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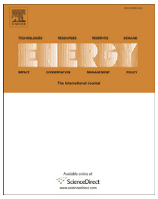

Thermodynamic analysis of a liquid air energy storage system

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ABSTRACT

The rapid increase in the share of electricity generation from renewable energy sources is having a profound impact on the power sector; one of the most relevant effects of this trend is the increased importance of energy storage systems, which can be used to smooth out peaks and troughs of production from renewable energy sources.

Besides their role in balancing the electric grid, energy storage systems may provide also several other useful services, such as price arbitrage, stabilizing conventional generation, etc.; therefore, it is not surprising that many research projects are under way in order to explore the potentials of new technologies for electric energy storage.

This paper presents a thermodynamic analysis of a cryogenic energy storage system, based on air liquefaction and storage in an insulated vessel. This technology is attractive thanks to its independence from geographical constraints and because it can be scaled up easily to grid-scale ratings, but it is affected by a low round-trip efficiency due to the energy intensive process of air liquefaction. The present work aims to assess the efficiency of such a system and to identify if and how it can achieve an acceptable round-trip efficiency (in the order of 50–60%).

1. Introduction

In recent years, the share of total installed capacity covered by intermittent renewable sources has increased impressively in many developed and non-developed countries; for example, in Italy the installed capacity of wind and photovoltaic plants has risen from 6.0 GW up to 27.0 GW in the period 2009–2013, while peak demand on the national grid in the same period was fairly constant, at approximately 52–54 GW [1].

This trend has underlined the importance of developing new grid-scale electric energy storage technologies, which could greatly improve the value of renewable energy sources acting as a buffer balancing their intermittent generation [2]. Furthermore, besides the most obvious services of load levelling and peak shaving, electric energy storage plants can find other applications [2,3], such as provision of balancing energy, spinning reserve, black-start services, price arbitrage, stabilization of conventional generation, island and off-grid storage, *etc.*, which are very important for electric grid management and can be another source of revenue for the storage plant [3].

At the moment, only two technologies can be considered mature for grid-scale energy storage [4,5]: PHES (pumped hydro) and CAES (compressed air energy storage). These options, though, both present a considerable drawback: the plant's location is constrained by geological features (such as the availability of an underground cavern for CAES). In particular, it is difficult to foresee any significant increase in pumped hydro capacity, at least in developed countries, because the most attractive sites have already been used. For these reasons considerable effort has been devoted by researchers worldwide in order to devise different technological options for electric energy storage that could provide efficient, economical, geographically unconstrained and environmentally safe solutions [2,4–8].

Among the innovative proposals for electric energy storage, CES (cryogenic energy storage) and in particular LAES (liquid air energy storage systems) hold great promise, because they rely on mature technologies developed for more established applications, such as the gas liquefaction industry, and are geographically unconstrained: energy is stored in a cryogenic fluid in liquid phase, thereby greatly reducing the volume of the reservoir needed in comparison to a more conventional CAES system.

A LAES pilot plant (350 kW/2.5 MWh) was developed in Scotland by the UK company Highview Power Storage [9], and a larger prototype plant (5 MW/15 MWh) is under construction in the UK

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[10]. The company and the researchers promoting this solution claim several advantages for LAES technology: high energy density; no geographical constraints; high storage capacity; low investment costs; long useful life; possibility of waste heat recovery from nearby industrial plants; no environmental hazards [11]. The expected performance of liquid air storage in terms of round-trip efficiency is in the range 50–60% [11], which may seem rather disappointing; however, the proponents of these plants observe that, as long as the overall storage capacity is smaller than the excess power generated by intermittent renewable energy sources, the round-trip efficiency has a smaller impact on the economic performance of the storage plant than the investment cost [11,12].

A few studies on the overall round-trip performance of LAES plants with different configurations are available in the literature. Chino and Araki [13] proposed an air liquefaction plant integrated with a conventional combined cycle power plant: when on-peak power demands increase, the plant is operated in energy recovery mode, in which compressed air is supplied to the combustor of the gas turbine by a cryogenic pump, fed with the liquid air stored in an insulated tank, instead of the conventional air compressor. The plant achieves high efficiency in the liquefaction section thanks to the recovery of cold exergy from liquefied air, which is stored in a storage medium and later used in the liquefaction section (at off-peak hours, when the plant is operated in energy storage mode). The resulting round-trip efficiency is higher than 70%.

Ameel et al. considered a storage plant based on a liquid air Rankine cycle [14]. In this case a round-trip efficiency of only around 43% was demonstrated, but the proposed configuration was peculiar because it relied on an external supply of liquid air to be added to the liquid air produced within the plant, and there seemed to be no integration of heat/cold storage.

