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EXERGY AND EXERGOECONOMIC MODEL OF A LIQUID AIR ENERGY STORAGE SYSTEM

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ABSTRACT

Liquid Air Energy Storage (LAES) represents an attractive option for developing large-scale electricity storage systems. The system can achieve a competitive round-trip efficiency (over 50%), and its operation can be quick and adaptable to rapidly changing loads (also providing frequency control and substituting current fossil-based solutions).
A LAES system already proposed is adapted to provide daily peakload support (15 MWh) to grids relying heavily on photovoltaic RES; the model analyzes in detail the exergy destruction with specific reference to heat transfer irreversibilities, which are crucial for cryogenic applications. The analysis is complemented by exergoeconomics using validated cost correlations, allowing for the determination of the progressive cost buildup per unit exergy. An input-output economic analysis is applied to calculate the cost of electricity to be released in the evening, using PV electricity available in high-radiation hours at an assumed cost of 0.1 €/kWh. Considering a 2-hour peakload operation, a cryogenic storage of about 120 m^3 of liquid air allows covering 15 MWh of peakload power with a round-trip efficiency η_{RT} = 0.558, at a cost of 0.44 €/kWh.

1 INTRODUCTION

Liquid Air Energy Storage represents an attractive energy storage technology with features complementary to the use of batteries, with specific reference to large units (grid applications, or support to large RES microgrids) (Legrand et al., 2019; Ding et al., 2025; Damak et al., 2020). The technology has been demonstrated at pilot scale (Morgan et al., 2015), achieving a limited round-trip efficiency because of the small demonstration size (about 250 kW). LAES systems are attractive for several features: the power density is high compared to other means for storing electricity, long-term storage is possible, and the system can be placed into operation very rapidly so that it can effectively support variable RESs and grid stabilization. The main shortcomings of LAES have been identified by the required large scale to be competitive with other storage technologies for electricity.
The suitability of LAES to be applied in Mediterranean climates has been largely disregarded. In southern countries (Italy, France, Spain, Greece, and the emerging African countries), the main resource for RES is provided by photovoltaics, which have become widely applied (over 40 GW peak potential in Italy). The predictability of local solar radiation is today excellent over the 2-3 day time period, which is necessary to plan a good grid power supply forecast matching as far as possible productivity and load. Today, in most countries, the peakload (often occurring in summer at the evening, because of the large use of air conditioning units) is covered by fossil fuels, which are becoming expensive and are not compatible with modern environmental policies approved in all EU countries. Indeed, the cost of electricity in the evening is today over twice the cost at noon when PV systems are largely feeding the grid. The main alternative to using fossil fuels for peakload management is represented by the introduction of electricity storage. Both large and small, distributed storage solutions are becoming popular – most of them relying on the use of batteries (which represent a problem from several points of view – from the capability of quick intervention to end-of-life and use of critical materials). A LAES

system with a relatively small cryo tank but large power units (turbines for the production mode, usually 2 h or shorter; and compressors for the accumulation mode, typically 4 to 8 hours depending on the month) can represent an attractive solution, whose performance in terms of roundtrip and system/component efficiency, as well as for economics, deserves to be investigated.

2 REFERENCE CASE

The reference case is a well-documented plant proposed originally by Guizzi et al. (2015). A marginally adapted schematic is included as Figure 1. In this last, both circuits needed for (A) accumulation (left) and (B) Production are represented The system proposed relies on two sensible cold storage loops: a first one using Methanol (15°C/-59.2°C); and a second one using Propane (-59.2°C/-180°C). The heat recovered from the two-staged compression is stored in a sensible heat storage (Essotherm 656; 15°C/353°C). A cryogenic expander provides the final cooling leading to partial separation of O_2 and N_2 in the stream (Points 8-9-10). Liquid air is produced (stream 9) and stored in the LAES storage. The separator stream (10-12) is poor in Oxygen and is recycled to the compressor inlet, mixing with air taken from the environment (Point 0).

