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Energy management of a renewable-based isolated micro-grid by optimal utilization of dump loads and plug-in electric vehicles

Afsaneh Saffar, Ahmad Ghasemi *

Department of Electrical and Computer Engineering, Jundi-Shapur University of Technology, Dezful, Iran

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ABSTRACT

This paper proposes a new day-ahead energy management system (EMS) for an off-grid fishing island micro-grid (MG). The MG considered in this work is well equipped with smart grid infrastructure and embedded with plug-in electric vehicles (PEVs). Moreover, it is a green and fossil fuel free MG without any conventional power plant. The MG provides its load demand by solely renewable generations, including wind farms (WF) and photovoltaic (PV) power plants. Therefore, keeping balance between generation and demand is a difficult task in day-ahead operation planning of this MG. In order to overcome this obstacle, the MG uses a mega-scale battery energy storage system (BESS). However, the capacity of the BESS is limited and it is not economically feasible to increase the BESS capacity. Therefore, the MG considers PEVs G2V/V2G operation modes planning and dump loads optimal utilization as supplementary balance options. The main dump loads in this MG are industrial fish refrigerators (IFRs) and reverse osmosis desalination system (RODS). These dump loads in addition to PEVs' G2V/V2G modes of operation are scheduled in the EMS proposed in this paper. Numerical studies show that the proposed EMS reduces total daily wasted energy and energy not served by 96% and 30% respectively.

1. Introduction

1.1. Aim

Electrification of isolated areas, like islands far from the grid, is a challenging issue that has attracted a great deal of attention in recent years. *Green island* projects as a viable solution are going on all over the world aiming to utilize renewable energy resources for supplying local loads [1]. Maintaining the balance between generation and demand is a critical requirement of these projects [1]. However, the off-grid operation and the uncertainty associated with renewables makes it difficult to keep the balance between generation and demand. Usually, the excess energy generated by renewables is wasted as heat. Moreover, some loads may not be served in peak hours to keep the balance. Thanks to smart grid (SG) and MG concepts development, new and more efficient options like PEVs and dump loads scheduling are now available. However, these potentials have not been activated practically yet. Therefore, the aim of this paper is to propose a solution based on optimal scheduling of dump loads, PEVs' G2V/V2G modes of operation and BESS for isolated MG operation management.

1.2. Literature review

Delivering electricity to people who are living in remote isolated areas like islands is a difficult and costly task. As a promising solution for this problem, off-grid operation of isolated MGs has been studied in the literature. In [2] the economic implications of power production in small islands has been reviewed. Moreover, the potential of renewables to reduce the cost of providing electricity for remote islands consumers has been studied in this paper [2]. In [3] a techno-economic study has been presented for sustainable development of renewables to supply the energy demand of a remote island. The results show that the conventional diesel power plant can be replaced by renewables in a self-sustainable manner to achieve energy independence in remote islands [3]. In [4] an emerging active distribution network concept called micro-grid is reviewed and introduced as an interesting approach for future stand-alone mini-grids. Furthermore, an existing mini-grid of Kythnos island, Greece is presented in this paper as an example of isolated island electrification with the help of renewables [4]. In [5] a technical and economic analysis of a solely renewable-based hybrid energy system is carried out. The results show that a reasonable decrease on the cost of system components would bring the cost of energy to the level of energy produced by fossil fuels or even lower [5]. In [6] an integrated planning

* Corresponding author.
E-mail address: aghasemi@jsu.ac.ir (A. Ghasemi).

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Nomenclature

Sets and Indices

t	set of hours
i, j	sets of buses

Variables

$b_{i,t}^{APEV,Ch}$	binary decision variable showing the availability of the APEV for charging
$b_{i,t}^{APEV,Dch}$	binary decision variable showing the availability of the APEV for discharging
$b_{i,t}^{BESS,Ch}$	binary decision variable showing the charge status of the BESS
$b_{i,t}^{BESS,Dch}$	binary decision variable showing the discharge status of the BESS
$b_{i,t}^{RODS}$	binary decision variable showing the ON/OFF status of the RODS
$b_{i,t}^{IFR}$	binary decision variable showing the ON/OFF status of the IFR
$P_{i,t}^{BESS,Ch}$	amount of power charged to the BESS (MW)
$P_{i,t}^{BESS,Dch}$	amount of power discharged from the BESS (MW)
$P_{i,t}^{APEV,Ch}$	amount of power charged to the APEV (MW)
$P_{i,t}^{APEV,Dch}$	amount of power discharged from the APEV (MW)
$P_{i,t}^{Wind}$	power generation of the wind farm power plant (MW)
$P_{i,t}^{PV}$	power generation of the PV power plant (MW)
$P_{i,t}^{RODS}$	power demand of the RODS (MW)
$P_{i,t}^{IFR}$	power demand of the RODS (MW)
$P_{i,t}^{D}$	power demand of load (MW)
$P_{i,t}^{G}$	net generated power (MW)
$P_{i,t}^{PNS}$	power not supplied (MW)
$P_{i,t}^{EP}$	excess power (MW)
P_{t}^{Loss}	total power loss (MW)
$Q_{i,t}^{D}$	reactive power demand of load (MVAR)
$Q_{i,t}^{G}$	net generated reactive power (MVAR)
$SOC_{i,t}^{APEV}$	the APEV state of charge
$SOC_{i,t}^{BESS}$	the BESS state of charge
$V_{i,t}$	voltage magnitude of buses (kV)
δ_{i}^{t}	voltage angle of buses (rad)
$S_{ij,t}$	apparent power flow from bus i to bus j (MVA)

Parameters

$C_{i,t}^{BESS,Ch}$	degradation cost of the BESS when it is charged ($/MWh)
$C_{i,t}^{BESS,Dch}$	degradation cost of the BESS when it is discharged ($/MWh)
$C_{i,t}^{APEV,Ch}$	degradation cost of the APEV when it is charged ($/MWh)
$C_{i,t}^{APEV,Dch}$	degradation cost of the APEV when it is discharged ($/MWh)
C^{PNS}	the cost of power not supplied ($/MWh)
$P_{i,t}^{APEV,Ch,max}$	maximum charge rate of the APEV
$P_{i,t}^{APEV,Dch,max}$	maximum discharge rate of the APEV
$\eta_{i,t}^{APEV,Ch}$	charging efficiency of the APEV
$\eta_{i,t}^{APEV,Dch}$	discharging efficiency of the APEV
$\eta_{i,t}^{BESS,Ch}$	charging efficiency of the BESS
$\eta_{i,t}^{BESS,Dch}$	discharging efficiency of the BESS
$P_{i,t}^{BESS,Ch,max}$	maximum charge rate of the BESS
$P_{i,t}^{BESS,Dch,max}$	maximum discharge rate of the BESS
$P^{RES,min}$	minimum generation of RES
$P^{RES,max}$	maximum generation of RES
$SOC^{BESS,min}$	minimum SOC level of the BESS
$SOC^{BESS,max}$	maximum SOC level of the BESS
$SOC^{APEV,min}$	minimum SOC level of the APEV
$SOC^{APEV,max}$	maximum SOC level of the APEV
E_{i}^{RODS}	daily energy demand of the RODS
E_{i}^{IFR}	daily energy demand of the IFR
Y_{ij}^{t}	magnitude of Y-bus matrix element
θ_{ij}	angles of complex Y-bus matrix elements (rad)
$V^{\max}$, $V^{\min}$	maximum and minimum limits on bus voltages, respectively (kV)
$S_{ij}^{\max}$	upper limit for apparent power flow from bus i to bus j (MVA)

Function

C	total cost ($)

Abbreviations

MG	micro-grid
V2G	vehicle to grid
G2V	grid to vehicle
EMS	energy management system
PEV	plug-in electric vehicle
APEV	aggregated plug-in electric vehicle
WF	wind farm
PV	photovoltaic
BESS	battery energy storage system
IFR	industrial fish refrigerator
RODS	reverse osmosis desalination system
SG	smart grid
SOC	state of charge
CS	case study
PNS	power not supplied
ENS	energy not supplied
EP	excess power
EE	excess energy
PEM	point estimate method
V2G	vehicle to grid
G2V	grid to vehicle
RES	renewable energy source

model is developed to investigate the techno-economic performances of a high renewable energy-based stand-alone MG. In this paper operation scheduling of an isolated MG is optimized considering different demand-side management strategies [6]. In [7] authors argue that traditional approaches to rural electrification based on grid extension, are not suited for remote island regions. They suggest that energy management systems (EMSs) improving sustainable operation of off-grid systems need to be developed [7]. The EMS makes it possible to operate BESS facilitating the operation management of stand-alone power systems. In [8] a stand-alone renewable-based power system with BESS for remote islands has been proposed. The results of techno-economic evaluation show that the proposed hybrid power system with BESS is a practical and cost effective solution for remote islands electrification [8].

