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Improvements perspectives of cryogenics-based energy storage

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Abstract. Advanced exergy-based analyses provide the information for potential of improvement of energy-conversion systems from exergetic, economic and environmental point of view. These analyses are applied to Cryogenic-based Energy Storage (CES) also known as Liquid Air Energy Storage (LAES). Advantages such as (a) lack of geographical restrictions, (b) low environmental impact and the fact that it is (c) based on mature technology, drive further the research on this energy storage system. An adiabatic LAES system charged with Heylandt liquefaction of air process is analysed. Parameters such as exergy destruction, investment cost, cost associated with the exergy destruction, as well as the environmental impact associated with the thermodynamic irreversibilities are split into avoidable/unavoidable and endogenous/exogenous parts. Aspen Plus® software was used to simulate the LAES system and Engineering Equation Solver was used to conduct the conventional and advanced exergy-based analyses. The dependence of the improvement of each component with the rest of the system was found and all components present higher exogenous exergy destruction than endogenous. The component with the highest potential for improvement is the main heat exchanger in the discharge unit. Focusing on improvement of the components that were found to be the most inefficient ones with the highest exergy destruction, CES is expected to become thermodynamically and economically feasible.

1 Introduction

In the past years, especially since the Paris Agreement at the 21st Conference of the Parties of the UNFCC, 195 countries have signed the agreement to keep the increase in global average temperature below 2 °C according to the pre-industrial levels and also to limit the increase to 1.5 °C.

The rapid increase of renewables technologies such as wind and solar power integrated to the power grid is therefore promoted by many countries. Increasing interest in energy storage systems that do not endanger the power network stability while introducing fluctuating renewable energies to the grid are of great importance and are being rapidly developed. The share of renewable energy worldwide is supposed to reach 12.4 % in 2023 in all sectors combined [1].

This paper discusses a feasible solution: Cryogenic-based Energy Storage, currently at precommercial state and still under development with a Technology Readiness Level of 8 (TRL=9 is the maximum) [5]. Contrary as the two most common and commercial large-scale energy storage technologies; Pumped Hydro Systems (PHS) and Compressed Air Energy Storage systems (CAES), CES does not present any geographical limitations and can be constructed much faster [2,3]. Efficiencies reported until now are promising for LAES, but the criteria where CES outstands the most is the considerably higher energy density than PHS and CAES.

The operation of the system consists in three units: charge, storage and discharge. The charging unit liquefies air when excess electricity is available, for this process different and well-proven air configuration systems can be used such as Kapitza, Linde, Heylandt Claude and variations of these configurations. The air is compressed to pressures around 150 bar and further expanded and liquefied [5]. The liquid air is stored at ambient pressure and low temperature of approximately -196 °C in storage vessels like those for liquid natural gas. Finally, the discharge unit can produce electricity when the demand is higher in a Rankine cycle, where the liquid air is re-gasified, superheated and expanded [4].

2 State of the art

In present, two LAES pilot plants exist in the United Kingdom, one research plant at the University of Birmingham of 350 kW/2.5 MWh and one of the private company Highview Power Storage of 2 MW. Currently, a bigger plant of 200 MW is being developed by the same company [4].

Even though, the CES concept was first introduced by the University of Newcastle more than forty years ago and it was first built more than twenty years ago by Mitsubishi Heavy Industries, it is still a relevant topic since considerably improvements were found that made the technology more attractive to investors and researchers. The first LAES pilot plant of 2.6 MW air liquefaction unit and power recovery system operated independently reported a low roundtrip efficiency and decreased the interest in this technology. Later, Hitachi researchers proposed a LAES plant that could reach 70 % round trip efficiency if the integration of air liquefaction unit and power recovery regenerator is considered. Implementing solid materials and liquids as cold carriers in the heat recovery network are the key to reach this efficiency [4]. These results caught the attention of the private company, Highview Power Storage, that decided to work together with the University of Leeds in 2009 to demonstrate the advantages of this technology by building a 350 kW/2.5 MWh LAES system in Slough, Scotland. Two years later the plant became operational and is now in the research institute for CES in the University of Birmingham. The company completed the construction of a 5 MW/15MWh pre-commercial LAES system last year. The enterprise is also planning a 200 MW/1.2 GWh GigaPlant that would prove the large-scale capacity of this system [6]. The costs are estimated to decrease at a learning rate of 17.5 % [7]. The initial investment costs of a first-of-a-kind daily cycling unit are expected to reduce significantly from 880 – 2.580 €2017/kW to 555 – 1.480 €2017/kW when the technology reaches its maturity.