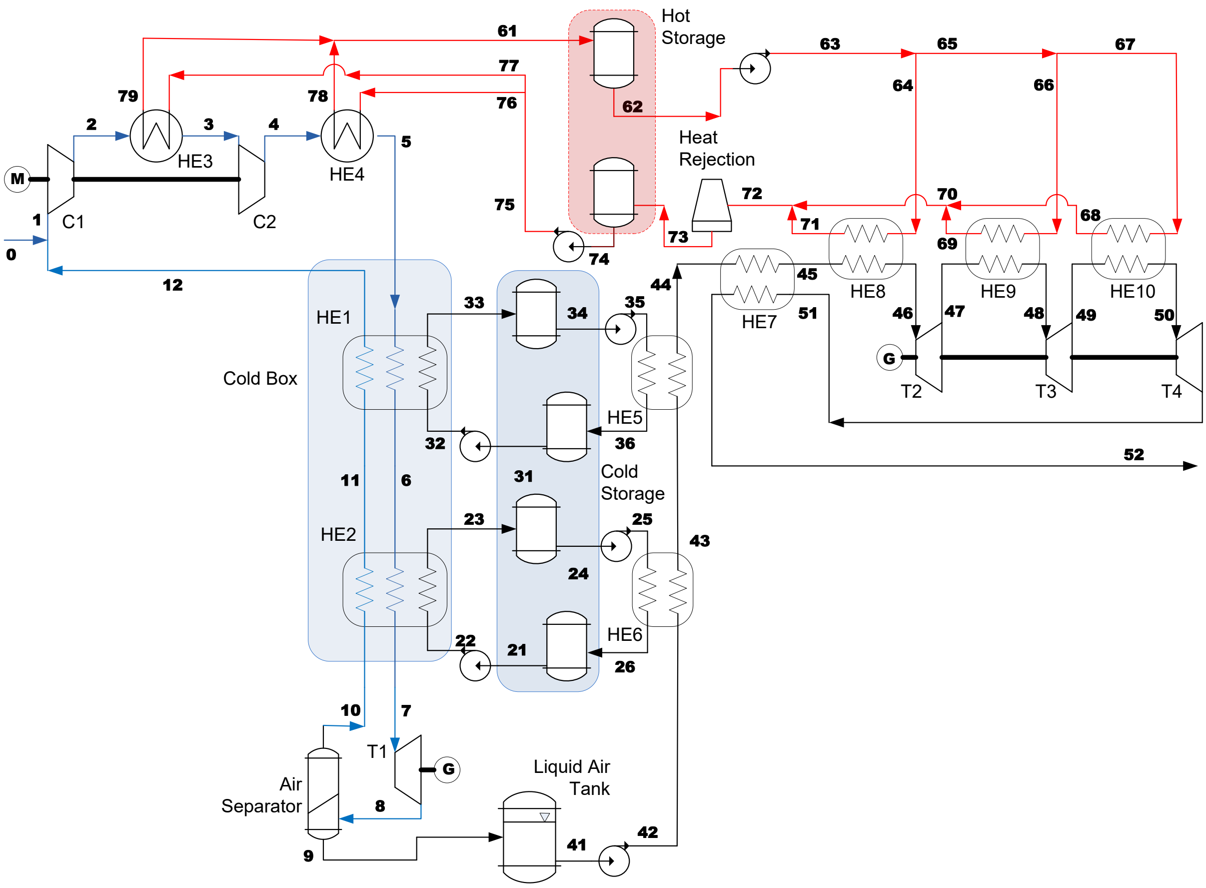

Figure 1: Plant layout – Left: Accumulation - Right: Production

The pressure, temperature, and composition conditions were maintained for all streams, as they had been the object of careful optimization. For all points, enthalpies and entropies were calculated using REFPROP properties for air and/or mixtures of oxygen and nitrogen, where it was necessary (basically, for the accumulation circuit; standard air is evolving in the production loop). The values of exergy (specific, e, and overall, E) were also calculated.
The original design conditions referred to a very large cryogenic tank (over 5000 m^3) for liquid air long-term storage; while the nominal flow rate was about 1 kg/s throughout both circuits, leading to a power

size of about 450 kWe (for the three turbines). The duration of the accumulation and production modes was the same.

