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Comparison of different power generators in PV-battery-power generator hybrid system †

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Abstract

Nowadays, the use of solar panels for generating electricity is common. Given the discontinuous nature of solar energy, the use of batteries to store energy in the day and supply it at night is essential. However, using one auxiliary power system (APS) can reduce the number of solar panels needed, reduce the cost, and increase reliability. In this study, the combination of different auxiliary systems with solar panels and batteries is compared in terms of economical efficiency, ecological compatibility, and reliability. Auxiliary systems include diesel generator, gas generator, solid oxide fuel cell (SOFC), and micro gas turbine. Of course, in this study, the effect of fuel price, technology development in SOFC cost, change in the power of auxiliary power system and also change in the maximum number of panels have been considered. A multi-objective evolutionary algorithm was used to obtain the best solutions of every configuration. The evolutionary algorithm is Pareto envelope-based selection algorithm (PESA). According to the results and necessity of using a backup power generator, the most ecological and economical recommended hybrid system is the hybrid system with target SOFC. Therefore, if SOFC technology develops rapidly, using SOFCs as the auxiliary system will be cheaper than others and ecologically the most compatible. Also from ecological point of view, the use of systems such as gas generators or diesel generators is not justified.

Keywords: Photovoltaic; Multi-objective; SOFC; Diesel generator; Gas generator; Micro-turbine

1. Introduction

The depletion of fossil fuel reserves and the pollution caused by conventional energy sources have made necessitous the exploitation of renewable energy sources (RES). These alternative energy production systems, such as Photovoltaic (PV) systems, are being supported by many governments on a worldwide basis. Discontinuity due to the energy produced by solar panels necessitates the use of batteries. On the other hand, auxiliary systems can be used to minimize cost and maximize reliability. The best auxiliary system is that which produces the least emission and has the least cost. Baniasad Askari and Ameri [1] studied a simple optimization method for calculating the optimum configurations of photovoltaic-battery (PV-bat) systems with high reliability and minimum cost. They found different system configurations with high reliability in the first stage, and then selected the least costly system configurations in the second stage. Due to the high price of solar panels, in order to reduce the cost and of course increase the reliability, utilizing an auxiliary system is recommended. Some power generation systems that can be associated with this system are diesel generator, gas generator, micro gas turbine, and solid oxide fuel cell.

Diesel generators give relatively high efficiency. These devices change the diesel combustion energy to electricity. The combination of diesel generators with solar panels and batteries are often used. Nafeh [2] has sized a PV/Diesel generator hybrid energy system to meet the load for about 100% availability. The operation of the diesel generator and the number of the PV modules and batteries were optimized for a given load characteristic and a given diesel generator that would achieve a minimum initial cost and a desired depth of discharge for battery storage. Dufo and Bernal [3] optimized a PV-Diesel system by HOGA program (hybrid optimization by genetic algorithms) and compared it with a stand-alone PV-only system. Their results showed the economical advantages of the PV-hybrid system. Baniasad and Ameri [4] used PV-diesel-battery power systems to meet typical load requirements in a remote region in Kerman, Iran. They used a simple two-step optimization method that found different system configurations with high reliability in the first step, and then selected the minimum cost system configurations in the second step. Due to the low price and availability of natural gas (NG) in Iran, the use of gas generator is suitable. The combi-

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nation of a gas generator with solar panels has not been considered so far. In this study, this combination will be compared with other combinations. Micro gas turbines (MGT) have recently been considered especially in combination with other devices. Degobert et al. [5] studied the possibility of using a photovoltaic system combined with a high speed micro-turbine. They considered a simple and effective modelling of the PV and MTG generators and verified the effectiveness of the proposed hybrid system by simulation. Lastly, they showed that short-term storage was necessary to reduce the fast fluctuations of power in the case of sensitive loads. Costamagna et al. [6] considered the model of the hybrid system obtained by coupling the micro gas turbine and the SOFC. This model allowed the evaluation of the design and of design behavior of the hybrid system. Solid oxide fuel cells are developing. They have relatively high efficiency, low noise (they do not have movement components) and little emission. Because of high temperature products, SOFCs are suitable to combine with gas turbine or micro gas turbine. Lee et al. [7] described the power managements of a UAV's hybrid electric propulsion systems. They considered three electric propulsion systems with different power sources, i.e. solar cells, fuel cells, and batteries. Each power source was modelled in Matlab/Simulink and integrated into the power system. For fuel cells and batteries, their simulation process was verified via a comparison between the simulation results and available flight test results of UAVs. Park et al. [8] analysed the influence of steam injection on the performance of hybrid systems combining a solid oxide fuel cell and a gas turbine. They examined two different configurations (pressurized system and ambient pressure system) and compared the effects of injecting steam, generated by recovering heat from the exhaust gas, on system performances. They concluded that without steam injection, the pressurized system generally exhibits higher system efficiency than the ambient pressure system, and the effect of the steam injection on system efficiency varies depending on system configurations and design conditions.

The combination of solar panels with fuel cells has often been studied, but usually proton exchange membrane (PEM) fuel cells are used. Silva et al. [9] presented an economical assessment and optimization of a hybrid distributed generation system, comprised of a PV system, PEM fuel cell, and batteries as potential sources of energy for isolated communities in the Amazon region. Their paper outlined some policies to promote the use of renewable energy sources in isolated areas in Brazil derived from the pilot project. Eroglu et al. [10] proposed a photovoltaic/wind/PEM fuel cell hybrid power system for stand-alone applications demonstrated with a mobile house. They showed that different renewable sources can be used simultaneously to power off-grid applications.

Because of the large number of variables usually considered and the mathematical models applied, classical optimization techniques may consume excessive CPU time or even prove unable to take into account all the characteristics associated with the posed problem. During the last 3 decades, heuristic techniques have been applied. One of the most widely used heuristic techniques has been the multi-objective evolutionary algorithms (MOEAs). Dufo and Bernal [11] applied the strength Pareto evolutionary algorithm to the multi-objective design of isolated hybrid systems, minimizing both the total cost and the unmet load. Sadeghi and Ameri [12] presented a multi-objective optimization method for calculating the optimum configurations of photovoltaic-battery systems with high reliability and minimum cost for different tilt angles of the panels.

