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Techno-economic analysis of a Liquid Air Energy Storage (LAES) for cooling application in hot climates

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Abstract

This work investigates the technical and economic feasibility of a Liquid Air Energy Storage (LAES) for building demand management applications. The thermodynamics and processes of the LAES configuration, as well as the description of the daily cooling energy demand profile, are described in details and the assumptions and constraints are pointed out. The quantitative analysis has been carried out for a daily cooling energy demand of an existing office building, located in Singapore, locality characterized by a typical hot climate. A thermodynamic analysis has been carried out for LAES configuration by means of the Aspen HYSYS® process simulation code. Under the technical assumptions formulated, LAES achieves an overall round trip efficiency of 45% with a specific consumption of 0.20 kWh/kgLA. The exergy analysis shows that LAES is characterized by an exergy efficiency of 84% and 67 % for the liquefaction and the discharge processes, respectively; the compressor and the power turbines account for the highest exergy losses. Finally, the economic results show that under the actual condition of peak tariff and off-peak tariff in Singapore, the investment proposed is not convenient but in case of high values of LAES round trip efficiency and lower OPT the investment may be attractive. However, future works have to deal with the limitations introduced in the analysis, such as neglecting LAES operation costs, and the uncertainty related to capital costs figures.

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Keywords: Energy storage, Liquid air, Cold Economy, Cryogenic, Demand side management.

Nomenclature

COP	Coefficient of Performance	\dot{m}	Mass flow (ton/day)
E	Energy (kWh)	\dot{Q}	Cooling Power (kW _{th})
\dot{E}_x	Exergy flow (kW)	\dot{W}	Electric Power (kW)
LAES	Liquid Air Energy Storage	η	Efficiency

<i>Subscripts</i>			
ch	Charge phase	HTF	Heat Transfer Fluid
Compr	Compressor	IC	Intercooler
CT	CryoTurbine	P	Pump
d	Discharge phase	PT	Power Turbine
e	Electric	TES	Thermal Energy Storage
HEs	Heat Exchangers	th	Thermal
HGCR	High Grade Cold Recycle	WHR	Waste Heat Recovery

1. Introduction

The concept of a sustainable cold economy was first introduced in a paper published by Liquid Air Energy Network and the Institution of Mechanical Engineers [1]. A cold economy involves the concept of recovery of waste cold energy [2], cold energy storage [3], higher efficiency in cold generation and demand side management for cooling energy [4]. Demand side management is a mean to increase the overall efficiency of the entire electricity network - from generation to the end use - which consists of optimizing the allocation of resources, limiting the peak demand and shaping the demand depending on the necessity of the grid [5]. In this context cooling energy storage can play an important role in shaving the peak demand burdening electric grid. Indeed, cold energy storage can be used to develop demand side management strategies to shift the load from peak to off-peak hours (thus exploiting price arbitrage potential) even in presence of renewable energy.

Liquid Air Energy Storage (LAES) is a long term cryogenic energy storage technology, with very high specific energy (214 Wh/kg) [6] suitable for mid to large scale applications. One of the most interesting features of LAES technology is that it can produce both electricity and cooling energy at the same time: electrical power from the generator and cold power from the regasification process and turbine outlet.

The main goal of this work is the thermodynamic and economic analysis of a LAES configuration in order to approach building demand management in hot climates. The School of Art, Design and Media (SADM), located within the Nanyang Technological University (NTU) campus in Singapore, has been taken as reference case. The simulation of LAES is computed by means of the Aspen HYSYS® process simulation code: LAES configuration is modeled and implemented in the software in order to fulfill the energy cooling demand imposed by the energy audit of ADM building.

