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Preliminary assessment of waste heat recovery solution (ORC) to enhance the performance of Liquid Air Energy Storage system

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Abstract

Liquid Air Energy Storage (LAES) is a novel energy storage system that stocks up energy by means of air liquefaction and recovers the cryogenic energy when required. The performance of LAES is actually limited both by the inefficiencies of liquefaction and discharge section leading to lower value of round trip efficiency compared to other energy storage solutions.

This work investigates the thermodynamic feasibility of an integrated energy system consisting of a LAES system and Organic Rankine Cycle (ORC) in order to recover the waste heat released by the compression phase. To further improve the round trip efficiency of LAES, different integrated LAES-ORC system configurations have been modelled by means of the numerical software EES-Engineering Equation Solver v.10, which allows to compute the thermo-physical properties of the working fluids throughout the whole cycles. The LAES-ORC integrated systems are compared in terms of different performance indices such as electric power output, round trip efficiency of stand-alone and integrated systems and recover efficiency of ORC. Moreover, since the potential benefits of waste heat recovery by means of ORC introduces a new capital and operative cost, an economic analysis has been carried out in order to determine the impact of ORC introduction in LAES economy. The results show that a tight integration between LAES and ORC allows to significantly improve the round efficiency (up to 20%) and reduce the pay-back period of stand-alone LAES as high as 6 %.

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1. Introduction

Nowadays, the modern society is increasingly becoming dependent on renewable energy sources in order to achieve a partial decarbonization of electricity grid. According to IEA [1], by 2040 renewable energy sources might be able to produce approximately 60% of the power generated, almost half of this from wind and solar PV, leading to an average emissions intensity of electricity generation equal to 85 g_{CO2}/kWh (vs current 515 g_{CO2}/kWh). However, one of the main issues related with renewable energy sources is due to their intermittent and unprogrammable nature [2] that does not guarantee the required match between the periods of high energy production to periods of high energy demand. A possible solution to overcome that issue is provided by energy storage systems, either thermal or electrical [3]. In this sector, a novel and promising technology that guarantees at the same time large volumetric energy density and no geographical constrains is represented by Liquid Air Energy Storage system [4]. In addition, LAES relies on a consolidated technology based on commercially available components that limits possible development risks and ensures long life to the system (30-40 years) [5]. However, a bottleneck to the current development of LAES is represented by the low value of round trip efficiency principally due to the large amount of energy consumption during the charge phase. Analyzing the performance of a small air liquefaction plant for LAES, Borri et al. [6] have linked the low exergy efficiency value achieved by the system with the total rejection of heat of compression to the environment. In their thermodynamic analysis of LAES, both Guizzi et al. [7] and Tafone et al. [8] have highlighted that, despite the presence of a hot storage section capable to partially recover the waste heat discharged by compression phase, the major contribution to exergy losses is again represented by heat rejection after air superheaters.

The present paper aimed to propose a novel LAES system by coupling it with a waste heat recovery solution, namely an Organic Rankine Cycle, potentially able to totally harness the whole waste heat discharged by the charge phase of LAES. The stand-alone LAES and the integrated LAES-ORC systems will be described in detail in the following sections and simulated, in steady state operation, by means of EES, Engineering Equation Solver v.10 [9]. The simulation code allows to evaluate and compare the performance of the different systems both from thermodynamic and economic point of view.

Nomenclature

COGE	Cogenerative Configuration	LAES	Liquid Air Energy Storage
EES	Engineering Equation Solver	LAORC	LAES-ORC integrated system
ELE	Full electric configuration	MAC	Main Air compressor
EVAP	ORC Evaporator	ORC	Organic Rankine Cycles
FIT	Feed-in tariff	RAC	Recycle Air compressor
HGCR	High Grade Cold Recycle	SH	SuperHeater
HGWR	High Grade Warm Recycle	WH	Waste Heat
K	ORC Condenser	WHR	Waste Heat Recovery

2. Models description

This section will provide a brief description of the process flow diagrams of the systems simulated by means of the numerical software EES. The following assumptions will be valid throughout the energetic and economic analysis: any pressure losses in the components other than the expander are neglected; auxiliary electrical losses are not included; cycle components are assumed to work as steady-state-flow devices.

