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A thermo-economic analysis and comparison of pumped-thermal and liquid-air electricity storage systems

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HIGHLIGHTS

- PTES has a lower TRL but the potential to achieve higher roundtrip efficiencies.
- LAES efficiency is enhanced through the utilisation of waste heat/cold streams.
- LAES has lower power/energy capital costs and a lower levelised cost of storage.
- PTES appears economically more competitive at higher electricity buying prices.
- Components involving power input/output dominate the initial capital expenditure.

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ABSTRACT

Efficient and affordable electricity storage systems have a significant potential to support the growth and increasing penetration of intermittent renewable-energy generation into the grid from an energy system planning and management perspective, while differences in the demand and price of peak and off-peak electricity can make its storage of economic interest. Technical (e.g., roundtrip efficiency, energy and power capacity) as well as economic (e.g., capital, operating and maintenance costs) indicators are anticipated to have a significant combined impact on the competitiveness of any electricity storage technology or system under consideration and, ultimately, will crucially determine their uptake and implementation. In this paper, we present thermo-economic models of two recently proposed medium- to large-scale electricity storage systems, namely ‘Pumped-Thermal Electricity Storage’ (PTES) and ‘Liquid-Air Energy Storage’ (LAES), focusing on system efficiency and costs. The LAES thermodynamic model is validated against data from an operational pilot plant in the UK; no such equivalent PTES plant exists, although one is currently under construction. As common with most newly proposed technologies, the absence of cost data results to the economic analysis and comparison being a significant challenge. Therefore, a costing effort for the two electricity storage systems that includes multiple costing approaches based on the module costing technique is presented, with the overriding aim of conducting a preliminary economic feasibility assessment and comparison of the two systems. Based on the results, it appears that PTES has the potential to achieve higher roundtrip efficiencies, although this remains to be demonstrated. LAES performance is found to be significantly enhanced through the integration and utilisation of waste heat (and cold) streams. In terms of economics on the other hand, and at the system size intended for commercial application, LAES (12 MW, 50 MWh) is estimated in this work to have a lower capital cost and a lower levelised cost of storage than PTES (2 MW, 11.5 MWh), although it is noted that the prediction of the economic proposition of PTES technology is particularly uncertain if customised components are employed. However, when considering the required sell-to-buy price ratios, PTES appears (by a small margin) economically more competitive above an electricity buy price of ~0.15 $/kWh, primarily due to its higher roundtrip efficiency. When considering the two systems at the same capacity, the costs are similar with a slight edge to PTES. Finally, it is of interest that the most expensive components in both systems are the compression and expansion devices, which suggests that there is a need to develop affordable high-performance devices for such systems.

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Nomenclature

C	specific waste cold, J kg^{-1} or cost
c	specific heat capacity, J kg^{-1} K^{-1}
D	diameter, m
F	factor
f	pressure loss factor
h	specific enthalpy, J kg^{-1}
I	cost index
l	losses
M	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
P	pressure, bar
Q	heat, J (or Wh)
r	pressure ratio
s	specific entropy, J kg^{-1} K^{-1}
T	temperature, K
t	time, s
U	overall heat transfer coefficient, W m^{-2} K^{-1}
V	volume, m^3
W	work, J (or Wh)
$\dot{W}$	power, W

Greek letters

β	heat leakage factor
ε	void ratio
η	efficiency
θ	temperature ratio
ρ	density
ω	uncertainty

Subscripts

amb	ambient
B	base
BM	bare module
c	compressor or cold
ch	charge
ct	cryogenic turbine
dis	discharge
e	expander
ev	evaporation
h	hot
l	liquid
LA	liquid air
M	material
P	purchase
p	pressure or pump
rt	roundtrip
T	tank/storage vessel
t	turbine
v	vessel

Abbreviations

BP	Buy Price
CAES	Compressed Air Energy Storage
LAES	Liquid-Air Energy Storage
LCOS	Levelised Cost of Storage
NPV	Net Present Value
PHS	Pumped Hydroelectricity (or Hydro) Storage
PHES	Pumped-Heat Electricity Storage
PTES	Pumped-Thermal Electricity Storage
SP	Sell Price
STB	Sell-to-Buy
TRL	Technology Readiness Level

Other symbols are defined in the text where they are used.

1. Introduction

The growth and increasing penetration of intermittent renewable-energy generation as part of a transition to more sustainable energy future [1,2] is expected to support the growing interest in energy storage. Energy storage can play a key role in enabling the widespread deployment of a range of distributed technologies, e.g., solar, for the generation of electricity [3–5], heat or both [6–8], across scales and applications. This paper focuses on electricity storage [9]. An affordable and efficient electricity storage technology can support this increased penetration and promote greater independence from fossil fuels, while being beneficial toward reduced emissions by displacing low-efficiency, low load-factor backup electricity generation as well as by avoiding the use of legacy plants used to meet peak demand. In regards to economics, electricity storage can become of financial interest by the difference between off-peak and peak demands and the consequential difference in the price of electricity. Nonetheless, important technical as well as economic performance indicators are known to have a considerable impact on the competitiveness of relevant solutions. Bulk electricity storage technologies with some commercialisation maturity, such as compressed air and pumped hydro, have been extensively studied in literature and have been demonstrated in large-scale plants [10]. However, limitations associated with these technologies, such as geographical and/or geological location restrictions, have encouraged the development of alternative electricity storage technologies, which are not (or, less) inherently restricted by these constraints.

The paper focuses on comparing from both technical and economic perspectives two such recently-proposed medium- to large-scale thermo-mechanical electricity storage technologies, namely liquid-air (LAES) and pumped-thermal electricity storage (PTES), which are currently under development but at different technology readiness levels (TRLs) [11]. The LAES system, a technology developed by Highview Power Storage [12], liquefies air at about $-196\,^{\circ}$C by using electricity and stores this at near atmospheric pressure in insulated storage vessels, therefore effectively storing electricity in the form of cold liquid air. When electricity is needed, the liquid air is pressurised, heated by exposure to ambient or even higher-temperature heat supplied by waste-heat sources, and finally expanded through a turbine to generate power [12,13].

The operation of a LAES system can be divided into three main stages/processes: charging, storage and discharging. Charging involves the supply of liquid air that can be provided by an independent supplier or an onsite air liquefaction plant, storage involves the storage of liquid air in an insulated vessel, and discharging involves power generation in the power recovery unit [13]. In this paper, a LAES system configuration 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 [13], thus offering an advantage for rapid development. A working LAES pilot plant with a 350-kW power capacity and 2.5-MWh energy storage capacity is currently under operation [14,15], for which roundtrip efficiencies of 7–12% have been recorded depending on a number of operational parameters [13,14], although it is important to note that there is a significant potential for achieving considerably higher efficiencies at larger scales as has been suggested in Refs. [13–16]. The operation and performance of this LAES pilot plant as well as the prospective of the LAES system have also been studied in Refs. [14,15].

PTES (also referred to as ‘pumped-heat electricity storage’, or PHES, in the literature) is another recently proposed energy storage technology that stores electricity in the form of sensible heat in insulated storage vessels containing of an appropriate storage medium, such as a packed bed of gravel or pebbles [17]. PTES (presented in Fig. 2) comprises primarily two hot/cold thermal reservoirs (HR, CR) at different