GT'_{NOCT}	Solar radiation in NOCT (normal operating cell temperature) (kW/m^2) for portable PV
GT_{SCT}	Solar radiation in STC (standard test conditions) (kW/m^2)
GT'_{SCT}	Solar radiation in STC (standard test conditions) (kW/m^2) for portable PV
$NOCT$	Normal operating cell temperature (°C)
$NOCT'$	Normal operating cell temperature (°C) for portable PV
N_{PVs}	Number of series cells in PV module
N'_{PVs}	Number of series cells in portable PV module
N_{PVp}	Number of parallel cells in PV module
N'_{PVp}	Number of parallel cells in portable PV module
$P_{MG}\,(t)$	Main grid power at time t (kW)
$P_{WT}\,(t)$	Wind turbine power at time t (kW)
$P_{WT}{}^{PORT}\,(t)$	Portable wind turbine power at time t (kW)
$P_{PV}\,(t)$	PV power at time t (kW)
$P_{PV}{}^{PORT}\,(t)$	Portable PV power at time t (kW)
$P_{CHP}\,(t)$	CHP power at time t (kW)
$P_{MT}\,(t)$	MT power at time t (kW)
$P_{Boiler}\,(t)$	Boiler power at time t (kW_{heat})
$P_{Buy}\,(t)$	Buying power at time t (kW)
$P_{Sell}\,(t)$	Selling power at time t (kW)
$P_{Battery}{}^{PORT}(t)$	Battery power for PRER at time t (kW)
$P_{ES}\,(t)$	Electrical storage power at time t (kW)
$P_{TS}\,(t)$	Thermal storage power at time t (kW_{heat})
$P^{max}{}_{E\text{-}dech}$	Electrical storage maximum discharge rate
$P^{max}{}_{E\text{-}ch}$	Electrical storage maximum charge rate
$P^{max}{}_{T\text{-}dech}$	Thermal storage maximum discharge rate
$P^{max}{}_{T\text{-}ch}$	Thermal storage maximum charge rate
P_{MT}^{max}	Maximum MT power (kW)
P_{Boiler}^{max}	Maximum boiler power (kW_{heat})
P_{CHP}^{max}	Maximum CHP power (kW)
P_{Line}	Line transfer power limit (kW)
$P_{PV,\,STC}$	Maximum test power in STC (standard test conditions) (kW)
$P'_{PV,\,STC}$	Maximum test power in STC (standard test conditions) (kW) for portable PV
R_{PRER}	Revenue by PRER ($/kWh)
t	Time (h)
$T_j\,(t)$	Cell temperature of PV at time t (°C)
$T_j{}'\,(t)$	Cell temperature of portable PV at time t (°C)
$TE_S\,(t)$	Thermal storage energy at time t (kWh_{heat})
$T_{LD}\,(t)$	Thermal load demand at time t (kW_{heat})
TE_S^{max}	Maximum thermal storage energy (kWh_{heat})
TE_S^{min}	Minimum thermal storage energy (kWh_{heat})
TF_{CHP}	CHP heat to power ratio
T_{amp}	Environmental temperature (°C)
T'_{amp}	Environmental temperature (°C) for portable PV
T_{jstc}	Reference cell temperature (°C) of PV
T'_{jstc}	Reference cell temperature (°C) of portable PV
V_t	Wind speed at time t (m/s)
V^{nom}	Nominal wind speed (m/s)
$V^{nom'}$	Nominal wind speed (m/s) for portable WT
$V^{cut\text{-}in}$	Minimum wind speed (m/s)
$V^{cut\text{-}in'}$	Minimum wind speed (m/s) for portable WT
$V^{cut\text{-}out}$	Maximum wind speed (m/s)
$V^{cut\text{-}out'}$	Maximum wind speed (m/s) for portable WT
η_{CHP}	CHP generator electrical efficiency
η_{Boiler}	Boiler generator electrical efficiency
η_{Boiler}	MT generator electrical efficiency
$\eta^E{}_C$	Electrical storage charge efficiency
$\eta^T{}_C$	Electrical storage discharge efficiency
$\eta^T{}_C$	Thermal storage charge efficiency
$\eta^T{}_D$	Thermal storage discharge efficiency
η^w	Wind generator power coefficient
$\eta^{w'}$	Wind generator power coefficient for portable WT
ρ	Air density (kg/m^3)
ρ'	Air density (kg/m^3) for portable WT
γ	Power-temperature coefficient
γ'	Power-temperature coefficient for portable PV
θ	Time interval

Abbreviations

CHP	Cool-Heat-Power
DG	Distributed generation

DR	Demand response	MILP	Mixed integer linear programing
ES	Electrical Storage	PV	Photovoltaic
EMS	Energy management system	PRER	Potable Renewable Energy Resource
ESS	Energy storage system	PORT	Portable
GA	Genetic algorithm	MG	Main grid
MT	Micro Turbine	TS	Thermal Storage
MINLP	Mixed integer non-linear programing	WT	Wind Turbine

lower targeted load size limited to 100–200 kW [5]. On the other hand, in market-based programs, the consumers can adjust their demands voluntarily upon economic notices from the network operators and get price discount or other incentives, in return. Regular market-based methods involve demand bidding, dynamic pricing, and time of use rates [5].

Based on the previous illustration regarding demand response, it could be a well-adopted concept on microgrids. A microgrid is a small grid including renewable and conventional generating systems, demand management programs, energy storage systems, and electrical-thermal loads that can operate connected to the main grid or in islanding mode [6]. Microgrid energy management has been studied from many perspectives such as minimizing energy cost and CO2 emission [7], minimizing operation cost and increasing economic performance [8], achieving green energy management by minimizing energy costs, pollutant emissions, and maximizing penetration of renewable energy [9], improving dynamic performance by considering economic aspect [10], maximizing revenue of microgrid and decreasing environmental pollution [11,12], and improving reliability of microgrid [13]. Furthermore, demand side management is another important issue that has been studied in microgrids at recent years [14–22]. In this regard, several issues have been studies such as: heating-cooling systems as an effective structure in energy management [19], reserve and energy scheduling methods [20], demand response coordination for various demands and implementation in real microgrid [21], and effects of consumers in all part of system such as carbon production [22]. As well, uncertainty can be pointed out as the other important concern related to the energy management in microgrids [23–29]. In general, uncertainty can be explained as the probability of discrepancy between the forecasted and the real values [27]. Loads, wind speed, and solar radiation are the most important parameters that are modeled by normal (Gaussian) or Weibull distribution functions [30,31].

With respect to the energy management problem in microgrids, it can be concluded that this problem can be expressed as a constrained MILP or MINLP. The proposed optimization problem can be solved by using meta-heuristic optimization algorithms or mathematical methods such as multi-layer ant colony optimization [32], GA [33], artificial neural network and modified bacterial foraging algorithm [34], hyper-heuristic algorithms [35], multi period artificial bee colony combined with Markov chain [36], and multi-period gravitational search algorithm [37]. In addition, intelligent methods, powerful and flexible mathematical methods and softwares such as GAMS [37], CPLEX [38], and GUROB [39] are used to solve such a complex problems.