In [9] a method has been proposed for load demand management of a grid connected MG based on the produced power in which the uncertain parameters of uncontrolled resources are taken into consideration. The BESS is added to the network based on the modeling of

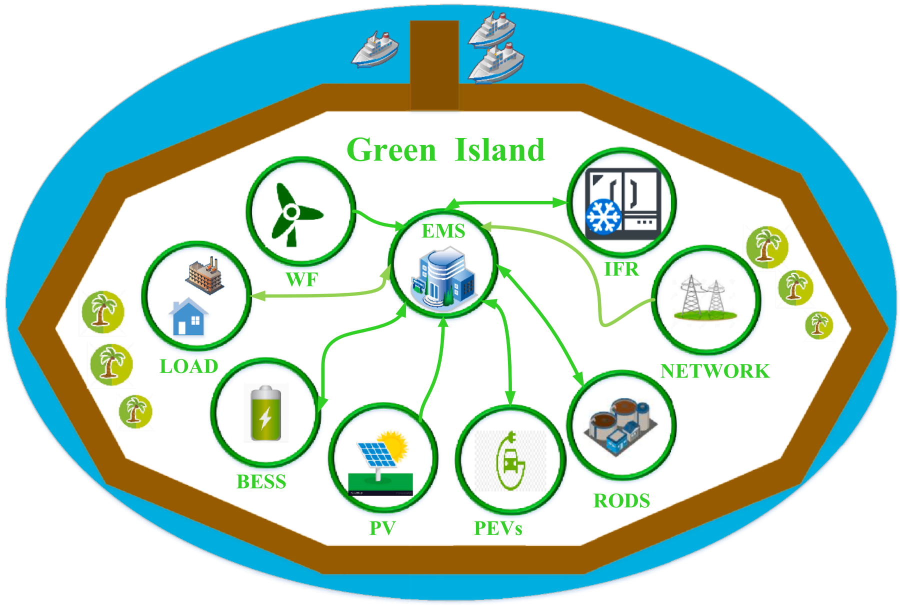

Fig. 1. The proposed EMS for MG day-ahead scheduling.

demand management to reduce operation costs of the MG [9]. In [10] different storage and non-storage power balancing methods in isolated MGs have been reviewed. Although storage methods facilitate the operation management of isolated power systems, the stochastic and volatile behavior of renewables makes it difficult to keep the balance between generation and demand. In order to overcome this burden, dump loads are applied when the generation exceeds demand [11]. Dump loads usually dissipate the excess energy as heat through electric heaters [11]. However, this excess energy can be utilized efficiently to supply some certain loads improving the welfare of people who live in remote islands such as desalination system and industrial refrigerators. These loads can be scheduled in a manner that increase the flexibility of the isolated power system. On the other hand, load shedding is applied in the situation that demand exceeds the generation [12]. However, load shedding reduces consumers' welfare and system efficiency. In recent years, the deployment of SG technology and advancements in PEVs charge/discharge modes of operation make the opportunity for stand-alone MG operators to keep the balance between generation and demand with more flexibility. In [13] an electricity generation scheduling method coordinated with PEV charging in an industrial MG considering PV generation has been proposed. However, the discharge mode of PEVs and uncertainty of renewables have not been considered in this work [13]. In [14] an operation strategy of PEVs for a smart MG is proposed. The application of PEVs as energy resources in V2G mode provides several grid support applications in both connected and isolated operation modes [14]. In [14] a comprehensive analysis on the charge/discharge management of PEVs in G2V and V2G modes has been presented [15]. The scheduling of PEVs energy exchange in an isolated MG considering PEV availability in multiple places during the daytime and in the evening is the main focus of this work [15]. The results show the effectiveness of the proposed charge/discharge management strategy in providing sustainable power supply for consumers of a stand-alone MG [15].

In valuable researches reviewed here, several solutions have been proposed for energy management of an isolated MG. However, some solutions like using a backup diesel generator is not appropriate for a renewable-based isolated MG and some solutions like load shedding may reduce consumers' welfare and system efficiency. Moreover, the idea of schedulable loads optimal planning has not been applied as a viable solution for an off-grid MG energy management. Furthermore, a comprehensive EMS, considering more realistic conditions like the uncertainty associated with renewables has not been developed for an off-grid remote island energy management.

1.3. Contribution

In this paper a comprehensive EMS for day-ahead operation of an isolated MG providing electricity for people who live in a remote island is presented. The island is equipped with SG technology and embedded with PEVs. Moreover, a desalination plant with water storage is used to provide drinking water of the island. The main occupation of the island is considered to be fishing and therefore large-scale industrial fish refrigerators are operated in the island. The MG supplies the electricity demand of the island by renewable generation units including wind and PV power plants. Furthermore, a BESS is operated by the MG to smooth the fluctuations of generated power. The proposed EMS in this paper considers the uncertainty of renewables and uses the potential of PEVs and the BESS charge/discharge modes of operation to keep generation and demand in balance. Moreover, schedulable loads in the MG including desalination system and industrial refrigerators are planned in a manner that optimally utilize the excess energy in off-peak hours. Therefore, in summary the main contribution of this work are as follows.

1 A new stochastic EMS for day-ahead operation planning of a renewable-based isolated MG is proposed.
2 Schedulable loads including desalination system and industrial refrigerators are optimally planned to utilize the excess energy.

1.4. Paper organization

The remaining parts of the paper are laid out as follows: in Section 2, MG components and the proposed EMS are introduced. In Section 3, Mathematical formulation is presented. Case studies and numerical results are illustrated in Section 4. Finally, some related conclusions are derived in Section 5.

2. MG model and the EMS

The MG considered in this work is located in a remote fishing island. The island is supposed to be green and fossil fuel-free area embedded

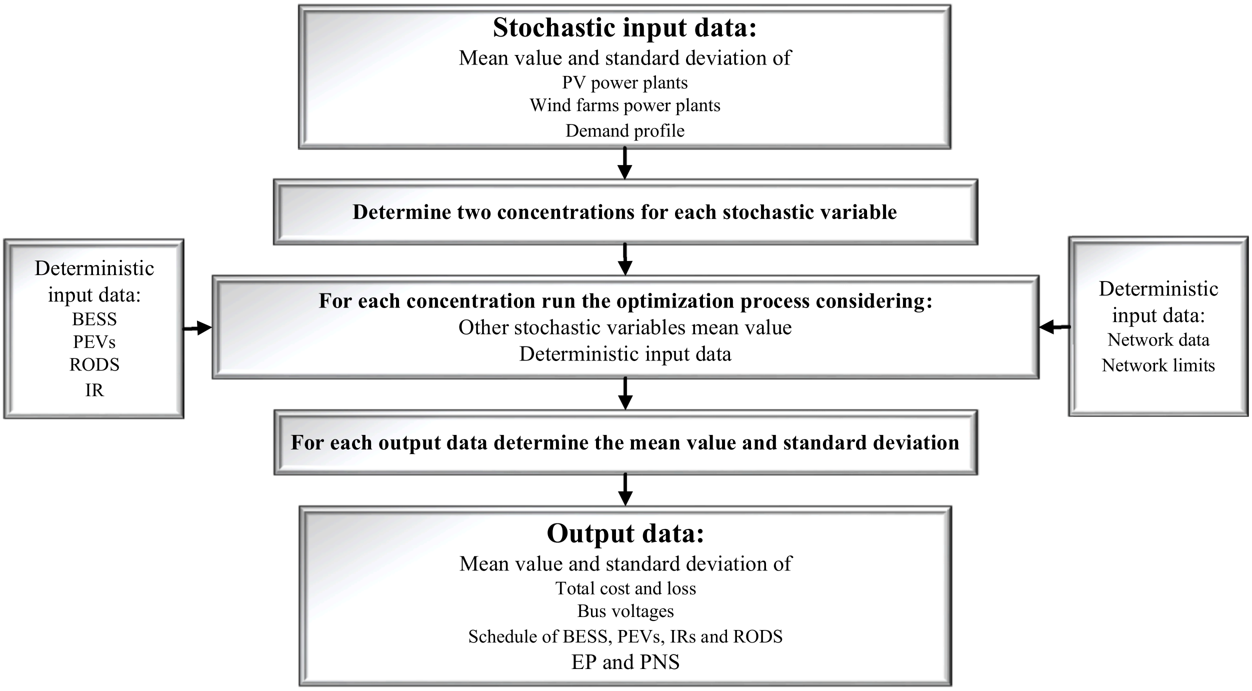

Fig. 2. Flowchart of the EMS scheduling optimization.

with PEVs. Renewable-based generation units including wind and PV power plants are operated in the island to supply energy demand of consumers. In order to compensate renewable energy fluctuations, the MG operates a BESS. Drinking water of the island is provided by a desalination plant with a water storage. Moreover, industrial fish refrigerators are operated in the island to store fish and other marine catch. The MG is equipped with SG technologies and has required infrastructure to use the potential of PEVs charge/discharge and schedulable loads including desalination system and industrial refrigerators planning for maintaining the balance between generation and demand. The components and their connections of the stand-alone MG considered in this work are shown in Fig. 1.

