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Abstract

Implementation of carbon capture and storage, nuclear power stations and wide utilisation of renewable energy sources have been identified as capable of reducing around 42% of the energy sector's cumulative CO_2 emissions between 2009 and 2050. In scenarios assuming high shares of renewable energy sources in the energy portfolio, the energy storage technologies and the remaining power generating assets would need to flexibly balance the energy supply and demand. With nuclear power plants operating at base load, this task would be handled by flexible fossil fuel power plants with CO_2 capture. However, mature CO_2 capture systems were shown to impose high efficiency penalties (8–12.5% points) and are better suited for base-load operation. An emerging calcium looping process, which has been initially considered for energy storage, has been found to offer lower efficiency penalties (5–8% points). This study presents a concept of the calcium looping process with inherent energy storage for decarbonisation of the coal-fired power plant. Analysis has revealed that the possible routes for energy storage in this process include $CaO/CaCO_3$ solids storage, $CaO/Ca(OH)_2$ solids storage and cryogenic O_2 storage systems. Comparison of the $CaO/CaCO_3$ storage and cryogenic O_2 storage systems revealed that implementation of the latter would result in higher turndown of the entire system and would offer higher energy density. Also, the hydration reaction was found to improve the energy density of the $CaO/CaCO_3$ energy storage system by 57.4%, from 307.2 kWh/m^3 to 483.6 kWh/m^3. Economic evaluation of the proposed concepts revealed that application of the cryogenic O_2 storage system in the calcium looping CO_2 capture process has the potential to increase the profitability of the integrated system, even over the reference coal-fired power plant without CO_2 capture.

Key Words: Carbon capture, calcium looping, energy storage, decarbonisation, coal-fired power plant.

1 INTRODUCTION

The International Energy Agency[1,2] has predicted that to limit the global mean temperature increase to 2°C, around 42% of the cumulative CO_2 emission from the energy sector, between 2009 and 2050, can be mitigated through implementation of carbon capture and storage (CCS), nuclear power stations and utilisation of renewable energy sources. The greatest challenge of such a scenario is the intermittence of the renewable energy sources[3], which would affect operation of the existing energy network[4,5], especially in cases when their share in the energy portfolio would exceed 50%[1]. As the nuclear power plants operate at base load, fossil fuel power plants would need to flexibly balance energy supply and demand, so that neither energy produced from renewable energy sources is wasted (high renewables generation period) nor energy shortages occur (low renewables generation period). Such periods of variable load operation or no operation would impose energy and economic penalties on the fossil fuel power systems, especially for plants with CCS that are better suited for base-load operation[6].

Due to their capacity of decoupling energy supply and demand[7], energy storage technologies can increase the degree of energy utilisation and thus should be widely deployed along with low-emission technologies. However, the energy storage could contribute to CO_2 emission reduction only in the scenario of renewables penetration[8,9]. Otherwise, the energy storage could increase CO_2 emissions by an extent which depends on carbon prices and share of coal-based power generation in the energy portfolio[1,8]. For this reason, a synergy between renewable energy sources, fossil fuel power generation and energy storage needs to be reached.

Presently about 145.8 GW of energy is stored globally, most of which as mechanical energy in pumped hydro storage plants (97.5%), and compressed air and flywheel energy storage techniques (1.0%). Interestingly, the share of thermal energy storage technologies surpassed electro-mechanical storage in 2013, and now accounts for 1.2% of the global energy storage capacity[10]. These technologies utilise media capable of storing thermal energy at low or high temperature, which can be recovered in the form of cold or heat depending on the process demand[11,12]. Moreover, thermal energy storage systems are claimed to have the potential for improving the flexibility of the electricity grid, increasing the degree of the energy utilisation[13,14], and balancing the mismatch between energy supply and demand[15]. These technologies do not have the disadvantages of pumped hydro storage and compressed air storage, such as requirements of specific site topology, and relatively high capital cost, which could have a negative environmental footprint[11,12].

Thermal energy storage systems can be classified as sensible heat, latent heat, and thermochemical energy systems[13,16,17]. The last mechanism, in which heat is used to sustain an endothermic chemical reaction and is released in the reverse reaction, is claimed to offer high energy densities[13,18], especially if one of the regeneration stage products is in the vapour phase[19]. Despite being proposed for energy storage in the mid-1970s[19,20], the process involving either hydration or carbonation of CaO is still considered among the best candidates for energy storage[18]. A novel process design based on the reversible CaO hydration reaction for storing heat from a concentrated solar field has been recently analysed by Criado et al.[21]. The proposed configuration comprises a single atmospheric pressure circulating fluidised bed, which can operate as hydrator and regenerator, and two silos for CaO and $Ca(OH)_2$ storage. This study revealed that, at maximum thermal output of 100 MW_{th}, the system offered an energy storage density of 260 kWh_{th}/m^3 and a round-trip efficiency of 63%. Edwards and Materić[22] proposed a process based on reversible carbonation of CaO in the calcium looping process (CaL) that comprised two independent reactors – atmospheric pressure calciner (solar tower receiver) and pressurised fluidised bed carbonator – and three reservoirs for CaO, $CaCO_3$ and CO_2 storage. In addition, air leaving the carbonator is fed to a gas expander for power generation. The plant net thermal efficiency was found to be between 40–46%. Finally, Vandersickel et al.[23] proposed to integrate a process similar to the integrated gasification combined cycle power plant, with the difference being that only CaO and $CaCO_3$ are stored, and the heat for calcination is provided through oxy-combustion of syngas diverted from the gas turbine. In this system, the existing Selexol unit is by-passed and the carbonator is used to capture CO_2 from the syngas during the peak-demand period. Nevertheless, the primary function of this system is energy storage and unloading the existing CO_2 capture system. Such configuration was found to operate with a round-trip efficiency of 61%, and allowed for changing the power output by +25% (peak-load) and -20% (off-peak) with respect to a nominal 550 MW_{el}. However, this study did not consider variation of the power generation system during part-load operation, which would lead to a further reduction of the power output during the calcination step.

Although the carbonation reaction offers nearly 50% higher theoretical energy density (1222 kWh/m^3) compared to that of hydration (833 kWh/m^3)[13], there are some concerns that need to be resolved prior to large-scale deployment. These include capability for electrical energy storage[12], reduction of sorbent activity[19], and requirement for temporary CO_2 storage[18]. Also, the CaL process was proposed by Shimizu et al.[24] for CO_2 capture from fossil fuel power plants. Not only has this process been proven to impose lower net efficiency penalty (5–8% points)[25–28] compared to more mature CO_2 capture technologies (8–12.5% points)[29–32], it also has the ability to increase the net power output of the integrated system by more than 50%[28,33,34]. More importantly, this system can accept an excess amount of electricity produced in the renewable energy sources to drive the air (for O_2 production) and CO_2 compressors and has a permanent source of CO_2 from the fossil fuel power plant. Finally, it can operate with higher carbonation conversions (higher energy density) when a hydration stage is employed[35].

