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

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Applied Energy, 191, 2017, 193-203

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Hanak, D.P., Powell, D., and Manovic, V. (2017), "Techno-economic analysis of oxy-combustion coal-fired power plant with cryogenic oxygen storage", *Applied Energy*, 191, 193–203, doi: 10.1016/j.apenergy.2017.01.049

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Abstract

Around 43% of the cumulative CO_2 emission 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 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.

Key Words: Oxy-combustion, coal-fired power plant, energy storage, cryogenic oxygen storage, process modelling, process simulation, techno-economic analysis

1 INTRODUCTION

According to the International Energy Agency [1,2], around 43% of the cumulative CO_2 emission 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] that 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 kWh/m^3 [20] and 313 kWh/m^3 [18], respectively, that compare favourably with compressed air energy storage characterised with the energy density ranging between 3 and 40 kWh/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 8–13% points [34–36]. Yet, this figure can be reduced to 3 and 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 and leads to higher CO_2 emissions [25,38], or implementing cryogenic O_2 storage as a means of low-temperature energy storage [22] that would allow utilising variations in the daily electricity prices [18,25]. Namely, liquid O_2 from the ASU can be stored during the off-peak periods of low electricity prices in order to unload the system during peak periods, which are characterised by higher electricity prices [39]. The main benefits of implementing cryogenic O_2 storage into the oxy-combustion CFPP are increased net power output available at peak time, improved flexibility and reduced O_2 venting [14,25]. These benefits are available at low capital expense, as only a few pieces of equipment are required [14]. Considering the variability in daily energy prices and grid demand, application of cryogenic O_2 storage was found to be a feasible option to enable flexible operation of the nuclear power plant [40] and increase profitability of the air-combustion CFPP retrofitted with the calcium looping process by up to 2.3%. The latter system was shown to produce higher profits in the current economic climate than the air-combustion CFPP without CO_2 capture, regardless of the efficiency penalty of 8.6%$_{HHV}$ points [18]. The techno-economic feasibility of implementing peak and off-peak operation of the ASU in the oxy-combustion CFPP has been proven by Hu et al. [8]. This study showed that the system comprising the oversized ASU can increase the peak power of the retrofitted system by up to 123 MW_{el}, while reducing its average net efficiency by only 0.3% points. Having employed the net present value approach to assess the economic feasibility of the system, the study by Hu et al. [8] indicated that the evaluated system has the potential to reduce the annual economic penalty by up to 20%, depending on the peak electricity prices and duration of the peak periods.

Considering the important role of oxy-fuel technology in the future energy portfolio, this study aims to evaluate the techno-economic feasibility of implementation of cryogenic O_2 storage in the oxy-combustion CFPP without the need for ASU oversizing to accommodate the energy storage capability. The performance of such a system is benchmarked against the air-combustion CFPP without CO_2 capture and energy storage. This is achieved by employing high-fidelity process models, which are able to provide a reliable prediction under off-design operating conditions, to quantify the thermodynamic performance of the considered scenarios. Importantly, in addition to quantifying the power generation and environmental characteristics, the key performance indicators characterising the energy storage capability of the considered scenarios, such as energy density and specific energy, are also estimated. Furthermore, the economic feasibility of implementation of cryogenic O_2 storage is quantified in terms of the levelised cost of electricity, cost of CO_2 avoided and daily profit. Although these are the key economic performance indicators that are widely utilised to assess the economic performance of CO_2 capture technologies [41–44], these parameters have not been considered in other studies. In addition, to account for the variability in the future economic climate, the effect of the variation in carbon tax and the peak price difference on the daily profit is evaluated. Finally, as opposed to other studies, the potential for utilisation of the excess electricity generated by renewable energy sources, and its effect on the performance of the oxy-combustion CFPP, are evaluated.