In this paper, a multi objective and stochastic programing is presented for energy management in microgrid. The proposed problem optimizes cost and pollution at the same time. The proposed planning utilizes PRER in demand side to increase flexibility of microgrid performance. As a result, consumer could easily supply a part of its energy even when microgrid can't meet the demand. A typical Microgrid is studied, where the production side includes wind turbine, PV, CHP, micro turbine, and boiler. On the other side, demand side contains thermal-electrical loads and PRER. As well, thermal and electrical storages are incorporated in the planning. Microgrid can operate connected to, or isolated from, the main grid and it is allowed to sell or buy energy. In the proposed planning, there are several uncertain parameters such as wind speed, solar radiation, thermal, and electrical loads and this leads to a multi objective stochastic programming. Augmented Epsilon-constraint method is applied to solve the proposed multi objective problem. This method is one of the powerful tools for solving multi-objective problems. Problem is expressed as is a MILP and solved by CPLEX12.5.1. Several simulations, case studies, comparative studies, and sensitivity analysis are carried out to demonstrate the efficiency and viability of the proposed methodology.

2. Problem modeling

Mathematical modeling of the microgrid components is given as follows.

2.1. Wind turbine modeling

Because of variation in wind speed, wind turbine output power is modeled as a probability function. Wind turbine output power depends on wind speed and wind turbine characteristic. As a result, the generated power by wind turbine is affected by many factors such as wind speed, wind direction, turbine position, turbine size, and dynamic performance of the generator [40]. Fig. 1 shows wind turbine output power versus wind speed and it is clear that the output power is limited by cut-in and cut-out speeds [41]. Wind turbine output power (P_{WT}) is given by (1).

$$P_{WT} = \begin{cases} 0 & \forall t \ : \ V^{cutin} \geq Vt \text{ and } V^{cutout} \leq Vt \\ 0.5 \cdot \rho \cdot A \cdot \eta^{W} \cdot \min(V_t, V^{nom})^3 & \forall t \ : \ V^{cutin} \leq \ Vt \ \leq \ V^{cutout} \end{cases} \tag{1}$$

2.2. Photovoltaic modeling

PV output power depends on cells temperature and solar irradiance at maximum power point (MPP) situation that can be expressed as (2) [42]. Cell temperature of PV is calculated by (2) and then output power of PV at each time can be achieved by (3).

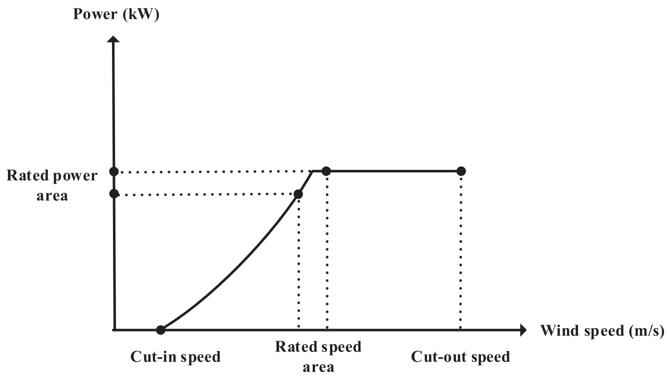

Fig. 1. Wind turbine output power versus wind speed.

$$T_j(t) = T_{amp} + \frac{G_T(t)}{G_{T_{STC}}} \times (NOCT - 20) \tag{2}$$

$$P_{PV}(t) = \left(\begin{array}{l} \left[P_{PV,STC} \times \frac{G_T(t)}{G_{T_{STC}}} \times (1 - \gamma \times (T_j(t) - T_{jSTC}))\right] \times \\ N_{PVs} \times N_{PVp} \end{array} \right) \tag{3}$$

2.3. ESS modeling

Because of using electrical and thermal generating systems, thermal and electrical energy storages are needed. Thermal and electrical energy storage systems allow to store the excess thermal and electrical energies for later consumptions [43]. Model of electrical and thermal energy storages are shown through (4)–(11) [34]. Where, output power of electrical storage is achieved from (4) and output power of thermal storage is obtained from (8).

$$P_{ES}(t) = E_S(t) - E_S(t-1) \quad t = 1, 2, \ldots, T \tag{4}$$

$$P_{WT}^{PORT} = \begin{cases} 0 & \forall t \ : \ V^{cutin'} \geq Vt \text{ and } V^{cutout'} \leq Vt \\ 0.5 \cdot \rho' \cdot A' \cdot \eta^{W'} \cdot \min(V_t, V^{nom'})^3 & \forall t \ : \ V^{cutin'} \leq Vt \leq V^{cutout'} \end{cases} \tag{12}$$

$$E_S^{\min} \leq E_S(t) \leq E_S^{\max} \tag{5}$$

$$\begin{cases} E_S^{\min} - E_S(0) \leq \sum_{k=1}^{t} P_{ES}(k) \leq E_S^{\max} - E_S(0) \\ (\forall t = 1, 2, \ldots, T) \end{cases} \tag{6}$$

$$E_S(0) = E_S(T) \tag{7}$$

$$P_{TS}(t) = TE_S(t) - TE_S(t-1) \quad t = 1, 2, \ldots, T \tag{8}$$

$$TE_S^{\min} \leq TE_S(t) \leq TE_S^{\max} \tag{9}$$

$$\begin{cases} TE_S^{\min} - TE_S(0) \leq \sum_{k=1}^{t} P_{TS}(k) \leq TE_S^{\max} - TE_S(0) \\ (\forall t = 1, 2, \ldots, T) \end{cases} \tag{10}$$

$$TE_S(0) = TE_S(T) \tag{11}$$

As shown in (5), the energy in batteries should be limited between minimum and maximum levels to avoid reducing batteries life time. In each hour, $P_{ES}(t)$ must be chosen subject to these limits. Charging and discharging powers are limited by (6). The initial and final state of charge must be equal as described by (7). All points related to the electrical storage as mentioned above, should also be considered for thermal storage as shown through (9)–(11).

2.4. Portable resources modeling

Portable renewable energy resources include small-scale portable wind turbine and PV along with adequate energy storage systems. These devices are installed by consumers to take part in curtailable programs. These consumers have back-up generations that can supple their loads during short-term periods of times to meet the load demand reduction requirements. The operational cost and pollution related to such infrastructures is commonly neglected.

Power that produced by portable wind turbine is calculated by (12). Also, portable PV cell temperature is obtained by (13) and generated power of PV is given by (14). These resources can be used in microgrid concerning technical or economic conditions based on a contract between microgrid and consumers to reduce or switch off loads at short-term periods of times. The produced power by these generators should be stored in sufficient batteries for being utilized during contract times. By this way, consumers make profit form the contract and can supply their energy. Total amount of power achieved by PRER and its storage system is defined by (15). Electrical load in the presence of PRER is defined by (16). Also, the consumers' profit from demand response by using PRER is achieved as (17). As seen in (15) and (16), all of the produced power by portable resources is stored in storage system and this power is restored, when necessary.

$$T'_j(t) = T'_{amp} + \frac{G'_T(t)}{G'_{T STC}} \times (NOCT' - 20) \tag{13}$$

$$P_{PV}^{PORT}(t) = \left(\begin{array}{l} \left[P'_{PV,STC} \times \frac{G'_T(t)}{G'_{T STC}} \times \left(1 - \gamma' \times \left(T'_j(t) - T'_{jSTC}\right)\right)\right] \times \\ N'_{PVs} \times N'_{PVp} \end{array} \right) \tag{14}$$

$$P_{Battery}^{PORT}(t) = \sum_{t=1}^{T} \left(P_{WT}^{PORT}(t) + P_{PV}^{PORT}(t)\right) \tag{15}$$

$$\begin{cases} \sum_{t=1}^{T}\left(E_{LD}(t) - P_{Battery}^{PORT}(t)\right) = \sum_{t=1}^{T}(P_{WT}(t) + P_{PV}(t) + P_{MT}(t) + \\ P_{CHP}(t) + P_{ES}(t) + P_{Buy}(t) - P_{Sell}(t)) \end{cases} \tag{16}$$

$$DR_{REV}(t) = \sum_{t=1}^{T} P_{Battery}^{PORT}(t)\cdot R_{PRER}\cdot\theta \tag{17}$$

3. Problem formulation

In this section, objective functions, constraints, and all parts of problem are mathematically formulated.

3.1. Objective functions

The purpose of the proposed method is to find the optimal output for generators and batteries subject to technical constraints. In this paper, two objective functions are defined and minimized at the same time based on augmented Epsilon-constraint method. First one is the total operational cost of microgrid and the second one is environmental pollution.

3.1.1. Total cost

Total operational cost of microgrid is defined as (18).

$$\begin{cases} F(\mathrm{Cos}\ t) = \sum_{t=1}^{T}(C_{CHP}(t) + C_{Wind}(t) + C_{Boiler}(t) + C_{PV}(t) \\ C_{Buy}(t) - C_{Sell}(t) + C_{ES}(t) + C_{TS}(t) + C_{MT}(t)) \end{cases} \tag{18}$$

Where,

$$C_{CHP}(t) = \begin{pmatrix} \sum_{t=1}^{T}\left(\frac{C_{Fuel}\cdot P_{CHP}(t)\cdot\theta}{\eta_{CHP}} + C_{OP-CHP}\cdot P_{CHP}(t)\cdot\theta\right) + \\ C_M - CHP \end{pmatrix} \tag{19}$$

$$C_{Wind}(t) = \sum_{t=1}^{T} C_{OP-WT}\cdot P_{WT}(t)\cdot\theta + C_{CONS-WT} \tag{20}$$

$$C_{PV}(t) = \sum_{t=1}^{T} C_{OP-PV}\cdot P_{PV}(t)\cdot\theta + C_{CONS-PV} \tag{21}$$

$$C_{Boiler}(t) = \begin{pmatrix} \sum_{t=1}^{T}\left(\frac{C_{Fuel}\cdot P_{Boiler}(t)\cdot\theta}{\eta_{Boiler}} + C_{OP-Boiler}\cdot P_{Boiler}(t)\cdot\theta\right) + \\ C_{M-Boiler} \end{pmatrix} \tag{22}$$

$$C_{MT}(t) = \begin{pmatrix} \sum_{t=1}^{T}\left(\frac{C_{Fuel}\cdot P_{MT}(t)\cdot\theta}{\eta_{MT}} + C_{OP-MT}\cdot P_{MT}(t)\cdot\theta\right) + \\ C_{M-MT} \end{pmatrix} \tag{23}$$

The cost of CHP, WT, PV, boiler, and MT are described by (19)–(23), respectively. The first term of (19) includes fuel cost, the second and third terms represent the operational and maintenance cost, respectively. Wind turbine and PV variable and fixed costs are specified by (20) and (21), respectively. The first terms of (22) and (23) indicate the cost of generation for the boiler and the micro turbine, respectively, and the second and third terms specify the operational and maintenance cost, respectively.

Costs of buying and selling power at each time are described by (24) and (25), respectively. Furthermore, operation and maintenance costs of the electrical and thermal batteries are shown by (26) and (27), respectively.

$$C_{Buy}(t) = \sum_{t=1}^{T} C_{Buy}\cdot P_{Buy}(t)\cdot\theta \tag{24}$$

$$C_{Sell}(t) = \sum_{t=1}^{T} C_{Sell}\cdot P_{Sell}(t)\cdot\theta \tag{25}$$

$$C_{ES}(t) = \sum_{t=1}^{T} C_{OP-ES}\cdot P_{ES}(t)\cdot\theta + C_{M-ES} \tag{26}$$

$$C_{TS}(t) = \sum_{t=1}^{T} C_{OP-TS}\cdot P_{TS}(t)\cdot\theta + C_{M-TS} \tag{27}$$

3.1.2. Pollution

Environmental pollution caused by microgrid and main grid generation is defined as (28).

$$\begin{cases} F(Emission) = \sum_{t=1}^{T}(EM_{CHP}(t) + EM_{MT}(t) + \\ EM_{MG}(t) + EM_{Boiler}(t)) \end{cases} \tag{28}$$

Where,

$$EM_{CHP}(t) = \sum_{t=1}^{T} P_{CHP}(t)\cdot EF_{CHP}\cdot\theta \tag{29}$$

$$EM_{Boiler}(t) = \sum_{t=1}^{T} P_{Boiler}(t)\cdot EF_{Boiler}\cdot\theta \tag{30}$$

$$EM_{MT}(t) = \sum_{t=1}^{T} P_{MT}(t)\cdot EF_{MT}\cdot\theta \tag{31}$$

$$EM_{MG}(t) = \sum_{t=1}^{T} P_{Buy}(t)\cdot EF_{MG}\cdot\theta \tag{32}$$

Where, (29)–(32) indicate the produced pollution by CHP, boiler, MT, and main grid, respectively.

3.2. Problem constraints

Microgrid energy management includes many constraints such as power balance, storage, produced power, and etc. These constraints limit operation of microgrid and make output responses to be feasible. As a result, microgrid should operate under technical constraints as follows:

$$\begin{cases} \sum_{t=1}^{T} E_{LD}(t) = \sum_{t=1}^{T} (P_{WT}(t) + P_{PV}(t) + P_{MT}(t) + \\ P_{CHP}(t) + P_{ES}(t) + P_{Buy}(t) - P_{Sell}(t)) \end{cases} \tag{33}$$

$$\sum_{t=1}^{T} T_{LD}(t) = \sum_{t=1}^{T} (P_{Boiler}(t) + P_{CHP}(t) \cdot TF_{CHP}(t) + P_{TS}(T)) \tag{34}$$

$$P_{CHP} \le P_{CHP}^{\max} \tag{35}$$

$$P_{Boiler} \le P_{Boiler}^{\max} \tag{36}$$

$$P_{MT} \le P_{MT}^{\max} \tag{37}$$

$$\begin{cases} P_{ES}(t) \big/ \eta_D^E \le P_{E-dech}^{\max} & for\ \ disch\ (P_{ES}(t) > 0) \\ -\eta_C^E \cdot P_{ES}(t) \le P_{E-ch}^{\max} & for\ ch\ (P_{ES}(t) < 0) \end{cases} \tag{38}$$

$$\begin{cases} P_{TS}(t) \big/ \eta_D^T \le P_{T-dech}^{\max} & for\ \ disch\ (P_{TS}(t) > 0) \\ -\eta_C^T \cdot P_{TS}(t) \le P_{E-ch}^{\max} & for\ ch\ (P_{TS}(t) < 0) \end{cases} \tag{39}$$

$$(P_{Buy}(t)\ or\ P_{Sell}(t)) \le P_{Line} \tag{40}$$

$$R_m(t) = \left(\frac{Total\ capacity(t) - Peak\ load(t)}{Peak\ load(t)} \right) \times 100\% \tag{41}$$

$$R_m^{\min}(t) \le R_m(t) \le R_m^{\max}(t) \tag{42}$$

Total produced power (thermal or electrical) in each interval should be equal to the total load (thermal or electrical) demands as given by (33) and (34), respectively. It is worth mentioning that CHP produces electrical and thermal powers at the same time. The constraints on the produced power by CHP, boiler, and micro turbine are given through (35)–(37), respectively. The limitations on charging-discharging powers for electrical and thermal batteries are specified by (38) and (39), respectively. Negative and positive values indicate the discharging and charging states, respectively. The capacity of line between the microgrid and the main grid is limited by (40). Finally, reserve margin is specified by (41) and (42).

4. Solving problem

This paper proposes a stochastic and multi objective programing. In order to solve such a multi objective programing an accurate method, i.e., augmented Epsilon-constraint mathematical model, is utilized. Scenario generation and reduction is one of the most important parts of the proposed stochastic problem that is defined in this section.

4.1. Augmented Epsilon-constraint method

The Epsilon-constraint method is mainly used to solve multi objective problems [44]. It optimizes one of the objective functions while it considers the other objective functions as a constraint. In order to solve the energy management problem, advanced model of this method (augmented Epsilon-constraint) is applied to get better results. This method has some advantages since it doesn't alter the original feasible region and is able to produce non-inferior solutions, independent from the scaling of the objective functions [45]. Thus, a multi objective problem with augmented Epsilon-constraint can be defined as follows [45]:

In order to force the program to produce efficient and optimal objective functions in defined constraints, new relation (43) is defined as follows:

$$\begin{aligned} &\max(f_1(x) + \delta \times (s_1 + \ldots + s_p)) \\ &\text{subject to} \\ &f_2(x) - s_2 = e_2 \\ &f_3(x) - s_3 = e_3 \\ &\ldots \\ &f_p(x) - s_p = e_p \\ &x \in s \text{ and } s_i \in R^+ \end{aligned} \tag{43}$$

Assumed that above formulation (43) just produces efficient solutions and proposed planning have alternative optima that one of them (exhibited by x') dominates other achieved optimal solutions. As a result, this case is defined by (45).

$$\begin{cases} e_2 + s_2 \le e_2 + s_2', \\ e_3 + s_3 \le e_3 + s_2', \\ \ldots \\ e_p + s_p \le e_p + s_p' \end{cases} \tag{44}$$

Based on (44), with considering at least one strict inequality and by adding these relations, (45) will be achieved.

$$\sum_{i=2}^{p} s_i < \sum_{i=2}^{p} s_i' \tag{45}$$

It is suggested to replace s_i by s_i/r_i to avoid any scaling problems. So, final objective function will be defined by (46).

$$\max(f_1(x) + eps \times (s_2/r_2 + \ldots + s_p/r_p)) \tag{46}$$

Where, δ is a small amount (between 10^{-3} and 10^{-6}). Vector of decision variables, p objective functions, feasible region, and range of ith objective function are defined by $x, f_p(x), s$, and r_i, respectively. The final equation given by (46) is used to solve the multi objective problem.

4.2. Stochastic programing

Wind speed, solar radiation, and loads are modeled as stochastic parameters. In order to model the stochastic programming, scenario generation and reduction technique is applied. The uncertain parameters are assumed to have a continuous probability distribution function (PDF) with 30% standard deviation. Then, the continuous PDF is estimated by discrete PDF including N_n steps. If there are M_m uncertain parameters, and each parameter is estimated by N_n steps, therefore, there are $N_n^{Aa^*Mm}$ scenarios. Where, A_a shows the time intervals of next 24-h (e.g., six time intervals and each one including 4 h). After producing all scenarios and the probability related to each scenario, the most probable scenarios with the highest possibility of occurrence are selected. This approach results in a trivial error at the outputs, but it significantly reduces the simulation time.

5. Test system

The microgrid considered in this paper includes thermal and electrical loads, wind turbine, PV, boiler, CHP, micro turbine, thermal and electrical storages, and finally PRER. Fig. 2 shows structure of the proposed microgrid incorporating PRER. Energy management is carried out for 24-h that is divided into six 4-h intervals. The uncertain parameters are assumed to have 30% standard deviation. Among a large number of scenarios, only 50 scenarios which have the highest probability of occurrence are simulated.

