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Techno-economic Optimization of Combined Cooling, Heat and Power System Based on Response Surface Methodology

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ABSTRACT

In the present work, the statistical analyses are presented to study the economic indexes of Net Present Value (NPV) and Simple Payback Period (SPB) as response functions for the Combined Cooling, Heating and Power (CCHP) system. The CCHP performance is simulated with the aid of thermodynamic modeling, and also economic equations are presented for economic simulation. An attempt is made to study the effect of some economic factors (interest ratio, fuel cost, lifetime, and electricity sell price) on the system's responses. Based on the Design of Experiment analysis, regression models are presented to quantify the effects of these parameters on the Net Present Value and Simple Payback Periods. This novel approach is developed utilizing the response surface methodology (RSM) based on the central composite design (CCD) method. Sensitivity analysis of the economic parameters was also examined in this research. Optimal values of these parameters were obtained for the two economic indexes as response functions.

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NOMENCLATURE

A	Surface area (m^2)	*Pes*	Electricity sell price ($/kWh)
AOH	Annual operation hour (hr)	$\dot{Q}$	Heat load (kW)
Ben	Annual benefit ($/Year)	R_m	Mass flow rate ratio
C_0	Investment cost ($)	r_p	Pressure ratio
C_m	Annual O&M cost ($/Year)	*SPB*	Simple pay-back period (Year)
c_p	Specific heat capacity (kJ/kg K)	*T*	Temperature (^{0}C)
cf	Fuel cost ($/kWh)	*W*	Work (kW)
COP	Coefficient of performance	*X*	Concentration of solution
CPCEI	Chemical engineering plant cost index	**Subscript**	
DHW	Domestic hot water	*a*	Air
FC	Annual combustion chamber fuel consumption cost ($/Year)	*Abs*	Absorber
h	Enthalpy (kJ/kg)	*ARS*	Absorption refrigeration system
HRSG	Heat recovery steam generator	*c*	Compressor/Cooling
ir	Interest ratio (%)	*cc*	Combustion chamber
IRR	Internal rate of return (%)	*cool*	Cooling load
k	Specific heat ratio	*Con*	Condenser
LHV	Lower heating value (kJ/kg)	*CRS*	Compression refrigeration system
$\dot{m}$	Mass flow rate (kg/s)	*CW*	Cooling water

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N	Lifetime period (Year)	*Eva*	Evaporator
NPV	Net present value ($)	*f*	Fuel
P	Pressure (bar)	*g*	Gas
PEC	Purchase cost ($)	*Gen*	Generator
GT	Gas turbine cycle	*t*	Turbine
h	Heating	*th*	Thermal
Hx	Heat exchanger	**Greek Symbols**	
max	Maximum	η	Efficiency/ Isentropic efficiency (%)
min	Minimum	ΔP	Pressure drop (bar)
ORC	Organic rankine cycle	ΔT	Temperature difference (^{0}C)
P	Pump	ΔT_{lm}	Log mean temperature difference (^{0}C)
S	Strong solution	ΔX	Concentration difference of strong and weak solution
st	Steam	ϵ	Effectiveness factor

INTRODUCTION

Energy expenditure is per se related to economic prosperity in Iran as well as around the world. Electricity generation is one of the most important and successful parts of development and prosperity. Nowadays, steam modern gas turbine, and diesel power plants used independently or in combined cycle mode are the most plants to generate electricity in Iran. Much attention to pollutions and greenhouse gas emissivity in the power generation plants and concerns about the amount of storage and price of fossil fuels has propelled the widespread growth of technologies that can supply electricity from waste heat recovery or renewable sources. However, the possibility of using renewable energy and combined cooling, heating, and power (CCHP) plant has been received many considerations due to the climate of Iran. CCHP is swiftly gaining popularity, especially in the commercial and even residential parts, as they provide a reliable energy source.

The study and analysis of different cogeneration systems in recent years due to energy consumption have been considered. The existence of an electricity generation system with cooling and heating load supply capability can make the system self-sufficient in terms of the need for a generation network and maintain emergency power conditions. One of the most basic analyzes of cogeneration systems is energy optimization and thermodynamic analysis, which also allows the analysis of system sensitivity and determination of optimal layout. Bloomquist et al. [1] examined each piece of equipment in the cogeneration system. Thermodynamic modeling of cogeneration systems based on renewable sources and the use of non-fossil fuels has also been investigated, which have excellent performance while reducing emissions. Ebrahimi et al. [2, 3], in a cogeneration system, studied and evaluated parameters such as turbine inlet pressure and temperature on cycle and equipment performance and optimized the maximum cycle efficiency with the help of a genetic algorithm. Exergy analysis confirmed the maximum exergy degradation in the steam generation section. In a review study of trigeneration systems, Cho et al [4]. discussed optimization processes to improve system performance. Finally, by reviewing the work done by other researchers from various perspectives, they pointed to the gaps in the system, such as energy policy review, empirical validation, technology proof through feasibility, and integration of evaluation criteria for trigeneration systems. Pirkandi et al. [5] optimized the cogeneration system according to the input parameters by considering the exergy efficiency and net power as the objective functions of the genetic algorithm. They also examined the sensitivity analysis of the objective functions based on the input parameters. Mohammadi et al. [6] studied the thermodynamic analysis of CCHP, including organic Rankine cycle, gas turbine, and ammonia-water absorption refrigeration system. Parametric analysis by considering the changes of input parameters on the output of heating, cooling, and electrical systems was investigated. It was found that three parameters of pressure ratio, inlet temperature to gas turbine and inlet temperature of organic Rankin cycle turbine, are the main affecting parameters.

Economic analysis and investigation of consumption costs in cogeneration systems was also a major part of the study, which is the most important topic in cogeneration systems. In some scientific researches, various techno-economic studies have been performed in association with CCHP and cogeneration energy systems.

