International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0515

DESIGN OF A LIQUID AIR ENERGY STORAGE - ECONOMIC VS THERMODYNAMIC CRITERIA

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ABSTRACT

Thermo-mechanical energy storage deployment in future energy grids presumes economic profitability is achieved through their operation. However, suitable technology design should not be pursued regardless of a technical evaluation of storage performance. In this paper, a combined economic and thermodynamic analysis is used to point out what are the guidelines for optimal size of a Liquid Air Energy Storage (LAES) system. Results show payback time around 25 years. They also suggest that, while financially a smaller liquefier should be preferable, this on the other hand implies higher thermodynamic inefficiencies.

Keywords: Liquid Air Energy Storage, Economic analysis, Thermodynamic analysis, System design

NOMENCLATURE

Abbreviations	
LAES	Liquid Air Energy Storage
PBT	Payback time
STOR	Short Term Operating Reserve
MILP	Mixed integer linear programming
Symbols	
C	Cost [k£]
P	Power [MW]
K	Capacity [MWh]
t	Time [hour]
w	Specific work [kJ/kg]
η	Efficiency [%]

1. INTRODUCTION

In order to underpin the future transition towards low-carbon power systems, electric energy storage is regarded as a key solution [1]. Large scale plants offer high energy capacity at low specific cost; thus, they are suitable for complementing power-oriented solutions such as batteries.

Liquid Air Energy Storage (LAES) is a large-scale, thermo-mechanical technology where electricity is stored as liquid air at cryogenic temperatures [2]. LAES comprises three main sub-processes, namely plant charging (liquefaction), storage via low-pressure vessels and plant discharging, through a direct Rankine power cycle [3]; Figure 1 shows a schematic. Among competing technologies, this solution exhibits competitive roundtrip efficiency and one order of magnitude higher energy density [4], while not being subject to any geographical constraints. In addition, LAES can be independently sized, meaning the liquefier, storage tanks and power production unit can be tailored to the needs of the specific application.

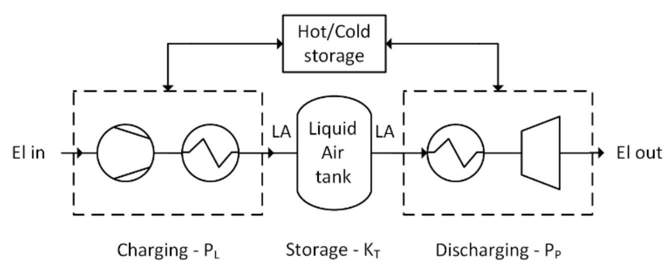

Figure 1: schematic of LAES concept

Available literature deals mainly with technical characterisation of LAES [5], [6] and its assessment as

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).
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part of the grid [7], [8]. In doing so, plant design parameters are generally provided as model input, under suitable assumptions; only few papers deal with the actual sizing of LAES. Nonetheless, information on plant design is key, not only for costing exercises, but also in affecting plant thermodynamic operation.

The present paper aims at investigating further this gap. First, a pathway towards optimal LAES design in the UK market is discussed. Second, an evaluation on how and when the thermodynamic process is influenced by plant size is detailed.

2. METHODOLOGY

The numerical framework adopted for this study relies on the interaction between an economic and thermodynamic evaluation of LAES. The approach is presented in the flow chart of Figure 2; its implementation was carried out entirely through MATLAB environment.

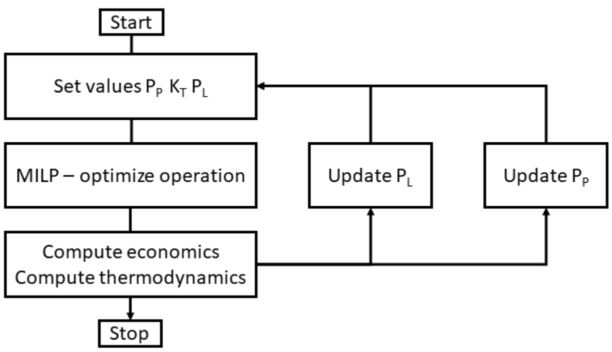

Figure 2: flow chart of the adopted numerical framework

For every given combination of design parameters, an optimal dispatch problem is solved to maximise the revenues from LAES operation. As operating strategy, arbitrage is considered alone and along with provision of reserve capacity, under Short Term Operating Reserve (STOR). In doing this, perfect knowledge of electricity price signal π_t is assumed, as well as of STOR calls, with hourly timestep. The MILP problem is detailed as follows, for the case on arbitrage alone:

