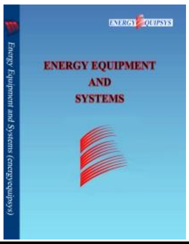
Energy Equip. Sys./ Vol. 7/No. 1/March 2019/ 67-79

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
www.energyequipsys.com



Techno-economic operation optimization of a HRSG in combined cycle power plants based on evolutionary algorithms: A case study of Yazd, Iran

Author

Maryam Khademi [a*]
Atefeh Behzadi Forough [b]
Ahmad Khosravi [a]

[a] Department of Applied Mathematics, Islamic Azad University South Tehran Branch, Tehran, Iran

[b] Department of Energy Engineering, Sharif University of technology (SUT), Tehran, Iran

Article history:

Received : 9 September 2018
Accepted : 10 October 2018

ABSTRACT

In this research study, energy, exergy and economic analyses is performed for a combined cycle power plant (CCPP) with a supplementary firing system. The purpose of this analyses is to evaluate the economic feasibility of a CCPP by applying an optimization techniques based on Evolutionary algorithms. Actually, the evolutionary algorithms of Firefly, PSO and NSGA-II are applied to minimize the cost function and to optimally adjust the operating design variables of a CCPP. The input parameters are measured in real case study (i.e., Yazd city, Iran) and they are used to model and optimize the system performance. The cost objective function is formed from several parts: Operating cost, capital cost and exergy destruction cost. In following of optimization procedure, a thermo-economic method is employed to compare the impact of operating parameters from an economic standpoint by COMFAR III (Computer Model for Feasibility Analysis and Reporting) software. The economic analysis consists of determination of NPV, sensitivity analysis and calculation of break-even point. The results showed that the optimization results are economically more feasible than the base case. In addition, among different optimization techniques, Firefly algorithm improves the economic justification of CCPP. At the end, the results of sensitivity analysis show that by decreasing the operation costs, fixed assets and sales revenue by 40%, the IRR increases by 6.7%, 42.8% and decreases by 41.4%, respectively. Furthermore, the lowest sensitivity of IRR is related to operation cost, while the highest sensitivity of IRR is corresponding to variations of fixed assets.

Keywords: Techno-Economic Analysis, Firefly Algorithm, PSO, NSGA-II, COMFAR, CCCP.

1. Introduction

Optimization of combined cycle power plants (CCPPs) is one of the most important aspect of producing electrical energy used by human, and the importance of this kind of generation is quite clear to everyone. Therefore, finding ways to analyze and optimize the performance of CCPPs must be prioritized. Heat recovery steam generators (HRSGs) are an important part of a CCPP that recovers energy from turbine exhaust gases and increases the total efficiency of system. Therefore, the most desirable design of HRSGs in CCPPs is a controversial subject because of rising in fuel prices and decreasing the fossil fuel resources.

A major objective of electric power market deregulation is to present more competition options and therefore to reduce the production costs of electricity in power plants. Electric power industry reforms have been motivated due to several factors including high electricity prices which leads to other factors. In this way,

* Corresponding author: Maryam Khademi
Department of Applied Mathematics, Islamic Azad University South Tehran Branch, Tehran, Iran
Email: khademi@azad.ac.ir

Technology development also plays an important part. Increases in the level of production technology can make the proposed process more efficient [1]. In recent years, the ever-growing demand for electric power has greatly increased the interest in application of CCPPs. This is mainly because of their high efficiency and relatively low investment costs relative to the other technologies [2]. These two factors — demand and market prices — can all be affected to decide to build the new power plants [3]. Iran suffers from a power shortage. There is concern over the high consumption of power in Iran as it is predicted that the country will face the shortage of 3,000 megawatts of power in peak hours in 2018. Also, due to the increasing demands for natural gas, it is playing a more important role in the energy system [4]. So it is essential to find some solutions to improve the consumption of fuel in power plants and increase the energy system efficiency. The optimization technique using evolutionary algorithms such as PSO, Firefly and NSGA-II could be applied to a lot of engineering problems to reach the best way for improving the system performance.

A combined cycle power plant consists of three basic units: a gas turbine unit, a heat recovery steam generator (HRSG) that produces steam from the turbine exhaust heat, and a steam turbine cycle that generates electricity from that steam. The temperature of waste heat released from the gas turbine is high enough to be utalized in the HRSG. In any system with thermal exhaust, if the temperature is higher than 200° C, there is a potential to capture the waste heat and to use it for heating in an industrial process, or in the case of higher temperatures, to produce electricity. More precisely, at the exhaust temperature of 550° C, the waste heat from an open cycle power plant has “high quality”, and it can be used to produce electricity. In a combined cycle power plant, the waste heat from the gas turbine is sent through a waste heat boiler, more commonly known as a heat recovery steam generator (HRSG), to produce steam. In a conventional power plant, the boiler is fed with fuel and then the hot gases from the combustion of fuel passes through the boiler to produce steam. In a waste heat boiler or a HRSG, there is no fuel supply, but the hot gas exhaust from the nearby gas turbine passes through the HRSG to produce steam. Steam generated in the HRSG is then supplied to a turbine to produce electricity, in the same way it is done in a conventional steam power plant. With a multiple-pressure HRSG, the steam turbine will typically have multiple steam admission points. In a three-stage steam turbine, HP, IP and LP steam produced by the HRSG is fed into the turbine at different points [5-8]. Heat recovery steam generator (HRSG) is a part that connects the gas turbines cycle and the steam turbines cycle in a combined-cycle power plant [9-11].

In recent years, the evolutionary algorithm has been widely used to optimize the complex problems in energy systems and there is now a growing collection of published applications [12, 13]. The performance principle of evolutionary algorithms is based on iterative methods as they can modify the values of the process variables whenever a new individual in the population considered by the algorithm is created [14, 15].

The subject of minimizing the system costs by applying these optimization techniques have gained ample attention due to the high losses of energy in power plants; therefore, much of current research on optimization of HRSG is focused on minimization of exergy loss. Ahmadi et al. [16] particularly carried out genetic algorithm in power plant cycles by exergoeconomic principals. Khademi et al. [17, 18] compared and contrasted the PSO and GA results for the gas-turbine power plant. A steam turbine power plant is thermo-economically modeled and optimized using NSGA-II and ANN by Hajabdollahi et al. [8]. Behzadi Forough. [27] modeled an integrated Solid Oxide Fuel Cell (SOFC)/ Micro Gas Turbine (MGT) and performed multi objective optimization using NSGA-II to. But in the studied literatures there is not a comprehensive economic analysis and actually, the system performance has not been investigated through practical point.