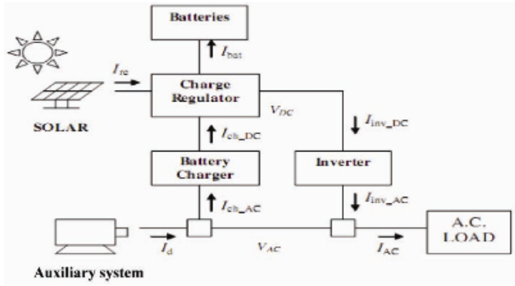

Fig. 1. PV-battery- auxiliary system.

Iran contains an estimated 27 Trillion Cubic meter in proven natural gas reserves, surpassed only by Russia in the world. As a result, Iran has the second largest natural gas reserves in the world and also, there is a natural gas pipeline in most parts of the country. Furthermore, Iran has a good solar energy potential. Therefore, the use of solar radiation and natural gas for local power generation is recommended.

The majority of papers consider diesel generator or PEM fuel cell as the auxiliary system for the hybrid system, and none of them has compared different power generation systems. This study compares different auxiliary systems to obtain the best one in terms of economical efficiency, ecological agreement, and reliability for combination with solar panels and batteries (Fig. 1). First, for every configuration (PV panels-batteries-diesel generator, PV panels-batteries-SOFC, PV panels-batteries-gas generator, and PV panels-batteries-MGT), the best solutions (Pareto frontier) are determined by a MOEA. After that, by comparing the Pareto frontiers, a better configuration for supplying a sample load has been introduced. Also, the effect of power change in APS and the effect of a change in the maximum number of panels are considered from ecological and economical point of view. No study, displaying the best combination of power generation systems, has been done previously. In the present work, a multi-objective evolutionary algorithm (PESA) has been used to select the best auxiliary system.

2. Mathematical model of the components

A detailed mathematical model of the components of the hybrid system (PV panels, batteries, auxiliary system, inverter) is shown in forthcoming subsections.

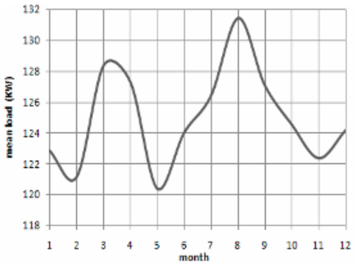

Fig. 2. Monthly average hourly load.

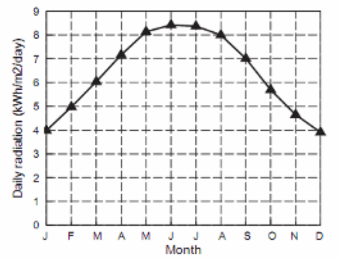

Fig. 3. Monthly average daily radiation.

2.1 Load demand

In the present work, load demand is a representation of remote households in Kerman, which are far from the utility grid. The measured annual average electric energy consumption of 500 typical households is considered. The diagram of sample load has been plotted in Fig. 2, which shows mean electrical load for every month.

2.2 PV panels

The solar energy calculations are made by using the hourly solar radiation data. The electricity generated by the PV systems is directly related to the solar energy received by the PV panels while the PV panels can be placed at different tilt angles and orientations. Most local solar observatories only provide solar irradiance data on a horizontal plane (radiation in Kerman for different month of the year has been shown in Fig. 3). Thus, an estimate of the total solar radiation incident on any required sloping surfaces is needed. In the present work, the slope of the PV panels is considered to be constant and equal to the latitudinal (30˚ N) position of Kerman, Iran. The HDKR model (Hay, Davies, Klucher, Reindl model) [13] is utilized to estimate the total solar radiation on the tilted surface:

$$I_T = (I_b + I_d A_i)R_b + I_d(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + (I_b + I_d)\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

where I_b and I_d are direct normal and diffuse solar radiations. A_i is the anisotropy index, and R_b is the geometric factor, which are defined as below:

$$A_i = \frac{I_b}{I_o} \quad (2)$$

$$R_b = \frac{\cos\theta}{\cos\theta_z}\,. \quad (3)$$

In the above relations, I_o is the integrated hourly extraterrestrial radiation on a horizontal surface; θ and θ_z are incidence and zenith angles, respectively. f is the cloudiness factor and is given by the following equation:

$$f = \sqrt{\frac{I_b}{I_b + I_d}}\,. \quad (4)$$

In Eq. (1), β is the slope of PV panels and ρ_g, the ground reflectance (also called Albedo), is the fraction of solar radiation incident on the ground that is reflected. A typical value of ground reflectance for grass-covered areas is 20 per cent, snow-covered area is 70 per cent, grass-plot area is 30 per cent, and desert dry lands are 45 per cent. In this article, the ground reflectance value is considered to be 45 per cent according to the Kerman climate (dry/desert-covered area).

Hourly power output from PV system is given by:

$$P_{PV} = I_T \eta_m \eta_{pc} P_f A_{PV} \quad (5)$$

where A_{pv} is the total area of the PV modules in m^2, η_m is the module reference efficiency (0.11), P_f is the packing factor (0.91), and η_{pc} is the power conversion efficiency (0.83). The module reference efficiency η_m can be estimated from the current and voltage of the PV module at maximum power point:

$$\eta_m = Cu_{mp} V_{mp} / G A_{cs} \quad (6)$$

where Cu_{mp} is the current at maximum power point (A), V_{mp} is the voltage at maximum power point (V), and A_{cs} is the area of a single PV module (m^2). The solar radiation at reference condition G in Eq. (6) is $1000 W/m^2$.

It is assumed that there are about 5000 m^2 of land for PV panels. Every 200 W photovoltaic panel occupies about 1.5 m^2. Taking into account the space required for rows and equipment, up to 2660 panels can be arranged. Therefore, the number of PV panel can change from s0 to 2660.

