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Optimal and Intelligent Designing of Stand-alone Hybrid Photovoltaic/Wind/Fuel Cell System Considering Cost and Deficit Load Demand Probability, Case Study for Iran (Bushehr City)

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Abstract
This paper presents the optimal and intelligent design of photovoltaic-wind-hydrogen system with the aim of minimizing the overall cost of the system and considering the reliability constraints based on annual radiation and wind speed data in Bushehr city. The hydrogen storage system includes an electrolyzer, a hydrogen storage tank and a fuel cell. Overall costs of hybrid systems include initial investment costs, maintenance and operation and replacement of components, and reliability constraint indicate deficit load demand probability (DLDP). In this study, the decision variables were optimized system capacity including number of solar panels, wind turbine, electrolyzer power capacity, mass of hydrogen storage tank, fuel cell capacity and power transfered with inverter by Grey Wolf Optimization (GWO) algorithm that has high convergence speed and accuracy. System design is presented in different scenarios of hybrid system combinations. To verify the proposed method, the results are compared with the results of Particle Swarm Optimization (PSO) algorithm. The simulation results show that the GWO method performs better in design of optimization with lower overall cost and better DLDP than the PSO in different combinations. The results show that photovoltaic -hydrogen storage due to the low wind speed potential in Bushehr city is the optimal combination based on cost and reliability for load supply based on renewable resources hybrid systems. In addition, the results show that the use of higher efficiency inverters reduces energy production costs and improves load reliability. In addition, the results indicate that the outage of renewable units in the design problem has a significant effect on system cost and reliability.

Keywords: Photovoltaic-wind-hydrogen system, Overall system cost, Deficit load power probability, Grey wolf optimization algorithm.

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1. INTRODUCTION

In recent years, the importance of utilizing renewable energy sources has increased. Due to the dispersed nature of many regions of Iran, grid-independent systems that use renewable energy sources are suitable options for supplying electricity to isolated areas [2-1]. The purpose of the design of hybrid systems is to optimize the capacity of the equipment so that, in addition to minimizing system costs, load demand is adequately met or, at times, high reliability. Therefore, achieving optimum equipment capacity is important in optimizing the design of hybrid systems [3]. In [4], optimized design of hybrid wind-photovoltaic-diesel hybrid systems with battery storage system with the aim of minimizing annual system costs, probability of energy not supplied and fuel pollution costs using multi-objective quasi-evolutionary algorithm. In [5], the design of a wind-photovoltaic system with a fuel cell storage system with the aim of minimizing the annual cost of the system and considering the probability of energy not supplied the load using the artificial bee algorithm is presented. In [6], optimal design of wind-photovoltaic system based on indicators of probability of shortage of load, surplus generation capacity, probability of unmet energy, cost of project useful life, surface energy cost and life cycle cost of generating units are presented along with battery bank. In [7], the optimal design of hybrid wind-photovoltaic-diesel-battery systems is presented with the aim of minimizing the cost of present value and taking into account the overall energy shortage of the system. In this study, the optimal combination of system equipment was obtained based on the lowest cost. In [8], the design of a hybrid wind-photovoltaic-diesel hybrid system with a battery storage system with the aim of minimizing the annual cost of the system and considering reliability and pollution using a quasi-evolutionary algorithm is presented. In [9], it uses wind-photovoltaic hybrid systems with a fuel cell storage system to provide a single charge off the grid using a particle swarm optimization algorithm. In [10], technical and economic design of photovoltaic-biomass-fuel cell hybrid systems is presented, taking into account the different initial investment costs of the fuel cell. In [11], the optimization of the wind-photovoltaic system with the fuel cell storage system with the aim of minimizing the annual cost of the system and considering the probability of not supplying the load using the imperial competition algorithm. In [12], optimization of the wind-photovoltaic system with the fuel cell system by considering reliability indices include lost load expectation and also probability of load loss using flower pollination algorithm. In [13], an iterative approach based on optimization of hybrid wind-photovoltaic-diesel-battery systems is presented with the aim of minimizing the cost of present value and taking into account the overall system energy shortage.

In this study, optimal and intelligent design of hybrid photovoltaic-wind system is presented with hydrogen storage based on fuel cell for Bushehr city with reliability/cost assessment. In this study, the grey wolf optimization (GWO) method [14] is used which is inspired by the group hunting behavior of grey wolves. The grey wolf method is a powerful way to solve problems and has high convergence speed. In this study, optimal and intelligent system design is done in different combinations including photovoltaic-wind-fuel cell hybrid (HPVWTFC), photovoltaic-fuel cell (HPVFC) and wind-fuel cell (HWTFC) based on GWO method for Bushehr. The best combination of hybrid system is determined in view of cost and reliability for Bushehr. To validate the GWO method, its performance in system design has been compared and analyzed with particle swarm optimization method. has been compared and analyzed with particle swarm optimization method.

Contributions of the paper are as follows:

- A framework for designing of a renewable hybrid photovoltaic-wind-fuel cell system based on hydrogen storage for Bushehr region as a case study as new research
- Using of real data of solar irradiance and wind speed of Bushehr of hybrid system designing
- Designing of different combination based on renewable sources and hydrogen storage for Bushehr as a new research
- Determination of best combination of hybrid system for Bushehr considering Cost/Reliability evaluation
- Application of well-known meta-heuristic algorithm named grey wolf optimizer (GWO) for optimal designing of the hybrid system
- Comparison of the cost of energy (COE) (cost for each kWh supplying the load) obtained for Bushehr with some regions in Iran with different hybrid systems
- Also evaluation of considering outage rate of renewable energy sources in cost and reliability of designing

2. HYBRID SYSTEM UNDER STUDY

The studied hybrid systems consisting of photovoltaic panels, wind turbines, inverters and storage systems including electrolyzer, hydrogen tank and fuel cell are shown in Fig. 1. When the power output of renewable units exceeds the load power, the electrolyzer generates hydrogen with receiving extra power. When the total power output of the renewable units is equal to the load power, then the total power is injected into the load by the inverter. When the generation power of renewable units is less than the load power, then the fuel cell compensates the lack of load power by receiving hydrogen from the tank.