In the present case we are rather considering a short-term use of the production section, based on an analysis of the daily market price of electricity in Italy in 2023 (Manfredi et al., 2026). The energy storage plant would be operated daily from March to October in support of the high contribution of photovoltaics to the Italian grid, effectively displacing the supply of electricity from the grid to the evening hours. The design conditions were an accumulation time h_A = 8 h in the morning, and a production time h_P = 2 h in the evening. The sizing criterion was to use commercially available cryogenic tanks for the storage of liquid air (two tanks of 60 m^3 each). A constant extraction flow rate of 14.6 kg/s resulted in the evening production mode. In order to charge the two reservoirs over the reference accumulation time, the flow rate of the main compressors is 4.336 kg/s.

Based on these assumed design conditions, the whole plant was sized. Table 1 summarizes the calculation of the thermodynamic variables for all streams, while Table 2 reports the sizing of the main equipment.

Table 1: Conditions for all streams.

Stream	$\dot{m}$ [kg/s]	p [kPa]	T [°C]	O_2 [-]	h [kJ/kg]	s kJ/(kg K)]	e [kJ/kg]	E [kW]
0	3.650	100	15.0	0.23	290.3	6.853	0	0.0
1	4.336	100	14.6	0.2047	290.9	6.853	0.5	2.0
2	4.336	1480	396.1	0.2047	687.4	6.946	370.3	1606.0
3	4.336	1465	35.0	0.2047	308.7	6.138	224.5	973.4
4	4.336	18100	408.8	0.2047	705.1	6.229	594.7	2579.0
5	4.336	17919	35.0	0.2047	281.7	5.326	431.4	1871.0
6	4.336	17740	-27.4	0.2047	198.7	5.027	434.5	1884.0
7	4.336	17562	-175.2	0.2047	-77.4	3.287	659.7	2861.0
8	4.336	102	-194.2		-93.9	3.377	617.5	2677.0
9	3.650	102	-194.2	0.23	-126.2	2.982	699.0	2551.0
10	0.686	102	-194.2	0.07	78.2	5.479	183.7	126.1
11	0.686	101	-33.8	0.07	245.8	6.647	14.8	10.1
12	0.686	100	12.5	0.07	293.7	6.833	9.1	6.2
22	4.418	100	-180.2	Propane	-182.2	-1.235	364.1	1609.0
23	4.418	100	-59.2	Propane	62.7	0.4379	126.8	560.4
25	17.670	100	-59.2	Propane	62.7	0.4379	126.8	2241.0
26	17.670	100	-180.2	Propane	-182.2	-1.235	364.1	6432.0
32	1.895	100	-59.2	Methanol	-1353.0	-4.179	26.4	50.1
33	1.895	100	15.0	Methanol	-1180.0	-3.488	0.0	0.0
35	7.577	100	15.0	Methanol	-1180.0	-3.488	0.0	0.0
36	7.577	100	-59.2	Methanol	-1353.0	-4.179	26.4	200.3
41	14.600	100	-194.4	0.23	-126.4	2.974	695.9	10159.0
42	14.600	6500	-191.3	0.23	-116.0	3.012	695.2	10149.0
43	14.600	6500	-62.9	0.23	180.4	5.206	359.4	5247.0
44	14.600	6500	11.7	0.23	269.8	5.572	343.5	5015.0
45	14.600	6500	157.9	0.23	427.6	6.02	372.2	5434.0
46	14.600	6500	343.3	0.23	624.5	6.4	459.7	6711.0
47	14.600	1654	177.0	0.23	451.0	6.47	265.9	3882.0
48	14.600	1654	343.3	0.23	624.5	6.798	345.0	5037.0
49	14.600	420.9	177.6	0.23	452.6	6.867	153.0	2234.0
50	14.600	420.9	343.3	0.23	624.6	7.192	231.4	3379.0
51	14.600	100	171.0	0.23	446.1	7.266	31.8	463.5
52	14.600	100	15.0	0.23	288.3	6.828	0.0	0.0

Table 1 (Continued): Conditions for all streams.

