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Techno-economic analysis of oxy-combustion coal-fired power plant with cryogenic oxygen storage

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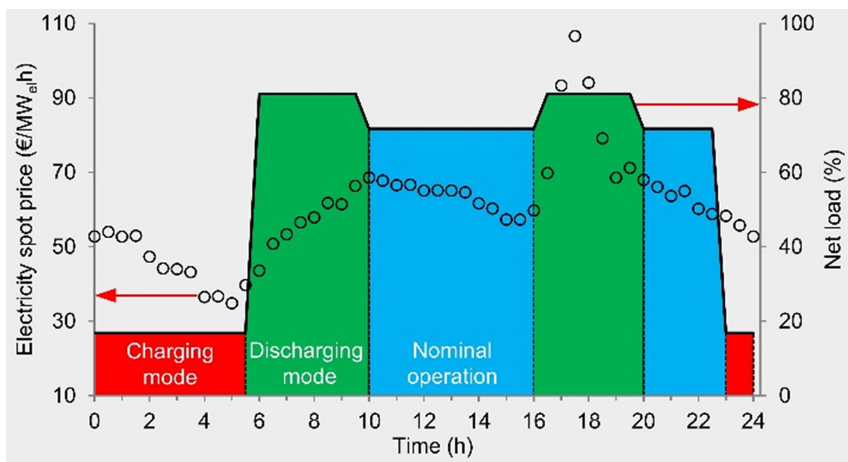
HIGHLIGHTS

- Oxy-combustion coal-fired power plant with cryogenic O_2 storage was assessed.
- Cryogenic O_2 storage was shown to have high energy density and specific energy.
- Cryogenic O_2 storage increased the daily efficiency penalty by 1.1–1.3%$_{HHV}$ points.
- Benefits of energy storage were found to be available at low capital investment.
- Implementation of energy storage can improve the daily profit by 3.8–11.6%.

GRAPHICAL ABSTRACT



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ABSTRACT

Around 43% of the cumulative CO_2 emissions from the power sector between 2012 and 2050 could be mitigated through implementation of carbon capture and storage, and utilisation of renewable energy sources. Energy storage technologies can increase the efficiency of energy utilisation and thus should be widely deployed along with low-emission technologies. This study evaluates the techno-economic performance of cryogenic O_2 storage implemented in an oxy-combustion coal-fired power plant as a means of energy storage. Such system was found to have high energy density and specific energy that compare favourably with other energy storage technologies. The average daily efficiency penalty of the analysed system was 12.3–12.5%$_{HHV}$ points, which is higher than the value for the oxy-combustion coal-fired power plant without energy storage (11.2%$_{HHV}$ points). Yet, investment associated with cryogenic O_2 storage has marginal effect on the specific capital cost, and thus the levelised cost of electricity and cost of CO_2 avoided. Therefore, the benefits of energy storage can be incorporated into oxy-combustion coal-fired power plants at marginal capital investment. Importantly, implementation of cryogenic O_2 storage was found to increase the daily profit by 3.8–4.1%. Such performance would result in higher daily profit from oxy-combustion compared to an air-combustion system if the carbon tax is higher than 29.1–29.2 €/tCO_2. Finally, utilisation of renewable energy sources for cryogenic O_2 production can reduce the daily efficiency penalty by 4.7%$_{HHV}$ points and increase the daily profit by 11.6%. For this

Abbreviations: ASU, air separation unit; CCS, carbon capture and storage; CPU, CO_2 compression and purification unit; CFPP, coal-fired power plant.

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Nomenclature

AC	cost of CO_2 avoided (€/tCO_2)	*FCF*	fixed charge factor (–)
C	capital cost (€/kW_{el})	*FOM*	fixed operating and maintenance cost (€)
C_0	reference capital cost (€/kW_{el})	*LCOE*	levelised cost of electricity (€/$MW_{el}h$)
CE	CO_2 emission cost (€)	$\dot{m}_{CO_2}$	rate of CO_2 emission (kg/s)
CF	capacity factor (–)	$\dot{m}_{storage\ media}$	rate of media to storage (kg/s)
CTS	CO_2 transport and storage cost (€)	*P*	daily profit (€)
D_V	energy density (kWh/m^3)	*R*	revenue from electricity sales (€)
D_m	specific energy (kJ/kg)	*SCF*	specific fuel cost (€/$MW_{el}h$)
e_{CO_2}	specific CO_2 emission (gCO_2/$kW_{el}h$)	*TCR*	total capital requirement (€)
$\dot{E}_{stored}$	quantity of energy stored (MW)	*VOM*	variable operating and maintenance cost (€/$MW_{el}h$)
FC	fuel cost (€)	η_{th}	net thermal efficiency (–)

reason, a synergy between fossil fuel electricity generation and renewable energy sources via CO_2 capture integrated with energy storage needs to be commercially established.