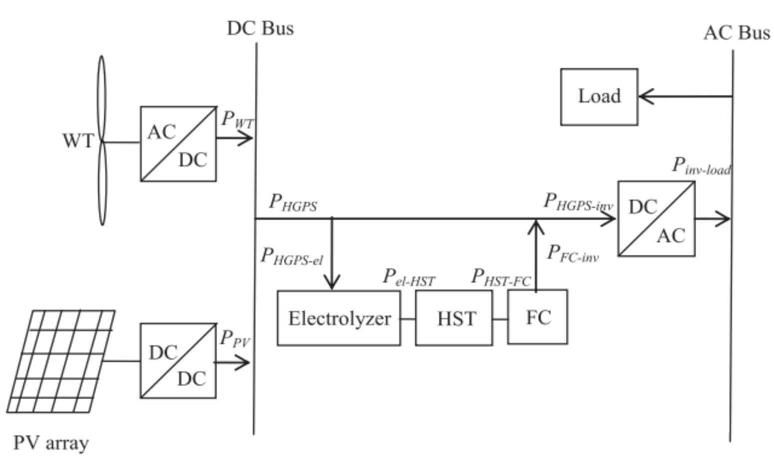

Fig. 1. Schematic of HPVWTFC system [11].

2.1. Mathematical Modeling of the Study System

The system studied consists of solar panels, wind turbines, electrolyzers, hydrogen tank and fuel cell. Following is a modeling of each system components.

2.1.1. Solar Panel Modeling (PV)

The output power of the solar array is obtained by considering the effective component of the solar radiation perpendicular to the diagonal plane (S_P), the rated power of the array ($P_{PV,Rated}$), and the DC / DC converter efficiency ($\eta_{PV,mppt}$) [4].

$$P_{PV} = P_{PV,Rated}\eta_{PV,mppt}\left(\frac{S_P}{1000}\right) \quad (1)$$

$$S_P = S_t \sin(h+\theta_{PV}) \quad (2)$$

where, S_t is the instantaneous radiation on the diagonal surface, S_p is the effective component of the solar radiation perpendicular to the diagonal, θ_{PV} is the angle of the panel relative to the earth's surface, and the angle h of the solar altitude (the angle between the path of the sun and the horizon).

If the number of solar arrays N_{PV} is equal, the total power generated by the solar arrays is defined as follows:

$$P_{PV,T}(t) = N_{PV}.P_{PV}(t) \quad (3)$$

2.1.2. Wind Turbine Modeling (WT)

The power generation relation of each wind turbine at time t is obtained from the following equation [12, 11].

$$P_{WT} = \begin{cases} 0 & ; v_W \le v_{cut\,in}, v_W \ge v_{cut\,out} \\ P_{\max} \times \left(\dfrac{v_W - v_{cut\,in}}{v_{rated} - v_{cut\,in}}\right)^m & ; v_{cut\,in} \le v_W \le v_{rated} \\ P_{\max} + \dfrac{P_{furl} - P_{\max}}{v_{cut\,out} - v_{rated}} \times (v_W - v_{rated}) & ; v_{rated} \le v_W \le v_{furl} \end{cases} \quad (4)$$

where, v_w is wind speed, $P_{\max}$ is nominal power of the wind turbine and v_{cut-in} , $v_{cut-out}$ and v_r respectively, are the low cutoff speed, the high cutoff speed and the rated wind speed. P_{furl} is output power which is at high cutoff speed.

If the wind turbines are equal N_{WT} and the number of panels is equal N_{PV}, then the total power generated by the wind turbines as well as the solar arrays is defined as follows:

$$\begin{aligned} P_{WT,T}(t) &= N_{WT}.P_{WT}(t) \\ P_{PV,T}(t) &= N_{PV}.P_{PV}(t) \end{aligned} \quad (5)$$

The sum of total power produced by the system is defined as follows:

$$P_{HGPS} = N_{WT}.P_{WT} + N_{PV}.P_{PV} \quad (6)$$

2.1.3. Electrolyzer

It is produced using an electrolyzer based on the decomposition of hydrogen. The electrolyzer power is as follows [12, 11].

$$P_{el-HST} = P_{HGPS-el} \times \eta_{el} \tag{7}$$

where, η_{el} is the efficiency of the electrolyzer and P_{ren-el} is power injected into the electrolyzer by renewable sources.

2.1.4. Hydrogen Storage Tank

The hydrogen energy stored in the tank for each hour t is formulated as follows [12, 11].

$$\begin{aligned} E_{HST}(t) = E_{HST}(t-1) \\ + P_{el-HST}(t).\Delta t \\ - \frac{P_{HST-FC}(t)}{\eta_{HST}}.\Delta t \end{aligned} \tag{8}$$

η_{HST} is storage tank efficiency. The hydrogen mass of the reservoir is obtained as follows [12, 11].

$$m_{HST}(t) = \frac{E_{HST}(t)}{HHV_{H_2}} \tag{9}$$

HHV_{H_2} is thermal value of hydrogen which is 39.7 kW/kg [11-12]. The maximum and minimum amount of hydrogen in the tank are as follows.

$$E_{HST,\min} \le E_{HST}(t) \le E_{HST,\max} \tag{10}$$

2.1.5 Fuel cCell

The fuel cell output power is as follows:

$$P_{FC-inv} = P_{tank-FC} \times \eta_{FC} \tag{11}$$

Where, η_{FC} is fuel cell efficiency.

2.1.6 Inverter

The inverter prepares DC power to AC power for delivery to AC load. The power of the inverter to load is as follows:

$$P_{inv-load} = \left(P_{FC-inv} + P_{HGPS-inv}\right) \times \eta_{inv} \tag{12}$$

η_{inv} indicates the efficiency of the inverter.

3. PROBLEM FORMULATION

3.1. Optimization Target Function

The objective function of the design problem is to minimize system costs. System costs include investment costs (CC), maintenance costs (MC), and equipment replacement costs (RC) followed by net present cost of load losses (NPC_{loss}).

Energy production costs are defined as follows [12, 11].

$$NPC_i = N_i \times \left(CC_i + RC_i K + MC_i PWA\right) \tag{13}$$

Where N denotes the number of units or equipments in kW or kg. K and PWA are conversion factors of costs.

$$PWA = \frac{(1+ir)^n - 1}{ir(1+ir)^n} \tag{14}$$

$$K = \sum_{n=1}^{Y} \frac{1}{(1+ir)^{L.n}} \tag{15}$$

That is, L represents the number of replacements and n is useful life of the equipment. It is the real interest which is given by the $ir_{nominal}$ nominal interest rate and annual inflation rate (f) as follows.

$$ir = \frac{ir_{nom} - f}{1+f} \tag{16}$$

The cost of not providing the system load is as follows:

$$NPC_{loss} = LOEE \times C_{loss} \times PWA \tag{17}$$

where, C_{loss} is cost of cutting off the load per kilowatt-hour in dollars.

The general objective function of the problem is defined as follows:

$$\min\left\{C_{Total}\right\} = \sum_i NPC_i + NPC_{loss} + Penalty \tag{18}$$

The $Penalty$ phrase in the objective function is to penalize the objective function in the absence of a reliability constraint.

