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Research article

Thermoeconomic analysis of a novel multi generation system combined with compressed air energy storage and sulfur dioxide-based ejector cooling system

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Abstract

A new compressed air energy storage system integrated with combined cooling, heating and electricity is proposed and investigated in this study. The investigated system uses sulfur dioxide as the working fluid for the cogeneration system to produce coolant from the ejector cooling and heating sub-system. The review here includes a detailed thermodynamic and thermo-economic analysis. The proposed system is examined from different perspectives and the performance of the system is quantified through the output parameters. In addition, a case study is conducted to evaluate the performance of the system in a specific case. In addition, a sensitivity analysis is performed to follow the behavior of the system under different conditions. The results of thermodynamic analysis show energy efficiency of 21% and exergy efficiency of 55% for the proposed system. In addition, with the economic analysis, the total cost of the system is 232$/GJ. This work may provide a new method to increase the efficiency of the thermodynamic performance of multi generation systems.

Keywords: Compressed air storage, Ejector, Gas turbine, Cogeneration, Economic analysis

1- Introduction

Considering that companies and manufacturers have limited capital and financial resources to provide the required electrical and electronic equipment due to competition, a new and beneficial way must be found to reduce investment and production costs in order for the financial application to be sustainable. Efficient and effective measures have been taken to reduce energy production costs and improve the use of thermal waste in energy production systems. Fossil fuels should be used by taking into account the high cost of eliminating pollution and environmental problems and effects such as ozone layer depletion, greenhouse gases, temperature inversion, acid rain, and the poor and non-renewable conditions of these oils. It will be very beneficial for new methods to be cost-effective. Therefore, current can be provided at the desired location using production methods and three types of electricity can be created, namely heating and cooling, using electrical equipment. This method is technically and economically good for customers and has high business value. Producing electricity at the point of consumption will significantly reduce the cost as it will reduce the cost of transporting electricity from the generator to the point of use. The use of synchronous production systems increases the efficiency of the system, helps protect the environment, reduce pollution and preserve natural ecosystems. Currently, electrical and electronics companies are in competition to increase efficiency, and the production of electrical equipment has been adopted to provide good performance at a rate of 80%. The electric generator has an efficiency of about 30%, while the combined cycle uses two cycles, and the efficiency of the gas is about 50% [1]. According to a study by the International Maritime Organization, the global shipping industry contributed 1056 million tons of carbon dioxide emissions in 2018. This figure constituted 2.89% of the total anthropogenic carbon dioxide emissions worldwide [2]. Hence, there exists significant potential in the adoption of waste heat recovery systems (WHRS) for the ship's engine, as they enable the recovery of waste heat from ships, thereby enhancing energy efficiency and reducing fuel consumption of ships[3]. It can be seen that the high performance of the combination of heat and electricity compared to other generators has made it the focus of many researchers, so the integrated energy use can be used when determining the cost of purchasing electricity. Integrated equipment is effective in reducing energy consumption and environmental pollution. Today, combined heat and power has proven to be effective in increasing energy efficiency and reducing pollution. This technology is a professional and flexible way of combining heat and electricity, which is received by different customers with different needs in many parts of the world [4]. Biomass gasification is one of the preferred thermochemical conversion technologies for obtaining an intermediate gaseous fuel from biomass feedstocks such as agricultural residues, which can eventually be fed into an engine–generator set to obtain electrical energy [5]. Combined heat and power systems are popular worldwide because of their ability to save energy, reduce greenhouse gas emissions, and provide