Stream	$\dot{m}$ [kg/s]	p [kPa]	T [°C]	O_2 [-]	h [kJ/kg]	s [kJ/(kg K)]	e [kJ/kg]	E [kW]
62	17.320	100	353.3	Oil	851.8	1.946	292.3	5062.0
63	17.320	100	353.3	Oil	851.8	1.946	292.3	5062.0
64	5.774	100	353.3	Oil	851.8	1.946	292.3	1687.0
65	11.550	100	353.3	Oil	851.8	1.946	292.3	3375.0
66	5.774	100	353.3	Oil	851.8	1.946	292.3	1687.0
67	5.774	100	353.3	Oil	851.8	1.946	292.3	1687.0
68	5.774	100	195.9	Oil	417.0	1.144	88.7	512.0
69	5.774	100	194.4	Oil	413.1	1.135	87.3	503.7
70	11.550	100	195.2	Oil	415.0	1.139	88.0	1016.0
71	5.774	100	170.0	Oil	353.8	1.002	66.4	383.5
72	17.320	100	186.9	Oil	394.6	1.094	80.5	1395.0
73	17.320	100	15.0	Oil	26.8	0.09733	0.0	0.0
74	17.320	100	15.0	Oil	26.8	0.09733	0.0	0.0
75	17.320	100	15.0	Oil	26.8	0.09733	0.0	0.0
76	2.277	100	25.0	Oil	45.5	0.1595	0.8	1.9
77	2.036	100	25.0	Oil	45.5	0.1595	0.8	1.7
78	2.277	100	353.3	Oil	851.8	1.946	292.3	665.6
79	2.036	100	353.3	Oil	851.8	1.946	292.3	595.1

Table 2: Components data sheet (A= Accumulation; P =Production).

Component	W [kW]	Q [kW]	S $[m^2]$	V $[m^3]$	C $[10^3€]$	C_M $[10^3€]$
C1 (A)	1719	-	-	-	1065	
C2 (A)	1719	-	-	-	1065	
T1 (A)	71.5	-	-	-	46.5	
P (P)	151.7		-	-	84.3	
T2 (P)	2533	-	-	-	836	
T3 (P)	2510	-	-	-	830	
T4 (P)	2606	-	-	-	855	
HE1 (A)	-	360	17	-	16.9	
HE2 (A)	-	1197	95	-	54.7	
HE3 (A)	-	1642	223	-	97.8	
HE4 (A)	-	1836	503	-	170	
HE5 (P)	-	1308	305	-	121	
HE6 (P)	-	4327	327	-	127	
HE7 (P)	-	2301	494	-	168	
HE8 (P)	-	2875	177	-	83.4	
HE9 (P)	-	2533	143	-	72.2	
HE10 (P)	-	2511	140	-	71	
Cooling Tower (P)	-	6047	-	-	134	
LAS Liquid Air Storage	-	-	-	120	47	
CSM Cold Storage Methanol	-	-	-	2*68.6	90	47
CSP Cold Storage Propane	-	-	-	2*212	647	97
HS Hot Storage (Essotherm 650)	-	-	-	2*184	179	573

3 METHODOLOGY

3.1 Exergy analysis

The specific exergy was calculated as a state function for all streams as follows:

$$e = (h - h_o) - T_o (s - s_o) \quad (1)$$

For all substances, the reference conditions were taken at T_o = 15 °C and p_o = 100 kPa. The total exergy of each stream is given by

$$E = \dot{m}\, e \quad (2)$$

Table 3 collects the equations for all exergy destructions and losses, and for the direct/indirect expression of the exergy efficiency.

Table 3: Equations applied for Exergy destructions (D) and loss (L).

