

# ***Simulation of Thermodynamic Efficiency and Plant Equipment Finance for Cryogenic Energy Storage Systems as Applied to Medium to Large Scale Liquid-Air Electricity-Storage***

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## **Abstract**

Cryogenic energy storage systems have a significant potential to add intermittent renewable-energy sources in power grid. Differences in demand and price of peak and off-peak electricity can make its storage of economic interest. Technical parameters such as roundtrip efficiency, energy and power capacity; as well as economic indices such as capital, operating and maintenance costs; are anticipated to have influence on selection of any storage technique. In this paper, thermo-economic models of medium-to-large-scale Liquid-Air Energy Storage is explained, focusing on efficiencies and costs. The model is validated against data taken from an operational pilot plant. Costing effort that includes multiple costing approaches based on the module costing technique is presented, with the overriding aim of conducting a preliminary economic feasibility assessment. The system performance is found to be significantly enhanced through the integration and utilization of waste heat (and cold) streams. In terms of economics on the other hand, system is estimated in this work to have a lower capital cost and a lower leveled storage cost.

**Keywords:** Electricity, Efficiency, Energy, Cryogenic Energy Storage, Cost, Economy, Finance

## INTRODUCTION

Introduction of highly intermittent renewable sources of energy as part of fast transition to electricity sustainability in future is expected to support growing need for energy storage [1,2]. This paper focuses on highly efficient and financially cheap electricity storage method, namely Liquid Air Energy Storage (LAES). In economic point of view, electricity storage becomes financially interesting if the difference between off-peak and peak demands and the consequential difference in the price of electricity [1, 2].

LAES system liquefies air at about  $-196^{\circ}\text{C}$  by using electricity and stores this at near atmospheric pressure in well-insulated storage vessels (austenitic stainless steel or invar tanks), therefore effectively storing electricity in the form of a cryogen (cold liquid air). When electricity is needed, the liquid air is pressurized, heated by exposure to ambient or even higher-temperature heat supplied by a waste-heat, and finally expanded through gas turbine to produce power [3,4].

Operation of a LAES system can be divided into three main stages/processes: charging (producing cryogen) and storage (storing liquid air), and discharging (producing electricity). Charging step involves the

production and supply of liquid air for equivalent excess off-peak electricity that can be provided by an independent supplier or an onsite air liquefaction plant, storage involves the storage of liquid ai in an insulated vessel, and discharging involves power generation in the power recovery unit [3, 4].

In this paper, a LAES system set-up is considered as represented in Fig.1 that uses an on-site liquefaction unit to liquefy air and waste heat is provided by an over-the-fence supplier, which is assumed to be available to the plant. Although LAES as a technology is considered emerging, the essential components for its construction can be considered mature and readily available thus, offering an advantage for rapid development [3, 4]. Pilot plant with 350 kW power capacity and 2.5MWh energy storage capacity is currently working in UK. Based on economic perspective, high initial capital cost is mainly due to equipment (i.e., expanders, turbines and compressors). LAES is low in terms of t power capital cost and energy capital cost. Buying price (BP) of electricity was found to have a significant effect on the minimum required Sell-to-Buy ratio at low BPs, with the required ratio diminishing as BP increases due to operating energy costs becoming dominant

over other cost factors (capital expenditure, maintenance costs). LAES was compared at equal capacities even though this potentially means that LAES was analyzed at significantly lower than intended capacities. At this size, power capital cost, energy capital cost and overall levelled cost for LAES were estimated to be slightly higher; as opposed to the estimates at nominal capacities. Furthermore, the minimum required STB ratios of LAES and PTES were observed to be very similar at the lower end of BPs with PTES becoming slightly more competitive at lower BPs than before. Finally, in terms of competitiveness against other technologies, the power capital cost at nominal capacities of LAES was compared against those of existing technologies based on literature data. While it is expected that LAES will improve relative to competing technologies as their maturity and readiness levels develop, and bearing in mind that LAES has certain characteristics that allow them to be employed in applications where few competing technologies are intended to function, it was promising to observe that in terms of power capital cost LAES was already found to be more competitive than a variety of existing technologies.

Further work could include the application of learning curves, applicable to such novel

technologies, in order to project their competitiveness against existing/mature and other early-stage alternative technologies. The effect of learning curves is expected to depend on the room for improvement of each technology in terms of both performance and cost. This presents another interesting aspect for further investigation.

Furthermore, approximate cost estimates are presented in the present study based on a simplified approach which assumes that equipment can be used for the construction of the systems of interest whose costs can be captured accurately by the standard correlations used in this work. As the maturity of these systems increases, it is expected that more information will be available and that the cost estimates can be further refined.

Finally, the scalability of the technologies to other capacities and the variation of power to energy storage capacities can introduce a variability in the economic estimations that would be interesting to investigate [5-7].