Li et al. studied a LAES system integrated with a nuclear power plant [15]. The heat input in the recovery section of the energy storage system was supplied by steam bled from the nuclear power plant, with a turbine inlet temperature of 280 °C; the recovery and the liquefaction section were thermodynamically coupled by means of a cold storage system, based on a pair of thermal fluids (propane and methanol) selected because of their comparatively large heat capacity. The system reached a round-trip efficiency higher than 70%, thanks to the tight integration between recovery and liquefaction sections, to a turbine configuration with three reheatings, and also to quite optimistic values of isentropic efficiencies and pinch-point temperature differences.

In this paper a LAES system is studied, which shares some features on one hand with the plant proposed in Ref. [15] (with particular reference to the liquefaction and cold storage section), and on the other with an adiabatic CAES plant (heat recovery and storage from the intercooling of compressed air). This configuration, which is described in detail in the following section, allows to evaluate the performance of a stand-alone LAES system, i.e. a system that does not rely on any external heat input (such as waste heat from an industrial plant or heat derived from an adjacent power plant).

2. Plant layout

The layout of the proposed LAES plant is represented in Fig. 1.

In the liquefaction island, air is first compressed to high pressure, in a two-step intercooled process where heat is recovered by a thermal oil which is then stored at relatively high temperatures in a hot storage section. Intermediate pressure ratios are selected in order to minimize compressor work, therefore achieving the maximum storage efficiency for a given overall pressure ratio. The thermal oil here considered is Essotherm 650, as modelled in the Media library of the Modelica software package [16].

The compressed air is then cooled in a cold box by means of the returning air from the air separator and by cold fluids stored in a Cold Storage section, before flowing in a cryoturbine; this expansion produces a vapour–liquid mixture that is collected and separated into a gas stream and a liquid stream in the air separator. The liquid air thus produced is stored in a tank, which effectively performs the most important storage function in this energy storage plant, at approximately 80 K and atmospheric pressure.

When the plant is operated in energy recovery mode, liquid air is pumped from its tank and heated up to near-ambient temperature by the cold fluids: in this way, it is possible to store liquefied air's cold exergy in the Cold Storage section, and reuse it later to liquefy air at very high efficiency. The cold fluids considered in this paper are the same as in Ref. [15], i.e. propane and methanol, given their high heat capacity, which reduces the storage volume required. This solution is preferred to storing cold energy in solid media such as pebbles or concrete [17,18] because, as shown in Ref. [15] and by preliminary calculations by the authors as well, it requires a significantly smaller storage volume. In any case, it must be pointed out that this choice does not alter the thermodynamic process and, consequently, the plant's overall performance.

The pumped air flows first in a regenerator, then in a superheater, where it is heated by the thermal oil stored in the Hot Storage section, and finally through a turbine. The expansion is divided in three steps with interheating, again accomplished by means of the thermal oil. Intermediate pressure ratios are chosen so as to maximize the turbine work output, therefore achieving the maximum recovery efficiency for a given overall expansion ratio. The thermal oil is returned to the Hot Storage section, where it is collected in an ambient-temperature tank, after having been cooled in the heat exchanger labelled as “heat rejection” in Fig. 1. Indeed, this is essentially the only component in the plant where heat is rejected to the environment, since air is discharged from the regenerator at temperatures very close to ambient temperature.

The constitutive equations for the proposed plant were implemented and solved, for stationary operation, in Matlab. The thermodynamic properties of all fluids, with the exception of the thermal oil Essotherm 650, were evaluated by means of the REFPROP 9.1 software [19]. Ambient air was considered as a mixture of only nitrogen and oxygen, with mass fractions of 77% and 23% respectively; thermodynamic properties of nitrogen and oxygen are evaluated in REFPROP according to Refs. [20] and [21] respectively.

3. Results and discussion

3.1. Performance indicators

3.1.1. Round-trip efficiency and liquid air yield

The results of the simulations will be presented in this section mainly with reference to a few selected performance parameters, among which the most important is certainly the round-trip efficiency η_{RT}, simply defined as the work output in recovery mode divided by the work input in storage mode:

$$\eta_{RT} = \frac{W_{out}}{W_{in}} = \frac{m_{1R} w_T}{m_1 w_C} \tag{1}$$

Here w_T and w_C represent the net specific work of the air turbine and compressor, respectively. For the power plant described in Fig. 1, with a two-step compression and a three-step expansion, the net specific work output is calculated by means of energy conservation equations applied to each component (turbines and pump), where changes in kinetic and potential energy can be neglected with respect to changes in static enthalpy: