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Liquid air energy storage: a potential low emissions and efficient storage system

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Abstract

The current increase in the deployment of new renewable electricity generation systems is making energy storage more and more important at small and large scales in order to guarantee and secure supply of electricity. An ideal energy storage technology would have a high power rating, a large storage capacity, high efficiency, low costs and no geographic constraints. The use of air as energy carrier has been studied since the 20[th] century with the first compressed air energy storage (CAES) systems. This technology is still recognized to have potential but it is geographically constrained where suitable geological tanks are available unless compressed air is stored in pressurized tanks with significant costs. Liquid Air Energy Storage (LAES) represents an interesting solution due to his relatively large volumetric energy density and ease of storage. This paper focuses on power recovery from liquid air, either with or without combustion. Two layouts are modeled with Aspen HYSYS® simulation software and compared in terms of roundtrip and fuel efficiencies.

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Keywords: Liquid Air Energy Storage; Cryogenic; Energy Storage; Air Expansion.

Nomenclature

CAES	Compressed Air Energy Storage
E_{air}	Air liquefaction energy per kg liquid air [kWh/kg]
E_{tot}	Recovered energy per kg liquid air [kWh/kg]
η_{rt}	Roundtrip efficiency
η_{fuel}	Fuel utilization efficiency
LAES	Liquid Air Energy Storage

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LHV_{CH4}	Methane Lower Heating Value [MJ/kg]
mf_{air}	Liquid air mass flow rate [kg/h]
mf_{CH4}	Methane mass flow rate [kg/h]
P_{air}	Liquid air pump power [kW]
P_{tot}	Total power output [kW]
P_{turb}	Turbines power output [kW]
PV	Photvoltaic

1. Introduction

On of the key strategies to mitigate carbon dioxide emissions from electricity generation is the use of renewable energy. In recent years a huge renewable power capacity was installed in several countries, with the majority of plants using solar and wind energy, which are intermittent and unprogrammable sources. Renewable power represented approximately 58.5% of net additions to global capacity in 2014, with significant growth in all regions. Wind, solar PV and hydro power dominated the market. By year's end, renewable energy systems will represent 27.7% of the world's power generating capacity, enough to supply an estimated 22.8% of global electricity [1].

Further increase in renewable energy in some areas where the installed power has reached almost 50% of the overall capacity cannot be reasonably expected unless large scale energy storage systems are installed to help balance the supply and demand curves by shifting the times of high energy production to times of high energy demand. This is extremely important for urban areas, where the demand of energy is highly concentrated and clean and safe systems are privileged.

Compressed air energy storage (CAES) has been studied since 20th century for city-wide scale. In last 50 years utility-scale plants have been studied and built, from Germany to USA. CAES has a relatively high roundtrip efficiency but to be cost effective it must be employed with large and appropriate underground storage volumes (salt caverns, abandoned mines).

Unfortunately suitable geological formations with the characteristics suitable for CAES are not common and the alternative of underground steel tanks requires huge investments [2]. On the other hand, liquid air can be compactly stored in simple and smaller tanks thanks to its energy density and pressure. Cryogenic fluids can be stored for many months in low pressure insulated tanks with losses as low as 0.05% by volume per day.

Liquid Air Energy Storage (LAES) represents an interesting solution [3] whereby air is liquefied at -195°C and stored. When required, the liquid air is pressurized, evaporated, warmed with an higher temperature source and expanded in turbines to generate electricity. Warm and cold storage could improve significantly roundtrip efficiency [4].

The present paper focuses on electrical power generation from liquid air, with and without addition of combustion. Two different layouts are modeled and compared in terms of roundtrip efficiency and methane efficiency (defined in paragraph 3).

2. Materials and method

For this analysis the Aspen HYSYS® [5] process simulation code was selected. Only six pure components are selected from HYSYS source database: nitrogen, oxygen, ambient air, methane, water and carbon dioxide. The property package is the classical Peng-Robinson. Only one reaction is implemented for methane combustion :

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

Liquid air comes from storage as a mixture of molecular oxygen and nitrogen, respectively 0.76 and 0.24 in mass fractions, at -195°C and 2 bar. Pump and turbines are considered with an adiabatic efficiency of 75%. Heat exchangers are countercurrent flow type with small pressure drops (around 0.5%).

