Applied Energy 137 (2015) 800–811

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Parametric studies and optimisation of pumped thermal electricity storage ☆

Joshua D. McTigue [a], Alexander J. White [a,*], Christos N. Markides [b]

[a] Cambridge University Engineering Department, Trumpington Street, Cambridge CB2 1PZ, United Kingdom
[b] Department of Chemical Engineering, Imperial College London, London SW7 2AZ, United Kingdom

HIGHLIGHTS

- PTES is modelled by cycle analysis and a Schumann-style model of the thermal stores.
- Optimised trade-off surfaces show a flat efficiency vs. energy density profile.
- Overall roundtrip efficiencies of around 70% are not inconceivable.

ARTICLE INFO

Article history:
Received 21 March 2014
Received in revised form 5 August 2014
Accepted 7 August 2014
Available online 11 September 2014

Keywords:
Electricity storage
Thermal energy storage
Irreversibility
Heat transfer
Optimisation

ABSTRACT

Several of the emerging technologies for electricity storage are based on some form of thermal energy storage (TES). Examples include liquid air energy storage, pumped heat energy storage and, at least in part, advanced adiabatic compressed air energy storage. Compared to other large-scale storage methods, TES benefits from relatively high energy densities, which should translate into a low cost per MW h of storage capacity and a small installation footprint. TES is also free from the geographic constraints that apply to hydro storage schemes. TES concepts for electricity storage rely on either a heat pump or refrigeration cycle during the charging phase to create a hot or a cold storage space (the thermal stores), or in some cases both. During discharge, the thermal stores are depleted by reversing the cycle such that it acts as a heat engine. The present paper is concerned with a form of TES that has both hot and cold packed-bed thermal stores, and for which the heat pump and heat engine are based on a reciprocating Joule cycle, with argon as the working fluid. A thermodynamic analysis is presented based on traditional cycle calculations coupled with a Schumann-style model of the packed beds. Particular attention is paid to the various loss-generating mechanisms and their effect on roundtrip efficiency and storage density. A parametric study is first presented that examines the sensitivity of results to assumed values of the various loss factors and demonstrates the rather complex influence of the numerous design variables. Results of an optimisation study are then given in the form of trade-off surfaces for roundtrip efficiency, energy density and power density. The optimised designs show a relatively flat efficiency vs. energy density trade-off, so high storage density can be attained with only a modest efficiency penalty. After optimisation, losses due to pressure drop and irreversible heat transfer in the thermal reservoirs are only a few percent, so roundtrip efficiency is governed mainly by the efficiency of the compression and expansion processes: overall roundtrip efficiencies approaching those for pumped hydro schemes might be achievable whilst simultaneously attaining energy storage densities of around 200 MJ m^{-3}, but this is contingent upon attaining compression and expansion efficiencies for the reciprocating devices that have yet to be proven.

1. Introduction

The finite nature of fossil fuel reserves together with a wide range of health and environmental concerns arising from the release of combustion products have been acting as drivers for the increasing uptake of renewable sources of energy, such as solar and wind [1]. These energy sources have the potential to reduce the overall dependence on fossil fuels and the emissions arising from their use, however, both solar (especially PV) and wind energy are associated with variable, intermittent and (particularly for wind) uncertain outputs. Beyond the economic considerations of using a significant fraction of inherently variable power generation, the intermittent nature of these energy sources has given rise

☆ This paper is included in the Special Issue of Energy Storage edited by Prof. Anthony Roskilly, Prof. Phil Taylor and Prof. Yan.

* Corresponding author. Tel.: +44 (0)1223 765310; fax: +44 (0)1223 765311.
E-mail address: ajw36@cam.ac.uk (A.J. White).

