

Research papers

Exergoeconomic evaluation of Adiabatic Compressed Air Energy storage: Effects of pressure ratio and configuration

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ABSTRACT

An exergoeconomic analysis of three configurations of Adiabatic Compressed Air Energy Storage systems: 3-stage, 5-stage and 7-stage at a constant pressure ratio of 2.42, and three 5-stage systems at pressure ratios of 2.42, 2.70 and 3.00 was conducted using the Specific Exergy Costing method. The exergetic costs, exergy destruction cost rates, and exergy-based monetary costs were calculated. The results show that due to the inherent exergy destruction in the expanders, the exergetic costs and the exergy-based monetary costs of electricity are the lowest at the first expanders, which operate at the highest pressure. The exergetic costs increase in the subsequent expanders. The study also reveals that the average exergetic cost of electricity is almost constant at 1.461 kWh/kWh for all configurations at a pressure ratio of 2.42. However, these costs increase for the 5-stage systems, operating at higher pressure ratios to 1.507 kWh/kWh at a pressure ratio of 2.70 and 1.552 kWh/kWh at a pressure ratio of 3.00. Similar trends are observed when analysing the exergy-based monetary costs. The average exergy cost for all configurations at a pressure ratio of 2.42 is around \$0.42/kWh but gradually increases to \$0.43/kWh for the 5-stage system at a pressure ratio of 3.00, assuming a purchase cost of electricity of \$0.25/kWh. The study concludes that exergy costs depend more on system design, particularly thermal management, than on the final pressure of the system and that exergoeconomic analysis plays a crucial role in designing efficient energy storage systems.

Nomenclature

c	exergy-based monetary cost (\$ J ⁻¹ or \$ kWh ⁻¹)
c	exergetic cost (J J ⁻¹ or kWh kWh ⁻¹)
CAES	Compressed Air Energy Storage
CRF	Capital Recovery Factor
$\dot{C}$	cost rate (\$ s ⁻¹)
e	specific exergy (J kg ⁻¹)
E	exergy (J)
$\dot{E}$	exergy flow rate (J s ⁻¹)
i	interest rate
n	number of years

P	pressure (Pa)
PR	pressure ratio
τ	operating time (h)
T	temperature (K)
Z	capital cost (\$)
$\dot{Z}$	capital cost rate (\$ s ⁻¹)
y_{DI}, y_{DII}	exergy destruction ratio (type I or type II)

Subscripts and superscripts

0	reference state
D	destruction

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e	exit
F	fuel
i	inlet
k	component number
P	product
q	stream associated with energy and exergy transfer by heat
tot	total
w	stream associated with energy and exergy transfer by work

1. Introduction

The growing use of renewable energy sources increases the need for energy storage. Among various energy storage technologies, thermo-mechanical energy storage systems, particularly Compressed Air Energy Storage (CAES), are receiving more attention.

Many aspects of CAES systems have been analysed or are still being studied using different methods and approaches. Technical aspects, such as the performance and efficiency of CAES, are typically investigated using traditional thermodynamic analysis methods, including energy and exergy analysis. The traditional energy analysis method primarily focuses on the quantity of energy transferred into and out of the system, whereas the exergy analysis method enables engineers to identify the location and magnitude of irreversibilities within the components of energy systems. However, although the application of both these methods and additional optimisation can lead to more efficient designs, the optimised systems are not necessarily economically feasible, as economic aspects such as capital costs or operational costs are not considered. To analyse energy conversion and storage systems using traditional thermodynamic and economic methods, a new branch of engineering, called thermoeconomics, was developed. Later, the term “exergoeconomics” was proposed by Tsatsaronis to describe the combination of exergy analysis and economics [1,2].

Exergoeconomic analysis is an important step in achieving the optimal design of energy conversion systems. This analysis facilitates the design of systems where the costs of products can be reduced, ensuring both efficiency and economic viability. Furthermore, the exergoeconomic analysis method can evaluate the performance of each system component, identifying the critical components that offer the highest potential for system improvement. Therefore, obtaining a balance between thermodynamic and economic performance is significantly important for the rational design of energy conversion systems [3]. The use of cost accounting approaches, as part of exergoeconomic analysis, allows for the calculation of exergy cost, offering a logical basis for pricing.

Over the last three decades, various exergoeconomic analysis methods have been used to analyse different energy conversion systems [4], refrigeration systems with latent heat storage [5], district heating systems with thermal energy storage [6], cogeneration system integrated with solar thermal system and wind turbine [7], novel liquid air energy storage coupled with an off-shore wind farm [8], solar-based trigeneration system [9] and others. To facilitate more detailed analysis, advanced exergoeconomic methods have been developed later and used to analyse various energy conversion systems, including cogeneration systems [10], complex combined cycle power plant with CO₂ capture [11], gas engine heat pump [12], simple air refrigeration system [13] and others. Collectively, these studies have demonstrated that exergoeconomic analysis provides a comprehensive assessment of energy system performance, encompassing both efficiency and cost.

In recent years, exergoeconomic analysis has been increasingly applied to analyse various energy storage systems, including Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) systems. Buffa et al. [14] studied a 7-stage compression and 6-stage expansion Adiabatic Compressed Air Energy Storage (ACAES) system, which was designed using commercially available compressors, expanders, intercoolers, and reheaters. Water was used as the working fluid to cool the compressed air after compression and to heat the air

before expansion. The hot water was stored in thermal energy storage tanks. An off-design performance analysis was conducted, an exergoeconomic evaluation was performed, and finally, the electricity costs were calculated. The results showed that the exergy destruction varied across all stages in the compressors, intercoolers, reheaters, and expanders. The highest exergy destruction was observed in the compressors during the charging stage, in the expanders during the discharging stage, and in the compressor intercoolers. The electricity cost for each expander varied between 65 and 76 €/MWh, with an average cost of approximately 70 €/MWh. An overall exergy efficiency of 52 % was achieved in the proposed system.

Bagdanavicius and Jenkins [15] investigated two CAES systems: one with Thermal Energy Storage (TES) connected to a District Heating Network (DHN) and one without TES. Both systems consisted of 4-stage compression and 2-stage expansion processes. Natural gas was used to preheat the air before expansion in both systems. The compressed air was cooled using water in both systems. The results indicated that the maximum exergy destruction occurred in the heat exchangers used to cool the air during the charging phase. This was attributed to the significant temperature difference between the hot compressed air and the cooling water. The exergy cost of electricity was \$0.1120/kWh, and the exergy cost of heat was \$0.2224/kWh for the CAES system with TES. For the CAES system without TES, the exergy cost of electricity was \$0.1389/kWh. It was reported that the exergy efficiency of CAES with TES increased from 50.1 % to 55.8 % compared to simple CAES systems.

An exergoeconomic analysis of a Combined Cooling, Heating and Power (CCHP) plant integrated with a CAES system was conducted by Yao et al. [16]. They examined the trade-off between the total exergy efficiency and the specific cost of the final product using an evolutionary multi-objective algorithm. An exergoeconomic analysis of an ideal design case revealed important performance metrics and identified critical limitations. The results indicated that decreasing the size of the gas engine improved the exergy efficiency but increased the unit product costs. However, the use of a trigeneration system significantly enhanced the overall exergy efficiency of the system. It was concluded that the investment costs of the main components of the CAES system, such as compressors, heat exchangers, and storage tanks, were critical and should be reduced to lower the product costs.

Nabat et al. [17] investigated a constant pressure CAES system. The system was designed to increase the performance of energy storage by minimising exergy destruction and enhancing production capacity and energy storage density. Energy, exergy, economic, and exergoeconomic analysis methods were applied, and an optimisation was performed to find the most optimal solution. The results of the study showed that a roundtrip efficiency of 68.28 % and an exergetic roundtrip efficiency of 66.01 % were achieved. A considerable amount of exergy destruction was attributed to the high-temperature TES system. The economic evaluation showed a construction cost of \$27.68 million, with a projected profit of \$40.02 million and a payback time of 5.11 years. The total cost of the products and the levelized cost of electricity were estimated to be \$21.15/GJ and \$190.40/MWh, respectively.

Alirahmi et al. [18] investigated a multigeneration system incorporating CAES to produce power, cooling, and potable water, using energy, exergy, and exergoeconomic analysis and optimisation. The results demonstrated that a round-trip exergy efficiency of 50.6 %, a cost rate of 322.8 \$/h, and a CO₂ emission index of 246 kg/MWh could be achieved for the most optimal system. The authors concluded that the system performance was affected by several parameters, including air storage pressure, charging-to-discharging pressure ratio, and the gas turbine inlet temperature. According to the authors, “the storage pressure had the highest effect on the cost rate”, and the “charging-to-discharging pressure ratio had the highest effect on the round-trip exergy efficiency” [18].

In another study, Bushehri et al. [19] used energy, exergy, economic, and exergoeconomic analyses to investigate a novel large-scale multigeneration system comprising an Organic Rankine Cycle, and Reverse

Osmosis integrated with CAES, for the production of potable water, domestic hot water, and electricity. The findings showed that the round-trip efficiency and exergetic round-trip efficiencies were 73.54 % and 55.01 %, respectively. A large portion of the incoming exergy was lost, with 47.42 % of this exergy destruction occurring in the high-temperature TES, highlighting its significant impact on the overall system efficiency. Considering an initial investment of \$7.24 million, the system reached a payback time of 3.3 years and an estimated profit of \$24.54 million. The cost rates of the products were \$729.02/h for electricity, \$117.80/h for freshwater, and \$6.94/h for domestic hot water.

Razmi and Janbaz [20] conducted an exergoeconomic analysis of a cogeneration system composed of the Organic Rankine Cycle and an absorption refrigeration cycle integrated with ACAES. The effects of failure and the repair rates on the costs of electricity and chilled water were analysed using the exergoeconomic analysis and the Markov method. The authors reported that the cost of electricity varied between \$0.02945/kWh, assuming a purchase cost of electricity at \$0.01/kWh, and \$0.1085/kWh, assuming a purchase cost of electricity at \$0.06/kWh. The cost of chilled water increased from \$0.1189 per kWh to \$0.2159 per kWh due to the rising cost of electricity. The economic analysis revealed that the payback time of the proposed system was initially 2.9 years but increased to 3.01 years when availability considerations were taken into account. It was found that the operating periods of the system could significantly affect the payback time. The shortest payback time of 2.95 years can be achieved for an operating period of approximately 5 h (charging and discharging) per day.