Id.	Expression	Mode	Type	Eq.
Compressor C1	$\dot{W}_{C1} + E_1 - E_2$	A	D	(3)
Oil IC HE 3	$E_2 + E_{77} - E_3 - E_{79}$	A	D	(4)
Compressor C2	$\dot{W}_{C2} + E_3 - E_4$	A	D	(5)
Oil AC HE 4	$E_4 + E_{76} - E_5 - E_{78}$	A	D	(6)
Cold Methanol HE 1	$E_5 + E_{11} + E_{32} - E_6 - E_{12} - E_{33}$	A	D	(7)
Cold Propane HE 2	$E_6 + E_{10} + E_{22} - E_7 - E_{11} - E_{23}$	A	D	(8)
Cryo Expander T1	$E_7 - E_8 - \dot{W}_{T1}$	A	D	(9)
Separator	$E_8 - E_9 - E_{10}$	A	D	(10)
Mixing Node 0-12-1	$E_0 + E_{12} - E_1$	A	D	(11)
Cryo Pump	$\dot{W}_P + E_{41} - E_{42}$	P	D	(12)
Cold Propane HE 6	$E_{25} + E_{42} - E_{26} - E_{43}$	P	D	(13)
Cold Methanol HE 5	$E_{35} + E_{43} - E_{36} - E_{44}$	P	D	(14)
Regenerative HE 7	$E_{44} + E_{51} - E_{45} - E_{52}$	P	D	(15)
Oil Heater HE 8	$E_{45} + E_{64} - E_{46} - E_{71}$	P	D	(16)
Air Turbine T 2	$E_{46} - E_{47} - \dot{W}_{T2}$	P	D	(17)
Oil Heater HE 9	$E_{47} + E_{66} - E_{48} - E_{69}$	P	D	(18)
Air Turbine T 3	$E_{48} - E_{49} - \dot{W}_{T3}$	P	D	(19)
Oil Heater HE 10	$E_{49} + E_{67} - E_{50} - E_{68}$	P	D	(20)
Air Turbine T 4	$E_{50} - E_{51} - \dot{W}_{T4}$	P	D	(21)
Mixing node 68-69-70	$E_{68} + E_{69} - E_{70}$	P	D	(22)
Mixing node 70-71-72	$E_{70} + E_{71} - E_{72}$	P	D	(23)
Air Cooler HE 10	$E_{72} - E_{73}$	P	L	(24)
E_{in}	$\dot{W}_{C1} + \dot{W}_{C1} - \dot{W}_{T1}$	A		(25)
E_{out}	$\dot{W}_{T2} + \dot{W}_{T3} + \dot{W}_{T4} - \dot{W}_P$	P		(26)
η_{xD}	E_{out}/E_{in}			(27)
η_{xInd}	$1 - \sum EXDL/E_{in}$			(28)

3.2 Plant economics

In order to calculate the economic balance of the plant, a lifetime of 35 years was assumed. Standard rules (Turton et al. 2017) were applied for the evaluation of the Total Capital Cost over the lifetime (including Direct and Indirect Costs, 10% maintenance and 8% contingencies, and an annual interest rate of 4%), starting from the application of cost correlations for the Purchase Equipment Cost of each relevant plant component (Wu et al., 2020) and applying the necessary CEPCI adjustments. Considering the power rating in production mode $W_P = 7.5$ MW (for a daily storage capacity of 15 MWh), the overall specific cost was calculated to about 1933 €/kW, which is considered competitive at the present market conditions. The Purchase Equipment Costs of all relevant components are listed in Table 2. The most expensive items are the compressors, followed by the power turbines. The cost of thermal/cold storage is not negligible: notably, the material cost (C_M) prevails for the large hot oil storage, while the tank cost is relevant for the smaller cryogenic propane tanks.

3.3 Exergoeconomics

An exergoeconomic analysis (Bejan et al. 2004) was applied to the LAES plant. The cost of the specific exergy of each stream was determined based on three contributions:

$$c_{e,i} = c_{e,i1} + c_{e,i2} + c_{e,i3} \tag{29}$$

Where $c_{e,1}$ represents the "fuel" cost (that is, the cost of the exergy spent to "drive" the component), $c_{e,2}$ represents the "feedstock" cost (that is, the cost of the exergy stream to be transformed into a useful product by the component), and $c_{e,3}$ represents the "Capital" cost (that is, the cost corresponding to investment and maintenance over the whole life cycle). Along the progressive transformation of all streams, the SPECO rules (Lazzaretto and Tsatsaronis, 2006) are applied for calculating the cost of the exit product stream from each component. The necessary auxiliary equations were applied following the standard exergoeconomic guidelines (Bejan et al., 1989).
Loops are determined by mass recycle or regenerative heating: this is respectively the case for stream 1 in the Accumulation section:

$$c_{e,1} = \frac{c_{e,12}E_{12} + c_{e,0}\,E_0}{E_1} \tag{30}$$

($c_{e,0}\,E_0$ was assumed to be 0 – the cost and exergy of inlet air from the environment). The second case is stream 46 in the Accumulation section:

$$c_{e,45} = \frac{c_{e,44}E_{44} + c_{e,51} * (E_{51} - E_{52}) + Z_{HE8}}{E_{45}} \tag{31}$$