3.2. System Reliability Model

The mathematical hope of generating system energy is defined as follows [12, 11].

$$E\left[P_{HGPS}\right] = N_{PV} \times P_{PV} \times A_{PV} + N_{WT} \times P_{WT} \times A_{WT} \tag{19}$$

where, A_{PV} and A_{WT} are availability of solar and wind units.

The hope of a break is expressed as follows for one year:

$$LOLE = \sum_{t=1}^{N} E\left[LOL\left(t\right)\right] \tag{20}$$

where, $E[LOL(t)]$ is the definite mathematical expectation at times t:

$$E\left[LOL\right] = \sum_{s \in S} T_S \times P_s \tag{21}$$

where, T_s the probable duration of the load, P_s is the probability of being in s condition and S all possible conditions of the hybrid system.

$$LOEE = EENS = \sum_{t=1}^{N} E\left[LOE\left(t\right)\right] \tag{22}$$

where, $E[LOE(t)]$ is mathematical expectation of the load cut off at time t which is as follows:

$$E\left[LOE\right] = \sum_{s \in S} Q_s \times P_s \tag{23}$$

where, Q_s is amount of load cut off per kW hour in the condition.

In order to have a reliable system, hybrid power systems should consider deficit load demand probability (DLDP). When the DLDP is equal to zero, the entire load demand is met. DLDP equals one indication that the entire load is not supplied. DLDP is between zero and one. The DLDP is formulated as follows:

$$DLDP = \frac{LOEE}{\sum_{t=1}^{N} D\left(t\right)} \tag{24}$$

where, $D(t)$ is power consumption is expressed in kWh per hour t.

The equivalent load factor (ELF) is as follows [12, 11].

$$ELF = \frac{1}{N} \sum_{t=1}^{N} \frac{Q\left(t\right)}{D\left(t\right)} \tag{25}$$

3.3. Constraints

$$DLDP \le DLDP_{\max} \tag{26}$$

$$(2)\, E\left[ELF\right] \le ELF_{\max} \tag{27}$$

$$0 \le N_{PV} \le N_{PV,\max} \tag{28}$$

$$0 \le N_{WT} \le N_{WT,\max} \tag{29}$$

$$0 \le \theta_{PV} \le \pi/2 \tag{30}$$

$$E_{HST}\left(0\right) \le E_{HST}\left(8760\right) \tag{31}$$

where, $N_{PV,\max}$ and $N_{WT,\max}$ is maximum number of solar arrays and wind turbines.

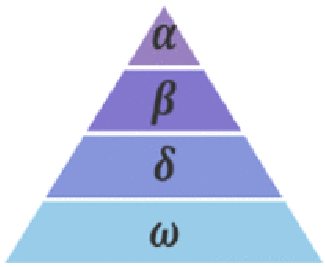

Fig. 2. Leadership hierarchy in gray wolves group [14].

$DLDP_{\max}$ and $ELF_{\max}$ is maximum of DLDP and ELF. θ_{PV} refers to angle of installation of solar arrays.

4. PROPOSED OPTIMIZATION METHOD

4.1 Gray Wolf Optimization (GWO) Algorithm

The GWO algorithm models the hunting behavior and social behavior of gray wolves. The leadership hierarchy of this algorithm is expressed by the parameters α, β, δ, and ω plotted in Figure 2. α is recognized as the main leader of the group and is responsible for many decisions such as hunting and resting places. The wolf β assists α in decision. Wolf ω, should always be ready to replace the top wolves. The wolves δ are the last group to be allowed to eat [14].

The gray wolf encircles his prey while hunting. We use the following equation to model this blockade mathematically [14].

$$\vec{D} = \left|\vec{C}.\vec{X}_P(t) - \vec{X}(t)\right| \tag{32}$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A}\vec{D} \tag{33}$$

where t is the repetition number, $\vec{A}$ and $\vec{C}$ are coefficient vector, $\vec{X}_P$ prey position vector and $\vec{X}$ position vector of a gray wolf.

The coefficient vector is calculated as follows [14].

$$\vec{A} = 2\vec{a}\vec{r}_1 - \vec{a} \tag{34}$$

$$\vec{C} = 2\vec{r}_2 \tag{35}$$

The top three wolves in the group have more knowledge of prey. The three best elements of the group are stored and the rest of the wolves (ω) change their position based on the position of the top three wolves as follows [14].

$$\vec{D}_\alpha = \left|\vec{C}_1\vec{X}_\alpha - \vec{X}\right|, \vec{D}_\beta = \left|\vec{C}_2\vec{X}_\beta - \vec{X}\right|, \vec{D}_\delta = \left|\vec{C}_3\vec{X}_\delta - \vec{X}\right| \tag{36}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{a}_1\vec{D}_\alpha, \vec{X}_2 = \vec{X}_\beta - \vec{a}_2\vec{D}_\beta, \vec{X}_3 = \vec{X}_\delta - \vec{a}_3\vec{D}_\delta \tag{37}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{38}$$

4.2. Implementation of GWO Algorithm in Problem Solving

In this study, the design of hybrid PV/wind/fuel cell hybrid system based on GWO method with the aim of minimizing the total annual cost of the system and also the cost of failure is presented. The optimization variables are optimized by the GWO algorithm. The number of replicates per GWO 100 and population 50 is determined by trial and error. The optimization steps are as follows:

Step 1) Applying system data. Solar radiation and wind speed data of Bushehr city as well as load demand data, technical and economic parameters of the design are given.

Fig. 3. Location of Bushehr city in Iran [15].

Step 2) Initialize the algorithm parameters. Variables are defined as variables that are randomly selected for each member of the population taking into account each of the constraints.

Step 3) Calculate the target function value for each population member of the GWO method.

Step 4) Select the best population member. The cost objective function values for each member of the population of the GWO method are examined and the lowest cost wolf is selected as the best solution.

Step 5) Population Update GWO Method

Step 6) Calculate the cost per updated population.

Step 7) Replacing the objective function in steps 4 to 6 replaces it if step 6 is better than step 4.

Step 8) Verify the convergence conditions. Go to Step 9 if the convergence conditions are met and then go to Step 5.

Step 9) Save the results and stop the algorithm.

5. SIMULATION RESULTS AND DISCUSSION

5.1. System Data

Solar intensity data and annual wind speed data of Bushehr city with geographic location of 28 ° 55'N and 50 ° 55'E have been applied to the design program [15]. The location of Bushehr city in Iran is shown in Figure 3. The curve shows the changes in wind speed and solar radiation over the year in Figures 4 and 5, respectively. The demand is also presented annually with a 100 kW peak in Figure 6. The technical and economic equipment parameters of the various system equipment are presented in Table 1. The hybrid system conditions are also presented in Table 2. In this paper, Table 2 assumes that the system will be fined $ 5.6 per kilowatt-hour, or as a cost of utilities. This table presents peak load values, equivalent load cutoff coefficients, system useful life and interest rates.