Esmailion, Soltani [21] also studied a multigeneration system integrated with a CAES system for the production of electricity, cooling, heating, potable water, hydrogen, and sodium hypochlorite. The analysis comprised three subsystems: a Combined Cooling, Heating and Power (CCHP) unit, a desalination unit, and a CAES system. The results of the study showed that the energy-based round-trip efficiency was 74.5 %, while the exergetic efficiency was 60.2 %. The annual outputs of the system were 2.6 GWh of electricity, 0.4 GWh of cooling, 0.5 GWh of heating, 410000 m³ of hydrogen, 87400 m³ of water, and 9.2 tons of sodium hypochlorite. The exergetic efficiencies of separate subsystems were 50.1 % for CAES, 27.2 % for CCHP, and 9.7 % for the desalination unit. The total exergy destruction rate of the system was 1528 kW, with CAES contributing 84.4 %, the desalination unit 3.7 %, and CCHP 11.9 %. It was also found that the levelised costs of the products were \$0.045/kWh for electricity, \$2/m³ for desalinated water, \$0.18/kWh for cooling, and \$0.14/kWh for heating loads. They also highlighted challenges associated with the proposed system, including high initial investment, geographical constraints, and lower energy and exergy density compared to liquid air energy storage systems.

Mazloun, Sayah and Nemer [22] carried out an optimisation of an isobaric three-stage ACAES system with water-based TES using exergoeconomic analysis. The Specific Exergy Costing (SPECO) method was used in this study to calculate the cost rates of each stream, and the results were fed into the optimisation model. The results of the study showed that a round trip efficiency of 55.1 % and an energy density of 11.9 kWh/m³ could be achieved for the proposed ACAES. The analysis also showed that the highest energy losses of 34 % were observed in the rotating machinery and 9 % in the heat exchangers. The average electricity cost was determined to be 0.3166 €/kWh, based on the assumption that the electricity purchase cost was 0.1114 €/kWh. Using the exergoeconomic model combined with a genetic algorithm, an optimisation was also conducted. The results of optimisation demonstrated that a reduction of operational costs by 3.7 % and a decrease in investment costs by 5.6 % could be achieved while improving efficiency by 2.7 % due to the enhancement of the heat exchanger pinch point. A sensitivity analysis revealed that the storage cycle required a minimum capacity of 20 MW for optimal performance.

In the previously mentioned studies, the exergy and exergoeconomic analysis methods were used to evaluate the operation of integrated or

standalone CAES systems operating under specific conditions, with fixed maximum storage pressure. However, to understand the effect of maximum system storage pressure on CAES operation, a more detailed investigation is needed. One of the first attempts to study the effect of pressure on the costs of the Adiabatic Compressed Air Energy Storage (ACAES) system components, such as compressors, turbines, and heat exchangers, was conducted by Baniamerian et al. [22,23]. In these studies, cost equations for the ACAES components were developed, taking into account their operating pressures and conditions. To avoid high air temperatures after the compression stage, a fixed pressure ratio of 2.42 was chosen, and ACAES systems consisting of 1 to 7 compression and expansion stages in the range of 10 to 350 bar were analysed. Using the proposed cost equations, the specific costs, expressed in \$ per kW of installed power, were calculated. It was concluded that the costs of compressors and expanders decreased when the storage pressure increased; however, the cost of heat exchangers increased. Despite this fact, it was found that the overall cost of all equipment was reduced at higher storage pressure, resulting in lower ACAES cost at high pressure.

To better understand the formation process of the final product cost and to evaluate the costs of exergy destruction in ACAES at different storage pressures, an exergoeconomic analysis was conducted in this study. The objectives of the study were:

- To investigate the effect of air storage pressure and different configurations of ACAES systems on the operation of the systems components, the cost rate of exergy destruction in different components, and the cost formation process, using exergoeconomic analysis methods.
- To demonstrate the additional capabilities and advantages of exergoeconomic analysis methods for evaluating energy storage and energy conversion systems.

Similar 3-stage, 5-stage, and 7-stage ACAES systems, operating with the same pressure ratio per stage, utilising water as a heat transfer fluid for thermal energy storage, as in the study by Baniamerian et al. [22,23], were analysed in this study. The Specific Exergy Costing (SPECO) method [25] was used to conduct the exergoeconomic analysis. The exergy destruction costs, exergetic costs and monetary costs of heat, electricity and compressed air were calculated. The variations in exergy costs depending on the change in pressure ratios for 5-stage ACAES systems were also analysed.

2. Description of Adiabatic Compressed Air Energy storage system

In this study, three variations of Adiabatic Compressed Air Energy Storage (ACAES) systems: 3-stage, 5-stage, and 7-stage systems were investigated. A schematic diagram of a typical 3-stage ACAES system is shown in Fig. 1. The same design principles were applied for the 5-stage and 7-stage ACAES systems.

The ACAES system (Fig. 1) operates in two phases: charging and discharging. During the charging phase, air is compressed by compressors 1, 3, and 5. After each compression stage, the air is cooled in heat exchangers 2, 4, and 6 using water as heat transfer fluid. The heated water is then pumped and stored in Thermal Energy Storage (TES). The compressed air after the final compression stage is directed to the air storage (AS) tank or an underground cavern.

During the discharging stage, the air is released from the storage, preheated, and expanded in the turbines. Hot water from the TES is used to preheat the air in heat exchangers 14, 16, and 18. The expanded hot air then passes through expanders 15, 17, and 19 before being released into the atmosphere after the final expansion stage.

In this study, several assumptions were made. To ensure that water remained in the liquid phase, it was assumed that the TES operates with water at a maximum of 90 °C, simplifying its design. The pressure ratio for all compressors and expanders was set at 2.42 for the basic case,

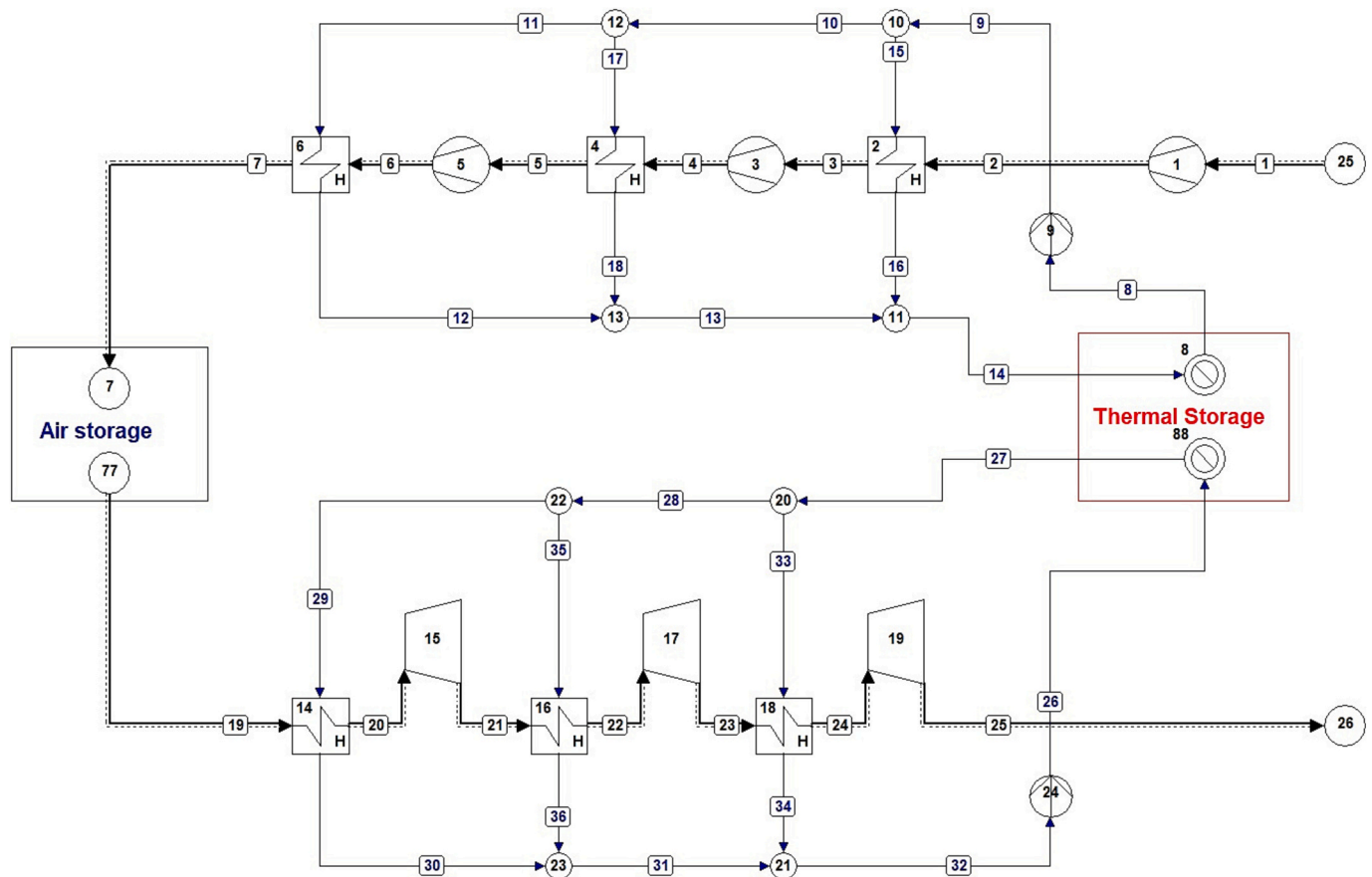


Fig. 1. Adiabatic Compressed Air Energy Storage system (1, 3, 5 – compressors; 2, 4, 6, 14, 16, 18 – heat exchangers; 15, 17, 19 – expanders; 9, 24 – water pumps).

similar to other studies [22,23]. The air storage pressure was kept constant. While there are multiple ways to achieve this, due to the constraints of the study, it was difficult to include all approaches, and the system for maintaining pressure was not considered. Maintaining constant pressure ensured a constant air temperature after the compressors and consistent isentropic efficiency. Also, it was demonstrated that the round-trip efficiency of such storage systems was higher compared to isochoric ACAES [24]. To investigate the effect of pressure

ratio on the exergy costs, two additional cases at PR = 2.7 and 3 were analysed for a 5-stage ACAES. The modelling parameters for all ACAES systems analysed in this study are shown in Table 1.

