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Performance evaluation of various cryogenic energy storage systems

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ABSTRACT

This work compares various CES (cryogenic energy storage) systems as possible candidates to store energy from renewable sources. Mitigating solar and wind power variability and its direct effect on local grid stability are already a substantial technological bottleneck for increasing market penetration of these technologies. In this context, CES systems represent low-cost solutions for variability that can be used to set critical power ramp rates. We investigate the different thermodynamic and engineering constraints that affect the design of CES systems, presenting theoretical simulations, indicating that optimization is also needed to improve the cryogenic plant performance.

1. Introduction

Exergy gives the maximum potential of a renewable source to generate work, and different methods to evaluate the natural exergy have been discussed by several authors [1–5]. The flow availability (α) of natural sources, in a reversible process, can be evaluated by Eq. (1) that quantifies the specific exergy in an arbitrary point.

$$\alpha = \left(h - T_0 s + \frac{1}{2}V^2 + gZ\right) - (h_0 - T_0 s_0 + gZ_0), \quad (1)$$

where h is the specific enthalpy, T is the absolute temperature, s is the specific entropy, V is the velocity, Z is the elevation, g is the gravity, and subscript 0 refers to the dead state and the arbitrary elevation reference. For example, wind speed natural availability can be approximated by $\frac{1}{2}V^2$, and potential energy from reservoirs can be approximated by $g(z - z_0)$. This flow availability can be converted into useful forms of energy, for example by converting it into angular-momentum using turbines which is later converted into electric energy at the cost of new irreversibilities. During these processes, the total extracted work (W) is obtained from the exergy balance equation, Eq. (2).

$$W = (\alpha_1 - \alpha_2) - I, \quad (2)$$

where I represents the process irreversibility, the difference $\alpha_1 - \alpha_2$ is the availability (maximum work) between thermodynamic states 1 and 2, respectively. Eventually electric energy is transmitted to the grid line or transferred to energy storage devices. The purpose of energy storage is to transform part of the converted availability (see Eq. (1)) in to an ordered (manageable) form of energy conversion. This type of technology has been targeted as one of the solutions to enable higher penetration of volatile renewable resources, such as solar and wind, into the power grid [6].

One of the devices used to recover this availability is the LAES (liquid air energy storage), also called CES (cryogenic energy storage). The first CES system dates from 1900 [7], when the Tripler Liquid Air Company designed a liquid–air fueled car for competing with the steam and electric vehicles of those days. During the oil crisis in the 1970s, the interest in cryogenic cars returned. At the same time emerged the interest of using air liquefaction as an energy storage system [8].

In the literature [9,10], the term CES [7], or LAES, generally is used to refer to energy storage of liquefied air. Currently, hydrogen and air/nitrogen are two of the most promising alternatives of CES

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Nomenclature

E	exergy, kW
g	gravity, m s^{-2}
h	enthalpy, kJ kg^{-1}
I	irreversibility, kJ kg^{-1}
k	specific heat ratio
L	conditional parameter of Eqs. (6) and (7)
m	mass, kg
MFR	mass flow ratio, $\dot{m}_{exp}/\dot{m}_{liq}$
n	conditional parameter of Eqs. (6) and (7)
$\dot{m}$	mass flow rate, kg s^{-1}
P	pressure, Pa
q	quality
R	universal gas constant, kJ kg^{-1} K^{-1}
s	entropy, kJ kg^{-1} K^{-1}
t	time, s
T	temperature, K
U	internal energy, kJ/kg
V	velocity, m s^{-1}
v	specific volume, m^3/kg
W	work, kJ
$\dot{W}$	power, kW
x	proportion of liquid produced
z	proportion of bypassed mass flow
Z	height, m

Greek

α	flow availability, kJ kg^{-1}
ε	effectiveness
γ	proportion of saturated vapor inside the tank
η	process efficiency
ρ	density, kg/m^3
ψ	overall efficiency

Subscripts

0	dead state
a,b,c,d,e	geometric position in Fig. 1
bpt	bypass turbine
cla	Claude cycle
col	Collins cycle
exp	expansion circuit
ht	heat exchanger
i	inlet
ie	isentropic
iso	isothermal
l	saturated liquid
lin	Linde–Hampson cycle
liq	liquefaction circuit
o	outlet
p	pump
st	storage
t	turbine
v	saturated vapor

working fluids [11,9]. However, Li et al. [9] compared hydrogen and air/nitrogen for energy storage, concluding that even with similar efficiency liquefied air is more competitive as an energy carrier in terms of capital costs. Recently, Akhusrst [7] published a report regarding the use of liquid–air in the energy and transport systems, indicating the important potential of CES for those applications. In terms of CES applications Li et al. [12] proposed a combination of nuclear power plants and CES for load shifting at peak hours. The same authors proposed a new hybrid system comprised of a solar thermal plant and a cryogen fueled power system [13], indicating that this approach provides more power than the summation of the two systems working separately. Zhang et al. [14] assessed the operational benefits of using CES in an existing air separation plant, looking for new potential opportunities of the technology, as load shifting by storing purchased energy and selling it back during higher-price periods, thus creating additional revenues. When applied to a real-world industrial plant, authors concluded that CES can be very attractive, mainly for underutilized air separation plants. According to Hadi and Zadeh [15], the relatively high energy density and high efficiency of energy conversion, make CES a singular method for energy storage. Chen et al. [16] highlight that CES is a low-footprint technology, and can be also used to provide cooling and refrigeration. Hadi [15] presented an investigation of the economic viability and profitability of CES systems. Li et al. [17] presented a critical assessment on cryogen as an energy carrier, highlighting that direct expansion combined with a Rankine cycle is promising when carbon dioxide capture is used, as detailed in Ref. [18]. Despite the importance of CO_2 capturing [19,20] and cascading cycles [21–23], the work here presented gives attention to the liquid air physical exergy in a direct expansion process.

The overall efficiency of liquid air production ranges between 11% and 50%, depending on the plant size [9]. After the liquefaction process, the availability of the liquid air is used to produce electricity. This conversion has a large potential for loosing energy to atmosphere due to the cryogenic temperature resulting in a lower efficiency (up to 40%). Looking for a higher efficiency, Chen et al. [10] patented a cycle to recover this physical exergy, producing liquid air at the same time as air is expanded and electricity is produced (this process is better explained in the following section). The novel solution of CES, conceived by Chen et al. [10], is based on Linde–Hampson cycle. Ameel et al. [24] simulated the cycle proposed by Chen et al. and concluded that it is very sensitive to the efficiency of the heat exchanger, compressor and turbine. The authors concluded that this cycle reaches a maximum efficiency of 43.3% without using any external source of energy, and 63.7% considering an isothermal expansion at 400 K.

In this work we evaluate again the solution proposed by Chen et al. [10], and introduce other alternatives based on Claude and Collins cycles. The presented solutions can reach higher values of efficiency, when compared to the Chen et al. [10] approach, as demonstrated in the following sections.

2. Methodology

This section was divided in two subsections. Aspects related to the liquefaction process are shown in the first part of this section. In the second part, a discussion on the expansion circuit is presented.

2.1. Liquefaction circuit

The purpose of the liquefaction circuit is to produce liquid nitrogen from atmospheric air. Industrial production of liquid nitrogen began in England, France and Germany in 1902, pioneered by Willian Hampson, Carl Linde, Georges Claude, and Charles Tripler [25]. Linde patented his cycle in 1903 [26], which is considered the simplest approach to produce liquid from gases (see ref. [27]), but it