Many researchers have studied the different configurations of trigeneration systems to maximize performance and minimize system costs. Mone et al. [7] showed the positive role of cogeneration systems, and the feasibility study revealed that the use of cogeneration systems in commercial gas turbines from an economic point of view and the payback period is affordable. Silveira et al. [8] studied the thermo-economic analysis of the educational building cogeneration system based on energy and exergy analysis of the equipment to satisfy

30% of the building energy requirements. Ziher and Poredos [9] evaluated the annual costs of a health center based on a cogeneration system. Their results showed that CCHP would be very suitable for buildings that need constant electricity, cold, and heat generation throughout the year. Mago and Charma [10] have analyzed and optimized the CCHP system based on energy storage and economic costs, and environmental issues. The objective function has been performed by considering the supply of required electric and thermal charge, based on the constraints of minimizing the initial energy consumption, the operating cost, and the amount of carbon dioxide produced. Also, a hybrid model based on the simultaneous optimization model of all three parameters of initial energy consumption, operating cost, and reduction of pollutants emissions has been studied and developed. Ghaebi et al. [11] studied and analyzed the energy, exergy, and thermo-economics of a CCHP. Calculations have been performed to obtain fuel consumption values, refrigeration and heat value, net output power, the efficiency of the first and second laws, and exergy degradation of equipment. The effect of input parameters on cycle performance has been examined, and it was announced that the combination of a gas turbine with HRSG and absorption chiller would be highly cost-effective.Yan et al. [12] investigated gas CCHP systems in Beijing and presented a model for sharing energy efficiency based on the economic productivity of grid companies. Analysis of the economic sensitivity of the CCHP system with gas proved that fuel prices and electricity prices influence the revenue of the CCHP gas system. Fani and Sadraddini [13] investigated equipment size minimization based on trigeneration strategies and economic optimization strategy for the solar CCHP system in an educational office building. They also determined system efficiency, equivalent daily cost, and carbon dioxide reduction. Results showed a reduction in the daily operating cost of the system in the economic optimization model of the cycle compared to the other three strategies.

Although the thermodynamic study is a powerful tool to examine and optimize an energy system, statistical techniques can improve the results. Design of experiments (DoE) is assigned to organizing experiments to gather scientific data by statistical methods, resulting in reliable and objective outcomes [14]. DoE is a set of mathematical and statistical methods to reduce the number of experiments and find the effect of parameters (factors) affecting response in a process [15]. On this subject, limited research has been done using statistical methods such as Taguchi response surface methodology to study parameters of thermodynamic systems [16–21].

To the best of the authors' knowledge, there has not been any comprehensive examination of the economic analysis of the proposed system using the response surface methodology. The advantages presented by the RSM optimization can be summarized as determining the interaction between the independent variables, modeling the system mathematically, and saving time and cost [14]. This motivated the authors to establish the present analysis. Therefore, this study aims to apply statistical approaches of analysis of variance and response surface methodology to obtain the effective parameters,interaction parameters and optimized parameters on the economic analysis of the CCHP system.

In this paper, the thermo-economic analysis of a cogeneration system for a residential building is examined. The objectives of the present study are evaluating financial indicators (Net present value and Simple Payback Period), sensitivity analysis and optimization of economic parameters (fuel cost, intrest ratio, lifetime and electricity sell price) using the response surface methodology.

SYSTEM DESCRIPTION

In this study, the combination of heating, cooling, and power generation system for a 40-unit residential complex with a total area of 4000 square meters is examined. To achieve our cooling and heating demands, different equipment subsystem combinations could be considered. Due to the gas turbine cycle as the main source of power generation upstream of the flowsheet, it is possible to choose two common arrangements (GT/ORC/ARS) and (GT/ARS/ORC). However, due to the use of ORC in all seasons and the use of ARS only in the hot seasons of the year and also the need for high temperature gas in the evaporator of ORC to have a suitable heat transfer to the working fluid of ORC, layout configuration (GT/ORC/ARS)was selected as the appropriate arrangement.

A gas turbine cycle is responsible for power generation. The exhaust gases of the GT cycle are used as the heat source in the organic Rankine cycle, such that gas turbine and organic Rankine cycles supply electricity power demand. Also, heat exchangers are applied for providing hot water. In order to provide cooling load in hot seasons, the absorption refrigeration cycle is utilized. Also, to supply heating load in cold seasons with the help of a three-way valve, the absorption refrigeration system is cut off, and heat exchange between hot exhaust gas and water is activated (Figure 1).

MATHEMATICAL MODELING

Gas turbine cycle

The following assumptions are the basis for subsequent calculations of the energy-balance equations on different parts of the GT cycle.

- A constant isentropic efficiency is supposed for both compressor and turbine.

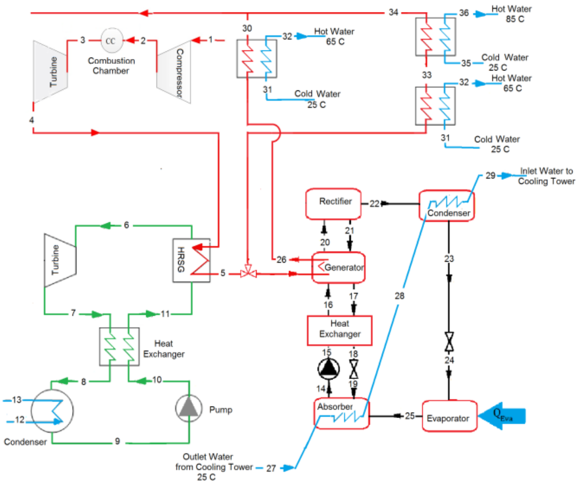


Figure 1. Schematic diagram of proposed CCHP

- All processes are assumed to be a steady-state and steady flow.
- Both flue gases and air are considered as an ideal gas mixture, and natural gas is used as fuel in the combustion chamber.

The standard thermodynamic equations for the gas turbine cycle according to the Brayton cycle can be stated as follows:

$$\dot{m}_a = \dot{m}_1 = \dot{m}_2 \tag{1}$$

$$T_2 = T_1\left(1 + \frac{1}{\eta_{c,GT}}\left(r_{p,GT}^{\frac{k-1}{k}} - 1\right)\right) \tag{2}$$

$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4} \tag{3}$$

$$W_C = \dot{m}_a\, c_{p.a}\,(T_2 - T_1) \tag{4}$$

$$\dot{m}_g = \dot{m}_3 = \dot{m}_2 + \dot{m}_f \tag{5}$$

$$\eta_{cc,GT} = \frac{\dot{m}_3 c_p T_3 - \dot{m}_2 c_p T_2}{\dot{m}_f (LHV)} \tag{6}$$

$$P_3 = P_2\,(1 - \Delta P) \tag{7}$$

$$T_4 = T_3\left(1 - \eta_{t,GT}\left(1 - \left(\frac{P_3}{P_4}\right)^{\frac{1-kg}{kg}}\right)\right) \tag{8}$$

$$W_{GT} = \dot{m}_g c_{p.g}(T_3 - T_4) \tag{9}$$

$$\eta_{th,GT} = \frac{W_{Net,GT}}{\dot{m}_f \times \eta_{cc,GT} \times (LHV)} \tag{10}$$

where k_g=1.33 and the $c_{p.a}$ and $c_{p.g}$ are considered to be a temperature variable function mentioned on References [22, 23]. The constant values of input parameters related to gas turbine cycle are represented in Table 1.