3. Methodology

To analyse the ACAES systems, a steady-state thermodynamic analysis was first conducted. The systems were modelled, and energy and

Table 1
Modelling parameters of ACAES systems.

Parameter	3-stage	5-stage	7-stage
Charging phase			
Pressure ratio	2.42	2.42	2.70
Air storage pressure (bar)	14.2	83.0	143
Isentropic efficiency of compressors	0.85	0.85	0.85
Polytropic efficiency of compressors	0.867	0.867	0.869
Air mass flow rate (kg/s)	10	10	10
Cooling water mass flow rate (kg/s)	10.2	17.1	19.5
Air temperature (°C):			
- After compressors	~121	~121	~135
- After heat exchangers	22	22	22
Cooling water temperature (°C):			
- Supply	20	20	20
- Return	90	90	90
Total electrical input power (kW)	3010	5021	5735
Heat output to TES (kW _{th})	2990	5001	5715
Discharging phase			
Isentropic efficiency of turbines	0.85	0.85	0.85
Polytropic efficiency of turbines	0.833	0.833	0.831
Air mass flow rate (kg/s)	10	10	10
Heating water temperature (°C):			
- Supply	90	90	90
- Return	20	20	20
Total electrical output power (kW):	2062	3437	3806

exergy values were determined using Cycle-Tempo software [25]. The exergy values were calculated assuming the following reference state parameters: $P_0 = 1$ bar and $T_0 = 25$ °C.

Performing exergy and exergoeconomic analysis, it is convenient to define *fuel* and *product* streams for each component [26,27]. The *fuel* stream is defined as the amount of exergy consumed by the component, and the *product* stream represents the useful exergy output delivered by the component. For example, in the case of a turbine, the *fuel* is the exergy difference between the high pressure and temperature gas entering the turbine and the lower pressure gas exiting it, while the *product* is the exergy associated with the mechanical work produced by the turbine. In this study, the *fuel* and *product* exergy streams were identified and calculated for each component.

Using the concepts of *fuel* and *product*, and ignoring the exergy loss associated with heat transfer to the surroundings, the exergy destruction in component k , $\dot{E}_{D,k}$, was calculated using the following equation:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \quad (1)$$

Where $\dot{E}_{F,k}$ is the exergy input (*fuel*) (kW), and $\dot{E}_{P,k}$ is the useful exergy output (*product*) of the component (kW).

To assess the performance of the system components, the exergy destruction ratio can be used as an indicator. In this study, two types of exergy destruction ratios were calculated for each system component. The exergy destruction ratio (type I), y_{DI} , was determined using the equation below [26]:

$$y_{DI} = \frac{\dot{E}_{D,k}}{\dot{E}_{tot}} \quad (2)$$

Here $\dot{E}_{D,k}$ is the exergy destruction rate in the component (kW), and $\dot{E}_{tot}$ is the total exergy rate supplied to the overall system (kW). This parameter indicates how much exergy was destroyed in each component of the system per 1 kW of exergy (electricity) transferred to the system during the compression stage.

The exergy destruction ratio (type II), y_{DII} , was calculated using the following equation [26]:

$$y_{DII} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,tot}} \quad (3)$$

Here $\dot{E}_{D,tot}$ is the total exergy destruction rate (kW) within the system. This parameter indicates how much exergy was destroyed in each component per 1 kW of exergy destroyed in the entire system.

To perform an exergoeconomic analysis, a commonly used method, the Specific Exergy Costing (SPECOC) method [27], was applied. Two types of exergoeconomic analyses were conducted in this study. First, a non-monetary exergoeconomic analysis, known as exergetic costing analysis, was performed. Using this method, the exergetic costs of each stream and the final products, expressed in kJ required / kJ produced or kWh required / kWh produced, could be calculated. The exergetic cost represents the amount of exergy required to produce a unit of output in a system. It is the inverse of the exergy efficiency and is particularly useful because it allows the observation of how the cost (non-monetary cost) of exergy increases across different system components. To perform the exergetic costing analysis, first, the exergy cost balance equations were constructed for each system component:

$$\sum_e (c_e \dot{E}_e)_k + (c_w \dot{E}_w)_k = \sum_i (c_i \dot{E}_i)_k + (c_q \dot{E}_q)_k \quad (4)$$

Here c_i , c_e , c_w , and c_q represent the average exergetic costs of exergy streams at the inlet and at the exit, and the exergetic costs associated with exergy transfer by work and heat (kJ/kJ or kWh/kWh). $\dot{E}_i$, $\dot{E}_e$, $\dot{E}_w$, and $\dot{E}_q$ denote the exergy flow rates at the inlet and at the exit, as well as those associated with the exergy transfer by work and heat (kW).

To complete the exergoeconomic analysis, in addition to developing the main exergoeconomic balance equations, auxiliary equations should be constructed because the number of exergy streams exceeds the number of system components. In this study, auxiliary equations were developed for certain components of the ACAES system using the SPECOC method [27]. Finally, to validate the model, the exergy balance equation for the complete ACAES system was formulated:

$$\sum_e (c_w \dot{E}_w)_e = \sum_i (c_w \dot{E}_w)_i \quad (5)$$

The model was verified by ensuring that the balance equation (Eq. 5) was satisfied.

To conduct an exergoeconomic analysis and to calculate monetary exergy costs, the following assumptions were made:

- 10 % return on investment;
- 20-year investment repayment period;
- 3285 annual operating hours of ACAES;
- Operation and maintenance costs were not included;
- An electricity price of \$0.25/kWh was used in this study.

Similar principles were applied to calculate the monetary exergy costs as discussed above. First, the main exergoeconomic balance equations were formulated for each component:

$$\sum_e (c_e \dot{E}_e)_k + (c_w \dot{E}_w)_k = \sum_i (c_i \dot{E}_i)_k + (c_q \dot{E}_q)_k + \dot{Z}_k \quad (6)$$

Here c_e , c_i , c_w , c_q represent the average exergy-based monetary costs of exergy streams at the inlet and at the exit, as well as the exergy costs associated with exergy transfer by work and heat (\$/kJ or converted to \$/kWh); $\dot{E}_i$, $\dot{E}_e$, $\dot{E}_w$, $\dot{E}_q$ are the exergy flow rates at the inlet and at the exit, and the exergy streams associated with exergy transfer by work and heat (kW); $\dot{Z}_k$ is the cost rate associated with capital investment for component k (\$/s).

The cost rates associated with capital investment were calculated using the following equation:

$$\dot{Z}_k = Z_k \frac{CRF}{\tau \bullet 3600} \quad (7)$$

Here Z_k represent the purchase cost of equipment (\$), CRF is the Capital Recovery Factor and τ is annual operating hours.

The Capital Recovery Factor was calculated using the following equation:

$$CRF = \frac{i \bullet (1 + i)^n}{(1 + i)^n - 1} \quad (8)$$

Here i represent the rate of interest, n is the total number of years.

When performing exergoeconomic analysis, a crucial stage in this process is calculating or estimating the capital cost of equipment. The capital costs of the ACAES system components: compressors, turbines, and heat exchangers, were calculated using the equations proposed in the study by Baniamerian et al. [22,23]. To estimate the cost of air storage, various sources were reviewed and analysed [28–31]. The general consensus is that the cost of air storage caverns can range from \$40 to \$100 per cubic meter. Therefore, an average cost of around \$70/

Table 2

Capital costs of equipment of ACAES system.

Equipment	3-stage ACAES	5-stage ACAES	7-stage ACAES
Compressors, million \$	0.782	0.948	1.02
Heat Exchangers, million \$	0.391	0.881	2.19
Turbines, million \$	0.515	1.10	2.18
Air storage, million \$	2.00	2.00	2.00
Total, million \$	3.69	4.93	7.39

m³ was used in this study. The capital costs of the equipment are listed in Table 2.

To complete the analysis, auxiliary equations were formulated using the principles of the SPECO method. The final exergy costs of the products were determined by solving a system of equations that consisted of both the main and auxiliary eqs. A more detailed description of the application of the SPECO method can be found elsewhere [32].

When the system of equations was solved, the cost flow rates $\dot{C}$ associated with the corresponding exergy streams were calculated using the following equations:

$$\dot{C}_{i,k} = c_{i,k} \dot{E}_{i,k} \quad (9)$$

$$\dot{C}_{e,k} = c_{e,k} \dot{E}_{e,k} \quad (10)$$

Here $\dot{C}_{i,k}$ and $\dot{C}_{e,k}$ are the cost rates at the inlet and at the outlet of the component (\$/s).

Using the *fuel* and *product* concept, the cost rates associated with *fuel* stream $\dot{C}_F$ and the cost rates associated with the *product* stream $\dot{C}_P$ were introduced, and the specific unit costs of *fuel* and *product* were calculated. The relationship between the specific exergy costs and the cost rates could be described using equations:

$$\dot{C}_{F,k} = c_{F,k} \dot{E}_{F,k} \quad (11)$$

$$\dot{C}_{P,k} = c_{P,k} \dot{E}_{P,k} \quad (12)$$

Here $\dot{C}_{F,k}$ and $\dot{C}_{P,k}$ are the cost rates of *fuel* and *product* streams of the component (\$/s); $c_{F,k}$ and $c_{P,k}$ are the specific unit costs of *fuel* and *product* (\$/kJ); $\dot{E}_{F,k}$, $\dot{E}_{P,k}$ exergy flow rates of *fuel* and *product* streams (kW).

To validate the model, the exergoeconomic balance equation for the complete ACAES system was used:

$$\sum_e \dot{C}_e = \sum_i \dot{C}_i + \sum_k \dot{Z}_k \quad (13)$$

The model was verified by ensuring that the balance equation (Eq. 13) was satisfied.

As it is seen from the methodology description above, the exergetic cost (expressed in kJ/kJ or kWh/kWh) and the exergy-based monetary cost (\$/kJ or \$/kWh) have slightly different meanings, despite using similar calculation methods. The exergetic cost represents the amount of exergy required to produce a unit of exergy in a product, such as electricity, heating, or cooling. It is the inverse of exergy efficiency but provides more detailed information about the cost formation process within the energy conversion system. The exergy-based monetary cost represents the monetary value of the exergy stream or product.

