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Hybrid power plant for energy storage and peak shaving by liquefied oxygen and natural gas

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HIGHLIGHTS

- Thermodynamic analysis of a hybrid system with storage and production.
- A method for comparing system performances with different kind of plant is defined.
- Optimized arrangements, reach very high equivalent round trip efficiencies.
- Oxy-combustion only produces carbon dioxide and water.
- Carbon dioxide can be easily liquefied, using cold liquefied natural gas.

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ABSTRACT

The increasing penetration of renewable energy sources in the electricity generation scenario forces to face new challenges to achieve an effective management of the power system both in technical and economic terms. Traditional energy storage solutions, like electrochemical cells and pumped hydro energy storage appear critical in terms of economic sustainability and site-dependency. The use of compressed air as energy storage has been investigated since the 20th century, but, in its first configuration, it was affected by site constraints as pumped hydro plants do. Liquid air energy storage has the chance to overcome those limits, but the experimental studies have far reached low efficiency. However, by rising the highest cycle temperature with the addiction of fossil fuel energy, these results can be largely improved.

The paper deals with the thermodynamic analysis of a hybrid system including energy storage and production based on a liquid air energy storage plant where only oxygen is liquefied, while liquefied natural gas is used as fuel. In the production phase, liquefied oxygen and natural gas react in an oxy-combustion chamber where a large amount of water is added to keep the temperature at an acceptable level by evaporation. The system does not require an external water supply since all the water needed is produced by the cycle itself, allowing the plant to be placed also in remote areas with poor water resources. At the beginning of the cycle, both the reagents are liquid at very low temperature (below $-150\,^{\circ}\mathrm{C}$) and they need heat to be gasified; a large amount of this heat can be recovered from the combustion products, which, being cooled at suitable pressure, release liquid carbon dioxide which can thus be easily separated. Optimized arrangements, compared to the performances of the best available hybrid peak plants, even with sufficiently conservative hypotheses, reach high equivalent round trip efficiencies, even higher than 90%.

1. Introduction

Energy storage systems are becoming more and more important for power system operation with a continuously increasing share of generation from not dispatchable renewable sources. In 2016 more than a hundred billion dollars has been invested in PV based plants and a similar amount also in wind farms.

Hybrid systems for storage and generation of electricity help keeping the balance between power generation and demand in the electrical systems having a high share of production from variable and stochastic renewable sources (such as solar photovoltaics and wind), thus enabling the system to have a high energy and economic-financial effectiveness in providing the grid with regulation services [1], even in systems with load and generation uncertainty [2].

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These systems, jointly managed with renewable generation, enable creating integrated systems able to follow a guaranteed production program and, therefore, to participate in the electricity market, overcoming the dispatching priority method used for subsidizing the generation from renewables.

Key features of these integrated hybrid systems can be:

- have a long-term electricity storage able to compensate the production surplus for at least one day (e.g. for a photovoltaic production system) or one week (e.g. for a wind power system), i.e. from ten to hundreds of equivalent running hours at rated power;
- a high energy efficiency of the production subsystem, especially when fossil fuels are used.

Several different options exist for deploying large storage systems, mainly based on pumped hydroelectric storage, electrochemical storage and compressed air energy storage as shown in the review presented in [3]. Across the various technologies, electrochemical storage has probably the highest round-trip efficiency but cannot be economically used for charge-discharge cycles longer than some hours, since they show good performance mainly during cycles with a high power to energy ratio.

When dealing with longer cycles with daily or weekly storage, pumped hydro and compressed air are to be considered. Nowadays, more than 99% of the storage capacity available worldwide in power systems (excluded the fuel reservoir of thermal units) comes from pumped hydro energy storage (PHES) plants [3]. The most critical issue for these systems is finding a suitable location and, in developed countries, almost all technically and economically available sites have been used [4]. Compressed air energy storage has been widely studied during the 20th century and two large plants were built in 1978 and 1991. Although studies claims these systems have a high efficiency and several projects are being developed for further increasing their efficiency as presented in the detailed review reported in [5], finding suitable locations where a geological hermetic tank is available is a difficult task. High pressure and large volumes are needed for coping with a reasonable amount of stored energy. Studies performed in the ‘80s have analysed the chance of using steel tanks for storing the compressed air but the relevant costs have resulted extremely high. In any case compressed air must be heated by an external source, before expanding for recovering the stored energy. Although the heat available during the air compression stage can in principle be stored and later used [5], this strategy poses quite critical issues, as plant size, cost and complexity.