Table 1. constant value of the gas turbine input parameters

Parameter	**Unit**	**Value**
Air mass flow rate	kg/s	3
Compressor inlet pressure (P_1)	bar	1.013
Compressor inlet temperature (T_1)	^{0}C	15
Pressure ratio (r_p)	--	12
Lower heating value (LHV)	kJ/kg	46515
Turbine inlet temperature (T_3)	^{0}C	1185
Gas turbine isentropic efficiency ($\eta_{t,GT}$)	%	87
Compressor isentropic efficiency ($\eta_{c,GT}$)	%	85
Combustion chamber efficiency ($\eta_{cc,GT}$)	%	95
Combustion chamber pressure drop (ΔP_{GT})	%	2

Organic rankin cycle

Toluene is selected as working fluid based on the operating temperature and pressure of the organic rankine cycle. The heat required for the ORC is provided by heat exchanging between the toluene and the exhust flue gas of the gas turbine cycle in the heat recovery steam generator. The following assumptions are considered to simulate the ORC model:

- All processes are supposed to be adiabatic.
- The pump and turbine have a constant isentropic efficiency.
- All processes are steady-state and steady-flow.

$$W_{T,ORC} = \dot{m}_{ORC}(h_6 - h_7) \tag{11}$$

$$W_{P,ORC} = \dot{m}_{ORC}(h_9 - h_8) \tag{12}$$

$$\dot{m}_a(h_4 - h_5) = \dot{m}_{ORC}(h_6 - h_{11}) \tag{13}$$

$$\dot{m}_{CW}(h_{12} - h_{13}) = \dot{m}_{ORC}(h_9 - h_8) \tag{14}$$

$$W_{net,ORC} = W_{T,ORC} - W_{P.ORC} \tag{15}$$

$$\eta_{th,ORC} = \frac{(W_{T,ORC} - W_{P,ORC})}{\dot{m}_{ORC}(h_6 - h_{11})} \tag{16}$$

$$R_m = \frac{\dot{m}_{ORC}}{\dot{m}_{CW}} \tag{17}$$

The constant input parameters value considerd for the ORC cycle are shown in Table 2.

Absorption refrigration system

A single-stage ammonia-water absorption system is applied to supply the cooling load demand of a building. The following hypotheses have been employed for the thermodynamic modeling of ammonia-water absorption refrigeration systems [6, 24].

- The system operates at steady-state conditions.
- At points 14, 17, and 23, there is only Saturated Liquid.

Table 2. Constant input parameters value considerd for ORC cycle

Parameter	Unit	Value
Turbine inlet temperature (T_6)	^{0}C	360
Turbine inlet pressure (P_6)	bar	28
Condenser pressure (P_8)	bar	0.08
Condenser temperature difference ($\Delta T_{con,ORC}$)	^{0}C	5
Toluene mass flow rate ($\dot{m}_{ORC}$)	kg/s	0.2
Condenser chilled water temperature (T_{12})	^{0}C	25
Turbine isentropic efficiency ($\eta_{t,ORC}$)	%	80
Pump isentropic efficiency ($\eta_{P,ORC}$)	%	70
Pressure drop (ΔP_{ORC})	%	2
Mass flow rates ratio (R_m)	--	0.245

- At points 22, 25, there is only Saturated Vapor.
- All equipment is assumed to be adiabatic.
- The pressure drop inside the heat exchanger and all tubes are neglected.
- The pump has a constant isentropic efficiency, and the heat exchanger has a specific effectiveness factor.

Each component was considered a control volume with inlet and outlet streams, taking into account the heat transfer and work interaction based on the following thermodynamic relations:

$$\dot{m}_{16} + \dot{m}_{21} = \dot{m}_{17} + \dot{m}_{20} \tag{18}$$

$$\dot{m}_{20} = \dot{m}_{21} - \dot{m}_{22} \tag{19}$$

$$\dot{m}_{16}X_{16} + \dot{m}_{21}X_{21} = \dot{m}_{17}X_{17} + \dot{m}_{20}X_{20} \tag{20}$$

$$\dot{m}_{22}X_{22} + \dot{m}_{21}X_{21} = \dot{m}_{20}X_{20} \tag{21}$$

$$\dot{m}_{14}X_{14} = \dot{m}_{19}X_{19} + \dot{m}_{25}X_{25} \tag{22}$$

$$\dot{m}_5 h_5 + \dot{m}_{16}h_{16} + \dot{m}_{21}h_{21} = \dot{m}_{17}h_{17} + \dot{m}_{20}h_{20} + \dot{m}_{26}h_{26} \tag{23}$$

$$\epsilon_{HX} = \frac{T_{18}-T_{17}}{T_{15}-T_{17}} \tag{24}$$

$$\dot{m}_{14}(h_{16} - h_{15}) = \dot{m}_{17}(h_{18} - h_{19}) \tag{25}$$

$$\dot{Q}_{Eva,ARS} = \dot{m}_{24}(h_{25} - h_{24}) \tag{26}$$

$$\dot{W}_{P,ARS} = \dot{m}_{14}(h_{15} - h_{14}) \tag{27}$$

$$COP = \frac{\dot{Q}_{Eva,ARS}}{\dot{Q}_{Gen,ARS} + \dot{W}_{P,ARS}} \tag{28}$$

The constant input parameters value assumed in the ARS are shown in Table 3.

Table 3. Constant input parameters value assumed for ARS

Parameter	Unit	Value
Pure ammonia concentration (X_{NH3})	kg/kg	0.999
Pump isentropic efficiency ($\eta_{P,ARS}$)	%	85
Effectiveness factor of heat exchanger (ϵ_{HX})	%	80
High pressure (P_{max})	bar	20
Low pressure (P_{min})	bar	4.7
Mass flow rate of Ammonia-Water solution($\dot{m}_{ARS}$)	kg/s	4.5
Concentration of strong solution (X_s)	kg/kg	0.466
Concentration difference of strong and weak solution (ΔX)	kg/kg	0.088

Domestic hot water production and heating load system

According to Figure 1, heat exchangers provide the building's heating load and hot water consumption at a temperature of 65 °C . Considering the residential building consumption (200 liters per day per person), the amount of hot water in the heat exchanger is approximately equal to 0.37 kg /s.