2.1. Stand-alone LAES

A 10 MW_e commercial size LAES plant has been taken as reference for design purpose in EES. Since one of the most interesting features of LAES is that besides producing electric energy it also provides free cooling energy as a co-product of the expansion/regasification process, LAES can also be thought as a poly-generation system capable

to be integrated with an air conditioning system in order to supply a well-defined cooling load. Depending on that aspect, two operational configurations can be distinguished: a full electric configuration (ELE), where the only output is the electric power released by the LAES, and a cogenerative configuration (COGE) that provides both electrical and cooling power. The process flow diagrams of both the configurations are represented in Fig. 1, where the cogenerative section is underlined by the dashed lines. The main energy vector is liquid nitrogen (LN₂) while the thermal energy storages, labeled in the figures as HGCR and HGWR, make use of air and Therminol 66 respectively as heat transfer fluids. The charge, discharge and LN₂ storage pressures are obtained from a thermodynamic optimization of LAES round trip efficiency carried out by means of EES.

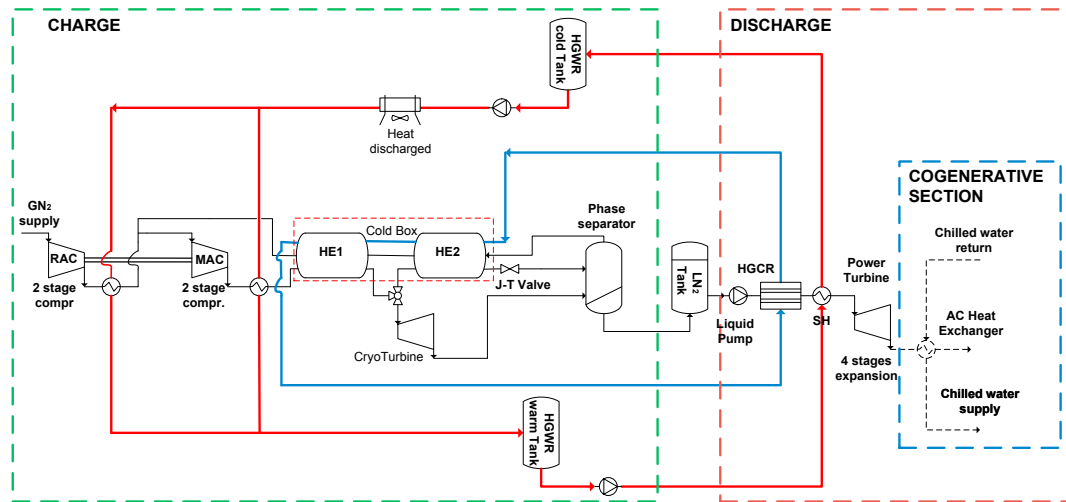


Fig. 1. Stand-alone LAES – full electric and cogenerative configurations (dashed lines).

Table 1. Process parameter for LAES systems

Parameters	Value
Nitrogen inlet temperature [°C]	25
Charge pressure [bar]	100
Discharge pressure [bar]	180
Liquid Nitrogen storage pressure [bar]	8
HE1 pinch point ΔT [°C]	5
HE2 pinch point ΔT [°C]	3
ICs pinch point ΔT [°C]	5
Hot end temperature approach SHs [°C]	10
Isentropic efficiency of compressors [%]	85
Isentropic efficiency of cryoturbine [%]	75
Isentropic efficiency of pump [%]	80
Isentropic efficiency of power turbines [%]	80

LAES system can be separated into three sub-processes: charge, store and discharge. During the charge phase, the gaseous nitrogen is compressed in 4 stages compression (2 for MAC and 2 for RAC) with intercooling, cooled and turned into liquid nitrogen after passing through throttle valve and phase separator; the liquid nitrogen is thus stored in low pressure cryogenic tank. During the discharge phase, liquid nitrogen is pumped to a pressure of 180 bar and heated up to gaseous nitrogen by the HGCR, then expands to ambient pressure in turbines with reheating processes. The gaseous nitrogen is therefore re-heated between 4 stages to achieve quasi isothermal expansion. In

order to increase the round trip efficiency of LAES, two thermal energy storage are implemented: HGCR and HGWR. The high grade cold recycle has been implemented by means of a regenerator that stores the cold energy released by LN_2 during the discharge phase. The high grade warm recycle is a waste heat recovery system that stores the heat of compression released during charge phase in order to use it during the re-heating process of gaseous nitrogen. In full electric configuration, the hot end approach ΔT at superheaters SH ($\Delta T = T_{\text{HTF,hot}} - T_{\text{N}_2,\text{hot}}$) imposes the turbine inlet temperature of nitrogen. Conversely, in cogenerative configuration, the turbine inlet temperature of gaseous nitrogen is constrained by a defined turbine outlet temperature (5°C). Such a value is required by the air conditioning system (i.e. water cooled chiller with an average COP of 5) thermally coupled with the LAES by means of air cooled heat exchangers; the parameters used to model the LAES system are shown in Table 1.