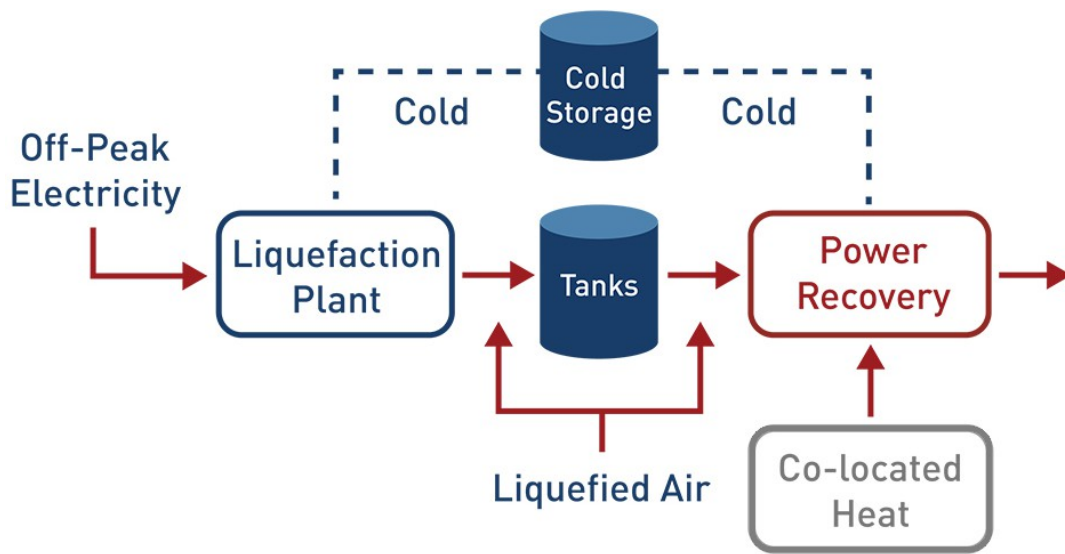


**Fig.1 Flow of material and energy in LAES system**

## MATERIALS & METHODS

**Thermodynamic model:** Following the thermodynamic principles and operation strategies of the LAES system in introduction section, a thermodynamic model has been analyzed with literature based thermo physical properties. Table 1 enumerates and explains various equations that load the efficiency of this storage system.

**Table 1 Equations used in thermodynamic calculations**

|                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                         |                                                                                                                                                                         |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Efficiency                                                                                                                                                                                                                                                                                                                                                                                                                 | $\eta_{rt} = \frac{W_{dis}}{W_{ch}}$                                                                                                                                                    | $\eta_{rt}$ -roundtrip efficiency of this storage system, $W_{dis}$ -(net) work output during the discharge period, $W_{ch}$ -(net) work input during the charge period |
| Work input                                                                                                                                                                                                                                                                                                                                                                                                                 | $W_{ch} = w_l M_{LA}$                                                                                                                                                                   | $M_{LA}$ -capacity of the liquid air storage tank, $w_l$ -work input required per unit of mass of liquid air produced                                                   |
| Power input                                                                                                                                                                                                                                                                                                                                                                                                                | $\dot{W}_{ch} = \dot{m}_{l,LA} w_l$                                                                                                                                                     | $\dot{W}_{ch}$ -power capacity required for liquefaction during the charge phase, $\dot{m}_{l,LA}$ -liquid air mass production rate                                     |
| Specific work input                                                                                                                                                                                                                                                                                                                                                                                                        | $w_l = \frac{\{[T_{c,in}(s_{c,in} - s_{c,out}) - (h_{c,in} - h_{c,out})] - x(h_{e,in} - h_{e,out})\}[(h_{e,in} - h_f) - C_r(1 - L)]}{(h_{c,in} - h_{c,out}) + x(h_{e,in} - h_{e,out})}$ |                                                                                                                                                                         |
| $h_f$ -specific enthalpy of air at atmospheric pressure and aquality of 0 (i.e. saturated liquid), $T_{c,in}$ -temperature of air at the inlet of the compressor; $h$ and $s$ - specific enthalpies and entropies at the inlet or outlet of the expander and compressor, distinguished by using subscripts ‘in’ and ‘out’ to represent inlet and outlet respectively, and subscripts ‘e’ and ‘c’ to represent expander and |                                                                                                                                                                                         |                                                                                                                                                                         |

compressor respectively.  $x$  - ratio of diverted mass of air for expansion to the total mass flow rate of compressed air,  $Cr$ -specific waste-cold available from the evaporation of liquid air during discharging,  $(1-L)$ -ratio of recovered and recycled waste-cold delivered during charging. Fig.2 explains inputs to this equation.

|                  |                                                                           |                                                                                                                                                                                                                           |
|------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Power output     | $\dot{W}_{dis,net} = \sum_{i=1}^{N_{ts}} \dot{W}_{t(i)} - \dot{W}_p$      | $\dot{W}_{dis,net}$ - power output over the discharging time, $\dot{W}_p$ -power input required for the cryogenic pump, $\dot{W}_t$ -power outputs from a turbine stage, $N_{ts}$ -number of turbine stages               |
| Evaporation loss | $l_{ev} = \left( \frac{Q_{hg,ld}}{h_f} \right) / M_{LA}$                  | $l_{ev}$ -evaporation losses, $t_{id}$ -idle time, $Q_{hg}$ -heat gains from the environment, $h_f$ -specific enthalpy of air at atmospheric pressure                                                                     |
| Heat transfer    | $Q_{hg} = U \left[ \pi H_T D_T + \frac{\pi D_T^2}{2} \right] (T_a - T_T)$ | $U$ -overall HT coefficient, $H_T$ and $D_T$ - height and diameter of storage tanks respectively, $T_a$ -ambient temperature, $T_T$ -liquid air storage temperature                                                       |
| Waste cold       | $V_{wc} = \frac{M_{wc}}{\rho_{wc} (1 - \varepsilon)}$                     | $V_{wc}$ -waste-cold storage volume, $\rho_{wc}$ -density of the storage material (5175 kg/m <sup>3</sup> ), $\varepsilon$ -void ratio, $M_{wc}$ -mass of the storage medium (magnetite, Fe <sub>3</sub> O <sub>4</sub> ) |

