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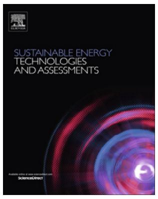

Original Research Article

Thermodynamic analysis of a hybrid energy storage system based on compressed air and liquid air

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ABSTRACT

As renewable electricity generation capacity increases, energy storage will be required at larger scales. Compressed air energy storage 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, on the other hand, does not need a pressurised storage vessel, can be located almost anywhere, and has a relatively large volumetric exergy density at ambient pressure. However, it has lower roundtrip efficiency than compressed air energy storage technologies. This paper analyses a hybrid energy store consisting of a compressed air store at ambient temperature, and a liquid air store at ambient pressure. Thermodynamic analyses are then carried out for the conversions from compressed air to liquid air (forward process) and from liquid air to compressed air (reverse process), with notional heat pump and heat engine systems, respectively. Preliminary results indicate that provided the heat pump/heat engine systems are highly efficient, a roundtrip efficiency of 53% can be obtained. Immediate future work will involve the detailed analysis of heat pump and heat engine systems, and the economics of the hybrid energy store.

Introduction

It is almost certain that in the near future, electricity generation from renewable energy sources, particularly solar and wind, will account for a large portion of the overall generation capacity. Wind power accounted for ~39% of renewable power capacity added worldwide in 2012, followed by ~26% each for solar PV and hydropower [1]. The UK aims to reduce greenhouse gas emissions by 80% by 2050 [2]. To alleviate the problems caused by burning of fossil fuels, renewable generation capacity must be increased – and this calls for a secure, sustainable and reliable energy supply system. It is here that energy storage is expected to play a key role.

Compressed air energy storage (CAES), historically, has been used as a ‘spinning reserve’ for power smoothing applications. For CAES to be cost effective, it must be employed at large scales (e.g. underground salt caverns, depleted aquifers), but suitable geologies for large-scale CAES are not available “on demand”. Thus, this paper investigates employing an above-ground compressed air energy store by supplementing it with a liquid air energy store. Although CAES has relatively high roundtrip efficiency, above-ground components in steel tanks can incur significant storage costs (see Table 1 [3]). Liquid air energy storage (LAES), on the other hand, has the advantage that it can be compactly stored and can be located almost anywhere. Since the efficiency of liquefaction plants depends strongly on their scale [4], the proposed system attempts to make use of the different characteristics of CAES and LAES: it comprises a compressed air store of relatively lower energy storage capacity, a liquid air store of higher energy storage capacity, and machinery to transform between the two states of air. When electricity prices are low, and the compressed air tank is nearly full, electricity can still be bought by converting some amount of compressed air into liquid air. Conversely, when electricity prices are high, and the compressed air tank is nearly empty, electricity can still be sold to the grid by converting liquid air back to compressed air, and then to electricity.

This paper concerns the design of a thermodynamic system for the conversion of compressed air to liquid air and back, with notional heat pump and heat engine systems, respectively.

Background on liquid air energy storage (LAES)

If one removes sufficient heat from an isolated mass of air, it will liquefy. A simple air liquefaction cycle, the Linde–Hampson

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Table 1
Representative costs of CAES systems from various sources. Adapted from Ref. [3].

Source of estimate	Power related cost ($/kW)[1]	Storage cost ($/kWh)[2]
Schoenung and Hassenzahl (2003) (bulk storage)	425	3
Schoenung and Eyer (2008) (distributed gen./surface)	550	120
EPRI-DOE (2003) (salt mine 300 MW)	270	1
EPRI-DOE (2003) (surface 10 MW)	270	40
EPRI (2003) (salt/porous/hard rock/surface)	350 (all)	1/0.10/30/30
EPRI-DOE (2004) (salt/surface)	300	1.74/40

[1] Investment cost of the storage technology per unit of rated output power.
[2] Investment cost of the storage technology per unit of energy storage capacity.

cycle, is shown in Fig. 1, and it employs the Joule–Thomson effect to produce liquid air. At ambient pressure, air becomes completely liquid at 78.9 K. There has recently been a surge of interest in using liquid air as an 'energy carrier', i.e. an energy storage medium, as reported in [5–7], owing to its relatively high exergy density competitive with existing battery technologies [7]) and its potential as a clean transport fuel [5]. Thus, LAES can be thought of as a thermo-electric storage device which stores energy as a temperature difference between two thermal reservoirs [8]. Generally, the LAES cycle involves [9]: (a) The charging of the liquid air store (i.e., the liquefaction process), with the liquid air then stored in a thermally insulated tank at near-ambient pressures; (b) The discharging of the liquid air store, where power is recovered by first pressurising the liquid air, then supplying thermal energy to the fluid, and subsequently expanding to generate work output. This in turn drives a generator to feed electricity back to the grid; (c) 'Cold recycle', where cold thermal energy released during discharge is stored, and is used to minimise the liquefaction work during charging.

