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Microgrid application of liquefied air energy storage (LAES) systems

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Abstract. An energy and economic analysis on small-scale LAES (liquefied air energy storage) system is presented. The LAES operative parameters were analyzed via MATLAB simulations. The optimal case is given with a flowrate of 1000 kg/h and 4 turbine expansions, resulting in a net electric power output in the discharging process of 260 kW and the optimal values are 450 K for inlet temperature and 150 bar for the discharge pressure. For the charging process the specific consumption is significantly affected by the storage pressure. Also the round trip efficiency is influenced by the storage pressure: for a storage pressure of 8 bar, it is about 25% compared to the 12% in case of a storage pressure equal to 1.10 bar. The LCOS obtained is between 1.2 €/kWh and 1.8 €/kWh. This values are higher than other results in literature due to the scale of the system.

1. Introduction

The evolution of the energy transition based on renewable energy sources (RES) reached an important milestone with the recognition from the European Union (EU) of the importance of energy communities. In fact, with two Directives [1-2] the EU has given the definitions of the energy communities and asked the Member States to introduce them into their national legislations. Energy communities are emerging in the huge transformation of the electrical systems. The paradigm based on centralized generation is being replaced by a system based on distributed generation. In the energy community scenario, energy storage systems (ESS) has also become one of the key building blocks providing distribution grids with lots of benefits in terms of stability, reliability, quality, and control. Small-scale applications of ESS are therefore needed.

There is a wide range of ESS to store electrical energy. A common approach is classifying ESS in accordance to the form of used energy: mechanical, electrochemical, chemical, electrical and thermal energy storage systems [3].

The most common mechanical storage systems are pumped hydroelectric power plants, compressed air energy storage (CAES), flywheel energy storage and mechanical springs. Electrochemical storage systems consist of various types of batteries. Chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers and, finally, electrical storage systems include double-layer capacitors and superconducting magnetic energy storage [3-9]. Technologies used for high power ranges and energy capacities are pumped hydro storage (PHS) and CAES [10].

CAES uses the surplus electricity to compress air. The high-pressure air is saved in sealed devices (such as underground mine, large air storage tank) and is released to drive the expander generating electricity when the demand of electricity is high. It is used only in stationary applications. There are seven commissioned CAES facilities worldwide (four of these in the United States) and three large facilities are under construction in China [11]. New approaches, based on hybrid systems are being explored to potentially balance cost/performance trade-offs. For example, in the Netherlands, CAES was recently combined with Li-ion batteries for ancillary services. This approach is expected to both extend the Li-ion life and significantly improve the total lifetime cost [11]. Because of the storage characteristics of large capacity and long-term, CAES has attracted the attention and research of a large number of scholars around the world. The Huntorf power station in Germany and the Mcintosh power station in United States are two typical large-scale CAES power stations in the world. CAES technology is a research hotspot of large-scale energy storage technology at present. Analyses in literature show that CAES could potentially compete with Li-ion for about 60 GWh of the total 150-GWh projected capacity required in 2030 [12].

An upgrade of the CAES technology is Liquid air energy storage (LAES). With a working principle similar to that of CAES, LAES uses liquid air as the medium for energy storage [13]. The benefits are: i) energy storage density much higher than CAES, ii) no restriction on geographical condition. The development of LAES technology began in 2005 when the Leeds University in the UK and Highview Power completed the first full-system patent of LAES technology. In addition, the first complete independent demonstration LAES system in the world was built in Slough, UK, in 2011 [14].

At present, there have been a lot of studies on the performance, economy and dynamic simulation of large-scale LAES. The research is devoted to improve the overall efficiency of the system by improving the performance of the components or to coupling LAES with other systems to make full use of the excess energy [15-18].