2.3 Batteries

Battery bank storage is sized to meet the load demand during non-availability period of renewable energy sources. At any time t, the charged quantity of the battery bank is subject to the following two constraints:

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad Cu_{bat,max}(t) \le Cu_{max}\,. \quad (7)$$

In the above relations, SOC_{min} (0.3) and SOC_{max} are the minimum and maximum SOC of the battery, respectively, SOC(t) is the battery SOC at each hour of the year, and Cu_{max} is the maximum charge current which is determined as a battery specification by its manufacture. In the present study, the maximum value of the SOC (SOC_{max}) is 1, and 0.3 is utilized as the value of the SOC_{min} according to the battery specifications. Depending on the PV and wind energy production and the load power requirements, the state of battery charge can be calculated from the following equations:

Battery charging,

$$SOC(t+1) = SOC(t) \times [1-\sigma(t)] + \frac{Cu_{bat}(t) \times dt \times \eta_{ch}(t)}{C_{bat}} . \quad (8)$$

Battery discharging,

$$SOC(t+1) = SOC(t) \times [1-\sigma(t)] - \frac{Cu_{bat}(t) \times dt \times \eta_{dch}(t)}{C_{bat}} . \quad (9)$$

where Cu_{bat} is the hourly mean of instantaneous current of the battery, σ(t) is the hourly self-discharge rate, which 0.018 percent is used in this study. η_{ch} and η_{dch} are the charge and discharge efficiency of the battery, respectively. In this study, η_{ch} and η_{dch} are considered the same and equal to 0.927.

2.4 Auxiliary systems

Given the discontinuous nature of solar energy, the use of batteries to store energy in the day and supply it at night and one auxiliary power system to produce power when panels and batteries cannot supply the load, as well as utilizing. Diesel generator, gas generator, solid oxide fuel cell (SOFC), and micro gas turbine are considered as auxiliary power systems.

The specific fuel consumption is defined as the fuel consumption required to produce 1 kWh of energy, and it is equal to the hourly fuel consumption for supplying a given load during 1 h. According to Skarstein and Uhlen [14], the hourly fuel consumption can be approximated as follows:

$$F.C. = A \times P(t) + B \times P_n \quad (10)$$

where A and B are constants, P(t) is the power generated at t moment, and P_n is the rated/nominal power.

The efficiency in % of the lower heating value (LHV) is calculated as:

$$\eta = \frac{P(t)}{F.C. \times 3600 \times LHV} \times 100 . \quad (11)$$

2.4.1 Diesel generator

A diesel generator is the combination of a diesel engine with an electrical generator (often called an alternator) to generate electrical energy. Diesel generating sets are used in places without connection to the power grid as emergency power-supply if the grid fails, as well as for more complex applications such as peak-lopping, Grid Support, and export to the power grid. In this study, diesel generator is used as an auxiliary system for solar panels. The plan brings generator sets online and takes them off line depending on the demands of the system at a given time.

The fuel consumption of the diesel generator, ConsDG (l/h), is modelled as Eq. (10). A and B are the coefficients of the consumption curve of the diesel generator. The specifications of diesel generator of Perkins 1104-C2 model are used to obtain these constants (A = 0.166 lit/kWh, B = 0.064 lit/kWh).

2.4.2 Gas generator

Natural gas generator usage should generally increase as it is the cleanest burning fossil fuel. Compared with oil and coal, natural gas generators produce lower emissions of nitrogen, sulphur, and greenhouse gasses like carbon dioxide. Natural gas generators also do not produce a pungent odor as a gasoline or diesel fuelled one would. For people with houses powered with some natural gas, the comparison of the gas bill and the electricity bill will definitely show how much cheaper gas is. So natural gas generators are cleaner and cheaper, but they are not as efficient as diesel generators. For residential electrical power generation using natural gas, the fuel supply is already supplied and there is no need to purchase extra fuel and store it. Gas lines are already in place, delivering natural gas that can be used by power generators.

The fuel consumption of the gas generator, ConsGG (m^3/h), is modelled as Eq. (10). A and B are the coefficients of the consumption curve of the gas generator. The specifications of gas generator of Generac QT100 model are used to obtain these constants (A = 0.327 m^3/kWh, B = 0.054 m^3/kWh).

2.4.3 Micro turbine

Gas turbines use the chemical energy from fossil fuels to increase the internal energy of the working fluid in a combustor. Micro turbine systems have many claimed advantages over reciprocating engine generators, such as higher power-to-weight ratio, low emissions and few, or just one, moving part. However, reciprocating engine generators are quicker to respond to changes in output power requirement and are usually slightly more efficient, although the efficiency of micro turbines is increasing.

The fuel consumption of the micro gas turbine, ConsMGT (m^3/h), is modelled as Eq. (10). A and B are the coefficients of the consumption curve of the micro gas turbine. The specifications of the micro gas turbine of TurbecT100 model are used to obtain these constants (A = 0.286 m^3/kWh, B = 0.023 m^3/kWh).

2.4.4 Solid oxide fuel cell

A solid oxide fuel cell (SOFC) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel. Fuel cells are characterized by their electrolyte material; the SOFC has a solid oxide or ceramic, electrolyte. Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. The largest disadvantage is the high operating temperature which results in longer start-up times and mechanical and chemical compatibility issues.

The fuel consumption of the solid oxide fuel cell, Cons-SOFC (m^3/h), is modelled as Eq. (10). A and B are the coefficients of the consumption curve of the solid oxide fuel cell. The specifications of the solid oxide fuel cell of Bloomenergy ES-5400 model are used to obtain these constants (A = 0.181 m^3/kWh, B ≈ 0 m^3/kWh).

For decades, experts have agreed that solid oxide fuel cells (SOFCs) hold the greatest potential of any fuel cell technology. With low cost ceramic materials and extremely high electrical efficiencies, SOFCs can deliver attractive economics. But until now, there were significant technical challenges inhibiting the commercialization of this promising new technology. SOFCs operate at extremely high temperature (typically above 800°C). This high temperature give them extremely high electrical efficiencies and fuel flexibility, both of which contribute to better economics, but it also creates engineering challenges. By solving these engineering challenges with breakthroughs in materials science and revolutionary new design, target SOFC will be a cost-effective technology.