Where $c_{e,51}$ is determined by the performance of the group of components HE8-T2-HE9-T3-HE10-T4. Moreover, in order to couple the Accumulation and Production sections, the following condition was applied in order to consider the cost of the cryogenc liquefied air tank:

$$c_{e,41} = c_{e,9} + \frac{Z_{LAS}}{E_{41}} \tag{32}$$

(cost of stored liquefied air per unit exergy).

The resulting calculated costs of the relevant streams is collected in Table 4.

Table 4: Calculated unit cost of exergy [€/MJ] for the relevant streams (3 cost components).

Stream	c_e	c_{e1}	c_{e2}	c_{e3}
1	0.1194	0.1194	0	0
2	0.03257	0.00015	0.02975	0.002667
3	0.05412	0.05371	0	0.000404
4	0.0406	0.02043	0.01852	0.00166
5	0.05634	0.05598	0	0.000365
6	0.05602	0.05593	5.24E-05	3.6E-05
7	0.03854	0.0369	0.001562	7.68E-05
8	0.03854	0	0	0
9	0.03854	0.03854	0	1.12E-06
10	0.03854	0	0	0
11	0.03854	0	0	0
12	0.03854	0	0	0
41	0.03856	0.03854	0	1.86E-05
42	0.03904	0.03859	0.000415	3.34E-05
43	0.07561	0.07551	0	0.000097
44	0.0792	0.07911	0	9.69E-05
45	0.07591	0.0731	0.002684	0.000124
46	0.06151	0.06146	0	5E-05
47	0.06151	0	0	0
48	0.04747	0.04742	0	5.76E-05
49	0.04747	0	0	0
50	0.03147	0.03138	0	8.44E-05
51	0.03147	0	0	0
52	0.03147	0	0	0

The exergoeconomic analysis is usually represented also at the level of system components, considering the fuel and product of each of them (Lazzaretto and Tsatsaronis, 2006). Specifically, the cost increase across the component is represented by r_k:

$$r_k = \frac{\dot{C}_{Pk} - \dot{C}_{Fk}}{\dot{C}_{Pk}} \quad (33)$$

The indicator f_k describes the relevance of capital + maintenance cost over the total cost (including exergy destruction and exergy loss of the component):

$$f_k = \frac{Z_k}{Z_k + c_{f,k} EXDL_k} \quad (34)$$

Having defined thus the Product and Fuel for each component, the component exergy efficiency can also be calculated as:

$$\varepsilon_k = \frac{E_{Pk}}{E_{Fk}} = 1 - \frac{E_{Dk}}{E_{Fk}} \quad (35)$$

4 RESULTS

4.1 Exergy balance

The system operates on the whole as a power-to-power device. The round-trip efficiency is thus given by the ratio of the net power output to the net power consumption and is η_{RT} = 0.558.
The exergy efficiency can be calculated from Eq. 27 (direct approach); as EXT_{in} is the net power input and EXT_{out} is the net power output, $\eta_{xD} = \eta_{RT}$ = 0.558.
Further insight about the distribution of exergy destructions can be gained by considering the indirect calculation of η_{xInd} (Eq. 28). This approach considers the relative exergy destruction or loss in each component of the system. A graphical summary is shown in Figure 2.