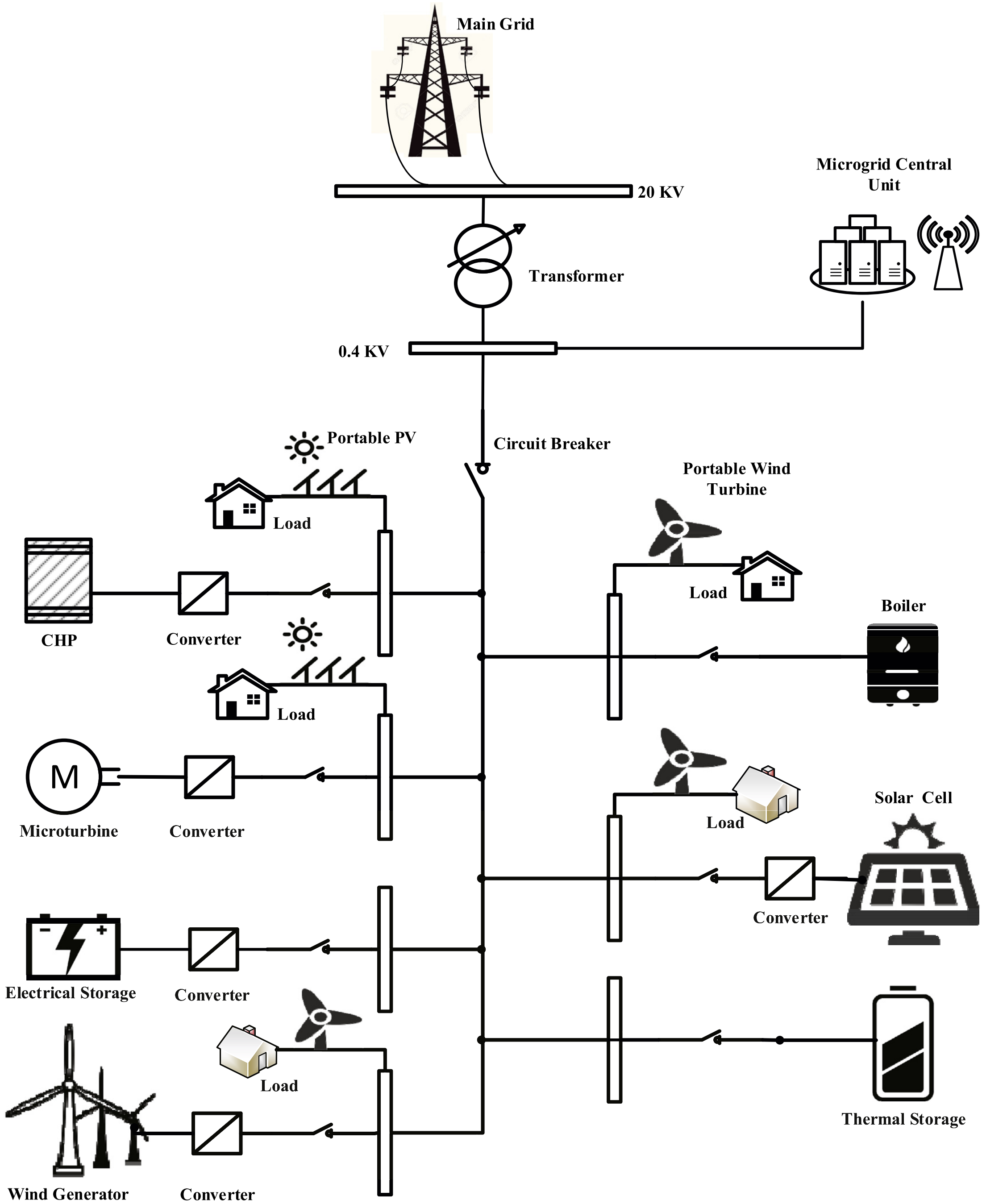

Fig. 2. Microgrid network and PRER places.

Table 1
Emission factors [34].

Emission type	Emission factors (Kg/Mwah)			
	MT	Boiler	CHP	Grid
CO2	724	845	822	922
SO2	0.0036	2.545	0.0085	3.583
NOx	0.2	1.812	0.3	2.295

Table 2
Batteries factors and efficiency factors [46].

η_{CHP}	0.35	η^{W}	0.59
η_{Boiler}	0.8	η^{E}_{D}	0.95
η_{MT}	0.3	η^{T}_{C}	0.98
η^{E}_{C}	0.95	η^{T}_{D}	0.98
E_S^{max} (kWh)	40	$P^{max}_{E\text{-}dech}$ (kW)	20
E_S^{min}(kWh)	2	$P^{max}_{E\text{-}ch}$ (kW)	20
TE_S^{max} (kWh)	40	$P^{max}_{T\text{-}dech}$ (kW)	20
TE_S^{min}(kWh)	2	$P^{max}_{T\text{-}ch}$ (kW)	20

Four parameters including wind speed, solar radiation, thermal, and electrical loads are regarded as uncertain parameters. As well, C_{Fuel}, TF_{CHP}, P_{line}, R_{PRER} are equal to 0.027 \$, 1.3, 30 kW, and 0.1 \$/kWh, respectively. Also, Reserve margin is between 5% till 10% of maximum load. All other necessary parameters are listed in

Table 3
PV and WT characteristics [41,42,46].

T_{amp} (°c)	20	$V^{cut-out}$ (m/s)	25
T_{jstc} (°c)	25	N_{PVs}	70
GT_{SCT} (kW/m^2)	1	N_{PVp}	30
NOCT (°c)	45.5	γ	0.043%
ρ (kg/m^3)	1.23	A (m^2)	30
V^{nom} (m/s)	12	$P_{PV,\ STC}$ (kW)	0.165
V^{cut-in} (m/s)	5	GT_{NOCT} (kW/m^2)	0.8

Table 4
PRER characteristics [41,42,46].

T'_{amp} (°c)	20	$V^{cut-out'}$ (m/s)	22
T'_{jstc} (°c)	25	N'_{PVs}	20
GT'_{SCT} (kW/m^2)	1	N'_{PVp}	10
NOCT' (°c)	45.5	γ'	0.043%
ρ' (kg/m^3)	0.8	A' (m^2)	10
$V^{nom'}$ (m/s)	12	$P'_{PV,\ STC}$ (kW)	0.165
$V^{cut-in'}$ (m/s)	5	GT'_{NOCT} (kW/m^2)	0.8

Table 5
Power limitation and number of installed generators.

Generators	Power limit (kW)		Number
	Min	Max	n
CHP	0	90	1
Boiler	0	250	1
MT	0	30	1
WT	0	40	2
PV	0	25	4
PV^{PORT}	0	4	6
WT^{PORT}	0	2.5	6

Table 6
Maintenance and operation costs.

Components	Cost ($)	
	Maintenance or constant ($)	Operation ($/kW)
CHP	0.002	0.005
Boiler	0.002	0.005
MT	0.001	0.004
WT	0.002	0.005
PV	0.001	0.003
ES	0.001	0.004
TS	0.001	0.004

Tables 1–6. Finally, selling and buying prices, loads profiles, and wind speed and solar radiation are depicted in Figs. 3–5, respectively.

6. Simulation results

In order to achieve accurate results with more details, simulation results are divided into five cases. First, multi objective planning by augmented Epsilon-constraint method is analyzed. Second, results of the proposed planning are comprehensively discussed. Third, impacts of uncertainty are included in the proposed modeling. Fourth, PRER is added to the problem and its effects are studied. Finally, a comprehensive sensitivity analysis is proposed.

6.1. Multi objective planning by augmented Epsilon-constraint method

The maximum and minimum values of the objective functions based on the augmented Epsilon-constraint method are listed in Table 7 (payoff Table). Based on the function's primacy (cost or pollution), one of these sets are obtained. Also, more sets of objective functions are obtained but some of them are not optimal and neglected (based on Lexicographic optimization technique). As a result, the optimal solution is shown in Fig. 6. In order to select one of the optimized solutions, cost and pollution are assumed lower than 120 $ and 3800 kg, respectively. Hence, 118.257 $ and 3792.66 kg are achieved for cost and pollution, respectively. Regarding this case, decision maker has more options to select.

6.2. Results of the proposed multi objective and stochastic planning

The proposed method is applied on the given test case. The produced power by PRER is stored in batteries with sufficient capacity. As well, it is assumed that the generated power by PRER is restored to supply the loads at last time interval. As a result, objective functions and the produced power by microgrid components considering PRER are shown in Table 8 and Fig. 7 shows the generated power by PRER at each time interval. As shown in Table 8, because of low demand for energy at first time interval, the produced power by MT is zero. Moreover, electrical and thermal storages are charged from previous day. In order to obtain profit, 30 kW is sold to the main grid. The produced power by CHP is reduced from 58.661 kW to 53.634 kW in second interval. Due to correlation between CHP and boiler powers, the produced power by boiler is increased from 124.376 kW_{heat} to 128.486 kW_{heat}. Since the generated power by wind turbine is decreased, all storages are discharged to meet load demand and the amount of selling power is still 30 kW. By increasing PV power at third interval, the generated power by CHP is reduced from 53.634 kW to 37.432 kW. On the other hand, the produced power by boiler is increased to a higher value to meet thermal load. The extra power is also stored in energy storage systems. The produced power by wind turbine is decreased to zero at fourth interval. Therefore, the produced power by CHP and MT are increased from 37.316 kW to 71.316 kW and 1.866 kW–2.494 kW, respectively. By increasing CHP power, boiler decreases its power from 130.335 kW to 82.468 kW. The storages are also discharged to supply the loads. The amount of selling power is decreased slightly. In fifth interval, thermal and electrical loads are increased simultaneously. Thus, the produced power of MT and CHP are increased. At this time, 0.8555 kW is purchased from main grid to meet electrical load. At last interval and in spite of increasing load, the amount of the produced power by CHP and MT are decreased from 84.281 kW to 8.6163 kW and 6.074 kW–0 kW, respectively. Also, selling power to the main grid is increased to 29.025 kW. The main reason of such issue is to apply PRER and restoring their energy at last time interval. As shown in Table 8, by utilizing PRER, CHP and MT have more capacity to produce power at peak load. Also, the produced power by boiler is increased (cause increasing pollution) following reducing CHP power as well as the storages are discharged to meet thermal and electrical loads. The consumer and microgrid profits are listed in Table 9. It is clear that by both the microgrid and the consumer get profit as 6.29 $ and 9.27 $, respectively.

6.3. Impact of uncertainty on the planning

In order to show the impact of uncertainty on the planning as well as demonstrating the advantages of the proposed stochastic planning, results considering a deterministic approach are presented in Table 10. In the deterministic approach, the uncertainty is not considered in the planning. In other words, the uncertain parameters are set on their mean value as a fixed value. Results show that the planning cost and pollution obtained with the stochastic method are higher than those obtained with the deterministic

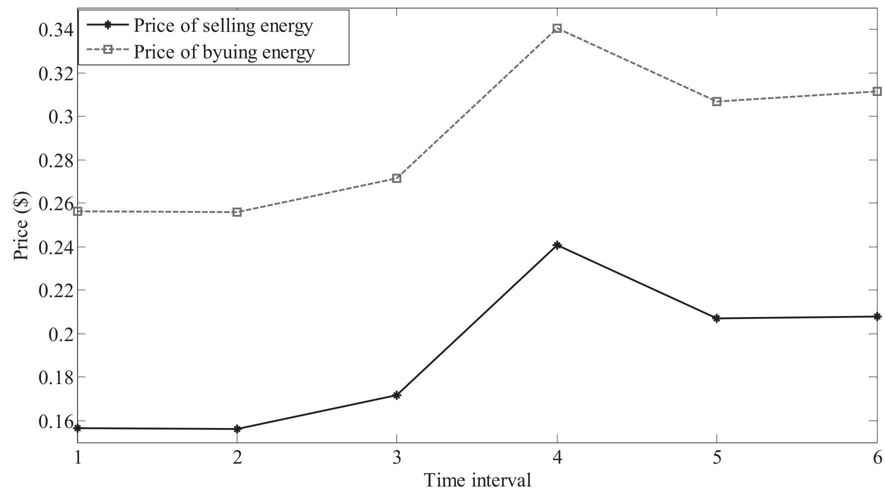

Fig. 3. Selling and buying prices during 24 h (i.e., six time intervals) [47].

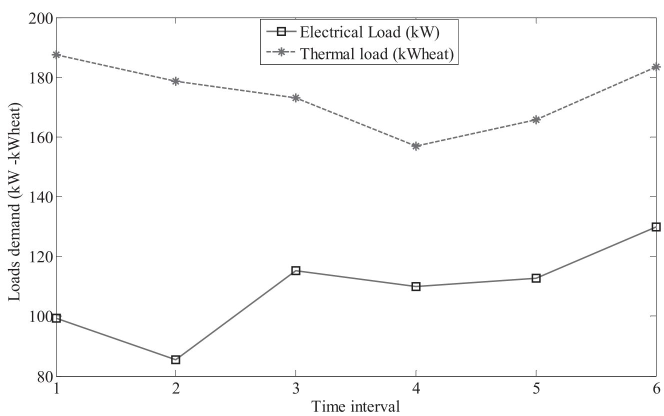

Fig. 4. Electrical and thermal loads during 24 h (i.e., six time intervals).

Table 7
Augmented Epsilon-constraint payoff table for multi objective problem.

Functions primacy	Cost ($)	Pollution (kg)
Total cost	114.5	3901.3
Environmental pollution	125.25	3720.9

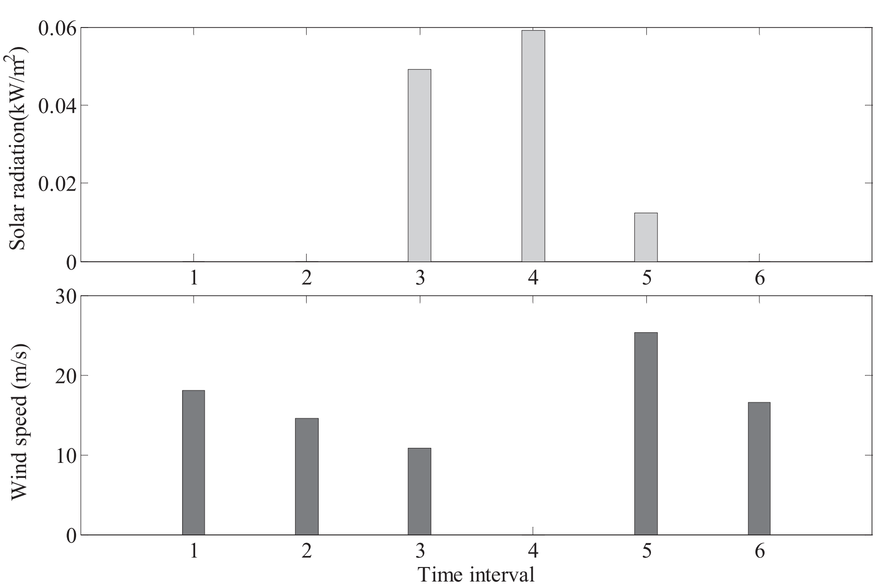

Fig. 5. Wind speed and solar radiation during 24 h (i.e., six time intervals).

approach by 114% and 104%, respectively. Through comparing Tables 8 and 10, in the deterministic approach, the produced power by MT is zero except fifth time interval. Due to the uncertainty in the stochastic approach, the generated power by the MT is increased that increases the pollution. It is worth remarking that during the fifth time interval, the produced power by the CHP in the stochastic planning is lower than deterministic method. This is due to increasing the generated power by wind turbine. As well, by increasing the generated power of conventional generators such as the CHP, the boiler and MT, the pollution is increased during first to fourth time intervals. In order to show the robustness and superiority of the stochastic programming, wind turbine and CHP output

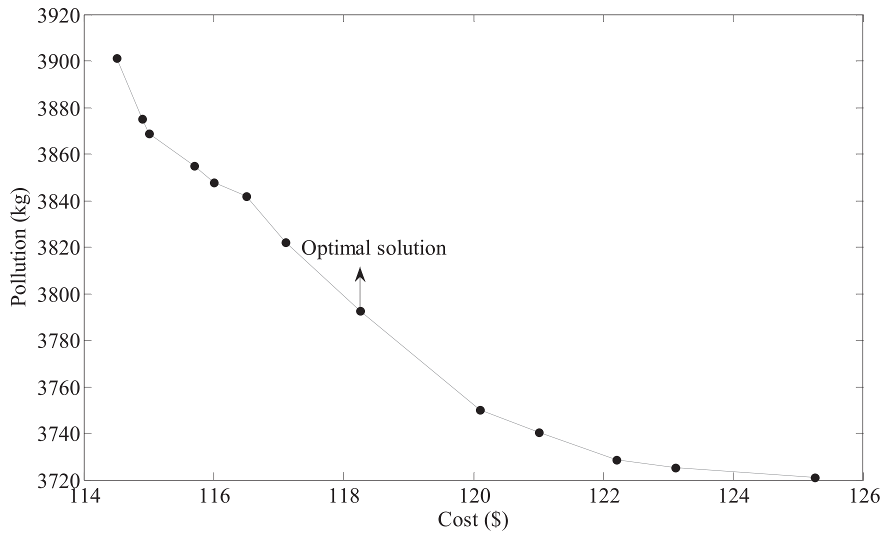

Fig. 6. Optimal solution based on augmented Epsilon-constraint method.

Table 8
Results of the proposed multi objective and stochastic planning with PRER.

Time interval	P_{CHP} (kW)	P_{MT} (kW)	P_{Boiler} (kW_{heat})	P_{WT} (kW)	P_{PV} (kW)	P_{ES} (kW)	P_{TS} (kW)	P_{Sell} (kW)	P_{Buy} (kW)
1	58.661	0	124.376	75.241	0	5	5	30	0
2	53.634	1.162	128.486	70.832	0	−1.957	−2.22	30	0
3	37.432	1.866	130.335	49.968	65.088	2.0258	11.025	30	0
4	71.316	2.494	82.468	0	78.466	−1.718	−3	29.917	0
5	84.281	6.074	75.054	11.286	16.578	4.65	−3	0	0.8555
6	8.6163	0	192.856	74.21	0	−3	−2.805	29.025	0
Total cost by proposed planning ($)					118.257				
Total pollution by proposed planning (kg)					3792.66				

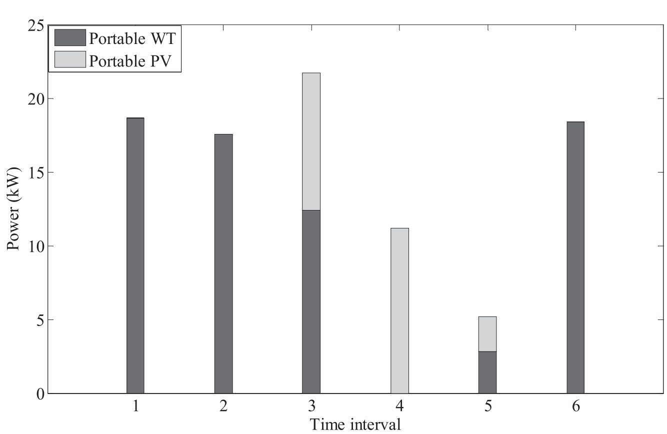

Fig. 7. PRER generation at different time intervals.

Table 9
Obtained revenue for consumers and microgrid by PRER.

Components	Revenue ($)
Microgrid	6.29242
Consumer	9.27058
Total revenue	15.563

powers are reduced by 5% and the reserve margin for both the stochastic and deterministic cases is depicted for electrical load in Figs. 8 and 9. It is clear that under the deterministic approach, the reserve margin constraint is violated while the stochastic planning can successfully tackle the uncertainty. Thus, the stochastic programming is more robust and even can support the network under higher level of uncertainties. Hence, high planning cost of the stochastic planning is acceptable and justifiable.

6.4. Impact of PRER on the planning

Planning objective functions and final results excluding PRER are presented in Table 11. It is clear that cost is increased from 118.257 $ to 133.82 $ due to reduction in selling power to the main grid and increasing CHP and MT powers at last time interval. By increasing CHP power at last time interval, the produced power by boiler is decreased. Environmental pollution is also reduced from 3792.66 kg to 3691.8 kg due to reducing the produced power by boiler. Moreover, the produced power by CHP is on the maximum capacity.

6.5. Sensitivity analysis

The aim of this section is to find parameters or constraints that have more effect on the planning. Sensitivity analysis on some parameters is presented in Table 12. Reserve margin constraint is an important parameter in the planning. As shown in Table 12, by increasing electrical minimum reserve margin, the generated power by CHP as well as total cost are increased. On the other hand, because of decreasing boiler power, the environmental pollution is decreased from 3792.66 kg to 3766.9 kg. As well, changing the initial energy of ESS makes an effect on the pollution and cost. This issue is due to reducing the generated power by components such

Table 10
Results of the multi objective and deterministic planning with PRER.

