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Techno-economic Analysis of Different Liquid Air Energy Storage Configurations

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With the increasing use of renewables in energy systems, grid stability becomes a major issue due to the intermittent nature of energy sources such as solar and wind. To compensate for the unstable renewable energy sources, storage technologies have been regarded as effective methods. Liquid air energy storage (LAES) has gained wide attention due to its inherent advantages: geographically unconstrained and high energy density. This work presents a techno-economic analysis of an LAES system with a storage capacity of 10 MW / 80 MWh. Three different layouts of the LAES are evaluated and compared based on net present value (NPV) and payback period. The economic results show that the LAES system with a 2-stage compressor and a 3-stage expander (Case 1) has the largest NPV of 918.1 M$, which is 33.7 % and 10.7 % larger than a system with a 4-stage compressor and a 4-stage expander without (Case 2) / and with (Case 3) an additional Organic Rankine Cycle (ORC). In addition, the shortest payback period of 6.2 y is obtained in Case 1 compared to 6.9 and 6.4 y for Cases 2 and 3. This means that Case 1 is the most profitable layout for the studied LAES systems.

1. Introduction

One of the deep environmental concerns is greenhouse gas emissions and their impact on climate change. It is reported that global warming can only be mitigated if the CO_2 emissions are reduced by at least 40 % by the year 2030 compared to 1990 (European Commission, 2014). This will promote the development of low-carbon energy sources, such as renewable energy. The most widely used renewables beyond hydroelectric power are solar and wind energies, which are characterized by intermittency. Consequently, the increasing share of renewable power connected to the grid requires a flexible energy system with fast response abilities. Appropriate energy storage technologies can be used to handle unstable and unpredictable renewables as well as surplus grid capacity during low demand hours. Energy storage can also be used for additional power generation during high demand hours. This is referred to as peak shaving and valley filling (Strbac, 2008).

While thermal energy storage is increasingly important, the focus of this work is electricity storage, since power is one of the most convenient forms of energy. The most mature technologies for storing electricity is pumped hydroelectric energy storage (PHES) (Rozali et al., 2013), compressed air energy storage (CAES) and batteries (Aneke and Wang, 2016). However, some features of the mentioned technologies have limited their deployment, such as geographical constraints of PHES and CAES, and high capital cost of batteries. The concept of liquid air energy storage (LAES) was first proposed in 1977 (Smith, 1977). The main advantages of LAES are being geographically unconstrained and having high energy density. However, the main drawback for the LAES is that the round-trip efficiency (RTE), which is the ratio between the power production in the discharge mode and the power consumption in the charge mode, is lower compared to PHES, CAES and batteries.

Most existing publications focus on techno-economic analyses of a specific layout for the LAES system (Borri et al., 2021). However, there is a lack of comparison between different configurations for a standalone LAES, which will also be valuable for integrated systems between the LAES and other energy conversion processes. In the work of Liu et al. (2020), the thermodynamic optimum was found to be for few compression stages with large pressure ratios. The effect of compressors with high pressure ratios on the cost estimation for the LAES

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system is neglected in most studies (Borri et al., 2021). In this work, a techno-economic analysis of three different layouts for the LAES is investigated, and this can be regarded as an extension of the purely thermodynamic study by Liu et al. (2020). It is found that the highest RTE is obtained when there is a 2-stage compressor and a 3-stage expander in the LAES, and this is selected as Case 1. However, a system with a maximum energy efficiency is not necessarily the most economic option. One of the challenges for the best LAES configuration (highest RTE) is that the pressure ratios of the compressor stages are relatively large, and an extra cost factor has been applied to compressors with high pressure ratios for fair comparison with other processes. Case 2 is an LAES system with a 4-stage compressor and a 4-stage expander, which has moderate pressure ratios of less than 4. Case 3 is testing the economic feasibility of Case 2 with an additional Organic Rankine Cycle (ORC) to utilize the unused part of compression heat. The evaluation indexes (NPV and Payback Period) of different LAES configurations are compared, and the most economical layout of the LAES is identified.