To get a better understanding of the cost formation process in the ACAES, additional parameters – the exergy destruction cost rates for each component – were calculated using the following equation:

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \quad (14)$$

Here $\dot{C}_{D,k}$ is the exergy destruction cost rate (\$/s) in the component k, $\dot{E}_{D,k}$ is the exergy destruction rate (kW) for the component k and $c_{F,k}$ is the specific unit exergy cost of *fuel* stream (\$/kJ).

Finally, a relative cost difference, which indicates the change in the cost of exergy, was calculated using the equation:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \quad (15)$$

Here $c_{F,k}$ and $c_{P,k}$ are the specific unit costs of *fuel* and *product* (\$/kJ).

4. Results of exergoeconomic analysis of ACAES systems

4.1. Exergy and exergetic costing analysis

The results of the exergy analysis, particularly the exergy destruction ratios for three different systems: 3-stage, 5-stage and 7-stage ACAES operating at a pressure ratio of 2.42, are presented in Fig. 2. As explained previously, the exergy destruction ratio type I (y_{DI}) shows how much exergy is destroyed in a particular component of the ACAES system compared to the amount of exergy transferred to the system. The exergy destruction ratio type II (y_{DII}) indicates the proportion of exergy destroyed in a particular component compared to the total exergy destroyed.

The graphs (Fig. 2) show that the compressors and expanders have the highest exergy destruction ratios I and II. The exergy destruction ratio I for both compressors and expanders vary between 0.037 and 0.040 for the 3-stage ACAES, between 0.022 and 0.024 for the 5-stage ACAES, and between 0.016 and 0.017 for the 7-stage ACAES. These results indicate that the exergy destruction in individual compression and expansion devices reduces in the systems with more stages at the same isentropic efficiency. However, because more devices are used, the total amount of exergy destruction increases.

The exergy destruction ratio II in the compressors is around 0.134, 0.080, and 0.057 for the 3-stage, 5-stage, and 7-stage systems, respectively. The exergy destruction ratio II in the expanders decreases from approximately 0.147 for all expanders in the 3-stage ACAES to approximately 0.088 in the 5-stage system and 0.062 in the 7-stage system. The exergy destruction ratio II for heat exchangers on the compression side is consistently and significantly higher than those on the expansion (discharging) side for all systems. It changes from 0.047 for the 3-stage system to ~0.029 for the 5-stage systems and ~0.020 for the 7-stage system. The exergy destruction in the heat exchangers on the expansion side remains very low, at approximately 0.006 for the 3-stage system, 0.0045 for the 5-stage system, and 0.003 for the 7-stage system. This difference is due to the choice of temperature regime for the TES system. The maximum temperature of cooling water is allowed to reach 90 °C, while the temperature of air for the basic case (PR = 2.42) can reach 121 °C. During the discharging stage, it is assumed that the water temperature is 90 °C and the air temperature before the expander rises to 86 °C. Due to a small pinch point, the exergy destruction in the heat exchangers during the discharging stage is minimal.

In general, the exergy destruction ratios I and II decrease for all components in 5- and 7-stage ACAES systems, although the overall exergy destruction increases from 837 kW for the 3-stage system to 1399 kW for the 5-stage system (at PR = 2.42) and 1961 kW for the 7-stage system.

A 5-stage ACAES at three different pressure ratios, 2.42, 2.70, and 3.00, were analysed to assess the change of exergy destruction ratio depending on the pressure ratio. The exergy destruction ratio type I values at different system components are shown in Fig. 3. The results show that the exergy destruction ratio for compressors decreases from approximately 0.022 to 0.021 as the pressure ratio increases. A very small change in the exergy destruction ratio is observed for expanders, where it remains almost constant at ~0.024. However, the exergy destruction in the heat exchangers during the compression stage increases from approximately 0.008 to around 0.014, and the exergy destruction ratio in the heat exchangers on the discharging side remains very low, at approximately 0.004, independently of the pressure ratio. This significant change in the exergy destruction ratio in the heat exchangers on the compression side is due to the choice of the cooling water temperature, which is limited to 90 °C, while the air temperature after compression can reach 149 °C for a system at PR = 3.0. Due to the larger temperature difference between the hot air and the cooler water, a greater exergy destruction is obtained in the heat exchangers. Therefore, although the exergy destruction ratio in compressors decreases, the total exergy destruction increases from 1399 kW to 1662 kW and 1936 kW at

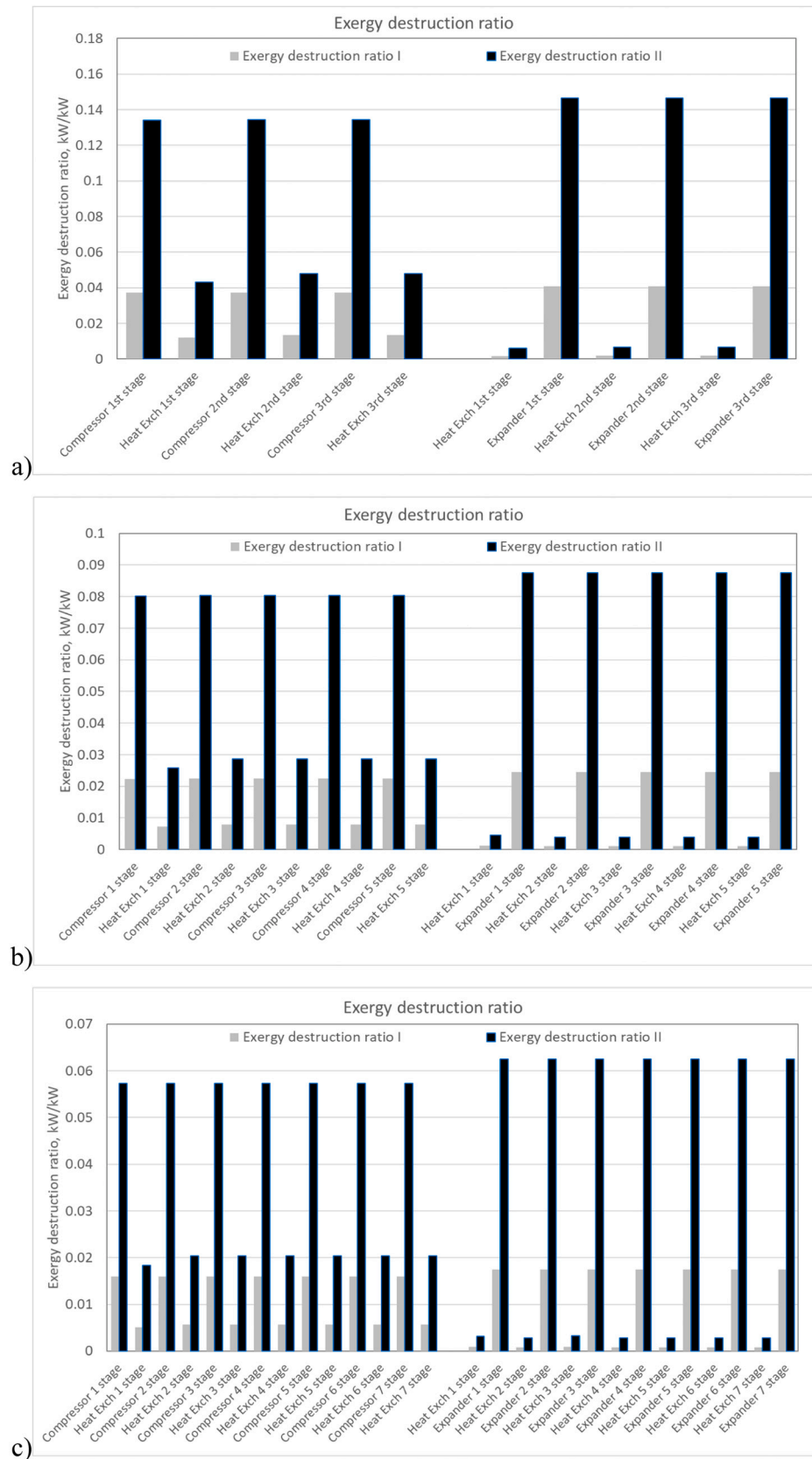


Fig. 2. Exergy destruction ratio (y_{DI} and y_{DII}) in 3, 5 and 7-stage ACAES systems: a) 3-stage ACAES, b) 5-stage ACAES, c) 7-stage ACAES.

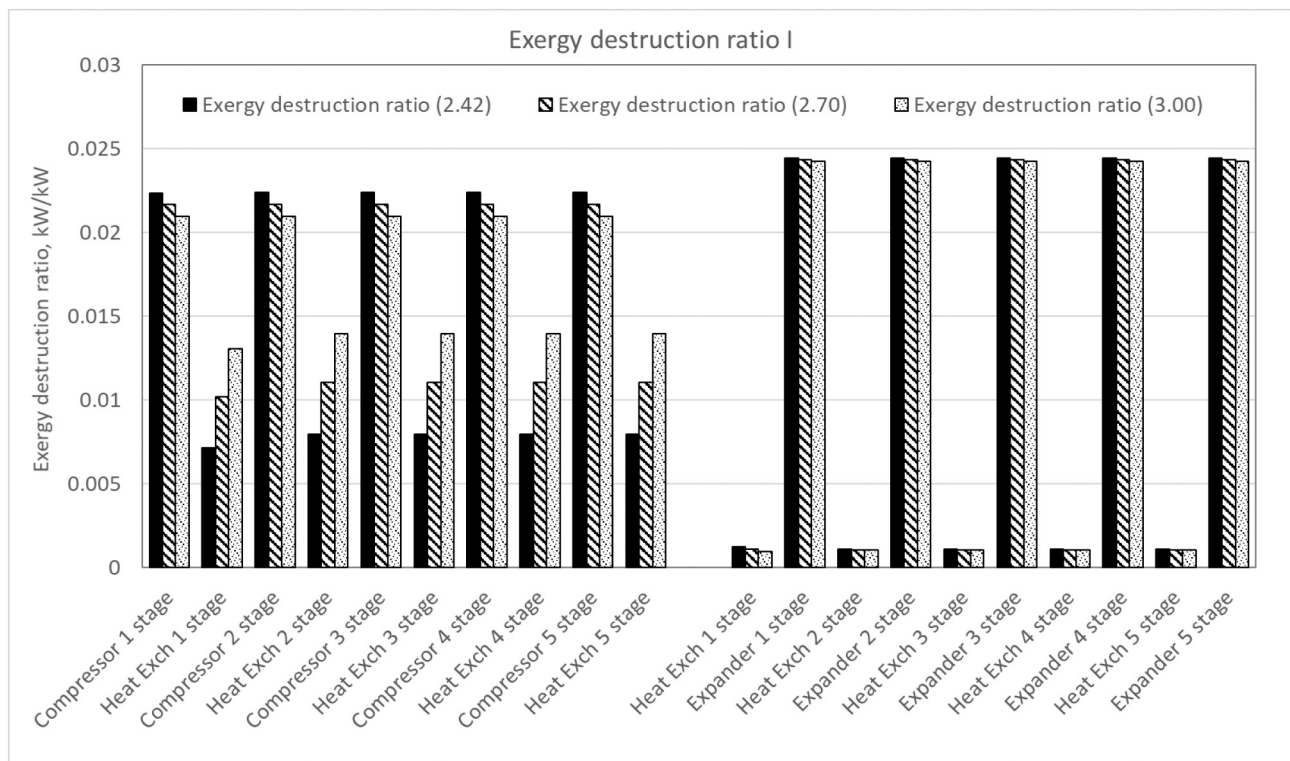


Fig. 3. Exergy destruction ratio type I, y_{DI} , in 5-stage ACAES system at different pressure ratios (PR = 2.42, 2.70 and 3.00).