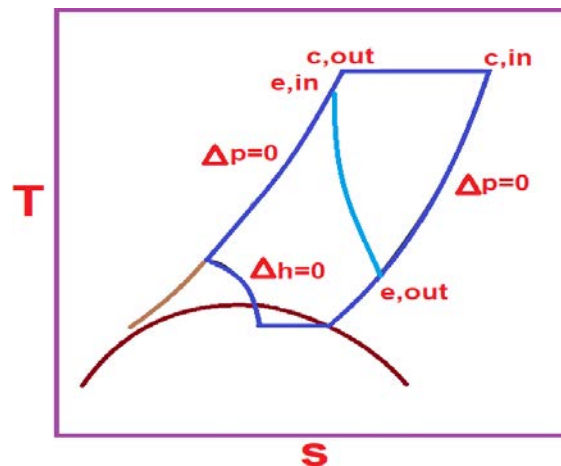


**Fig.2 T-s diagram of LAES liquefaction-Claude cycle**

**Overall costing approach:** The costing of emerging technologies is challenging and can involve substantial uncertainties. Consequently, tenders from manufacturers are usually essential for the improved accuracy of such costing exercises. Tables 2-5 enumerates and explains various equations that manipulates cost of this storage system with reasonable accuracy.

**Table 2 Equations used in costing by Turton**

|                            |                                                                                                                         |                                                                                                                                                                                                                                                                                                         |  |
|----------------------------|-------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| Cost at analysis time      | $C_a = C_b \left( \frac{I_a}{I_b} \right)$                                                                              | Cb and Ca-costs at base (data collection) time and analysis time respectively, $I_b$ and $I_a$ -cost indexes at base and present year respectively                                                                                                                                                      |  |
| Component cost             | $\ln C_B^0 = K_1 + K_2 \ln A + K_3 (\ln A)^2$                                                                           | $C_B^0$ -component cost; $K_1$ , $K_2$ and $K_3$ -constants, A-size/capacity of component                                                                                                                                                                                                               |  |
| Compressor / Turbine costs | $C_{BM} = C_P^0 F_{BM}$                                                                                                 | $C_{BM}$ -bare module cost, $F_{BM}$ -bare module cost factor (3.30 and 3.50 for compressors and power recovery systems respectively), $C_P^0$ -base purchase cost (compressor and power recovery turbine)                                                                                              |  |
| Pump / Vessel cost         | $C_{BM} = C_P^0 (B_1 + B_2 F_M F_p)$                                                                                    | $B_1$ and $B_2$ -are constants that can be found for each equipment (for pumps; the values are 1.89 and 1.35 respectively; and for vessels, the values are 2.25 and 1.82 respectively), $F_M$ -material factor (for pumps, it is 1.5), $F_p$ -pressure factor for pumps and pressurized storage vessels |  |
|                            | $\ln F_{P(pump)} = C_1 + C_2 \ln P + C_3 (\ln P)^2$                                                                     | $C_1$ , $C_2$ and $C_3$ -constants (eg., -0.3935, 0.3957 and -0.0023 respectively), $P$ -gauge pressure (bar)                                                                                                                                                                                           |  |
|                            | $F_{p(vessel)} = \frac{1}{0.0063} \left\{ \frac{(P+1)D}{2[850-0.6(P+1)]} + 0.00315 \right\}$<br>for $t_{ves} > 0.0063m$ | $D$ -vessel diameter, $t_{ves}$ -vessel thickness                                                                                                                                                                                                                                                       |  |

**Table 3 Equations used in costing by Seider**

|            |                                                                |                                                                                                                                                                                                                                                          |  |
|------------|----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| Compressor | $C_{P,c} = F_D F_M C_{B,c}$                                    | C <sub>B,c</sub> -compressor base purchase cost(calculated based on power consumption), F <sub>D</sub> and F <sub>M</sub> -constant factors (for electric motor drive and construction material, they are 1), C <sub>p,c</sub> -compressor purchase cost |  |
|            | $C_{B,c} = e^{(R_{1,c} + R_{2,c} \ln Z)}$                      | R <sub>1,c</sub> and R <sub>2,c</sub> -factor that vary depending on compressor type(selected 7.9661 and 0.80 respectively), Z-power consumption (horse power)                                                                                           |  |
| Vessel     | $C_{P,v} = F_M C_V + C_{PL}$                                   | C <sub>p,v</sub> -estimated purchase cost of a vessel, C <sub>v</sub> -vessel purchase cost based on weight(Y)                                                                                                                                           |  |
|            | $C_V = e^{[R_{1,v} + R_{2,v} \ln Z + R_{3,v} (\ln Z)^2]}$      | R <sub>1,v</sub> , R <sub>2,v</sub> and R <sub>3,v</sub> -factots that vary according to its orientation                                                                                                                                                 |  |
|            | $C_{PL} = R_{1,vp} D^{R_{2,vp}} L^{R_{3,vp}}$                  | D-vessel's internal diameter, L-tangent-to-tangent Length; R <sub>1,vp</sub> , R <sub>2,vp</sub> and R <sub>3,vp</sub> -factors that account for the cost of platforms and ladders                                                                       |  |
| pump       | $C_{P,p} = F_J F_M C_{B,p}$                                    | C <sub>p,p</sub> -pump purchase cost; F <sub>M</sub> -constant, ie, construction material constant (value 1)                                                                                                                                             |  |
|            | $C_{B,p} = e^{[R_{1,p} - R_{2,p} \ln S + R_{3,p} (\ln S)^2]}$  | C <sub>B,p</sub> -pump base cost; R <sub>1,p</sub> , R <sub>2,p</sub> and R <sub>3,p</sub> -factots (values are 9.7171, 0.6019 and 0.0519, respectively), S=Q√H, Q-volumetric flow rate, H-pump head (feet)                                              |  |
|            | $F_J = e^{[(U_{1,pt} - U_{2,pt} \ln S) + U_{3,pt} (\ln S)^2]}$ | F <sub>J</sub> –variable factor; U <sub>1,pt</sub> , U <sub>2,pt</sub> and U <sub>3,pt</sub> -factors (assumed to be 9.8846, -1.6164 and 0.0834 respectively)                                                                                            |  |
| Turbine    | $C_{P,t} = R_{1,t} Z^{R_{2,t}}$                                | C <sub>p,t</sub> -purchase cost of power recovery turbine; R <sub>1,t</sub> and R <sub>1,t</sub> -factors (assumed to be equal to 530 and 0.81, respectively)                                                                                            |  |
|            | $C_{BM} = C_P F_{BM}$                                          | C <sub>BM</sub> -bare module indirect cost, C <sub>p</sub> -purchase cost, F <sub>BM</sub> -base module factor                                                                                                                                           |  |