2. Material and Methods

2.1 Energy Cooling Demand Data

The case study covered in this paper is for a building located in Singapore; air conditioning for the building is provided by water cooled chillers: the chiller plant is fitted with three water cooled chillers. Chillers (CH) A and B are fitted with centrifugal compressor, using R-123 refrigerant, having a cooling capacity of 1582 kW_c each. Chiller C is fitted with a screw compressor, using R-134a refrigerant, having a cooling capacity of 1055 kW_c. Chiller B usually provides the cooling energy demand exceeding the capacity of chiller C. Chiller A is usually used as backup unit. Usually, the building is closed on Sundays and Public Holidays (PH) and therefore none of the chillers operates during these periods.

The energy audit of the building and the analysis of both cooling load and COP of the cooling system have been already assessed by a previous study [4] that has utilized real data obtained by monitoring the chiller system over 4 months. Since in Singapore there is no real alternation in climate between summer and winter, the measured cooling load is almost steady throughout the year, thus, based on the behavior of the building over 4 months, a representative cooling load profile for a typical working day has been

provided, as shown in Fig. 1. Three different operating phases can be identified for the cooling system: a peak-load phase in the morning between 07:00 and 09:00; a maintaining phase, between 09:00 and 19:00, that covers most of the day when the cooling load ranges between 1000-1200 kW_c; a partial load phase, between 19:00 and 23:00, where the reduction of cooling demand is due to lower occupancy of the building. The average COP of the chiller system is 5.343 (during office hours between 08.30 and 17:30). The energy audit and the analysis of both cooling load and COP of the cooling system has underlined potential for further improvement of its techno-economic performance.

The purpose of the present work is to assess the economic viability of using Liquid Air Energy Storage (LAES) to implement demand side management strategies in order to exploit the price arbitrage potential due to the difference between peak and off-peak electric tariffs in Singapore. In particular, LAES is used to replace the less efficient chillers (chillers A and B) between 09:00 and 19:00. The proposed strategy would be that of running the LAES together with chiller C (more efficient than chillers A and B) in order to reduce the peak load during the maintain phase (yellow area in Fig.1) so that only the most performing chiller (chiller C) needs to operate; the other two serve as backup units. In this case, the LAES would be charged during night time with consequent economic benefit due to price arbitrage.

