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Compressed air energy storage with liquid air capacity extension

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HIGHLIGHTS

- A hybrid energy storage system involving compressed air and liquid air is proposed.
- Thermodynamic analysis based on exergy is carried out on the proposed system.
- Turnaround efficiency is comparable to energy recovery from pure liquid air systems.
- Storage duration is critical for economic viability of the proposed system.

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ABSTRACT

As renewable electricity generation capacity increases, energy storage will be required at larger scales. Compressed Air Energy Storage (CAES) at large scales, with effective management of heat, is recognised to have potential to provide affordable grid-scale energy storage. Where suitable geologies are unavailable, compressed air could be stored in pressurised steel tanks above ground, but this would incur significant storage costs. Liquid Air Energy Storage (LAES), on the other hand, does not need a pressurised storage vessel, can be located almost anywhere, has a relatively large volumetric exergy density at ambient pressure, and has relatively low marginal cost of energy storage capacity even at modest scales. However, it has lower roundtrip efficiency than compressed air energy storage technologies. This paper carries out thermodynamic analyses for an energy storage installation comprising a compressed air component supplemented with a liquid air store, and additional machinery to transform between gaseous air at ambient temperature and high pressure, and liquid air at ambient pressure. A roundtrip efficiency of 42% is obtained for the conversion of compressed air at 50 bar to liquid air, and back. The proposed system is more economical than pure LAES and more economical than a pure CAES installation if the storage duration is sufficiently long and if the high-pressure air store cannot exploit some large-scale geological feature.

1. Introduction

In 2012, wind power accounted for 39% of renewable power capacity added worldwide, followed by 26% each for solar PV and hydropower [1]. The capacities of the major renewable energy sources are expected to increase in the future. Increasing renewable energy penetration, especially wind, is crucial for decarbonising the grid. As an example, the UK aims to reduce greenhouse gas emissions by 80%, based on 1990 levels, by 2050 [2]. But renewable energy sources, for example wind, are intermittent, and the associated uncertainty with electricity generation from such sources can lead to grid stability issues [3,4]. It is here that bulk energy storage technologies, such as Pumped Hydro Storage (PHS) or Compressed Air Energy Storage (CAES), are expected to play a key role, by offering services primarily in energy management (load levelling and following, power balancing, peak shaving, etc.) [5].

The case for CAES has been made by many [6–11] and need not be rehearsed again here. CAES at large scales has historically been used as a "stand by" power source for smoothing applications. For CAES to be cost effective, it must be employed at large scales (e.g. underground salt caverns, aquifers), but geological constraints prevent widespread deployment of this variant of CAES technologies. An alternative is aboveground storage of compressed air in pressurised steel tanks, but it can incur significant storage costs (see Section 2.1).

In the recent past, Liquid Air Energy Storage (LAES) has experienced a surge in interest [12] and has been considered a possible candidate for bulk storage of electrical energy, particularly in the UK [13]. Liquid air, unlike compressed air, has high energy density

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Nomenclature

A	total heat transfer area (m^2)
A_f	secondary (fin) heat transfer area (m^2)
A_o	free-flow area (m^2)
A_p	primary heat transfer area (m^2)
A_w	area of the wall (m^2)
$\dot{B}$	flow exergy of a fluid (W)
C	compressor
C_p	specific heat capacity at constant pressure (J/kg K)
C_v	specific heat capacity at constant volume (J/kg K)
D	diameter of the outer shell (m)
D_h	hydraulic diameter (m)
E	expander
G	mass flow velocity (kg/m^2 s)
J	Colburn factor
L_{eff}	effective total length of the fin (m)
L_f	effective fin length (m)
L_1	length of the heat exchanger (m)
L_2	width of the heat exchanger (m)
N	number of stages in an *MEHXp*/*MCHXp* unit
N_f	number of fins
N_{off}	number of offset fins
N_p	number of passages
N_{SP}	number of separating plates
P	pressure (Pa)
P_w	wetted parameter (m)
Pr	Prandtl number
$\dot{Q}$	heat content of a stream (W)
Re	Reynolds number
R_p	pressure ratio across one stage of a compressor/an expander
R_w	wall resistance (K/W)
T	temperature (K)
UA	global conductance (W/K)
V	vent to the atmosphere
$\dot{W}_{net}$	rate of net work into/out of the system (W)
a	plate thickness (m)
b	fin height (m)
d	diameter of the inner tube (m)
g	acceleration due to gravity (m/s^2)
h	specific enthalpy (J/kg)
k	thermal conductivity (W/m K)
l	fin length for conduction (m)
m	fin parameter (m^{-1})
$\dot{m}$	mass flow rate (kg/s)
p_f	fin pitch (m)
s	specific entropy (J/kg K)
t_w	wall thickness (m)
x	liquid fraction
y	vapour fraction
AH	after-heater
$Amb.$	ambient conditions
PC	pre-cooler
$MCHXp$	multistage compression with heat exchangers in parallel
$MEHXp$	multistage expansion with heat exchangers in parallel

Greek

ΔH_{2p}	latent heat associated with phase change of air (J/kg)
ΔT	temperature difference between the hot and cold fluids (K)
ΔT_{2p}	film to wall temperature difference during phase change of air (K)
α	heat transfer coefficient (W/m^2 K)
γ	ratio of specific heat
δ	fin thickness (m)
ε	heat exchanger effectiveness (%)
ξ	interrupted fin length in the fluid flow direction (m)
η	efficiency (%)
η_f	fin efficiency (%)
η_o	heat transfer surface effectiveness (%)
μ	viscosity (N s/m^2)
ρ	density (kg/m^3)

Subscripts/superscripts

CA	compressed air
F	forward conversion process
LA	liquid air
R	reverse conversion process
air	air (real gas properties)
$cold$	cold stream in a heat exchanger unit
$comp$	compressor
$elec, CA$	electricity to compressed air (or vice versa)
$elec, LA$	electricity to liquid air
ex	exergy
exp	expander
f	fin
hot	hot stream in a heat exchanger unit
i	inner
iso	isothermal
l	liquid
m	mean
o	outer
pri	primary air
ref	refrigerant (ideal gas properties)
s	isentropic process
sec	secondary air
w	wall
$2p$	two-phase

and can thus be compactly stored. LAES also has the strong advantage that it can be located almost anywhere. It does not need a pressurised vessel for storage, just a well-insulated container.

In this paper, we propose a novel hybrid energy storage system which comprises an aboveground compressed air storage tank supplemented with a liquid air storage tank. To the authors' knowledge, an energy storage system comprising both compressed air and liquid air storage technologies has not been proposed before. The system attempts to exploit the different characteristics of CAES and LAES, i.e., the relatively higher roundtrip efficiency of CAES, and low cost per unit of energy storage capacity of LAES. The system comprises a compressed air store of relatively lower energy storage capacity, a liquid air store of higher energy storage capacity (the efficiency of liquefaction plants depends strongly on their scale [14]), and machinery to transform between the two states of air. The low-frequency components of power are associated with large quantities of stored energy and are mainly handled by the conversion between liquid air and compressed air. The higher-frequency components of power are mainly handled by CAES alone. Thus, when electricity prices are low, and the compressed air tank is nearly full, electricity can still be drawn from the grid by converting some amount of compressed air into liquid air. Note that the first step in an air liquefaction process is the compression of ambient air. Conversely, when electricity prices are high, and the compressed air tank is nearly empty, electricity can still be exported to the grid by converting liquid air back to