5.2. Simulation Scenarios

Optimized and intelligent designing of hybrid systems is implemented in various combinations of hybrid systems including photovoltaic/fuel cell (HPVFC), wind/fuel cell (HWTFC) and photovoltaic/wind/fuel cell (HPVWTFC). The optimization of the hybrid system is performed using GWO algorithm and the performance of the proposed method is compared with the particle swarm optimization (PSO) method. In this paper, the simulations are performed in the following five scenarios.

- **Scenario 1)** HPVWTFC optimal designing
- **Scenario 2)** HPVFC optimal designing
- **Scenario 3)** HWTFC optimal designing
- **Scenario 4)** Optimal designing considering inverter efficiency changing
- **Scenario 5)** Optimal designing considering renewable units outage rates

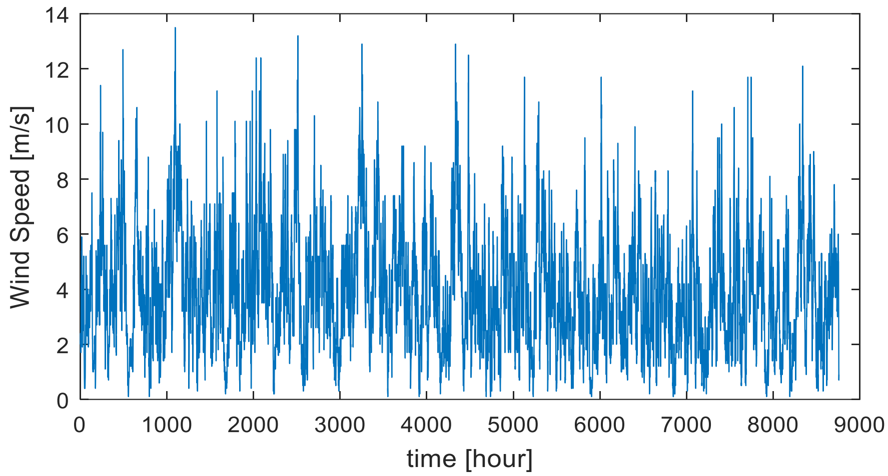

Fig. 4. Wind speed during one year [15].

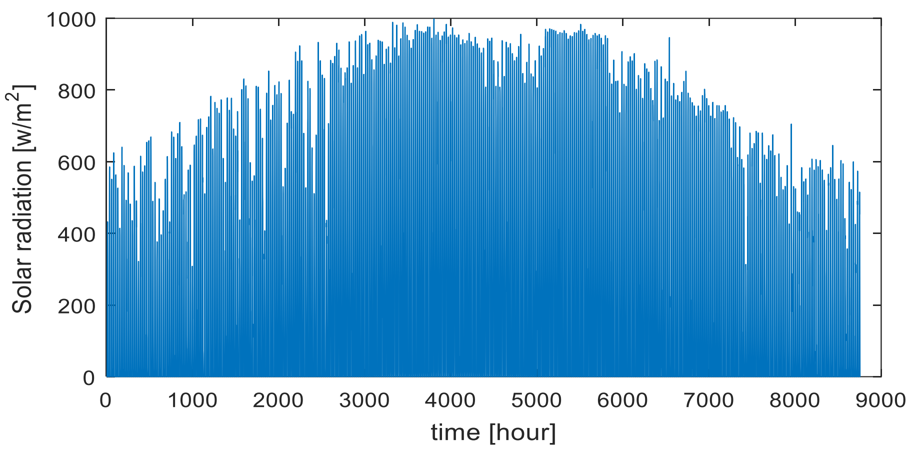

Fig. 5. The intensity of the sun's radiation over a year [15].

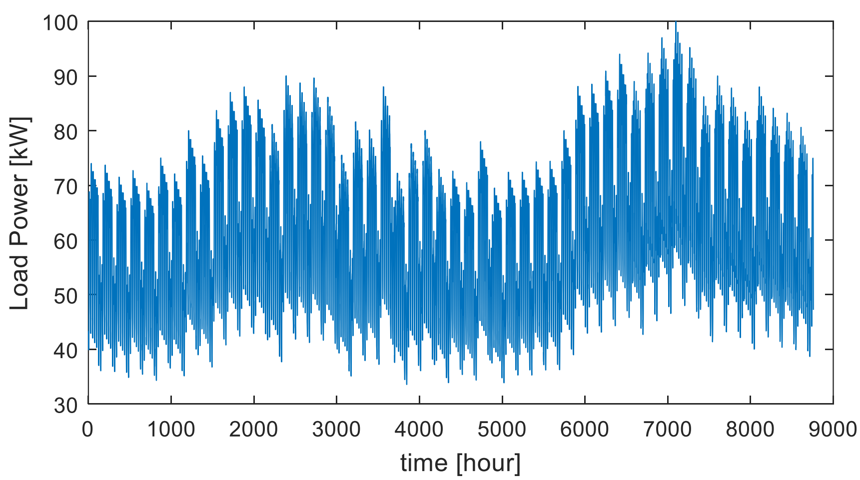

Fig.6. Annual load change curve.

Table 1. ***System Equipment Parameters [11-12].***

Device	Investment Cost (US$/unit)	Replacement Cost (US$/unit)	Maintenance and Repair Cost (US$/unit-yr)	Availability (%)	Efficiency (%)	Lifetime (Year)
Wind Turbine	19400	15000	75	96	-	20
PV panel	7000	6000	20	96	-	20
Electrolyzer	2000	1500	25	100	75	20
Hydrogen Tank	1300	1200	15	100	95	20
Fuel cell	3000	2500	175	100	50	5
Converter DC/AC	800	750	8	99.89	90	15

Table 2. ***Requirements for the studied system [11-12].***

System lifespan	Real interest rate	ELF_{max}	Load peak	Cost of load loss
20 yrs	6 %	0.01	100 kW	5.6 US$/kWh

5.2.1. First Scenario Results (HPVWTFC System)

In the first scenario, the results of the design of HPVWTFC hybrid systems using GWO method and comparison of its performance with PSO method with $DLDP_{max}$=1% and ELF_{max}=1% are presented. The convergence curves of the GWO method with the PSO method are presented in Figure 7. As can be seen, the proposed GWO method achieves optimal results with lower iteration, higher convergence speed and lower convergence tolerance than the PSO method, and has a lower cost, which confirms the superiority of the proposed method.