2.1. Renewable energy sources (RESs)

2.1.1. Wind power plant

The relationship between output power of a wind turbine ($P(\nu)$) and wind speed (ν) is non-linear. It is represented by operational parameters of wind turbine including cut-in, cut-out and rated wind speeds [16]. Eq. (1) presents wind power output of a wind farm as a function of the wind farm capacity (Cap_w), based on the model presented in [17].

$$P(\nu) = Cap_w \times \begin{Bmatrix} 0 & 0 \leq \nu \leq \nu_i \\ a + b\nu^3 & \nu_i \leq \nu \leq \nu_r \\ 1 & \nu_r \leq \nu \leq \nu_o \\ 0 & \nu \geq \nu_o \end{Bmatrix} \tag{1}$$

where parameters a, and b are given as follows [17].

$$a = \frac{\nu_i^3}{\nu_i^3 - \nu_r^3} \tag{2}$$

$$b = \frac{1}{\nu_r^3 - \nu_i^3} \tag{3}$$

2.1.2. PV power plant

PV power generation unit is a renewable-based power plant absorbing sunlight and convert it into electricity. The power output of the PV panel is proportional to the solar radiation received by the panels [18] and it is formulated as follows.

$$P_{PV}(t) = P_{PV,r}\eta_{PV}\frac{E_{PV}(t)}{E_{stc}}(1 + \alpha_{PV}(\tau_{PV}(t) - \tau_{stc})) \tag{4}$$

where, $P_{PV,r}$ is rating of PV panel. η_{PV} is the efficiency of PV panel.$E_{PV}(t)$ is solar radiation induced. E_{stc} is the normal radiation at standard test conditions and α_{PV} is PV panel temperature coefficient. $\tau_{PV}(t)$ and τ_{stc} are PV panel temperature and the normal temperature of cells respectively.

2.2. Energy management system (EMS)

The proposed EMS takes distribution network and BESS data and forecasted day-ahead hourly generation of wind and PV power plants and demand profile as input data. Then, gives day-ahead optimal scheduling of the BESS, desalination system and refrigerator, expected operation cost, total excess power (EP) and power not supplied (PNS) as output data. It should be mentioned that, the power generation of renewables and demand profile are estimated based on weather forecast and historical data, which is beyond the scope of this study. The proposed EMS is illustrated in Fig. 2.

3. Mathematical formulation

3.1. Objective function

In the proposed EMS, the objective function is the minimization of the total operation cost. The operation cost (C) includes the cost of BESS and PEVs battery degradation and the cost of power not supplied. The operation cost of wind and PV power plants is negligible and has not been considered in this work. Thus, the objective function is formulated as follows.

$$\min \quad C = \sum_t \sum_i \begin{pmatrix} P_{i,t}^{BESS,Ch}.C^{BESS,Ch} + P_{i,t}^{BESS,Dch}.C^{BESS,Dch} + P_{i,t}^{PEV,Ch}.C^{PEV,Ch} + \\ P_{i,t}^{PEV,Dch}.C^{PEV,Dch} + C^{PNS}.P_{i,t}^{PNS} \end{pmatrix} \tag{5}$$

where, $P_{i,t}^{BESS,Ch}$, $P_{i,t}^{BESS,Dch}$, $P_{i,t}^{PEV,Ch}$ and $P_{i,t}^{PEV,Dch}$ are the charge and discharge

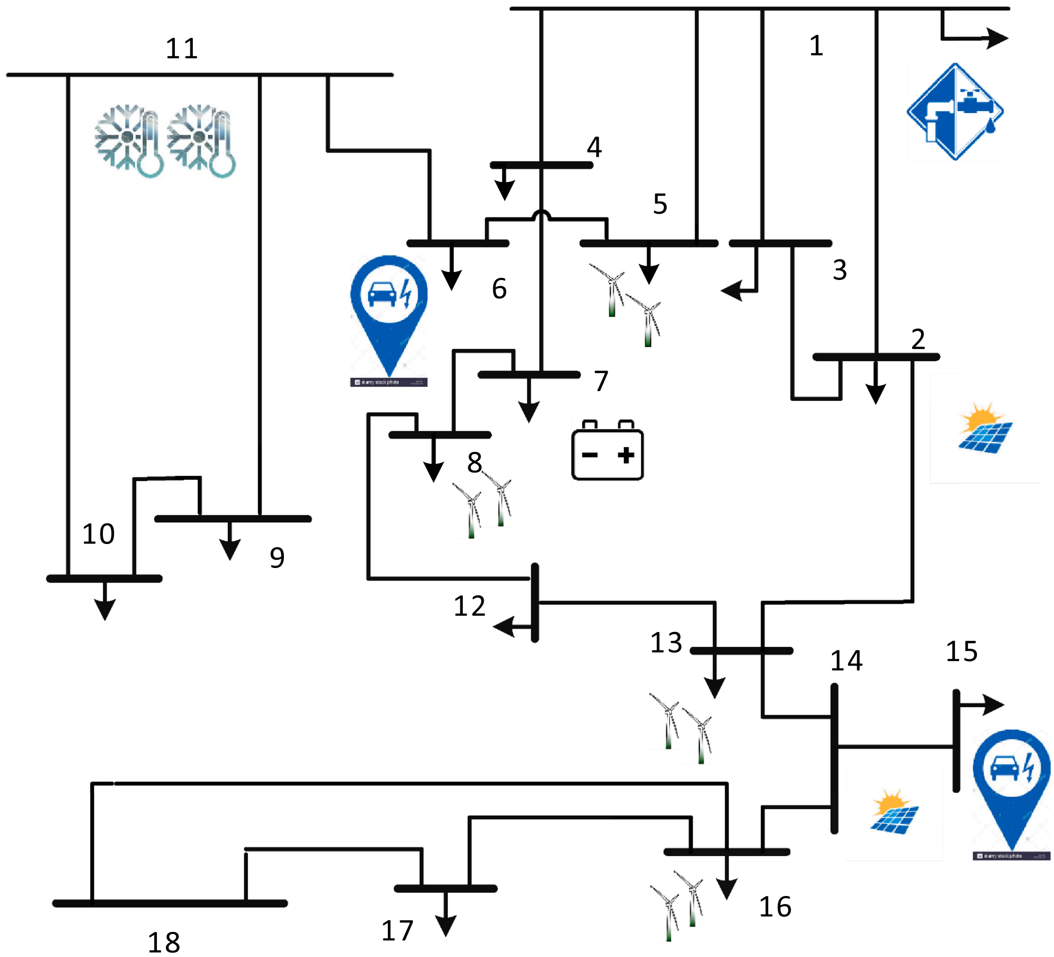

Fig. 3. The MG distribution grid.

power of the BESS and the charge and discharge power of PEVs respectively. Moreover, $C^{BESS,Ch}_{i,t}$, $C^{BESS,Dch}_{i,t}$, $C^{PEV,Ch}_{i,t}$and $C^{PEV,Dch}_{i,t}$ are the charge and discharge cost of the BESS and the charge and discharge cost of PEVs respectively. $P^{PNS}_{i,t}$and $C^{PNS}$are the power not supplied (PNS) and the cost of power not supplied respectively. It should be mentioned that the operation cost of renewable power plants is insignificant and has been neglected in this work.