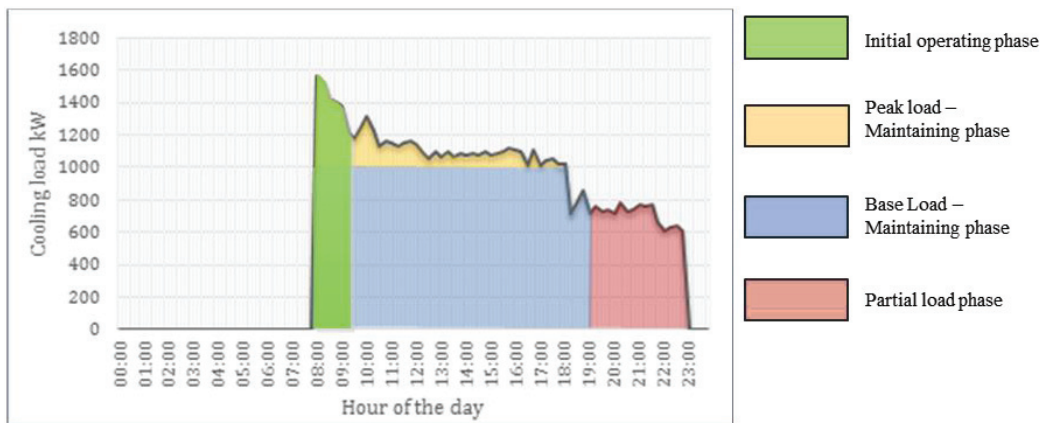


Fig. 1. Cooling load profile for a typical normal operative day

2.2 LAES design

Liquid Air Energy Storage system can be separated into two processes: charge and discharge. The compressed air is cooled and turned into liquid air after passing through throttle valve and phase separator; the liquid air is thus stored in low pressure cryogenic tank. In order to increase the process efficiency, a high grade cold storage has been implemented by means of an heat exchanger denominated HGCR that store the cold energy released by air during the discharge process. A packed bed regenerator, filled with porous solid, could be employed for such a purpose [7]. During the discharge process, liquid air from the tank will go through a cryogenic pump and heated up to gaseous air by the cold storage medium, then expands to ambient pressure in turbines with reheating processes. The air working fluid is therefore re-heated between 4 stages to achieve quasi isothermal expansion. An intermediate circuit with thermal oil (DOWTHERM Q) as heat transfer fluid is used as thermal energy storage in order to store compressed heat and superheat air during each expansion phase. In order to fulfil the cold energy demand required by the building, the air at turbine outlet (5 °C) is thermally coupled with the water cooling circuit, by means of a heat exchanger. Fig. 2 shows a simplified schematic of the LAES process. Taking into account the data provided from manufacturers [8], the following assumptions will be valid throughout the numerical analysis carried out with Aspen Hysys:

- Air is introduced at atmospheric pressure and at a temperature of 25 °C;
- 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 during the two separate processes;
- minimum approach temperature in Cold box heat exchangers is set to 1 K;
- isentropic efficiencies of compressor η_C and cryoturbine η_{CT} are set respectively to 0.9 and 0.8;
- isentropic efficiencies of power turbines η_{PT} and cryogenic pump η_P are set to 0.8

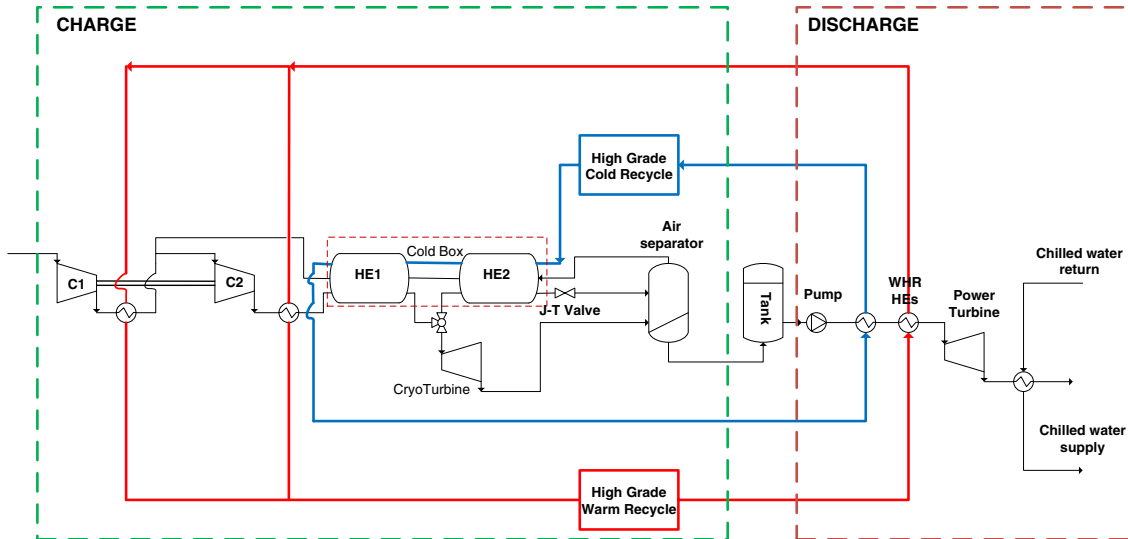


Fig. 2 Simplified schematic of the LAES charge (left) and discharge (right) process

2.3 Performance assessment indexes

On the basis of the hypothesis mentioned earlier, the following performance parameters were calculated:

- Overall round trip efficiency, defined as the ratio of the sum between the net power recovered during discharge and the cooling load (converted to electricity by means of COP term) provided over the compression power during charging :

$$\eta_{RT} = \frac{\dot{W}_{discharge}}{\dot{W}_{charge}} = \frac{\sum \dot{W}_{PT,d} - \dot{W}_{P,d} + \frac{\dot{Q}}{COP}}{\sum \dot{W}_{Compr,ch} - \sum \dot{W}_{CT,ch}} \quad (1)$$