Time interval	P_{CHP} (kW)	P_{MT} (kW)	P_{Boiler} (kW_{heat})	P_{WT} (kW)	P_{PV} (kW)	P_{ES} (kW)	P_{TS} (kW)	P_{Sell} (kW)	P_{Buy} (kW)
1	53.972	0	121.62	75.241	0	5	5	30	0
2	47.398	0	128.93	75.241	0	−3	−3	30	0
3	24.354	0	138.18	55.431	68.153	3	12	30	0
4	66.286	0	81.594	0	82.161	−3	−3	30	0
5	90	5.039	59.743	0	17.359	6	−3	0	0
6	0.465	0	194.99	75.241	0	−3	−3	30	0
Total cost by proposed planning ($)					103.09				
Total pollution by proposed planning (kg)					3635.5				

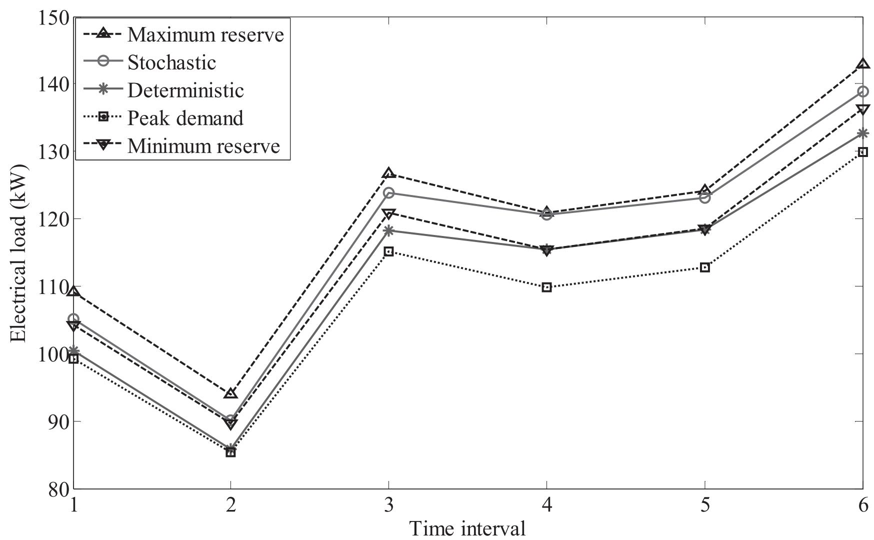

Fig. 8. Reserve margin for stochastic and deterministic planning following 5% reduction in output power of WT.

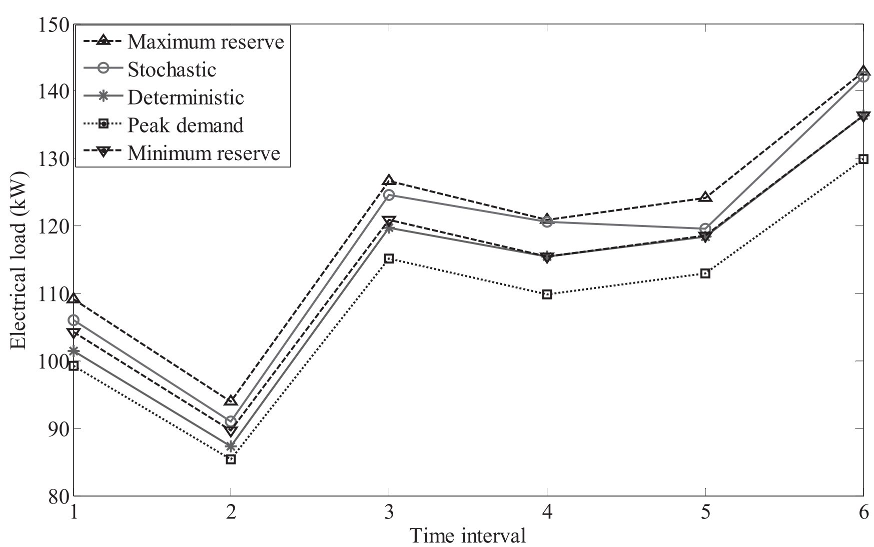

Fig. 9. Reserve margin for stochastic and deterministic planning following 5% reduction in output power of CHP.

as CHP and MT. When initial energy of the batteries is increased, the generated power by conventional generators is decreased that results in reducing cost and pollution from 118.257 $ and 3792.66 kg to 116.513 $ and 3773.54 kg, respectively. By increasing line limitation, the selling power to the main grid is increased and decreases the cost from 118.257 $ to 96.95 $. However, because of increasing CHP power and decreasing boiler power, the pollution is decreased from 3792.66 kg to 3716.8 kg. Increasing the margin of acceptable wind speed makes effect on pollution and cost at the same time. It is clear that increasing this constraint by 30% decreases cost and increases the pollution. In fact, by increasing pure generation by WT, the produced power by CHP is decreased and boiler should produce more power to meet thermal load. Thus, pollution is increased from 3792.66 kg to 3890.66 kg. Selling and buying prices

Table 11
Results of the multi objective and stochastic planning without PRER.

Time interval	P_{CHP} (kW)	P_{MT} (kW)	P_{Boiler} (kW_{heat})	P_{WT} (kW)	P_{PV} (kW)	P_{ES} (kW)	P_{TS} (kW)	P_{Sell} (kW)	P_{Buy} (kW)
1	58.661	0	124.376	75.241	0	5	5	30	0
2	54.152	1.162	114.58	70.832	0	−2.474	10.53	30	0
3	39.69	1.866	140.64	49.968	65.088	−0.074	−1.725	29.998	0
4	69.03	2.807	85.442	0	78.466	−0.098	−3	29.917	0
5	84.184	9.364	75.331	11.286	16.578	1.621	−3	0	0.8555
6	90	3.825	87.063	74.21	0	1.025	−2.805	27.665	0
Total cost without PRER ($)					133.82				
Total pollution without PRER (kg)					3691.8				

Table 12
Sensitivity analysis of the proposed planning.

Case Specifications	Objective functions	
	Cost ($)	Pollution (kg)
Nominal case	118.257	3792.66
60% Increasing electrical minimum reserve margin	122.076	3776.90
50% Increasing electrical storage initial energy	116.513	3773.54
50% Increasing Thermal storage initial energy	117.850	3782.98
20% Increasing transfer line limitation	96.950	3716.80
30% Increasing Vcutout and Vcutin	107.50	3890.66
20% Increasing selling price	118.10	3792.66
20% decreasing buying price	15.570	3792.66
10% decreasing CHP heat- power coefficient	123.28	3902.04

are the other important parameters that show great change on the cost. Heat to power coefficient of CHP is the last parameter that is analyzed in this section. As seen, by decreasing this coefficient the amount of total cost and pollution are increased from 118.257 $ and 3792.66 kg to 123.28 $ and 3902.04 kg, respectively. This change is because of increasing the produced power by boiler.

7. Conclusions

This paper considers pollution together with cost and optimizes them at same time in microgrid energy management problem. Also, uncertain parameters like wind speed, solar radiation, and load are included in the planning. This paper also Considers PRER as a demand response concept in microgrid management. Eventually, a stochastic and multi objective problem is addressed for microgrid energy management. Scenario generation and reduction techniques are applied to cope with the problem. Augmented Epsilon-constraint method is used to solve the proposed multi objective problem. Results show that by applying PRER, cost is decreased from 133.82 $ to 118.257 $ and the produced power by CHP and MT are reduced to the lower amounts at last time interval. Also, the derived profit by this method is equal to 15.563 $ that 9.27058 $ belongs to consumer and 6.29242 $ is for microgrid. As well, by decreasing CHP power at last time interval, the produced power by boiler is increased that leads to increasing the pollution from 3691.8 kg to 3792.66 kg.

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