**Table 4 Equations used in costing by Couper**

|            |                                                               |                                                                                                                                                  |
|------------|---------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Compressor | $C_{P,c} = U_{1,c}Z^{U_{2,c}}$                                | $C_{p,c}$ -purchase cost of compressor; $U_{1,c}$ and $U_{2,c}$ -factors for compressors (7190 and 0.61, respectively)                           |
| Turbine    | $C_{P,t} = U_{1,t}Z^{U_{2,t}}$                                | $C_{p,t}$ -purchase cost of turbine; $U_{1,c}$ and $U_{2,c}$ -factors for turbines (378 and 0.81, respectively)                                  |
| Vessel     | $C_{P,v} = F_M C_V + C_{PL}$                                  | $C_{p,v}$ -vessel purchase cost                                                                                                                  |
|            | $C_V = U_{1,v} e^{[(U_{2,v}-U_{3,v}\ln Y)+U_{4,v}(\ln Y)^2]}$ | $U_{1,v}$ , $U_{2,v}$ , $U_{3,v}$ and $U_{4,v}$ -factors (assumed to be 1.218, 9.100, 0.2889 and 0.04576, respectively)                          |
|            | $C_{PL} = U_{1,vp} D^{U_{2,vp}} L^{U_{3,vp}}$                 | $U_{1,vp}$ , $U_{2,vp}$ and $U_{3,vp}$ -factors (assumed to be 300, 0.7396 and 0.7066, respectively)                                             |
| Pump       | $C_{P,p} = F_J F_M C_B$                                       | $C_{p,p}$ -pump purchase cost; $F_M$ -constant, ie, construction material constant (value 1)                                                     |
|            | $C_B = U_{1,p} e^{[(U_{2,p}-U_{3,p}\ln S)+U_{4,p}(\ln S)^2]}$ | $C_B$ -base purchase cost ; $U_{1,p}$ , $U_{2,p}$ , $U_{3,p}$ and $U_{4,v}$ -factors (assumed to be 1.39, 8.833, 0.6019 and 0.0519 respectively) |
|            | $F_J = e^{[(U_{1,pt}-U_{2,pt}\ln S)+U_{3,pt}(\ln S)^2]}$      | $F_J$ -factor; $U_{1,pt}$ , $U_{2,pt}$ and $U_{3,pt}$ -factors (assumed to be 9.8846, -1.6164 and 0.0834 respectively)                           |
|            | $C_{BM} = C_P F_{BM}$                                         | $C_{B,M}$ -bare module indirect cost, $C_p$ -purchase cost, $F_{BM}$ -base module factor                                                         |

**Table 5 Equations used in other equipment costing**

|                |                                                                             |                                                                                                                                     |
|----------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Generator      | $C_B^0 = 1.85 \times 10^6 \left( \frac{W}{1.18 \times 10^4} \right)^{0.94}$ | $C_B^0$ -base cost for equipment such as generator (in €), $W$ -power output (in kW)                                                |
| Heat exchanger | $CE = CV \frac{Q}{\Delta T_m}$                                              | $CE$ -heat exchanger capital value cost, $CV$ -C value cost, $Q$ -duty of heat exchanger, $\Delta T_m$ -mean temperature difference |

## RESULTS & DISCUSSION

**Thermodynamic performance:** LAES technology has been demonstrated to some extent, with the construction and testing of a pilot plant with a rated power of 350 kW and energy storage capacity of 2.5 MWh. A comparison of data from this first LAES pilot plant, against model predictions is used here to validate the model.

Uncertainties in the model input parameters and variables are quantified by considering upper and lower bounds. Fig.3 shows that, in terms of losses, the most influential factors on the roundtrip efficiency of LAES are the efficiencies of the cryogenic turbine in the liquefaction plant, the compressor, and the turbine in the power generation unit. The efficiency of all three components

shows a similar, positive linear relationship with the system's roundtrip efficiency. Variations to important operational factors are also considered, including the amount of cold recycled and utilized which, for positive deviations from the nominal values, is clearly found to be the dominant factor. However, when negative deviations from the nominal value are considered, its effect is similar in magnitude to that of the turbine inlet temperature  $T_{t,in}$ . The pressure increase at the pump outlet is also found to be a contributing factor towards a higher roundtrip efficiency over the range considered of parameters although less so. Model data is cross-checked with a pilot plant trials. Since the pilot plant is a first-of-a-kind (FOAK) and was tested under varying conditions, its components are expected to experience sub-optimal operation (and performance). Therefore, based on nominal (intermediate 'best' guess) values presented, Fig.4 shows results obtained from the present LAES system model.