In the last years, the use of the Liquid Air Energy Storage (LAES) technology has started to be more and more considered and investigated. Instead of being compressed at very high pressure, air is liquefied and stored in low pressure adiabatic tanks having a small size if compared to the volumes needed for compressed air energy storage (CAES). As a matter of fact, LAES specific energy is significantly higher (ranging between 150 and 250 Wh/kg) with respect to CAES one (30–60 Wh/kg) [6]. Volume loss is limited to 0.05% per day [7]. Air is cooled down to −195 °C and liquefied using excess energy generation. When liquefied air needs to be used to recover the energy stored, it will be pressurized by means of a pump with a remarkable energy saving compared to gaseous air compression, then vaporised using the heat available at ambient temperature or with the help of a combustion process or even exploiting the residual heat of an industrial process. Mechanical work (and hence electrical energy) is obtained by air expansion in turbines.

One of the first papers presented on LAES is [8] where an interesting data on plant size is given comparing the reservoir needed for a 5 h 50 MW storage: it reports that 450000 m^3 are needed with a 500 m drop for hydro storage, 120000 m^3 at 80 bar for compressed air and just 1400 m^3 for liquid air.

Some proposals foresee the adoption of thermal storage systems for improving the round trip efficiency of the plant. Heat is released during the liquefying process and reused during the air evaporation instead of an external source such as fossil fuel [9]. A comprehensive analysis is shown in [10] where a study indicates a maximum round trip efficiency of 86% can be achieved with ideal isothermal compression and expansion and without using fossil fuel. Accounting for real machine efficiencies, round trip efficiency drops below 50%. Further studies with a Rankine cycle, give similar outcomes as shown in the works reported in [11,12] and [13]. The efficiency of the liquefying process is the most critical issue and various solutions have been proposed for improving the round trip efficiency increasing the complexity of the cycle [6], or using cold liquefied natural gas as a cooling source [14], or by combining the needs for domestic cooling as presented in the three studies reported in [15–17].

Considering the results already presented in [4], and that liquid nitrogen and oxygen do not mix with each other with problems of stratification in cryogenic tanks, the proposal of this work is to use liquefied oxygen (LOx), instead of liquefied air, together with liquefied natural gas (LNG) used to increase the maximum cycle temperature and achieve the result that combustion products are just water and carbon dioxide. The liquid oxygen storage also needs less volume with respect to liquid air storage with benefit in terms of heat losses. Liquid water is used to keep the temperature of the oxy-combustion at reasonable values and the carbon dioxide in the exhaust is liquefied, at suitable pressure, by releasing the heat to the oxygen which needs to be evaporated.

The aim of the paper is to propose a new process and check its thermodynamic feasibility while assessing reasonable values for the efficiency the process might have. The process is optimized to get the maximum possible efficiency accounting for physical constraints and reasonable configuration and parameter choices. It is not intended to design a real plant and to simulate the actual cycle including detailed models of the components.

2. Hybrid power system for electric energy storage and production

The hybrid system taken as reference for the present study is shown in the block diagram of Fig. 1

It can be characterized by the rated values of four variables:

- the rated power of the electricity generation system P_e,
- the rated power of the oxygen liquefaction process P_o,
- the mass quantities which can be stored in terms of liquid oxygen Q_o and liquid methane Q_m.

It is clear that the maximum power exchanged with the network will be the maximum value between P_e and P_o.

The power values P_e and P_o will be determined on the basis of the

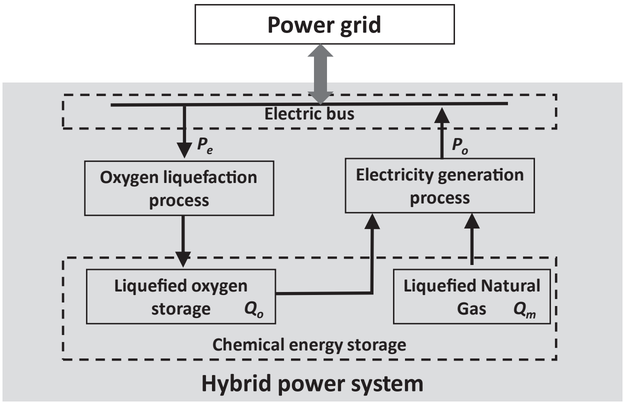

Fig. 1. Principle scheme of the plant and rated characteristics.