viable options for energy reform and economic benefits. The combustion of fossil fuels such as coal or natural gas produces large amounts of energy and waste. In general, mechanical devices convert the energy produced by the combustion of the fuel into electrical energy. However, a large proportion of thermal energy is wasted and released into the environment, and there is great potential to utilise this unused thermal energy through combined heat and power [6]. Trigeneration systems maximise the use of waste heat from the main boiler to provide heat for the home and hot water for industrial processes. A trigeneration machine can be twice as efficient as a conventional generator. Finally, trigeneration systems produce electricity similar to conventional systems and can be used as backup power. This also reduces fuel and electricity costs and carbon dioxide production from fossil fuel plants compared to coal-fired power plants. All these benefits make trigeneration systems a commercial electricity generator [7]. Nowadays, compressed air technology has become important and necessary for all industrial production. Look around you, almost every product around you uses compressed air in its production process [8]. Compressed air is air whose volume is reduced by applying energy. The decrease in air volume eventually results in air pressure. This pressure is used for air or pneumatic tools. In other words, compressed air is air that increases pressure by decreasing volume. Energy can be stored from compressed air. Today, compressed air, like electricity, is the driving force of any factory or workshop. This clean energy does not require millions of dollars, unlike electricity, on the other hand, wind energy equipment is cheaper than electrical equipment [9]. Much research has been done in this area. Liguey et al. [10] addressed the multi-objective optimization problem of synchronous generation systems in construction. The results show that synchronous generation systems in workplaces and hospitals have better performance than residential systems. Konur et al. [11] analyzed the fuel-saving potential of integrating ORC systems in ships. The optimal choice for the working fluid is R1336mzz (Z). The system yielded a 15% reduction in the diesel generator's fuel consumption and a 5.16% decrease in the ship's fuel consumption. Afonaa-Mensah et al. [12] proposed a hybrid system for electrification of remote areas in Ghana, consisting of a photovoltaic system, a diesel generator, and a battery system. Their results reveal that integrating renewable energy in off-grid areas reduces electricity costs; however, achieving parity with the national grid requires further interventions and government policies to promote the adoption of sustainable energy in rural communities. Mehdi et al. [13] Combined heat and power with absorption and compression chillers. They reported energy consumption of 4 and 6 GJ using absorption and compression chillers respectively. Hai et al. [14] Use organic Rankine cycle and use water pump to avoid condenser in combined heat and power. The results show that water chiller is the least cost for the proposed process. Segeza et al. [15] studied computer systems with add-on modules to improve the accuracy of synchronous production systems. Cross-validation method was used to determine the numerical form and coefficients of the experimental study. The optimization accuracy of synchronous production systems is improved by using established calibration models and empirical power. Khanmohammadi et al. [16] the machines they recommended included the Kalina cycle, the refrigeration machine, the heating machine, and the work machine. They reported that the 449 kW reverse osmosis unit had the highest damage output of the system. Safavi et al. [17] evaluated a series of production systems for commercial air conditioning systems. The results showed that the process produced 230 to 260 grams of carbon dioxide per kWh. Wang et al. [18] developed a double pressure evaporation process in a multiple production system by using a common condenser. The results show that the boiler and condenser have the most damage and the damage of exergy is reduced by 32% with optimization. Zhang et al. [19] conducted a study on different energy absorption systems driven by waste heat generation in the sCO2 cycle. The optimality of the sCO2/APC system was also confirmed by thermodynamic and thermodynamic measurements. Fan et al. [20] developed a combined air conditioning, heating, and power (CCHP) system including an sCO2 system, an ejector refrigeration cycle (ERC), and an ORC. The results showed that the new CCHP system could increase efficiency by 9.17% and reduce total cost of goods by 5.05%. Yuan et al. [21]

