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 (m²)
AOH  Annual operation hour (hr)
Ben  Annual benefit ($/Year)
C₀  Investment cost ($)  
Cₜ  Annual O&M cost ($/Year)
cₚ  Specific heat capacity (kJ/kg K)
cf  Fuel cost ($/KWh)
COP  Coefficient of performance
CPCEI  Chemical engineering plant cost index
DHW  Domestic hot water
FC  Annual combustion chamber fuel consumption cost ($/Year)
h  Enthalpy (kJ/kg)
HRSG  Heat recovery steam generator
ir  Interest ratio (%)
IRR  Internal rate of return (%)
k  Specific heat ratio
LHV  Lower heating value (kJ/kg)
m  Mass flow rate (kg/s)
Pes  Electricity sell price ($/KWh)
Q̇  Heat load (kW)
Rₚ  Mass flow rate ratio
rₚ  Pressure ratio
SPB  Simple payback period (Year)
T  Temperature (°C)
W  Work (kW)
X  Concentration of solution

Subscript
a  Air
Abs  Absorber
ARS  Absorption refrigeration system
c  Compressor/Cooling
cc  Combustion chamber
cool  Cooling load
Con  Condenser
CRS  Compression refrigeration system
CW  Cooling water

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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 modem 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 were 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 technoeconomic 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. Zihir 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 Charm [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, interest 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.
• 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:

\[ \dot{m}_a = \dot{m}_1 = \dot{m}_2 \quad (1) \]
\[ T_2 = T_1 \left( 1 + \frac{1}{\eta_{cc,GT}} \left( \frac{r_{p,GT}}{r_{p,GT}} - 1 \right) \right) \quad (2) \]
\[ r_p = \frac{P_2}{P_1} = \frac{P_2}{P_a} \quad (3) \]
\[ W_C = \dot{m}_a c_{p,a} (T_2 - T_1) \quad (4) \]
\[ \dot{m}_g = \dot{m}_3 = \dot{m}_2 + \dot{m}_f \quad (5) \]
\[ \eta_{cc,GT} = \frac{\dot{W}_{GT}}{\dot{m}_a c_{p,a} (T_2 - T_1)} \quad (6) \]
\[ P_3 = P_2 (1 - \Delta P) \quad (7) \]
\[ T_4 = T_3 \left( 1 - \eta_{GT,GT} (1 - \left( \frac{\dot{W}_{GT}}{\dot{m}_g c_{p,g} (T_3 - T_4)} \right)^{\frac{1}{k_p}} \right) \quad (8) \]
\[ W_{GT} = \dot{m}_g c_{p,g} (T_3 - T_4) \quad (9) \]
\[ \eta_{th,GT} = \frac{W_{net,GT}}{m_f \eta_{cc,GT} (LHV)} \quad (10) \]

where \( k_p = 1.33 \) 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 (\( T_1 \)) | \(^\circ\text{C}\) | 15 |
| Pressure ratio (\( r_p \)) | -- | 12 |
| Lower heating value (LHV) | kJ/kg | 46515 |
| Turbine inlet temperature (\( T_3 \)) | \(^\circ\text{C}\) | 1185 |
| Gas turbine isentropic efficiency (\( \eta_{c,GT} \)) | \% | 87 |
| Compressor isentropic efficiency (\( \eta_{c,GT} \)) | \% | 85 |
| Combustion chamber efficiency (\( \eta_{a,GT} \)) | \% | 95 |
| Combustion chamber pressure drop (\( \Delta P_{GT} \)) | \% | 2 |

### Organic rankine 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 exhaust 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.

\[ W_{T,ORC} = \dot{m}_{\text{ORC}} (h_a - h_f) \quad (11) \]
\[ W_{P,ORC} = \dot{m}_{\text{ORC}} (h_a - h_f) \quad (12) \]
\[ \dot{m}_a (h_a - h_f) = \dot{m}_{\text{ORC}} (h_a - h_{11}) \quad (13) \]
\[ \dot{m}_{\text{CW}} (h_{12} - h_{13}) = \dot{m}_{\text{ORC}} (h_a - h_f) \quad (14) \]
\[ W_{net,ORC} = W_{T,ORC} - W_{P,ORC} \quad (15) \]
\[ \eta_{th,ORC} \approx \frac{W_{T,ORC} - W_{P,ORC}}{\dot{m}_{\text{ORC}} (h_a - h_{11})} \quad (16) \]
\[ R_m = \frac{\dot{m}_{\text{ORC}}}{\dot{m}_{\text{CW}}} \quad (17) \]