2.2. Integrated systems LAES-ORC

As already stated in Section 1, the most significant exergy loss of LAES takes place during the charge phase: in a typical compression operation, approximately 90% of the electrical input is lost as heat [10]. In order to further improve the efficiency of LAES, a waste heat recovery based on Organic Rankine Cycle is coupled with the LAES in order to partially recover the large amount of exergy lost during gaseous nitrogen compression.

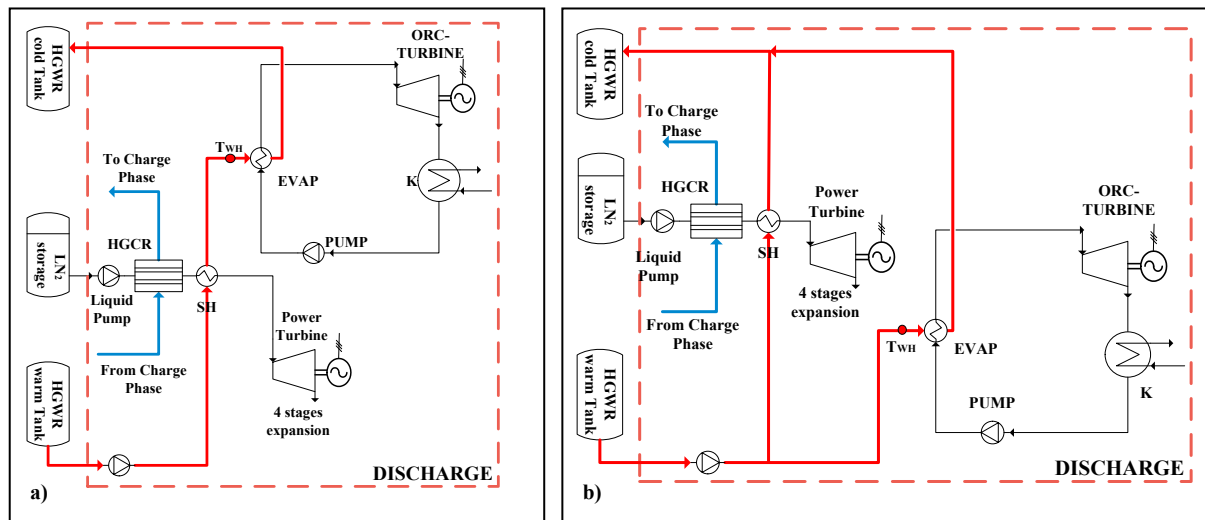


Fig. 2. (a) LAORC-1 and (b) LAORC-2 integrated systems.

Two integrated systems LAES-ORC are proposed and shown in Fig. 2a and Fig. 2b. The first LAES-ORC system (LAORC-1) exploits the waste heat downstream of the superheating process of gaseous nitrogen. In alternative, as shown in Fig. 2b, a further integrated system is introduced (LAORC-2) which harnesses the waste heat by means of a mass flow derivation of Therminol 66 from the HGWR. Due to the different heat source temperatures available for the ORC (T_{WH} [$^\circ\text{C}$]) [11], R134a and R245fa have been assumed as the ORC working fluids for the first and second LAORC systems respectively; the parameters used to model the ORC plants in EES are summed up in Table 2.

Table 2. Process parameter for ORC plant.

Parameters	Value
EVAP pinch point ΔT [$^\circ\text{C}$]	5
Condensation temperature [$^\circ\text{C}$]	25
Isentropic efficiency of pump [%]	80
Isentropic efficiency of turbine [%]	80

The results of the simulations will be presented in the next section with reference to the following performance parameters:

- Round trip efficiency of the systems:

$$\eta_{RT} = \frac{P_{net,d,LAES} + P_{net,ORC} + \frac{\dot{Q}_{c,LAES}}{COP_{AC}}}{P_{net,ch,LAES}} \quad (1)$$