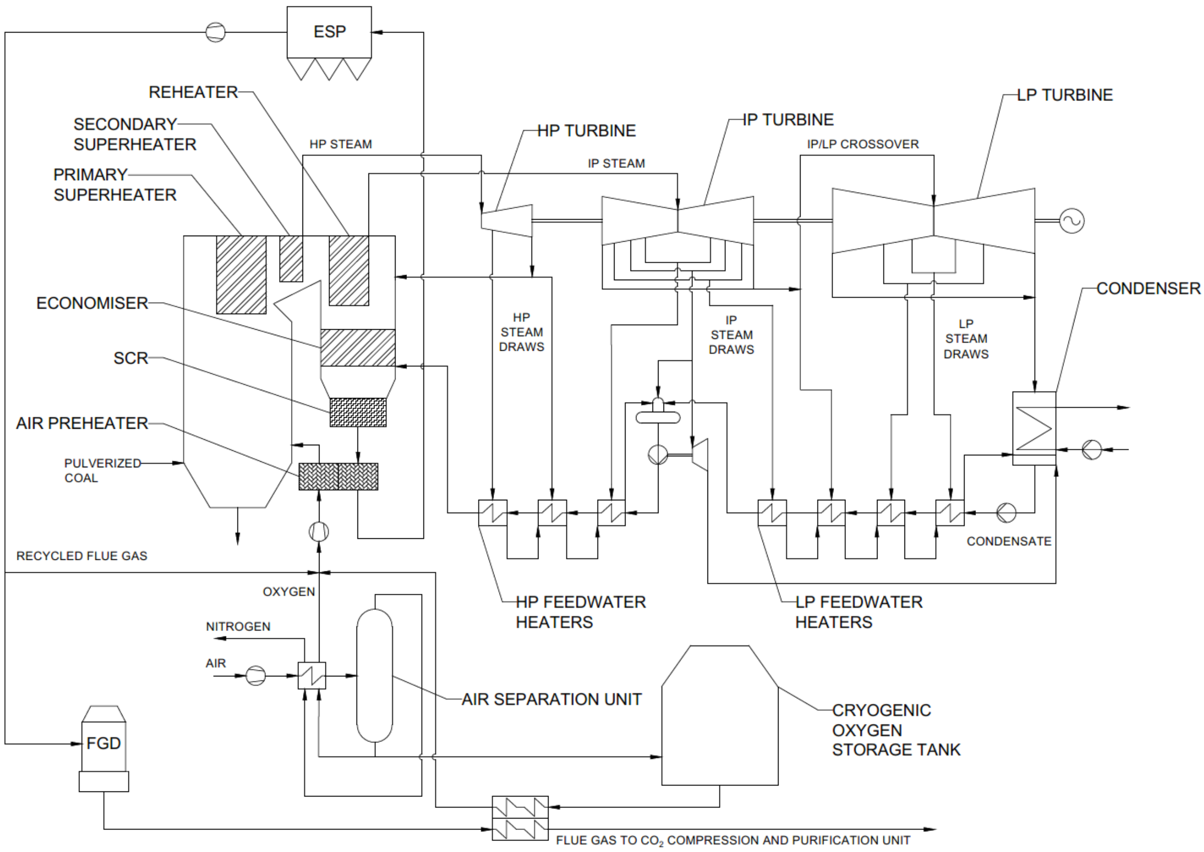


Figure 1: Oxy-combustion coal-fired power plant with cryogenic oxygen storage

2 PROCESS DESCRIPTION

2.1 Oxy-combustion coal-fired power plant

A core of the analysed concept is the 660 MW_{el} oxy-combustion CFPP (Figure 1). This system is a retrofit of the 660 MW_{el} air-combustion CFPP (Table 1) that comprises a once-through steam boiler with flue gas treatment train and a supercritical steam cycle with single steam reheating stage, and the process model of which has been previously developed and thoroughly validated [45]. The once-through steam boiler has been modified to operate in an oxygen-rich environment via implementation of the ASU, the CPU, and partial flue gas recycling. The cryogenic ASU is a standard double-column, the model of which has been developed based on the operating conditions of the Polk integrated gasification combined cycle power plant by Tampa Electric [46,47] and adapted to reflect the Linde process [48]. The high- and low-pressure column operate at 5.6 and 1.3 bar, respectively, and are filled with 350Y structured packing [48]. The ASU columns are sized to operate with 75% flooding when processing 265.4 kg/s of air under nominal operating mode without cryogenic O_2 storage. To enable part-load operation, two ASU trains, which each deliver a 95%$_{vol}$ O_2 stream, are considered. Three air compressors are considered to enable part-load operation. These units are modelled using the polytrophic compression model with constant stage polytrophic efficiency (79–80%). The specific power requirement of the ASU was found to be 245 kWh/tO_2, which is within the range reported in the literature (184–260 kWh/tO_2) [8,31,32]. To maintain similar operating conditions in the combustion chamber to the reference air-combustion case, about two-thirds of the flue gas from the oxy-combustion of coal is recycled [8]. Due to the higher heat capacity of CO_2 with respect to N_2, the concentration of O_2 in the oxidising medium is fixed at 27%$_{vol}$ [35]. In addition, it is assumed that the adapted once-through boiler operates with excess air and air ingress of 20% (base load) and 2%, respectively. The flue gas produced in the oxy-combustion of coal, which comprises more than 60%$_{vol}$ CO_2, is then purified from water and other incondensable species in the CPU. The CPU is based on a double-flash separation unit with internal cooling [49] that delivers CO_2 at conditions suitable for its transport and storage (110 bar [44], >90%$_{vol}$ CO_2 [50]). Yet, as opposed to the study by Posch and Haider [49], the waste stream leaving the CPU at 28.5 bar is expanded in a turbo-expander to reduce the parasitic load. As a result, the specific power requirement is 130–140 kWh/tCO_2, which is close to the average values reported in the literature (90–170 kWh/tCO_2) [33].

Table 1: Summary of the key process assumptions

Parameter		**Value**
Air-combustion coal-fired power plant		
Combustor	Design excess air ratio (%$_{vol,dry}$)	20.0
Supercritical steam cycle	Design live/reheat steam temperature (°C)	537.0/565
	Design live/reheat steam pressure (bar)	242.2/44.3
	Final feedwater temperature (°C)	280.0
	Feedwater heater terminal temperature difference (°C)	3.0
	Feedwater heater minimum temperature approach (°C)	3.0
	Isentropic efficiency of compressors (%)	80.0
	Isentropic efficiency of high-pressure steam turbine (%)	89.6
	Isentropic efficiency of intermediate-pressure steam turbine (%)	91.7
	Isentropic efficiency of low-pressure steam turbine (%)	85.7
	Isentropic efficiency of pumps (%)	85.0
	Electrical efficiency of generator (%)	98.7
Oxy-combustion coal-fired power plant		
Combustor	Design excess air ratio (%$_{vol,dry}$)	20.0
	Design air ingress (%$_{vol,wet}$)	2.0
	Design O_2 content in oxidising medium (%$_{vol,wet}$)	27.0
Auxiliary equipment		
CO_2 purification compression unit	Polytrophic efficiency of CO_2 compressors (%)	78.0-80.0
	Isentropic efficiency of CO_2 pump (%)	80.0
	Intercooling temperature (°C)	40.0
	CO_2 initial compression pressure (bar)	30.0
	CO_2 final pressure (bar)	110.0
	CO_2 final temperature (°C)	30.0
Air separation unit	O_2 purity (%$_{vol}$)	95.0
	Polytrophic efficiency of air compressors (%)	79.0-80.0
	Intercooling temperature (°C)	40.0
	Final air pressure (bar)	5.8

At base load, the heat generated from the oxy-combustion of coal is used to raise live steam at 537°C and 235 bar. It is sent to a high-pressure (HP) turbine cylinder where it is expanded to 45.2 bar. Steam is then returned to the boiler where it is reheated to 554°C, before it is sent to an intermediate-pressure (IP) turbine, and subsequently to the two low-pressure (LP) turbines. Differences in the operation of the supercritical steam cycle in the oxy-combustion case stem from lower flue gas flow rate of 605.2 kg/s compared to 704.7 kg/s in the reference air-combustion case (Table 1). To enhance the overall power cycle efficiency, steam is extracted from the turbines for feedwater heating. A feedwater heating train consists of five LP feedwater heaters, the last of which is called a deaerator and is a mixed feedwater heater, and three HP feedwater heaters.