designed combined cooling and power (CCP) using carbon dioxide as the working fluid. They compared the performance of two independent CCPs with the new CCP system and concluded that this proposal is suitable for lower turbine inlet pressures compared to the independent CCP. Also, the absorption refrigeration cycle (ARC) is suitable for the use of low temperature air to produce cooling energy. Wu et al. [22] studied the combined sCO2/ammonia ARC system by thermodynamics and thermodynamic measurements. They reported that ARC can achieve the purpose of cooling and power generation and improve the efficiency. Martin-Hernandez et al. [23] investigated and determined the efficiency of three methods, namely amine adsorption, high release adsorption and membrane separation, to produce bio-CH4 while capturing CO2. The results showed that using the 13X zeolite high release adsorption method to capture CO2 was the most economical and capital cost effective. Melpuia et al. [24] performed an energy-economic and energy-environmental analysis to evaluate the design of refrigerators using absorption-compression refrigeration and ORC methods. The irreversibility and exergy efficiency of this process are 83.4kW and 69%, respectively. Ghorbani et al. [25] developed a combined system for cogeneration of liquefied natural gas and liquefied carbon dioxide using a biogas purification unit and combined water process. The results showed that the specific energy consumption, total energy and energy efficiency were 0.4761 kWh/kg bioLNG, 0.7311 and 0.7258, respectively. Hosseini et al. [26] studied the production of electricity from biogas from fuel oxide products. First, two strategies of direct biogas injection into SOFC and biogas purification were compared, and then biogas injection into SOFC was compared. The results show that the system works well under modified biogas pretreatment conditions, and the energy efficiency and exergy efficiency reach 51.10% and 52.3%, respectively. Direct injection of untreated biogas into SOFCs can provide energy and efficiency between 37.2% and 38.6%. Ebrahimi et al. [27] developed a new combination for the utilization of waste biogas and co-production of waste gas biomethane (bioCH4) and liquid carbon dioxide (CO2). Their financial analysis showed that the payback period and the main cost of the product were 4.45 years and 0.8189 USD/m3 biomethane, respectively. Also, the sensitivity analysis showed that due to the increase of methane component of virgin biogas from 55 mol% to 75 mol%, the total thermal efficiency increased to 72.50% and the air-ground heat decreased to 7808 kW.

The review of past studies showed that most of the investigated cogeneration systems combined with air energy storage system suffer from low thermal efficiency. Therefore, in the current research, a new arrangement of combining the air energy storage system with the cogeneration system has been introduced, which brings high thermal efficiency. It can also be seen that the combination of ejector-Rankin cooling cycle based on sulfur dioxide has not been done in previous studies, which is the innovative aspect of the present research. In addition, comprehensive thermodynamic and economic analysis with EES software along with parametric evaluation has been done on the proposed system. The inputs to the integrated system are electricity for air compression and fuel for the combustion process. On the other hand, the outputs of this heating cycle produced from the intercooler, aftercooler and second heat exchanger are the cooling load in the evaporator unit and electricity in the gas turbines and sulfur dioxide. The aim of this research is to provide a complete thermodynamic and economic analysis for the new combined system of simultaneous production with air energy storage based on the sulfur dioxide ejection cooling cycle.

2- System description

The schematic of the combined cogeneration system with air energy storage investigated in this study is shown in Fig. 1. The surrounding air is compressed by a low-pressure air compressor and then cooled by thermal oil before the high-compression stage in the cooler. The air then enters the aftercooler where it cools to near freezing temperatures. During exhaust, thermal oil is used to warm the air before it enters the combustion chamber. Methane is used to increase the inlet temperature of the gas turbine. The exhaust gas enters the gas turbine and expands to ambient pressure. Then, heat from the superheater must be supplied to the synchronous generation system. The sulfur dioxide is pumped to higher pressures before entering the heat exchanger. The hot sulfur dioxide then enters the superheater to increase efficiency. Some of the sulfur dioxide leaving the turbine is preheated in the first heat exchanger and cooled before entering the ejector unit. The remaining sulfur dioxide expands to a lower level and exits the turbine before entering the second heat exchanger. The sulfur dioxide, known as the flow, is introduced into the first stage of the injector at the engine inlet. Sulfur dioxide enters the suction nozzle, where in the next step the ejector mixes with the sulfur dioxide coming out of the drive nozzle. The mixed stream enters the diffusion unit in the last stage of the ejector, and its pressure increases and its velocity decreases. The two-phase flow is separated in a mechanical separator unit. Saturated liquid sulfur dioxide enters the expansion valve before cold is produced in the evaporator unit, and saturated vapor sulfur dioxide enters the compressor before mixing with cold air from the second heat exchanger. The mixed stream is cooled and condensed in heat exchanger four and the cycle repeats.