Interestingly, it is observed that the effect deviations from nominal is significantly greater than at positive deviations, such that the benefit in efficiency from increasing the pressure ratio decreases substantially at higher pressure ratios. This is evident at the negative extreme end of pressure ratios

where an increase in roundtrip efficiency of around 20% absolute, or close to 50% relative, is achieved by an increase in normalized pressure ratio of just 0.17. (from  $-0.50$  to  $-0.33$ ). Subsequently, when other factors such as material strengths and costs involved are accounted for, the increase in pressure ratio beyond a certain point may not be beneficial in a cost-benefit optimization analysis. The roundtrip efficiency at the higher end of pressure ratios reaches values of  $\sim 80\%$ , which is considered high.

The roundtrip efficiency is also expected to decrease with the increase in storage time as a result of heat losses to the environment, especially if the storage vessels are not well insulated. Nevertheless, with sufficient insulation these heat losses can be reduced, especially in a system which is aimed for frequent use without long idle storage durations. Subsequently, they are not considered in the present analysis. Fig.5 compares LAES with all possible energy storage techniques.

**Table 6 Thermodynamic Performance estimation**

|                                                                                                                                                                                                                     |                                                                                                                                                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| $\omega_R = \left[ \left( \frac{\partial R}{\partial x_1} \omega_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} \omega_2 \right)^2 + \left( \frac{\partial R}{\partial x_3} \omega_3 \right)^2 \right]^{1/2}$ | $\omega_R$ -overall uncertainty;<br>$\omega_1, \omega_2, \dots, \omega_n$ -uncertainties<br>associated with the $n$<br>independent input variables |
| Since the pilot plant is a first-of-a-kind (FOAK) and was tested under varying conditions, its components are expected to experience sub-optimal operation (and performance)                                        |                                                                                                                                                    |

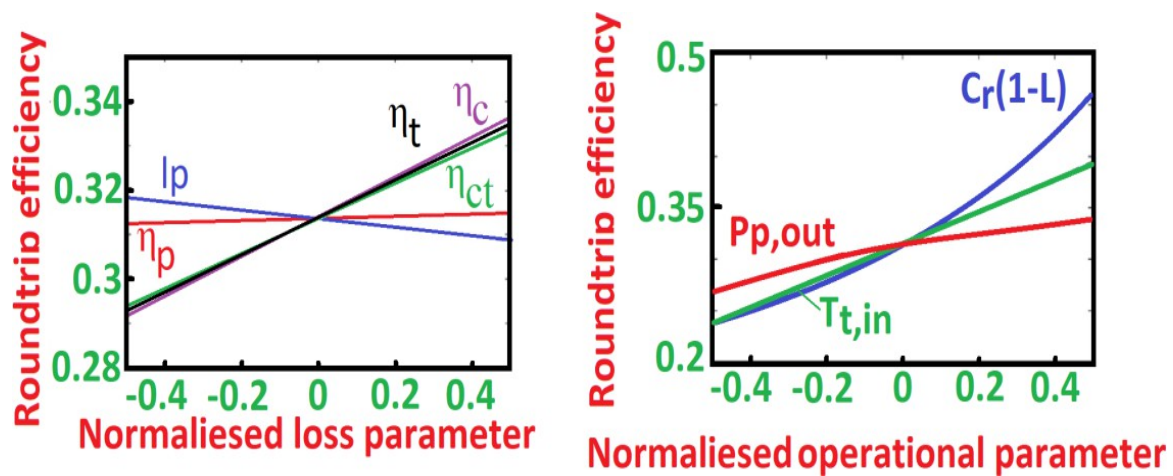


**Fig.3 Roundtrip efficiency in terms of losses and operational parameters**

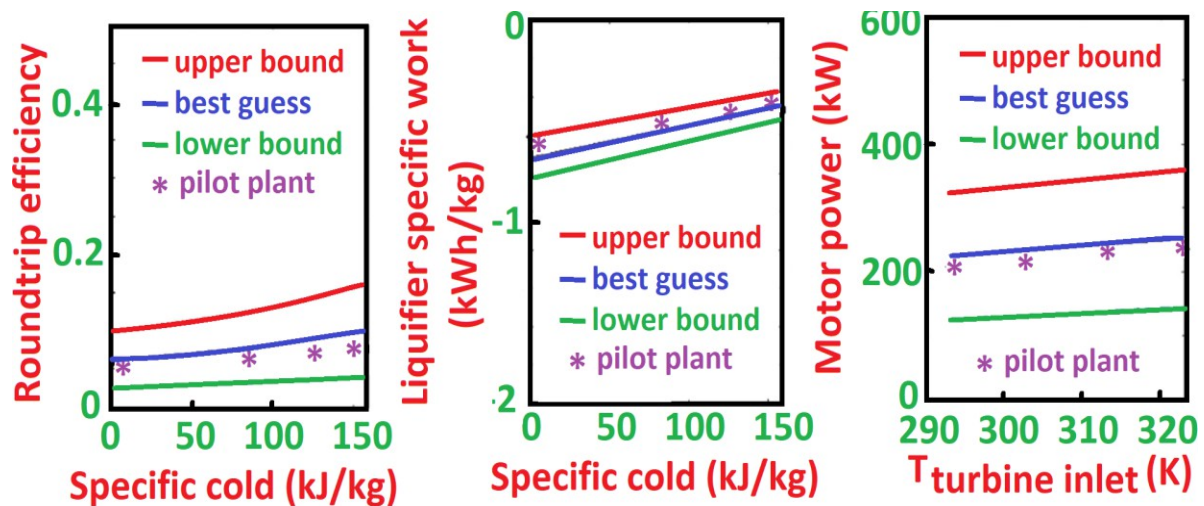


**Fig.4 Comparison of model output data with pilot plant data**

Economic and Financial Feasibility: Components involving power generation and/or consumption were accountable for the greatest capital cost shares (see Fig.6). Liquefaction plant and power recovery plant of LAES system were found to cumulatively account for about 70% of its total capital cost. Subsequently, once more, the practice of waste-cold utilization can play a crucial role in the LAES system, since the decrease in quantity of utilized

waste-cold can allow an increase in the power and energy capital costs of LAES as a result of the requirement of a higher power capacity compressor capable to match the equivalent liquid air yield. Furthermore, the allocation of capital expenditure for LAES with respect to rated power output, energy capacity and absolute cost is shown in Fig.7.