Interest in LAES goes back as far as 1977 when Smith [10] proposed a cycle using adiabatic compression and expansion, and reported an energy recovery efficiency of 72%. But this configuration required, most importantly, a regenerator which could withstand temperatures between −200 °C and 800 °C, pressures up to 100 bar, and allow contact with both compressed air and liquid air. Ameel et al. [11] analyse a combined Rankine cycle with Linde liquefaction process, and report that 43% of the energy can be recovered from liquid air. Power recovery from cryogen via an indirect Rankine cycle is one of four major methods of extraction of cold exergy [12], the other three being: (a) 'Direct expansion' cycle where pressurised cryogen is supplied with thermal energy from ambient or waste heat sources, and then expanded to extract work; (b) Indirect Brayton cycle where the cryogen cools down the gas at the inlet to a compressor, then the compressed gas is heated further before expansion. Here, the cryogen is used to minimise compression work; (c) Combination of either Rankine cycle with direct expansion or Brayton cycle with direct expansion.

More recently, a cryogenic energy storage system for electrical energy storage which uses liquid air/nitrogen as the energy carrier coupled with a natural gas-fuelled closed Brayton cycle was proposed [13]. The carbon dioxide produced in the cycle is captured as dry ice, and the roundtrip efficiency is reported as 54%. Here, helium is used as the 'blending gas' (it circulates within the system and is not consumed) to control the temperature of the natural gas after combustion in an oxygen rich environment, and before it enters a gas turbine. It is reported in Ref. [14] that for the system proposed in Ref. [13], capital costs dominate, and the air liquefaction unit accounts for a large part of the capital costs. The authors report that both the capital and peak electricity costs of the system are comparable with combined cycle gas turbine (CCGT) plant. The cost of the cryogenic tank depends, of course, on the capacity, and in terms of cost per rate of liquefaction, $30,000/(tonne/day) for a liquefaction plant with capacity of 500 tonne/day is suggested.

A demonstration LAES plant (350 kW/2.5 MWh) was built in 2008 in Slough, UK, and detailed analysis and results from the testing of this pilot plant can be found in Ref. [9].

Thermodynamic analysis of a 'series' hybrid energy storage system based on compressed air and liquid air

It should be noted that the term 'series' here means that all energy transactions with the grid will be via the compressed air energy store. Thus, the liquid air store acts as *overflow* capacity. The forward process (charging of the liquid air store), is an air liquefaction process, and the reverse process (discharging of the liquid air store) is the energy recovery process, where the recovery is accomplished by converting liquid air to compressed air and finally to electricity, rather than from liquid air to electricity via processes similar to those described in the previous section.

Ideal, reversible hybrid energy storage system

Storing liquid air is storing exergy because as ambient heat is allowed back into the air, it will evaporate and thus expand, and so can be used to do work. Thus, all pumped thermal electricity storage systems are implicitly exergy storage systems. This section describes the configuration of an ideal reversible system and outlines an exergy analysis for this system. Based on this ideal system, considerable insight is gained into what features a practical system should have. It should be noted that an isobaric compressed air store is assumed for the analyses carried out.

In the ideal (reversible) case for the hybrid energy storage system shown in Fig. 2, there is no loss of exergy – all of the flow

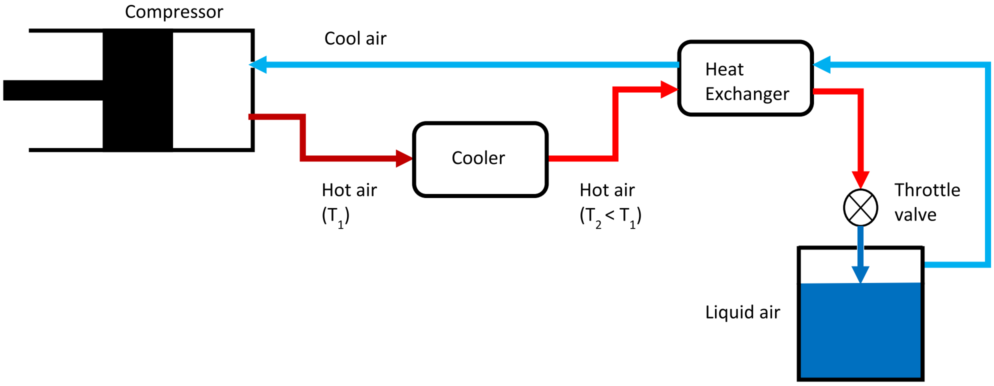

Fig. 1. A simple air liquefaction cycle.

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