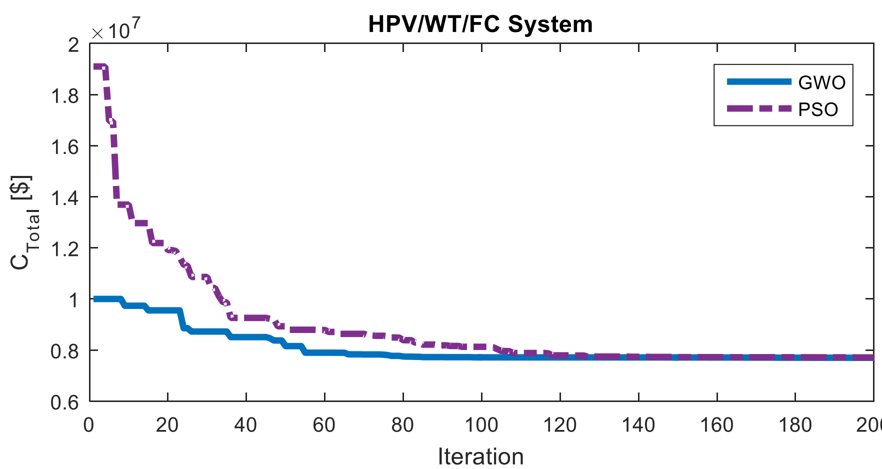

Fig. 7. Convergence curve of GWO and PSO in design of HPVWTFC system (Scenario1).

Table 3. ***Optimal components capacity in HPVWTFC system design (Scenario 1).***

Algorithm	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}	N_{WG}
GWO	46.03	95.20	90.05	470.61	366.52	715	0
PSO	43.70	95.04	89.47	248.46	376.38	756	0

Table 4. ***Costs and reliability indices for HPVWTFC system design (Scenario 1).***

Algorithm	$LOLE\,(hr/yr)$	$DLDP$	$LOEE\,(MWh/yr)$	ELF	$C_{Total}\,(MUS\,\$)$
GWO	**241**	**0.0021**	**1.115**	**0.0014**	**7.697**
PSO	258	0.0023	1.231	0.0016	7.709

Numerical results of HPVWTFC system design based on GWO and PSO methods including optimal equipment capacity and cost and reliability indices are presented in Tables 3 and 4, respectively. It is observed that the proposed methods did not utilize wind energy to supply load on hybrid systems. Because of the wind situation in Bushehr, it does not have the potential to generate energy in the form of renewable hybrid systems and is not economical. Therefore, optimization methods have neglected the cost of hybrid systems due to the high cost of using wind energy. Optimization variables based on GWO method are 715 solar panels, 366.52 kW electrolyzer power, 470.61 kg tank hydrogen mass, 90.05 kW fuel cell power, 95.20 kW inverter to solar load angle and 46.03-degree solar panels angle. It can be seen that the cost of GWO and PSO methods is $ 7.697 and $ 7.709 million, DLDP is 0.0021 and 0.0023,respectively, and the number of fixed hours per year is 241 and 258 hours, respectively.

The curves of solar panel power generation and tank storage energy changing over a year (for the GWO method) are shown in Figures 8 and 9, respectively.

Figure 10 also shows the power transfer to the inverter, the electrolyzer to the tank, and the fuel cell to the inverter, as well as the power to the electrolyzer, the fuel cell, and the inverter to load over a year.

The curve of changes in reliability indices including LOEE, DLDP and LOLE over a year (for the GWO method) is shown in Figure 11.

5.2.2. Second Scenario Results (Optimized Design of HPVFC Hybrid Systems)

In the second scenario, the results of HPVFC hybrid system design using GWO method and comparing its performance with PSO method with $DLDP_{max}$=1% and ELF_{max}=1% are presented. The convergence curves of the

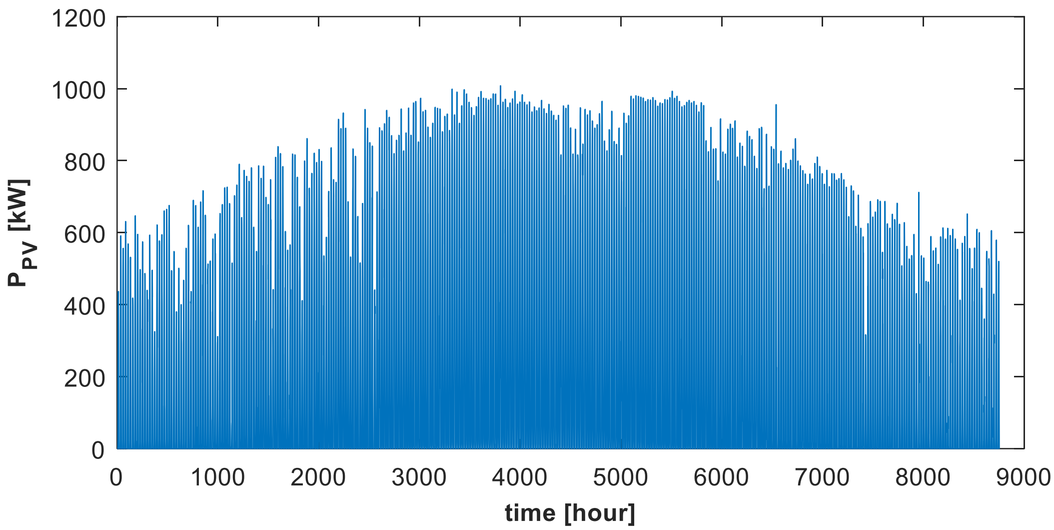

Fig. 8. Solar panel power generation curve over one year (Scenario 1).

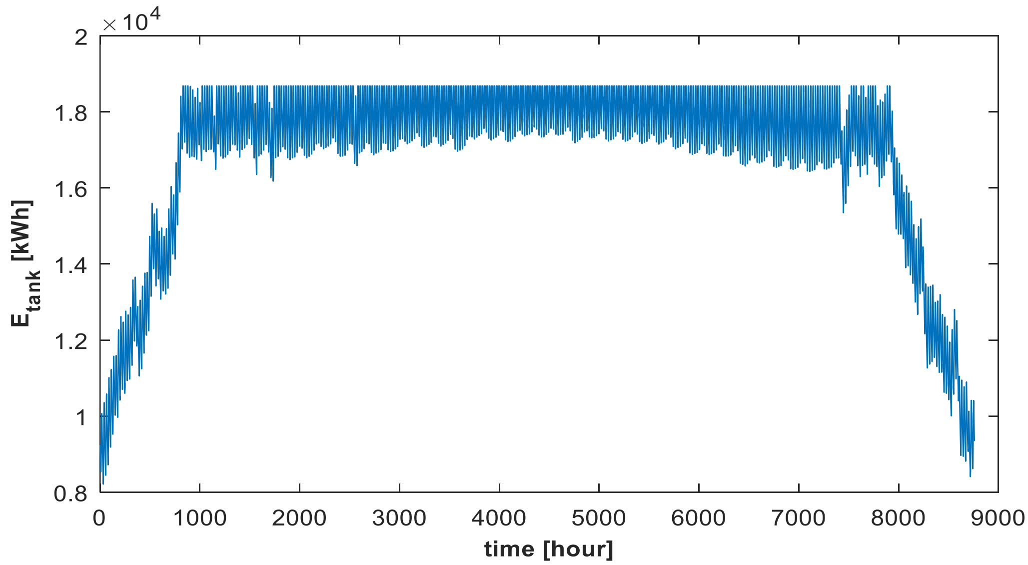

Fig.9. Tank energy during one year (Scenario 1).