2.2 Inherent oxygen storage capability

One of the main sources of parasitic load in the oxy-combustion CFPP is the power requirement to run the air compressors in the ASU. As it is possible to extract liquid O_2 at high density (~1280 kg/m^3) from the ASU, it can be stored in a cryogenic tank for utilisation to satisfy the daily variation in the market electricity prices to reduce the economic penalty, and thus to increase the profitability of the oxy-combustion CFPP. Namely, during off-peak periods characterised with low electricity prices, the oxy-combustion power plant would operate with the minimum load of 40% while the ASU would operate with its maximum load (100%). Although the ASU parasitic load would increase compared to the case with no O_2 storage, the produced excess O_2 would be stored in the cryogenic tank (charging mode). This O_2 can then be utilised during peak periods (discharging mode) characterised with high electricity prices. During the latter period, the ASU load, and thus the parasitic load are reduced, increasing the revenue from electricity sales at that time.

It needs to be highlighted that the oxy-combustion CFPP is assumed to operate in the demand-following mode with a minimum load of 40%. The part-load and off-design operation of both the reference air- and oxy-combustion CFPPs are considered in detail using a Stodola's ellipse law [51] to account for variability of the steam pressure in the steam cycle, Salisbury's equation [52] to account for variability of the isentropic efficiency of the steam turbine sections, and the general pressure drop correlation [53] to account for the off-design pressure drop in the heat exchanger sections of the once-through boiler. The ASU compressors can operate with a minimum load of 75% without recycling or venting, while the cold box operates at a minimum load of 50% [37]. This implies the need for three compression trains and two ASU trains to reach the minimum load of around 40% for the entire system. Due to the same minimum constraint, three compression trains are required in the CPU. It is also assumed that liquid O_2 is stored in the cryogenic tank at 1.2 bar at around -182°C, which is maintained by the waste N_2 leaving the ASU [8].

3 PROCESS PERFORMANCE EVALUATION

3.1 Considerations

To evaluate the performance of the considered process, a process model of the oxy-combustion CFPP has been developed in Aspen Plus V8.8 by incorporating the ASU and the CPU models, as well as partial flue gas recycle into the existing model of the air-combustion CFPP [45]. The key model assumptions were discussed in the previous section and summarised in Table 1. The model is used to evaluate the performance of the following cases:

Case 1: Oxy-combustion CFPP without cryogenic O_2 storage;

Case 2: Oxy-combustion CFPP with cryogenic O_2 storage and ASU operating with minimum load of 40%;

Case 3: Oxy-combustion CFPP with cryogenic O_2 storage and possible ASU shut-down for peak periods.

The thermodynamic performance of the proposed system needs to be characterised by the key performance indicators related to its power generation and energy storage capabilities. For this reason, the energy storage capacity is characterised with energy density (D_V) and specific energy (D_m) defined in Eq. (1) and Eq. (2) as the ratio of the energy stored ($\dot{E}_{stored}$) and the rate of media to storage ($\dot{m}_{storagemedia}$). The power generation performance, in turn, is characterised with net power output ($\dot{W}_{net}$) and net thermal efficiency (η_{th}), which is defined in Eq. (3) as the ratio of the net power output and the heat input from fuel combustion ($\dot{Q}_{fuel}$). Finally, environmental performance is represented in Eq. (4) as the specific CO_2 emissions (e_{CO2}) defined as the ratio of CO_2 emission rate ($\dot{m}_{CO2}$) and the net power output.

$$D_V = \frac{\dot{E}_{stored}}{3.6 \times \dot{m}_{storage\ media}} \rho_{storage\ media} \tag{1}$$

$$D_m = 1000 \times \frac{\dot{E}_{stored}}{\dot{m}_{storagemedia}} \tag{2}$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{fuel}} \tag{3}$$

$$e_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \tag{4}$$

The economic performance of the proposed system is compared with the reference air-combustion CFPP without CO_2 capture and O_2 storage in terms of the levelised cost of electricity (*LCOE*) and the cost of CO_2 avoided (*AC*) that are calculated according to Eq. (5) and Eq. (6) [54–56], respectively.

$$LCOE = \frac{TCR \times FCF + FOM}{\dot{W}_{net} \times CF \times 8760} + VOM + \frac{SFC}{\eta_{th}} \tag{5}$$

$$AC = \frac{LCOE_{capture} - LCOE_{ref}}{e_{CO_2,ref} - e_{CO_2,capture}} \tag{6}$$

These parameters correlate thermodynamic performance indicators, such as net power output, net thermal efficiency (η_{th}), capacity factor (*CF*) and specific emissions (e_{CO2}), with economic performance, such as total capital requirement (*TCR*), variable (*VOM*) and fixed (*FOM*) operating and maintenance costs, specific fuel cost (*SFC*), and the fixed charge factor (*FCF*), which considers the system's lifetime and project interest rate.

Table 2: Economic model assumptions

Parameter		Value
Air-combustion coal-fired power plant	Reference equipment capital cost (€/kW$_{el,gross}$) [59]	1222.6
	Reference power output (MW$_{el,gross}$) [59]	580.2
Oxy-combustion coal-fired power plant	Reference equipment capital cost (€/kW$_{el,gross}$) [59]	1467.7
	Reference power output (MW$_{el,gross}$) [59]	785.9
Cryogenic O_2 storage tank	Reference equipment capital cost (€/m^3) [8]	800000
	Reference volume (m^3) [8]	2500
Scaling factor	Power plant (-) [60]	0.67
	Cryogenic O_2 storage tank (-) [8]	0.6
Other economic parameters	Variable cost as a fraction of total capital cost (%) [56,61]	2.0
	Fixed cost as a fraction of total capital cost (%) [56,61]	1.0
	Carbon tax (€/tCO_2) [56,61]	0.0
	CO_2 transport and storage cost (€/tCO_2) [62]	7.0
	Coal price (€/t) [61,63]	40.6
	Expected lifetime (years) [56,61]	25
	Project interest rate (%) [56,61]	8.78
	Capacity factor (%) [56,61]	80

The capital cost of the power plants and storage equipment is determined using the exponential method function [57] with economic data presented in Table 2. The cryogenic O_2 storage capacity is estimated based on liquid O_2 density of ~1280 kg/m^3 and conservative operating conditions that enable utilisation of the excess amount of electricity generated from renewable energy sources (Section 4). These operating conditions include a maximum O_2 discharge rate of 129.4 kg/s, which allows shutting the ASU down, over the maximum discharge time of 12 h and 3% design margin. Moreover, fixed and variable operating and maintenance costs are calculated as a fraction of total capital cost, while operating costs associated with fuel consumption, and CO_2 storage, transport and emission are determined based on process simulation outputs using economic data from Table 2.