The CaL process can, therefore, be seen as a promising technology for decarbonisation of the power sector as it has the ability to both decarbonise the fossil fuel power plant in an efficient manner and increase power generation flexibility. Hence, the fossil fuel power plant would not only meet its emission reduction targets, but also operate efficiently even in the energy portfolio containing large shares of intermittent renewable energy sources. In this study, the concept of CaL with inherent energy storage for CO_2 capture from coal-fired power plants is proposed and possible routes for energy storage in the proposed concept are identified. Finally, techno-economic performance of the selected routes is evaluated to analyse their degree of energy utilisation and profitability compared to the system without energy storage.

2 CONCEPT PROCESS DESCRIPTION

2.1 Calcium looping process

A core of the proposed concept is the CaL process proposed by Shimizu et al.[24] for CO_2 capture, which comprises two interconnected fluidised bed reactors operating at atmospheric pressure. In the first reactor, a carbonator, CO_2 is removed from the flue gas stream via calcium-based sorbent. In the second reactor, a calciner, the sorbent is regenerated at a high temperature, provided through oxy-combustion of fuel. High-temperature operation of the CaL process allows for recovery of high-grade heat from the carbonator and the process streams. As a result high-pressure steam can be generated and utilised for power generation in a secondary steam cycle.

Yet, due to the decay of maximum sorbent conversion with the number of carbonation/calcination cycles[36], which can drop to around 5–14% after 30 cycles depending on sulphur content in the flue gas and the fuel used in the calciner[37,38], part of the sorbent needs to be replenished in the system. To achieve a higher conversion in the carbonator, the sorbent can be reactivated through hydration (CaL-HYD)[35,39,40]. As a result of 60% sorbent hydration, the maximum sorbent conversion in the carbonator is about 55% after 15 cycles[41]. In the concept process proposed here, the low-pressure steam required for hydration can be extracted from the secondary steam cycle. Hydrated sorbent can be directed to either the carbonator or the calciner (Figure 1). However, the latter route increases the calciner heat load, and although that heat can be regenerated, the need for a larger air separation unit and CO_2 compression unit incurs higher capital costs, making this route less attractive. In addition, around 4–10% of sorbent[42] could be elutriated due to attrition. As a result, a higher fresh limestone make-up rate would be required, leading to higher maximum sorbent conversions, at the expense of higher heat requirement in the calciner. Yet, a higher fresh limestone make-up rate would lead to higher average sorbent conversions in the carbonator, reducing the sorbent looping rate required for 90% capture and thus, the heat requirement in the calciner.

2.2 Routes for energy storage and CO_2 capture

Having analysed the process flow diagrams of the CaL process for CO_2 capture, three viable options for energy storage have been identified (Figure 1):

- cryogenic O_2 storage (green dashed lines),
- $CaO/CaCO_3$ solids storage (grey dashed lines),
- $CaO/Ca(OH)_2$ solids storage (grey and red dashed lines, CaL-HYD only).

During the off-peak period, any of the identified energy storage systems can operate in the charging mode, which means that liquid O_2 is produced and/or the sorbent is regenerated in the calciner (in the CaL-HYD scenario reactivated sorbent is first fed to the carbonator). Under such operating mode, the air separation unit, the CO_2 compression unit and the calciner operate at their nominal capacity, while the power plant operates at its minimum load of 40%. This will lead to higher fuel consumption and higher power consumption for air separation and CO_2 compression compared to the system operating at 40% load without the energy storage. During the peak-demand period, the coal-fired power plant operates at its nominal capacity, while the stored O_2 and/or regenerated sorbent is utilised to unload the air separation unit and the CO_2 compression unit, reducing their power requirements, and to reduce the heat requirement of the calciner. Therefore, the proposed concept would benefit from using more fuel during off-peak periods, storing its chemical energy when the electricity price is low, and using this energy to reduce the fuel consumption and/or the system’s power requirement during the peak periods characterised by higher market prices for electricity. Such operation is expected to increase the flexibility and the profitability of the integrated system.

It needs to be highlighted that the carbonator is assumed to follow the power plant load changes, maintaining 90% CO_2 capture. Also, the air separation unit compressors can operate with a minimum load of 75% without recycling or venting, while the cold box operates at a minimum load of 50%[45]. This implies the need for three compression trains and two air separation unit 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 CO_2 compression unit. The calciner, on the other hand, can operate with a minimum load of 25%[46,47]. 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 air separation unit[43], while the sorbent is stored at high temperature in the solid storage tanks. As claimed by Arias et al.[6], the heat losses in the solid storage tanks, characterised by a low surface-to-volume ratio, are negligible. Ma et al.[44] showed that storing energy using solid materials, such as ash or sand, in the insulated tanks can reach thermal efficiencies exceeding 99%. Such low heat losses (<1%) are a result of combined effects of highly effective thermal insulation and self-insulation of the particles. Assuming short-term $CaO/CaCO_3$ solids storage (<12h) in the tanks insulated with concrete walls and refractory lining, which was also considered by Ma et al.[44], heat losses are not expected to affect the process performance by much and thus they are neglected in this concept study. Nevertheless, at the process design stage and for long-term storage (days to weeks), the effect of heat loss on process performance needs to be taken into account.