GWO method along with the PSO method are presented in Figure 12. The proposed GWO method achieves a better value of the objective function at lower iteration and with higher convergence speed than the PSO method.

Numerical results of HPVFC system design based on GWO and PSO methods including optimum equipment capacity and cost and reliability indices are presented in Tables 5 and 6, consecutively. The GWO method uses a larger number of solar panels than the PSO method, but it is in contrast to the greater contribution of the storage system by the PSO method. Optimization variables based on GWO method are 763 solar panels, 392.76 kW electrolyzer power, 73.29 kg tank hydrogen mass, 85.31 kW fuel cell power, 93.52 kW inverters transferred power with 45.64 degrees solar panels load angle. Costs for GWO and PSO methods are $ 7.695 and $ 7.697 M$, DLDP is 0.0018 and 0.0019, respectively. The LOLE is obtained 216 and 267 hours, respectively. The GWO is obtained less cost versus PSO that is validated the suitable performance of the proposed method.

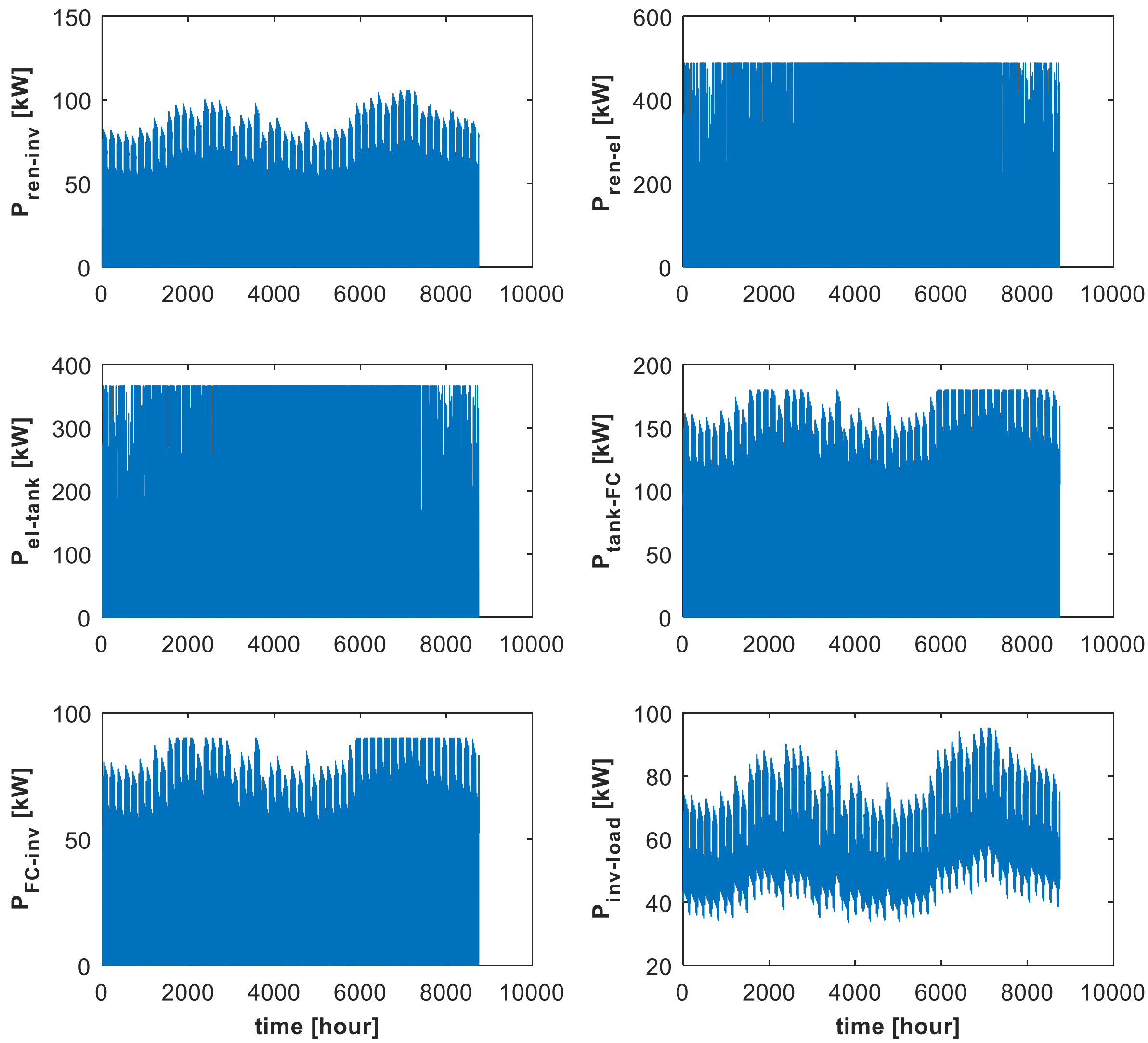

Fig. 10: Capacity of system components during one year (Scenario 1).