2.5 Inverter

A power inverter, or inverter, is an electrical device that changes direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. In this study, ten 10 kW inverter with 92% efficiency has been used.

3. Objective functions

The objective functions are:

- The annualized cost: ANC ($/year).
- The loss of power supply percent: LPSP (%).
- The CO_2 emission: (kg/year).

3.1 Annualized cost

In finance, the annualized cost (ANC) is the cost per year of owning and operating an asset over its entire lifespan. ANC is often used as a decision making tool when comparing investment projects of unequal lifespans. In the present study, to compare different configurations of economical aspects, annualized cost is used. In order to calculate ANC, annualized initial capital cost, annualized replacement cost, and annualized operating and maintenance cost will be added.

Annualized initial capital cost: $C_{accap} = C_{cap} \cdot CRF(i,\, R_{proj})$

C_{acap}, C_{cap}, CRF, i, R_{proj} are annualized initial capital cost, initial capital cost, capital recovery factor, real interest rate, and system lifespan respectively.

Real interest rate: $i = \dfrac{f - i'}{f + 1}$.

i' and f are nominal interest rate and inflation, respectively.

Capital recovery factor: $CFR(i,\, R_{proj}) = \dfrac{i(1+i)R_{proj}}{(1+i)R_{proj-1}}$.

Annualized replacement cost:

$$C_{arep} = C_{rep} \cdot f_{rep} \cdot SFF(i,\, R_{comp}) - S.SFF(i,\, R_{proj}).$$

C_{arep}, C_{rep}, f_{rep}, SFF, R_{comp}, S are annualized replacement cost, replacement cost, ratio of capital recovery factor, sinking fund factor, and lifespan of component and salvage value, respectively. Sinking fund factor:

$$SFF\,(i, N) = \frac{i}{(1+i)^N - 1}\,,\; N = R_{com\,p}, R_{proj}\,.$$

Salvage value:

$$S = C_{rep} \times \frac{R_{rem}}{R_{comp}}\,,\quad R_{rem} = R_{comp} - (R_{proj} - R_{rep}),$$

$$R_{rep} = R_{comp} \times INT\left(\frac{R_{proj}}{R_{comp}}\right).$$

Ratio of capital recovery factor:

$$f_{rep} = \begin{cases} CRF(i,\, R_{proj}) \,/\, CRF(i,\, R_{rep}) & if\;\; R_{rep} > 0 \\ 0 & if\;\; R_{rep} = 0. \end{cases}$$

Operating and maintenance costs are usually annualized.

Annualized cost:

$$ANC = C_{accap} + C_{arep} + C_{a\,O\&M}\,. \tag{12}$$

Fuel prices in Iran and other places are different. In the present study, comparison is done based on two fuel prices:

1. Iran fuel price

Table 1. Fuel prices.

	Diesel ($/gal)	Natural gas ($/$m^3$)
International fuel	3.943	0.167
Iran fuel	0.778	0.156

Table 2. Specifications of different components.

	Power	Initial capital cost ($/kW)	Replacement cost ($/KW)	O&M cost per year ($/kW)	Life span (years)
PV panel	200 W	1000-3000	0	0.0025	25
Battery	3000 Ah	100	90	0.005	15
Inverter	10 kW	200-400	360-450	0.0015	15
DG	100 kW	150-400	135-360	0.01	20
SOFC	100 kW	3000	2700	0.0086	15
SOFC target	100 kW	450	405	0.0086	15
GG	100 kW	200-400	180-360	0.01	20
MGT	100 kW	700-900	630-810	0.015	10

2. International fuel price

Table 1 shows the price of fuel. In Iran fuel price is multi-rate so the mean fuel prices are used. Table 2 shows the initial, replacement, operation, and maintenance cost of different components. This table also shows the lifespan of different components. The mean value of price range in Table 2 is considered in computations.

The SOFC stakeholders stated that the DOE factory cost targets were very aggressive. The high cost of SOFC systems is somewhat unexpected because they do not use a platinum catalyst. In the achievability of the DOE cost concludes that are based on anticipated technical advances and improvements in the manufacturing capability of the fuel cell industry, a 2020 target of \$450/kW is provided as a "factory cost" objective by DOE [15].

3.2 Loss of power supply percent

Reliability of the system is expressed in terms of loss of power supply percent (LPSP). The objective function, LPSP, can be described by:

$$LPSP = \frac{\sum_{t=1}^{N_h} hours\,[CU_{supply}(t) < Cu_{needed}(t)]}{N_h} \times 100\,. \tag{13}$$

In the above relation, N_h is the number of time intervals (8760, number of hours in a year) and $I_{needed}(t)$ is the current needed by the load, which can be expressed as:

$$Cu_{needed}(t) = \frac{p_{bad}(t) - P_{PV}(t)}{V_{bat}} \times \eta_{batt} \tag{14}$$

$$Cu_{supply}(t) = \min\left(\frac{0.2 \times C_{bat}}{dt}, \frac{C_{bat} \times (SOC(t) \times (1-\sigma(t)) - SOC_{min})}{dt}\right). \tag{15}$$

$Cu_{needed}(t)$ is the current required for the load at hour t and $Cu_{supply}(t)$ is the current supplied by the system at hour t. η_{batt} is considered 0.86. $P_{load}(t)$ is the electrical load power requirements at hour t and $P_{PV}(t)$ is the power generated by PV modules at hour t.

3.3 Emissions

Table 3 shows CO_2 and NOx emission of different auxiliary systems for unit fuel consumption. The hours of auxiliary systems operation and therefore, fuel consumptions are specified, so emission of different auxiliary systems will be determined.