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

### Absorption refrigeration 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.
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:

\[ m_{16} + m_{21} = m_{17} + m_{20} \]  \hspace{1cm} (18)
\[ m_{20} = m_{21} - m_{22} \]  \hspace{1cm} (19)
\[ m_{16}X_{16} + m_{21}X_{21} = m_{17}X_{17} + m_{20}X_{20} \]  \hspace{1cm} (20)
\[ m_{22}X_{22} + m_{21}X_{21} = m_{20}X_{20} \]  \hspace{1cm} (21)
\[ m_{14}X_{14} = m_{19}X_{19} + m_{25}X_{25} \]  \hspace{1cm} (22)
\[ m_{2}h_{5} + m_{14}h_{16} + m_{21}h_{21} = m_{17}h_{17} + m_{20}h_{20} + m_{26}h_{26} \]  \hspace{1cm} (23)
\[ \epsilon_{HX} = \frac{T_{16} - T_{17}}{T_{15} - T_{17}} \]  \hspace{1cm} (24)
\[ m_{14}(h_{16} - h_{13}) = m_{17}(h_{18} - h_{19}) \]  \hspace{1cm} (25)
\[ \dot{Q}_{\text{Eva,ARS}} = m_{24}(h_{25} - h_{24}) \]  \hspace{1cm} (26)
\[ \dot{W}_{\text{P,ARS}} = m_{14}(h_{15} - h_{14}) \]  \hspace{1cm} (27)
\[ \text{COP} = \frac{\dot{Q}_{\text{Eva,ARS}}}{\dot{W}_{\text{P,ARS}}} \]  \hspace{1cm} (28)

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

### Table 2. Constant input parameters value considered for ORC cycle

| Parameter                  | Unit | Value |
|----------------------------|------|-------|
| Turbine inlet temperature  | °C   | 360   |
| Turbine inlet pressure     | bar  | 28    |
| Condenser pressure         | bar  | 0.08  |
| Condenser temperature difference | °C | 5     |
| Toluene mass flow rate     | kg/s | 0.2   |
| Condenser chilled water temperature | °C | 25    |
| Turbine isentropic efficiency | %   | 80    |
| Pump isentropic efficiency  | %    | 70    |
| Pressure drop              | %    | 2     |
| Mass flowrates ratio       |      | 0.245 |

### Table 3. Constant input parameters value assumed for ARS

| Parameter                           | Unit | Value |
|-------------------------------------|------|-------|
| Pure ammonia concentration (X_{ARS})| kg/kg| 0.999 |
| Pump isentropic efficiency (\eta_{\text{ORC}}) | % | 85 |
| Effectiveness factor of heat exchanger (\varepsilon_{H}) | % | 80 |
| High pressure (P_{max})             | bar  | 20    |
| Low pressure (P_{min})              | bar  | 4.7   |
| Mass flowrate of Ammonia-Water solution (\dot{m}_{ARS}) | kg/s | 4.5 |
| Concentration of strong solution (X) | kg/kg | 0.466 |
| Concentration difference of strong and weak solution (\Delta X) | 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.

\[ C_0 = C_{0,GT} + C_{0,ORC} + C_{0,ARS} + \sum C_{0,HX,DHW} \]  \hspace{1cm} (29)
\[ C_{0,GT} = PEC_{\text{com}} + PEC_{\text{cc}} + PEC_{\text{turb,GT}} \]  \hspace{1cm} (30)
\[ C_{0,ORC} = PEC_{\text{con,ORC}} + PEC_{\text{pump,ORC}} + PEC_{\text{turb,ORC}} + PEC_{\text{HRSG,ORC}} \]  \hspace{1cm} (31)
\[ C_{0,ARS} = PEC_{ARS} + PEC_{\text{GT}} \]  \hspace{1cm} (32)
\[ PEC_{ARS} = 540 \left(Q_{\text{cool}}\right)^{0.872} \]  \hspace{1cm} [25]  \hspace{1cm} (33)
\[ PEC_{CRS} = \left(482 \left(Q_{\text{cool}}\right)^{-0.07273} - 159.7\right)Q_{\text{cool}} \]  \hspace{1cm} [25]  \hspace{1cm} (34)
\[ PEC_{\text{boiler}} = 2.05 \left(Q_{\text{DHW}}\right)^{0.87} \]  \hspace{1cm} [25]  \hspace{1cm} (35)
\[ C_{0,GSHP} = 285 \times \text{Load} \]  \hspace{1cm} [26]  \hspace{1cm} (36)
\[ C_m = C_{m,GT} + C_{m,ORC} + C_{m,HX-DHW} + C_{m,ARS} \]  \hspace{1cm} (37)
\[ C_{m,GT} = 0.1 C_{0,GT} \]  
\[ C_{m,ORC} = 0.03 C_{0,ORC} \]  
\[ C_{m,ARS} = 0.01 C_{0,ARS} \]  
\[ C_{m,GHP} = 0.01 C_{0,GHP} \]  
\[ C_{m,HW- DHW} = 0.2 C_{0,HW- DHW} \]  
\[ FC_{GT} = m_f \times LHV \times cf \times AOH \]  
\[ \dot{W}_{Net} = \dot{W}_{Net-GT} + \dot{W}_{Net-ORC} - \dot{W}_{CT} \]  
\[ Ben_{ELC} = \dot{W}_{Net} \times Pes \times AOH \]  
\[ Ben_{cooling} = \frac{(C_{0ARS}-C_{0GHP})}{N} + Q_{cool} \times Pes \times \frac{AOH}{COP_{CRS}} \]

\[ Ben_{heating} = \frac{(C_{0GHP}-C_{0ARS})}{N} + Q_{heat} \times Pes \times \frac{AOH}{COP_{CRS}} \]  
\[ Ben_{DHV} = \frac{(C_{0boiler}-C_{0GHP})}{N} + m_f \times LHV \times cf \times AOH \]