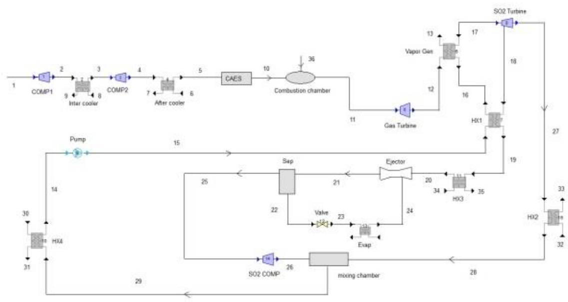


Fig. 1 Schematic of the proposed system

3-Thermodynamic analysis

For the thermodynamic analysis of the system, it is necessary to examine the thermodynamic properties of each point of the system using the mass and energy balance equation [28].

$$\sum m_i = \sum m_e \quad (1)$$

$$Q - W = \sum m_e h_e - \sum m_i h_i \quad (2)$$

The specific exergy of the system is calculated with the following relationship [29]:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \quad (3)$$

The primary data for modeling the studied system are shown in Table 1.

Table 1: Primary data

Parameter	Value
Compressor isentropic efficiency (%)	80
Turbine isentropic efficiency(%)	75
Pump isentropic efficiency(%)	70
Air compressor 1 inlet temperature (c)	15
Air compressor 1 inlet pressure (kPa)	101
Air compressor 1 inlet mass flow rate (kg/s)	0.09
Air compressor 2 inlet temperature (c)	319
Air compressor 2 inlet pressure (kPa)	240
So2 turbine inlet temperature (c)	451
So2 turbine inlet pressure (kPa)	12000
Ejector inlet temperature (c)	36
Ejector inlet pressure (kPa)	8000
So2 compressor inlet temperature (c)	16
So2 compressor inlet pressure (kPa)	5241

For the ejector subsystem, a series of assumptions must be considered, including pressure drop nozzle and actuator, suction nozzle, mixing section and diffuser efficiency. The relationships in Table 2 are used to model the ejector.

Table 2: Mathematical relations used for the ejector

system components	Exergy destruction equation
Ejector mass bubble ratio	$\mu=\frac{m_{sf}}{m_{pf}}$
Ejector pressure increase ratio	$\pi_{eje}=\frac{p_{ex}}{p_{sf}}$
Isentropic efficiency of moving nozzle	$\eta_{sf}=\frac{h_{pf}-h_{noz}}{h_{pf}-h_{noz,is}}$
Energy balance between the nozzle section and the primary fluid	$h_{pf}-h_{noz}=\frac{1}{2}v_{noz}^2$
Conservation of momentum in the mixing section	$V_{mf}=\frac{v_{noz}}{1+\mu}$
Energy balance for the ejector	$h_{out}=\frac{h_{pf}+h_{sf}\mu}{1+\mu}$
Mixing efficiency	$\eta_{mix}=\frac{v_{mf,s}^2}{v_{mf}^2}$
Energy balance equation between the mixing and outlet sections	$h_{out}-h_{mf}=\frac{1}{2}v_{mf,is}^2$
Diffuser efficiency	$\eta_{dif}=\frac{h_{out,is}-h_{mf}}{h_{out}-h_{mf}}$

With complete thermodynamic analysis on the system, the following relationships are used to calculate the energy efficiency and exergy of the system.

$$\eta_{energy}=\frac{W_{GT}+W_{ST}+Q_{evap}+Q_{IC+}+Q_{AC}-W_{SC}-W_{SC}}{W_{air\ Comp1}+W_{air\ Comp2}+m_{36}LHV} \quad (4)$$

$$\eta_{exergy}=1-\frac{E_{dist,total}}{W_{air\ Comp1}+W_{air\ Comp2}+m_{36}e_{36}} \quad (5)$$