pressure ratios of 2.42, 2.70, and 3.00, respectively, due to the increased exergy destruction in the heat exchangers. This observation emphasises the importance of carefully selecting temperature regimes when integrating TES and ACAES systems.

The results of the exergetic costing analysis of 3-, 5-, and 7-stage ACAES systems are presented in Fig. 4. It is seen that the cost of

electricity in the first expander is consistently lower compared to other expanders, ranging from approximately 1.35 to 1.37 kWh/kWh for all ACAES systems. The exergetic cost increases in the following expanders. In the 3-stage system, the exergetic cost rises from 1.37 to about 1.56 kWh/kWh. In the 5-stage ACAES, the cost increases from around 1.36 to approximately 1.62 kWh/kWh in the last expander. In the 7-stage

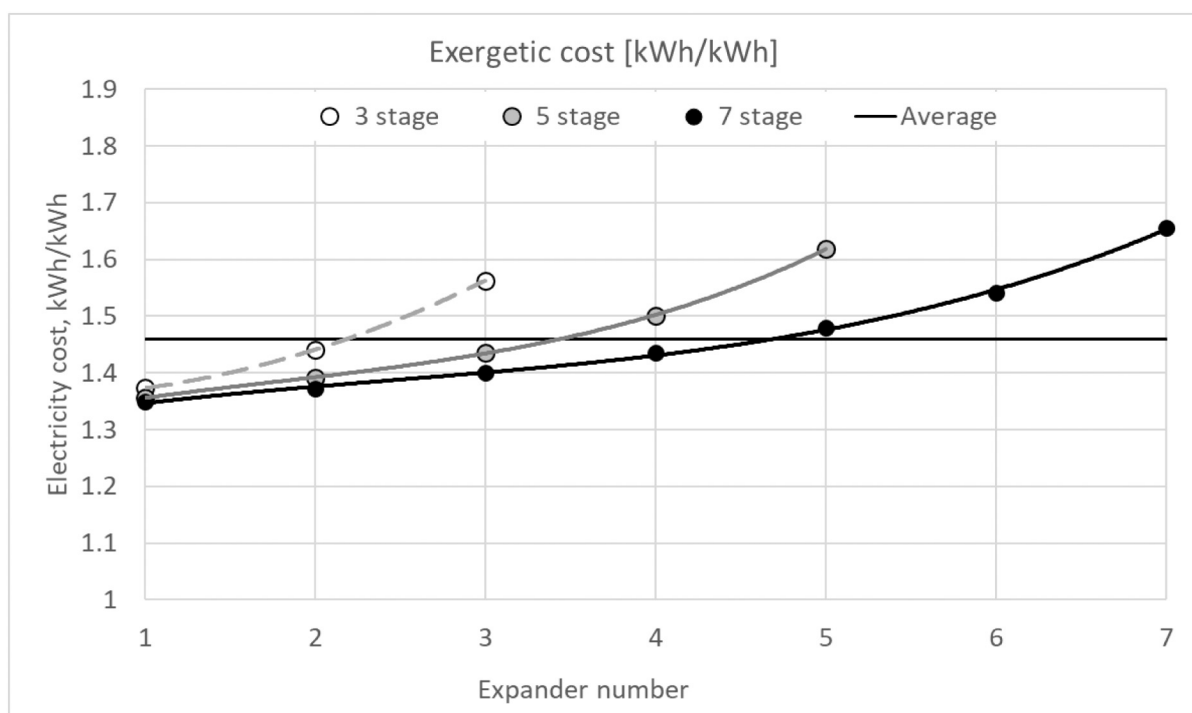


Fig. 4. Exergetic cost of electricity in 3-stage, 5-stage, and 7-stage ACAES (at PR = 2.42) at different expanders. The numbers on the X-axis represent the expander number, starting from the highest-pressure expander (Expander 1, etc.). The horizontal solid line indicates the average exergetic cost for all systems.

system, the cost increases from around 1.35 to about 1.66 kWh/kWh in the last expander. This cost increase is associated with the additional exergy destruction in subsequent expanders.

Even though the exergetic costs at different expanders vary, the average exergetic cost remains nearly identical, indicating that, on average, 1.46 kWh of exergy is required to generate 1 kWh of electricity, regardless of the number of stages and the final pressure of the system. This analysis demonstrates that the exergetic costs of products vary in multistage ACAES systems; therefore, it can be applied to analyse other multistage thermomechanical energy storage systems.

In Fig. 5, the exergetic costs of the 5-stage ACAES system at various pressure ratios (2.42, 2.70, and 3.00) are presented. The figure shows that the exergetic cost for the first expander varies between 1.36 kWh/kWh and 1.38 kWh/kWh for all pressure ratios. As expected, the exergetic cost increases in subsequent expanders, reaching a maximum in the final expander. The average exergetic cost of the 5-stage ACAES system is approximately 1.46 kWh/kWh at a pressure ratio of 2.42, around 1.51 kWh/kWh at a pressure ratio of 2.7, and approximately 1.55 kWh/kWh at a pressure ratio of 3. These results demonstrate that increasing the pressure ratio affects the average exergetic cost differently from what is observed when comparing the 3-, 5-, and 7-stage systems. This increase is attributed to the rise in the exergy destruction ratio in the heat exchangers on the compression side, despite a decrease in the exergy destruction ratio in compressors and expanders (Fig. 3). The reason for that is the choice of temperature regime for the cooling process of compressed air, as explained above.

4.2. Exergy-based monetary costing analysis

Another objective of this study was to conduct an exergy-based monetary costing analysis and to calculate the cost of exergy destruction and the final cost of the products. The costs of exergy destruction and the relative cost difference for 3-, 5-, and 7-stage ACAES are presented in Fig. 6. The results indicate that the cost of exergy destruction in all compressors is approximately \$0.008/s (~\$29/h) for all ACAES

systems. In the expanders, the cost of exergy destruction is higher than in the compressors, increasing after each expansion stage. For the 3-stage ACAES system, the exergy destruction cost in the turbines increases from approximately \$0.011/s (~\$39/h) to \$0.013/s (~\$47/h) in the last expander (Fig. 6a). Similar trends are observed in the 5-stage and 7-stage systems, where the cost of exergy destruction in the compressors remains constant at around 0.008 \$/s. At the same time, in the expanders, it increases from approximately \$0.010/s (~\$36/h) to \$0.013/s (~\$47/h) (Fig. 6b and c).

The cost of exergy destruction in the heat exchangers remains relatively low, at \$0.003/s (~\$11/h) on the charging side and even lower, at \$0.001/s (~\$4/h), on the discharging side for all ACAES systems (Fig. 6). These trends suggest that the compressors and expanders contribute more significantly to the overall cost of exergy destruction, as expected, due to their higher exergy destruction ratio compared to the heat exchangers (see Fig. 2).

The relative cost difference for the compressors in the 3-stage ACAES system decreases from approximately 0.19 in the first compressor to 0.15 in the last compressor, while for all expanders, it remains nearly constant at around 0.20 (Fig. 6a). The relative cost difference for compressors and expanders in the 5-stage and 7-stage ACAES systems follows a similar trend as in the 3-stage ACAES system. In the 5-stage ACAES system, the relative cost difference for the compressors decreases from approximately 0.19 to 0.14 (Fig. 6b), and in the 7-stage ACAES system, it decreases from around 0.19 to 0.13 (Fig. 6c). The relative cost difference remains almost constant for the first three expanders, which operate at higher pressure in both the 5-stage and 7-stage systems. However, a slight increase in the relative cost difference can be observed in the last few expanders, from 0.20 to 0.22 in the 5-stage ACAES system and from 0.20 to 0.26 in the 7-stage ACAES. These results suggest that the increase in product cost within the compressors and expanders is relatively small, even though the cost of exergy destruction is higher compared to that in the heat exchangers.