Economic analysis

This section briefly summarizes the cost and economic model applied for CCHP. Costs and revenues must be identified at the beginning of the work and then aligned over a specified period for economic analysis. The total annual cost includes the annual investment cost, annual maintenance, and operational cost according to Equations (29) to (48). Also, constants parameters of economic indexes for different types of equipment are given in Table 4.

$$C_0 = C_{0,GT} + C_{0,ORC} + C_{0,ARS} + \sum C_{0,HX\_DHW} \tag{29}$$

$$C_{0,GT} = PEC_{com} + PEC_{cc} + PEC_{tur,GT} \tag{30}$$

$$C_{0,ORC} = PEC_{con,ORC} + PEC_{pump,ORC} + PEC_{tur,ORC} + PEC_{IHX,ORC} + PEC_{HRSG,ORC} \tag{31}$$

$$C_{0,ARS} = PEC_{ARS} + PEC_{CT} \tag{32}$$

$$PEC_{ARS} = 540(Q_{cool})^{0.872} \quad [25] \tag{33}$$

$$PEC_{CRS} = (482(Q_{cool})^{-0.07273} - 159.7)Q_{cool} \quad [25] \tag{34}$$

$$PEC_{boiler} = 205(Q_{DHW})^{0.87} \tag{35}$$

$$C_{0,GSHP} = 285 \times Load \quad [26] \tag{36}$$

$$C_m = C_{m,GT} + C_{m,ORC} + C_{m,HX-DHW} + C_{m,ARS} \tag{37}$$

$$C_{m,GT} = 0.1\ C_{0,GT} \tag{38}$$

$$C_{m,ORC} = 0.03\ C_{0,ORC} \qquad \text{[27, 28]} \tag{39}$$

$$C_{m,ARS} = 0.01\ C_{0,ARS} \qquad \text{[29]} \tag{40}$$

$$C_{m,GSHP} = 0.01\ C_{0,GSHP} \qquad \text{[30]} \tag{41}$$

$$C_{m,HX-DHW} = 0.2 C_{0,HX-DHW} \tag{42}$$

$$FC_{GT} = m_f \times LHV \times cf \times AOH \tag{43}$$

$$\dot{W}_{Net} = \dot{W}_{Net-GT} + \dot{W}_{Net\_ORC} - \dot{W}_{CT} \tag{44}$$

$$Ben_{ELC} = \dot{W}_{Net} \times Pes \times AOH \tag{45}$$

$$Ben_{cooling} = \frac{(C_{0,CRS} - C_{0,ARS})}{N} + Q_{cool} \times Pes \times \frac{AOH_c}{COP_{CRS}} \tag{46}$$

$$Ben_{heating} = \frac{(C_{0,CRS} - C_{0,HX})}{N} + Q_{heat} \times Pes \times \frac{AOH}{COP_{CRS}} \tag{47}$$

$$Ben_{DHW} = \frac{(C_{0,boiler} - C_{0,HX})}{N} + m_{f,boiler} \times LHV \times cf \times AOH \tag{48}$$

All of the equipment cost values obtained before 2018 have been updated to 2018 by applying the Chemical Engineering Plant Cost Index (CEPCI) [31] from Equation (49).

$$C_{0,new} = C_{0,ref} \left(\frac{CEPCI_{new}}{CEPCI_{ref}} \right) \tag{49}$$

A wide number of indexes can be applied to the economic analysis such that the Handbook of Financial Engineering [32] considers the Net Present Value (NPV) and Simple Payback Period (SPB) as the most popular and famous used indicators mentioned in Equations (50)-(51), respectively.

Table 4. purchase costs of subsystem equipment

Subsystem	**Equipment**	**Purchase cost of equipment**	**Year**
Gas turbine cycle	Compressor	$PEC_{com,GT} = \left(\frac{71.1\ \dot{m}_a \times r_p}{0.9 - \eta_{com,GT}} \right) \times ln(r_{p,GT})$	1996
	Combustion Chamber	$PEC_{cc,GT} = \left[\frac{46.08 \dot{m}_a}{0.995 - \left(\frac{P_{out}}{P_{in}} \right)} \right] \times (1 + exp(0.018\, T_{out} - 26.4))$	1996
	Turbine	$PEC_{tur,GT} = \left(\frac{479.34\ \dot{m}_g}{0.92 - \eta_{tur}} \right) \times ln(r_p) \times (1 + exp(0.036\, T_{out} - 54.4))$	1996
Organic rankine cycle	Turbine	$log_{10}(PEC_{Tur,ORC}) = 2.6259 + 1.4398\, log_{10}(\dot{W}_{Tur}) - 0.1776[log_{10}(\dot{W}_{Tur})]^2$	2008
	Pump	$log_{10}(PEC_{P,ORC}) = 3.3892 + 0.0536 log_{10}(\dot{W}_P) + 0.1538[log_{10}(\dot{W}_P)]^2$	2008
	Condenser	$PEC_{con,ORC} = 1773 \times \dot{m}_{ORC}$	1996
	Recuperator	$log_{10}(PEC_{Re}) = 4.6656 - 0.1557 log_{10}(A) + 0.1547[log_{10}(A)]^2$	2008
	HRSG	$PEC_{HRSG} = 6570 \times \left(\frac{Q}{\Delta T_{lm}} \right)^{0.8} + 21276 \times m_{st} + 1184.4 \times m_g^{1.2}$	1996
Domestic hot water	Heat Exchanger	$PEC_{HX\_DHW} = 4122 \times \left(\frac{m_g(h_i - h_e)}{18\, \Delta T_{lm}} \right)^{0.6}$	1996

$$NPV = -C_0 + \sum_{i=0}^{N} \frac{(Ben - C_m - FC)}{(1 + ir)^i} \tag{50}$$

$$SPB = \frac{C_0}{(Ben - C_m - FC)} \tag{51}$$

Statistical analysis

Response surface methodology, which has proven itself in many disciplines and energy applications, is a computer-based procedure for modeling and optimization [33]. This method aims to specify and optimize the effects and degrees of several economic input factors on the CCHP economical indexes.

To investigate the effect of the economic parameters on NPV and SPB as economic responses, the response surface methodology (RSM), one of the subsets of the experimental design process, has been used. The method of design of experiments (DOE) prepares experimental programs according to a statistical model established to achieve the objectives set for the experiments most effectively and cost-effectively by organizing and using the results of the experiments. The combination of these two techniques allows the researcher to achieve significant results [14]. In engineering, many phenomena are modeled based on some theories, some of which cannot have a mathematical model due to a large number of controlling factors, unknown mechanisms, or computational complexity. Response surface methodology is one of the identification methods in DOE and engineering-related sciences. This method uses a set of mathematical and statistical techniques those are useful for modeling and analyzing problems. In this method, a way to estimate the interactions, quadratic effects, and even the local level of response is embedded using a suitable experimental design.

Table 5 presents the range of independent economic variables for analyzing the NPV and SPB as response functions.

The ranges of the electricity sales price and fuel price are based on 25% changes compared to the current price presented in literature [34–36].

In RSM, a frequently applied second-order polynomial equation is used to fit the response functions. The relevant model terms are presented in Equation (52).

Table 5. Independent economic parameters and their level ranges

Factor	Name	Units	Min (-1)	Max (+1)
A	ir	%	0.0800	0.1600
B	N	year	10.00	20.00
C	cf	$/kWh	0.0006	0.0010
D	Pes	$/kWh	0.0135	0.0225

$$y_k = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum\sum_{i<j}^{k} \beta_{ij} x_i x_j \quad (52)$$

where Y is the response function and β_0, β_j, β_{ij}, and β_{jj} is a constant coefficient, a slope or a linear effect of the input factor x_i, an interaction effect between input factor x_i and x_j and the quadratic effect of input factor x_i, respectively.