$$Max \sum_{t=1}^{T} (out_t^P - x_t^L P_L)\, \pi_t \qquad 2.1$$

$$x_t^P P_P^{min} \leq out_t^P \leq x_t^P P_P^{MAX} \qquad 2.2$$

$$K_t = K_{t-1} - (out_{t-1}^P - x_{t-1}^L P_L\, \eta)\Delta t \qquad 2.3$$

$$0 \leq K_t \leq K^{MAX} \qquad 2.4$$

$$K_{end} = K_0 \qquad 2.5$$

Constraints act to limit the power output of the LAES between an upper (P_P^{MAX}) and a minimum ($0.5 P_P^{MAX}$) threshold. Mass conservation across the storage tank is imposed (Eq. 2.3 and 2.4), together with initial and cyclability conditions (Eq. 2.5). x_t^P and x_t^L are two integer variables that assume unit value when LAES is discharging or charging, respectively. η=60% is considered as storage efficiency in the first place, in agreement with similar studies [9].The optimisation is run over two representative months: December 2017 for winter conditions and June 2017 for summer.

Once the operational profile is known, firstly economic and then thermodynamic analysis is carried out on top of the results from the optimization: the approach is described below in more detail. Design space explored for the LAES involved power output P_P from 50 to 250 MW, with liquefaction size spanning from 0.5 to the nominal value of the power recovery unit. Tank capacity was fixed to accommodate 3 hours of plant discharge.

2.1 Economic evaluation

Financial assessment in the current case required splitting LAES investment cost as a function of the three independent sub-systems considered:

$$C_{inv} = C_L + C_T + C_P \qquad 2.6$$

where subscripts L, T and P refer to liquefier, tank and power recovery unit, respectively. For each cost contribution, functions directly available from the analysis of Highview Power were used [10]:

$$C_L = 68\,825 \left(\frac{P_L}{80}\right)^{0.6} \qquad 2.7$$

$$C_T = 7\,567 \left(\frac{K_T}{430}\right)^{0.6} \qquad 2.8$$

$$C_P = 14\,848 \left(\frac{P_P}{50}\right)^{0.6} \qquad 2.9$$

Here, power is expressed in MW; capacity is in MWh for the tank. Costs (in 2012 k\$ in Eq. 2.7-2.9) were converted to 2017 k£, according an equivalence factor of 1.58 [10]. The indicator used to gauge economic performance was a static payback time (PBT), where the yearly revenue stream C_{rev} was computed after the optimization and supposed to remain invariant over the years:

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$$PBT = \frac{C_{inv}}{C_{rev}} \quad 2.10$$

2.2 Thermodynamic evaluation

From a thermodynamic point of view, system roundtrip efficiency is expected to vary according to LAES power output, in virtue of off-design conditions. This effect was captured in this study by deriving a normalized relationship between plant specific work output and power output. A detailed off-design LAES model developed by the authors for the case of a 100 MW plant was used for this purpose. A third order polynomial satisfactory captured the dependence:

$$y = 0.052 + 1.27x - 0.064x^2 - 0.25x^3 \quad 2.11$$

In Eq. 2.11, y is the ratio between the actual specific work output and its rated value, whereas x is given by the punctual plant power output over the nominal. Once the plant duty cycle was known from the MILP optimization, Δt_{actual} was computed. It represents the timespan that can *actually* be sustained at power output out_t^P causing a liquid air consumption $K_{t+1} - K_t$. Its value could be Δt at most, in the case of rated power output. An actual LAES efficiency was thus computed to be compared with the constant 60% value:

$$\eta_{RT} = \frac{\sum_{t=1}^{T} out_t^P \Delta t_{actual}}{\sum_{t=1}^{T} x_t^L P_L \Delta t} \cdot 100 \quad 2.12$$