The daily profit (*P*) is calculated using the approach employed by Mac Dowell and Shah [58]. This is defined in Eq. (7) as the difference between the daily revenue from electricity sales (*R*) and daily operating costs associated with fuel consumption (*FC*), CO_2 transport and storage (*CTS*), and CO_2 emissions (*CE*). These costs are estimated based on process simulation outputs and economic data reported in Table 2.

$$P = R - (FC + CTS + CE) \tag{7}$$

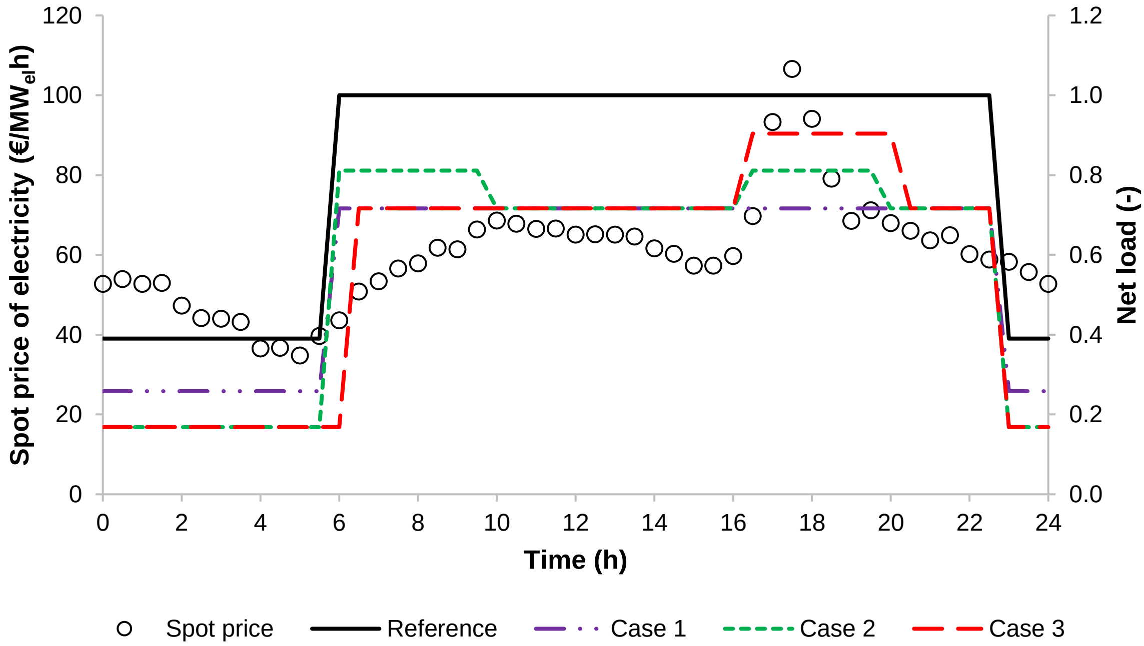


Figure 2: Daily net load variations for the considered cases

Furthermore, the daily profit of the considered cases is assessed under the daily variable load operation. The hypothetical load variations presented in Figure 2 reflects the daily variation in the system's net power output with respect to the nominal net power output of the reference air-combustion CFPP for the considered CO_2 separation and energy storage cases. It needs to be highlighted that if the ASU is allowed to be shut down during the peak periods (Case 3), the system can operate in the discharging mode for a shorter time compared to the system with the ASU operated at reduced load (Case 2). This is because the charging time is similar in both cases. Importantly, a shutdown and re-activation of the ASU may incur additional energy penalty. As a result, the time required to re-activate this unit and re-establish the desired product purity ranges between 2 and 10 h, depending on whether the cryogenic liquid is stored on-site, which may incur an additional capital requirement, or discarded [64,65]. Nevertheless, as the semi-cold start-up can be considered after a few days of ASU shutdown [64], it is expected that the energy losses during the planned shutdown of the ASU for the period of 4 h/d (Case 3) would be relatively small. Therefore, it is assumed that the unit's ability to deliver the O_2 stream at desired purity will be restored within a time period shorter than 2 h.

3.2 Thermodynamic performance evaluation

An analysis of the energy storage characteristics of cryogenic O_2 storage revealed that to store O_2 at a rate of 64.8 kg/s a daily storage capacity of around 4500 m^3 is required. Such a system can achieve high energy density and specific energy of 315.9 $kW_{el}h/m^3$ and 885.2 kJ/kg, respectively (Table 3). Such characteristics compare favourably with other energy storage technologies, such as pumped hydro energy storage (D_V=0.5–2 $kW_{el}h/m^3$; D_m=1.8–7.2 kJ/kg [21,22]), compressed air energy storage (D_V=3–6 $kW_{el}h/m^3$; D_m=108–216 kJ/kg [21,22]), lead-acid batteries (D_V=50–90 $kW_{el}h/m^3$; D_m=108–180 kJ/kg [21,22]), and Li-ion batteries (D_V=200–500 $kW_{el}h/m^3$; D_m=270–720 kJ/kg [21,22]). This proves that such a system can be expected to improve flexibility and profitability of the oxy-combustion CFPP, and other CO_2 capture systems such as calcium looping [18] or chemical looping combustion, by providing means that would allow utilising the daily variation in electricity price.

Table 3: Summary of techno-economic performance indicators

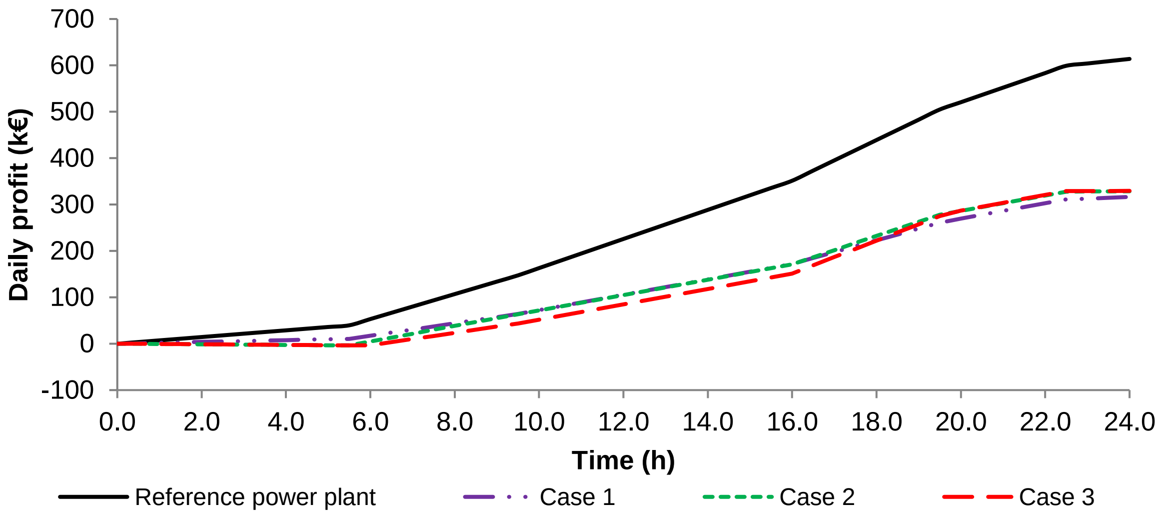
	Reference power plant		Case 1		Case 2		Case 3	
Charging (C)/Discharging (D) performance indicators	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**
Net power output (MW_{el})	247.0	633.0	163.5	453.4	106.5	513.5	106.5	572.14
Net thermal efficiency ($\%_{HHV}$)	34.5	38.8	22.8	27.8	14.9	31.5	14.9	35.0
Net efficiency penalty ($\%_{HHV}$) points	-	-	11.7	11.0	19.6	7.3	19.6	3.8
CO_2 intensity factor ($gCO_2/kW_{el}h$)	969.0	835.0	155.6	93.2	238.9	80.5	238.9	71.7
Daily average performance indicators								
Average daily net thermal efficiency ($\%_{HHV}$)	37.5		26.3		25.2		25.0	
Average daily net efficiency penalty ($\%_{HHV}$)	-		11.2		12.3		12.5	
Average daily CO_2 intensity factor ($gCO_2/kW_{el}h$)	874.1		111.4		132.2		135.5	
Instantaneous performance indicators								
Net power generation turndown (-)	2.6		2.8		4.8		5.4	
Energy density ($kW_{el}h/m^3$)	-		-		315.9		315.9	
Specific energy (kJ/kg)	-		-		885.2		885.2	
Economic performance indicators								
Specific capital cost (€/$kW_{el,net}$)	1389.7		1897.8		1899.5		1900.3	
Levelised cost of electricity (€/$MW_{el}h$)	39.71		54.65		54.68		54.70	
CO_2 avoided cost (€/tCO_2)	-		20.14		20.18		20.20	

An analysis of the thermodynamic performance for the selected cases (Table 3) has revealed that modification of the reference air-combustion CFPP to the oxy-combustion CFPP (Case 1) results in an efficiency penalty of 11.0–11.7$\%_{HHV}$ points, depending on the operating load of the system. Moreover, the net power output of such a system has decreased by 179.6 MW_{el} and 83.5 MW_{el} at loads of 100% and 40%, respectively. This energy penalty has arisen primarily from the power requirement of the ASU (56%) and the CPU (31%), which in total accounted for about 87% of the parasitic load in the considered system. Although such parasitic load results in a considerable efficiency penalty compared to novel CO_2 capture and separation technologies, such as calcium looping that was shown to result in an efficiency penalty of 6–8% points [34,66–68], it is predicted that the specific power requirement of the ASU will reduce from up to 260 kWh/tO_2 [8,31,32] to 140 kWh/tO_2 [69], which could reduce the efficiency penalty to 5–7% points [37]. The efficiency penalty can also be reduced by increasing the degree of heat and work integration between the ASU and the CPU. Yet, such considerations are beyond this study's scope. Since the efficiency penalty of the considered oxy-combustion CFPP reflects data reported in the literature (8–13% points) [34–36], it is used to prove the techno-economic benefits of incorporating the cryogenic O_2 tank as a means of energy storage.