http://dx.doi.org/10.1016/j.apenergy.2014.08.039
0306-2619/

Nomenclature

A	area, m^2
c_s	solid specific heat capacity, J kg^{-1} K^{-1}
c_p	gas specific heat capacity, J kg^{-1} K^{-1}
C_f	friction coefficient in packed bed
D	reservoir diameter, m
d_p	particle diameter, m
E	stored energy, J
f_p	fractional pressure loss
G	mass flow per unit (open) area, kg s^{-1} m^{-2}
h	local heat transfer coefficient, W m^{-2} K^{-1}
ℓ	length scale, m
L	reservoir length, m
M_s	mass of storage material, kg
$\dot{m}$	gas mass flow rate, kg s^{-1}
p	pressure, Pa
q	heat transfer per unit mass, J kg^{-1}
r_v	volume (compression) ratio
$\dot{S}_{irr}$	entropy generation rate, J K^{-1} s^{-1}
St	Stanton number = h/c_pG
S_v	surface area to volume ratio, m^{-1}
t	time, s
T	temperature, K
V_s	swept volume, m^3
w	specific work, J kg^{-1}
$\dot{W}$	power input/output, W
α	heat leakage factor, dq/dw
α_t	gas thermal diffusivity, m^2 s^{-1}
β	pressure ratio
γ	ratio of specific heats
χ	roundtrip efficiency
ε	void fraction or clearance ratio
η, η_v	polytropic, volumetric efficiency
Λ	dimensionless reservoir length
Π	reservoir utilisation factor
ρ	density, kg m^{-3}
ρ_E	energy density, J m^{-3}
ρ_P	power per unit flowrate, J m^{-3}
σ	valve-to-piston open area ratio
τ	time scale, s, or temperature ratio

Subscripts and superscripts

c, h	cold, hot
chg	charge
dis	discharge
g	gas
s	solid
CE	compressor–expander
EC	expander–compressor
1–4	points on cycle, as shown in Fig. 1

Abbreviations

CAES	compressed air energy storage
PHS	pumped hydro storage
PTES	pumped thermal energy storage

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

to concerns regarding their reliable integration into the electric grid. These factors have led to the widely accepted recognition that energy storage forms an essential part of efficient and sustainable future energy systems, in particular ones featuring significant amounts of renewable resources. In the UK, for example, it is estimated that over the next few decades the integration of intermittent sources into the power infrastructure will require storage capacities of the order of hundreds of GW h – an order of magnitude greater than current capacity [2].

Pumped hydro storage (PHS) is currently the dominant large-scale energy storage technology, with over 99% of the world's installed storage capacity in this form. However, the high initial cost and geographical constraints of PHS mean that many new technologies are emerging, including batteries, flow batteries, compressed air storage (CAES) and, of particular interest here, thermal energy storage (TES). A comprehensive review of these technologies is given in Ref. [3]. TES systems suitable for large-scale storage (i.e., >100 MW h) include: cryogenic systems for which energy is stored within tanks of liquid air or liquid nitrogen; pumped heat storage where energy is stored in high temperature reservoirs, either as 'sensible heat' or 'latent heat'; and hybrid systems that simultaneously exploit both hot and cold thermal storage. Proposals for new types of CAES (notably 'Advanced-Adiabatic' CAES, or AA-CAES) also include a thermal storage component. Despite the variety of detailed arrangements, all TES systems effectively make use of some form of heat pump during the charge phase to extract thermal energy from a low temperature source and deliver it (together with the energy from the electrical work input) to a higher temperature sink. Energy flows are then reversed during discharge such that the system operates as a heat engine. Since the maximum (Carnot) efficiency of the heat engine is precisely the reciprocal of the maximum coefficient of performance of the heat pump, the round-trip efficiency is limited only by the reversibility of the system's various processes.

The present paper focuses on a form of TES system referred to here as 'pumped thermal' electricity storage (PTES),[1] several independent patents for which seem to have emerged almost simultaneously [4–7]. A similar system also seems to have been proposed much earlier [8]. For the particular variant of PTES considered here, based mainly on that described in Ref. [6], the charging (heat pumping) phase is achieved by an electrically driven reverse Joule–Brayton cycle, which establishes a temperature difference between two packed-bed thermal stores. Electrical energy is thus converted to thermal energy that then resides in the stores. When electricity is required, the cycle operates in forward (heat engine) mode, returning heat from the hot to the cold store, thereby recovering electrical work.

The important factors in determining the merit of any electrical energy storage technology are its round-trip efficiency (i.e., the fraction of electrical energy input retrieved upon discharge) and its capital costs per MW installed capacity and per MW h of storage. In this respect, PTES benefits from relatively high energy density, which implies a small plant footprint and low capital cost per MW h. (Comparison of a few large-scale storage technologies suggests that PTES might achieve an energy density roughly an order of magnitude greater than that for CAES and two orders of magnitude greater than for PHS [9].) However, power density (as opposed to energy density) is also an important factor as it impinges on the size and cost of the machinery and hence on the cost per MW. Table 1 provides an approximate comparison of power densities for a few different technologies. The figures have been compiled by computing the maximum exergetic flux for each technology (e.g., at the maximum pressure and temperature for PTES) divided by the local density of the working fluid. The figure for PTES is clearly quite low by comparison, suggesting that con-

[1] Also known as 'pumped heat' electricity storage (PHES).