2. System description

The flowsheet of an LAES system is shown in Figure 1. The LAES consists of the compression part, the energy recovery part (hot and cold), and the expansion part. In the compression part, air is sent to a multi-stage compressor by consuming off-peak electricity during low demand periods. The high-pressure air is then sent to the cold energy recovery part, where compressed air is cooled in the cold box and partially liquified after being expanded to atmospheric pressure. Liquid air is stored in a cryogenic tank under atmospheric pressure and will be sent to a pump and evaporators during high demand periods. The cold energy from liquid air regasification is transferred to the compressed air by cold energy recovery cycles. In the expansion part, the regasified air is sent to a multi-stage expander to produce power. Heat is sent from the compression part to the expansion part by a hot energy recovery cycle, and this heat is used to preheat and later reheat air to increase power production.

Table 1: The main operating parameters and key performance indicators of various LAES configurations.

Parameters	Unit	Case 1	Case 2	Case 3
Molar flow rate of air	kmol/h	2,131.62	2,745.96	2,650.67
Pressure ratio of compressor stages	-	13.05	3.67	3.67
Charging pressure	bar	171.85	187.12	187.12
Discharging pressure	bar	148.41	159.81	159.81
Compression work	MW	15.00	16.09	15.53
Expansion work	MW	10.00	10.00	9.65
Net work output from ORC	MW	-	-	0.40
Liquid yield	%	86.21	86.62	86.62
RTE	%	66.65	62.16	64.41

From the results of the thermodynamic analysis for different LAES configurations by Liu et al. (2020), Case 1 has the highest RTE and the highest pressure ratio of compressor stages among the studied standalone LAES configurations. Conventional compressors cannot achieve a pressure ratio of 13. Since the cost data for unconventional compressors with high pressure ratios are uncertain, an extra cost factor is applied for these units as discussed in Section 3.1.1. In Case 2, the pressure ratio is within the normal range (less than 4) and conventional compressors can be used. From the work of Liu et al. (2020), it is shown that the performance of the LAES is improved when an ORC is used to convert the unused part of compression heat to work, and this is referred to as Case 3. Cases 1 and 2 are variants of the LAES system shown in Figure 1, and the only difference between them is the number of compression and expansion stages. An additional power cycle used in Case 3 makes it different from Cases 1 and 2, as illustrated in Figure 2. In this work, it is assumed that the LAES system has a storage capacity of 10 MW / 80 MWh to provide auxiliary services to renewable power plants. The main operating parameters and key performance indicators of the three cases are listed in Table 1.

3. Methodology and Economic Data

3.1 Economic model

First, the total capital investment cost, total annual operating cost, the depreciation of capital investment and the annual income are presented. Then economic evaluation indexes are introduced. Finally, the initial conditions and assumptions for cost estimation of the LAES system are provided in this section.