4. Multi-objective optimization evolutionary algorithm

The implemented multi-objective algorithm is based on PESA [16] because it has approximately fast convergence, probably due to its higher elitism intensity and it also has good accuracy. PESA has two parameters concerning population size i.e PI (the size of the internal population IP) and PE (the maximum size of the archive or external population). It has one parameter concerning the hyper-grid crowding strategy. The main steps in this algorithm are (i) generate and evaluate each of an initial internal population (IP) of PI chromosomes and initialize the external population (EP) to the empty set.(ii) Incorporate the non-dominated members of IP into EP.(iii) If a termination criterion has reached then stop, returning the set of chromosomes in EP as the result. Otherwise, delete the current contents of IP and repeat the following until PI new candidate solutions have been generated. With probability P_c, select two parameters from EP. Produce a single child via uniform crossover and mutate the child via bit-flip mutation. With probability (1-P_c) select one parent and mutate it to produce a child. (iv) Repetition of the same process.

1. Generate and evaluate each of an initial internal population (IP) of PI chromosomes.
2. Initialize the external population (EP) as empty set.
3. For t = 1 to number of generations.
3.1. Incorporate the non-dominated members of IP into EP.
3.2. Delete the current content of IP.
3.3. Until obtaining new solution of PI.
3.3.1. Select two parents from EP with probability P_c.
3.3.2. Recombine this two parents for obtaining one offspring.
3.3.3. Mutate the offspring.
3.3.4. Select one parent from IP with probability (1-P_c).
3.3.5. Mutate the parent to produce one offspring.
3.3.6. Add the two obtained offspring into IP.
4. Return to 3.

This algorithm is in charge of finding the designs that manage to, simultaneously, minimize the ANC of the system, the pollutant emissions, and the LPSP. It has been developed using the MATLAB programming language. The algorithm (MOEA) can search for the configuration of PV panels, batteries, auxiliary system, and inverter which minimizes the three objectives mentioned.

5. Results

The purpose of this study is the determination of the best auxiliary system for combination with solar panels and batteries to supply a sample load. The combination of different auxiliary systems with solar panels and batteries is compared in terms of economical efficiency, ecological compatibility, and

Table 3. CO_2 and NOx emission per unit fuel consumption for different auxiliary systems.

	CO_2 emission	NOx emission
Diesel generator	2.487 (kg/lit diesel)	0.0388 (kg/lit diesel)
Solid oxide fuel cell	1.931 (kg/m^3 NG)	0.00003838 (kg/m^3 NG)
Gas generator	1.931 (kg/m^3 NG)	0.00215 (kg/m^3 NG)
Micro gas turbine	1.931 (kg/m^3 NG)	0.00095 (kg/m^3 NG)

Table 4. Part load and full load efficiency.

	50% load	75% load	Full load
Diesel generator	34%	39%	43.4%
Solid oxide fuel cell	—	55.3%	52.2%
Gas generator	20.8%	23.5%	24.8%
Micro gas turbine	27.7%	29.5%	29.8%

reliability. First, for every configuration, the best solutions (Pareto frontier) are determined by PESA MOEA. After that, by comparing the Pareto frontiers, a better configuration is determined to supply the sample load. In this study, four configurations have been compared with each other:

1. Solar panels, batteries, diesel generator.
2. Solar panels, batteries, solid oxide fuel cell.
3. Solar panels, batteries, gas generator.
4. Solar panels, batteries, micro gas turbine.

Also, the effect of power change of APS and change in panel number upper limit is considered to determine an appropriate auxiliary power and suitable maximum number of panels.

Table 4 shows the part load and the full load efficiency of different auxiliary systems. DG, GG, and MGT have lower efficiency in the part load operation than in the full load operation. But the SOFC has higher efficiency in the part load operation than in the full load operation. It is obvious that the SOFC has the maximum efficiency and GG has the minimum efficiency.

The hybrid system includes some panels, some batteries, some inverters, and an auxiliary system. Installation space of panels is limited, and so the maximum number of panels is limited. In this study, 5000 m^2 of land is considered for panel installation. Every panel occupies 1.5 m^2 and due to the space needed for rows and other equipment, namely the maximum number of panels is 2660. So the number of panels can change only from 0 to 2660. By increasing the number of panels, cost rises, LPSP reduces, and power generation increases. Auxiliary power system is used when panels and batteries cannot supply the load. APS application increases when the number of panels, hence, the power generation of the panels decreases. However, this hybrid system may sometimes fail to supply the needed load and therefore, it does not meet the required load.

Fig. 4 shows the Pareto frontiers for the hybrid systems when diesel generators with different power rates are used as APS. It is obvious that the minimum available LPSP by APS of 50 kW power rate is about 1.6%. If the power of APS increases to 100 kW and 150 kW, minimum LPSP decreases to 0.7% and 0.38%, respectively. LPSP = 1.6%, LPSP = 0.7%, and LPSP = 0.38% mean that for 140.16 hours, 61.32 hours, and 33.28 hours of the year, respectively, the needed load is not supplied. In this work, LPSP = 1% is considered as a desirable LPSP. This means that for 87.6 hours of the year and about 14.4 minutes of the day, the needed load cannot be supplied.

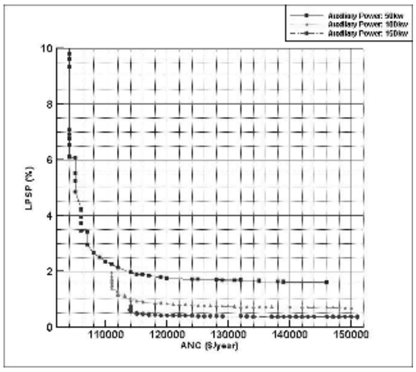

Fig. 4. Pareto frontiers for different APS power, international fuel price, and hybrid system with DG.