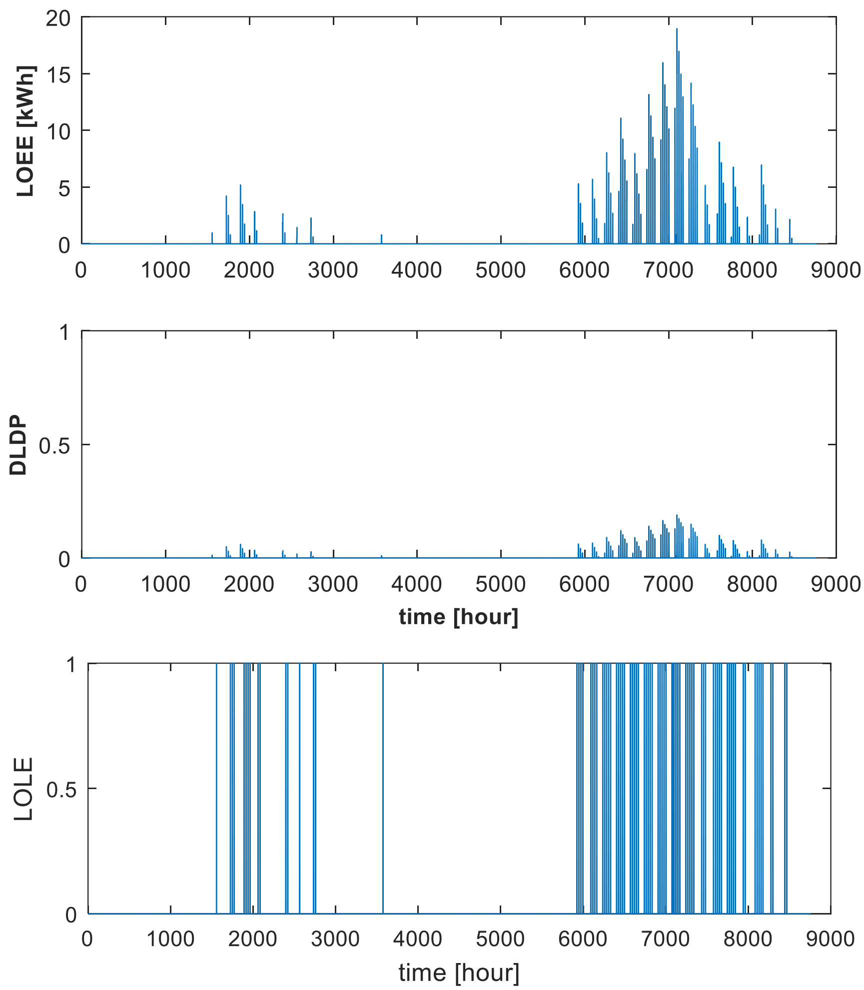

Fig.11. Curve of changes in reliability indices including LOEE, DLDP, and LOLE over one year (Scenario 1).

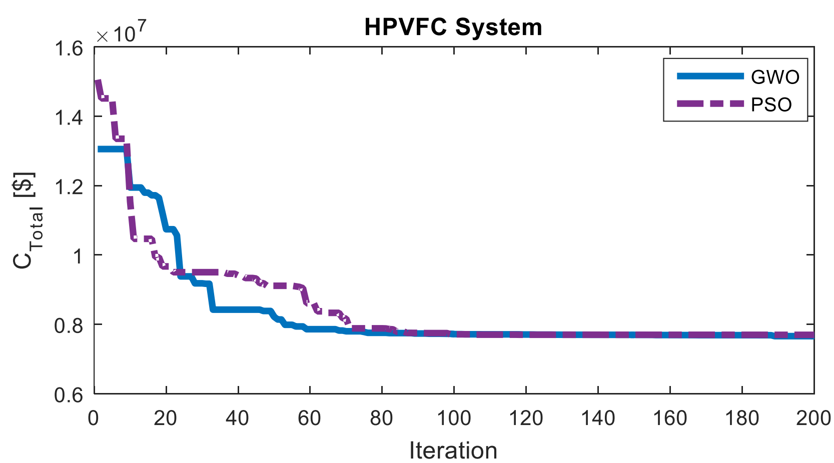

Fig. 12. Convergence curve of GWO and PSO in HPVFC system design (scenario 2).

Table 5. ***Optimal capacity of components for HPVFC system design (Scenario 2).***

Algorithm	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}
GWO	45.64	93.52	85.31	73.29	392.76	763
PSO	44.73	92.82	90.04	95.92	378.10	745

Table 6. ***Cost values and reliability indices in HPVFC system design (Scenario 2).***

Algorithm	$LOLE\,(hr\,/\,yr)$	$DLDP$	$LOEE\,(MWh\,/\,yr)$	ELF	$C_{Total}\,(MUS\,\$)$
GWO	**216**	**0.0018**	**0.988**	**0.0013**	**7.695**
PSO	267	0.0019	0.993	0.0015	7.697

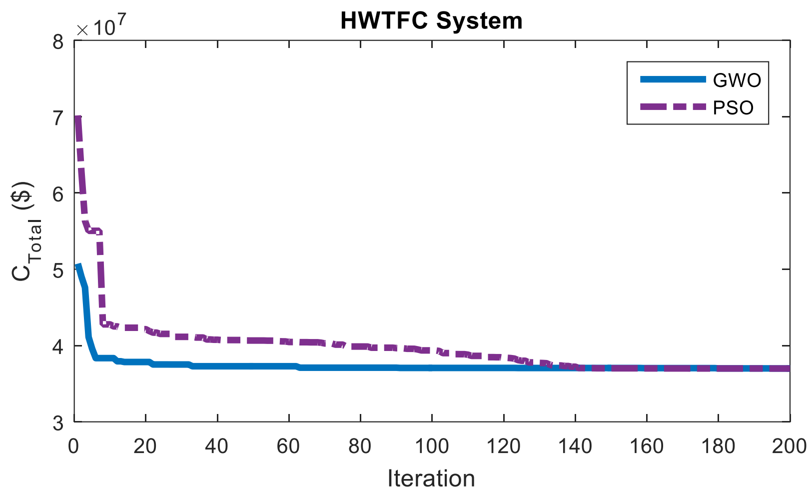

Fig.13. Convergence curve of GWO and PSO in HWTFC system design (scenario 3).

5.2.3. Third Scenario Results (Optimal Design of HWTFC System)

The design results of HWTFC hybrid system are presented in the scenario 3, based on GWO and comparing its performance with PSO with $DLDP_{max}$=1% and ELF_{max}=1%. The convergence curve of the GWO method along with the PSO method are presented in Figure 13. It is clear that the performance of the proposed GWO method is better than the PSO method due to the convergence in the number of iterations and the higher convergence speed.

Numerical results of HWTFC system design based on GWO and PSO methods including optimum components capacity and cost and reliability indices are presented in Tables 7 and 8, respectively. The contribution of wind turbines in both GWO and PSO methods has been similar. GWO optimization variables are obtained as 1393 turbines, 1996.30 kW electrolyzer, 1999.99 kg hydrogen tank mass, 86.65 kW fuel cell power and 99.11 kW inverter transmission power. Costs for GWO and PSO methods are 36.99 and 37.02 M$, respectively which is approximately 550% more than HPVFC, DLDP amounts which are 0.01 and 0.01, respectively. The LOLE is obtained 673 and 678 hours for GWO and PSO, respectively. As can be seen, due to the inadequate wind speed potential in Bushehr, HWTFC system is not recommended.