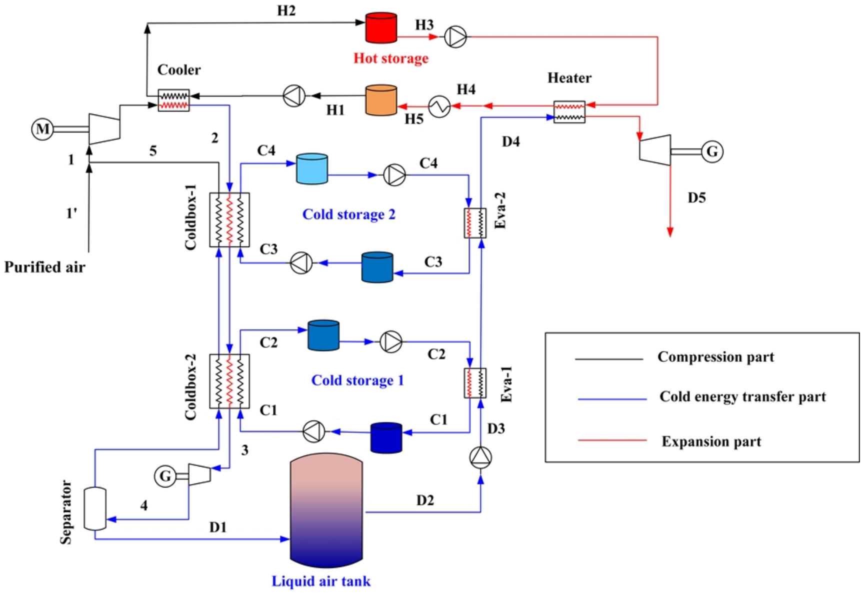

Figure 1: Flowsheet of the LAES system

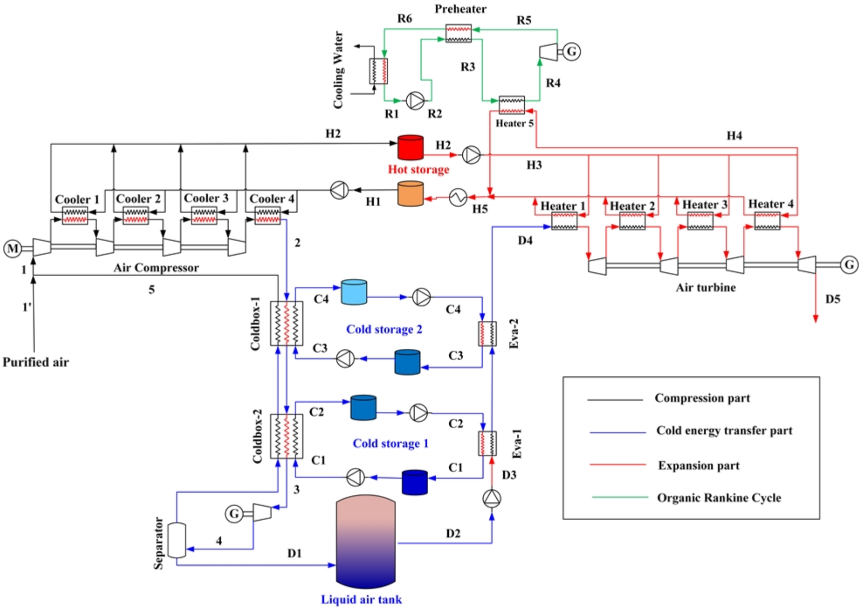

Figure 2: Flowsheet of the LAES system with an additional ORC

3.1.1 Total capital investment cost

Total capital investment cost (C_{TCI}) consists of total bare-module investment cost (C_{BM}), contingency cost and contractor fee (C_{CC}), land acquisition cost (C_{LA}), and working capital cost (C_{WC}), as shown in Eq(1). The bare-module investment cost of each component in the LAES system is provided in Table 2. The C_{CC} and C_{WC} are estimated to 18 %, and 15 % of total capital investment cost (Turton et al., 2013). The C_{LA} is calculated based on the assumption of a standalone LAES requiring 19,218 m^2 with a land price of 3.47 $\$/m^2$ (Cui et al., 2021).

$$C_{TCI}=C_{BM}+C_{CC}+C_{LA}+C_{WC} \tag{1}$$

3.1.2 Total annual operating cost

Total annual operating cost (C_{AOC}) is composed of maintenance cost (C_{MC}), labor cost (C_{LC}), and utility cost (C_{UC}), as is shown in Eq(2). The C_{MC} is calculated as 6 % of total capital investment in the three case studies. The C_{LC} is estimated by assuming that the LAES plant is operated by 20 workers with an annual salary of 56,310 \$/person (Bureau of Labor Statistics, 2020) in all three cases. The C_{UC} is the sum of electricity cost during low demand hours for power consumption in compressors and cooling water cost for cooling duties.

$$C_{\mathrm{AOC}} = C_{\mathrm{MC}} + C_{\mathrm{LC}} + C_{\mathrm{UC}} \tag{2}$$

3.1.3 Depreciation of capital investment

The depreciation of capital investment (C_{D}) is the difference between the purchase and installation cost before the plant is put into operation and the gains obtained by selling equipment when the plant is closed. This is taken as an expense each year. In this work, the C_{D} is calculated by using the year-average method, see Eq(3).

$$C_{\mathrm{D}} = \frac{C_{\mathrm{TCI}} \cdot \eta_{\mathrm{f}} \cdot (1-\beta)}{N_{\mathrm{f}}} \tag{3}$$

Here, η_{f} is the conversion rate of the total capital investment (%); β is the residual value rate (%); and N_{f} denotes the depreciation period (y). In this study, η_{f} and β are assumed to be 95 % and 5 % .