MODEL VALIDATION

In order to check the accuracy and validity of the model, a comparison is made between the thermodynamic data simulated in EES software and the data published in the articles. Tables 6 and 7 show the values obtained from the calculation code and the data in the literature. As can be seen, there is a good agreement between the present work results and the data published in the literature.

RESULTS AND DISCUSSION

Table 8 shows the thermodynamic characteristics of each stream in the cycle. The model is simulated in the EES software, and mass, concentration, and energy balance are utilized for all components. As stated earlier, this system is capable of producing domestic hot water. The electricity generation, cooling, and heating capacity of the

Table 6. Comparison of some parameters of gas turbine cycle compared to reference [37]

Point	T(C)		P(bar)		$\dot{m}$(kg/s)	
	Peresent work	Ref.	Peresent work	Ref.	Peresent work	Ref.
1	20	20	1.01	1.01	500	500
2	376.8	374.65	12.12	12.16	500	500
3	900	900	11.64	11.67	506.2	508.54
4	452.6	452.71	1.03	1.03	506.2	508.54

Table 7. Comparison between obtained results and data in literature [6, 24]

Subsystem	Parameter	Present work	reference
Organic rankine cycle	ORC Turbine power (kW)	7.409	7.317
	ORC pump power(kW)	0.1578	0.156
	Evaporative heat transfer rate (kW)	22.194	22.190
Single stage absorption refrigeration system	Absorber heat transfer rate (kW)	273.8	273.9
	Generator heat transfer rate (kW)	327.4	327.5
	Condenser heat transfer rate (kW)	157.4	159.2
	Evaporator heat transfer rate (kW)	147	146.9
	Rectifier heat transfer rate (kW)	44.67	42.8
	Pump power (kW)	1.452	1.5
	COP	0.4471	0.447

proposed CCHP are approximately equal to 897 kW,641.1 kW, and 700kW, respectively. Also, the performance coefficient of the refrigeration system is equal to 0.481.

Table 8. Thermodynamic properties of each stream

Stream	Fluid	P(bar)	T(^{0}C)	h(kJ/kg)	$\dot{m}$(kg/s)
1	Air	1.013	15	288.53	3
2	Air	12.156	365.7	676.67	3
3	Flue gas	11.913	1185	1584.74	3.0639
4	Flue gas	0.993	601.2	923.31	3.0639
5	Flue gas	0.993	566.1	882.54	3.0639
6	Toluene	28	360	784.57	0.2
7	Toluene	0.082	230.2	564.86	0.2
8	Toluene	0.08	45.25	277.99	0.2
9	Toluene	0.08	40.25	-131.89	0.2
10	Toluene	30.24	41.82	-126.81	0.2
11	Toluene	29.68	184.6	160.06	0.2
12	Water	1.01	25	104.84	0.8163
13	Water	1.01	49.01	205.26	0.8163
14	Ammonia-water	4.706	43.23	-45.29	4.5
15	Ammonia-water	20	43.48	-43.11	4.5
16	Ammonia-water	20	94.56	190.71	4.5
17	Ammonia-water	20	117.9	309.16	3.8623
18	Ammonia-water	20	58.36	36.74	3.8623
19	Ammonia-water	4.706	58.62	36.74	3.8623
20	Ammonia-water	20	99.68	1477.21	0.6688
21	Ammonia-water	20	99.68	215.36	0.0311
22	Ammonia	20	57.17	1300.21	0.6377
23	Ammonia	20	49.35	236.98	0.6377
24	Ammonia	4.706	2.505	236.98	0.6377
25	Ammonia	4.706	3.476	1242.29	0.6377
26	Flue gas	0.993	177.7	452.68	3.0639
27	Water	1.01	25	104.75	33.9983
28	Water	1.01	33	138.22	33.9983
29	Water	1.01	37.77	158.16	33.9983
30	Flue gas	0.993	158.4	158.71	3.0639
31	Water	1.01	25	104.75	0.37
32	Water	1.01	65	272.08	0.37
33	Flue gas	0.993	548.6	575.48	3.0639
34	Flue gas	0.993	346.3	354.26	3.0639
35	Water	1.01	25	104.75	2.787
36	Water	1.01	85	355.92	2.787

Analysis of variance evaluates the statistical significance of the effects using the Fisher's test. Results show that except for the interest rate in the response function of the SPB, other parameters are significantly effective in both response functions. A survey of the statistical results of the models is manifested in Table 9. For both response functions, the Predicted R-squared is in reasonable agreement with the Adjusted R-squared. Adeq. Precision measures the signal-to-noise ratio, such that a ratio greater than 4 is desirable. The ratios of 15217.7206 and 62489.2852 for NPV and SPB, respectively, represent a suitable signal. These models can be used to navigate the design space.

The main effects of the economical parameters on the response functions are shown in Figures 2 and 3.

According to Figure 2, the sensitivity of the NPV index to the economic parameters of Table 5 is from the

Table 9. Models summary statistics for response functions

Response function	NPV	SPB
Units	$	Year
Study type	Response surface	
Design type	Central composite	
Design model	Quadratic	
Analysis	Polynomial	
Minimum	-422777	4.669
Maximum	776917	12.05
Mean	7946.74	7.48
R-squared	1.000	1.000
Adjusted R-squared	1.000	1.000
Predicted R-squared	1.000	1.000
Adeq. precision	15217.7206	62489.2852
Transform	--	Inverse
Model	Reduced quadratic	

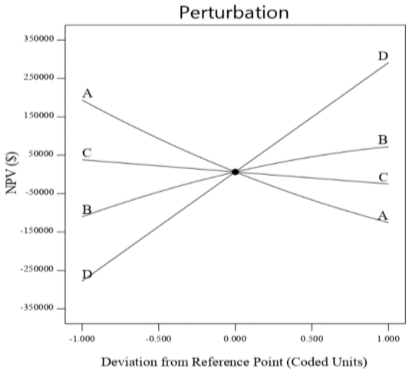


Figure 2. The main effects of the economic parameters on the NPV's response function, A) Interest ratio, B) Lifetime, C) Fuel cost, and D) Electricity sale price

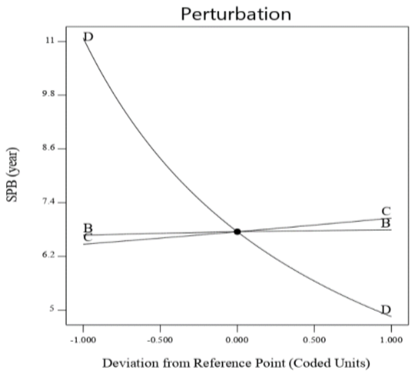


Figure 3. The main effects of the economic parameters on the SPB's response function, A) Interest ratio, B) Lifetime, C) Fuel cost, and D) Electricity sale price

highest to the lowest sensitivity, respectively, in the form of the electricity sale price, interest ratio, Lifetime, and fuel cost. The trend of changes in NPV is reversed by increasing the two parameters of interest ratio and electricity sale price, so that increasing electricity sale price has a positive role in increasing net present value and also increasing annual interest rate reduces NPV. On the other hand, as shown on Figure 3 the electricity sale price is the most sensitive among other economic parameters for SPB index and changes in interest ratio, will not affect SPB. However, it causes a reduction in NPV.