It is worthy to mention that exergy destruction is considered as an internal phenomenon (e.g. heat transfer irreversibilities or pressure drop in a heat exchanger), while exergy losses may be seen as external irreversibilities (e.g. discharge of a not useful stream to the environment). Therupon, the terms "exergy loss" and "exergy destruction" are called as "external" and "internal" exergy losses, respectively.

In this research paper, the thermodynamic simulation of the CCPP with HRSG is conducted and then optimization of the combined cycle power plant is performed using PSO, Firefly and NSGA-II algorithms. In the second part, to realize the system performance, the optimized results are compared from economic aspects. In addition, the effectiveness of HRSG as a part of CCPPs was evaluated from three major perspectives: 1) technical (energy), 2) economical , and 3) exergy using specific criteria. The proposed methodology is implemented into a real case study, Yazd power plant which is one of the greatest power generation installed capacity in the Iran's power grid. In the optimization process, the operating variables of the HRES in a CCGT are optimized using the proposed evolutionary algorithm and then, the COMFAR software are implemented to compare the optimization results and to select the most effective algorithm. It is worthy to mention that the optimization results are very useful in design of a real combined cycle power plant from thermodynamic and economic point of view.

In summary, the main innovations and contributions of this research article can be multi-folded as :

1) Comprehensive thermodynamic simulation of a real-world HRSG in Iran is conducted
2) Techno-economic evaluation of an existing HRSG is conducted
3) Optimization of Yazd CCPP as a real case study based on the novel framework of energy and exergy analysis is performed
4) Collection of real Yazd CCPP data and implementation them into the techno-economic optimization
5) There well-Known optimization algorithm namely, PSO, Firefly and NSGA-II are applied to determine the optimal design parameters
6) Detailed Economic justification of real sample of CCPP by implementation of COMFAR software
7) Evaluation of NPV, sensitivity analysis and calculation of break-even point as the effective economic criteria

The economic analysis results showed that the optimization results are economically more feasible than the base case. The Firefly algorithm had the best result of the other evolutionary algorithms. In addition, in the case of Firefly method, by decreasing the operation costs, fixed assets and sales revenue by 40%, the IRR increases by 6.7%, 42.8% and decreases by 41.4%, respectively. The results show that the lowest sensitivity of IRR is related to operations cost, while the highest sensitivity of IRR is corresponding to variations of fixed assets.

Nomenclature

r_c	Compressor pressure ratio
c_f	cost of fuel per unit of energy
$\dot{C}_D$	cost of exergy destruction
$\dot{C}$	cost per unit exergy
$\dot{m}$	mass flow rate (Kg/s)
T	Temperature (ºK)
IRR	Internal rate of return on investment
HRSG	heat recovery steam generator
LP	low pressure
CCPP	combined cycle power plant
P	pressure (bar)
S	specific entropy (KJ/Kmol.ºK)
h	specific enthalpy (KJ/Kmol)
$\dot{E}$	Exergy flow rate (MW)
LHV	lower heating value
$\dot{Z}_k$	capital cost rate
NPV	Net Present Value
TIT	turbine inlet temperature
SH	Superheater
LHV	lower heating value (kJ/kg)

Greek letters

η_{Sc}	Efficiency of the compressor
η_{St}	Efficiency of the turbine
η_{APH}	The effectiveness of the air preheater
ε	Exergetic efficiency
η	energy efficiency
ϕ	maintenance factor

Subscript

AC	air compressor
CC	combustion Chamber
CRF	capital recovery factor
D	destruction
Pp	pinch point
i	interest rate
k	component
Ph	Physical
Ch	Chemical
F	fuel for a component

2.Exergoeconomic analysis

In this study, real data and parameters of an existing CCPP are used and a real case study is evaluated. Yazd power plant is one of the greatest power generation installed capacity in the Iran's power grid. It is composed of steam power generation unit, gas turbine units of Siemens V 94.2 with the nominal capacity of 2x162.5 MW (as closed combined cycle 484 MW totally 3 units, 2*162 MW gas units and 1*160 MW steam unit). Table 1 and 2 show the Site Condition in Yazd City, Iran and detailed components of existing power plant, respectively.

All input parameters which are applied into optimization module are calculated based on the values of measured properties such as pressure, temperature and mass flow rate at various points in combined cycle power plant sited in Yazd, Iran. Tables 3-6 present the specifications and parameter values of CCPP exhaust gas, HP and LP systems, Heat Recovery Steam Generator and Auxiliary and Duct Burner, respectively. The presented data are very essential and useful information about this power plant that are used to the energy and exergy analyses. Indeed, by applying these measured data we are able to realize the simulation of the system performance and then improve the techno-economic aspects of a sample power plant.

Table 1. Site Condition (Yazd City, Iran)

Parameter	Value
Elevation above Sea Level	1180 m
Average Ambient Temperature / Relative Humidity (RH)	19 °C / 32 %
Minimum Ambient Temperature / Relative Humidity (RH)	-16 °C / 68 %
Maximum Ambient Temperature / Relative Humidity (RH)	45.6 °C / 12 %

Table 2. The detailed Components of Existing Power Plant

Component	Specification
Gas turbine, generator and auxiliaries	Two TUGA gas turbine generator (V94.2)
HRSGs	Two MBC dual pressure level waste
Steam turbine and generator (supplied by TUGA)	One TUGA condensing steam turbine
Gas Turbine Fuel	Natural gas: Normal Operation Gas oil: Emergency Operation

Table 3. Existing Plant, Exhaust gas specification with parameters values

Parameter	Value
Exhaust gas flow rate, kg/s	455.75
Exhaust gas temperature, deg. °C	543.3
Exhaust analysis[1]	
O_2 Wet (%) Vol.	15.682
H_2O Wet (%) Vol.	4.198
$CO_2 + SO_2$ Wet (%) Vol.	5.038
N_2 Wet (%) Vol.	73.848
Ar Wet (%) Vol.	1.235

Table 4. Parameters of HP and LP Systems with their values

HP steam condition at HP turbine stop valve at guarantee condition	
Parameter	**Value**
Flow (kg/s)	134
Pressure (bar)	90
Temperature (°C)	520
LP steam condition at LP turbine stop valve inlet at guarantee condition	
Parameter	**Value**
Flow (kg/s)	18
Pressure (bar)	8.50
Temperature (°C)	230

[1] These values are also important for analyzing chemical exergy.