At small-scale, Highview Power developed a 300 kW/2.5 MWh LAES pilot plant that has been operating in the UK since 2010. Literature studies on LAES small scale applications, applied to demand side management (i.e. load levelling, peak shaving, time shifting, backup power), are devoted to find the optimal plant configuration which minimizes the specific consumption of the air liquefaction process [19]. A preliminary analysis in [19] consists in comparing different liquefaction cycles by changing the operating parameters like pressure and recirculation fraction. From the simulation results, Claude and Kapitza cycles offer the lowest specific consumption; the performance is incremented of 25% with the two stage compression. From the study, the pressurization of the phase separator positively influences the performance, decreasing the specific consumption by 21% with a phase separator pressure of 4 bar. Also the combined effect of both pressurized phase separator and incremented operating pressure can decrement the specific consumption below 500 kWh/t. Increasing the operating pressures increases the sizes of the components, the complexity of the cycle and the costs.

The optimal configuration of an air liquefier can be a two stage compression Kapitza cycle with an operating pressure in the range of 38–45 bar and a phase separator pressure of 6 bar. This range of operating parameters provides a specific consumption range of 520–560 kWh/t which is interesting for LAES application in microgrids.

A study on a pilot plant scale LAES was carried out by Morgan et al. [20]; a round trip efficiency of 8% was obtained because of the small size of the pilot plant, and due to the fact that only 51% of the accessible cold was recovered.

In another work [21] the authors analyze the performance of a single-effect absorption chiller using a Water-Lithium Bromide solution combined with a small air liquefier with a liquid air production capacity of 0.834 t/h. In the suggested solution, the waste heat of the compression phase of the liquefaction cycle is recovered and used to run the absorption cycle, where the resulting cooling power is adopted to reduce the specific consumption and improving the exergy efficiency of the system. The results reveal a decrease of the specific consumption of about 10% (537 kWh/t to 478 kWh/t) and an increment of exergy efficiency of about 11.5%.

The paper by S. Mazzoni et al. [22] offers the use of polygeneration power plants in the smart energy scenarios as a valid option to the traditional production systems in terms of cost savings, pollutant emission reductions and for overall improvement in performance efficiency.

In this specific work the considered LAES system is a small scale one for microgrid application. In literature few studies are conducted about small scale LAES in microgrid application. “Microgrid scale” refers to a liquefaction plant with daily production between few tons and few tens of tons of liquid air. That correlates to a size of air liquefaction plant between lab and industrial scale. The modeling of the LAES system for energy and economic analyses is proposed, together with a comparison with literature data.

2. Methodology

The liquid air energy storage (LAES) operating principle includes 3 main phases: liquefaction of gaseous air when energy is available at off-peak times, storage of liquid air in insulated tanks and expansion of liquid air in turbines to generate power in the peak of demand. The research is carried out through MATLAB model and articulated in the following activities:

- Energy analysis of the LAES system with the calculation of the main operating parameters and the round trip efficiency
- Economic evaluation.

2.1. Energy analysis

Firstly the expansion process is analyzed, considering that the number of the expander units is in the range from two to four. The number of expanders in the expansion unit directly influences the energy output in the discharge phase, which also impacts the overall efficiency of the system. So, the electric power output in the expansion unit with different stages is calculated. Other two parameters of the discharging stage are evaluated: the efficiency of the cold storage and the effectiveness of the superheater. As far as the charging stage is concerned, the power consumption of the compression unit is estimated. Finally, the key parameter that describes the performance of the system - the round trip efficiency - is calculated.

2.1.1 Discharging stage. During the discharging stage, liquid air is pumped by a cryogenic pump from the storage tank and regasified to ambient temperature. The cold energy released during the regasification is stored in a Cold Storage System (CSS) in order to reuse the waste cold for the charging stage. The air expansion is a multi-stage process with superheaters (SHs). The CSS is modeled by means of its utilization factor (%), evaluated as the ratio between the effective thermal power recovered and the maximum available thermal power:

$$\eta_{HGCS} = \frac{\dot{Q}_{u,HGCS}}{\dot{Q}_{tot,HGCS}} \tag{1}$$

For the expansion unit, three different cases were analyzed: from 2 to 4 expansion stages. Air pressure and temperature entering the expansion stage are considered constant. The superheater is modeled as a two-stream heat exchanger. The total output power of the discharging stage is the net Electric power output of the system, $P_{net,d}$ and it is evaluated with the following equations, as elsewhere in literature [23-24]:

$$P_{net,d} = n_{ex} \cdot \dot{m}_{LA} \cdot cp_{ave,air} \cdot TIT \cdot (1 - \frac{1}{\alpha_e^{eta_{pol}}}) \tag{2}$$

$$eta_{iso,ex} = \frac{\alpha_e^{\frac{1}{eta_{pol}}-1}}{\frac{1}{n} - 1} \tag{3}$$

$$\alpha_e = (\beta_{ex})^{\frac{k-1}{k}} \tag{4}$$

where n_{ex} is the number of the expansion processes, $\dot{m}_{LA}$ [kg/h] is the liquid air production at the end of charge phase, $cp_{ave,air}$ [kJ/kgK] is the average isobaric specific heat of air, k is the specific heat ratio of air, eta_{pol} is the polytropic efficiency of the expansion process, β_{ex} is the expansion ratio, TIT is turbine inlet temperature [°C] and p_{amb} [bar] is the ambient pressure.

2.1.2 Charging stage. The charging stage is formed by a compression section and a liquefaction section. A recuperative process is included in the charging stage of the LAES. The recuperative process consists of two stages of compression, with intercooling, a recuperative heat exchanger, an expander, a J-T valve, a phase separator and liquid tank. The charging stage is modelled through the evaluation of the Specific Consumption (SC). The SC can be expressed as a function of both charge pressure and recirculation fraction, as expressed in [23]. Recirculation fraction x_{RF} is the ratio of the mass flow elaborated by the J-T valve and the mass flow entering the recuperative heat exchanger.

2.1.3 Round trip efficiency. The key parameter evaluated in the energy analysis is the round trip efficiency, η_{RT} [%], defined as [23-24]:

$$\eta_{RT} = \frac{P_{net,d}}{P_{net,ch}} \tag{5}$$

Where $P_{net,ch}$ [kW] is the net electric power consumed during the LAES charge phase, $P_{net,d}$ [kW] is the net electric power produced by the power turbines. The specific values of the produced and consumed net electric power are also evaluated per unit of produced liquid air:

- Specific electric power output (SP) [kW/kg]
- Liquefaction specific consumption (SC) [kW/kg]

2.2. Economic evaluation

The economic evaluation and comparison with other storage technologies was carried out calculating the Levelized Cost of Storage (LCOS), which offers a quick comparison of the cost of electricity-to-electricity storage systems [25]. The LCOS is defined as the total cost over the entire lifetime of the plant divided by the total amount of electricity produced by the storage system, and has been used in this study to evaluate the economic potential of the small-scale LAES system. It can be expressed as:

$$LCOS = \frac{I_o + \sum_{t=1}^{t=n} \frac{TC_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{EOUT_t}{(1+i)^t}} \tag{6}$$

Where I_o represents the capital expenditure for investment, TC_t denotes the annual total costs at year t, $EOUT_t$ stands for the annual electricity outputs, and n is the lifetime of the plant [years]. The annual costs and the annual electricity outputs are discounted with the interest rate i.

3. Results

In this section, the results of the energy and economic evaluation are presented and discussed with respect to the state of the art.

3.1. Energy results

The discharging stage was modelled assuming the following ranges:

- Discharging pressure p_d: 50–150 bar
- Storage pressure p_s: 1.10 and 8 bar.

Three cases are studied to evaluate the net Electric power output of the system and the SP: from 2 to 4 expansions. For each case the results are analyzed for two different mass flow rates (800 kg/h and 1000 kg/h). Data of the net Electric power output are compared in Table 1. In all the three cases, the net power output range is higher for a flow rate equal to 1000 kg/h.