As seen in Figures 4 and 5, the residual plots for NPV and SPB are randomly distributed and not followed by any organized model. Consequently, it can be concluded that the residual analysis does not manifest any model inadequacy, and the model is suitable for predicting the responses at a confidence level of 95%.

Furthermore, in the Predicted vs. actual values graphs, if the data are normally distributed, and regression models are fitted perfectly, the data graphs will be very close to the straight line at 45^0, as shown in Figures 6 and 7.

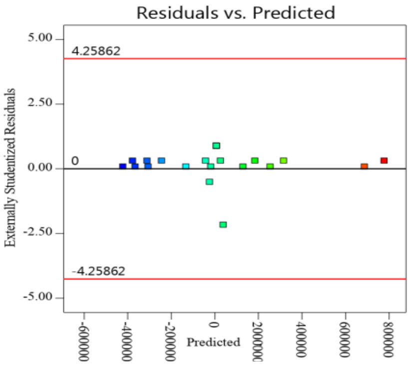


Figure 4. Plot of residuals vs. predicted value for NPV

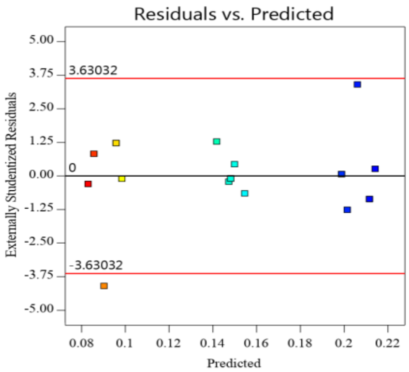


Figure 5. Plot of residuals vs. predicted value for SPB

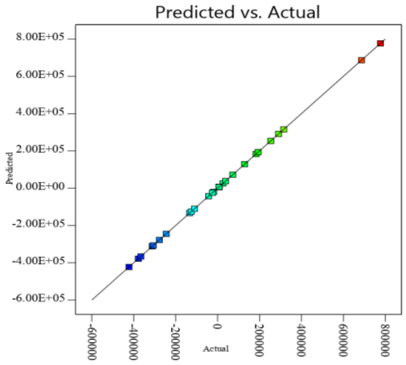


Figure 6. Predicted vs. actual values for the NPV's regression model

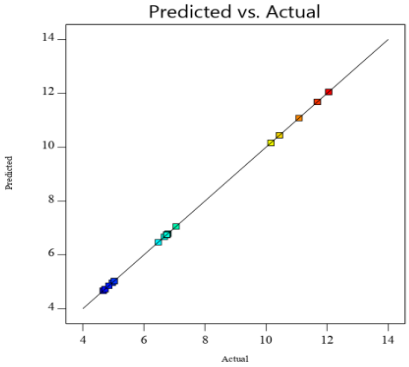


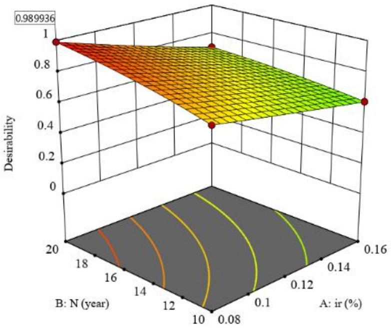
Figure 7. Predicted vs. actual values for the SPB's regression model.

Optimization procedure

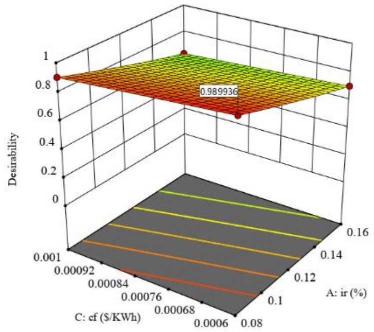
In the present study, the RSM optimizer is employed to optimize the economic parameters. A desirability function-based optimization procedure is used in this work [14, 38, 39]. The desirability function (DF) is an approach used for numerical optimization; it allows a score to a series of responses and selects factors settings for maximizing that score. The RSM optimizer is a tool used to optimize multi objectives like the NPV and SPB indexes. First, the goals should be distinguished for the optimization method, which is included: (1) maximum NPV, (2) minimum SPB of the system.

The numerical optimization was carried out by keeping all the parameters in the range and optimized the responses. The best fit model from the nonlinear regression models based on the CCD of each response was used for the goal of multiple response optimizations.

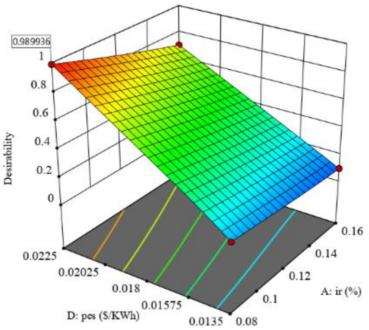
The contour of the desirability parameter of the optimization procedure is presented in Figure 8. CCD offers some optimized cases with the highest desirability (0.990) as the optimum operating factor based on the calculated desirability (Table 10).



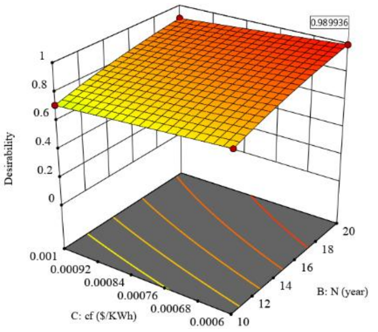
(A)



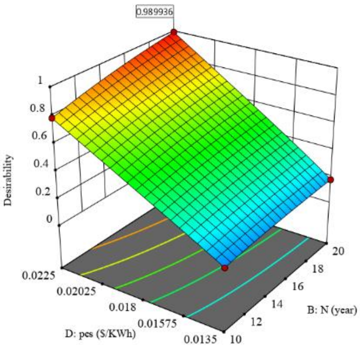
(B)



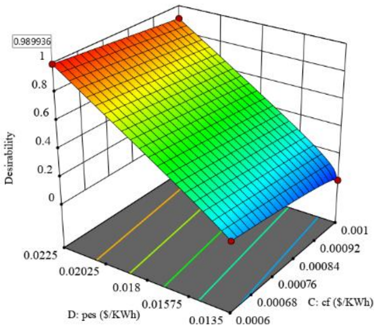
(C)



(D)



(E)



(F)

Figure 8. Desirability contour plots of the optimized economic parameters

Table 10. Optimal point for economical parameters of CCHP based on the desirability function

ir	N (year)	Cf ($/kWh)	Pes ($/kWh)	NPV ($)	SPB (year)	Desirability
0.080	20.000	0.001	0.022	776900.680	4.727	0.99

CONCLUSION

In this study, thermodynamic analysis of the configuration CCHP system was performed based on specific operational input parameters. The thermodynamic results showed that the system could produce approximately 890kW of electric power and provide a heating and cooling load of 640 and 700 kW of the proposed residential building, respectively.