- ORC recover efficiency:

$$\eta_{ORC} = \frac{P_{net,ORC}}{\dot{Q}_{WH,ORC}} \quad (2)$$

- Electric power output of the systems:

$$P_{e,tot} = P_{net,d,LAES} + P_{net,ORC} \quad (3)$$

- Capital cost of LAES and ORC:

$$CAPEX_{LAES} = C_{p,LAES} * P_{net,d,LAES} \quad (4)$$

$$CAPEX_{ORC} = C_{p,ORC} * P_{net,ORC} \quad (5)$$

- Annual income of the systems:

$$I = P_{e,tot} * h_d * N_{day} * FIT \quad (6)$$

where $P_{net,d,LAES}$ [kW] is the net electric power produced by the discharge phase of LAES; $P_{net,ORC}$ [kWe] is the net electric ORC power; $P_{net,ch,LAES}$ [kWe] is the electric power consumed by the charge phase of LAES; $\dot{Q}_{WH,ORC}$ [kW_{th}] is the thermal power available for ORC plant; $\dot{Q}_{c,LAES}$ [kW_c] is cooling power discharged by the LAES; $C_{p,LAES}$ [US\$/kWe] and $C_{p,ORC}$ [US\$/kWe] are the cost per power unit of LAES and ORC, respectively; h_d [h] represents the daily operation hours of the LAES in discharge phase; N_{day} [d/year] is the number of operative days during one year; FIT [US\$/kWh_e] is the feed-in tariff of the energy sold to the grid. Taking into account the capital costs and the annual incomes, the key performance index of the economic analysis, namely the pay-back period (PBP [years]), is evaluated.

3. Results and discussion

3.1. Energy analysis

Table 3 presents the simulation results of the different LAES systems modelled in this paper. As already stated, a basic differentiation between full electric and cogenerative LAES configuration has been assumed. The results of the two integrated LAORC systems have been compared against the stand-alone LAES which has been used as a baseline.

Based on the thermodynamic assumptions made in Section 2, the simulations show that round trip efficiencies of 48.2 % and 40.1 % are achieved by the LAES systems under full electric and cogenerative configuration for a total electric power production of 10 MW_e. As expected the round trip efficiency of LAES in full electric configuration is

sensibly higher than the one associated with LAES in cogenerative configuration. This is principally due the fact that the turbine inlet temperature in the latter configuration is constrained by the required cooling load that imposes an outlet turbine temperature of 5 °C. As a consequence, the thermal power discharged by LAES_{COGE} almost doubles the value obtained for LAES_{ELE} configuration leading in turn to a better potential for ORC electric power output.

Due to the additional electric power output of ORC plant by means of the low grade waste heat from the charge phase of LAES, the round trip efficiency of stand-alone LAES was found to be improved up to 53.08% and 48.17% for full electric and cogenerative configurations, respectively. However, the improvement in round trip efficiency of the LAORC-1 is smaller compared to the LAORC-2, especially considering full electric configuration. The reason is in the value of the heat source temperatures (T_{WH}) available for the different integrated systems: the lowest T_{WH} (97 °C) strongly limits the ORC efficiency to low level (4.5 %). In fact, even though the LAORC-1 system has larger amount of waste heat available, the electric power production is approximately 50 % lower than the LAORC-2. The disadvantage of low temperature heat source for LAORC-1 is partially mitigated in cogenerative configuration where T_{WH} is increased to 115.4 °C with a slight improvement of the ORC efficiency (6.28 %). Nevertheless, LAORC-2 still represents the most energy efficient system among the ones simulated since it was found to improve the round trip efficiency by 10% and 20 % for full electric and cogenerative configuration. Especially in the latter case, the efficiency losses of stand-alone LAES due to cooling demand are compensated by the ORC integration. Partially converting the large amount of waste heat into useful electric power, the integrated LAORC-2 system in cogenerative configuration is able to achieve round trip efficiency value comparable to the stand –alone LAES in full electric configuration.

Table 3. Simulation results for LAES_{ELE} and LAES_{COGE} configurations.

Performance parameters	LAES _{ELE}			LAES _{COGE}		
	Stand-alone LAES	LAORC-1	LAORC-2	Stand-alone LAES	LAORC-1	LAORC-2
η_{RT} [%]	48.2	50.5	53.1	40.8	44.8	48.2
$\dot{Q}_{WH,ORC}$ [kW_{th}]	-	10414	8470	-	15992	16092
T_{WH} [°C]	-	97	172.2	-	115.4	172.2
η_{ORC} [%]	-	4.6	11.4	-	6.3	11.4
$P_{e,tot}$ [kW_e]	10000	10474	10968	10000	11004	11840
$\dot{Q}_{c,LAES}$ [kW_c]	-	-	-	824.1	824.1	824.1

3.2. Preliminary economic analysis

In this section, a preliminary economic analysis, based on the assumptions specified in Table 4, is carried out in order to determine the economic viability of the integrated systems over the stand-alone LAES.