A significantly higher relative cost difference is observed for the heat exchangers on the charging side for all three ACAES systems. The

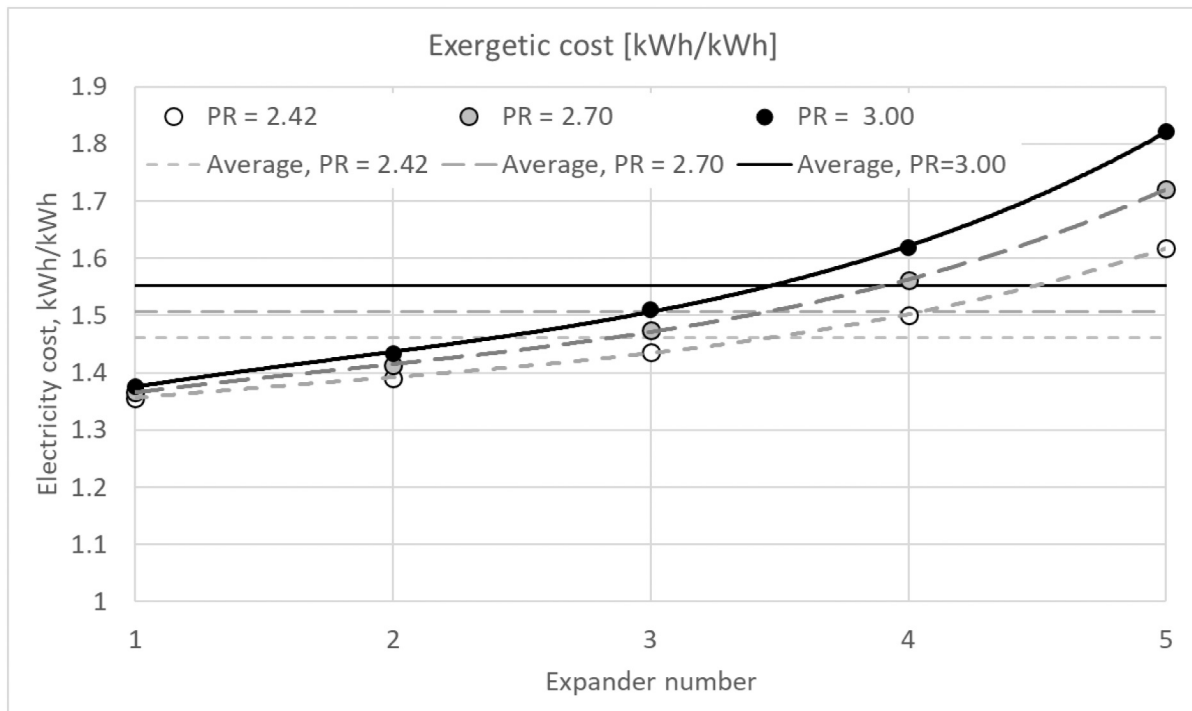


Fig. 5. Exergetic cost of electricity in three different 5-stage ACAES systems at a different pressure ratio (2.42, 2.70 and 3.00) and at different expanders. The numbers on the X-axis represent the expander number, starting from the highest pressure expander (Expander 1, etc.). Solid and dashed horizontal lines indicate the average cost for each pressure ratio.

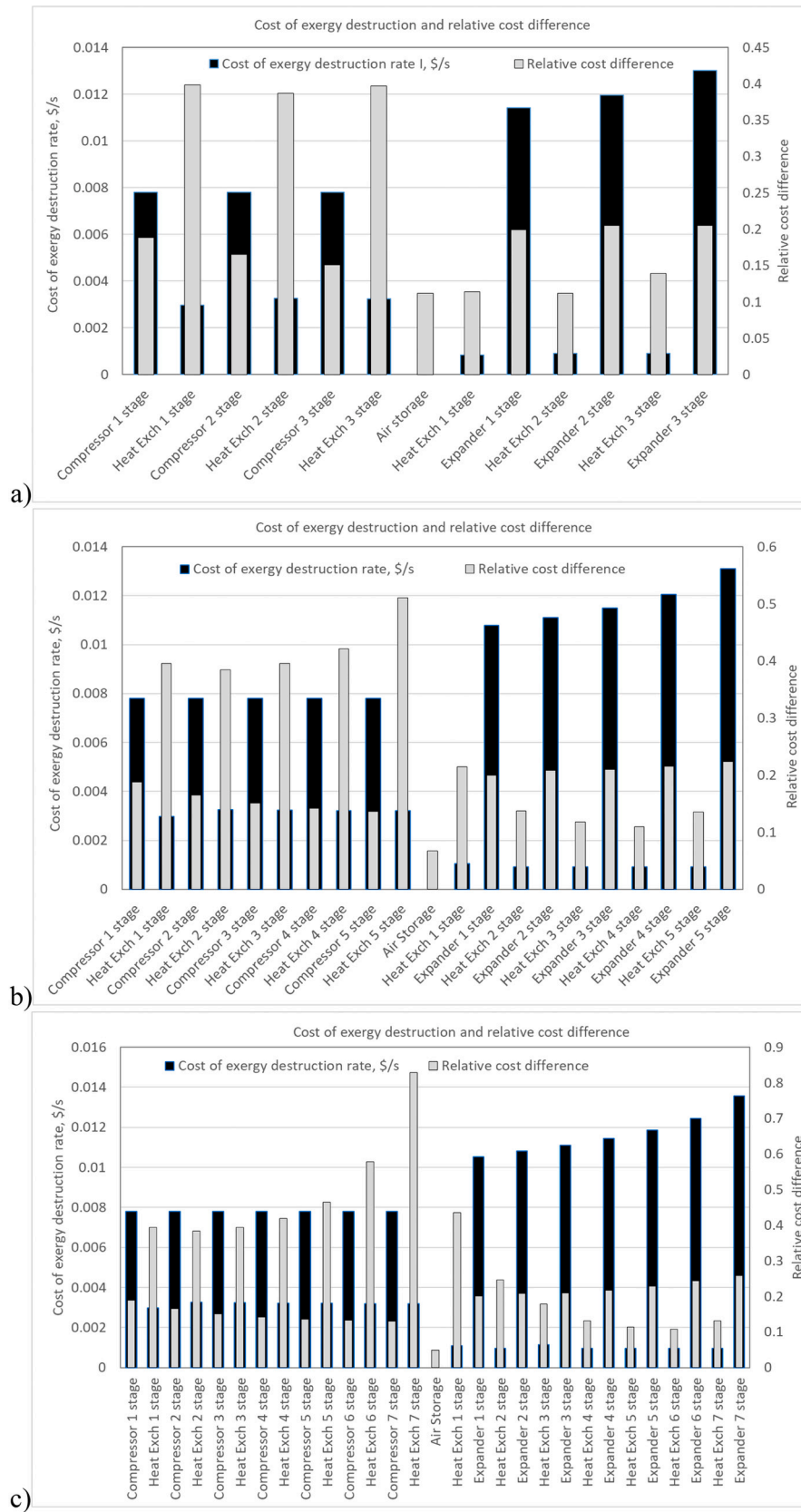


Fig. 6. Cost of exergy destruction and relative cost difference for components in 3, 5 and 7 stage ACAES system: a) 3-stage ACAES, b) 5-stage ACAES, c) 7-stage ACAES.

relative cost difference remains almost constant for the heat exchangers after the first three compression stages, at around 0.39 for all systems (Fig. 6). For the 5-stage ACAES, this value increases to 0.42 for the fourth heat exchanger and 0.51 for the fifth heat exchanger. For the 7-stage ACAES, the relative cost difference for the heat exchangers increases more significantly, from around 0.42 for the fourth heat exchanger to 0.47 for the fifth, 0.58 for the sixth, and 0.83 for the seventh heat exchanger. The primary reason for this change is the increased capital costs associated with heat exchangers designed for high-pressure

operations.

The relative cost difference for the heat exchangers on the discharging side is less than that for those on the compression side. For the 3-stage ACAES, the relative cost difference for heat exchangers ranges from 0.11 to 0.14. For the 5-stage ACAES, this indicator is the highest for the first heat exchanger, which operates at the highest pressure and is equal to 0.21. It decreases in subsequent heat exchangers, reaching a minimum of 0.10 in the fourth heat exchanger. For the 7-stage ACAES, the relative cost difference is the highest in the first heat exchanger at

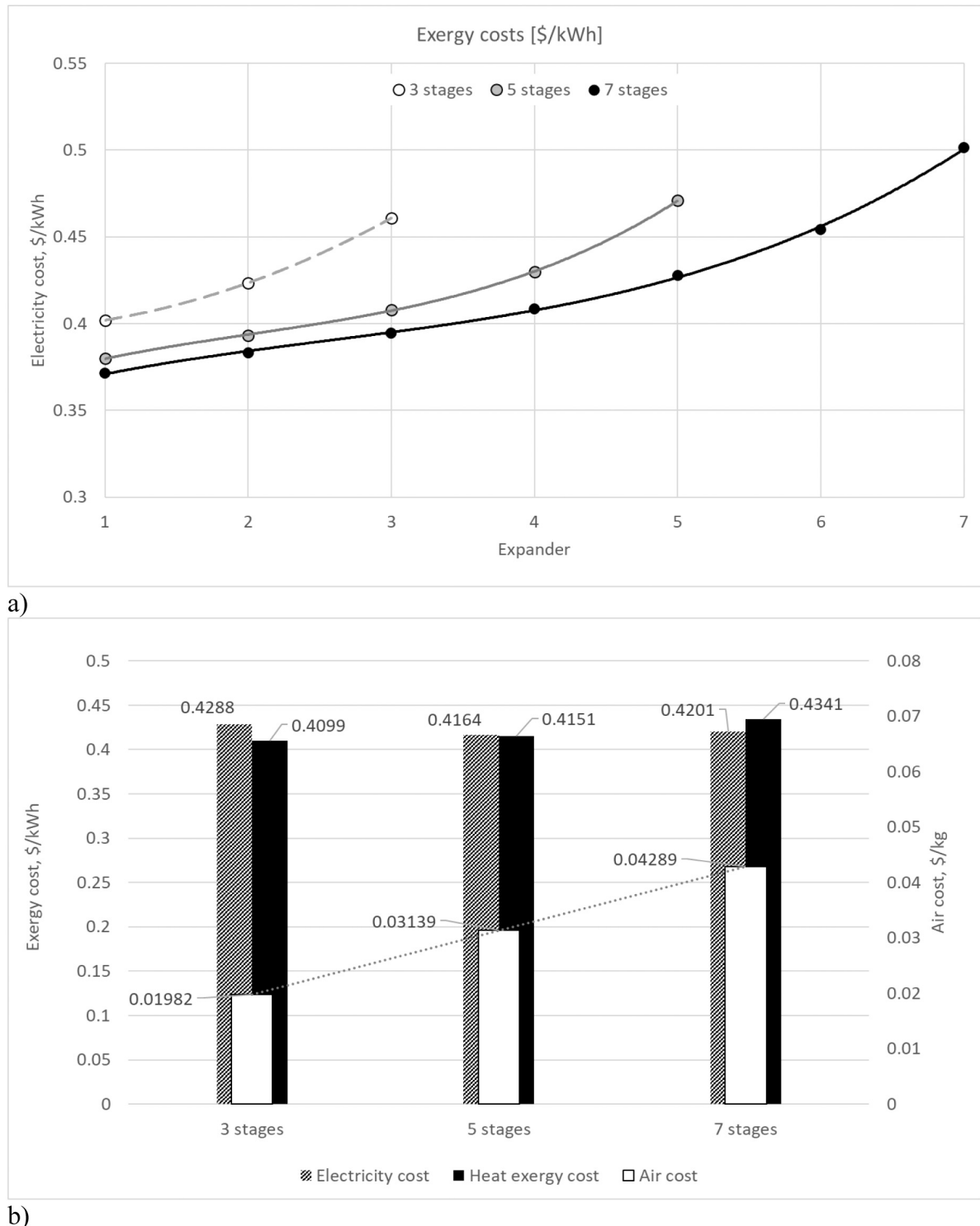


Fig. 7. Exergy costs of products in 3-, 5- and 7-stage ACAES system. a) Electricity cost at different expanders; b) average electricity, heat exergy and air costs.

0.43 and gradually reduces to approximately 0.11 in the sixth heat exchanger and 0.13 in the seventh.

Similar to the heat exchangers on the charging side, the main reason for the high relative cost difference is the high capital cost of heat exchangers that operate at high pressures. The lower relative cost difference observed for the heat exchangers on the discharging side, compared to those on the compression side, can be attributed to the significantly lower exergy destruction ratio in these heat exchangers

(Fig. 2). A lower exergy destruction ratio results in reduced exergy destruction costs and, consequently, a lower relative cost difference. This observation suggests that selecting an appropriate temperature regime for cooling compressed air after compression and heating air before expansion is a crucial step, and the system must be designed to minimise exergy destruction in these components.

The exergy costs of electricity, heat, and air for the 3-stage, 5-stage, and 7-stage ACAES systems are shown in Fig. 7. As seen from the graph,

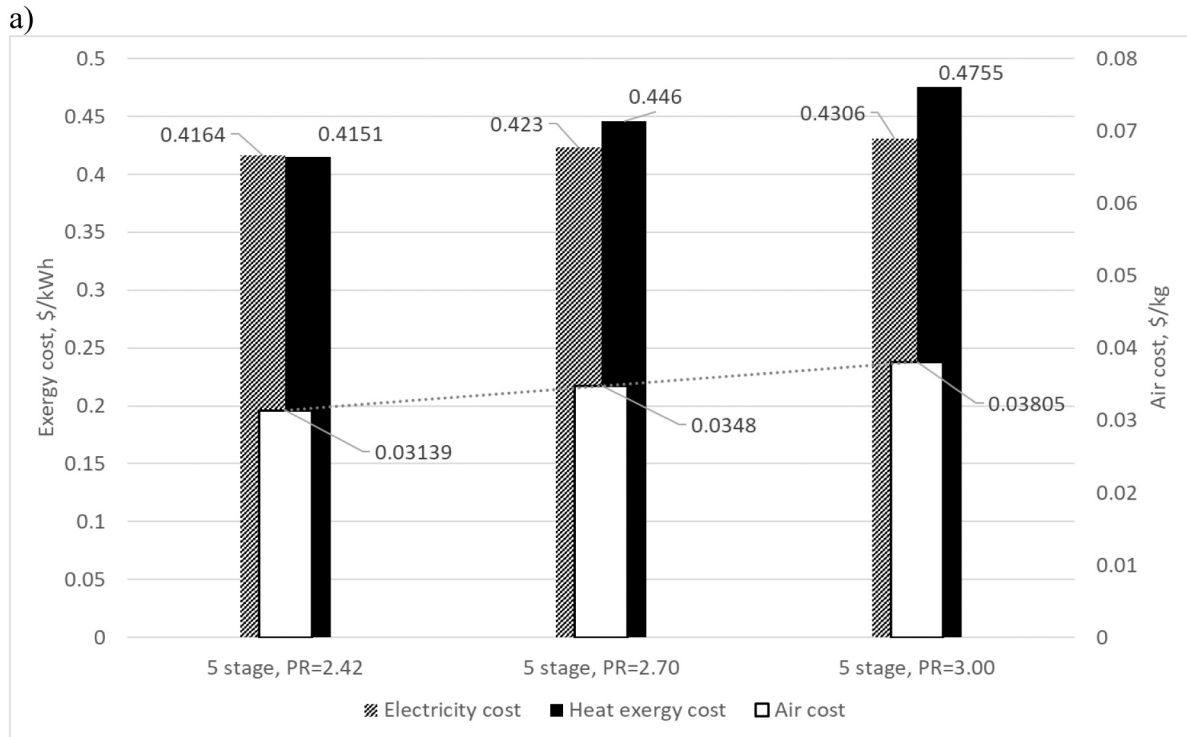
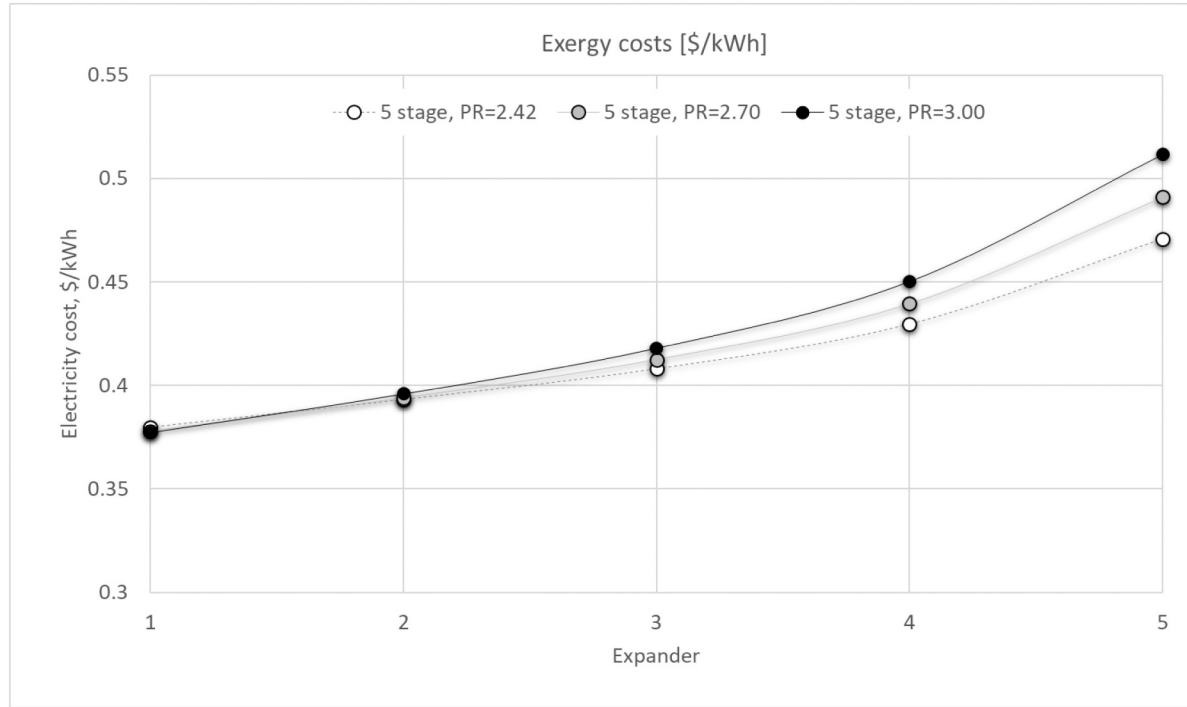


Fig. 8. Exergy costs of products in three different 5-stage ACAES at different pressure ratios (PR = 2.42; 2.70 and 3.00), a) Electricity cost at different expanders; b) Average electricity, heat exergy and air costs.

the electricity cost calculated at the first expander (Fig. 7a), which operates at the highest pressure, is the lowest and increases in the following expanders in all ACAES systems. This trend is consistent with the results of the exergetic costing analysis (Fig. 4). The average electricity cost for the 3-stage system is approximately \$0.4288/kWh. It slightly decreases to \$0.4164/kWh for the 5-stage ACAES and then increases again to \$0.4201/kWh for the 7-stage ACAES (Fig. 7b). This observation is consistent with the exergetic costing analysis results, which indicate that the average exergetic cost (expressed in kWh/kWh) remains constant for the 3-stage, 5-stage, and 7-stage ACAES systems (Fig. 4). The slight variations in exergy-based monetary costs (\$/kWh) are due to the differences in the capital costs of the system components. Although the cost of exergy destruction may remain similar across the different system configurations, the varying capital costs of the components result in slight differences in the final monetary cost of electricity.

The thermal energy stored in TES is not used externally but is utilised only internally. However, it is still worthwhile to assess how the cost of heat exergy changes. As shown in Fig. 7b, the exergy cost of heat increases gradually from approximately \$0.4099/kWh in the 3-stage system to \$0.4151/kWh in the 5-stage system and \$0.4341/kWh in the 7-stage system. A similar trend can be observed for the cost of air. The cost of air is expressed in \$/kg and depends on the amount of exergy contained in 1 kg of compressed air. As expected, the cost of air increases from \$0.0198/kg to \$0.0314/kg and \$0.0429/kg in the 3-stage, 5-stage, and 7-stage systems, respectively, due to the increase in the specific exergy of the compressed air.

The exergy costs of electricity, heat, and air for the three different 5-stage ACAES systems at varying pressure ratios are shown in Fig. 8. As shown in the graph (Fig. 8a), the electricity cost calculated at the first expander, which operates at the highest pressure, is the lowest and increases in the subsequent expanders across all ACAES systems. The average cost of electricity increases from \$0.4164/kWh to \$0.4230/kWh and \$0.4306/kWh in ACAES systems with PR = 2.42, 2.70, and 3.00, respectively (Fig. 8b). It is clear that the electricity cost is higher in the systems with higher pressure ratios, which is consistent with the trend observed in the exergy costing analysis (see Fig. 5). The costs of heat exergy and air also increase, as expected. The cost of heat exergy increases from \$0.4151/kWh to \$0.4460/kWh and \$0.4755/kWh in ACAES systems with PR = 2.42, 2.70, and 3.00, respectively (Fig. 8b). The cost of air increases from \$0.0314/kg to \$0.0348/kg and \$0.0381/kg in ACAES systems with PR = 2.42, 2.70, and 3.00, respectively.

When comparing different ACAES configurations, it is essential to note that the final pressure of the systems does not necessarily result in higher or lower exergy costs of electricity. For example, using the 7-stage ACES, where the highest pressure of 486 bar (at PR = 2.42) is reached, the exergy cost of electricity is \$0.4201/kWh. For the 5-stage ACAES, which reaches a maximum pressure of 143 bar (PR = 2.7) or 243 bar (PR = 3.0), the exergy costs are \$0.4230/kWh and \$0.4306/kWh, respectively, and are higher compared to the 7-stage ACAES.

Similarly, the exergy cost of heat in the 7-stage ACAES system is also lower (\$0.4341/kWh) than that of the 5-stage system at larger pressure ratios: \$0.4460/kWh for PR = 2.70 and \$0.4755/kWh for PR = 3.00. The main reason for the cost difference is due to the isentropic efficiencies of the turbomachinery and the design of the heating and cooling processes. The larger temperature difference between hot compressed air and cooling water results in higher exergy destruction costs in the heat exchanger and, consequently, in higher exergy costs of products.

5. Conclusion

In this study, an exergy and exergoeconomic analysis of 3-stage, 5-stage, and 7-stage ACAES systems, as well as three 5-stage ACAES configurations operating at different pressure ratios was conducted. The main objectives of the study were to analyse the exergy destruction process in the system components, evaluate the costs of exergy

destruction, and investigate the exergetic and exergy-based monetary cost formation processes. The secondary objective was to demonstrate the capabilities of exergoeconomic analysis methods for analysing energy storage systems. The Specific Exergy Costing (SPECO) method was used to examine the exergy cost formation process and calculate the final exergetic and exergy-based monetary costs of the products. The main findings and observations are provided below.

1. The exergetic and exergy-based monetary costs of electricity are the lowest at the first expander and increase at each following expander. This is because the exergy destruction increases at each subsequent expander and heat exchanger, resulting in a higher exergy cost as the air expands in each stage.
2. The exergetic costing analysis reveals that for the chosen configurations of ACAES systems, exergy destruction primarily occurs during the compression and expansion processes and remains relatively small in the heat exchangers on the expansion side for the 3-stage, 5-stage, and 7-stage ACAES configurations (PR = 2.42). Similar trends are observed for the 5-stage ACAES systems at different pressure ratios. However, due to the increase of exergy destruction in the heat exchangers on the compression side in the 5-stage ACAES systems at higher pressure ratios (2.70 and 3.00), the final exergetic cost of electricity increases, emphasising the importance of carefully designing the thermal management system in ACAES systems.
3. The exergy-based monetary cost analysis reveals similar trends to those observed in the exergetic cost analysis, although slight differences could be noticed. The exergy-based monetary costs of electricity for the 3-stage, 5-stage, and 7-stage ACAES configurations are not constant and vary due to the different capital costs of the components. Additionally, the exergy costs of electricity in the 5-stage ACAES system at higher pressure ratios (2.70 and 3.00) are higher compared to the 7-stage ACAES system at a pressure ratio of 2.42, despite the final pressure of the system being significantly lower. This indicates that the costs of the products depend more on the system design, specifically the thermal management of the system, than on the final pressure of the ACAES system.

The second important objective of the study was to demonstrate the feasibility of the exergoeconomic analysis method for analysing energy conversion and energy storage systems. The results demonstrate that using the exergoeconomic analysis, more detailed information about the costs of exergy destruction and the final costs of the products is obtained. Therefore, the exergoeconomic analysis should receive more attention when evaluating the performance of energy storage systems, as it facilitates more informed system design decisions.

CRedit authorship contribution statement

Audrius Bagdanavicius: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft. **Abdullah Masoud Ali:** Conceptualization, Investigation, Writing – original draft. **Edward R. Barbour:** Funding acquisition, Project administration, Writing – review & editing. **Maury Martins de Oliveira Junior:** Writing – review & editing. **Daniel L. Pottie:** Writing – review & editing. **Seamus Garvey:** Funding acquisition, Project administration, Writing – review & editing. **Zahra Baniamerian:** Investigation, Writing – review & editing. **Edward Hough:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Audrius Bagdanavicius reports financial support was provided by Engineering and Physical Sciences Research Council. If there are other authors, they declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- [1] G. Tsatsaronis, Combination of Exergetic and Economic Analysis in Energy-Conversion Processes, in: *Energy Economics and Management in Industry*, Proceedings of the European Congress, Pergamon Press, Oxford, England: Algarve, Portugal, 1984, pp. 151–157. April 2–5.
- [2] G. Tsatsaronis, Thermoeconomic analysis and optimization of energy systems, *Prog. Energy Combust. Sci.* 19 (1993) 227–257.
- [3] O. Arslan, A.E. Arslan, I. Kurtbas, Exergoeconomic and exergoenvironmental based multi-criteria optimization of a new geothermal district heating system integrated with thermal energy storage driven heat pump, *J. Build. Eng.* 73 (2023) 106733.
- [4] A. Abusoglu, M. Kanoglu, Exergoeconomic analysis and optimization of combined heat and power production: A review, *Renew. Sust. Energ. Rev.* 13 (9) (2009) 2295–2308.
- [5] A.H. Mosaffa, L.G. Farshi, Exergoeconomic and environmental analyses of an air conditioning system using thermal energy storage, *Appl. Energy* 162 (2016) 515–526.
- [6] O. Arslan, A.E. Arslan, I. Kurtbas, *Exergoeconomic and exergoenvironmental based multi-criteria optimization of a new geothermal district heating system integrated with thermal energy storage driven heat pump*. *Journal of building, Engineering* (2023) 73.
- [7] S.A. Makkeh, et al., Energy, exergy and exergoeconomic optimization of a cogeneration system integrated with parabolic trough collector-wind turbine with desalination, *J. Clean. Prod.* 273 (2020).
- [8] P. Jiang, et al., Thermodynamic, exergoeconomic, and economic analyses with multi-objective optimization of a novel liquid air energy storage coupled with an off-shore wind farm, *Sustain. Cities Soc.* 90 (2023) 104353.
- [9] H. Montazerinejad, P. Ahmadi, Z. Montazerinejad, Advanced exergy, exergoeconomic and exergoenvironmental analyses of a solar based trigeneration energy system, *Appl. Therm. Eng.* 152 (2019) 666–685.
- [10] G. Tsatsaronis, M.-H. Park, On avoidable and unavoidable exergy destructions and investment costs in thermal systems, *Energy Convers. Manag.* 43 (9) (2002) 1259–1270.
- [11] F. Petrakopoulou, G. Tsatsaronis, T. Morosuk, Evaluation of a power plant with chemical looping combustion using an advanced exergoeconomic analysis, *Sustain. Energy Technol. Assess.* 3 (2013) 9–16.
- [12] A. Gungor, et al., Advanced exergoeconomic analysis of a gas engine heat pump (GEHP) for food drying processes, *Energy Convers. Manag.* 91 (2015) 132–139.
- [13] T. Morosuk, G. Tsatsaronis, Advanced exergy-based methods used to understand and improve energy-conversion systems, *Energy* 169 (2019) 238–246.
- [14] F. Buffa, et al., Exergy and Exergoeconomic model of a ground-based CAES Plant for Peak-Load Energy Production, *Energies* 6 (2) (2013) 1050–1067.
- [15] A. Bagdanavicius, N. Jenkins, Exergy and exergoeconomic analysis of a compressed air energy storage combined with a district energy system, *Energy Convers. Manag.* 77 (2014) 432–440.
- [16] E. Yao, et al., Multi-objective optimization and exergoeconomic analysis of a combined cooling, heating and power based compressed air energy storage system, *Energy Convers. Manag.* 138 (2017) 199–209.
- [17] M.H. Nabat, et al., An investigation and multi-criteria optimization of an innovative compressed air energy storage, *J. Energy Storage* (2024) 76.
- [18] S.M. Alirahmi, et al., Process design, integration, and optimization of a novel compressed air energy storage for the coproduction of electricity, cooling, and water, *Renew. Sust. Energ. Rev.* 189 (2024) 114034.
- [19] M.C. Bushehri, et al., A comprehensive study of a green hybrid multi-generation compressed air energy storage (CAES) system for sustainable cities: Energy, exergy, economic, exergoeconomic, and advanced exergy analysis, *Sustain. Cities Soc.* 101 (2024).
- [20] A.R. Razmi, M. Janbaz, Exergoeconomic assessment with reliability consideration of a green cogeneration system based on compressed air energy storage (CAES), *Energy Convers. Manag.* 204 (2020) 112320.
- [21] F. Esmailion, et al., Exergoeconomic assessment of a high-efficiency compressed air energy storage system, *Renew. Sust. Energ. Rev.* 191 (2024) 114143.
- [22] Z. Baniamerian, et al., How pressure affects costs of power conversion machinery in compressed air energy storage; part I: Compressors and expanders, *J. Energy Storage* (2024) 89.
- [23] Z. Baniamerian, et al., How pressure affects costs of power conversion machinery in compressed air energy storage; part II: Heat exchangers, *J. Energy Storage* (2024) 86.
- [24] D. Pottier, et al., Comparative analysis of isochoric and isobaric adiabatic compressed air energy storage, *Energies* 16 (6) (2023).
- [25] Cycle-Tempo Release 5, Delft University of Technology, 1980–2007.
- [26] A. Bejan, G. Tsatsaronis, M. Moran, *Thermal Design, Optimization*, New, York: A Wiley-Interscience Publication. 542 (1996).
- [27] A. Lazzaretto, G. Tsatsaronis, SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems, *Energy* 31 (2006) 1257–1289.
- [28] Large-Scale Electricity Storage, The Royal Society, 2023, p. 99.
- [29] Hydrogen TCP-Task 42, Underground Hydrogen Storage: Technology Monitor Report, 2023, p. 153.
- [30] A.S. Lord, P.H. Kobos, D.J. Borns, Geologic storage of hydrogen: Scaling up to meet city transportation demands, *Int. J. Hydrog. Energy* 39 (28) (2014) 15570–15582.
- [31] Achieving the Promise of Low-Cost Long Duration Energy Storage, US Department of Energy, 2024, p. 50.
- [32] A. Bagdanavicius, N. Jenkins, G.P. Hammond, Assessment of community energy supply systems using energy, exergy and exergoeconomic analysis, *Energy* 45 (1) (2012) 247–255.