3.2. Constraints

3.2.1. PEV V2G and G2V model and constraints

All residential, commercial, industrial and office buildings in the island are supposed to be equipped with SG technology and PEV charge/discharge facilities. The PEVs are charged/discharged when they are parked at the buildings. It is assumed that PEVs are parked at residential areas of the island from 17:00 PM to 7:00 AM and are parked at commercial, industrial and office areas of the island from 8:00 AM to 16 PM. During these times, aggregated PEVs' (APEVs') batteries at a network bus are operated as a lumped BESS by the MG. The charging/discharging power constraints for this lumped BESS during the times when the PEVs are in the parking are as follows.

$$0 \leq P^{APEV,Ch}_{i,t} \leq b^{APEV,Ch}_{i,t}.P^{APEV,Ch,max}_{i,t} \tag{6}$$

$$0 \leq P^{APEV,Dch}_{i,t} \leq b^{APEV,Dch}_{i,t}.P^{APEV,Dch,max}_{i,t} \tag{7}$$

$$b^{APEV,Ch}_{i,t} + b^{APEV,Dch}_{i,t} = 1 \tag{8}$$

$$SOC^{APEV}_{i,t+1} = SOC^{APEV}_{i,t} + \frac{\eta^{APEV,Ch}_{i,t}.P^{APEV,Ch}_{i,t}}{C^{APEV}_{i}} - \frac{P^{APEV,Dch}_{i,t}}{\eta^{APEV,Dch}_{i,t}.C^{APEV}_{i}} \tag{9}$$

$$SOC^{APEV,min} \leq SOC^{APEV}_{i,t} \leq SOC^{APEV,max} \tag{10}$$

where, $b^{APEV,Ch}_{i,t}$ denotes the availability of APEV at bus *i* for charging at time t, $b^{APEV,Dch}_{i,t}$denotes the availability of APEV at bus *i* for discharging at time t, $P^{APEV,Ch,min}_{i,t}$and $P^{APEV,Dch,max}_{i,t}$ represent the peak charging/discharging limits, respectively. Moreover, Eq. (6) ensures that APEV cannot be charged and discharged at the same time. Eqs. (7) and (8) show the APEVs' state of charge (SOC) model and limits respectively. The SOC decreases when PEV owners drive their car, and increases when the PEV is connected to the charger at the parking. In order to encourage PEV owners to take part in V2G/G2V programs, their battery degradation cost is compensated.

3.2.2. BESS model and constraints

The model and constraints of the BESS are presented as follows.

$$SOC^{BESS}_{i,t+1} = SOC^{BESS}_{i,t} + \frac{\eta^{BESS,Ch}_{i,t}.P^{BESS,Ch}_{i,t}}{C^{BESS}_{i}} - \frac{P^{BESS,Dch}_{i,t}}{\eta^{BESS,Dch}_{i,t}.C^{BESS}_{i}} \tag{11}$$

$$SOC^{BESS,min} \leq SOC^{BESS}_{i,t} \leq SOC^{BESS,max} \tag{12}$$

Table 1
Characteristics of the BESS.

Bus no	Capacity (MWh)	P_{Ch}^{max} (MW)	P_{Dch}^{max} (MW)	η_{Ch}	η_{Dch}	Initial level 8 AM (MWh)	Final level 7 AM (MWh)	Minimum level (MWh)	$C^{BESS,Ch}$, $C^{BESS,Dch}$ ($/MWh)
7	1.5	0.15	0.15	0.93	0.93	0.5	0.5	0.1	12

Table 2
Characteristics of the APEV at bus 6.

Capacity (MWh)	P_{Ch}^{max} (MW)	P_{Dch}^{max} (MW)	η_{Ch}	η_{Dch}	Initial level 17:00 PM (MWh)	Final level 7:00 AM (MWh)	Minimum level (MWh)	$C^{PEV,Ch}$, $C^{PEV,Dch}$ ($/MWh)
1.5	0.15	0.15	0.93	0.93	0.5	1.5	0.2	12

Table 3
Characteristics of the APEV at bus 15.

Capacity (MWh)	P_{Ch}^{max} (MW)	P_{Dch}^{max} (MW)	η_{Ch}	η_{Dch}	Initial level 8:00 AM (MWh)	Final level 16:00 PM (MWh)	Minimum level (MWh)	$C^{PEV,Ch}$, $C^{PEV,Dch}$ ($/MWh)
1.5	0.15	0.15	0.93	0.93	0.5	0.9	0.2	12

Table 4
Characteristics of dump loads.

	Bus no	Daily demand (MWh)	Hourly demand (MW)	On time (hour)
IFR	11	0.9	0.05	18
RODS	4	3.6	0.3	12

Table 5
Characteristics of RESs.

RES	Bus no	$P^{RES,min}$ (MW)	$P^{RES,max}$ (MW)
WF1	5	0	1.8
WF2	8	0	1.3
WF3	13	0	1.2
WF4	16	0	2
PV1	14	0	0.6
PV2	18	0	0.6

$$0 \leq P_{i,t}^{BESS,Ch} \leq b_{i,t}^{BESS,Ch}.P_{i,t}^{BESS,Ch,max} \tag{13}$$

$$0 \leq P_{i,t}^{BESS,Dch} \leq b_{i,t}^{BESS,Dch}.P_{i,t}^{BESS,Dch,max} \tag{14}$$

$$b_{i,t}^{BESS,Ch} + b_{i,t}^{BESS,Dch} = 1 \tag{15}$$

The model of BESS SOC dynamics is presented in Eq. (11). Eqs. (12)–(14) denote the SOC, charging and discharging bounds for the BESS respectively. Eq. (15) presents charging/discharging status restrictions where the BESS is not allowed to charge and discharge at the same time.

3.2.3. Desalination system model and constraints

The desalination plant considered in this work is a reverse osmosis desalination system (RODS) which provides drinking water for people who are living in the island. This system is made up of four major stages/components: (1) pretreatment, (2) pressurization, (3) membrane separation, (4) post-treatment stabilization, and (5) drinking water storage [19]. In pressurization stage pumps raise the pressure of the pretreated water to an operating pressure by consuming electrical energy. Considering the capacity of desalination plant and the water reservoir, the desalination system and electrical pumps do not need to be operated for 24 h of the day. Therefore, the desalination system energy consumption model for providing enough daily drinking water can be presented as follows.

$$E_i^{RODS} = \sum_{t=1}^{24} P_{i,t}^{RODS}.b_{i,t}^{RODS} \tag{16}$$

where $P_{i,t}^{RODS}$, E_i^{RODS} and $b_{i,t}^{RODS}$ are the rated power, daily energy consumption and on/off status of desalination system respectively.

3.2.4. Industrial refrigerator model and constraints

Industrial refrigerators have been installed and are operated in the island to store caught fishes before delivering them to markets. It is known that the refrigerator does not run continuously 24 h per day. It has a thermostat that shuts off the refrigeration system when the refrigerator is cold enough [20]. Therefore, the refrigerator energy consumption model can be presented as follows.

$$E_i^{IFR} = \sum_{t=1}^{24} P_{i,t}^{IFR}.b_{i,t}^{IFR} \tag{17}$$

where $P_{i,t}^{IFR}$, E_i^{IFR} and $b_{i,t}^{IFR}$ are the rated power, daily energy consumption and on/off status of refrigerators respectively.

Table 6
Day-ahead generation forecast of stochastic DGs (WFs).

HOUR	WF1 (Bus 5)		WF2 (Bus 8)		WF3 (Bus 13)		WF4 (Bus 16)	
	Mean (MW)	St. De (MW)	Mean (MW)	St. De (MW)	Mean (MW)	St. De (MW)	Mean (MW)	St. De (MW)
$t = 8$	1.1438	0.0606	0.7638	0.0405	0.703	0.0186	1.2084	0.0704
$t = 9,\ldots,12$	1.3244	0.0877	0.8844	0.0703	0.814	0.0431	1.3992	0.0741
$t = 13,\ldots,16$	1.4147	0.0712	0.9447	0.0495	0.8695	0.0230	1.4996	0.0713
$t = 17,\ldots,20$	1.2642	0.074	0.8442	0.0737	0.7770	0.0309	1.3356	0.0855
$t = 21,\ldots,24$	1.0836	0.029	0.7236	0.0192	0.6660	0.0529	1.1448	0.0456
$t = 1,..,4$	0.8729	0.0347	0.5829	0.0154	0.5365	0.0284	0.9222	0.0391
$t = 5,\ldots,7$	1.1438	0.0606	0.7238	0.0405	0.703	0.0186	1.2084	0.0704

Table 7
Day-ahead generation forecast of stochastic DGs (PVs).