This study evaluates the effect of various influencing economic factors on indexes of NPV and SPB as response functions. Furthermore, RSM based optimization procedure is used to find the optimum economic factors. The main results of this work can be summarized as below:

- The electricity sale price is predominated sensitive parameter for both response functions.
- The changes due to lifetime are very small compared to the other effective economic parameters on SPB.
- Increasing in the interest ratio and fuel cost reduces the NPV, while increasing the electricity sell price and lifetime enhances it.

- The SPB is an increasing function of fuel cost and a decreasing function of electricity sell price.

The optimum condition of 8% of interest ratio, 0.001 $/kWh of fuel cost, 0.022 $/kWh of electricity sell price, and 20 years lifetime is proposed as the best case of the optimization process. Further, the optimized values of 776900.680$ and 4.727 years are achieved for the NPV and SPB, respectively.

Finally, the future research that can be addressed is the comparison of RSM optimization method with other optimization methods for thermo-economic analysis of CCHPs.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

1. Bloomquist, R. G. 2002. "Combined Heat and Power: Equipment Options and Application Alternatives." *Cogeneration & Distributed Generation Journal*, 17(4), pp.6–20. https://doi.org/10.1080/10668680209508983
2. Ebrahimi, M., Keshavarz, A. and Jamali, A. 2012. "Energy and exergy analyses of a micro-steam CCHP cycle for a residential building." *Energy and Buildings*, 45, pp.202–210. https://doi.org/10.1016/j.enbuild.2011.11.009
3. Keshavarz, A. and Ebrahimi, M. 2015. Combined Cooling, Heating and Power. Elsevier. https://doi.org/10.1016/C2013-0-18763-6
4. Cho, H., Smith, A. D. and Mago, P. 2014. "Combined cooling, heating and power: A review of performance improvement and optimization." *Applied Energy*, 136, pp.168–185. https://doi.org/10.1016/j.apenergy.2014.08.107
5. Pirkandi, J., Jokar, M. A., Sameti, M., Kasaeian, A. and Kasaeian, F. 2016. "Simulation and multi-objective optimization of a combined heat and power (CHP) system integrated with low-energy buildings." *Journal of Building Engineering*, 5, pp.13–23. https://doi.org/10.1016/j.jobe.2015.10.004
6. Mohammadi, A., Kasaeian, A., Pourfayaz, F. and Ahmadi, M. H. 2017. "Thermodynamic analysis of a combined gas turbine, ORC cycle and absorption refrigeration for a CCHP system." *Applied Thermal Engineering*, 111, pp.397–406. https://doi.org/10.1016/j.applthermaleng.2016.09.098
7. Moné, C. ., Chau, D. . and Phelan, P. . 2001. "Economic feasibility of combined heat and power and absorption refrigeration with commercially available gas turbines." *Energy Conversion and Management*, 42(13), pp.1559–1573. https://doi.org/10.1016/S0196-8904(00)00157-6
8. Silveira, J. L. and Tuna, C. E. 2003. "Thermoeconomic analysis method for optimization of combined heat and power systems. Part I." *Progress in Energy and Combustion Science*, 29(6), pp.479–485. https://doi.org/10.1016/S0360-1285(03)00041-8
9. Ziher, D. and Poredos, A. 2006. "Economics of a trigeneration system in a hospital." *Applied Thermal Engineering*, 26(7), pp.680–687. https://doi.org/10.1016/j.applthermaleng.2005.09.007
10. Mago, P. J. and Chamra, L. M. 2009. "Analysis and optimization of CCHP systems based on energy, economical, and environmental considerations." *Energy and Buildings*, 41(10), pp.1099–1106. https://doi.org/10.1016/j.enbuild.2009.05.014
11. Ghaebi, H., Amidpour, M., Karimkashi, S. and Rezayan, O. 2011. "Energy, exergy and thermoeconomic analysis of a combined cooling, heating and power (CCHP) system with gas turbine prime mover." *International Journal of Energy Research*, 35(8), pp.697–709. https://doi.org/10.1002/er.1721
12. Yan, B., Xue, S., Li, Y., Duan, J. and Zeng, M. 2016. "Gas-fired combined cooling, heating and power (CCHP) in Beijing: A techno-economic analysis." *Renewable and Sustainable Energy Reviews*, 63, pp.118–131. https://doi.org/10.1016/j.rser.2016.05.036
13. Fani, M. and Sadreddin, A. 2017. "Solar assisted CCHP system, energetic, economic and environmental analysis, case study: Educational office buildings." *Energy and Buildings*, 136, pp.100–109. https://doi.org/10.1016/j.enbuild.2016.11.052
14. Montgomery, D. 2017. Design and analysis of experiments. John wiley & sons.
15. Hatami, M., Cuijpers, M. C. M. and Boot, M. D. 2015. "Experimental optimization of the vanes geometry for a variable geometry turbocharger (VGT) using a Design of Experiment (DoE) approach." *Energy Conversion and Management*, 106, pp.1057–1070. https://doi.org/10.1016/j.enconman.2015.10.040
16. Roy, D., Samanta, S. and Ghosh, S. 2020. "Performance optimization through response surface methodology of an integrated biomass gasification based combined heat and power plant employing solid oxide fuel cell and externally fired gas turbine." *Energy Conversion and Management*, 222, pp.113182. https://doi.org/10.1016/j.enconman.2020.113182
17. Mojaver, P., Khalilarya, S. and Chitsaz, A. 2019. "Multi-objective optimization using response surface methodology and exergy analysis of a novel integrated biomass gasification, solid oxide fuel cell and high-temperature sodium heat pipe system." *Applied Thermal Engineering*, 156, pp.627–639. https://doi.org/10.1016/j.applthermaleng.2019.04.104
18. Mojaver, P., Jafarmadar, S., Khalilarya, S. and Chitsaz, A. 2020. "Investigation and optimization of a Co-Generation plant integrated of gasifier, gas turbine and heat pipes using minimization of Gibbs free energy, Lagrange method and response surface methodology." *International Journal of Hydrogen Energy*, 45(38), pp.19027–19044. https://doi.org/10.1016/j.ijhydene.2020.04.278
19. Pires, T. S., Cruz, M. E. and Colaço, M. J. 2013. "Response surface method applied to the thermoeconomic optimization of a complex cogeneration system modeled in a process simulator." *Energy*, 52, pp.44–54. https://doi.org/10.1016/j.energy.2012.12.049
20. Cali, M., Santarelli, M. and Leone, P. 2007. "Design of experiments for fitting regression models on the tubular SOFC CHP100kWe: Screening test, response surface analysis and optimization." *International Journal of Hydrogen Energy*, 32(3), pp.343–358. https://doi.org/10.1016/j.ijhydene.2006.05.021
21. Kazemian, M. E. and Gandjalikhan Nassab, S. A. 2020. "Thermodynamic Analysis and Statistical Investigation of Effective Parameters for Gas Turbine Cycle using the Response Surface Methodology." *International Journal of Engineering, Transaction C: Aspects*, 33(6), pp.894–905. https://doi.org/10.5829/ije.2020.33.05b.22
22. Valero, A., Lozano, M. A., Serra, L., Tsatsaronis, G., Pisa, J., Frangopoulos, C. and von Spakovsky, M. R. 1994. "CGAM problem: Definition and conventional solution." *Energy*, 19(3), pp.279–286. https://doi.org/10.1016/0360-5442(94)90112-0
23. Barzegar Avval, H., Ahmadi, P., Ghaffarizadeh, A. R. and Saidi, M. H. 2011. "Thermo-economic-environmental multiobjective optimization of a gas turbine power plant with preheater using evolutionary algorithm." *International Journal of Energy*