- Specific consumption [kWh/kgLA], defined as the net work required to liquefy a kg of liquid air:

$$S.C. = \frac{\sum \dot{W}_{Compr,ch} - \sum \dot{W}_{CT,ch}}{\dot{m}_{LA}} \quad (2)$$

- Exergy efficiency of liquefaction and discharge system:

$$\eta_{ex,ch} = \frac{\dot{Ex}_{LA} + \dot{Ex}_{HTF}}{\sum \dot{W}_{Compr,ch} - \sum \dot{W}_{CT,ch} + \dot{Ex}_{HGCR}} \quad (3)$$

$$\eta_{ex,d} = \frac{\sum \dot{W}_{PT,d} - \dot{W}_{P,d} + \frac{\dot{Q}}{COP} + \dot{E}x_{HGCR}}{\dot{E}x_{LA} + \dot{E}x_{HTF}} \quad (4)$$

where $\dot{E}x_{LA}$ represents the exergy flow rate of liquid air produced by the charge section; $\dot{E}x_{HTF}$ and $\dot{E}x_{HGCR}$ are the exergy flow rate associated with the hot thermal oil and the High Grade Cold Recycle, respectively.

- The economic analysis is based on the Annual economic savings (US\$) computed as the difference between the yearly operative costs before and after the introduction of the energy storage:

$$Savings_{econ,year} = \left(\frac{E_{shift,daily}}{COP} \cdot PT - E_{charge,daily} \cdot OPT + E_{discharge,daily} \cdot PT \right) * NOD \quad (5)$$

where $E_{shift,daily}$ is the amount of cooling energy to be shifted by means of the storage and COP represents the average COP of chiller during maintaining phase; $E_{charge,daily}$ is the daily electricity to charge, namely the amount of electricity to liquefy the air; PT and OPT [US\$/kWh] are the peak and off-peak tariffs, respectively, and NOD is the number of the operative days per year. The last term of the equation ($E_{discharge,daily} \cdot PT$) represents the cost savings due to the LAES electricity production that is supplied directly to the chillers and the other facilities of the building.

- The capital cost (US\$) of a LAES is a function of both the costs per energy unit and the costs per power unit [5]:

$$CAPEX = E_{discharge,daily} \cdot Cost \text{ per energy unit} + \sum \dot{W}_{PT,d} \cdot Cost \text{ per power unit} \quad (6)$$

where, according to [6] and [9], the cost per energy unit has been computed as 400 US\$/kWh_e and the cost per power unit as 1500 US\$/kW_e. Taking into account both the capital costs and the annual economic savings, it is possible to evaluate the payback period (years), the key performance index of the economic analysis.

3. Results and discussion

3.1 Exergy analysis

This section presents the results of the techno-economic study carried out in order to find the economic viability of the LAES according to its use in the cooling system management strategy. Based on the assumptions of Section 2, the simulations showed that, under an optimal charge and discharge pressures of 80 bar and 124 bar, respectively, a specific consumption of 0.20 kWh_e/kgLA and an overall round trip efficiency of 45 % could be achieved*. It was assumed that the new cooling system, integrating the cold

* It is worth pointing out that the extremely low value of specific consumption is achieved with the combined effect of the high grade cold storage and the pinch point assumption (1 K) imposed at both heat exchangers during the charge phase. Setting the pinch point to higher value (5 K) and neglecting the presence of HGCR, the specific consumption would increase to values around 0.5 kWh/kgLA affecting in turn the value of round trip efficiency.

storage and the existing chillers, had to satisfy a daily average cooling energy demand of 12,872 kWh_c, considering 275 operative days per year. The main performance parameters are specified in Table 1.