Recently, great potential in cost reduction and efficiency improvement through CES system integration was found [8].

This paper introduces advanced exergy-based methods split into avoidable/unavoidable and endogenous/exogenous to not only identify the limit to thermodynamic and cost improvements, but also to calculate the independency of the components with each other. The environmental impact of CES systems has also not yet been discussed in any of the reviewed literature. This paper aims to identify the economic potential of adiabatic CES systems through revealing the limit – the unavoidable part – of thermodynamic performance, interaction and dependence of results between each component – the endogenous part- and cost-effectiveness with advanced exergy-based methods.

3 Methodology

3.1 Exergy-based analyses

The exergy balance for the overall system can be written as [9]:

$$\dot{E}_{F,tot} = \dot{E}_{p,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot} \tag{1}$$

For the exergoeconomic analysis the cost associated with the exergy destruction is calculated according to [10]:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{2}$$

With help of an economic analysis, the investment cost rate $\dot{Z}_k$ is calculated to proceed with the cost balances and the specific cost per unit of exergy of the streams exiting each component is calculated as [9]:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \tag{3}$$

An exergoenvironmental analysis was also performed considering both exergy analysis and Life Cycle Assessment [11]. An environmental impact rate $\dot{B}_j$ and an environmental impact b are assigned for each exergy stream. The Eco-indicator 99 is used as an environmental indicator assigning Eco-indicator points (Pts) when the categories ecosystem, human health and natural resources are compromised [13]. With this analysis, exergy destruction is related to the environmental impact for each component with the environmental impact per unit of exergy of fuel, $b_{F.k}$, as showed [10]:

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \tag{4}$$

The environmental impact of electricity for low voltage electricity in Europe is 26 mPt/kWh or 7.22 mPt/MJ [14]. Depending on the country where the energy storage system is located this impact may vary. The air entering the air compressors have an associated environmental impact of 0 mPt/MJ.

3.2 Advanced exergy-based analyses

In the advanced exergy analysis the exergy destruction, cost associated with the exergy destruction, environmental impact and the investment cost are split into avoidable and unavoidable parts [12]. The unavoidable part is the part of the exergy destruction that is associated to technical limitations of a component. The exergy destruction can also be split into endogenous and exogenous. Operating at these conditions the system is referred to as the most efficient adiabatic LAES process. The avoidable part can be calculated as:

$$\dot{E}_{D,k}{}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}{}^{UN} \tag{5}$$

Where at a specific designed point, A:

$$\dot{E}_{D,k,A}{}^{UN} = \dot{E}_{P,k,A}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \tag{6}$$

Applying the same approach, the unavoidable investment cost and unavoidable cost rates can be calculated [16].

For the calculation of the endogenous and the exogenous parts of the exergy destruction, the theoretical

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fuel is calculated when the system operates at ideal conditions with no exergy destruction.

$$\dot{E}_{F,tot}^{T} = \dot{E}_{P,tot}^{R=T=constant} + 0 + \dot{E}_{L,tot}^{T} \quad (7)$$

To calculate the endogenous conditions, where all components behave at ideal conditions, except the component under study, hybrid conditions are calculated [12].

$$\dot{E}_{F,tot}^{H} = \dot{E}_{P,tot}^{R=T=H} + \dot{E}_{D,k}^{H} + \dot{E}_{L,tot}^{H} \quad (8)$$

The part from the exergy destruction that is not endogenous is known as exogenous and combination of the avoidable and unavoidable part of the exergy destruction can be obtained through the term $\dot{E}_{D,k}^{UN,EN}$ [15].

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN} \times (\frac{E_{D,k}}{E_{P,k}})^{UN} \quad (9)$$

4 Simulation

The simulated process consists of a Heylandt process to liquefy the air in the charging process and a Rankine cycle for the discharge process. The detailed simulation results were reported in [8]. Figure 1 shows the flow diagram of the evaluated system. This configuration was simulated using Aspen Plus® software.

Table 1 shows the values for the design parameters of the components at a (a) real, (b) optimal and (c) worst adiabatic liquid air energy storage system simulation process.

Detailed simulation for the advanced analysis was performed on component level for the three conditions mentioned above.