Table 5. The values of Heat Recovery Steam Generator and Auxiliary parameters

Condensate pre-heater inlet/outlet temperature at guarantee condition	
Parameter	**Value**
Inlet/outlet Temperature (deg. °C)	48 / 139.54
Expected Feed water temperature at HRSG economizer inlet during guarantee condition	HP (deg. °C): 153.71 LP (deg. °C): N/A
Flue gas temperature of main stack outlet	Temperature (deg. °C): 112.81
Gas pressure drop	300.00 mmH_2O based on static head

Table 6. Specifications of Duct Burner

Parameter	**Value**
Design temperature	631 °C
Location of burner	Before final HP super heater
Numbers of burners	3
Gas velocity (Maximum)	18 m/s
Emission Guarantee	No_x : Maximum 40.00 mg/MJ Co : Maximum 60.00 mg/MJ

Figure 1 shows the schematic diagram of a combined cycle power plant (CCPP) with a supplementary firing system. The configuration of the system in this figure is drawn based on the real case study of CCPP in Yazd City, Iran. Actually, the presented figure shows the role of HRSG in a combined cycle power plant as a middle system between gas turbine and steam turbine cycle. The high potential exhaust gas of gas turbine with supplementary fuel are imported into the HRSG to generate steam. As it can be seen, two levels of steam are generated in HRES which are High pressure (HP) and low pressure (LP). Two pressure level of steam are imported into steam generator where the power is secondly produced. The mentioned graphic shows how the exergy flows work in a sample CCPP infrastructure. In addition, the state points that were accounted for calculation of exergy flows are presented in this analysis.

In this study, energy and exergy analyses are performed for a real sample of CCPP. Therefore, to achieve this goal, energy balance and exergy balance equations of the CCPP are extracted regarding the different system equipment as the different control volumes. The mentioned balance equations are separately presented in Table 7 regarding duct burner, HP super heater, HP Evaporator, HP economizer, LP super heater, LP evaporator, DEA evaporator, COND PRE and pump. In addition, the state points of exergy flow determination are presented in Table 7.

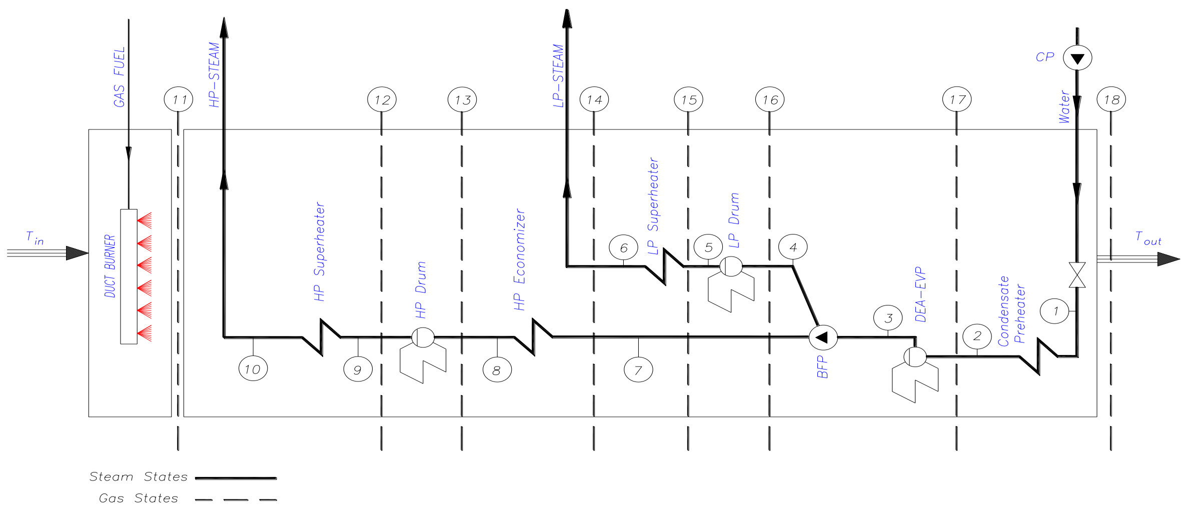


Fig.1. The schematic of the HRSG in combined cycle power plants with existing relevant flows

Table 7. The energy and exergy balance equations of CCPP regarding different control volumes

Name	Energy balance	Exergy balance
Duct burner	$\dot{m}_g C_p(T_{11}-T_{in})=\dot{m}_f LHV$	$Ex_D=\dot{m}_g ex_{in}+\dot{m}_f ex_f-\dot{m}_g ex_{11}$
HP SH	$\dot{m}_g c_p(T_{11}-T_{12})=\dot{m}_{s,HP}(h_{10}-h_9)$	$Ex_D=\dot{m}_g(ex_{11}-ex_{12})+\dot{m}_{w.HP}(ex_9-ex_{10})$
HP EVP	$\dot{m}_g c_p(T_{12}-T_{13})=\dot{m}_{s,HP}(h_9-h_8)$	$Ex_D=\dot{m}_g(ex_{12}-ex_{13})+\dot{m}_{w.HP}(ex_8-ex_9)$
HP ECO	$\dot{m}_g c_p(T_{13}-T_{14})=\dot{m}_{s,HP}(h_8-h_7)$	$Ex_D=\dot{m}_g(ex_{13}-ex_{14})+\dot{m}_{w.HP}(ex_7-ex_8)$
LP SH	$\dot{m}_g c_p(T_{14}-T_{15})=\dot{m}_{s,LP}(h_6-h_5)$	$Ex_D=\dot{m}_g(ex_{14}-ex_{15})+\dot{m}_{w.LP}(ex_5-ex_6)$
LP EVP	$\dot{m}_g c_p(T_{15}-T_{16})=\dot{m}_{s,LP}(h_5-h_4)$	$Ex_D=\dot{m}_g(ex_{15}-ex_{16})+\dot{m}_{w.LP}(ex_4-ex_5)$
DEA EVP	$\dot{m}_g c_p(T_{16}-T_{17})=\dot{m}_{s,LP}(h_3-h_2)$	$Ex_D=\dot{m}_g(ex_{16}-ex_{17})+\dot{m}_w(ex_2-ex_3)$
COND PRE	$\dot{m}_g c_p(T_{17}-T_{18})=\dot{m}_{s,LP}(h_2-h_1)$	$Ex_D=\dot{m}_g(ex_{17}-ex_{18})+\dot{m}_w(ex_1-ex_2)$

It should be noted that in both energy and exergy analysis, the $C_{p.Gas}$ is considered as a function of temperature variable as follows [2]:

$$C_{p.Gas}(T)=0.991615+\frac{6.997}{10^5}T+\frac{2.7129}{10^7}T^2-\frac{1.2244}{10^{10}}T^3 \quad (1)$$

The efficiency of CCPP is calculated based on the HRSG which is designed by using the pinch point technique. The minimum temperature difference between the inner and outer fluid during heat addition (pinch point) is considered as the limiting factor for heat transfer [19, 20].

The results of this paper are expected to provide incremental economic benefits through decrease in fuel consumption and improving the total system efficiency at Yazd Combined Cycle Power Plant. These goals will achieve by optimization of the power plant by applying the evolutionary algorithms and economic analysis. The cost analysis of the power plant has been carried out on the basis of the total capital investment, operating cost and revenue base on the local prices in Iran. Table 8 lists the average price of combined cycle units by using the international prices [21-23].

The cost of heating elements (i.e., including economizer, evaporator, super heater and deaerator evaporator) in combined cycle power plant could be measured based on the data of Table 8 and the following equation [22]:

$$C_{c.heating\ elements}=\left(K_{eva}A_{evp}+K_{eco}A_{eco}+K_{sh}A_{sh}+K_{DEA-EVP}A_{DEA-EVP}\right)_{LP}+\left(K_{eva}A_{evp}+K_{eco}A_{eco}+K_{sh}A_{sh}\right)_{HP} \quad (2)$$

The investment cost of duct burner takes the form of below according to its heating capacity [1, 21]:

$$C_{c.duct\ burner}=7000\times\dot{m}_f\times LHV\times\eta_{combustion} \quad (3)$$

where, the $\dot{m}_f$ is the fuel mass flow rate and $\eta_{combustion}$ is the combustion efficiency of the burners. The combustion efficiency is depended of several factors, such as excess air, type of input fuel, net stack temperature and etc. In this work, the amount of 78% is considered as an average combustion efficiency.

The optimal decision variables regarding the cost objective function obtained by applying the different evolutionary algorithm: PSO, Firefly and NSGA-II. In this optimization technique, solver finds the values for decision variables that satisfy the constraints. In addition, along with the best decision variables which are determined by PSO, Firefly and NSGA-II, the optimum system operating parameters will be optimized. The algorithm runs for 600 iterations each time. Each parameter is averaged by 600 times. These values reduce the system total cost per unit of generated steam exergy as the objective function [3, 22].

Table 8. The average price of combined cycle units (HRSG)

Element	Economizer K_{eco} $\$/m^2$	Evaporator K_{eva} $\$/m^2$	Super heater K_{Sup} $\$/m^2$	Deaerator evaporator $K_{DEA-EVP}$ $\$/m^2$
Price	33.8	44.56	95.1	40.87

The equation for calculation of system cost is presented as follows:

$$C_T = aC_c + C_{op} + C_E \times \dot{Ex}_D \times t_{op} \quad (4)$$

where, the first term (aC_c) in Eq.(4) determines the capital or investment cost of CCPP ($C_c = C_{c.heating\ elements} + C_{c.duct\ burner}$), and the parameter (a) is the annual recovery factor, which is an economic parameter. This parameter depends on the interest rate (i) and estimated equipment life time (k) explained in form of $\frac{i(1+i)^k}{(1+i)^k-1}$ [16, 22]. The interest rate (*i*) is 24% that is from Bank of Industry and Mine in IRAN. Also, third part of Eq. (4) is dedicated the cost of exergy destruction in system. In this way, there is possibility to account and reduce the exergy cost along with the other investment and operation costs of system.

Generally, the equivalent equation to calculate the total system cost is presented as Eq. (5). regarding consideration of the exergy destruction cost.

$$\dot{C}_{Tot} = \dot{C}_f + \sum_k \dot{Z}_k + \dot{C}_D \quad (5)$$

$$\dot{C}_F = c_f(\dot{m}_{f.cc} + \dot{m}_{f.DB}) \times LHV \quad (6)$$

Here, $\dot{Z}_k$, $\dot{C}_f$ and $\dot{C}_D$ are the purchase cost of each part of CCPPs (in this work, $C_{c.heating\ elements}$ and $C_{c.duct\ burner}$), fuel cost as an operating cost and cost of exergy destruction, sequentially. Furthermore, $\dot{C}_f$ is the fuel cost, which is supposed to be 0.003 $\$/_{MJ}$ in our analysis with regard to the cost of fuel in Iran [16, 22, 24, 25].

Table 9 shows the range of change in operating parameters as the decision variables that are defined by the engineering manufacture firm. These limitations of decision variables are input parameters of the optimization model and they are applied as the optimization constraints.

3.Results

The fuel considered for the combustion in the duct burner is natural gas with a LHV = 50000 kJ/kg. The fuel price is considered as $C_f = 0.003\ \$/_{MJ}$ base on the price in Iran. The power plant operates for 8000 hours per year when system operates at full load (i.e., about one month by the year the power plant will be off for the overhaul). The interest rate is assumed to be 24%, which is taken from the Bank of Industry and Mine in Iran. In this case, all of the components of the power plant is assumed to be operating for 20-year lifespan. The exergy unit price C_E is considered as 0.02 $/kWh, the average value of the selling price of electricity in Iran [3]. The total equations with the defined parameters are imported to the optimization module, where, the evolutionary algorithms optimize the system operation. Subsequently, the determined parameters of the HRSG model helps us to calculate the defined decision variables as the depended variables with thermodynamic methods by applying the Thermoflow software. The values of these determined parameters have shown in Table 10.

The main results of optimization are listed in Table 11. These results consist of the optimum operation decision variables of the mentioned case study that have been optimized by PSO, Firefly, NSGA-II.

At it is mentioned, the economic analysis of a sample CCPP is one of the main contribution of this work. In this way, the main methods used for project cost evaluation are the Net Present Cost (NPV) and Internal Rate of Return (IRR) methods. According to the mentioned methods, an investment project is viable if the NPV is positive or if the IRR is greater than the minimum required rate of return typically the cost of capital [26].

The internal rate of return (IRR) can be defined as the rate of return that makes the net present value (NPV) of all cash flows equal to

Table 8. The range of change in operation parameters [22]

Symbol	Parameter	Unit	From	To
P_{HP}	Pressure	MPa	5	15
P_{LP}	Pressure	MPa	0.4	7
PP_{HP}	Temperature	K	5	30
PP_{LP}	Temperature	K	5	30
$\dot{m}_{s,HP}$	Mass flow ratio	%	0.1	0.9
$\dot{m}_{DB}$	Duct burner mass flow rate	$\frac{kg}{s}$	0.5	1.2

Table 9. Determined parameters of HRSG thermal modeling at Yazd CCPP (with duct burner)

Determined parameters (optimization outputs)	Real Condition	PSO	Firefly	NSGA-II
Inlet gas temperature (°K)	816.25	890.20	904.18	816.45
Inlet gas flow rate $\dot{m}_g$ (kg/s)	456.3	496.49	504.09	455.75
Fuel consumption Duct burner $\dot{m}_{DB}$ (kg/s)	0.617	0.588	0.541	0.601
Exhaust Gas Conditions After Duct Burner Flow rate(kg/s)	456.917	488.21	504.090	456.901
Exhaust Gas Conditions After Duct Burner Temperature (°K)	866.24	844.17	833.02	864.95
Inlet water temperature (°K)	320	343.67	348.15	
Ambient temperature (°K)	293	293	293	293

Table 10. Optimum operation parameters of the dual pressure combined cycle power plant regarding different evolutionary algorithm

Decision variable	Real Condition (Base case)	PSO	Firefly	NSGA-II
r_c	10.40	10.78	11.21	10.61
η_c	0.815	0.829	0.831	0.821
η_{GT}	0.837	0.848	0.851	0.841
PP_{HP} (K)	281.49	283.21	285.26	282.65
PP_{LP} (K)	290.7	293.21	294.68	292.84
T_{HP} (K)	796.15	804.79	805.97	803.16
T_{LP} (K)	506.15	511.55	516.32	509.98
P_{Con} KPa	14.30	15.10	15.40	14.95
η_{Pump}	0.825	0.837	0.845	0.834
η_{St}	0.781	0.792	0.798	0.788

to zero. Both IRR and NPV are widely used to decide which investments to undertake and which investments not to make. The main difference is that NPV is calculated in cash, whereas IRR is a percentage value expected in return from a capital project.

By using the output of optimization results as they presented in Table. 10 and Table. 11 and with the defined real techno-economic parameters, the NPV of real base case CCPP is calculated using COMFAR software.

As the NPV is calculated based on the discounting rate, the plot of NPV respect to discounting rate variations is presented in Fig.2. The investment for sample CCPP is justifiable when the NPV is positive. As it can be seen, by increasing the discounting rate, the calculated NPV is decreased, until the NPV achieve Zero amount. In this point (A), the present value of cash inflows is equal to present value of cash outflows and the equivalent discounting rate is reported as a IRR. In this case, the IRR is equal to 46.92%. By more increase of discounting rate, the NPV gets the negative value, which is non affordable area to invest.

The summarized economic analysis for the base case and optimization results regarding three different evolutionary algorithms is shown and compared in Table 12. These results are outputs of COMFAR software. The net present values of the cash flows are shown using discount rates of 24 percent and 28%. The IRR, which is referred to as the discounted cash flow rate of return, is also presented. The IRR of the base case is 46.92 percent.

As it can be seen in Table. 12, evolutionary algorithms improve the economic justification of real CCPP in comparison with base case, as they increase the NPV (4.7%) and consequently leads to increase the IRR (2.3%). In addition, the other economic parameters are presented as break-even ratio (it is used to determine what rate of occupancy is needed to meet both operation expense and mortgage payments), normal and dynamic payback. Generally, evolutionary algorithms lead to enhance the all of economic parameters, but in among of them, the Firefly algorithm presents the best optimum economic results.

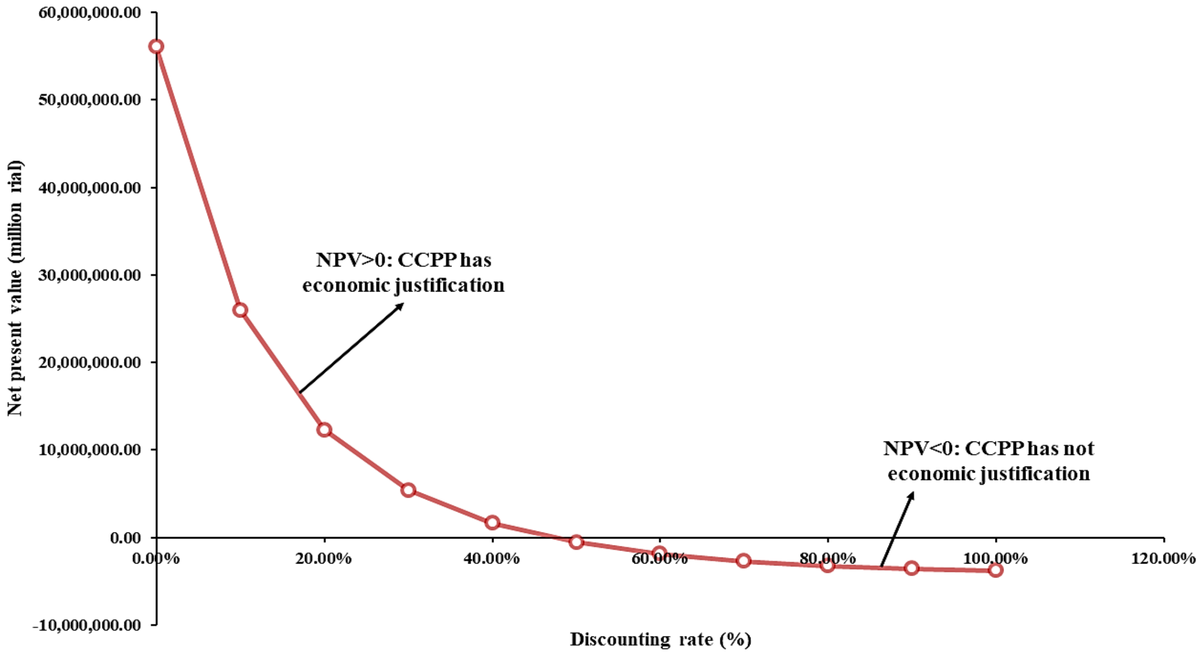


Fig. 2. Real condition Net Present Value respect to discounting rate for a real combined cycle power plant (Output of COMFAR software)

Table 11. The summarized economic analysis for different evolutionary algorithms

Optimized Economic Criteria	Real Condition	PSO	Firefly	NSGA-II
Net Present Value of Total Capital Invested at 24/00%	300303466.7 $	311754454.7 $	315382041 $	307692300 $
Internal rate of return on investment (IRR)	46.92%	47.75%	48.01%	47.46%
Net Present Value of Total Equity Capital Invested at 28/00%	215432762.3 $	225263234 $	228377453 $	221775945.7 $
Break-even ratio	41.88	40.95	40.66	41.27
Normal Payback	3.08 years	3.05 years	3.04 years	3.06 years
Dynamic payback	4.25 years	4.17 years	4.15 years	4.20 years
Price Of Electricity-Kw	8 cent(with government Subsidies)			
Cost Of Methane per m^3	16 cent			

A sensitivity analysis refers to the process of establishing in what areas or concerning which parameters of model is the most sensitive as well as specifying the ranges when possible. The idea is that we freeze all the variables except the one (s) analyzed and check how sensitive the NPV and/or the IRR are to change in that variable. In this economic study, the sensitivity analysis is performed to show how is sensitivity of IRR respect to variations of operation costs, increase in fixed assets and sales revenue. To achieve this goal, the operating costs, increase in fixed assets and sales revenue will be changed to show the influence them on IRR. It helps in assessing risk.

The results are presented in Table. 13, where in the right column the amount of variations of operation costs, increase in fixed assets and sales revenue are shown and the other columns express the variations of IRR regarding different optimization methods. As it can be seen in Table. 13, in the case of Firefly method, by decreasing the operation costs, fixed assets and sales revenue by 40% the IRR increases by 6.7%, 42.8% and decreases by

41.4%, respectively. The results show that the lowest sensitivity of IRR is related to operations cost, while the highest sensitivity of IRR is corresponding to variations of fixed assets.

Figure 3 shows the plots of sensitivity analysis of IRR for the base case (real case) which its numerical results are presented in Table. 13. The vertical axis is variation of IRR while the horizon axis is variations of operation costs, increase in fixed assets and sales revenue. Three plots are related to the impact of changes of ± 40% (from -20% to +20%) of operation costs, increase in fixed assets and sales revenue to the IRR.

The results analysis of base case is summarized as follows: The IRR of the base case is 46.92%; a 4% decrease in sales revenue results in a IRR of 44.45%, whereas an increase of 4% in sales revenue results in a IRR of 49.38%. A 4% decrease in operating cost results in a IRR of 47.39%, whereas an increase of 4% in operating cost results in a IRR of 46.46%. A decrease in fixed assets of 4% results in an increase in IRR of 49.02%, whereas an increase of 4% in fixed assets results in an increase in IRR of 44.98%.

Table 12. Sensitivity analysis results respect to variation of operation costs, increase in fixed assets and sales revenue with different cases (PSO, Firefly, NSGA-II and Real case)

Variation of IRR respect to variation of operating costs				Variation of IRR respect to increase in fixed assets				Variation of IRR respect to variation of sales revenue				Variations (%) of operating cost fixed assets sales revenue
Real	PSO	NSGA	Fire Fly	Real	PSO	NSGA	Fire Fly	Real	PSO	NSGA	Fire Fly	
49.24%	49.90%	49.67%	50.11%	59.36%	60.37%	60.01%	60.69%	34.36%	35.22%	34.92%	35.50%	**-20.00%**
48.78%	49.47%	49.23%	49.69%	56.42%	57.39%	57.05%	57.69%	36.92%	37.77%	37.47%	38.04%	**-16.00%**
48.32%	49.04%	48.78%	49.27%	53.74%	54.67%	54.34%	54.96%	39.45%	40.30%	40.00%	40.57%	**-12.00%**
47.85%	48.61%	48.34%	48.85%	51.28%	52.17%	51.86%	52.45%	41.96%	42.80%	42.50%	43.07%	**-8.00%**
47.39%	48.18%	47.90%	48.43%	49.02%	49.88%	49.57%	50.15%	44.45%	45.28%	44.99%	45.55%	**-4.00%**
46.92%	47.75%	47.46%	48.01%	46.92%	47.75%	47.46%	48.01%	46.92%	47.75%	47.46%	48.01%	**0.00%**
46.46%	47.32%	47.01%	47.59%	44.98%	45.78%	45.50%	46.03%	49.38%	50.20%	49.91%	50.46%	**4.00%**
45.99%	46.89%	46.57%	47.17%	43.17%	43.95%	43.67%	44.19%	51.83%	52.65%	52.35%	52.90%	**8.00%**
45.52%	46.46%	46.13%	46.75%	41.49%	42.24%	41.97%	42.48%	54.26%	55.08%	54.79%	55.33%	**12.00%**
45.06%	46.02%	45.68%	46.33%	39.91%	40.64%	40.38%	40.87%	56.69%	57.50%	57.21%	57.75%	**16.00%**
44.59%	45.59%	45.24%	45.91%	38.42%	39.13%	38.88%	39.36%	59.10%	59.91%	59.62%	60.17%	**20.00%**

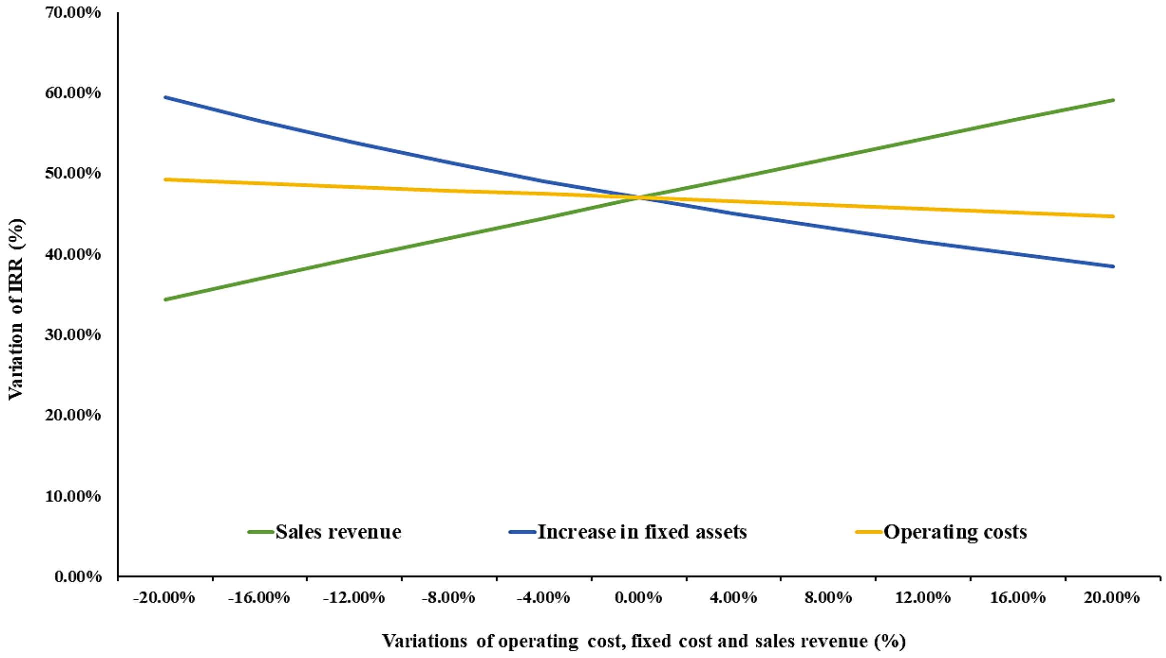


Fig.3. Sensitivity analysis of IRR respect to variations of operating cost, fixed cost and sales revenue (base case)

The point at which total of fixed and variable costs of a business becomes equal to its total revenue is known as the break-even point. Total variable and fixed costs are compared with sales revenue in order to determine the level of sales volume, sales value or production at which the business makes neither a profit nor a loss.

For power plants, the power is the product of a plant that will sell in Iran. Calculation of break-even point is important for every business because it tells business owners and managers how much sales are needed to cover all fixed cost as well as variable expenses of the business or the sales volume after which the business will start generating profit.

Thereupon, the break-even analysis is required to determine all of fixed and variable cost as well as sales revenue. In this work, the break-even analysis is performed to determine break-even point and the results for base case are shown in Fig.4. In this figure, the plot of fixed costs, total costs (i.e., fixed and variable costs) and sales revenue are drawn respect to capacity utilization. The intersection point of two curve (total cost and sales revenue) is called break-even point. This point is equivalent to 42.6% of capacity utilization. It means that when the CCPP produces power by 42.6% of its capacity, the sales revenue will be equal to the total cost.

4.Conclusions

Since the energy industries play with large amounts of money, the optimization of this systems particularly profit optimization has high importance on economic justification of power plants. In the combined cycle power plant (CCPP), heat recovery steam generator (HRSG) has a critical role as it connects the gas turbine cycle with steam turbine cycle in order to generate steam to produce electricity. Therefore, improvement of HRSG efficiency can affect the total system efficiency which is realized by several methods.

In the present research study, techno-economic analysis of HRSG was carried out to minimize the cost function and optimally adjust the operating parameters of the real CCPP as a case study. To achieve this aim, the approach discussed is optimizing the system by PSO, Firefly and NSAG-II as evolutionary algorithms. The operating decision variable are determined based on energy and exergy analysis which are considered as related equations in objective function and constraints. The input parameters are measured in real case study (i.e., CCPP in Yazd city, Iran) and they are used to run the optimization problem. Afterward, the results are analyzed and compared from an economic viewpoint by the COMFAR III software package. The economic analysis consists of determination of NPV, sensitivity analysis and calculation of break-even point.

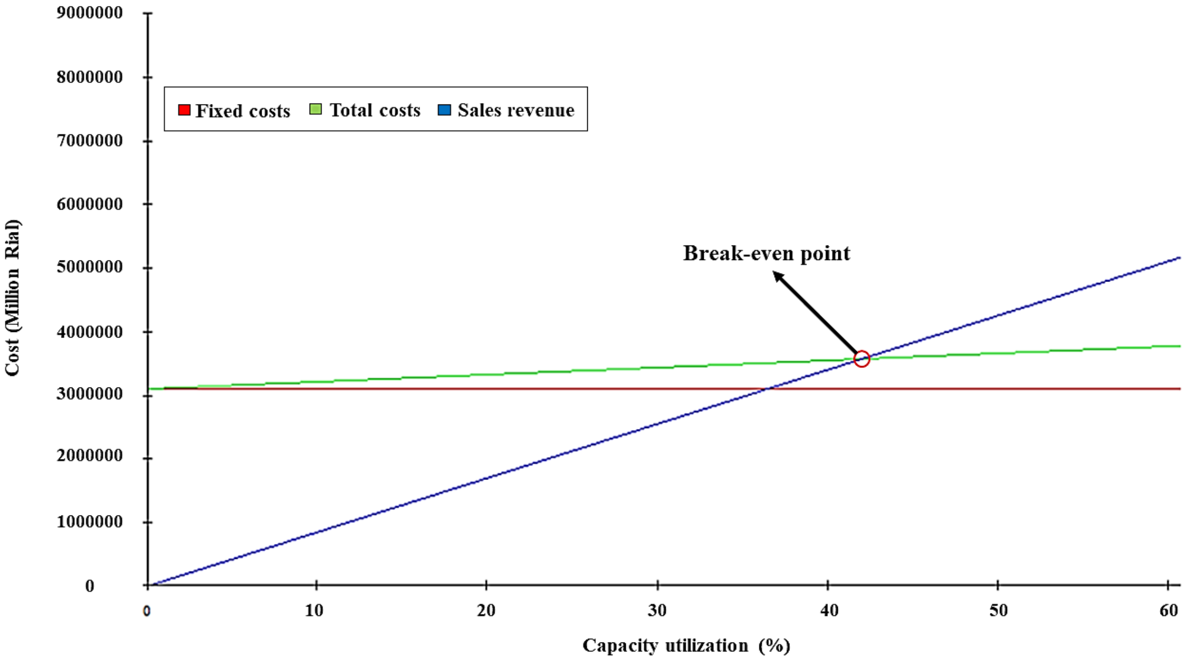


Fig.4. Break-Even Analysis: Fixed costs (MRial), Total costs (MRial) and sales revenue (MRial) respect to capacity utilization (%)

The economic analysis results showed that the optimization results are economically more feasible than the base case. The Firefly algorithm had the best result compared to other evolutionary algorithms. In addition, in the case of Firefly method, by decreasing the operation costs, fixed assets and sales revenue by 40%, the IRR increases by 6.7%, 42.8% and decreases by 41.4%, respectively. The results show that the lowest sensitivity of IRR is related to operations cost, while the highest sensitivity of IRR is corresponding to variations of fixed assets.