4-Economic analysis

Thermoeconomic analysis, widely used in energy systems, evaluates economic and thermodynamic performance simultaneously. This approach examines costs in a way that determines the economic efficiency of system components. This helps identify areas for improvement, optimization and cost-effective allocation of resources [30]. Although further investment can increase the efficiency of energy conversion technology, balancing investment cost with product increase plays an important role [31]. In the previous study, energy and exergy parameters were determined for each state point. In addition, it is important to establish cost equations to maintain cost balance among the various components of the system. The following relationship is used to calculate the investment rate and capital maintenance[32].

$$Z_k = CRF \times \frac{\varphi_r}{(N \times 3600)} \times PEC_k \quad (6)$$

where the factors φ, N and PEC are the maintenance factor, operating time in one year and investment cost of the part, respectively. Also, the CRF parameter shows the capital recovery coefficient, which is defined by the following relationship.

$$CRF=\frac{i(1+i)^n}{(1+i)^n-1} \quad (7)$$

Finally, the total cost of the system is obtained by dividing the annual cost by the total working hours during a year, which is considered 7446 hours per year [33]:

Z_{Toatal}=(TOC×φ×CRF)/t (8)

In the current study, using the updated cost functions shown in Table 3, an efficient economic analysis is done to improve the economic justification of using the proposed system [34, 35].

Table 3: Cost rate of system

system components	Cost rate
air compressor	$z=\left(\frac{39.5\times m_2}{0.9-eta_{comp}}\right)(\frac{P_2}{P_1})\,ln(\frac{P_2}{P_1})$
Combustion chamber	$z=\left(\frac{46.08\times m_{11}}{0.995-\frac{P_{10}}{P_{11}}}\right)(1+exp(0.018\times T_{11}-26.4))$
Gas turbine	$z=\left(\frac{479.34\times m_{12}}{0.92-eta_{tur}}\right)ln(\frac{P_{11}}{P_{12}})(1+exp(0.036\times T_{12}-54.4))$
heat exchanger	$z=2143\times(A_{heat\ exchanger})^{0.5}$
Sulfur dioxide turbine	$z=4750\times(W_{Turb})^{0.75}$
Pump	$z=200\times(W_{Pump})^{0.65}$
Steam thermal generator	$z=4122\times(A_{vapor,gen})^{0.6}$
ejector	Z=(16/14×989× m_{20})$(\frac{T_{24}}{P_{24}})^{0/05}$ $p_{21}{}^{0.75}$

5-Results

In this study, we introduced a new production system as well as an air energy storage system and combined it with a sulfur dioxide based ejector cooling system to find the best performance of the system concept. With the thermodynamic analysis performed on the proposed system, energy efficiency of 21% and exergy efficiency of 55% is reported, and it shows the proper functioning of the system and the optimal arrangement of the system's thermodynamic components. The results of thermodynamic analysis of the system are shown in Table 4.

Table 4: Results of Thermodynamic evaluation

Parameter	Value
Energy efficiency(%)	21
Exergy efficiency(%)	55
Gas turbine work (kw)	22.8
sulfur dioxide compressor Work (kw)	995.4
Sulfur dioxide turbine work (kw)	46959
Sulfur dioxide pump work (kw)	643.8

To improve the performance of the proposed system, it calculates the maximum exergy destruction among the thermodynamic components of the system and by providing methods to reduce the maximum exergy destruction in the system, the efficiency of the system increases significantly. As the results of calculating the exergy destruction of the system components are shown in Table 5, the exergy destruction of the whole system is calculated as 49189 kW and the highest exergy destruction occurs in the sulfur dioxide turbine and the air compressor has the lowest exergy destruction among the system components.

To expand the application of the proposed system in various industries by using the new working fluid of sulfur dioxide in the ejector cooling system and using thermodynamic components with efficient cost functions and up-to-date economic justification of the system has been improved. According to the results of the economic evaluation on the system, the total cost of the proposed system is calculated as 232 dollars per gigajoule, which indicates the appropriate commercialization and mass production capability of the studied system.