1. Introduction

According to the International Energy Agency [1,2], around 43% of the cumulative CO_2 emissions from the power sector between 2012 and 2050 could be mitigated through implementation of carbon capture and storage (CCS), and utilisation of renewable energy sources. The main challenge that prevents CCS from large-scale deployment in the power sector is the considerable capital and operating cost that would affect the cost of electricity. Although fossil fuels are bound to remain an important energy source, it is predicted that the share of renewable energy sources in the energy portfolio could increase to above 50% by 2050 [3]. The greatest challenge of renewable energy sources is, however, their intermittence [4,5] which would affect operation of the existing energy network [6,7]. Namely, the remaining power generation assets, mostly fossil-fuel power systems, would need to flexibly balance energy supply and demand, so that neither energy produced from renewable energy sources is wasted nor energy shortages occur [8]. Such periods of variable load operation or no operation would impose efficiency and economic penalties on the fossil-fuel power systems, especially for plants linked with CCS that are better suited for base-load operation [9]. Moreover, variation in the daily and/or annual energy demand could lead to situations in which electricity from renewable energy sources is produced in excess of the grid requirements. In these instances, the renewable energy sources must be switched off, leading to waste of energy and capital [10].

Due to their capacity of decoupling energy supply and demand [11], energy storage technologies can increase the efficiency of energy utilisation and thus should be widely deployed along with low-emission technologies [12]. Electricity storage via a cryogenic liquid route was first proposed in the late-1970s [13] and is currently being pioneered in the UK [14]. Such technology has been shown to be a feasible option for storage of electricity generated from renewable energy sources [15]. Cryogenic liquid storage is based on the liquefaction of air, and a potential separation of O_2 in the air separation unit (ASU), that requires electricity for air compression (charging mode). The liquid product can then be stored at a low temperature and atmospheric pressure in an insulated storage tank [8,16], which overcomes the dependence on availability of proper geological formations being the main drawback of compressed air energy storage [17]. Importantly, in the case of energy storage via cryogenic O_2 storage, liquid O_2 can be vaporised, and then utilised in the oxy-combustion process, unloading the ASU on demand (discharging mode) [8,18,19]. The key benefit of liquid air or O_2 energy storage is high energy density of 172 $kW_{el}h/m^3$ [20] and 313 $kW_{el}h/m^3$ [18], respectively, that compare favourably with compressed air energy storage characterised with the energy density ranging between 3 and 40 $kW_{el}h/m^3$ [20–22]. Yet, the only challenge of this technology is the requirement for proper insulation to ensure operation in a cryogenic region. It is also important to stress that energy storage could contribute towards CO_2 emission reduction only for high levels of renewable energy source penetration [23,24]. Otherwise, energy storage could increase CO_2 emissions, the extent of which depends on carbon prices and share of coal-based generation in the energy portfolio [3,23] and, therefore, a synergy between renewable energy sources, low-carbon fossil-fuel power generation and energy storage needs to be pursued.

Oxy-fuel combustion has been considered for decades as a means for improving techno-economic performance of many industrial processes, such as metals and glass production [25]. Currently, it is regarded as one of the three most important technologies for large-scale CO_2 capture and separation, along with mature chemical solvent scrubbing and emerging calcium looping [26–28]. In this technology, fuel is combusted in an O_2-rich environment, as opposed to conventional air combustion. A range of air separation technologies is currently available including the adsorption process, chemical process, polymeric membrane, ion transport membrane and cryogenic separation [19,29]. At the moment, the cryogenic ASU is the main technology for high-purity O_2 production at a large scale [30], and is often considered in analyses of the oxy-combustion coal-fired power plant (CFPP). Yet, the ASU and the CO_2 compression and purification unit (CPU), which is used to deliver CO_2 at desired pressure and purity, are highly energy intensive processes [8,25,31–33]. Therefore, the efficiency penalty associated with oxy-combustion CFPP has been shown to be between 8 and 13% points [34–36]. Yet, this figure can be reduced to 3–7% points [25,37], on reduction of the ASU power requirement. This can be achieved by increasing the degree of process integration. Nevertheless, such drop in the net thermal efficiency would affect the cost of electricity and the revenue from electricity sales.

This economic penalty can be reduced by phase CO_2 capture, which assumes periodic operation in an air-combustion mode