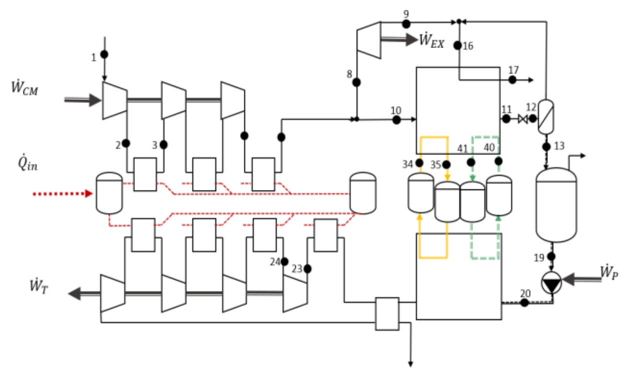

Fig. 1. Flow diagram of the adiabatic CES system

Table 1. Parameters for the real, unavoidable exergy destruction and unavoidable investment cost conditions

Component		**Real**	$\dot{E}_{D,k.A}^{UN}$	$\dot{Z}_{k.A}^{UN}$
Compressors	η (%)	85	90	70
Expander	η (%)	84	88	60
Turbines	η (%)	90	92	70
Pump	η (%)	75	80	65
Main HE 1	ΔT (K)	3.6	0.5	10
Main HE 2	ΔT (K)	4.8	0.5	10
Re-heaters	ΔT (K)	3	1	15
Intercoolers	ΔT (K)	3	1	15
Flasher	p (bar)	1.1	1.2	1.014

5 Results

Figure 2 shows the results obtained from the advanced exergy analysis. The compressors are the components with the highest share of the exergy destruction within the system. The only component with a higher avoidable than unavoidable exergy destruction is the main heat exchanger in the discharge unit, more than 60 % of the exergy destruction could be avoided if the component operates with a lower minimum temperature difference.

60 % of the exergy destruction within the compressors and 70 % of the exergy destruction within the turbines is unavoidable 95 % of the exergy destruction of the re-heaters in the discharge unit is unavoidable, representing the components with the highest percentage of unavoidable exergy destruction.

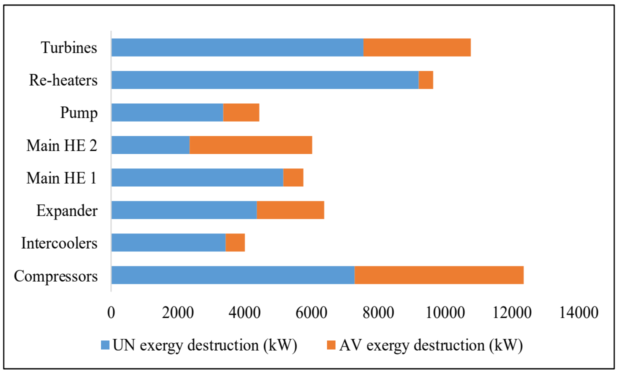

Fig. 2. Exergy destruction of every component divided by avoidable and unavoidable parts

Figure 3 represents the further split into endogenous and exogenous part for the exergy destruction. For all components, the avoidable exogenous exergy destruction is higher than the avoidable endogenous exergy destruction. In order to reduce the exergy destruction within a component the remaining components must be improved. For instance, to reduce the exergy destruction within the main heat exchanger in the discharge unit, the remaining components must be improved as well, since they are highly dependent from each other.

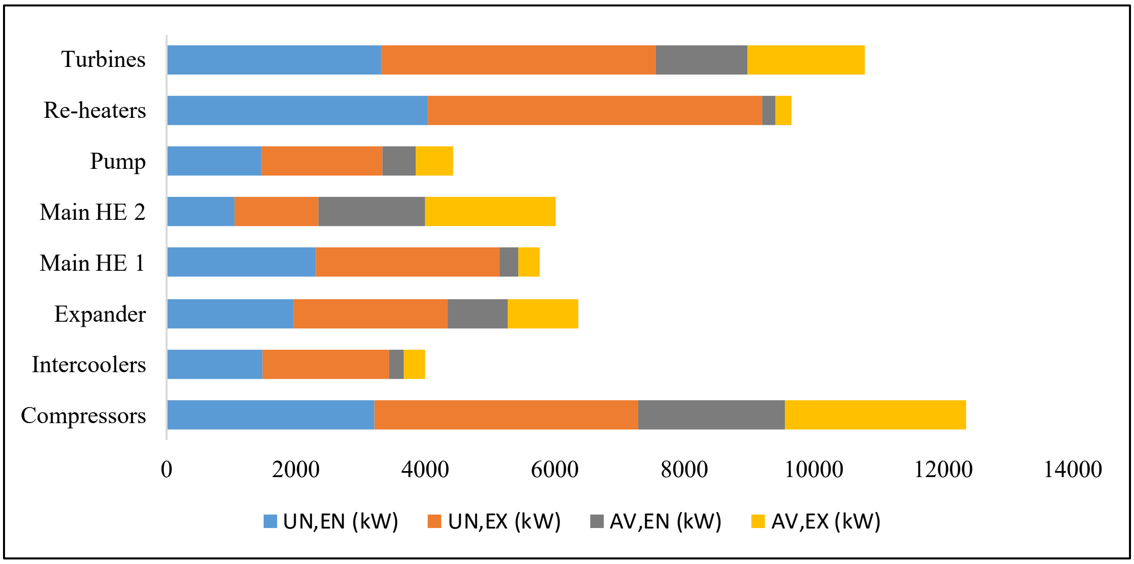

Fig. 1. Split of avoidable/unavoidable and endogenous/exogenous exergy destruction

Table 2 summarizes the values of the unavoidable and avoidable investment costs within the components with the highest avoidable investment cost in the LAES system under study. For the turbomachinery 80 % of unavoidable exergy destruction was consider and for the heat exchangers equations cost (previously published and discussed in detail in [6]) were used to calculate the new investment cost in the conditions of worst performance [8]. The component with the highest possibility for improvement is the re-heater 6, since 40 % of its investment cost could be avoided if the heat exchanger operates with a minimum temperature approach of 15 K and not 3 K.

Table 2. Splitting the investment cost into avoidable and unavoidable for the LAES system

Component	$\dot{Z}_{k,A}{}^{R}$ (€/h)	$\dot{Z}_{k,A}{}^{UN}$ (€/h)	$\dot{Z}_{k,A}{}^{AV}$ (€/h)	$\dot{Z}_{k,A}{}^{AV}$ (%)
Main heat exchanger 2	2621	1960	661	25
Turbine 1	975	780	195	20
Turbine 2	955	764	191	20
Turbine 3	949	759	190	20
Turbine 4	948	758	190	20
Cryogenic pump	844	675	169	20
Main heat exchanger 1	772	712	61	8
Re-heater 6	233	139	94	40

The turbines represent the highest share of total cost of exergy destruction within the system for its elevated cost, as shown in Figure 4. By increasing the efficiency of the turbines 2 %-point (from 90 % to 92 %), the cost associated with the exergy destruction for these components can be reduced by 30 %. The most relevant component is main heat exchanger 2 in the discharge unit, which has 60 % of avoidable cost of exergy destruction. However, this component operates at cryogenic temperatures and a more efficient component would be significantly expensive. The intercoolers and reheaters operate at quasi optimal conditions, because almost all cost of exergy destruction is unavoidable.

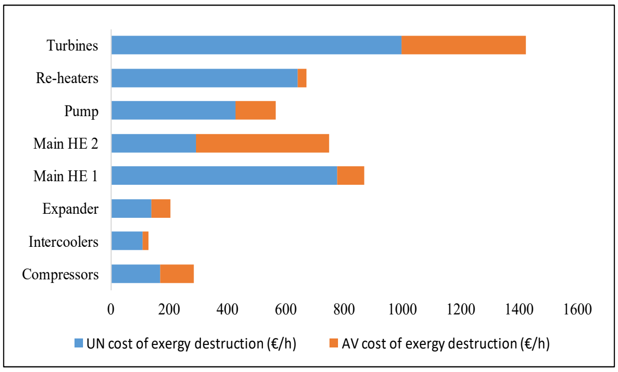

Fig. 2. Distribution of the avoidable and unavoidable cost of exergy destruction

The sum $(\dot{Z}_k + \dot{C}_{D,k})$ and its distribution between avoidable and unavoidable parts is presented in Figure 5. The main heat exchangers and the turbines play an important role because of their high cost.