Table 1

Simulation results

Parameter	Value
Cooling Demand	731 kWh _{th}
Power Rating	982 kW _e
Round trip efficiency	45%
Specific consumptions	0.20 kWh/kgLA
Exergy efficiency liquefaction	84 %
Exergy efficiency discharge	67 %

As illustrated by Figs.3-4, the results achieved with the exergy analysis show that the analyzed configuration achieves high level of exergy efficiency for the charging phase, thanks to the presence of a high grade cold storage, while exergy efficiency is sensibly lower for discharge process. Strictly in accordance with [10], the method employed to extract the cold exergy from the cryogen is the direct expansion method, a simple but also inefficient discharge process. In fact it does not fully use the cold energy of the cryogen since the cold energy discharged by liquid air in HGCR is recycled in order to decrease the specific consumption of the charging process. Moreover, since the cold energy is provided to the building by means of the flow at turbine outlet, the maximum air temperature at turbine inlet is limited by the chilled water supply temperature. Therefore, as emphasized by the notable dissipation of exergy flow linked with the waste heat recovery system, due to energy cooling demand, the system is not able to fully exploit the WHR provided during the compression phase.

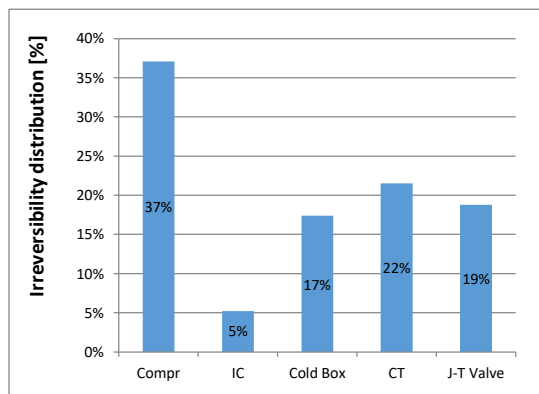


Fig.3. Irreversibility distribution for liquefaction process

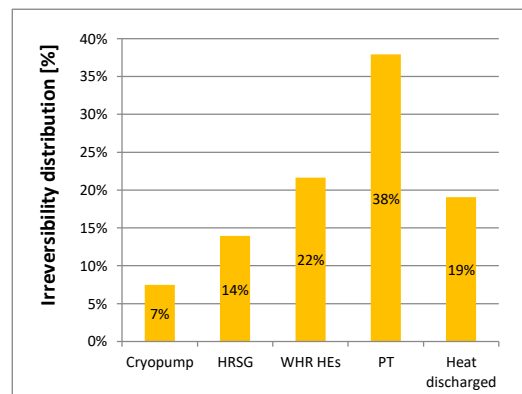


Fig. 4. Irreversibility distribution for discharge process

3.2 Economic analysis

The scenario analyzed is meant to exploit the price arbitrage potential due to the difference between peak and off-peak electricity tariffs in Singapore, shifting the daily average surplus due to cooling peak (731 kWh) in the average working day. In fact, during off-peak hours LAES is charged while from 09:00 to 19:00 chiller C supplies the cooling energy required to the building at its maximum capacity: whenever the energy demand exceeds this limit, the cold storage provides the surplus energy required. As shown by Table 2 the economic investment is not economic viable due to current low round trip efficiency (45 %), the actual PT/OPT of Singapore and the high COP of the chillers. It is worthwhile nothing that Singapore

represents the worst case scenario for the present study since the nominal COP of the chiller is sensibly higher compared to European standard characterized by lower COP values (≈ 3.5 -4).

Table 2
Economic results

	Round trip Efficiency (%)	PT (US\$/kWh _e)	OPT (US\$/kWh _e)	CAPEX (MUS\$)	Annual Savings (MUS\$)
Ref.Case	45	0.138	0.09	5.4	Negative

In order to investigate the combined effect of PT/OPT and round trip efficiency over the economic feasibility of the LAES coupled with the chillers, a sensitivity analysis has been carried out.