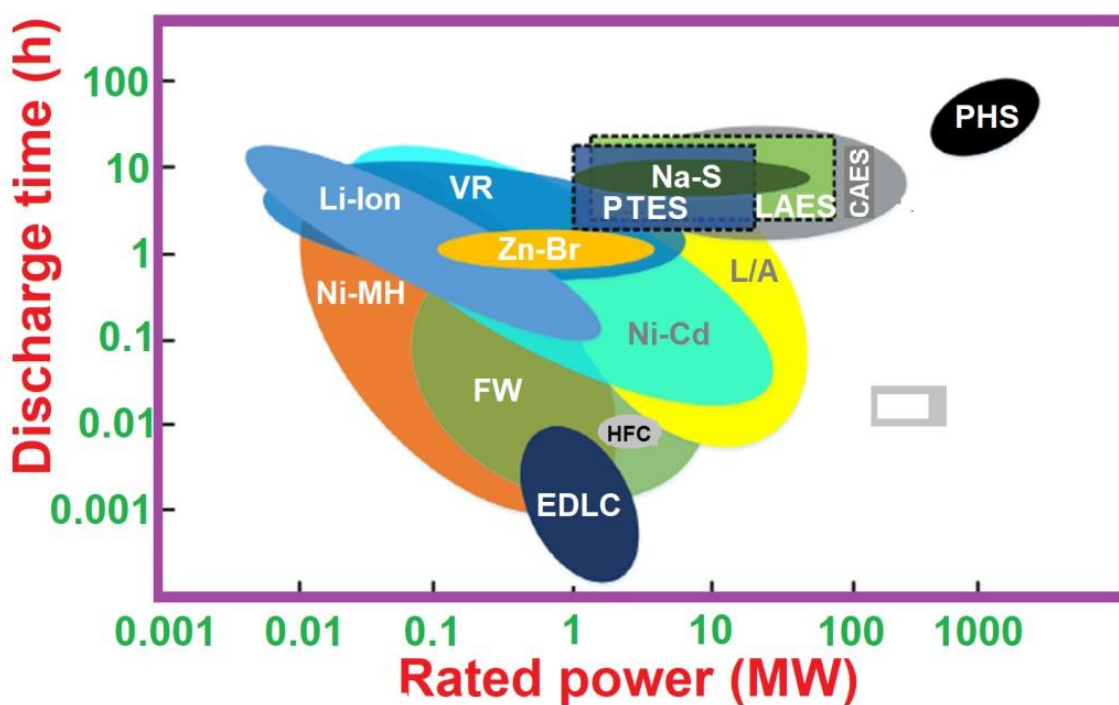


**Fig.5 Comparison of various energy storage techniques (EDLC-electrical double layer capacitor, Li-ion battery, Na-S battery, Ni-Cd battery, Zn-Br battery, VR-vanadium redox battery, L/A-lead/acid battery, Ni-MH battery, HFC-hydrogen fuel cell, CAES-compressed air energy storage, LAES-liquid air energy storage, PTES-pumped thermal energy storage, PHS-pumped hydro storage, FW-fly wheel)**

The liquefaction plant was found to be responsible for the greatest share in all three metrics while also showing the greatest cost variation; the power recovery unit follows second. An increase in energy or power output capacity is expected to increase the capital cost but potentially also increase the financial income from the operating the system, if it is utilized correctly, leading potentially to benefits from economies of scale. Since power consumption and/or generation devices were found to be more capital intensive, a marginal increase in rated power input or output should justify a higher marginal benefit in comparison to increasing energy capacity. Assuming scalability of the corresponding technology permits, the optimal energy to power ratio from an economic perspective should aim in the minimization of both power and energy capital costs. This is expected to be case specific and depended on a variety of factors, such as the electricity market and the variations in electricity prices (Fig.8). In order to consider these technologies within the wider context of competing electricity storage solutions, it is useful to refer to the chart compiled by the Energy Storage Association (ESA) based on literature data, shown in Fig.9. LAES is found to be competitive against technologies such as lithium-ion batteries, sodium sulfur batteries and hydrogen fuel cells. It is also

notable that the power capital cost ranges of the aforementioned technologies are greater than the range estimated for LAES. We now turn our attention to the financial feasibility of electricity storage systems over their lifetime, which is assumed in this work to be 30 years of daily cycling (i.e., 365 cycles per year) without component degradation. For this financial feasibility analysis, we incorporate the upfront capital expenditure along with its associated discount rate, the operational energy costs, and the annual maintenance costs. Since novel technologies, which lack plants at the commercial scale, are considered in both cases, non-negligible uncertainties exist in the maintenance costs and in the assignment of discount rate values from a commercial private perspective. Therefore, a range of maintenance costs and discount rates were employed for the execution of the analysis. In the case of discount rates, the ranges considered were 6–12%. For annual maintenance costs, the variation was considered to be in the range of 1.5–3.0% of the initial capital expenditure.. Similarly, an additional important level of uncertainty is introduced by the energy cost as it depends on various varying aspects such as location and fuel prices. Hence, the analysis was performed while considering a range of 0.028–0.083 \$/ kWh for off-peak electricity costs. The uncertainties and consequently