5.2.4. Compare the Results of Different Combinations of Hybrid Systems

A comparison of the results of different scenarios based on the GWO method is presented in Table 9. Review and comparison of results showed that according to cost and reliability indices, HPVFC combination is more economical and technical which is feasible option for cargo based on renewable resources hybrid systems for Bushehr city. As the results show, the cost of HPVFC system is lower than the other components and in addition, it has better reliability (less DLDP and LOLE) than the other components in load supply.

5.2.5. Results of The Fourth Scenario (Considering Inverter Efficiency Changing)

Numerical results of HPVFC system design using GWO method in terms of inverter efficiency changes are presented in Tables 10 and 11. In the basic case, the inverter efficiency is 90%. In this section, the results of the HPVFC system design with 95% efficiency for the inverter are presented in Table 10. As can be seen, increasing the efficiency of the inverter reduces the cost and improves reliability of system load. As the inverter efficiency increased, the DLDP decreased from 0.0018 to 0.0016 and LOLE from 216 to 209 hours.

Table 7. ***Optimal capacity of components for HWTFC system design (Scenario 3).***

Algorithm	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{WG}
GWO	99.11	86.65	1999.6	1996.30	1393
PSO	99.07	86.60	1998.5	2000	1393

Table 8. ***Costs and reliability indices for HWTFC system design (Scenario 3).***

Algorithm	$LOLE\,(hr/yr)$	$DLDP$	$LOEE\,(MWh/yr)$	ELF	$C_{Total}\,(MUS\,\$)$
GWO	**673**	**0.01**	**6.784**	**0.01**	**36.99**
PSO	678	0.01	6.799	0.01	37.02

Table 9. ***Comparison of the results of different scenarios (GWO method).***

Scenario	$LOLE\,(hr/yr)$	$LOEE\,(MWh/yr)$	***ELF***	***DLDP***	$C_{Total}\,(MUS\,\$)$
1 (HPVWTFC)	241	1.115	0.0014	0.0021	7.697
2 (HPVFC)	**216**	**0.988**	**0.0013**	**0.0018**	**7.659**
3 (HWTFC)	678	6.799	0.01	0.01	36.99

Table 10. ***Optimal capacity of components for HPVFC system design (Scenario 4).***

Parameter	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}
$\eta_{inv} = 90\%$	45.64	93.52	85.31	73.29	392.76	763
$\eta_{inv} = 95\%$	45.03	93.54	83.02	54.27	311.11	667

Table 11. ***Costs and Reliability indices for HPVFC system design (Scenario 4).***

Parameter	$LOLE\,(hr/yr)$	$DLDP$	$LOEE\,(MWh/yr)$	ELF	$C_{Total}\,(MUS\$)$
$\eta_{inv} = 90\%$	216	0.0018	0.988	0.0013	7.695
$\eta_{inv} = 95\%$	**209**	**0.0016**	**0.466**	**0.0011**	**6.773**

Table 12. ***Optimal capacity of components for HPVFC system design (Scenario 5).***

Scenario	θ_{PV}	P_{inv}	P_{FC}	M_{tank}	P_{el}	N_{PV}	N_{WG}
Without outage	45.64	93.52	85.31	73.29	392.76	763	--
With outage	44.60	93.56	89.99	409.20	367.03	757	--

Table 13. ***Cost Values and Reliability indices for HPVFC system design (Scenario 5).***

Scenario	$LOLE\,(hr/yr)$	$LPSP$	$LOEE\,(MWh/yr)$	ELF	$C_{Total}\,(MUS\$)$
Without outage	216	0.0018	0.988	0.0013	7.695
With outage	247	0.0021	1.130	0.0014	7.911

5.2.6. Fifth Scenario Results (considering outage rate)

In this section, the results of the HPVFC system design using the GWO method with the outage of renewable solar and wind units are presented in Tables 12 and 13. In the base case, Table 1, assumes the availability of 100% renewable units, in which the effect of a 4% outage rate or 96% availability [11-12] on the design of the HPVFC system is evaluated. As presented, considering the outage rate for renewable units due to their reduced capacity because of reduced availability, the overall cost of the system increased and the reliability of the load is undermined.

5.2.7. Results Comparison with Previous Studies

The obtained results from different combinations of hybrid system compared with previous studies are presented in Table 5. In this section, cost of energy (COE) for each kWh supplying the load demand is considered for comparison. The COE is variable for different regions because of variation of radiation and wind speed

Table 14. ***The results from different combinations compared with previous studies.***

Study	System	Region	COE ($/kWh)
[12]	PV/WT/FC	Ardabil	0.52
[16]	PV/WT/Diesel/Battery	Nahavand	1.87
[16]	PV/WT/Diesel/Battery	Rafsanjan	0.32
This paper	HPVWTFC	Bushehr	0.7149
This paper	HPVFC	Bushehr	0.7149
This paper	HWTFC	Bushehr	3.4357

condition. On the other hand, before the implementation of renewable hybrid power plants in each region, the COE should be assessed for the detailed knowledge of energy system engineers and designers regarding the radiation patterns and wind speeds of the region. Designers of hybrid energy systems determine the COE value for each of the system components for a particular region, whether the implementation of these systems is economical and reliable or not. The COE is defined as ratio of C_{Total} to $\sum_{t=1}^{N} D(t)$. The total load of system ($\sum_{t=1}^{N} D(t)$) is 538.31 MWh during 8760 hours. So, the COE is calculated 0.7149, 0.7114 and 3.4357 $ for HPVWTFC, HPVFC and HWTFC, respectively. The C_{Total} is equal to 7.697, 7.659 and 36.99 M$ for mentioned system respectively for 20 years project lifespan. So, the HWTFC system application is not economical for Bushehr. In other words, the unsuitable wind potential for this region causes excessive and irrational use of equipment and drastically increases energy costs. In table 14, the COE is compared for different studies with different combination and storage. As shown in Table 14, the COE of Bushehr for HPVWTFC and HPVFC is less than Nahavand (PV/WT/Diesel/Battery system) [16] and more than Ardabil [12] and Rafsanjan [16].

6. CONCLUSION

This paper presents the design of a hybrid HPVWTFC system with the aim of minimizing the overall costs and cost of load losses considering the reliability constraints for Bushehr city. The designing problem uses the radiation data and wind speed of Bushehr city. The optimum capacity of the hybrid system components is determined using the GWO algorithm to minimize the objective function problem. Simulations are implemented in different scenarios of hybrid system components. The simulation results showed that the GWO is able to determine the optimal system combination, ie HPVWTFC with the lowest overall cost and better reliability constraint. The results also showed that the HWTFC for Bushehr are not economic because of high cost. Evaluation of the GWO in designing different combinations of the hybrid system compared to PAO has shown that it performs better in achieving lower overall cost and better reliability. In addition, the results showed that the use of higher efficiency inverters improves reliability and considering the outage rate of renewable units undermines the reliability of the system load.

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