Table 2: Bare-module investment cost of each component in the LAES system

Component	Main variable	Method	Reference
Compressors	Capacity, $\dot{W}_C$ (kW)	246 \$/kW or 455.1 \$/kW[a]	(Latz, 2008)
Turbines	Capacity, $\dot{W}_T$ (kW)	268.5 \$/kW	(Latz, 2008)
Cryo-turbine	Capacity, $\dot{W}_{CT}$ (kW)	$11514 \cdot \dot{W}_{CT}^{\;0.67}$ \$/kW	(Ulrich and Vasudevan, 2004)
Heat storage	Volume, V (m^3)	$(242 \cdot V + 619300)$ \$/m^3	(Peters et al., 2003)
Aftercoolers and preheaters	Area, A (m^2)	$(1.43 + 2.068) \cdot \frac{65 \cdot A}{1000}$ \$/m^2	(Ulrich and Vasudevan, 2004)
Cold box and evaporators	Area, A (m^2)	$(160.6 + 281.1) \cdot \frac{A}{2000}$ \$/m^2	(Ulrich and Vasudevan, 2004)
Cold storage	Duty, $\dot{Q}$ (kWh)	15,125 \$/kWh	(Morgan et al., 2015)
Liquid air tank	Mass, $\dot{m}$ (t)	2,480.5 \$/t	(Morgan et al., 2015)
Liquid pump	Capacity, $\dot{W}_P$ (kW)	$2820 \cdot \dot{W}_P^{\;0.6}$ \$/kW	(Ulrich and Vasudevan, 2004)

[a] An extra cost factor of 1.85 is applied for Case 1 to handle compressors with high pressure ratios.

3.1.4 Annual income model

The profit can be obtained by selling the stored electricity during high demand hours. The annual income model (C_{AI}) is given in Eq(4).

$$C_{\mathrm{AI}} = \dot{W} \cdot C_{\mathrm{hd}} \cdot h_{\mathrm{an}} \tag{4}$$

Here, $\dot{W}$ denotes the power production in the discharging process (kW); C_{hd} is the electricity price during high demand periods (\$/kWh); and h_{an} represents the annual number of hours with power generation (h/y).
The key input parameters for economic estimation in this work are plant lifetime of 20 y, energy storage and release times of 8 h, 4,800 operating h/y, 10 % interest rate, and off-peak and on-peak electricity prices of 0.26 and 0.58 \$/kWh (Hawaii electric, 2022).

3.1.5 Economic evaluation index

The net present value (NPV) is a widely adopted parameter to evaluate profitability of a project. NPV is the difference between the present worth of cash flow (annual income, annual operating cost, and depreciation of capital cost) and the total investment cost, as shown in Eq(5). Here, i is the annual interest rate that in this study is set to be 10 %, while t is the service life of an LAES plant, which is assumed to be 20 y. A positive NPV means that the project is economically feasible, while a negative NPV means that the project is not profitable.

$$NPV = -C_{\mathrm{TCI}} + (C_{\mathrm{AI}} - C_{\mathrm{AOC}} + C_{\mathrm{D}}) \cdot \frac{(1+i)^t - 1}{i \cdot (1+i)^t} \tag{5}$$

The payback period is another commonly used parameter to estimate the time required to reach a break-even point (NPV = 0), which is the time when the capital investment of a project is completely recovered. The formula for the payback period is given in Eq(6).

$$Payback\ period = \frac{Total\ investment\ cost}{Annualized\ cash\ flow} = \frac{C_{\mathrm{TCI}}}{(C_{\mathrm{AI}} - C_{\mathrm{AOC}} + C_{\mathrm{D}}) \cdot \dfrac{(1+i)^t - 1}{i \cdot (1+i)^t}} \tag{6}$$

4. Results and Discussion

The techno-economic analysis of three cases studies related to different layouts of a standalone LAES system is conducted, and the economic performance of the three cases is discussed as follows.