Table 1: Net electric power output for two values mass flow rates (800 kg/h and 1000 kg/h).

N. expansions	Flow rate 800 kg/h	Flow rate 1000 kg/h
2	80-160 kW	100-200 kW
3	100-200 kW	120-240 kW
4	100-220 kW	140-260 kW

Table 2 shows the results of the discharging stage calculations considering the best conditions, while Table 3 shows the results of the charging stage calculations.

Table 2: Discharging stage calculations.

Case	N. expansions	P_d (bar)	TIT (K)	$\dot{m}_{LA}$ (kg/h)	P_{netd} (kW)
1	2	150	450	1000 kg/h	200
2	3	150	450	1000 kg/h	240
3	4	150	450	1000 kg/h	260

Table 3: Charging stage calculations.

Case	P_s (bar)	P_{ch} (bar)	SC (kW/kg)
1	1.10	50-100	2- 3.2
2	8	50-100	0.9-1.4

The round trip efficiency η_{RT} is evaluated for $\dot{m}_{LA}$=1000 kg and two different $p_{storage}$ (1.10 bar and 8 bar). Figure 1 shows the round trip efficiency η_{RT} as a function of the SC and the SP for the two values of storage pressure.

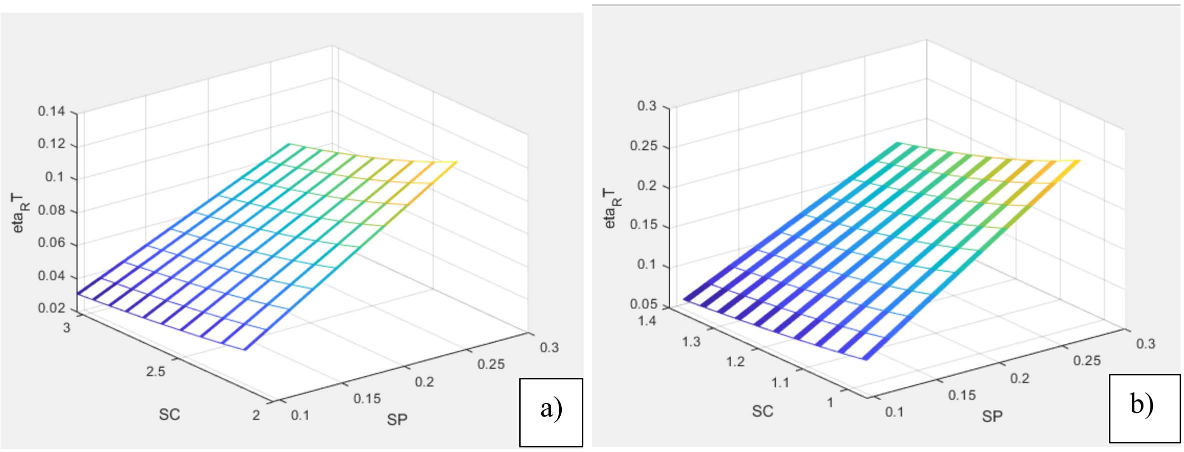

Figure 1: Performance of the $\boldsymbol{\eta_{RT}}$ *at* $\mathbf{p_{storage}}$*= 1.10 bar (a) and 8 bar (b).*

An increase of the SP and a decrease of the SC positively contributes to the η_{RT}. The increase of the SP is related to a higher TIT and a higher discharge pressure, the SC depends instead from the charging pressure. The two graphs allows to highlight the significant dependence of η_{RT} from the storage pressure. For a storage pressure equal to 1.1 bar, the range of the η_{RT} obtained is between 2% and 11%. For a storage pressure equal to 8 bar, **t**he range of the η_{RT} obtained is between 5% and 25%. This results are comparable with others in literature [23-24], showing that there is a strong dependence of the round trip efficiency on the storage pressure.