the sensitivity of the systems on these variables is captured by the error bars or bounds indicated in Fig.8. The financial analysis of the systems also included the total levelised cost of storage (LCOS) as well as their main cost elements independently on which each of the uncertainties considered is anticipated to have a different impact. With respect to the average total LCOS, the two systems were found to be close, with values of 0.29 \$/kWh. Considering the range of LCOS, it was found to be in the range of 0.14–0.46 \$/kWh. Since the only uncertainty considered which affects the estimated LCOS allocated to operational energy costs is the energy price, LAES is found to be more restrictive to location due to energy cost and more vulnerable to market fluctuations of electricity prices. This effect is potentially a consequence of the lower roundtrip efficiency observed in the LAES system and subsequently due to the greater energy input requirements per energy unit output. On the contrary, LAES's LCOS allocation to capital cost and its resulting sensitivity is considerably lower; thus presenting a lower risk related with capital investment. Additionally, it is worth noting that an improvement in roundtrip efficiency is expected to decrease the LCOS associated with operational energy costs but that is not essentially the case for the

other two elements of LCOS. This can be due to the potential cost trade-off associated with the incorporation of more expensive equipment that might be required for an insignificant increase in efficiency, for instance as a result higher operating pressures. Furthermore, to analyze the financial feasibility of the systems over their lifetimes, another important and insightful economic metric relevant to energy storage technologies is the sell-to-buy (STB) price ratio necessary for the system to become financially feasible. The terms sell price (SP) and buy price (BP) refer to the electricity price during peak and off-peak electricity demands respectively. Therefore, the ratio between SP and BP determines the STB. Here, the system is classified as financially feasible at the break-even point which is considered to be when the net present value (NPV), which takes into consideration finance costs, capital expenditure, operational costs and incomes, is equal to zero while assuming equal annual benefits over the lifetime of the system. Therefore, for each of the two systems to become financially feasible, the required minimum STB ratio was determined based on the variation of BP (shown in Fig.8), where any operating point at an STB ratio over the curve can be characterized as financially feasible. The curves show a monotonic decrease that is

sharp at lower BPs and shallower at BPs over  $\sim 0.20$   $\$/kWh$ , which is mainly due to the fact that at higher BPs the operational energy costs become the dominant cost of each system relative to capital costs and maintenance costs; thus the required STB ratio is driven mainly by the roundtrip efficiency of each system. Therefore, the required STB ratio becomes increasingly independent from the other cost factors. Specifically, at the lower end of BPs considered here, it shows a lower required STB ratio. Above a BP value of about 0.15  $\$/kWh$ , PTES appears to become the most financially competitive to other methods. Furthermore, another interesting

observation concerns the substantially greater uncertainty in the required STB ratio affiliated with low BP values compared to that at higher values. Consequently, at higher BP values both systems are found to be more robust in terms of required STB ratio in the market place. Since the two main elements of uncertainty in this analysis, apart from capital costing, are now the maintenance costs and discount rate (given that the uncertainty in energy costs is the varying parameter here), this plot also captures the effect of these factors on the financial feasibility of the systems

**Table 7 Costing parameters used for estimations (Turton model)**

| Parameters      | K <sub>1</sub> | K <sub>2</sub> | K <sub>3</sub> |
|-----------------|----------------|----------------|----------------|
| Storage vessels | 3.4974         | 0.4485         | 0.1074         |
| Compressors     | 2.2897         | 1.3604         | -0.1027        |
| Pumps           | 3.3892         | 0.0536         | 0.1538         |
| Turbines        | 2.7051         | 1.4398         | -0.1776        |

**Table 8 Bare module factors for Seider model and Couper model**

| Parameters      | F <sub>BM</sub> in Seider | F <sub>BM</sub> in Couper |
|-----------------|---------------------------|---------------------------|
| Storage vessels | 4.16                      | 2.8                       |
| Compressors     | 2.15                      | 1.3                       |
| Pumps           | 3.3                       | 2.8                       |
| Turbines        | 3.5                       | 1.5                       |

**Table 9 Parameters for simulation: pilot and nominal plant**

| Parametric values                                    | Pilot (350kW, 2.5MWh) | Nominal (12MW, 50MWh) |
|------------------------------------------------------|-----------------------|-----------------------|
| Turbine isentropic efficiency, $\eta_t$              | 0.6                   | 0.85                  |
| Cryogenic turbine isentropic efficiency, $\eta_{ct}$ | 0.8                   | 0.85                  |
| Cryogenic pump isentropic efficiency, $\eta_p$       | 0.6                   | 0.85                  |
| Pressure loss factor, $l_p$                          | 10%                   | 10%                   |
| Compressor efficiency, $\eta_c$                      | 0.8                   | 0.85                  |
| Pump outlet pressure, $P_{p,out}$ (bar)              | 56                    | 170                   |
| Turbine temperature, $T_{t,in}$ (K)                  | 337                   | 393                   |
| Specific waste cold utilization, $C_r(1-L)$ (kJ/kg)  | -                     | 170                   |