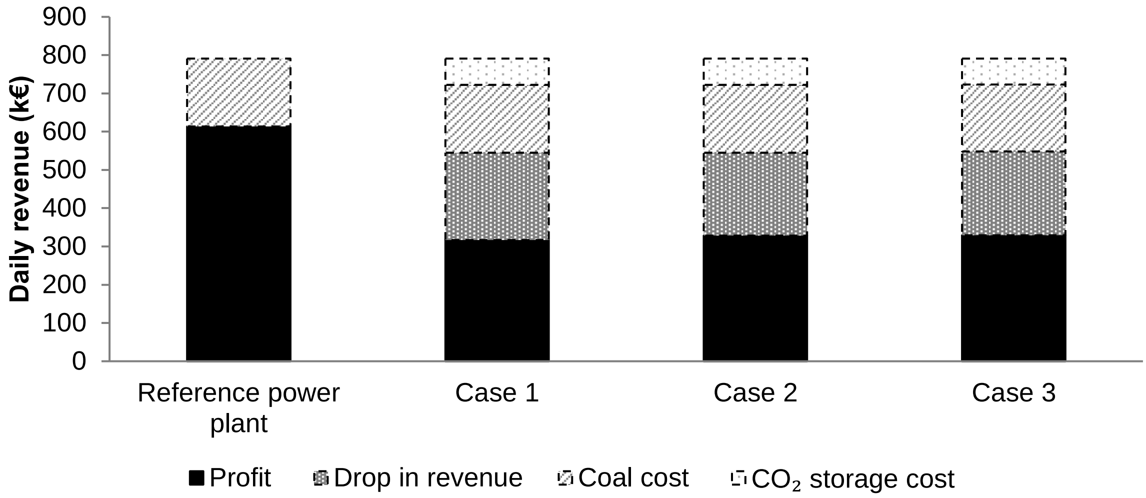
Analysis of the energy storage cases (Table 3) revealed that by unloading the ASU, the efficiency penalty can be reduced to 7.3%$_{HHV}$ points, when the ASU is operated at the minimum load of 40% and the remaining O_2 is provided from the cryogenic tank (Case 2), and to 3.8%$_{HHV}$ points if the ASU is switched off (Case 3). Such performance during the peak demand periods would allow maximising the revenue from electricity sales. This comes, however, at the expense of a higher efficiency penalty during the off-peak periods, which has been estimated to be 19.6%$_{HHV}$ points in both investigated cases. Considering the daily variability in the operating load of the system shown in Figure 2, implementation of energy storage increases the average daily efficiency penalty from 11.2%$_{HHV}$ points in Case 1 to 12.3%$_{HHV}$ points and 12.5%$_{HHV}$ points in Case 2 and Case 3, respectively. Such loss in the average daily performance results in slightly higher CO_2 intensity factor in the energy storage cases. Yet, implementation of cryogenic O_2 storage was found to have a positive effect on the turndown ratio of the considered system, which is defined as the ratio of the maximum and minimum net power output of the considered system, hence on the ability to flexibly adjust to the market conditions and utilise the price differences between the off-peak and peak periods. Namely, the turndown ratio was increased from 2.8 in the case of the oxy-combustion CFPP without cryogenic O_2 storage to 4.8 and 5.4 in Case 2 and Case 3, respectively. As the load of the ASU can be varied at a rate of 3–5% per minute [19,70], the proposed cases appear to be technically feasible and could provide high flexibility within the required operating timeframe.

3.3 Economic performance evaluation

An economic assessment of the considered cases has revealed that the specific capital cost of the entire system has increased by 508.1 €/kW$_{el,net}$ on modification of the reference air-combustion CFPP (1389.7 €/kW$_{el,net}$) to the oxy-combustion CFPP (1897.8 €/kW$_{el,net}$, Case 1), which is in agreement with other literature sources [8,59,71–73]. This resulted in a 37.6% increase in the levelised cost of electricity (Table 3). It is important to highlight that the addition of cryogenic O_2 storage has a marginal effect on the specific capital cost that increased by 1.7 €/kW$_{el,net}$ and 2.5 €/kW$_{el,net}$ in Case 2 and Case 3, respectively, regardless of the conservative sizing assumptions. This was found to marginally increase both levelised cost of electricity and cost of CO_2 avoided (Table 3). Therefore, the benefits of energy storage can be incorporated in the oxy-combustion CFPP at marginal capital investment.



a)

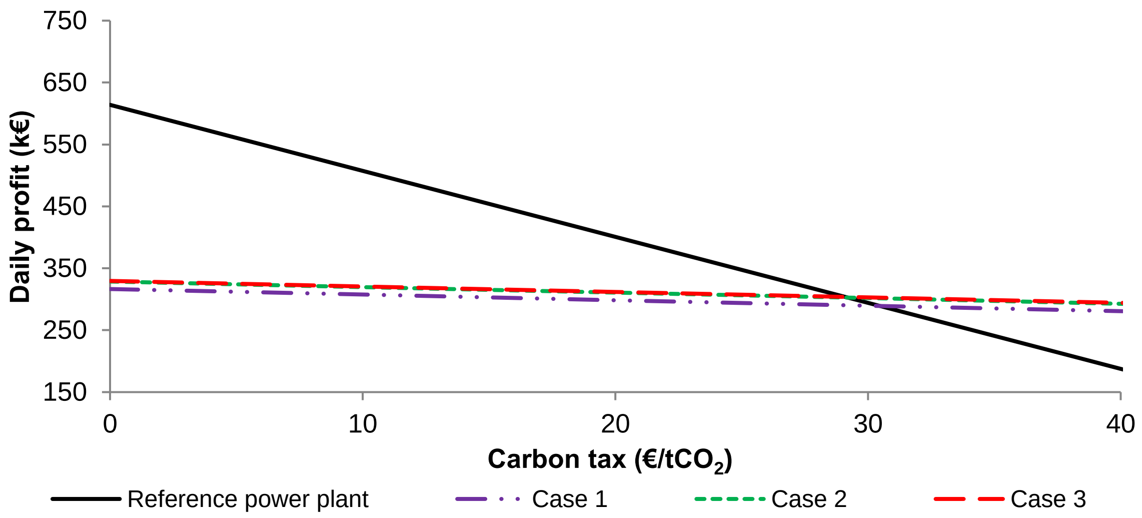


b)