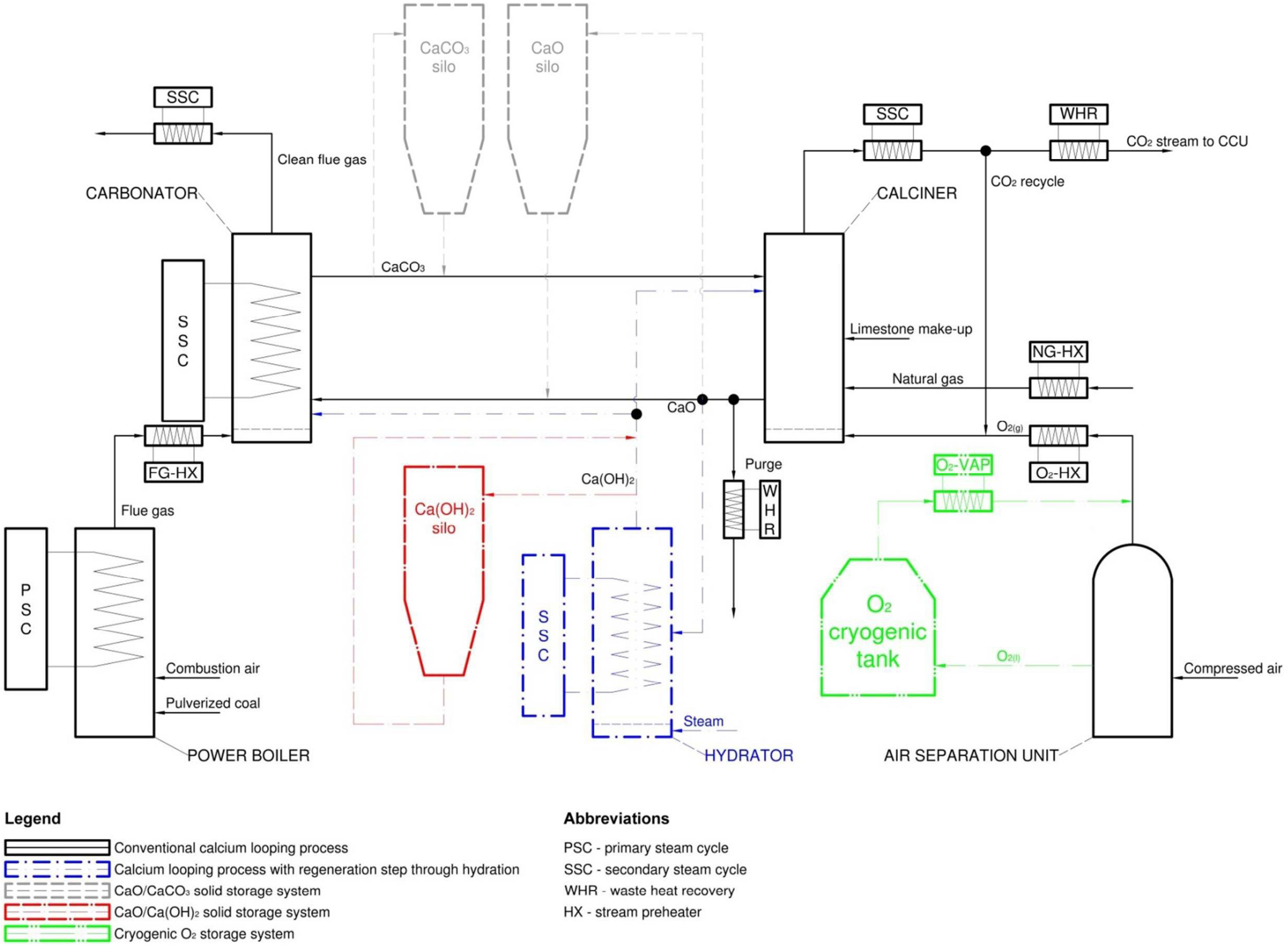

Figure 1: Schematic of coal-fired power plant retrofitted with calcium looping process for CO_2 capture and energy storage

3 PROOF OF CONCEPT

3.1 Considerations

After identifying possible routes for energy storage in the CaL plant integrated to the coal-fired power plant for CO_2 capture (Figure 1), the performance of the following scenarios is evaluated:

- CaL (Case 1) and CaL-HYD (Case 4) systems without energy storage;
- CaL (Case 2) and CaL-HYD (Case 5) systems with cryogenic O_2 storage;
- CaL (Case 3) and CaL-HYD (Case 6) systems with $CaO/CaCO_3$ solids storage.

Although other routes for energy storage based on permutations of the identified systems could be analysed, these are unlikely to offer any practical benefit over the selected cases. This is because, in all possible cases for energy storage, the minimum operating load of the calciner is limited by the minimum operating load of the air separation unit and the CO_2 compression unit. Therefore, further reduction in the minimum load of these systems would require additional compressors, leading to higher capital costs. Nevertheless, implementation of the energy storage system utilising the $CaO/Ca(OH)_2$ reaction for energy storage has lower energy density compared to that based on $CaO/CaCO_3$[13], and thus the heat storage capacity of the system would be lower.

To evaluate performance of the proposed concept, a model of the entire process has been developed in Aspen Plus™[32] with the key assumptions presented in Table 1. In addition to modelling of the CaL or CaL-HYD system, the air separation unit and the CO_2 compression unit were modelled in detail, to reliably assess process performance. The CO_2 capture system was scaled to remove 90% of the flue gas from the reference 660 MW_{el} coal-fired power plant, the process model of which has been described in detail elsewhere[48]. As opposed to the study by Vandersickel et al.[23], the part-load performance of the coal-fired power plant and the secondary steam cycle was evaluated in detail using the framework for part-load modelling presented in Hanak et al.[48].

Table 1: Key process model assumptions

Parameter		Value
Carbonator	Temperature (°C)	625
	Carbonation extent (-)	0.70
	Stoichiometric reactor. Average conversion model by Rodríguez et al.[49] with deactivation curves derived from experimental data from Sánchez-Biezma et al.[50] (non-hydrated sorbent) and Grasa et al.[41] (hydrated sorbent).	
Calciner	Temperature (°C)	900
	Calcination extent (-)	0.95
	Relative make up (Fresh limestone/Sorbent circulation rate)	0.04
	O_2 concentration in the calciner fluidising gas ($\%_{vo,wetl}$)	40.0
	O_2 excess ($\%_{vol,dry}$)	2.5
	Gibbs reactor. Gibbs free energy minimisation model.	
Hydrator	Temperature (°C)	500
	Steam-to-calcium ratio (molar basis)	1.3
	Stoichiometric reactor. Complete sorbent conversion.	
Secondary steam cycle	Design live/reheat steam temperature (°C)	593.3/593.3
	Design live/reheat steam pressure (bar)	242.3/49.0

The capacity of energy storage technologies is usually characterised with energy density (D_v) or a specific energy (D_m) defined in Eq. (1) and Eq. (2) as the ratio of the energy stored (E_{stored}) and the amount of storage media stored ($m_{storage\ media}$), while performance of the power generation systems is characterised with net power output (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 (Q_{fuel}). Environmental performance is represented as the specific CO_2 emissions (e_{CO2}) defined as the ratio of CO_2 emission rate (m_{CO2}) and the net power output.

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

$$D_m = 1000 \times \frac{\dot{E}_{stored}}{\dot{m}_{storage\ media}} \quad (2)$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{fuel}} \quad (3)$$

$$e_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \quad (4)$$

Because energy can be stored in thermal ($CaO/CaCO_3$ solids) and electrical (cryogenic O_2 storage) forms in the proposed concept, the above metrics cannot fully represent the performance of the integrated system. Therefore, the degree of energy utilisation (η_u), which is defined in Eq. (5) as the ratio of useful energy and total energy input, is used as a measure of overall process performance. In Eq. (5), the useful energy term comprises net power output (W_{net}), electricity stored through cryogenic O_2 storage ($W_{storage,out}$), and heat stored through $CaO/CaCO_3$ solids storage ($Q_{storage,out}$), while the total energy input comprises the chemical energy input from fuel combustion (Q_{fuel}), electricity input through utilisation of stored liquid O_2 ($W_{storage,in}$), and heat input through utilisation of stored $CaO/CaCO_3$ solids ($Q_{storage,in}$). Although the considered forms of energy differ in quality, similar metrics, called degree of fuel utilisation, have been widely applied to assess performance of combined heat and power generation systems[51].