Another thermodynamic performance indicator ζ was defined, as the ratio between the real specific work that can be produced by the liquid air storage during the operation and its maximum theoretical value:

$$\zeta = \frac{\sum_{t=1}^{T} w_t}{\sum_{t=1}^{T} x_t^P w_{rated}} \cdot 100 \quad 2.13$$

Finally, τ was computed as the percentage of total discharge time, during which the storage is experiencing off-design conditions:

$$\tau = \frac{\sum_{t=1}^{T} \Delta t_{off-design}}{\sum_{t=1}^{T} x_t^P \Delta t} \quad 2.14$$

3. RESULTS AND DISCUSSION

The economic results are presented in Figure 3 and Figure 4, as a map of LAES payback time as a function of the design parameters. In both the cases, the trend is similar, and outcomes suggest the optimal system size encompasses higher power output and liquefier rating around half this value. In the considered cases, the best system design comprises a 250 MW power recovery unit and a 125 MW liquefier. However, as the marginal reduction of PBT is lower for higher values of power output, a maximum may exist. A larger design space could be investigated to individuate it.

The impact of the power rating for the power recovery unit P_P is way higher than that for the liquefier (50 MW increase at 100 MW power output means a 10% PBT variation for P_L and 15% for P_P in the case of arbitrage only). When considering arbitrage and STOR together, this is even more true, because the power output is not only used for exploiting price differentials, but it also gives access to additional revenues from the availability for reserve services. An extra revenue mechanism impacts positively on LAES profitability: the minimum PBT for the considered cases is 24, against 28 years. Seasonal evolution of electricity prices also affects the expected incomes: in fact, extending the results obtained for winter to the whole year, payback period would reduce to 20 and 22 years, respectively.

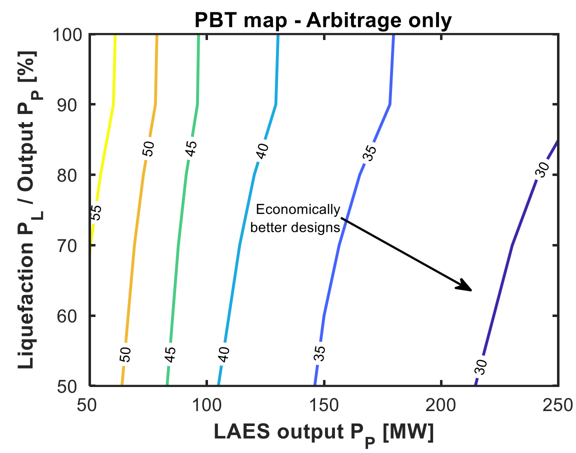

Figure 3: payback time map for arbitrage only

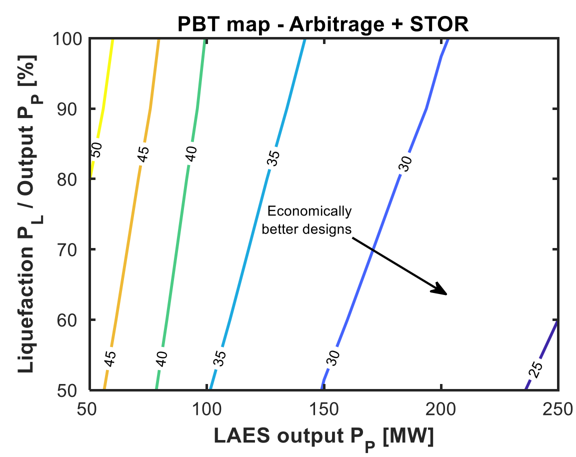

Figure 4: payback time map for arbitrage + STOR

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Considering the thermodynamic evaluation, the actual plant efficiency and the ζ parameter are plotted in the bar charts of Figure 5 and Figure 6. As a first outcome, LAES average roundtrip efficiency over the year is never at its design value of 60%. This is due to part-load operation, which takes place already under arbitrage scheme only. η_{RT} varies from 58.2% to 59% in this case. When operating LAES for arbitrage and STOR, the deviation is even more pronounced: η_{RT} is now between 56.5% and 57.3%. From τ=0.3, meaning 30% of discharge time run at off-design, τ becomes 1 for arbitrage plus STOR. The need to commit power to reserve services precludes the storage from being run at nominal conditions. In all the cases considered, 10% of power output was devoted to reserve service. Increasing this value further to boost revenues would imply a more consistent drift from rated conditions and higher thermodynamic inefficiencies in the process.

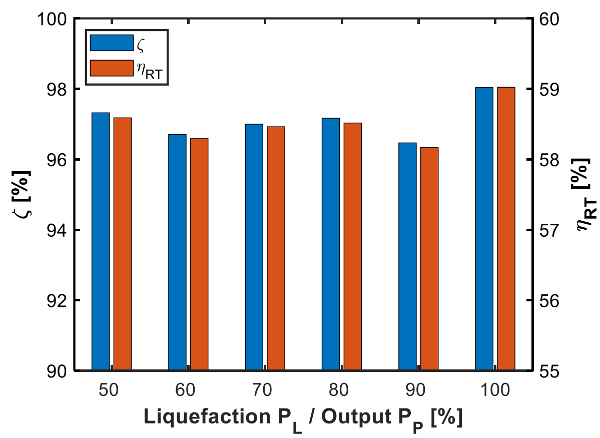

Figure 5: thermodynamic indicators for arbitrage only

The behavior of the ζ parameter resembles that for the efficiency. Even if the variations with different liquefaction sizes are somewhat limited, the higher values for both the indicators coincides with the biggest liquefaction plant. This trend suggests that the bigger the liquefaction plant the better the thermodynamic performance as part-load conditions will be less impactful (τ varies decreases from 0.3 to 0.15 for the conditions $P_L = P_P$). The explanation lays in the fact that there will be more availability of liquid air in this case and thus limited periods when running LAES at part-load.

It can be concluded that, in this analysis, purely economic or thermodynamic evaluation potentially lead to opposite design criteria. The economically optimal plant for this case is proved not to be the configuration with the highest efficiency.

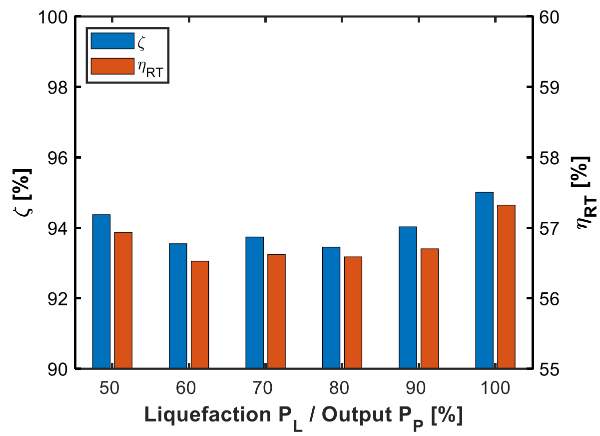

Figure 6: thermodynamic indicators for arbitrage + STOR

4. CONCLUSION

In this study, the tradeoff between economic and thermodynamic optimal design of thermo-mechanical energy storage was highlighted for a case-study, considering LAES in the UK energy market. Results show a plant with 250 MW output and 125 MW input to be economically the best. However, if financial profitability has to be set as ultimate goal for storage design, then LAES operation is forced to drift from rated values. In this case, proper understanding of the thermodynamic inefficiencies arising is fundamental for better system operation and deployment.

ACKNOWLEDGEMENTS

Dr A Sciacovelli acknowledges the finance support from EPSRC, UK (EP/R016402/1). Prof P Mancarella acknowledges the finance support from EPSRC, UK, through the MY-STORE project (EP/N001974/1).

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