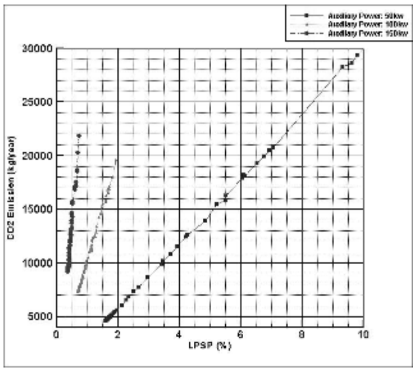

Fig. 5. Pareto frontiers for different APS power, international fuel price, and hybrid system with DG.

According to Fig. 5, CO_2 emission increases by increasing the power of APS. APS of 100 kW power supplies the desirable LPSP = 1%, and there is no need to increase the power of APS beyond it because excessive increase of APS power is unfavorable from ecological viewpoint. Because CO_2 emission and NOx emission both depend on fuel consumption, NOx emission has a similar behavior as CO_2 emission.

Figs. 6 and 7 show the Pareto frontier for the hybrid system that includes PV panels, batteries, inverters, and gas generator as APS. These figures show the effect of change in the power of APS on cost and emission, and they also suggest that LPSP does not depend on APS type. There is a difference between Figs. 4 and 5 (for combination of PV panels, batteries, inverters and diesel generator) and Figs. 6 and 7 (for combination of PV panels, batteries, inverters, and gas generator), which is the number of Pareto optimal sets. In this work, cost, CO_2 emission, and reliability are objective functions. According to MOEA, every Pareto optimal set must have at least one better objective function than other sets. Pareto optimal sets of the hybrid system with diesel generator are low because the diesel fuel price is relatively high. APS operation increases when the number of panels in the hybrid system decreases. So fuel consumption rises and because of high international diesel fuel price, the annualized cost of the hybrid system increases. Moreover, because of the low number of panels, LPSP in-

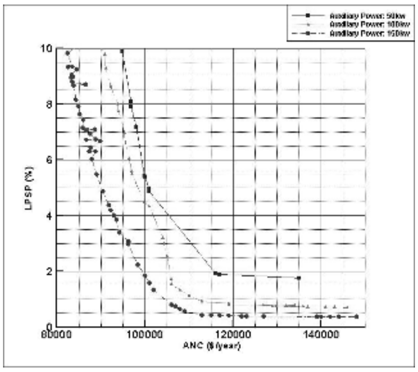

Fig. 6. Pareto frontiers for different APS power, international fuel price, and hybrid system with GG.

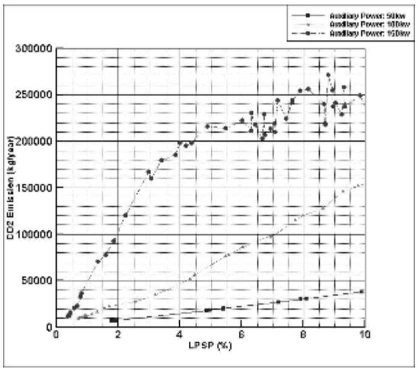

Fig. 7. Pareto frontiers for different APS power, international fuel price, and hybrid system with GG.

creases. A solution with high annualized cost and high LPSP is dominant and cannot be Pareto optimal set, so the number of Pareto optimal sets is low when the fuel price is high. But in the hybrid systems with gas generator that use NG as fuel, the number of optimal sets is large because the international price of NG is low.

Figs. 8 and 9 show the Pareto frontier of the hybrid system with diesel generator as APS which uses Iran diesel fuel price. Iran Diesel fuel price is lower than international diesel fuel price. For this reason, the number of Pareto optimal sets is much more than the previous case. Also, it is obvious that the mode of change in APS power does not depend on fuel price. Fuel price can only change the number of solutions. From ecological point of view, results do not change with Iran fuel price because emission does not depend on fuel prices.

For comparing different configurations, the best solutions for different configurations are determined by a multi- objective optimization algorithm (PESA), i.e. the best combinations of the number of panels and the number of batteries have been selected, and they have satisfied the objectives of the issues with the help of the auxiliary system. Pareto frontier has been plotted in ANC-LPSP, LPSP-CO_2, and LPSP-NOx coordinates for different configurations. Then, the diagrams of different configurations have been compared with each other. These diagrams are plotted for two fuel prices: international

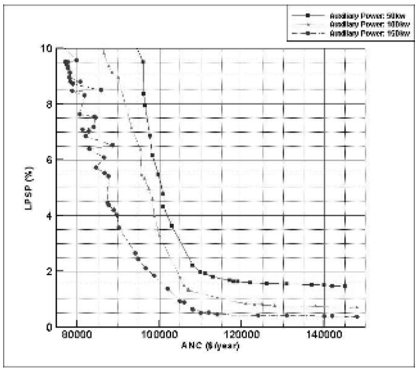

Fig. 8. Pareto frontiers for different APS power, Iran fuel price, and hybrid system with DG.

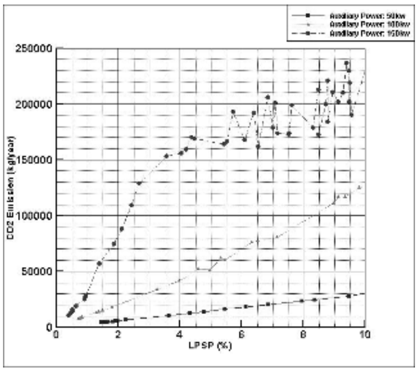

Fig. 9. Pareto frontiers for different APS power, Iran fuel price, and hybrid system with DG.

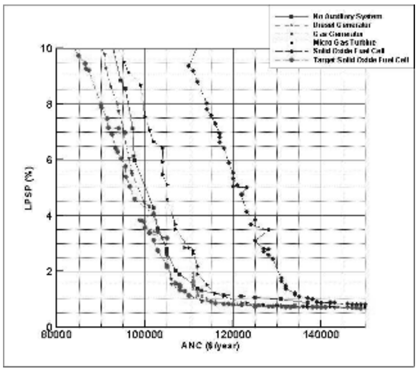

Fig. 10. Pareto frontiers of the hybrid system with different APS, international fuel price.

and Iran fuel prices.