Research, 35(5), pp.389–403. https://doi.org/10.1002/er.1696

24. Herold, K. E., Radermacher, R. and Klein, S. A. 2016. Absorption Chillers and Heat Pumps. CRC Press. https://doi.org/10.1201/b19625
25. Sanaye, S. and Hajabdollahi, H. 2014. "4 E analysis and multi-objective optimization of CCHP using MOPSOA." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 228(1), pp.43–60. https://doi.org/10.1177/0954408912471001
26. Ren, F., Wei, Z. and Zhai, X. 2021. "Multi-objective optimization and evaluation of hybrid CCHP systems for different building types." *Energy*, 215, pp.119096. https://doi.org/10.1016/j.energy.2020.119096
27. Georgousopoulos, S., Braimakis, K., Grimekis, D. and Karellas, S. 2021. "Thermodynamic and techno-economic assessment of pure and zeotropic fluid ORCs for waste heat recovery in a biomass IGCC plant." *Applied Thermal Engineering*, 183, pp.116202. https://doi.org/10.1016/j.applthermaleng.2020.116202
28. Abrosimov, K. A., Baccioli, A. and Bischi, A. 2020. "Techno-economic analysis of combined inverted Brayton – Organic Rankine cycle for high-temperature waste heat recovery." *Energy Conversion and Management*, 207, pp.112336. https://doi.org/10.1016/j.enconman.2019.112336
29. Mohammadi, K. and McGowan, J. G. 2019. "A thermo-economic analysis of a combined cooling system for air conditioning and low to medium temperature refrigeration." *Journal of Cleaner Production*, 206, pp.580–597. https://doi.org/10.1016/j.jclepro.2018.09.107
30. Paiho, S., Pulakka, S. and Knuuti, A. 2017. "Life-cycle cost analyses of heat pump concepts for Finnish new nearly zero energy residential buildings." *Energy and Buildings*, 150, pp.396–402. https://doi.org/10.1016/j.enbuild.2017.06.034
31. Chemical Engineering Plant Cost Index (CEPCI). Retrieved from https://www.chemengonline.com/2019-cepci-updates-january-prelim-and-december-2018-final/
32. Zopounidis Doumpos, Michael, Pardalos, Panos, C. 2008. Handbook of Financial Engineering (Vol. 18). Springer US. https://doi.org/https://doi.org/10.1007/978-0-387-76682-9
33. Mäkelä, M. 2017. "Experimental design and response surface methodology in energy applications: A tutorial review." *Energy Conversion and Management*, 151, pp.630–640. https://doi.org/10.1016/j.enconman.2017.09.021
34. Cardona, E., Piacentino, A. and Marchese, F. 2007. "Performance evaluation of CHP hybrid seawater desalination plants." *Desalination*, 205(1–3), pp.1–14. https://doi.org/10.1016/j.desal.2006.02.048
35. Jannatabadi, M., Rahbari, H. R. and Arabkoohsar, A. 2021. "District cooling systems in Iranian energy matrix, a techno-economic analysis of a reliable solution for a serious challenge." *Energy*, 214, pp.118914. https://doi.org/10.1016/j.energy.2020.118914
36. Cioccolanti, L., Savoretti, A., Renzi, M., Caresana, F. and Comodi, G. 2016. "Comparison of different operation modes of a single effect thermal desalination plant using waste heat from m-CHP units." *Applied Thermal Engineering*, 100, pp.646–657. https://doi.org/10.1016/j.applthermaleng.2016.02.082
37. Mohammadi, A., Ashouri, M., Ahmadi, M. H., Bidi, M., Sadeghzadeh, M. and Ming, T. 2018. "Thermoeconomic analysis and multiobjective optimization of a combined gas turbine, steam, and organic Rankine cycle." *Energy Science & Engineering*, 6(5), pp.506–522. https://doi.org/10.1002/ese3.227
38. Myers, R. H. and Montgomery, D. C. 2009. Response Surface Methodology, Wiley New York.
39. Wu, C. F. J. and Hamada, M. 2000. Experiments planning analysis and parameter design optimization. Jhon Wiley and Sons. Inc., Singapore.

Persian Abstract

چکیده

در کار حاضر، تجزیه و تحلیل آماری برای مطالعه شاخص‌های اقتصادی ارزش فعلی خالص و دوره بازپرداخت ساده به عنوان توابع پاسخ برای سیستم ترکیبی توان، حرارت و برودت ارائه شده است. عملکرد سیستم ترکیبی با کمک مدل‌سازی ترمودینامیکی شبیه‌سازی و معادلات اقتصادی نیز برای شبیه‌سازی اقتصادی ارائه شده است. تلاش گردیده تا تأثیر برخی عوامل اقتصادی (نسبت بهره، هزینه سوخت، طول عمر و قیمت فروش برق) بر پاسخ‌های سیستم مطالعه شود. بر اساس تجزیه و تحلیل طراحی آزمایش، مدل‌های رگرسیونی برای کمی کردن اثرات این پارامترها بر ارزش فعلی خالص و دوره بازپرداخت ساده ارائه شده است. این رویکرد جدید با استفاده از روش سطح پاسخ و بر اساس روش طراحی مرکب مرکزی توسعه یافته است. تجزیه و تحلیل حساسیت پارامترهای اقتصادی نیز مورد بررسی قرار گرفت. مقادیر بهینه پارامترهای اقتصادی برای دو شاخص اقتصادی به عنوان توابع پاسخ بدست آمدند.