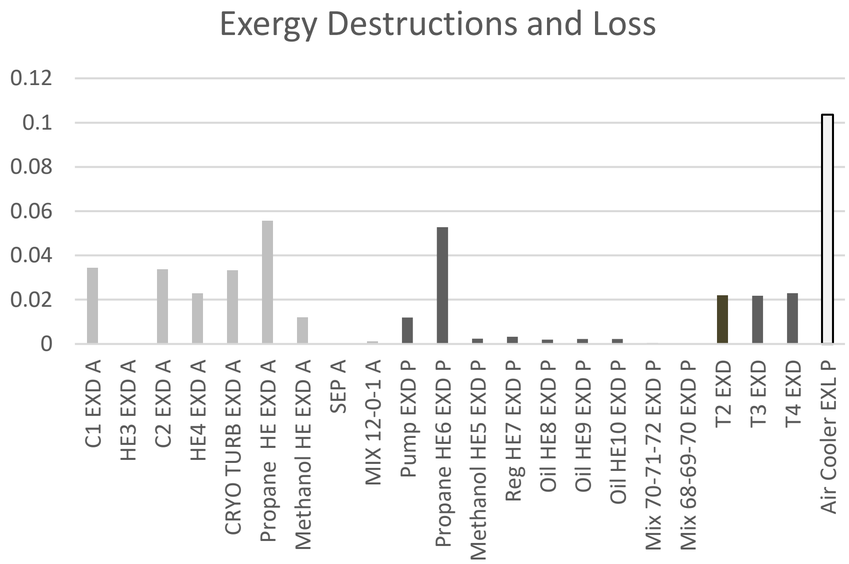

Figure 2: Non-dimensional exergy destructions and loss (air cooler)

The exergy balance (Figure 2) shows that the air cooler - the only exergy loss - represents the largest contribution (over 10%), followed by the heat transfer exergy destructions in the Air/Propane Heat Exchangers. The compressors and turbine/expander irreversibilities are in the range between 2% and 3.4%.
The design conditions were not altered from the original specifications, some of which were object of optimization (notably the pressure ratios of the accumulation and production cycle). Although some improvement is possible, the overall performance appears to be close to the top levels achievable with LAES (Damak et al. , 2020). It should be noticed that the cryo turbine has an exergy destruction EXD = 112 kW, although producing a power W = 71.5 kW, which represents a marginal recovery compared to the compressors rating (3440 kW for the two compressors). This happens because the isentropic efficiency of the cryo turbine is η = 0.7 – this is a difficult component, operating at extremely low temperature and with liquid air droplets condensing at the exhaust. Considering this, it would appear advisable to use a simple valve expansion in place of the cryo turbine.

4.2 LAES Plant Economics

An input/output economic balance for operation over one standard year of operation was performed. The LAES system with the design conditions (h_A =8 h; h_P = 2h; operation 8 months per year March to October) produces 3674 MWh and consumes 6600 MWh (round-trip efficiency η_{RT} = 0.558). The overall yearly operation cost is CY = 1620385 €/y, which are divided in CY_{Cap} = 784787 €/y; CY_{El} =

659903 €/y; CY_{Maint} = 175695 €/y. The resulting cost of the kWh produced is 0.44 €/kWh (4.4 times the assumed cost of green PV electricity at noon).

4.3 Exergoeconomics

The screening of Table 4 reveals that the cost of streams per unit exergy is progressively increasing when the high exergy levels connected to cryogenic conditions are reached. The highest cost in €/MJ is reached at point 44, that is, at the beginning of the power production section. As exergy is progressively extracted producing power, the exergy of the streams is decreasing until reaching stream 52 (where finally E_{42} = 0; equilibrium with environment; Table 1). The progressive decrease in exergy in the production mode explains the cost increase of the stream per unit exergy, as the overall exergy (kW) is at the denominator. Table 5 provides a synthethic view of the plant component exergoeconomics.

Table 5: Component exergoeconomic performance indicators

Component	Mode	ε_k [-]	f_k [-]	r_k [-]	$\dot{C}_F$ [€/s]	$\dot{C}_P$ [€/s]	$\dot{C}_D$ [€/s]
Compressor 1	A	0.933	0.571	0.168	172	187	**11.59**
Heat Exchanger 3	A	0.443	0.299	**1.276**	188	190	3.31
Compressor 2	A	0.934	0.576	0.167	172	187	**11.34**
Heat Exchanger 4	A	0.577	0.321	0.745	377	379	5.19
Turbine 1	A	***0.390***	***0.042***	**1.633**	25	26	**15.52**
Heat Exchanger 2	A	0.939	***0.031***	0.068	396	397	**24.37**
Heat Exchanger 1	A	0.979	***0.030***	0.022	380	380	7.98
Separator	A	1.000	0.995	0.000	354	354	0.000
Mix 0+12=1	A	0.323	0.000	2.100	0.87	0.87	0.587
Heat Exchanger 6	P	***0.366***	***0.025***	**1.736**	1426	1428	**70.63**
Heat Exchanger 5	P	0.921	0.174	0.088	1428	1430	8.33
Heat Exchanger 7	P	0.904	0.325	0.157	52	55	5.04
Heat Exchanger 8	P	0.996	0.169	***0.005***	1485	1486	5.93
Turbine 2	P	0.895	0.156	0.138	626	639	**65.56**
Heat Exchanger 9	P	0.994	0.172	***0.007***	860	861	5.01
Turbine 3	P	0.896	0.194	0.145	479	491	**50.04**
Heat Exchanger 10	P	0.991	0.232	***0.012***	382	383	3.40
Turbine 4	P	0.894	0.261	0.161	330	343	35.04