$$\eta_u = \frac{\dot{W}_{net} + \dot{Q}_{storage,out} + \dot{W}_{storage,out}}{\dot{Q}_{fuel} + \dot{Q}_{storage,in} + \dot{W}_{storage,in}} \quad (5)$$

To assess the profitability of the proposed concepts with respect to the reference coal-fired power plant without CO_2 capture, the levelised cost of electricity (*LCOE*) and the cost of CO_2 avoided (*AC*) are calculated according to Eq. (6) and Eq. (7)[52–54], respectively.

$$LCOE = \frac{TCR \times FCF + FOM}{\dot{W}_{net} \times CF \times 8760} + VOM + \frac{SFC}{\eta} \tag{6}$$

$$AC = \frac{LCOE_{capture} - LCOE_{ref}}{e_{CO_2,ref} - e_{CO_2,capture}} \tag{7}$$

These parameters allow assessing the economic viability of the proposed concept through correlating thermodynamic performance indicators, such as net power output, net thermal efficiency (η), capacity factor (CF) and specific emissions (E_{CO2}), with economic performance, such as total capital requirement (TCR), variable (VOM) and fixed (FOM) operating 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**
Coal-fired power plant	Reference equipment capital cost (€/kW$_{el}$)[42,52,54,57]	1100
	Reference power output (MW$_{el}$)[42]	575
Calcium looping plant	Reference equipment capital cost (€/kW$_{el}$)[58]	1252.3
	Reference heat input (MW$_{th}$)[58]	534.0
	Reference reactor volume (m^3)[58]	1150.5
Cryogenic O_2 storage tank	Reference equipment capital cost (€/m^3)[43]	800000
	Reference volume (m^3)[43]	2500
Solid storage tank	Reference equipment capital cost (€/MW$_{th,sensible}$)[44]	8.0
Other economic parameters	Variable cost as a fraction of total capital cost (%)[54,60]	2.0
	Fixed cost as a fraction of total capital cost (%)[54,60]	1.0
	Carbon tax (€/tCO_2)[54,60]	0.0
	Raw sorbent cost (€/t)[54,60]	6.0
	CO_2 transport and storage cost (€/tCO_2)[61]	7.0
	Coal price (€/t)[60,62]	40.6
	Natural gas price (€/t)[63]	157.1
	Expected lifetime (years)[54,60]	25
	Project interest rate (%)[54,60]	8.78
	Capacity factor (%)[54,60]	80

In addition, considering the average electricity prices in December 2014[55], the daily profit is calculated. Using the approach employed by Mac Dowell and Shah[56], Eq. (8)

allows calculating the daily short-run profit (*SRP*) as the difference between the daily revenue from electricity sales (*R*) and daily operating costs associated with fuel consumption (*FC*), sorbent make-up (*SC*), CO_2 transport and storage (*CTS*), and CO_2 emissions (*CE*).

$$SRP = R - (FC + SC + CTS + CE) \tag{8}$$

The capital cost of the coal-fired power plant and storage equipment is determined using the exponential method function[64] with economic data presented in Table 2. Taking the capital cost for an oxy-fuel circulating-fluidised bed system (C_0) as reference[58], Eq. (9) is employed to estimate the total capital cost of the CaL and CaL-HYD plants (*C*), considering the volume of the reactors (*V*) and the heat input to the calciner (Q_{calc}) with the scaling factors of 0.67 and 0.9, respectively. Moreover, the parameter representing the fraction of the total cost of a circulating fluidised bed reactor associated with the heat transfer surfaces (α) is assumed to be 0.85. It needs to be highlighted that in the CaL cases, this equation reduces to the exponential function used by Romano et al.[59]

$$C = C_0\left[\alpha\left(\frac{\dot{Q}_{calc}}{\dot{Q}_0}\right)^{SF,Q} + (1-\alpha)\left(\frac{V_{calc}}{V_0}\right)^{SF,V} + (1-\alpha)\left(\frac{V_{carb}}{V_0}\right)^{SF,V} + (1-\alpha)\left(\frac{V_{hyd}}{V_0}\right)^{SF,V}\right] \tag{9}$$

Fixed and variable operating and maintenance costs are calculated as a fraction of total capital cost, while operating costs associated with fuel and sorbent consumption, and CO_2 storage, transport and emission are determined based on process simulation outputs using economic data from Table 2.

Finally, performance of the selected cases for the proposed concept is assessed in the following operating modes:

- Charging mode in which the power plant operates at 40% load, while the considered energy storage system operates at 100% load,

- Discharging mode in which the power plant operates at 100% load, while the considered energy storage system operates at 40% load,
- Daily variable load operation in which the system operates in the charging mode during the off-peak period (11.00pm – 5.30am), discharging mode during the morning and evening peak periods (6:00am – 9.30am and 4.30pm – 7.30pm), and CO_2 capture only mode (no energy storage) in the remaining periods (10:00am – 4:00pm and 8:00pm – 10:30pm).[a]

3.2 Thermodynamic performance evaluation

A performance analysis conducted for the selected cases (Table 2) revealed that the turndown of the reference coal-fired power plant, which is a ratio of the maximum and minimum net power output reached by the system, was 2.56. Interestingly, similar turndown values were estimated for Case 1 (2.62) and Case 4 (2.60), in which the power plant was retrofitted with the CaL and the CaL-HYD systems for CO_2 capture only, respectively. This is because integration of these systems resulted not only in increase of the maximum net power output by 51.7% and 33.7%, respectively, but it also caused increases in the minimum net power output of 48.3% and 32.0%, respectively. Results presented in Table 2 show also that turndown of the integrated system with cryogenic O_2 storage increased to 3.30 (Case 2) and 3.15 (Case 5), while for the integrated system with $CaO/CaCO_3$ solids storage it reduced to 2.54 (Case 3) and 2.44 (Case 6). It should be noted that in the discharge mode, a reduction in the calciner load to 40% led to reductions in fuel and O_2 requirements, and thus, less high-grade heat was available for recovery from the process streams. This, in turn, resulted in less high-pressure steam generation and a drop in its pressure, which has been estimated according to the Stodola ellipse law[65]; hence lower maximum net power output. Cryogenic O_2 energy storage, therefore, appears

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[a] A hypothetical daily energy demand was adapted from MacDowell and Shah[56].

to be better suited to balance rapid changes of the energy demand, allowing for immediate increases of net power output by utilising O_2 produced in the air separation unit and stored in the cryogenic tank during the off-peak period. Importantly, a noticeable difference in net power output between the CaL and the CaL-HYD systems arose from differences in the amount of the high-grade heat available for recovery in these systems. Namely, the increase in the average sorbent conversion in the carbonator from 15.8% in the CaL system to 37.8% in the CaL-HYD system resulted in a lower solid looping rate required to achieve 90% CO_2 capture in the carbonator of the latter system. This, in turn, resulted in a reduction of the heat requirement for sorbent regeneration in the calciner, reducing the amount of recoverable heat from the carbonator and the process streams; hence less high-pressure steam was generated and used for power generation in the secondary steam cycle. The results obtained for the integrated system without energy storage were found to be consistent with the predictions by Wang et al.[66], who compared performance of the CaL and the CaL-HYD systems.