Table 4. Nominal assumptions for the economic analysis

Parameters	LAES _{ELE}	LAES _{COGE}
$C_{P,LAES}$ [$US\$/kW_e$] [12]	3062	3265
$C_{P,ORC}$ [$US\$/kW_e$] [13]	2000	2000
FIT [$US\$/kW_{he}$]	0.20	0.20
h_d [h]	2.5	2.5
N_{day} [d/year]	330	330

Throughout the whole economic scenario, the LAES is supposed to be coupled with a renewable energy source (solar, wind, etc.): therefore the energy required to charge the system is obtained directly from the surplus of

renewable energy. Moreover, the LAES is supposed to sell the energy produced at the same feed-in tariff of the renewable power plant. Taking into account the policy scenario currently in force in some countries [14], an average value of the feed-in tariff (0.20 US\$/kWh) is assumed.

As reported in Table 5, the economic analysis confirms that the LAORC-2 produces the best economic performance parameters compared to the other systems. It is worth nothing that while for full electric configuration the investment in ORC plant produces slight economic advantages over the stand-alone LAES system, in cogenerative configuration ORC it was found to improve the income by 18 % and reduce the pay-back period by 6 %. The reason of such a result is in the higher capital cost of stand-alone LAES_{COGE} and in the higher electricity production of ORC due to larger amount of waste heat available compared to full electric configuration.

Table 5. Economic results for LAES_{ELE} and LAES_{COGE} configurations.

Performance parameters	LAES _{ELE}			LAES _{COGE}		
	Stand-alone LAES	LAORC-1	LAORC-2	Stand-alone LAES	LAORC-1	LAORC-2
CAPEX [MUS\$]	30.62	31.57	32.56	32.65	34.66	36.33
I [MUS\$]	1.650	1.728	1.810	1.65	1.816	1.954
PBP [year]	18.56	18.27	17.99	19.79	19.09	18.6

Due to the uncertainty over the capital cost figure related to the relative novelty of LAES technology, a sensitivity analysis has been carried out for the LAES cost per power unit ($C_{p,LAES}$ [US\$/kWe]) in order to assess its influence over the economic feasibility of the integrated plant. Fig. 3 reports delta pay-back period, computed as the relative difference between the pay-back periods for the stand-alone LAES and the LAORC-2 ($\Delta PBP = (PBP_{LAES} - PBP_{LAORC-2}) / PBP_{LAES}$) vs. the cost per power unit for LAES.

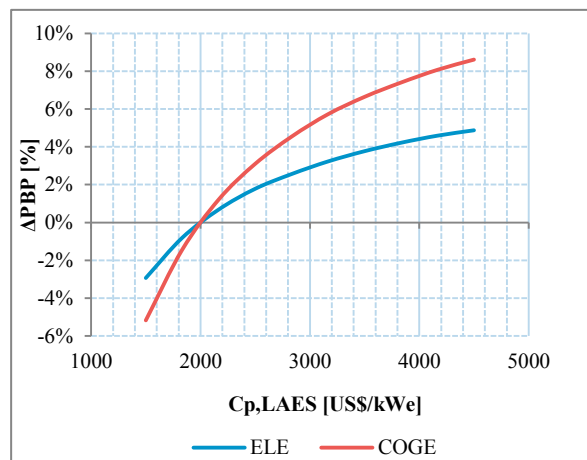


Fig. 3. ΔPBP function of $C_{p,LAES}$ for $C_{p,ORC} = 2000$ US\$/kWe.

Fig. 3 shows that the cogenerative configuration is the most sensitive to cost per power unit variation with a maximum decrease of pay-back period around 9 % (vs 5 % for full electric configuration). In addition to this, the graph shows that the prerequisite for the economic viability of the integrated LAORC system is that the cost per power unit of ORC must be lower than the one associated with LAES. In fact both curves in Fig. 3, intercept the x-axis at $C_{p,LAES} = 2000$ US\$/kWe, namely the cost per power unit assumed for ORC plant.

4. Conclusions

In this paper, a technical and economic feasibility analysis of the ORC integration for LAES has been carried out for two different integrated systems (LAORC-1 and LAORC-2) under full electric and cogenerative configurations. LAORC-2 is the best candidate system to recover the waste heat discharged by charge phase of LAES both from energetic and economical perspective due to its capacity to exploit the waste heat at higher temperature. The most remarkable results are achieved by cogenerative configuration where the integrated system, was found to improve the round trip efficiency and the annual income by 20 % and 18 %, respectively. Therefore, due to a well-designed integration between the storage system (LAES) and the recovery section (ORC), a LAORC system can be considered as a feasible solution for commercial scale hybrid energy storage where the need for both electric and cooling energy outputs is required. Nevertheless, the uncertainty over the capital costs figures of LAES may significantly affect the economic feasibility of the proposed system.

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