Table 3: Total cost figures and financial evaluation indexes of different LAES configurations

	Parameters	Unit	Case 1	Case 2	Case 3
Total investment cost	Compression part	M$	9.36	5.45	5.27
	Expansion part	M$	3.74	3.79	3.79
	Cryo-turbine	M$	0.92	1.14	1.11
	Liquid pump	M$	0.17	0.20	0.24
	Heat exchangers	M$	9.93	10.82	11.63
	Storage tanks	M$	3.24	4.04	3.94
	C_{LA}	M$	0.07	0.07	0.07
	C_{CC}	M$	4.78	4.58	4.68
	C_{WC}	M$	3.98	3.82	3.90
	C_{TCI}	M$	35.38	33.90	34.62
Total annual operating cost	C_{MC}	M$/y	2.12	2.03	2.08
	C_{LC}	M$/y	1.13	1.13	1.13
	C_{UC}	M$/y	9.36	10.04	9.70
	C_{AOC}	M$/y	12.61	13.20	12.90
	C_{D}	M$/y	1.23	1.15	1.17
	C_{AI}	M$/y	13.92	13.92	13.97
	NPV	M$	918.06	686.69	829.02
	Payback period	y	6.24	6.93	6.40

Table 3 with investment cost of equipment, annual operating cost, annual income, and economic evaluation indexes, shows that the three LAES configurations have different profitability. The total investment cost in Case 1 is the highest, followed by Case 3, while Case 2 has the lowest. Obviously, the extra cost factor applied to the cost model of compressors with high pressure ratios in Case 1 leads to a higher price of the compression part compared to Cases 2 and 3. However, due to the high efficiency of Case 1, the cost of other equipment is lower compared to Cases 2 and 3. It is worth noting that the annual income in the three cases are slightly different, which is caused by very small differences in the power output of the cases, but all of them are set to be close to 10 MW. The NPVs of the three cases are positive, which means that all of them are profitable. However, the largest NPV (918.1 M$) and the shortest payback period (6.2 y) are obtained in Case 1 due to its high system efficiency and low total annual operating cost. This indicates that Case 1 is the most economical layout of the studied cases. The payback periods for Cases 2 and 3 are 6.9 and 6.4 y. By comparing Cases 2 and 3, it can be found that not only the energy efficiency is increased, but the NPV is also increased with an additional ORC when there is a 4-stage compressor and a 4-stage expander in the LAES. The profit gained by the increased power output can justify the increased cost related to the additional ORC in Case 3.

5. Conclusions

In this work, a techno-economic analysis of three different layouts of a 10 MW / 80 MWh liquid air energy storage (LAES) is performed and the cases are compared. Case 1 is an LAES system with a 2-stage compressor and a 3-stage expander. LAES systems with a 4-stage compressor and a 4-stage expander are studied as Cases 2 and 3. Case 3 is identical to Case 2, except for an additional Organic Rankine Cycle (ORC) to utilize the unused part of compression heat. Net present value (NPV) and payback period are selected as economic evaluation indexes to indicate the profitability of different LAES processes. The results indicate that the NPV of the three cases is positive, which means that all of them are profitable. In addition, Case 1 has a much better economic performance than Cases 2 and 3 in terms of NPV and payback period. This is mainly a result from the high round-trip efficiency of the system and the low utility cost related to the purchase cost of off-peak electricity in Case 1. By comparing Cases 2 and 3, it can be concluded that the profit gained by the increased power output can justify the increased total investment cost with an additional ORC.

It can be obtained from the techno-economic analysis of three case studies that a standalone LAES with a storage capacity of 10 MW / 80 MWh is economically feasible. Compressors with high pressure ratios are favorable in an LAES system with the consideration of energy efficiency and economics. However, the profitability of different LAES systems is highly dependent on the on-peak and off-peak electricity prices, the number of annual operating hours, and the extra cost factor. A sensitivity analysis for the mentioned factors in different LAES configurations should be performed in future research. In addition, system scale has a significant effect on the economic performance of a process, which will also be considered in future work.

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