Table 2: Performance indicators for the considered energy storage and CO_2 capture routes[b] for the proposed process

	Reference power plant		Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
Charging (C) / Discharging (D) performance indicators	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**
Net power output (MW_{el})	247.0	633.0	366.4	960.0	307.5	1019.5	370.3	941.5	326.1	846.6	282.4	890.8	338.3	824.8
Net thermal efficiency ($\%_{HHV}$)	34.5	38.8	25.7	30.1	21.6	32.0	16.3	40.2	26.2	30.4	22.7	32.0	18.1	38.2
Energy utilisation degree (%)	34.5	38.8	25.7	30.1	25.7	31.4	37.7	33.6	26.2	30.4	26.2	31.5	39.1	32.4
Net efficiency penalty	-		8.8	8.7	12.9	6.8	18.2	-1.5	8.3	8.4	11.8	6.8	16.4	0.6
Energy utilisation degree penalty (%)	-		8.8	8.7	8.8	7.4	-3.2	5.1	8.3	8.4	8.3	7.3	-4.6	6.3
CO_2 intensity factor (gCO_2/kWh_{el})	969.0	835.0	65.3	55.0	77.8	51.8	64.6	56.1	73.4	62.4	84.8	59.3	70.7	64.1
Instantaneous performance indicators														
Net power generation turndown (-)	2.56		2.62		3.30		2.54		2.60		3.15		2.44	
Energy density[c] (kWh/m^3)	-		-		312.0		307.2		-		309.8		483.6	
Specific energy (kJ/kg)	-		-		900		700		-		900		1200	
Daily average performance indicators														
Average daily net thermal efficiency ($\%_{HHV}$)	38.1		29.4		29.5		29.4		29.7		29.8		29.7	
Average daily degree of energy utilisation (%)	38.1		29.4		29.9		33.0		29.7		30.1		33.0	
Average daily CO_2 intensity factor (gCO_2/kWh_{el})	853.6		56.4		56.3		56.8		63.9		63.8		64.2	
Economic performance indicators														
Levelised cost of electricity (€/MWh_{el})	37.2		82.7		82.7		82.7		74.2		74.2		74.2	
Cost of CO_2 avoided (€/tCO_2)	-		58.2		58.3		58.3		47.8		47.8		47.8	

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[b] Case 1 – CaL with no ES, Case 2 – CaL with cryogenic O_2 storage, Case 3 – CaL with $CaO/CaCO_3$ solids storage, Case 4 – CaL-HYD with no ES, Case 5 – CaL-HYD with cryogenic O_2 storage, Case 6 – CaL-HYD with $CaO/CaCO_3$ solids storage.

[c] The unit is kWh_{el}/m^3_{O2} in Case 2 and Case 5, and kWh_{th}/m^3CaCO_3 in Case 3 and Case 6.

Further analysis of process performance revealed that $CaO/CaCO_3$ solid storage system would yield higher net thermal efficiencies in the discharging mode (40.2%$_{HHV}$ in Case 3 and 38.2%$_{HHV}$ in Case 6), compared to cryogenic O_2 storage (32.0%$_{HHV}$ in both Case 2 and Case 5) and even compared to the reference power plant (38.8%$_{HHV}$). Yet, this is achieved at the expense of much lower net thermal efficiencies in the charging mode (16.3%$_{HHV}$ in Case 3 and 18.1%$_{HHV}$ in Case 6), when the solids converted in the carbonator need to be regenerated. Net thermal efficiency for the cryogenic O_2 storage system operating in the charging mode would result in an even lower efficiency penalty.

Yet, it is important to highlight that in estimation of net thermal efficiency, the net power output was considered as the only source of useful work in the system, while energy stored in the form of heat or electricity has not been taken into account. This can also be seen as the main reason for high net thermal efficiencies estimated for the discharging mode, since the energy input from the energy storage system was not considered. Performance analysis of the proposed concept routes revealed that the system with $CaO/CaCO_3$ storage has 12–13% points higher degree of energy utilisation than the cryogenic O_2 storage system. Yet, this did not directly correlate to system storage capacity. Estimation of energy density for both systems did not give a clear answer as to which system has higher energy storage capacity; for the former it was estimated to be 307.2 and 483.6 kWh_{th}/m^3 in Case 3 and Case 6, respectively, while for the latter it was 312.0 and 309.8 kWh_{el}/m^3 in Case 2 and Case 5, respectively. However, direct comparison of these values cannot be used to determine which system has higher energy storage capacity, due to different forms of energy used in the energy density estimation. For cases with the cryogenic O_2 storage system, operation in the charging and discharging mode was found not to affect performance of the secondary steam cycle, compared to the system without energy storage. It can be claimed that changes in net power output in these operating modes were directly related to the amount of thermal energy input in the boiler. By using the gross thermal efficiency of the system operating in the discharging ($38.4\%_{HHV}$) and charging mode ($34.5\%_{HHV}$), the energy density of cryogenic O_2 storage is recalculated to be 812.4–897.9kWh$_{th}$/m^3, which is higher than estimated values for the CaL and CaL-HYD with $CaO/CaCO_3$ storage. This implies that to store the same amount of fuel energy, cryogenic O_2 storage would require smaller volume than the $CaO/CaCO_3$ solids storage system, hence lower capital costs.

Incorporation of the sorbent regeneration step through hydration was found to result in a 57.4% increase in energy density and 71.4% increase in specific energy. This can be associated with the increase of average sorbent conversion in the carbonator from 15.8% to 37.8%, resulting in a reduction of unconverted CaO in the stored solids. As a result, the fraction of total thermal energy stored in the form of sensible heat reduced from 39.0% (Case 3) to 24.9% (Case 6), revealing that increased sorbent conversion promotes energy storage through chemical reaction. Also, it was estimated here that, for each per cent of sorbent conversion improvement, energy density and the specific energy can be increased by 8 kWh$_{th}$/m^3 and 21.6 kJ$_{th}$/kg, respectively. Therefore, not only would the systems including reactivation steps, such as the investigated CaL-HYD system with $CaO/CaCO_3$ solids storage, or using more efficient sorbents[67,68], require smaller reactors (hence lower capital cost), these would also achieve a higher degree of energy utilisation. Moreover, the $CaO/Ca(OH)_2$ step in the proposed concept was used to increase the energy storage capacity of the $CaO/CaCO_3$ system by increasing the average conversion of the sorbent, hence increasing the fraction of $CaCO_3$ in the stored solids. This approach differs from the system investigated by Criado et al.[21], who proposed to use the $CaO/Ca(OH)_2$ system as the primary energy storage system. This approach was found to increase the energy density of the $CaO/CaCO_3$ system to 483.6 kWh_{th}/m^3; that is 57% higher than the energy density of the $CaO/CaCO_3$ system without sorbent reactivation (307.2 kWh_{th}/m^3) and 86% higher compared to the $CaO/Ca(OH)_2$ system (260 kWh_{th}/m^3) evaluated by Criado et al.[21]. As a result, storage of the same amount of heat would require smaller volume in the $CaO/CaCO_3$ system with sorbent reactivation through hydration compared to the $CaO/Ca(OH)_2$ system, leading to lower capital cost of the entire CO_2 capture system with energy storage, which is proven in the economic analysis presented below. The only downside of using the CaL-HYD instead of the CaL system is marginally higher values for CO_2 intensity factor in most of the cases investigated (Table 2). This is a result of lower net power output for the regenerated system, caused by less high-grade heat available for recovery from the process streams.