Acknowledgements

The authors would like to thank the research council of the Islamic Azad University South Tehran Branch (contract No. 844) for supporting this research.

References

[1] Baukal Jr C.E., Industrial Burners Handbook. CRC press (2003).
[2] Bassily A., Modeling Numerical Optimization and Irreversibility Reduction of a Dual-Pressure Reheat Combined-Cycle. Applied Energy, 81(2): 127-151 (2005).
[3] Ghazi M., et al., Modeling and Thermo-Economic Optimization of Heat Recovery Heat Exchangers Using a Multimodal Genetic Algorithm. Energy Conversion and Management, 58: 149-156 (2012).
[4] Zheng Q.P., Pardalos P.M., Stochastic and Risk Management Models and Solution Algorithm for Natural Gas Transmission Network Expansion and LNG Terminal Location Planning. Journal of Optimization Theory and Applications, 147(2): 337-357 (2010).
[5] Tsatsaronis G., Thermoeconomic Analysis and Optimization of Energy Systems. Progress in Energy and Combustion Science, 19(3): 227-257 (1993).
[6] Sharifi H., Heat Recovery Boiler 1(1): 616. (2011).
[7] Sahoo P., Exergoeconomic Analysis and Optimization of a Cogeneration System Using Evolutionary Programming, Applied Thermal Engineering, 28(13): 1580-1588 (2008).
[8] Hajabdollahi F., Hajabdollahi Z., Hajabdollahi H., Soft Computing Based Multi-Objective Optimization of Steam Cycle Power Plant Using NSGA-II and ANN. Applied Soft Computing, 12(11): 3648-3655 (2012).
[9]Rosen M.A., Dincer I., Exergoeconomic Analysis of Power Plants Operating on Various Fuels, Applied Thermal Engineering 23(6): 643-658 (2003).
[10]Naserabad S.N., et al., Exergy-Energy Analysis of Full Repowering of a Steam Power Plant. Frontiers in Energy 9(1): p. 54-67 (2015).
[11]Ol'khovskii G.G., Combined Cycle Plants: Yesterday, Today, and Tomorrow (review) Thermal Engineering, 63(7): 488-494 (2016).
[12]Kang F., Xu Q., Li J., Slope Reliability Analysis Using Surrogate Models via New Support Vector Machines with Swarm Intelligence. Applied Mathematical Modelling, 40(11): 6105-6120 (2016).
[13]Kang F., Li J.-s., Li J.-j., System Reliability Analysis of Slopes Using Least Squares Support Vector Machines with Particle Swarm Optimization. Neurocomputing, 209: 46-56 (2016).
[14]Koch C., Cziesla F., Tsatsaronis G., Optimization of Combined Cycle Power Plants Using Evolutionary Algorithms. Chemical Engineering and Processing: Process Intensification, 46(11): 1151-1159 (2007).
[15]Khosravi A., et al., Comprehensive Review of Neural Network-Based Prediction Intervals and New Advances. IEEE Transactions on Neural Networks, 22(9): 1341-1356 (2011).
[16]Ahmadi P., Dincer I., Exergoenvironmental Analysis and Optimization of a Cogeneration Plant System Using Multimodal Genetic Algorithm (MGA). Energy, 35(12): 5161-5172 (2010).
[17]Khademi M., Khosravi A., Exergoeconomic Analysis and Optimisation of a Gas-Turbine Power Plant Using PSO, GA and Fuzzy Logic System. International Journal of Exergy, 19(2): 259-275 (2016).
[18]Alizadeh S., Khosravi A., Khademi M., A Fuzzy Logic-Based Approach to Verify the Optimized Parameters a Gas Turbine Power Plant by PSO Algorithm, in Fuzzy Systems (IFSC), 2013 13th Iranian Conference on, IEEE (2013).
[19]Kanoglu M., Dincer I., Performance Assessment of Cogeneration Plants,

Energy Conversion and Management, 50(1): 76-81 (2009).

[20]Kanoglu M., Dincer I., Rosen M.A., Understanding Energy and Exergy Efficiencies for Improved Energy Management in Power Plants. Energy Policy, 35(7): 3967-3978 (2007).

[21]Casarosa C., Donatini F., Franco A., Thermoeconomic Optimization of Heat Recovery Steam Generators Operating Parameters for Combined Plants. Energy, 29(3): 389-414 (2004).

[22]Ahmadi P., Dincer I., Thermodynamic Analysis and Thermoeconomic Optimization of a Dual Pressure Combined Cycle Power Plant with a Supplementary Firing Unit. Energy Conversion and Management, 52(5): 2296-2308 (2011).

[23]Hajabdollahi H., Ahmadi P., Dincer I., An Exergy-Based Multi-Objective Optimization of a Heat Recovery Steam Generator (HRSG) in a Combined Cycle Power Plant (CCPP) Using Evolutionary Algorithm. International Journal of Green Energy, 8(1): 44-64 (2011).

[24]Ahmadi P., Rosen M.A., Dincer I., Multi-objective Exergy-Based Optimization of a Polygeneration Energy System Using an Evolutionary Algorithm Energy, 46(1): 21-31 (2012).

[25]Ahmadi P., Dincer I., Rosen M.A., Exergy, Exergoeconomic and Environmental Analyses and Evolutionary Algorithm Based Multi-Objective Optimization of Combined Cycle Power Plants. Energy, 36(10): 5886-5898 (2011).

[26]Lohmann J.R., BAKSH S.N., The IRR, NPV and Payback Period and Their Relative Performance in Common Capitial Budgeting Decision Procedures for Dealing with Risk, The Engineering Economist, 39(1): 17-47 (1993).

[27]Behzadi Forough A., Roshandel R., Design and Operation Optimization of an Internal Reforming Solid Oxide Fuel Cell/Micro Gas Turbine integrated system based on multi objective approach, Applied Thermal Engineering 114: 561–572 (2017).