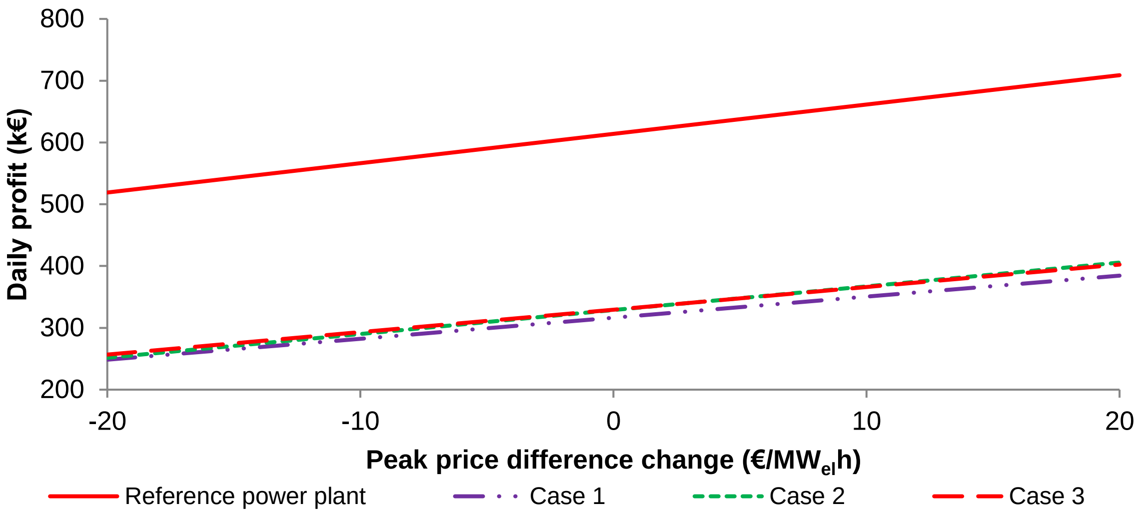
Figure 3: Economic evaluation of oxy-combustion coal-fired power plant with cryogenic O_2 storage a) comparison of daily profit; b) distribution of the daily revenue

As was expected from the thermodynamic performance analysis, modification of the reference air-combustion CFPP to the oxy-combustion CFPP (Case 1) reduced the daily profit by 48.5%, from 614.0 k€ to 316.5 k€ (Figure 3a). This can be mainly attributed to the substantial drop of daily revenue from electricity sales of 228.8 k€ (Figure 3b) that can be primarily associated to the substantial parasitic load of the ASU and CPU. To a lesser extent, the daily profit was reduced by the cost of CO_2 transport and storage (68.7 k€). Yet, implementation of cryogenic O_2 storage was found to increase the daily profit by 3.8% (328.7 k€) and 4.1% (329.6 k€) in Case 2 and Case 3 (Figure 3a), respectively, revealing the key benefit of the proposed system. Further increase of the profit can be achieved by optimising charging and discharging times, using optimisation methodology developed by Barbour et al. [74]. Such an increase is similar to the one reported for solvent storage in the scenario of the amine scrubbing retrofit to the CFPP, that resulted in 4% improvement in the daily profit [58]. Interestingly, allowing for the ASU shut-down during peak periods (Case 3) improves the daily profit by only 0.3% compared to the case in which the ASU is operated within the nominal load envelope of 40–100%. As the load of the ASU can be varied at a rate of 3–5% per minute [19,70], the system operated in the latter mode (Case 2) can be expected to provide higher flexibility at small economic footprint.

The daily profit of power generation systems is highly dependent upon the economic climate as the carbon tax is predicted to vary between 10–150 €/tCO_2 [18,75,76]. Figure 4a reveals that the daily profit of the air-combustion CFPP is highly affected by increases in the carbon tax, while the oxy-combustion cases are hardly affected due to their low CO_2 intensity. It needs to be highlighted that if the carbon tax exceeds 30.5 €/tCO_2, the oxy-combustion CFPP (Case 1) would generate higher daily profit than the air-fired CFPP. If cryogenic O_2 storage is implemented, the oxy-combustion CFPP would generate higher profit for a carbon tax of 29.2 €/tCO_2 and 29.1 €/tCO_2 in Case 2 and Case 3, respectively. Hence, given comparable economic performance of these cases, as well as lower energy losses and better expected flexibility in Case 2, the former would be preferable. Nevertheless, such performance agrees with carbon tax values ranging between 27 €/tCO_2 and 45 €/tCO_2 that were reported in the literature to yield higher profit for power systems with CO_2 capture over the unabated systems [77,78].



a)



b)

Figure 4: Effect of a change in a) carbom tax and b) peak price difference on daily profit

Furthermore, the effect of a change in the peak price difference, which is defined as a change of the peak price with respect to the reference spot price during the peak periods (Figure 2), on the daily profit is evaluated. Figure 4b indicates that independently of the peak price difference, the oxy-combustion CFPP will always generate lower daily profit compared to the air-combustion CFPP. This can be directly associated with a drop in the net power output due to the ASU and the CPU parasitic load. Importantly, an increase in the peak price difference results in a higher difference between the air-combustion and the oxy-combustion cases, which is a result of lower net thermal efficiency and net power output in the latter case (Table 3). Nevertheless, if the peak price is increased by 20 €/MW_{el}h, the daily profit of the oxy-combustion CFPP with cryogenic O_2 storage will be higher by 5.5% (405.7 k€) in Case 2 and 4.7% (402.5 k€) in Case 3 than that in the Case 1 (382.5 k€). Such a result indicates that it is more profitable to operate the ASU within the nominal load envelope of 40–100%, rather than shutting it down, as the system will operate in the discharging mode for a longer period of time. Nevertheless, as it was mentioned earlier, further improvement in the economic performance of the oxy-combustion CFPP with cryogenic O_2 storage can be achieved on optimising charging and discharging times.

3.4 Feasibility assessment

The techno-economic performance analysis conducted in this study has proven cryogenic O_2 storage to be a technically and economically viable option to increase profitability of the oxy-combustion CFPP. Namely, it has been shown that the energy storage capability can be implemented at a marginal increase in the capital cost (1.7–2.5 €/kW$_{el,net}$) and thus would cause negligible increase in the levelised cost of electricity. The daily profit of the system with cryogenic O_2 storage would be 3.8–5.5% higher than the figure for the oxy-combustion CFPP without energy storage, regardless of 1.1–1.3%$_{HHV}$ point drop in the average daily net thermal efficiency. Such improvement in the profit from electricity sales, along with improved system flexibility and reduced O_2 venting, would be beneficial to the power plant operators who consider retrofitting existing air-fired CFPPs or investing in new-built systems with energy storage capability. Importantly, these benefits will also be available to the operators of other power generation technologies that comprise ASU, such as calcium looping [18] and integrated gasification combined cycle power plants, as well as many industrial processes, such as metals and glass production, providing an economic incentive for the decarbonisation of the power and industrial sectors. Moreover, a wide deployment of systems with both CO_2 capture and energy storage capability would allow a continuous utilisation of fossil fuels in the energy portfolio and, at the same time, would alleviate the negative effect of renewable energy sources on the balance of electricity supply and demand.