Fig. 10 shows the Pareto frontier for international fuel prices in ANC-LPSP coordinate for the hybrid systems with different APS. Also, this figure considers an additional Pareto frontier that depends on the PV-battery hybrid system without APS. If there is enough land for PV panel installation, the needed load with LPSP = 1% can be supplied by putting the maximum number of PV panels equal to 2800 without needing APS. It is obvious that the ANC of the hybrid system without APS is lower than the ANC of the hybrid system with

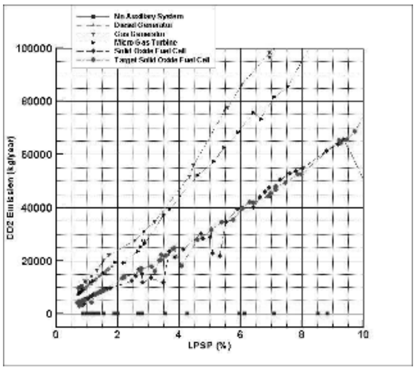

Fig. 11. Pareto frontiers of the hybrid system with different APS, international fuel price.

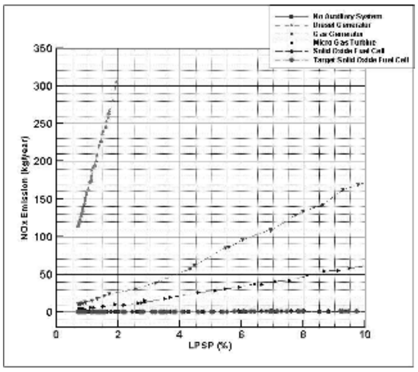

Fig. 12. Pareto frontiers of the hybrid system with different APS, international fuel price.

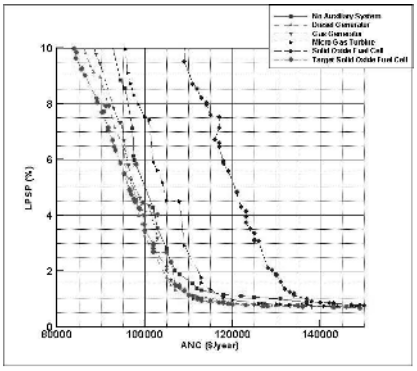

Fig. 13. Pareto frontiers of the hybrid system with different APS, Iran fuel price.

SOFC or MGT and higher than the ANC of the hybrid system with DG or GG or target SOFC. The difference between the ANC of different configurations is high at high LPSP; this difference decreases when LPSP decreases. The reason is that in low LPSP, the number of panels is high, and so the operation of APS is low. Because the efficiency of the SOFC is high and the price of NG (the fuel that is consumed in SOFC) is low, the least amount of ANC returns to the hybrid system with target SOFC. As previously mentioned, target SOFC mean SOFC with lower initial cost, which is accessible by technology improvement. After target SOFC, gas generator in the hybrid system causes lower ANC. In LPSP = 1%, the gas generator and target SOFC cause approximately equal ANC. The hybrid system with diesel generator is in third place from the economical point of view. Of course, the international diesel fuel price is very high, but due to the high efficiency of the diesel generator, it goes third from the economical viewpoint. MGT causes higher ANC than DG, and because of high initial price, SOFC has maximum ANC. If the difference between the ANC of the hybrid system with target SOFC and the hybrid system with SOFC be divided among 500 households, the use of SOFC causes 51$/year or 4.25$/month extra cost for every household. From LPSP = 0.8%, the reduction in LPSP by the increase in ANC is very low. The reason is that approximately all panels are used in LPSP = 0.8%, and the increase in the number of batteries can slowly reduce LPSP by spending much money.

Fig. 11 shows the Pareto frontier for international fuel prices in LPSP-CO_2 emission coordinate for the hybrid system with different APS. It is clear that the only component in the hybrid system for CO_2 or NOx generation is the auxiliary power system. So for example, the mean of SOFC CO_2 generation is the amount of CO_2 that the hybrid system with SOFC generates. The hybrid system without APS does not generate any emission. This figure shows that the SOFC generates the least CO_2 emission. The SOFC has high efficiency (about 52%), so for a specified power generation, it consumes approximately lower fuel and also, generates lower CO_2. It is observed that DG and MGT CO_2 generations are roughly equal. The worst APS in terms of CO_2 emission is GG. Fig. 12 shows the Pareto frontier for international fuel prices in LPSP-NOx emission coordinate for the hybrid systems with different APS. As can be observed, DG has a very bad position in NOx emission. Following that are GG and MGT, respectively. The SOFC importation of NOx to the atmosphere is extremely low.

Diesel generator generates relatively much more NOx. The reason could be the type of fuel and the operating temperature. The fuels with large carbon chain and high operating temperature make good conditions for nitrogen oxides generation. Figs. 10-12 show that in general, GG and target SOFC are economically better than DG, and also MGT and SOFC are ecologically better than DG. So if the initial cost of the SOFC reduces, it will be the best APS.

In terms of emission, there is no difference between international fuel price category and Iran fuel price category and the results match. Fig. 13 shows the Pareto frontier for Iran fuel prices in ANC-LPSP emission coordinate for the hybrid system with different APS. In this situation, because of low diesel fuel price, the ANC of the hybrid system with DG becomes lower than the ANC of the hybrid system with GG. In order to compare the ANC, CO_2 emission, NOx emission, the number of panels, and the number of batteries for the hybrid system with different APS's are shown in Table 5 for LPSP = 1%. If it is assumed that the land available for the PV panels is less

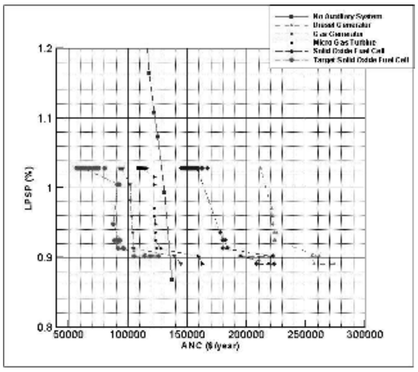

Fig. 14. Pareto frontiers of the hybrid system, international fuel price, maximum number of PV panels = 1330, power of APS = 370 kW.