According to the results of the economic evaluation of the studied system shown in Table 6, the ejector has the largest share of the cost rate among the system components, and the lowest cost rate in the system belongs to the air compressor.

5-1-Parametric analysis of the proposed system

Parametric analysis is a reliable method to determine the performance quality of a system under different conditions to gain a comprehensive understanding of the system. In the studied system, the effect of the main design parameters such as the isentropic efficiency of the compressor and the inlet temperature of the sulfur dioxide turbine on the performance of the proposed system has been evaluated.

Table 5: Exergy destruction of system components

Parameter	Value(kw)
Exergy destruction of after cooler	9.6
Exergy destruction of compressed air storage	41.41
Exergy destruction of the combustion chamber	25.69
Exergy destruction of air compressor one	1.9
Exergy destruction of air compressor two	2.06
Exergy destruction of evaporator	1957
Exergy destruction of ejector	90
Exergy destruction of mixing chamber	3.12
Exergy destruction of Sulfur dioxide compressor	961.8
Exergy destruction of Sulfur dioxide turbine	30255
Exergy destruction of gas turbine	2.39
Exergy destruction of heat exchanger one	7702
Exergy destruction of heat exchanger two	9696
Exergy destruction of heat exchanger three	40.36
Exergy destruction of heat exchanger four	349.5

Table 6: Cost of system components

Parameter	Value($/GJ)
cost of the combustion chamber	553
cost of the Air compressor one	125
cost of the Air compressor one	149.4
cost of the Sulfur dioxide compressor	841748
cost of the ejector	310647365
cost of the gas turbine	329.2
cost of the pump	13389
cost of the vapor generator	10287
cost of the Sulfur dioxide turbine	15157384
cost of the heat exchanger one	51512
cost of the heat exchanger two	59294
cost of the heat exchanger three	18377
cost of the heat exchanger four	3243

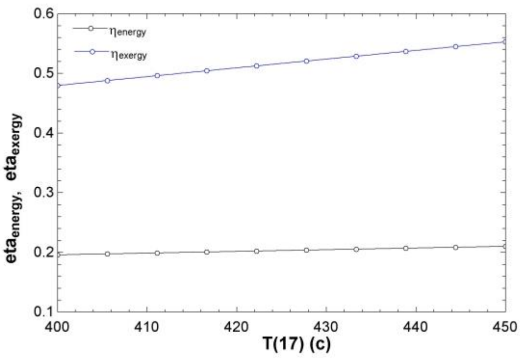
5-1-1-Effect of sulfur dioxide turbine inlet temperature changes on system performance

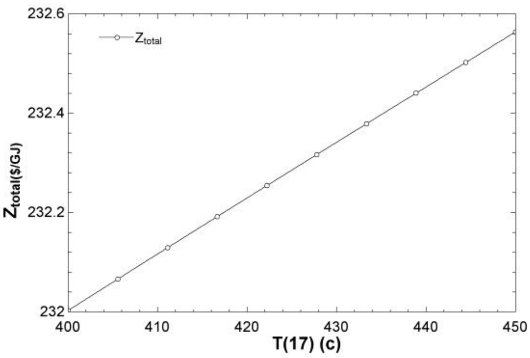
According to Fig. 2, when the inlet temperature of the sulfur dioxide turbine increases from 400°C to 450°C, the energy efficiency and exergy of the system are improved. The total cost of the system increases due to the increase in the inlet temperature of the sulfur dioxide turbine.

When the inlet temperature of the sulfur dioxide turbine increases, the exergy degradation in the system increases and the work capability decreases.

5-1-2-Effect of compressor isentropic efficiency changes on system performance

Increasing the isentropic efficiency of the compressor according to Fig. 3 improves the performance of the proposed system. The energy efficiency and exergy of the system increases under the influence of increasing the isentropic efficiency of the compressor. When we use a compressor with high isentropic efficiency, the exergy destruction in the system is reduced and the work performance is improved. The work consumed by the compressor is reduced by increasing its isentropic efficiency, and as a result, we need smaller equipment in the system and the total cost of the system is reduced.