HOUR	PV1 (Bus 14)		PV2 (Bus 18)	
	Mean (MW)	St. De (MW)	Mean (MW)	St. De (MW)
$t = 8$	0.0703	0.0093	0.0694	0.0018
$t = 9$	0.1443	0.0299	0.1423	0.0075
$t = 10$	0.2516	0.0133	0.2482	0.a0065
$t = 11$	0.2849	0.0075	0.2811	0.0233
$t = 12$	0.3885	0.0514	0.3832	0.0508
$t = 13$	0.4662	0.0123	0.4599	0.0244
$t = 14$	0.4921	0.0391	0.4855	0.0128
$t = 15$	0.481	0.0127	0.4745	0.0125
$t = 16$	0.481	0.0178	0.4745	0.0251
$t = 17$	0.407	0.0431	0.4015	0.0213
$t = 18$	0.296	0.0235	0.262	0.077
$t = 19$	0.2146	0.0114	0.2117	0.0168
$t = 20$	0.0333	0.0057	0.0328	0.0028
$t = 21,\ldots,24$	0	0	0	0
$t = 1,\ldots,7$	0	0	0	0

3.2.5. Security constraints

3.2.5.1. Power balance constraints. The power balance between the generation and consumption is obligatory for sustainable operation of the MG. The power balance constraint is presented as follows.

$$\sum_i P_{i,t}^{Wind} + P_{i,t}^{PV} + P_{i,t}^{BESS,Dch} + P_{i,t}^{APEV,Dch} + P_{i,t}^{PNS} = \sum_i \left(P_{i,t}^{RODS} + P_{i,t}^{IFR} + P_{i,t}^{BESS,Ch} + P_{i,t}^{APEV,Ch} + P_{i,t}^{D} + P_{i,t}^{EP}\right) + P_t^{Loss} \tag{18}$$

where, $P_{i,t}^{Wind}$, $P_{i,t}^{PV}$, $P_{i,t}^{BESS,Dch}$, $P_{i,t}^{BESS,Ch}$, $P_{i,t}^{APEV,Dch}$, $P_{i,t}^{APEV,Ch}$,$P_{i,t}^{RODS}$, $P_{i,t}^{IFR}$, $P_{i,t}^{D}$, $P_{i,t}^{EP}$, $P_{i,t}^{PNS}$ and $P_t^{Loss}$are wind power generation, PV power generation, BESS discharging power, BESS charging power, APEVs discharging power, APEVs charging power, desalination system rated power, refrigerator rated power, load demand power, excess power, power not supplied and power loss of the network respectively.

3.2.6. Network constraints

3.2.6.1. Power flow equations. The power-flow equations for active and reactive power at each hour and bus are presented as follows.

$$P_{i,t}^{G} - P_{i,t}^{D} = \sum_j \left|V_i^t\right|\left|V_j^t\right|\left|Y_{ij}^t\right|\cos\left(\theta_{ij} + \delta_j^t - \delta_i^t\right) \tag{19}$$

$$Q_{i,t}^{G} - Q_{i,t}^{D} = \sum_j \left|V_i^t\right|\left|V_j^t\right|\left|Y_{ij}^t\right|\sin\left(\theta_{ij} + \delta_j^t - \delta_i^t\right) \tag{20}$$

Where $P_{i,t}^{G}$ is calculated as follows.

$$P_{i,t}^{G} = P_{i,t}^{Wind} + P_{i,t}^{PV} + P_{i,t}^{BESS,Dch} + P_{i,t}^{PEV,Dch} + P_{i,t}^{NPS} - \left(P_{i,t}^{IFR} + P_{i,t}^{RODS} + P_{i,t}^{BESS,Ch} + P_{i,t}^{PEV,Ch} + P_{i,t}^{EP}\right) \tag{21}$$

3.2.6.2. Bus voltage constraint

$$V^{\min} \le V_{i,t} \le V^{\max} \tag{22}$$

3.2.6.3. Feeder flow constraint

$$S_{ij,t} \le S_{ij}^{\max} \tag{23}$$

3.3. Uncertainty modeling

Integrating renewable-based generations like PVs and WFs to the grid creates uncertainty, which is a critical challenge in power system planning. Two well-known methods of uncertainty modeling are Monte Carlo simulation and point estimate method (PEM). Although the larger number of scenarios can increase the accuracy, it may increase the computation time. Therefore, always a trade-off between the number of simulated scenarios and the computation time of the scenario-based optimization methods is considered. The two-point estimate method (2PEM), as a particular case of the PEM, is known as an efficient, robust and fast approach that only requires to solve 2 × m scenarios [21]. Therefore, it presents high levels of simplicity and accuracy. This method uses uncomplicated mathematical operations including mean value and standard deviation. To model m random variables using 2PEM, only solving 2 × m scenarios is needed to model the intrinsic uncertainty of m random variables [22]. Assume$L = \{l_1, l_2, \ldots, l_m\}$is a random variable with a mean value of μ_{l_v} and standard deviation of σ_{lv}. Z is a random quantity and a function of L as Z = f(l). Each concentration of random variable l_v can be defined with a weight (w_{vs}). The concentration of l_{vs} is defined as follows.

$$l_{vs} = \mu_{lv} + \xi_{vs}\sigma_{lv} \tag{24}$$

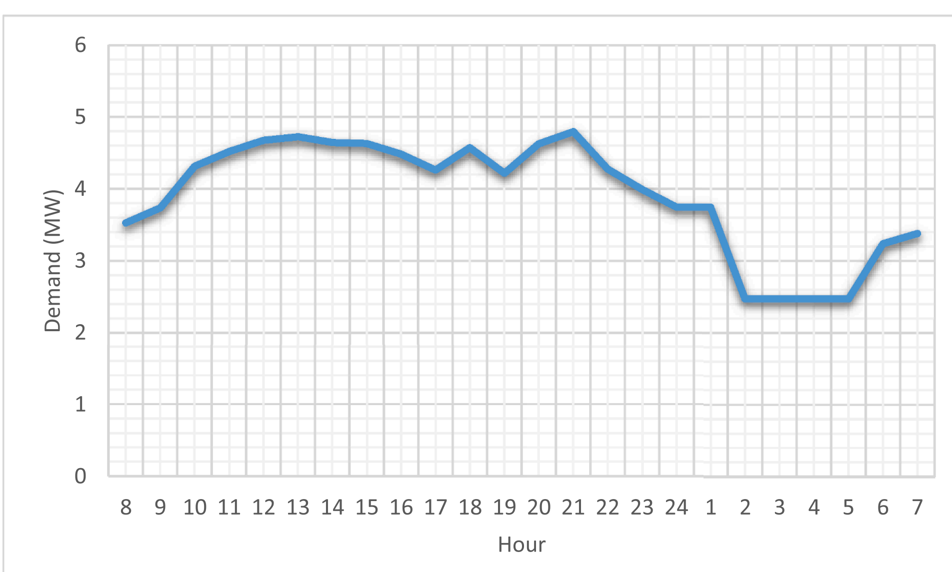

Fig. 4. Demand profile.

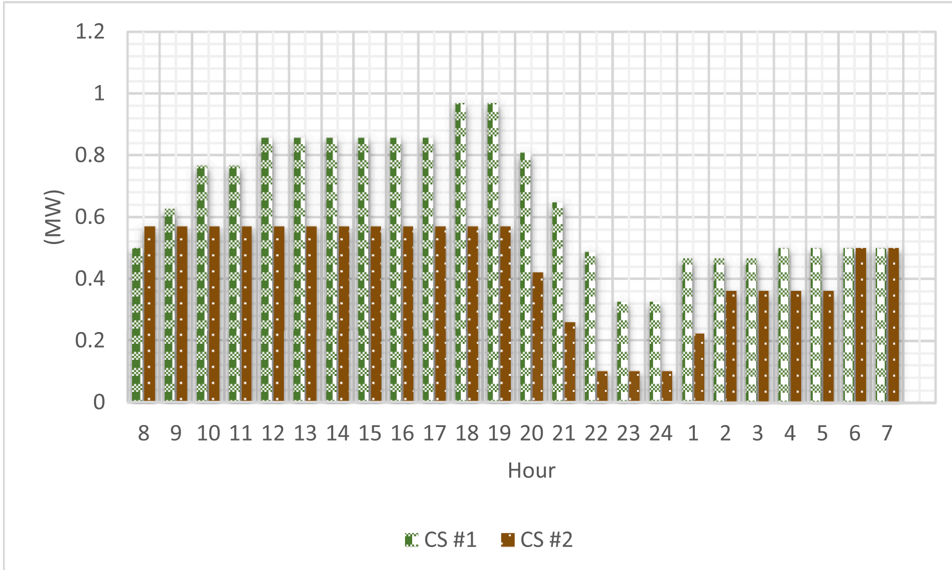

Fig. 5. The BESS stored energy level.