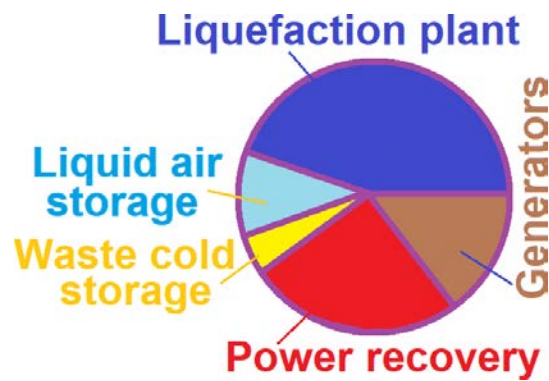


**Fig.6 Total capital cost allocation to main components**

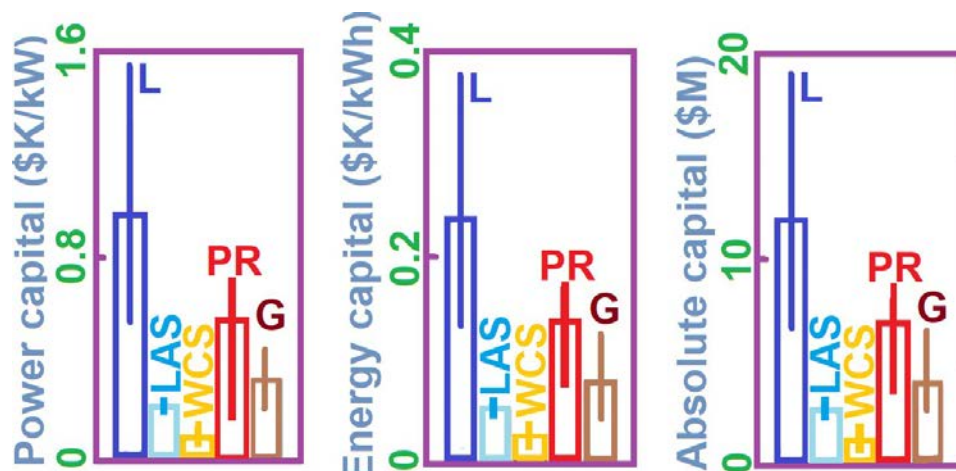


**Fig.7 Various capital costs (L-liquefaction plant, LAS-liquid air storage, WCS-waste cold storage, PR-power recovery, G-generators)**

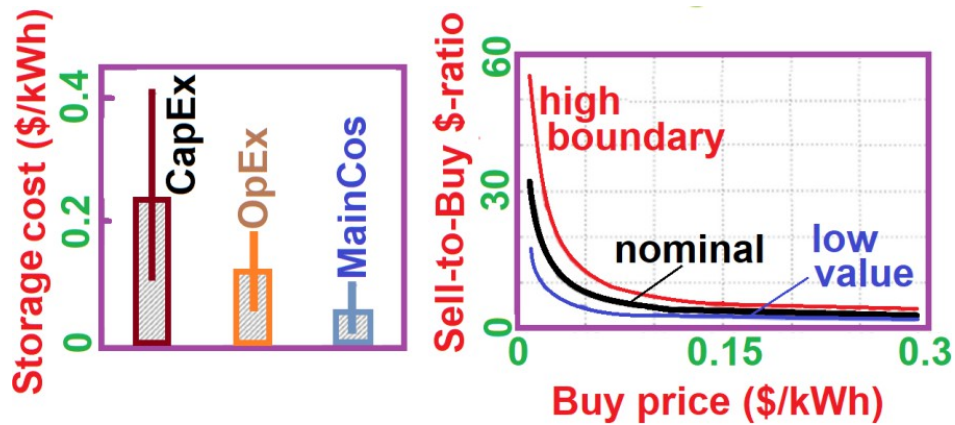


**Fig.8 Overall Levelised storage cost (CapEx-capital expenditure, OpEx-Operational expenses, MainCos-maintenance cost) and sell-to-buy price against electricity buy price**

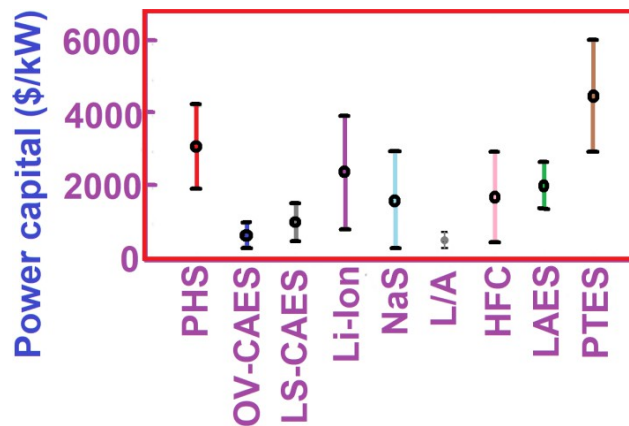


**Fig.9 Comparison of various electricity storage technologies (Li-ion battery, Na-S battery, L/A-lead/acid battery, HFC-hydrogen fuel cell, LS CAES -large scale underground compressed air energy storage, OV CAES- over ground compressed air energy storage, LAES-liquid air energy storage, PHS-pumped thermal energy storage, PHS-pumped hydro storage)**

## CONCLUSIONS

Models of medium-to-large-scale bulk LAES is developed to allow for a thermo-economic analysis focusing on roundtrip efficiency and costs. Efficiency is strongly dependent on the quantity of waste-cold recycled and utilised during the liquefaction stage in the charge cycle, and

the temperature of the waste-heat delivered during the power generation stage in the discharge cycle. These two elements provide significant opportunity to LAES against other bulk electricity storage technologies. LAES is mature and ready to use technology. It employs readily available equipment and so overall cost is

low. Finally, in terms of competitiveness against other technologies, the power capital cost at nominal capacities is cheap.

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