3.2 Economic results

The capital expenditure for investment consists of three terms; for each one the following values are assumed:

- Capital expenditure for the liquefier: 1100 €/kW
- Capital expenditure for the turbine: 270 €/kW
- Capital expenditure for storage tank: 25.3 €/kW.

The annual total cost (TC) is calculated as the sum of OPEXE (the annual energy based maintenance expense), OPEXP (the annual power based operating expense), EC (the annual electricity purchasing cost) and IC (the insurance costs for all the devices). The OPEXE is assumed equal to 0.00253 €/kW and the OPEXP equal to 10.67 €/kW [26]. The annual electricity purchasing cost is determined by the electricity price. Since the cost of electricity may vary over time, it is assumed an average electricity price of 3 €ct/kWh. As the price is influenced by the number of full load hours per year, both should be examined in combination. For this work it is assumed that the energy storage system working with two cycles per day and so 7300 cycles over the lifetime of 10 years. The insurance costs for all the devices is considered $0.5I_o$ [27].

The P_{netd} and P_{netch} are referred to the case of 4 expansions and $\dot{m}_{LA}$=1000 kg/h; and 170 kW is the storage capacity of the tank. The interest rate i is assumed 2% and the lifetime of the plant is 20 years. The range of the LCOS obtained is between 1.2 €/kWh and 1.8 €/kWh. Such values are higher than the range presented in literature for a large scale LAES system and equal to 0.21-0.649 €/kWh [26]. This may depend from the low round trip efficiency of the small scale system, in fact the LCOS decreases with the increment of the round trip efficiency.

Finally, another study [27] shows the LCOS for different storage systems. PSH system has the lowest cost with 5–9 €ct/kWh and CAES systems have a similar LCOS in the range 7–12 €ct/kWh. Li-ion batteries offer an LCOS between 23 and 37 €ct/kWh at 365 cycles per year; this value is higher than that of Pb batteries which present an LCOS of 15–19 €ct/kWh. VRF batteries have a LCOS of 32 €ct/kWh. The LCOS of battery technologies is expected to decrement in the next decade thanks to the technological developments and decreasing I_o.

Such LCOS values are low compared to the system analysed in this work. Nevertheless, both studies in [26-27] considered large-scale storage systems, as the comparison shows that there is an increase in costs in the small scale: a small scale cycle optimization is therefore necessary.

4. Conclusion

In this work, an energy and economic analysis on small-scale LAES is presented. The LAES operative parameters were analyzed via MATLAB simulations: specific consumption, net electric power output and round trip efficiency.

To evaluate the net electric power output three different cases were analysed: the first one considers 2 expansions, the second one 3 expansions and 4 in the last one. For each case the results are analysed for two different mass flow rates (800 kg/h and 1000 kg/h). The optimal case is given with a flowrate of 1000 kg/h and 4 turbine expansions, resulting in a net electric power output in the discharging process of 260 kW and the optimal values are 450 K for inlet temperature, 1000 kg/h for the mass flow rate and 150 bar for the discharge pressure.

For the charging process the specific consumption is significantly affected by the storage pressure. With its increase, a lower specific consumption is obtained considering the same range of the charge pressure and recirculation fraction, resulting in a maximum value of the specific consumption in the charging process of 1.4 kW and minimum value of 0.9 kW for a storage pressure of 8 bar compared to the 2-3.2 kW for a storage pressure of 1.10 bar. Also the round trip efficiency is influenced by the storage pressure.

Its increase allows to have a higher efficiency: for a storage pressure of 8 bar the round trip efficiency is about 25% compared to the 12% in case of a storage pressure equal to 1.10 bar.

For the economic feasibility, the range of the LCOS obtained is between 1.2 €/kWh and 1.8 €/kWh. These values are higher than any other technologies studied in literature in fact the LCOS varies between about 0.10 and 0. 60 €/kWh for the CAES, PSH, Li-ion, Pb and vanadium redox flow (VRF) batteries. This may be caused by the small scale of the system.

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