4 POTENTIAL FOR UTILISATION OF RENEWABLE ENERGY SOURCES

In the considered cases, cryogenic O_2 storage can be seen as a means to store the chemical energy of coal by sacrificing techno-economic performance during periods when the price of electricity is low and utilising this energy during peak periods that are characterised with high electricity prices. As has been proven in this and previous studies [18,58], such an approach for linking CO_2 capture and energy storage could result in higher daily profits. Yet, a further opportunity to improve process economic performance exists, if the excess energy from existing renewable energy sources is utilised. Namely, due to inaccuracies in the demand forecast or overestimation of the energy demand, some of the generators may be asked to reduce their power output. Although this does not impose an economic burden on fossil fuel operators, who save fuel on reducing the power output, renewable energy operators will lose subsidies when the power output is reduced. As a result, the latter operators need to be paid to reduce their power output to make a profit, which affects the cost of electricity [10]. To ensure affordable electricity prices in the future, the excess electricity generated from renewable energy sources should be utilised or stored, and the down-time of these units should be minimised.

The cryogenic O_2 storage concept investigated in this study requires 1377.7 MWh/d of electricity to fill the 4500 m^3 tank with liquid O_2. Considering the average amount of electricity constraint from the existing wind generation, which is electricity that cannot be utilised in the grid (3490.9 MWh/d in 2015) [10], the O_2 tank can be filled 2.5 times, providing all of the excess electricity can be utilised. Yet, even considering the fact that some part of this excess electricity cannot be transmitted due to grid constraint [10], and the O_2 tank can be filled only once per day, the daily efficiency and the daily profit in Case 2 would increase by 4.7%$_{HHV}$ points (from 25.2%$_{HHV}$ to 29.9%$_{HHV}$) and 11.6% (from 328.7 k€ to 366.9 k€), respectively. This proves that the link between fossil fuels and renewable energy systems via CO_2 capture integrated with energy storage would bring techno-economic benefits to both fossil fuel operators, who could reduce the efficiency and economic penalties associated with CO_2 capture systems without incurring additional costs associated with the land requirement by renewables, and to the existing renewable energy operators that would not be asked to switch off their assets. For this reason, a synergy between fossil fuels and renewable energy sources via CO_2 capture with energy storage needs to be commercially established. Such link should be thoroughly evaluated considering the dynamic responses of the entire energy portfolio, including nuclear, fossil fuel and renewable power sources. This would reveal the benefits of implementing energy storage to the fossil fuel power plants on the energy system level.

5 CONCLUSION

In this study, a concept of implementing cryogenic O_2 storage in the oxy-combustion coal-fired power plant as a means of energy storage was proposed and its techno-economic performance was evaluated. The thermodynamic performance analysis revealed that the cryogenic O_2 storage system is characterised with high energy density and specific energy (D_V=315.9 $kW_{el}h/m^3$; D_m=885.2 kJ/kg) that compares favourably with other energy storage technologies, such as pumped hydro energy storage, compressed air energy storage, as well as lead-acid and Li-ion batteries. Furthermore, on modification of the air-combustion coal-fired power plant to operate under an oxygen-rich environment and considering the daily variability in the operating load, the average daily efficiency penalty was estimated to be 11.2%$_{HHV}$ points. This was mainly associated with the power requirement of the ASU and the CPU. On implementation of cryogenic O_2 storage the average daily efficiency penalty increased to 12.3%$_{HHV}$ and 12.5%$_{HHV}$ points for the system with the ASU operating with minimum load of 40% (Case 2) and 0% (Case 3), respectively. Nevertheless, implementation of this system allowed the flexibility of the system to increase, which is reflected in an increased turndown ratio.

The economic performance evaluation has indicated that the investment in cryogenic O_2 storage has only marginally increased the specific capital cost of the system, and thus has barely increased the levelised cost of electricity and cost of CO_2 avoided. Therefore, the benefits of energy storage can be incorporated in the oxy-combustion coal-fired power plant at marginal capital investment. Importantly, this was found to increase the daily profit by 3.8% and 4.1% in Case 2 and Case 3, respectively, revealing the key benefit of the proposed system. Such performance would result in higher daily profit from the oxy-combustion coal-fired power plant compared to the air-combustion system if the carbon tax is higher than 29.1–29.2 €/tCO_2. The economic performance of the evaluated system can be further improved by both reduction of the ASU and the CPU power requirement, as well as utilisation of renewable energy sources for cryogenic O_2 production. The latter option can reduce the daily efficiency penalty by 4.7%$_{HHV}$ points and increase the daily profit by 11.6%. For this reason, a synergy between fossil fuels and renewable energy sources via CO_2 capture with energy storage needs to be commercially established.

NOMENCLATURE

AC	Cost of CO_2 avoided	€/tCO_2
C	Capital cost	€/kW_{el}
C_0	Reference capital cost	€/kW_{el}
CE	CO_2 emission cost	€
CF	Capacity factor	-
CTS	CO_2 transport and storage cost	€
D_V	Energy density	kWh/m^3
D_m	Specific energy	kJ/kg
e_{CO_2}	Specific CO_2 emission	gCO_2/kWh_{el}
$\dot{E}_{stored}$	Quantity of energy stored	MW
FC	Fuel cost	€
FCF	Fixed charge factor	-
FOM	Fixed operating and maintenance cost	€
$LCOE$	Levelised cost of electricity	€/MWh
$\dot{m}_{CO_2}$	Rate of CO_2 emission	kg/s
$\dot{m}_{storage\ media}$	Rate of media to storage	kg/s
P	Daily profit	€
R	Revenue from electricity sales	€
SCF	Specific fuel cost	€/MWh
TCR	Total capital requirement	€
VOM	Variable operating and maintenance cost	€/MWh
η_{th}	Net thermal efficiency	-

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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