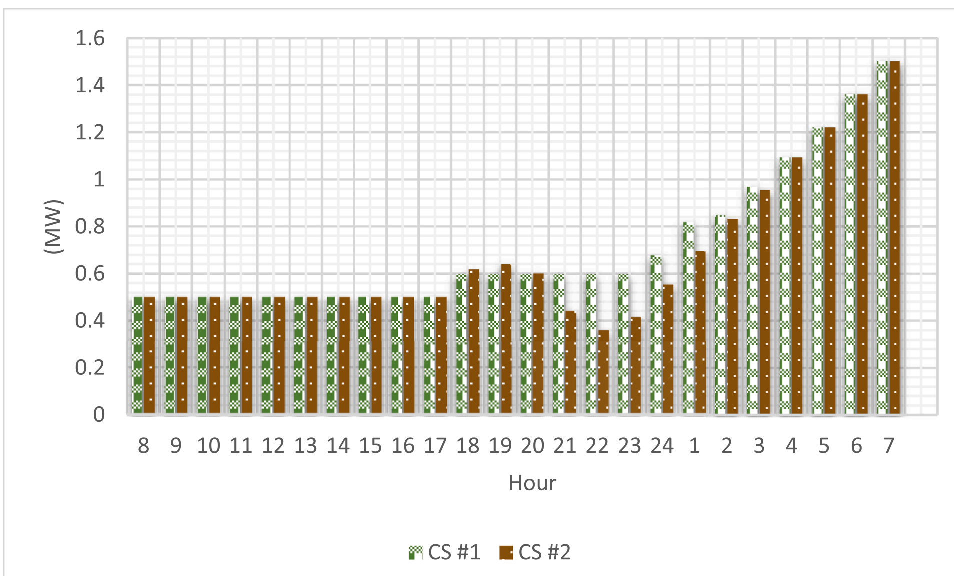

Fig. 6. The APEV at bus 6 stored energy level.

$$\xi_{vs} = \frac{\lambda_{v3}}{2} + \sqrt{m + \left(\frac{\lambda_{v3}}{2}\right)^2} \quad , \quad \xi_{vs} = \frac{\lambda_{v3}}{2} - \sqrt{m + \left(\frac{\lambda_{v3}}{2}\right)^2} \tag{25}$$

$$w_{v1} = -\frac{\xi_{v2}}{m(\xi_{v1} - \xi_{v2})}, \quad w_{v2} = -\frac{\xi_{v1}}{m(\xi_{v1} - \xi_{v2})} \tag{26}$$

$$\lambda_{v3} = \frac{E(l_v - \mu_{lv})^3}{\sigma_{lv}^3} \tag{27}$$

At each iteration, a variable concentration point and the mean value of other random variables are taken into account and the probabilistic information of the output variable are calculated as shown in Eq. (28).

$$Z_{v,s} = F(l_{v1}, l_{v2}, ..., l_{vs}, ..., l_{vm}) \tag{28}$$

The initial condition of the output is presented as follows.

$$E(Z) \cong E(Z) + \sum_s w_{vs} Z_{vs} \tag{29}$$

Finally, the output is presented in the form of expected value and standard deviation.

4. Numerical evaluation

4.1. Simulation data and model assumptions

The proposed model and energy management system is tested on an 18-buses 33 kV distribution network (Fig. 3) extracted from 30 buses system presented in [23]. The characteristics of the BESS is given in Table 1 based on data given in [24] with some modifications. Moreover, the data of APEVs, IRs, RODS PVs and WFs are presented in Tables 2–5 respectively. Moreover, the mean value and standard deviation of PVs and WFs forecasted power generation are presented in Tables 6 and 7 respectively. Furthermore, the mean value of forecasted demand is presented in Fig. 4. Finally, the cost of PNS has been set to 60$ per each megawatt hour.

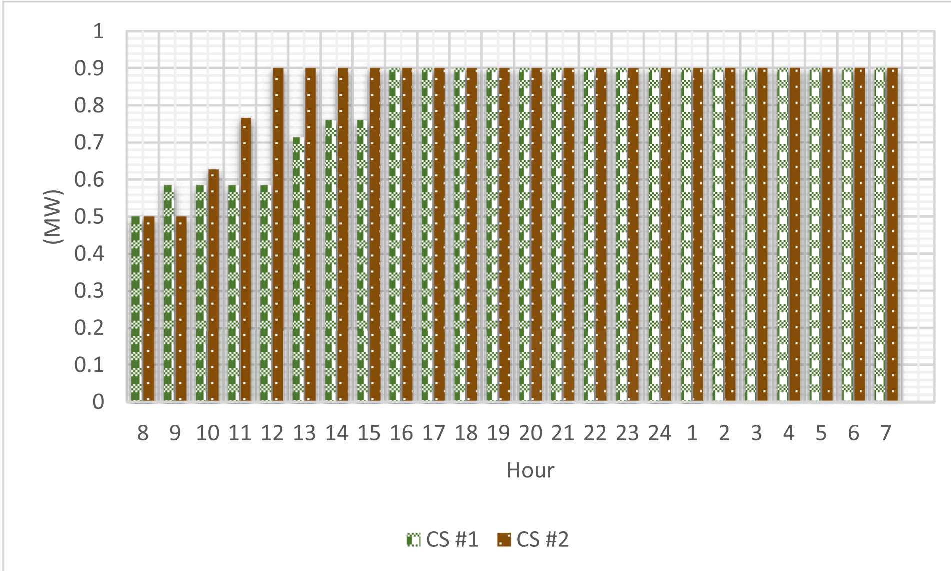

Fig. 7. The APEV at bus 15 stored energy level.

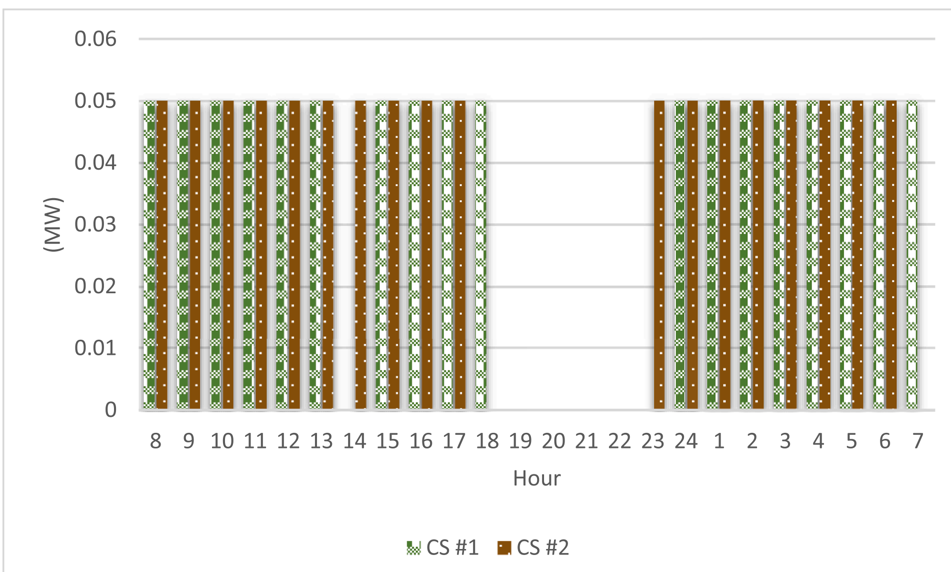

Fig. 8. The IFRs ON/OFF schedule.

4.2. Case studies (CSs)

In order to evaluate the effectiveness of the proposed EMS, two CSs have been performed in this section. In the CS #1, the V2G mode of the PEVs has not been activated and they just get charged through the grid. Moreover, in this case the RODS and IFRs have not been optimally scheduled by the EMS. Therefore, the only option of the MG to keep the generation and demand in balance is the BESS. In the CS #2, in contrast, the V2G mode has been activated and the charge/discharge pattern of the APEVs has been optimally scheduled by the EMS. Moreover, the RODS and IFRs have been optimally scheduled by the EMS to make balance between generation and demand. These CSs have been solved in General Algebraic Modelling System (GAMS) using the DICOPT (DIscrete and Continuous OPTimizer) solver [25]. DICOPT is a program for solving Mixed Integer Nonlinear Programming (MINLP) problems that involve linear binary or integer variables and linear and nonlinear continuous variables [25]. DICOPT is based on the extensions of the outer-approximation algorithm for the equality relaxation strategy [25]. The MINLP algorithm inside DICOPT solves a series of Nonlinear Programming (NLP) and Mixed-Integer Programming (MIP) sub-problems [25]. These sub-problems can be solved using any NLP or MIP solver that runs under GAMS [24]. The computation time on a core IV PC, 2.6 MHz with 4 GB of RAM for CS #1 and #2 is 221 and 257 s respectively. It should be noted that since input data like wind and PV generation and demand profile are stochastic, the results are probabilistic and have been presented in the form of mean value. Moreover, the scheduling time horizon is set to be 24 h, from 8:00 AM on one day to 8:00 AM the next day in order to consider PEVs park/travel periods accurately.

4.3. Results and discussion

As mentioned above, in CS #1 the BESS is optimally scheduled by the EMS in order to minimize the MG operation cost and keep the balance between generation and demand. In this case (#1) PEVs are scheduled to

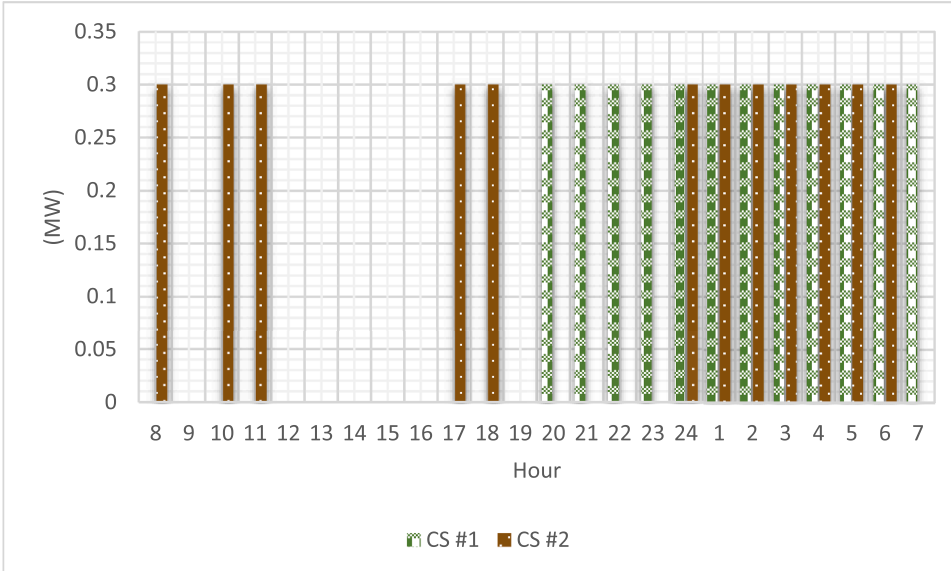

Fig. 9. The RODS ON/OFF schedule.

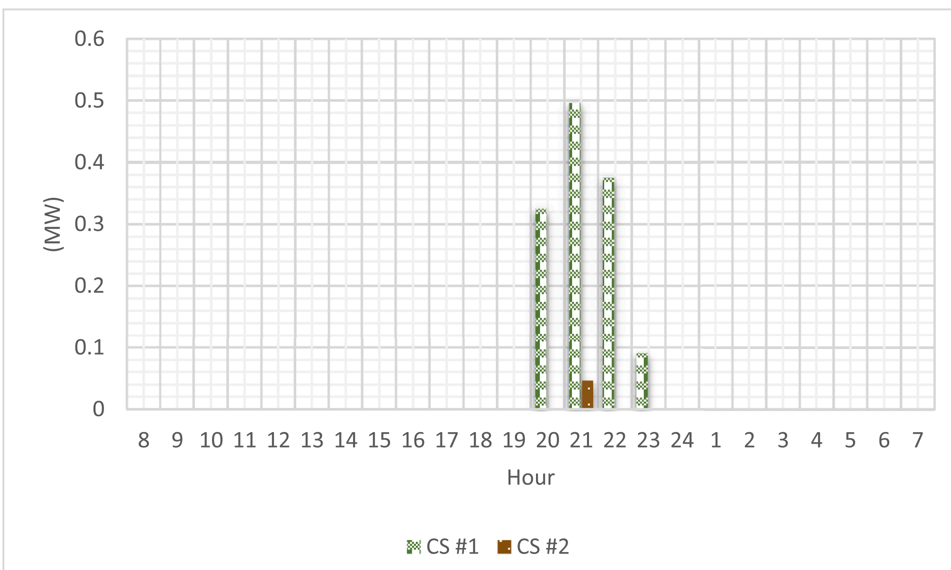

Fig. 10. The power not supplied.

be charged when they are parked in the parking and their V2G mode of operation has not been activated in this case. Moreover, in CS #1 the ON/OFF state of the RODS and IFRs are set by MG operator and has not been optimally scheduled by the EMS. In contrast, in CS #2, the V2G mode of PEVs is activated and their charge/discharge pattern is scheduled optimally by the EMS. Moreover, in this case (#2) the ON/OFF state of the RODS and IFRs are set optimally to reduce the operation cost of the MG and improve the balance management of the MG. Fig. 5 shows the BESS level of charge in CSs #1 and #2. The variation of charge level in CS #1 is more than CS #2. It is due to the fact that in CS #2 in addition to the BESS, APEVs are also scheduled optimally to keep the generation and demand in balance. Therefore, the BESS is less charged/discharged in CS #2. Moreover, the most discharge rate of the BESS is between hours 21–24 in both cases, because during these hours the generation of PV units is zero. Figs. 6 and 7 show APEVs at buses 6 and 15 level of charge respectively. As it can be seen from Figs 6 and 7, in CS #1, APEVs are only charged, however, in CS #2 APEVs are scheduled to be charged and discharged during the period that they are parked in the parking. Fig. 6 shows that the energy level of the APEV at bus 6 is reduced during hours 21 and 22. This is due to the fact that during these hours, demand is at the highest level (Fig. 4) and PV units do not generate power. Therefore, the APEVs are planned to be in V2G mode of operation in order to keep the generation and demand in balance. The operation scheduling of the IFRs has been presented in Fig. 8. The IFRs are equipped with thermostat used to control the interior temperature of refrigerator. As shown in Fig. 8, in CS #2 the IFRs' motor is set ON and is scheduled to operate during off-peak hours. Moreover, as it can be seen from Fig. 9, the RODS is scheduled by the EMS to be operated in CS #2 during off-peak hours. In the other word, the RODS is in the OFF state during hours 20–23 which are peak hours, while in CS #1 the RODS is in the ON state during these hours.

Optimal scheduling of the BESS, APEVs and dump loads in CS #2 reduces the PNS significantly as shown in Fig. 10. Fig. 10 shows that in CS #1 the MG is faced with PNS during peak hours 20–23 resulting in

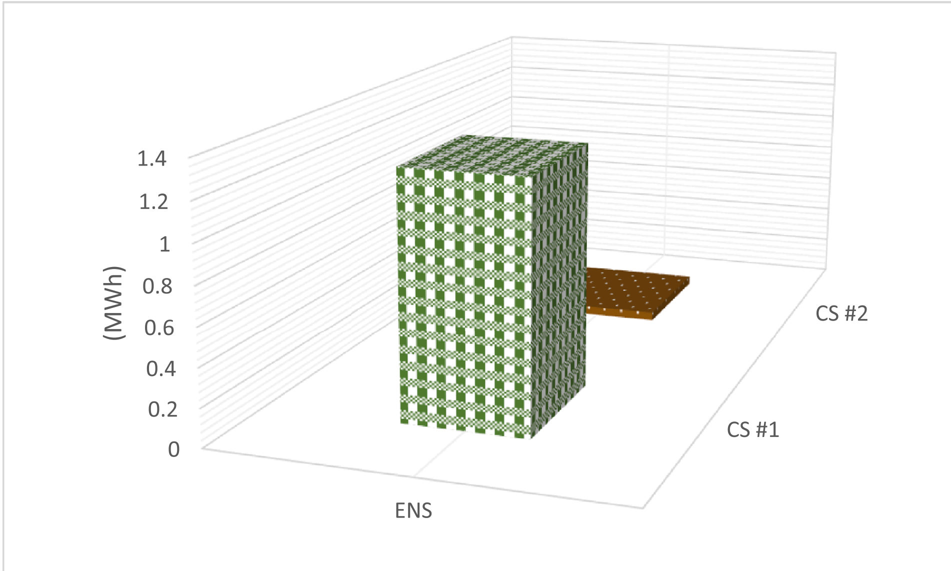

Fig. 11. The energy not supplied.

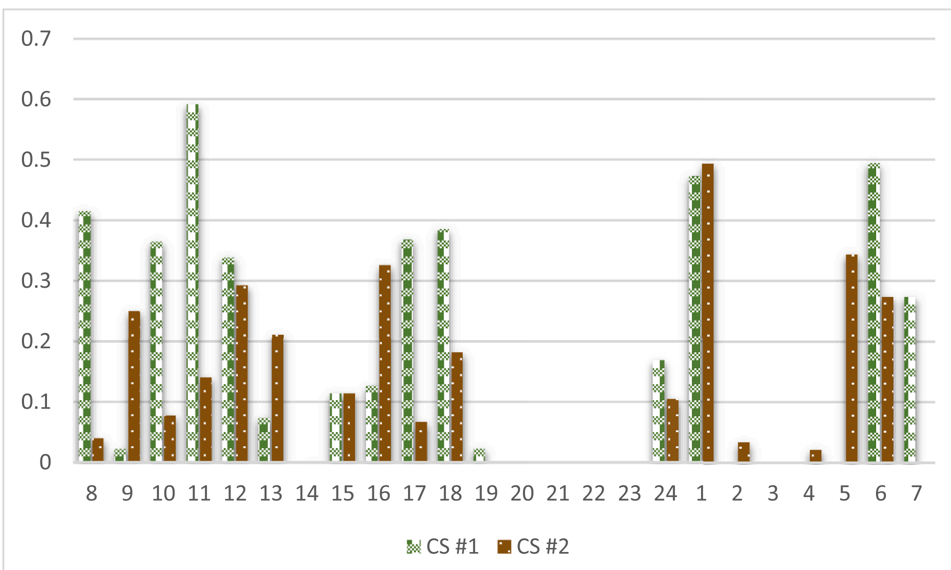

Fig. 12. The excess power.

dissatisfaction of consumers. However, the PNS is seen only during hour 21 in CS #2. The main reason of this improvement in CS #2 is less power consumption and more power discharge of the BESS and APEVs during peak hours. Moreover, the total value of energy not supplied (ENS) is reduced from 1.29 MW in CS #1 to 0.046 MW in CS #2 as can be seen in Fig. 11. Fig. 12 shows the EP during the optimization horizon. However, the EP is seen during one more hour in CS #2 in comparison with CS #1, the total value of the Excess energy (EE) during the day is significantly reduced in CS #2 (Fig. 13). Based on Fig. 13 the total EE in CS #2 is 4.23 MW which is 1.26 MW less than the total EE in CS #1. This is due to the fact that, the EMS shifts the power consumption of the RODS and IFRs to off-peak hours and therefore, the excess energy during these hours is consumed efficiently. Finally, Fig. 14 shows the total cost of the MG in CSs #1 and #2. The total cost in CS #2 is reduced to 110.74$ which is 70.86$ less than total cost in CS#1. It confirms that, the proposed EMS in this work not only reduces the EE and ENS, but also reduces the operation cost of the MG. It should be mentioned that in this work issues related to reliability and resiliency have not been considered. For instance, in cloudy/rainy days the generation of PVs reduces. In this condition, WFs as main energy sources of the MG can cover the low generation of PVs to some extent. Moreover, the BESS and APEVs facilitating energy management of the MG may be unavailable in some periods because of technical or other reasons. Therefore, to overcome power deficit in these conditions substantially, reliability and resiliency analysis should be performed, which will be the subject of future research of the authors.

5. Conclusion

A new EMS has been proposed in this paper for an isolated renewable-based MG located in a fishing island embedded with PEVs. In order to keep the balance between generation and demand the EMS schedules the BESS. Moreover, the V2G mode of PEVs is activated and their charge/discharge schedule is optimized to minimize the operation

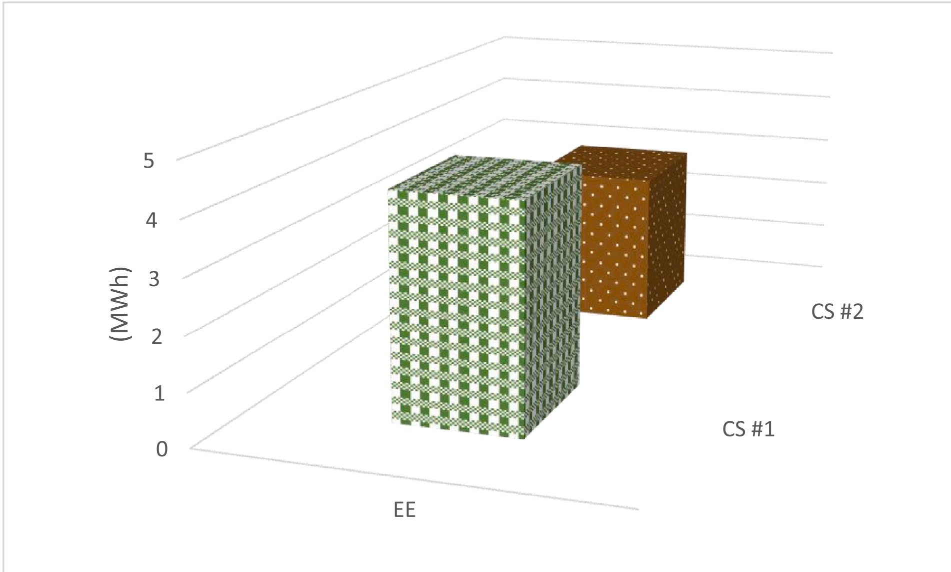

Fig. 13. The excess energy.

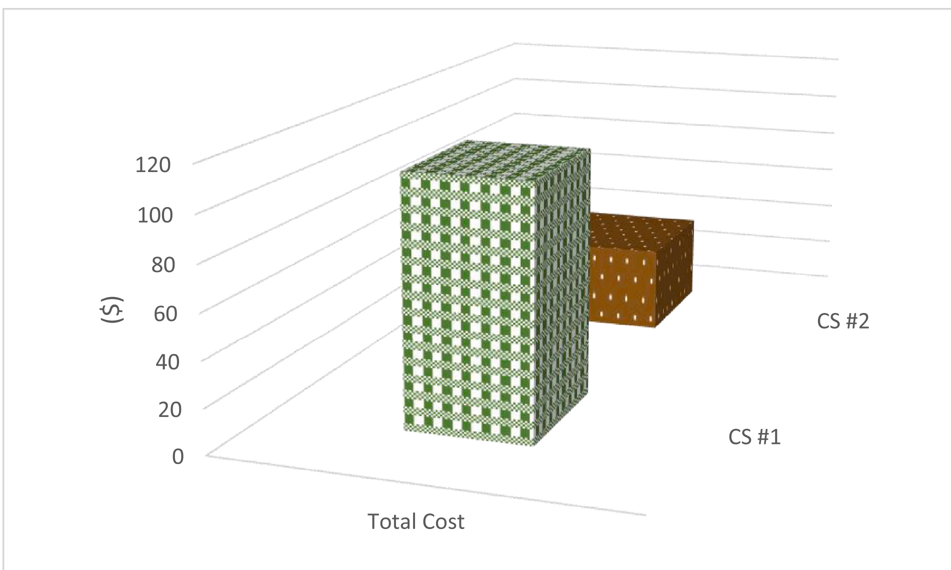

Fig. 14. The total cost.

cost of the MG and make balance between generation and demand at the same time. Furthermore, the EMS optimally schedules the RODS and IFRs as dump loads to reduce the PNS and EP of the MG. The uncertainty associated with renewable generation and demand have been taken into account in this work to increase the reality and accuracy of the proposed EMS. In order to validate the effectiveness of the proposed EMS, two case studies have been performed and results have been investigated extensively. The results show that the optimal scheduling of APEVs charge/discharge and dump loads operation in addition to the BESS in CS #2 not only reduces the operation cost of the MG by 65%, but also reduces the ENS and EE by 96% and 30% respectively. The most superior of the proposed EMS is that it is not connected to the grid and has not the option of dispatchable DGs to keep the generation and demand in balance. However, the results confirm that it minimizes the operation cost and improves the imbalance management of the MG significantly utilizing the potential of the APEVs and dump loads optimally.

CRediT authorship contribution statement

Afsaneh Saffar: Investigation, Methodology, Software, Visualization. **Ahmad Ghasemi:** Conceptualization, Investigation, Supervision, Project administration, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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