Analysis of the hypothetical daily energy demand curve adapted from MacDowell and Shah[56] revealed that the daily average degree of energy utilisation in the systems containing $CaO/CaCO_3$ storage (around 33%) and cryogenic O_2 storage (around 30%) was higher than in systems without energy storage (29.4% for Case 1 and 29.7% for Case 4). This implies that the systems with energy storage capability would result in higher degrees of energy utilisation. More importantly, as the periods of charging and discharging were equal in the hypothetical operating schedule, the average daily net thermal efficiency and the average daily CO_2 intensity factor were not affected much compared to the system without energy storage. Finally, the process evaluated in this study can conceptually be integrated with a solar power plant or wind turbine farm to utilise excess energy for sorbent regeneration or for liquid O_2 production, which can be utilised later to increase net thermal efficiency and the degree of energy utilisation.

3.3 Economic performance evaluation

The specific capital costs of the reference coal-fired power plant, the CaL system (Case 1) and the CaL-HYD system (Case 4) have been estimated to be 1206.5 €/kW$_{el,gross}$, 2981.6 €/kW$_{el,gross}$ and 2776.4 €/kW$_{el,gross}$, respectively. This is in agreement with other studies, which assumed the specific capital costs for coal-fired power plants of 1200 €/kW$_{el,gross}$ and for the CaL system of 2500-3000 €/kW$_{el,gross}$[25,52–54]. Moreover, specific capital cost of the integrated CaL and CaL-HYD systems was estimated to be 2023.4 €/kW$_{el,gross}$ and 1799.1 €/kW$_{el,gross}$, respectively, which is close to the range 1250–1740 €/kW$_{el,gross}$ estimated in other studies[42,52,54]. A slightly higher specific capital cost obtained in this study is caused by the assumption of maximising heat recovery for power generation in the CaL and CaL-HYD plants. Also, the higher energy density due to sorbent regeneration in Case 6, compared to Case 3, reduces the specific capital cost of the entire system. An additional capital cost associated with cryogenic O_2 storage and $CaO/CaCO_3$ solid storage increases the specific captial cost of the integrated CaL system only by 0.6 €/kW$_{el,gross}$ (Case 2) and 2.3 €/kW$_{el,gross}$ (Case 3), and of the CaL-HYD by 0.6 €/kW$_{el,gross}$ (Case 5) and 1.4 €/kW$_{el,gross}$ (Case 6). Hence, addition of energy storage capability does not change the levelised cost of electricity, the value of which is in agreement with results from Romano et al.[59] and Yang et al.[54], and has a negligible effect on the cost of CO_2 avoided (Table 2). Therefore, the inherent energy storage ability of the CaL and CaL-HYD systems is available at a very low additional capital cost to the CO_2 capture system.

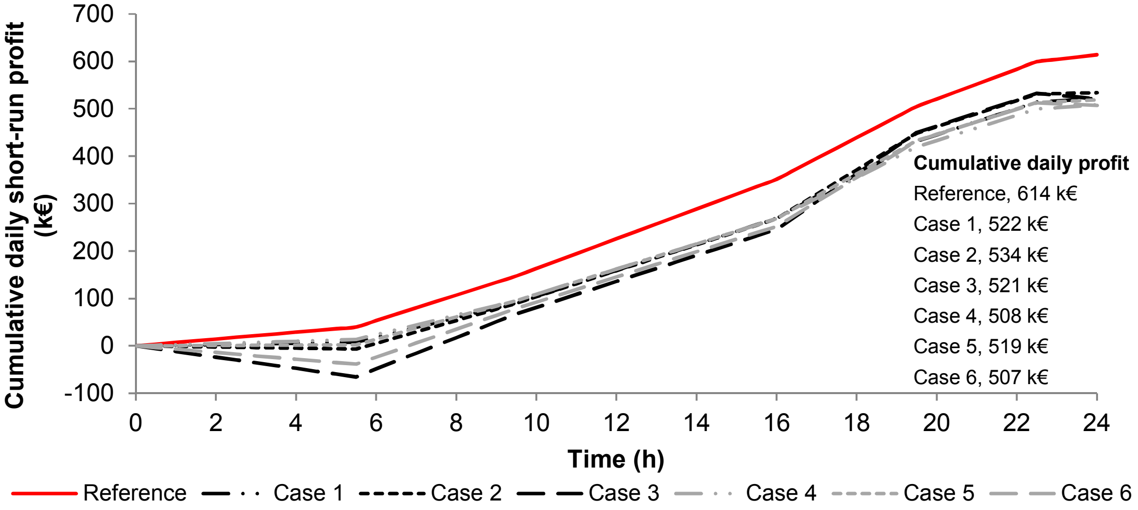


Figure 2: Comparison of the daily short-run profit

Implementation of the CaL (Case 1) and the CaL-HYD (Case 4) plants for CO_2 capture will reduce the daily short run profit by 15.0% and 17.2% (Figure 2), respectively, regardless of the better thermodynamic performance of Case 4 identified previously. This is due to 7.2% lower net power output in Case 4 with respect to Case 1 and thus lower expected revenue from electricity sales. Furthermore, addition of the cryogenic O_2 storage was found to increase the daily short-run profit of the CaL (Case 2) and CaL-HYD (Case 5) plants by 2.3% and 2.2%, respectively. Conversely, addition of the $CaO/CaCO_3$ solid storage system was found to slightly reduce the daily short-run profit of the CaL (Case 3) and CaL-HYD (Case 6) by 0.1% and 0.2%, respectively; yet it will increase the plant flexibility. Therefore, it appears as if the cryogenic O_2 storage system was more economically substantiated. Yet, with the secondary steam cycle designed for normal operating mode without energy storage, part-load opeartion of the calciner in discharging mode reduces the amount of recoveralbe heat that results in reduction of net power output in Case 3 and Case 6 by 0.2% and 0.3%, respectively.