Each curve presented in Fig. 5 and Fig. 6, for a defined value of overall round trip efficiency, shows the annual savings and the payback period of the system function of the OPT, expressed as a percentage of PT. It points out that for the reference case the break-even point of the investment is achieved only if the OPT is about 45 % of PT. Moreover, the annual savings are always positive just for value of round trip efficiency above 70%. As highlighted by Fig. 6, at high round trip efficiency ($>60\%$), the payback period tends to be economically remarkable (< 20 years) only if the off-peak energy tariff is about 20 % of the peak one. It is worthwhile nothing that such an analysis does not take into account the operative costs associated with LAES that may put at stake the economic feasibility of the investment or in alternative make it particularly profitable.

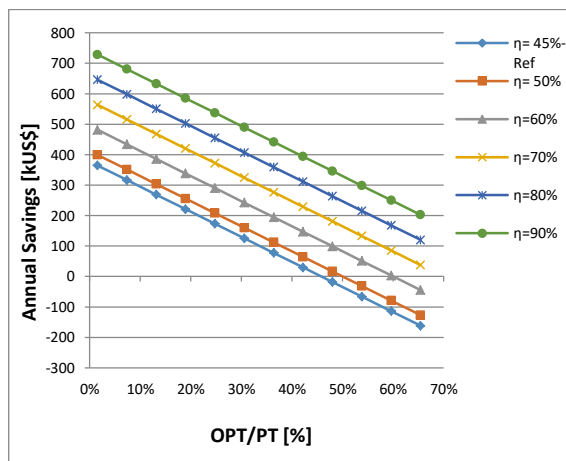


Fig.5. Annual Savings function of OPT and η_{RT}

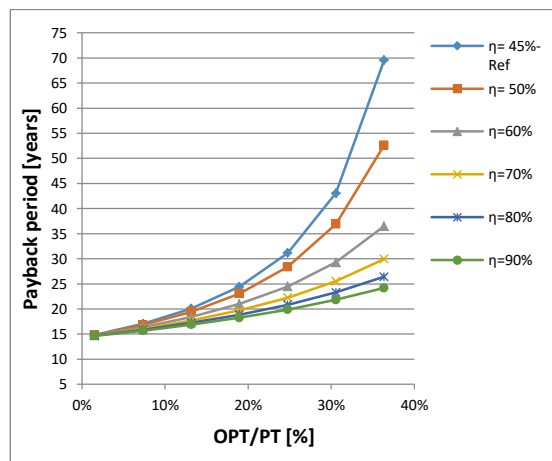


Fig. 6. Payback period function of OPT and η_{RT}

As a final remark, it is worthwhile pointing out that since the technology considered in this study has not achieved the market maturity: the figures for prices provided by literature can be considered more as estimates than actual market prices.

4. Conclusions

In this paper, a thermodynamic and economic analysis of LAES for building demand management in Singapore was studied. Even though three possible areas of intervention have been identified, in the proposed study it was decided to assess the LAES to exploit the difference between peak and off-peak electricity rate, thus leveraging on demand management strategies in order to reduce peak loads.

LAES configuration is described and the thermodynamic assumptions adopted are highlighted as well as the average daily cooling demand. The resulted value of round trip efficiency in cooperation with the high COP of chillers and the PT/OPT of Singapore does not allow to achieve the economic feasibility of the investment (negative annual savings). Analyzing the effect of PT/OPT and round trip efficiency over the economic key performance indices, for the reference case the break- even point is achieved only if OPT is approximately 45 % or below of the PT value. Even though the annual savings are always positive when the round trip efficiency of LAES is increased to higher level (>70%), the sensitivity analysis on pay-back period confirms that only at low OPT percentage of PT the investment may be attractive with a payback period inferior to 20 years. Nevertheless, both the remarkable uncertainty over the capital costs figures and the fact that the analysis does not take into account the operation costs associated with LAES, may significantly affect the economic feasibility of the new configuration.

Acknowledgements

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Biography

Alessio Tafone is a PhD candidate at Nanyang Technological University (NTU). He earned a MSc in Energy and Nuclear Engineering at the University of Bologna. His research activities are focused on waste heat recovery and thermal energy storage, with a focus on Liquid Air Energy Storage systems (LAES).