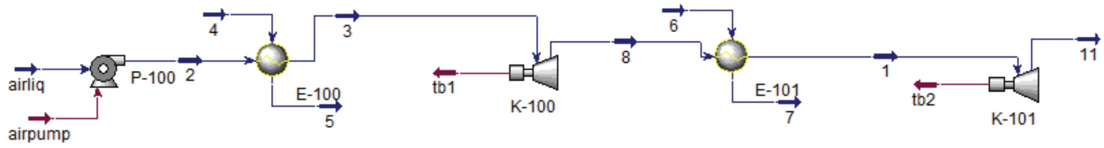


Fig. 1. Air expansion without combustion, *'baseline case'*

In Figure 1 the baseline layout is reported with ambient air (25°C @ 1bar) as upper temperature source. Liquid air from storage is pumped at 200 bar, evaporated and warmed in the first exchanger up to 20°C. After first expansion (to 30 bar) the air is warmed again with ambient air and finally expanded to ambient pressure.

This simple system, without any heat addition, can be considered as the baseline case to which all further ideas should be compared. No external energy is consumed, but the roundtrip efficiency it too low to make it interesting in comparison with any other energy storage system. In order to increase efficiency and specific work, a second layout with an external heat addition by means of natural gas combustion has been investigated. As shown in Figure 2 the first stages (pumping, evaporation and warming with ambient air) are the same as in the first configuration. Two conversion reactors are implemented with injection of compressed methane for combustion simulation, and a second heat exchanger completes the recuperation process from hot exhaust gases.

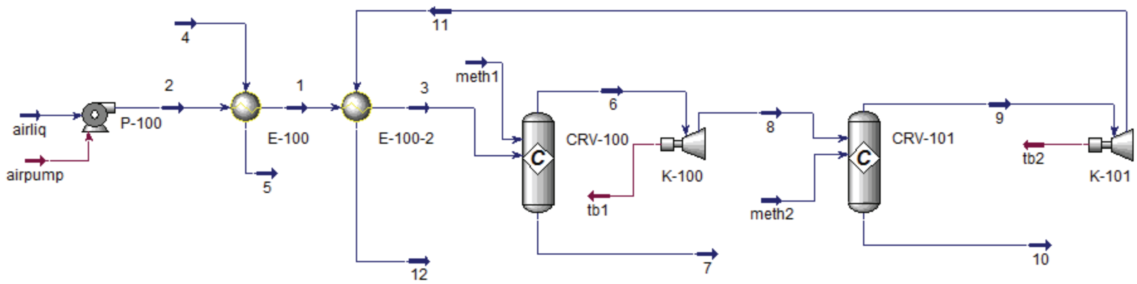


Fig. 2. Air expansion with combustion, *'natural gas case'*

3. Theory and calculations

The energy required for liquid air production was assumed as in (2). This value is quite conservative in comparison with the most advanced technology for liquid air production:

$$Eair = 0.5 \text{ [kWh/kg]} \quad (2)$$

Total output power takes account of liquid air pumping power and power exploited from turbines :

$$P_{tot} = P_{turb} - P_{air} \text{ [kW]} \tag{3}$$

Specific energy recovered is defined considering the total output power respect to liquid air massflow :

$$E_{tot}= P_{tot} / mf_{air} \text{ [kWh/kg]} \tag{4}$$

In case of natural gas combustion the specific combustion energy is calculated with reference to liquid air massflow :

$$E_{CH4} = LHV_{CH4}\ mf_{CH4}\ 10^6 / mf_{air}\ 10^3 \text{ [kWh/kg]} \tag{5}$$

The roundtrip efficiency could then be defined as:

$$\eta rt = Etot / (ECH4 + Eair) \text{ [-]} \tag{6}$$

Only in the *natural gas case*, fuel efficiency is introduced in order to evaluate the quality of fuel exploitation

$$\eta_{fuel} = P_{tot}\ 10^3 / LHV_{CH4}\ mf_{CH4}\ 10^6 \text{ [-]} \tag{7}$$

Liquid air mass flowrate (mf_{air} = 200 kg/h) and pressurization are the same in both cases. Turbines expansion ratio are identical too. Total natural gas mass flowrate is set to obtain a global excess of air in order to limit the maximum temperatures (temperature allowed at inlet turbine of 1400 K)

4. Results

In Table 1 the main parameters and results of simulations are summarized.

Tab. 1. simulation parameters and results

	baseline case	natural gas case
mf_{air} [kg/h]	200	200
mf_{CH4} [kg/h]	-	6.3 (3.8+2.5)
P_{air} [kW]	1.67	1.67
P_{turb} [kW]	11.96 (4.61+7.35)	83.08 (32.73+50.35)
P_{tot} [kW]	10.29	81.41
E_{tot} [kWh/kg]	0.051	0.407
E_{CH4} [kWh/kg]	-	0.438
η_{rt} [-]	0.10	0.43
η_{fuel} [-]	-	0.93

Natural gas combustion supplies heat at a very high temperature and leads to important benefits in terms of total power generated and roundtrip efficiency. Fuel efficiency rises up to a significant value of 0.93, which means that almost all the fuel energy is converted into work. This does not contradict the second law of thermodynamics since most of the heat is provided at ambient temperature using the ambient infinite heat capacity. However, this is an important parameter for the evaluation of different systems configurations.

As far as power and efficiency are concerned it should be pointed out that pump/turbines isentropic efficiency was set at 75%, which is a very conservative value. Furthermore, in the roundtrip efficiency the energy required for liquid air production was set at Eair=0.5 [kWh/kg]. This value is strictly related to the air liquefaction process and current air liquefaction processes could require as low as 0.35 [kWh/kg] which would raise the rountrip efficiency to values as high as 0.7, making this process very attractive in comparison with batteries and also with pumping hydro storage.

In both cases a remarkable amount of 'waste cooling power' results from liquid air evaporation and warming with ambient air, suggesting possibilities of storage and reutilization in liquefying process or other power generation cycles.

5. Conclusions

This paper presents one possible system configuration for liquid air energy storage. its performance was compared with the simplest possible possible system where no external energy, except heat from ambient air, is used in the regasification of liquid air. The baseline configuration has too low a roundtrip efficiency to be interesting in comparison with other energy storage options.

However, the system presented in this paper using an external heat source from natural gas combustion is quite efficient both in terms of roundtrip efficiency and in fuel efficiency. Since most of the parameters used in the simulation are not optimized, the potential for a further improvement in the performance as energy storage system is ample.

Therefore LAES may be a promising technology to store energy and use it at peak times with interesting performance. Additional configurations are being studied and will be compared in a future study. The integration with the liquid air production systems may also be beneficial for the overall performance of the energy storage system.

6. References

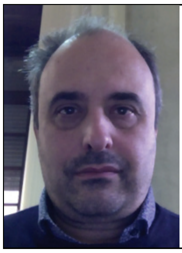
[1] www.ren21.net Renewables 2015 Global Status Report. (last accessed 28.09.15)

[2] Steward D, Saur G, Penev M, Ramsden T. Lifecycle cost analysis of hydrogen versus other technologies for electrical energy storage, NREL technical report TP-560-46719. Available at: http://www.nrel.gov/docs/fy10osti/46719.pdf; 2009 (last accessed 28.09.15)

[3] Bernd Ameel, Christophe T'Joen, Kathleen De Kerpel, Peter De Jaeger, Henk Huisseune, Marnix Van Belleghem, Michel De Paepe. Thermodynamic analysis of energy storage with a liquid air Rankine cycle doi:10.1016/j.applthermaleng.2012.11.037

[4] Robert Morgan, Stuart Nelmes , Emma Gibson , Gareth Brett. Liquid air energy storage – Analysis and first results from a pilot scale demonstration plant. doi:10.1016/j.apenergy.2014.07.109

[5] HYSYS v.8.6, Aspen Tech; 2014



Biography

Professor Umberto Desideri is full professor of thermal machines at the University of Pisa. He earned a MSc in Mechanical Engineering and a PhD in Energy Engineering.

His research activites are focused on energy systems optimization and he is author of more than 200 scientific papers.