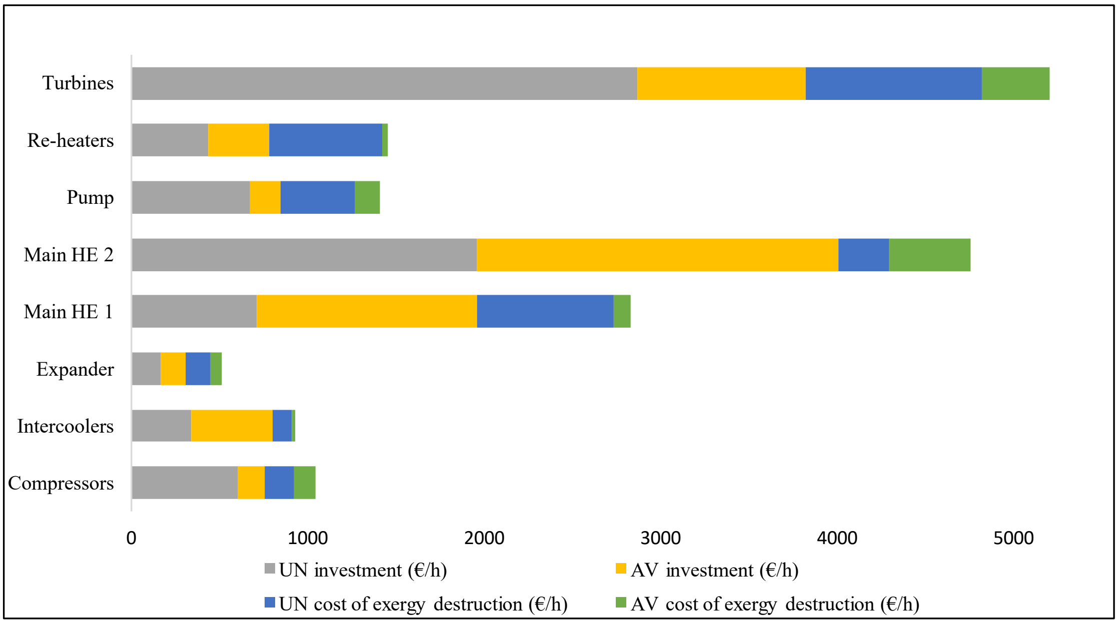

Fig. 3. Division of the sum of investment cost and cost of exergy destruction into avoidable and unavoidable parts ($\dot{Z}_{k,} + \dot{C}_{D,k,}$)

Within the exergoenvironmental analysis, the environmental impact due to the exergy destruction of each component was calculated. Operating at the best performance conditions, the system has an environmental impact of 66 % (calculated using Eco-Indicator 99), that cannot be avoided. Nevertheless, some components such as the compressors have 43 % of avoidable exergoenvironmental impact. The component that has the highest avoidable environmental impact is main heat exchanger in the discharge unit, it has 58 % of avoidable exergoenvironmental impact. Figure 6 represents the distribution between avoidable and unavoidable exergoenvironmental impact due to the exergy destruction in each component. The turbomachinery has a high share in the total environmental impact of the LAES system, as well as the reheaters.

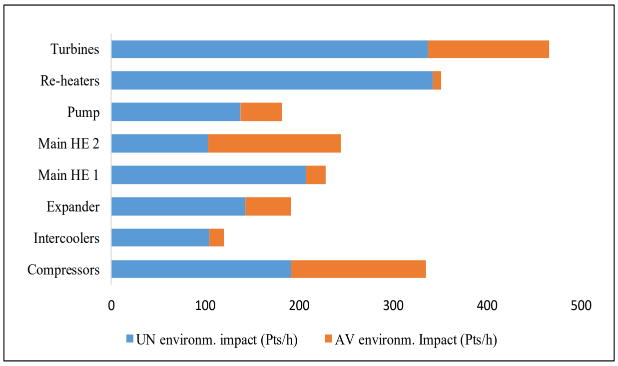

Fig. 4. Avoidable and unavoidable environmental impact associated with exergy destruction

6 Conclusions

1. 59-70% of the exergy destruction in the turbomachinery is unavoidable with exception of the cryogen pump (40 %).
2. The component with the highest possibility for improvement in performance and cost is the main heat exchanger 2 in the discharge unit.
3. The improvement of the isentropic efficiency in the turbomachinery avoids 30-41 % of the cost of exergy destruction in the respective component.
4. The total LAES system could prevent 34 % of its environmental impact due to avoidable exergy destruction. Main contributors are the turbines and compressors.
5. Exogenous exergy destruction is higher than endogenous for all components.
6. The exergy destruction of any of the components can be reduced by improving the remaining components.

Nomenclature

b	specific environmental impact, Pts/kJ
B	environmental impact rate, Pts/h
c	specific cost, $/kW
C	cost rate, $/h
E	exergy, kWh
p	pressure, bar
T	temperature, K
CAES	Compressed Air Energy Storage
CES	Cryogenic-based Energy Storage
HE	heat exchanger
LAES	Liquid Air Energy Storage
Pump	cryogenic pump
PHS	Pumped Hydro Storage
Z	investment cost

Greek symbols

ε	exergetic efficiency, %
η	isentropic efficiency, %
Δ	Difference

Subscripts and superscripts

·	time rate
AV	avoidable
D	destruction
EN	endogenous
EX	exogenous
F	fuel
H	hybrid
k	refers to a component
L	losses
P	product
R	real
T	theoretical
tot	total
UN	unavoidable

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