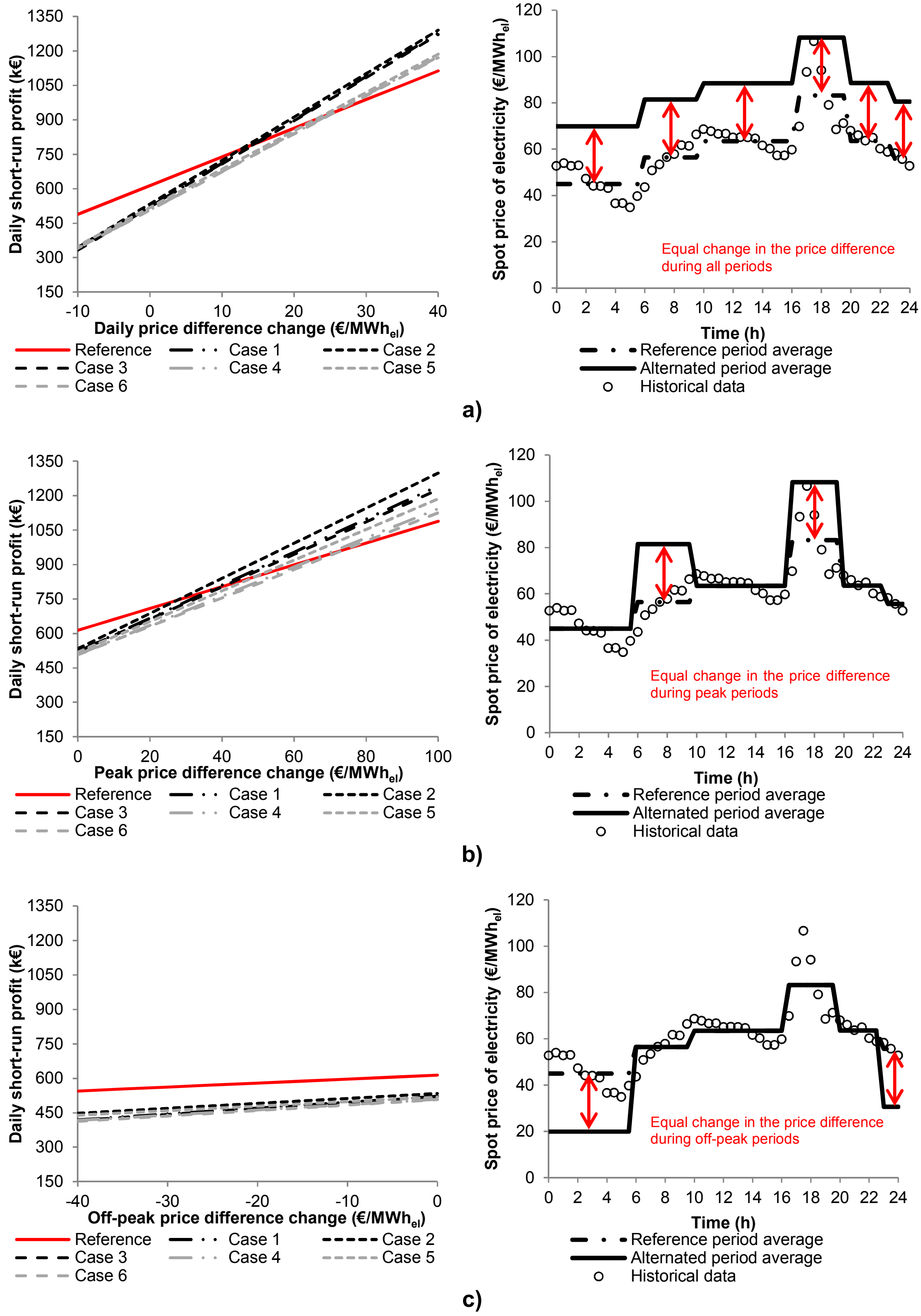
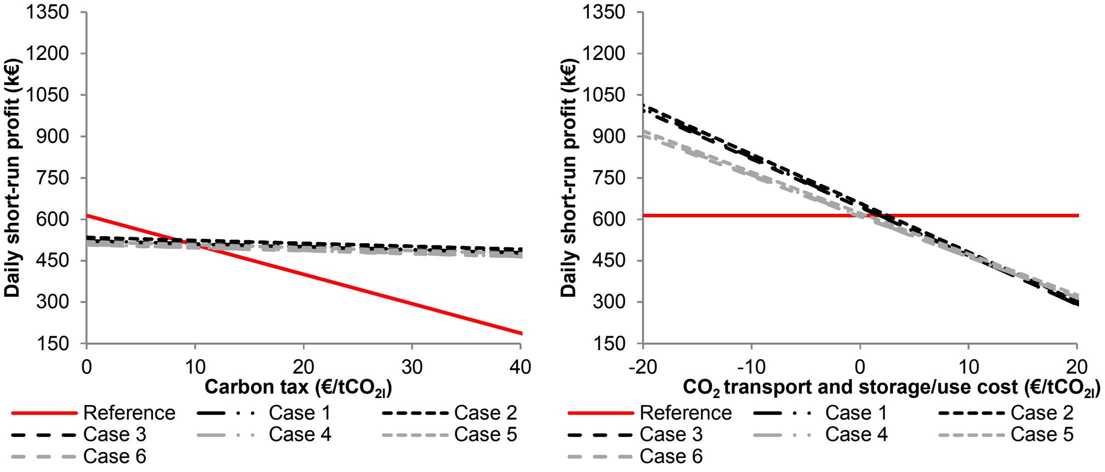


Figure 3: Effect of a change in the a) daily b) peak and c) off-peak price difference on daily short-run profit

As electricity prices are subject to annual fluctuations and to seasonal changes, the effect of the price difference, which is defined as change of the electricity price with respect to the reference value over the considered period, on the daily short-run profit, is evaluated. On increasing the daily price difference (Figure 3a), it was found that the concepts proposed in Case 2 and Case 3 would generate the same daily short-run profit as the reference coal-fired power plant without CO_2 capture if the daily price of electricity increases by 12.5 €/MWh$_{el}$ and 14.8 €/MWh$_{el,}$ respectively, while the CaL plant without energy storage will break even at the 14.4 €/MWh$_{el}$ increase in price difference. For the cases with sorbent regeneration through hydration, higher daily short-run profit would be achieved on increased price difference of 22.6–26.0 €/MWh$_{el}$, with the lowest increase associated to Case 5. Moreover, increased peak price difference (Figure 3b) of more than 27.4 €/MWh$_{el}$ and 49.2 €/MWh$_{el}$, would make the CaL (Case 2) and the CaL-HYD (Case 5) more economical than the reference coal-fired power plant. In addition, it was found that reduction of off-peak prices (Figure 3c) will not bring any additional benefit, as the loss of profit in the charging mode during low electricity price periods outweighs the benefits of discharging mode operated at peak times with higher prices. Nevertheless, this analysis revealed that the proposed concept, in particular the CaL plant with cryogenic O_2 storage system (Case 2), could generate daily short-run profit higher than the reference coal-fired power plant depending on the daily spot prices of electricity. Further increase of the profit can be achieved on determination of the optimal charging and discharging times, using optimisation methodology developed by Barbour et al.[69].