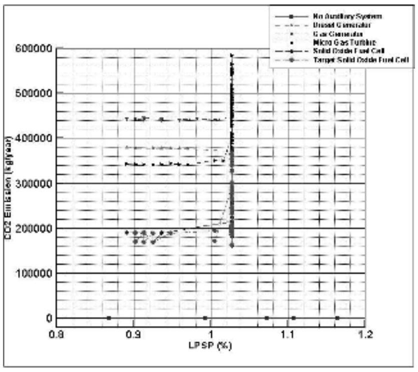

Fig. 15. Pareto frontiers of the hybrid system, international fuel price, maximum number of PV panels = 1330, power of APS = 370 kW.

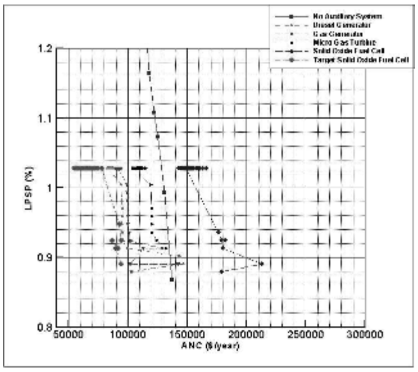

Fig. 16. Pareto frontiers of the hybrid system, Iran fuel price, maximum number of PV panels = 1330, power of APS = 370 kW.

than 5000 m^2, the maximum accessible number of PV panels reduces and inevitably, APS power must increase to supply the needed load. As an example, if 2500 m^2 of land is available, the maximum number of PV panels can be 1330, and the minimum power of APS to achieve LPSP = 1% is about 370 kW.

Fig. 14 shows the Pareto frontiers of different hybrid systems when the maximum number of panels decreases to 1330 (because of less available land). To achieve LPSP = 1%, the power of the APS must increase to at least 370 kW. This means that the contribution of the APS in power generation increases. The number of Pareto optimal sets is low because of the limited range of the number of panels. By high contribution of the APS in power generation, the ANC of the hybrid system with DG is higher than the other systems (because of expensive fuel).

Again, the target SOFC has the least ANC. Fig. 15 shows CO_2 emission for different LPSP's. It is clear that the hybrid system without APS has zero emission. The most CO_2 emission is generated by GG, which is followed by DG and MGT, respectively. SOFC has the best position among the hybrid systems with APS. It is obvious that with the increase in APS operation, the difference between the ecological position of DG and MGT grows, and MGT provides a better ecological condition.

Fig. 16 shows the Pareto frontiers for Iran fuel prices in ANC-LPSP coordinate for the hybrid systems with different APS's and the hybrid system without APS. The results are similar to international fuel price category, except for the Pareto frontier for the hybrid system with DG that causes lower ANC. From the ecological point of view, results do not change with Iran fuel price because emission does not depend on fuel prices. In order to compare the ANC, CO_2 emission, NOx emission, the number of panels, and the number of batteries for the hybrid system with different APS's are shown in Table 6 for LPSP = 1%.

Table 5. Annualized cost, CO_2 emission, NOx emission, number of panels, and number of batteries for LPSP = 1%, Max. number of panel = 2660, Power of APS = 100 kW.

		ANC ($/year)	CO_2 (kg/year)	NOx (kg/year)	Number of panels	Number of batteries
Int. fuel price	Target SOFC	112000	5800	0.1	2659	90
	SOFC	137000	5800	0.1	2651	93
	DG	114500	10500	163	2657	89
	GG	112500	13000	14	2652	91
	MGT	120000	10500	4.4	2641	96
Iran fuel price	Target SOFC	112000	5800	0.1	2646	91
	SOFC	137000	5800	0.1	2658	92
	DG	112000	10500	163	2650	101
	GG	112000	13000	14	2653	91
	MGT	119000	10500	4.4	2649	90
No APS (max. number of panel = 2800)		130000	0	0	2769	141

6. Conclusion

According to the survey conducted, the best ecological system is the PV-battery hybrid system. From the economical

Table 6. Annualized cost, CO_2 emission, NOx emission, number of panels, and number of batteries for LPSP = 1%, Max. number of panel = 1330, Power of APS = 370 kW.

		ANC ($/year)	CO_2 (kg/year)	NOx (kg/year)	Number of panels	Number of batteries
Int. fuel price	Target SOFC	91500	194000	3.72	1293	59
	SOFC	164000	194000	3.72	1295	56
	DG	216000	375000	5873	1330	35
	GG	102000	441000	490.9	1329	45
	MGT	122000	350000	172.3	1296	46
Iran fuel price	Target SOFC	71900	194000	3.72	1296	53
	SOFC	157000	194000	3.72	1293	59
	DG	94500	375000	5873	1326	45
	GG	99700	441000	490.9	1329	45
	MGT	119000	350000	172.3	1328	45
No APS (max. number of panel = 2800)		130000	0	0	2769	141

point of view, the difference between this hybrid system and the cheapest available hybrid system is little. But the PV-battery hybrid system has high dependence on atmospheric conditions. Therefore, backup power generator is an essentiality for it. The best ecological hybrid system with APS is the hybrid system with SOFC, and the best economical hybrid system is the hybrid system with target SOFC. So due to the necessity of APS existence, if SOFC technology develops rapidly, using SOFCs as auxiliary system will be cheaper than others and ecologically the most compatible. NOx emission and CO_2 emission of the SOFC-PV-battery are very low. Because they have no mobile pieces, they are very silent. So the best hybrid system for power generation is the hybrid system with target SOFC. The next ecologically appropriate system is MGT. The economical difference between this hybrid system and the cheapest available system (hybrid system with target SOFC) is not much. Results show that the economical difference between different systems is little. From NOx emission viewpoint, DG is in a very bad position, and from CO_2 emission viewpoint, GG is the worst. So due to ecological conditions, the use of systems such as gas generators or diesel generators is not justified.

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