High Values: **Bold** Low values: ***Bold + Italic***

5 CONCLUSIONS

A well-documented case study for an advanced Liquid Air Energy Storage system was validated and adapted to daily operation in support of the variability of solar photovoltaic electricity production. This represents a potentially attractive alternative with respect to the use of batteries, both in terms of lifetime and end-of-life management, and for the flexibility of intervention in support to the grid.
The system is designed as a 15 MWh electric storage unit, operating 8 h in Accumulation mode and 2 h in Production mode. This represents a typical situation in Mediterranean countries in summer. The storage requires a series of tanks (respectively Cold Tanks: Liquid air, Propane, Methanol; Hot tanks for Thermal Oil), with volumes in the range from 70 to 212 m^3 (Table 2).
The exergy analysis identified the Air Cooler as the largest contribution (Exergy Loss, about 10%); other relevant exergy destructions are represented by heat transfer irrversibilities in the Propane heat exchangers (both in accumulation and Production mode).
An exergoeconomic analysis was performed applying specific component cost correlations (developed for cryogenic applications). The exergoeconomic approach allows to monitor the progressive increase

of the cost of exergy streams passing across each component, which is the first step in the direction of analyzing solutions for the reduction of the final cost. The interpretation of the results of the exergoeconomic analysis (Table 5) show that Heat Exchanger 6 (the Propane/Liquid Air reheater) is the most critical component. Heat Exchangers 1 and 2 would deserve a higher capital investment, while the cryogenic turbine 1 could be substituted by a simple expansion valve without affecting much of the overall performance.
The overall input/output economic result must consider the minimum value represented by the round-trip efficiency ($\eta_{RT} = 0.558$), which sets a limit of about twice to the cost ratio of the electricity produced from the LAES storage. Indeed, it is necessary to add the components' costs (including maintenance) over the lifetime, which is expected to be much longer than for battery storage. 35 years were assumed in the present study, determining an overall yearly operation cost CY = 1620385 €/y, which can be divided into 48.4% Capital, 10.8% Maintenance, and 41% Electricity purchased from the grid at 0.1 €/kWh (the assumed cost of green PV electricity produced at high radiation conditions). The resulting cost of the stored kWh, which is available for sale to the grid in the evening, is 0.44 €/kWh.

NOMENCLATURE

c_e	Exergoeconomic cost of a stream, €/kJ or €/MJ (Table 4)
C	Component cost, € *1000
$\dot{C}$	Cost rate, €/s
CY	Yearly cost, €/y
DT	Temperature difference (°C)
e	Exergy, kJ/kg
E	Total exergy, kW
EXDL	Exergy destruction and Loss, kW
h	Enthalpy, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
O_2	Oygen mass fraction in the mixture, %
p	Pressure (kPa)
Q	Heat rate, kW
s	Entropy, kJ/(kgK)
S	Surface, m^2
T	Temperature (°C)
V	Volume, m^3
W	Power, kW
Z	Capital cost rate of a component, €/s
η	Efficiency

Acronyms/Subscripts

C	Compressor
CS	Cold Storage
D	Destruction (Exergy)
F	Fuel
HE	Heat Exchanger
HS	Hot storage
in	inlet
L	Loss (Exergy)
M	Material (Methanol, Propane, ET650)
o	Reference conditions
out	outlet
P	Product
T	Turbine (or expander)

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