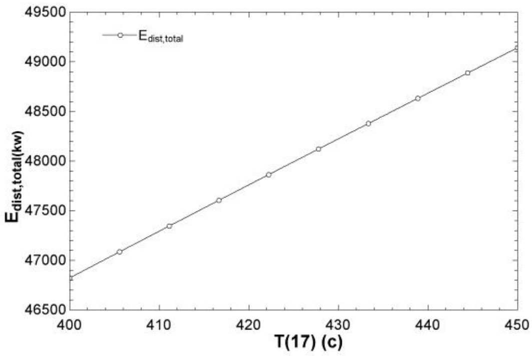


Fig. 2 Effect of sulfur dioxide turbine inlet temperature changes on different parameters

6-Conclusion

A new integrated sub-system of compressed air energy storage together with a multiple generation system based on sulfur dioxide ejection cooling system is proposed and investigated in this study. The proposed system has been investigated using energy, exergy and economic approaches. A detailed review of each system component has been carried out to find critical points and system defects. By changing the design parameters, the effect of their change on the system performance was further investigated. In the present study, by using sulfur dioxide in the ejector cooling system, we see an improvement in the thermodynamic performance of the proposed system compared to previous researches, and a new configuration of multiple production system is presented, which is combined with the air energy storage subsystem. The basic results of thermodynamic modeling showed that the energy efficiency and exergy of the system are 21 and 55%, respectively. By applying the updated and effective cost functions for the system components and by economic analysis with assumed initial economic data, the basic results of the economic analysis showed that the overall cost rate of the system is calculated to be 232 dollars per gigajoule. The results of the thermodynamic and economic analysis show that the proposed system works well and is economically viable and can take a significant step in the industrial development and waste energy storage of energy systems.

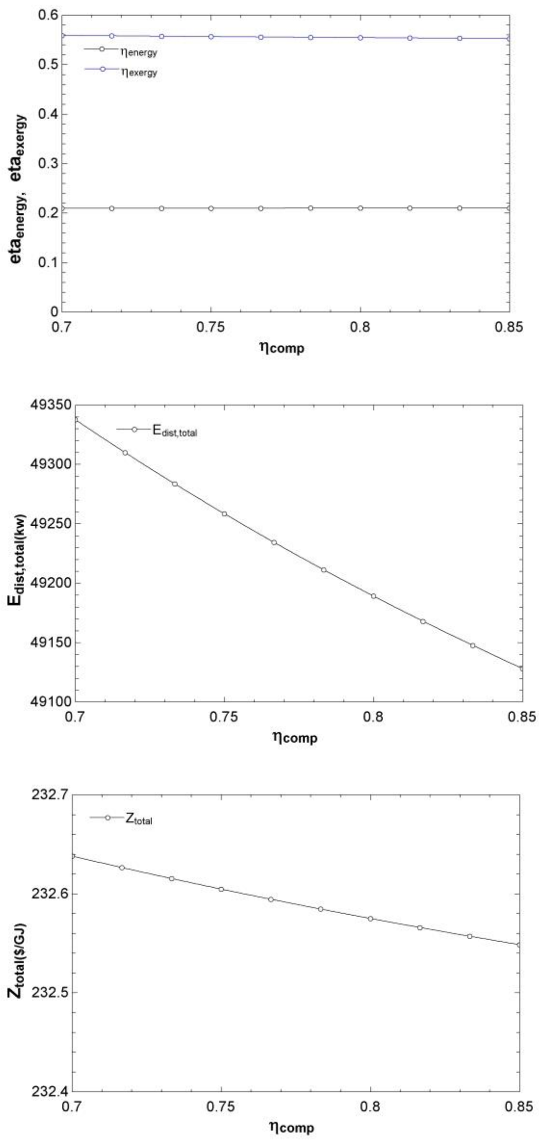


Fig. 3 The effect of changes in compressor isentropic efficiency on different parameters

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