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).

\[ C_{0,new} = C_{0,ref} \left( \frac{CEPCI_{new}}{CEPCI_{ref}} \right) \]  

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                           | \( PEC_{com,GT} = \left( \frac{21.3 m_{0,GT}}{0.9 m_{0,com,GT}} \right) \) \times \ln(r_{p,GT}) \) | 1996 |
|                            | Combustion Chamber                   | \( PEC_{com,GT} = \left( \frac{46.060 m_{0}}{0.995- \ln(T_{out})} \right) \times (1 + \exp(0.018 T_{out} - 26.4)) \) | 1996 |
|                            | Turbine                              | \( PEC_{tur,GT} = \left( \frac{479.34 m_{0}}{0.92- \ln(T_{out})} \right) \times \ln(r_\phi) \times (1 + \exp(0.036 T_{out} - 54.4)) \) | 1996 |
|                            | Turbine                              | \( \log_{10}(PEC_{tur,ORC}) = 2.6259 + 14.398 \log_{10}(\dot{W}_{ps}) - 0.1776[\log_{10}(\dot{W}_{ps})]^2 \) | 2008 |
|                            | Turbine                              | \( \log_{10}(PEC_{tur,ORC}) = 3.3892 + 0.0536 \log_{10}(\dot{W}_e) + 0.1538[\log_{10}(\dot{W}_e)]^2 \) | 2008 |
| Organic rankine cycle      | Condenser                            | \( PEC_{con,ORC} = 1773 \times m_{ORC} \)                                 | 1996 |
|                            | Recuperator                          | \( \log_{10}(PEC_{rec}) = 4.6656 - 0.1557 \log_{10}(A) + 0.1547[\log_{10}(A)]^2 \) | 2008 |
|                            | HRSG                                 | \( PEC_{HRSG} = 6570 \times \left( \frac{A_{HRSG}}{A_{HRSG,ref}} \right)^{0.8} + 21276 \times m_d + 1184.4 \times m_{T,ref} \) | 1996 |
| Domestic hot water         | Heat Exchanger                       | \( PEC_{DHW,HW} = 4122 \times \left( \frac{m_d \Delta_{h,HW}}{m_d \Delta_{h,ref}} \right)^{0.6} \) | 1996 |

\[ NPV = -C_0 + \sum_{t=0}^{N} \frac{(Ben_{cool} - FC)}{(1 + r)^t} \]  
\[ SPB = \frac{C_0}{(Ben_{cool} - FC)} \]

### 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).

$$y_k = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i \neq j} \beta_{ij} x_i x_j$$

where $Y$ is the response function and $\beta_0, \beta_j, \beta_{ij}$, and $\beta_{jj}$ 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

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**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   |

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

| Point | T(C) | P(bar) | m(kg/s) |
|-------|------|--------|---------|
|       | Present work | Ref. | Present work | Ref. | Present 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                              | 0.447        | 0.447     |
The proposed CCHP are approximately equal to 897 kW, 641.1 kW, and 700 kW, 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(°C) | h(kJ/kg) | 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  | 2305  | 236.98   | 0.6377  |
| 25     | Ammonia    | 4.706  | 3.476 | 124.29   | 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.
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°, as shown in Figures 6 and 7.

**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).

![Figure 8. Desirability contour plots of the optimized economic parameters](image)

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

| $i_r$ (year) | $C_F$ ($/kWh)$ | $P_{es}$ ($/kWh)$ | $NPV$ ($) | $SPB$ (year) | Desirability |
|-------------|---------------|------------------|----------|-------------|--------------|
| 0.080       | 20,000        | 0.001            | 0.022    | 776,900,680 | 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 890 kW 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 predominately 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 S/kWh of fuel cost, 0.022 S/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.

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چکیده
در کار حاضر، تجزیه و تحلیل آماری برای مطالعه شاخص‌های اقتصادی ارزش فعال خاص و دوره باربادخت ساده به عنوان تابع پایه برای سیستم ترکیبی توان، حرارت و بروزات ارائه شده است. عملکرد سیستم ترکیبی با کمک مدل‌سازی ترمودعم‌نیم‌شیئی سازی و معادلات اقتصادی بایان شده است. این تلاش گردیده تا تأثیر برخی عوامل اقتصادی (نسبت بهره، هزینه سوخت، طول عمر و مدت فروش برخ) بر پایش‌های سیستم مطالعه شود. بر اساس تجزیه و تحلیل طراحی آزمایش، مدل‌های رگرسیونی ارایه داده و پایش‌های فعال خاص و دوره باربادخت ساده ارائه شد.

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