Finally, economic performance of the proposed concepts is highly dependent upon the economic climate, as it is predicted that the carbon tax may vary between 10–

150 €/tCO$_2$[70,71]. Moreover, economic performance will vary depending on whether the produced CO$_2$ is transported and stored (the costs for which vary between 2.5–36 €/tCO$_2$[62,72] depending on the CO$_2$ transport method and storage location), or used, for example, for enhanced oil recovery at a supply price of 12-15 €/tCO$_2$[73,74]. Figure 4a reveals that the daily short-run profit of the reference coal-fired power plant is highly affected by increases in the carbon tax, while it is hardly affected in the remaining cases with 90% CO$_2$ capture. Importantly, when the carbon tax exceeds 8.3 €/tCO$_2$ for Case 2 (which is lower than the average price of 8.5 €/tCO$_2$ for the European emission allowances in November 2015[75]), and 11.1 €/tCO$_2$ for Case 6, the proposed concepts become more profitable than the reference coal-fired power plant. This implies that the proposed concept (Case 2) is already more profitable than the reference coal-fired power plant without CO$_2$ capture.



a) b)

Figure 4: Effect of a) carbon tax and b) cost of CO$_2$ transport and storage/use on daily short-run profit

Furthermore, it can be seen in Figure 4b that for the specific cost for CO$_2$ capture and transport of 2.5 €/tCO$_2$, the daily short-run profit for Case 2 is equal to that generated by the reference coal-fired power plant. On the other hand, for Case 6 to become more profitable than the reference coal-fired power plant, CO_2 would need to be sold for industrial use at prices higher than 0.3 €/tCO_2, which corresponds to negative values in Figure 4b. This shows that the profitability of the proposed concepts could greatly exceed that of the reference coal-fired power plant, if pure CO_2 produced in the proposed concepts is industrially utilised, even at low price.

4 CONCLUSIONS

In this study, a concept for the CO_2 capture plant based on CaL with inherent energy storage is proposed and evaluated in the coal-fired power plant retrofit scenario. The CaL was previously proposed for energy storage from solar power plants; however, challenges involving the requirement of temporary CO_2 storage and sorbent deactivation were identified. These were resolved in the proposed system as the power plant acts as a permanent source of CO_2 and hydration was used as a means for sorbent regeneration.

Analysis of the process revealed that possible routes for energy storage include $CaO/CaCO_3$ solids storage, $CaO/Ca(OH)_2$ solids storage and cryogenic O_2 storage systems. The comparison of $CaO/CaCO_3$ and cryogenic O_2 storage systems revealed that implementation of the latter would result in higher turndown of the entire system and offer higher energy density, hence requiring lower capital cost. Although performance of the integrated system with energy storage through a $CaO/Ca(OH)_2$ loop was not evaluated here due to the lower energy density of such system, the reactivation step was found critical in improving the performance of the $CaO/CaCO_3$ energy storage system. Not only did it increase net thermal efficiency, it increased the energy density by 57.4% and specific energy by 71.4% leading to a higher degree of energy utilisation. Importantly, the proposed CaL-HYD system with

$CaO/CaCO_3$ energy storage was found to offer 86% higher energy density than the conventional $CaO/Ca(OH)_2$ energy storage system. An increase in the energy density was found to be important from the economic perspective, as storing the same amount of heat in a lower volume would result in the specific capital cost of the CaL-HYD system lower by 6.8% compared to the CaL system.

The economic performance evaluation conducted in this section revealed that the addition of energy storage capability to the CaL and the CaL-HYD plants for CO_2 capture from the coal-fired power plant has a low impact on the total capital cost and thus on the levelised cost of electricity and the cost of CO_2 avoided. Moreover, analysis of the daily short-run profit revealed that Case 2, in which the CaL plant was equipped with the cryogenic O_2 storage system, will reduce the daily short-run profit of the coal-fired power plant by 15.0%. This case was found to have the lowest impact on system profitability. Yet, the proposed concept (Case 2) can generate higher profit when the carbon tax exceeds 8.3 €/tCO_2. As the price of the European emission allowances in November 2015 was 8.5 €/tCO_2, the proposed concept is already more profitable than the reference coal-fired power plant without CO_2 capture.

Further studies will aim to provide a detailed design of the proposed concepts of CO_2 capture with inherent energy storage for decarbonisation and to optimise the charging and discharging times to maximise the daily short-run profit. Also, the applicability of the proposed concepts in natural gas combined cycle power plants will be assessed. Finally, the inherent energy storage capability of other clean power technologies, such as chemical looping combustion and oxy-combustion, will be assessed.

Nomenclature

AC	Cost of CO_2 avoided	€/tCO_2
C	Capital cost of calcium looping system	€/kW_{el}
C_0	Reference capital cost of oxy-fuel circulating fluidised bed system	€/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}
$\dot{E}_{stored}$	Rate of energy to storage	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
R	Revenue from electricity sales	€
SC	Sorbent make-up cost	€
SCF	Specific fuel cost	€/MWh
SF,Q	Scaling factor for reactor heat input	-
SF,V	Scaling factor for reactor volume	-
SRP	Daily short run profit	€
TCR	Total capital requirement	€
$\dot{Q}_0$	Reference heat input	MW_{th}
$\dot{Q}_{calc}$	Heat input to the calciner	MW_{th}
$\dot{Q}_{fuel}$	Chemical energy input from fuel combustion	MW
$\dot{Q}_{storage,in}$	Heat input from $CaO/CaCO_3$ solids storage	MW
$\dot{Q}_{storage,out}$	Heat stored through $CaO/CaCO_3$ solids storage	MW
V	Volume of reactors	m^3
V_0	Reference volume of reactor	m^3
VOM	Variable operating and maintenance cost	€/MWh
$\dot{W}_{net}$	Net power output of the integrated system	MW
$\dot{W}_{storage,in}$	Electricity input from cryogenic O_2 storage	MW
$\dot{W}_{storage,out}$	Electricity stored through cryogenic O_2 storage	MW
α	Fraction of the total cost of a circulating fluidised bed	-

	reactor associated with the heat transfer surfaces	
η_{th}	Net thermal efficiency	-
η_u	Degree of energy utilisation	-

Abbreviations

CaL	Calcium looping process
CaL-HYD	Calcium looping process with sorbent reactivation step through hydration
CCS	Carbon capture and storage

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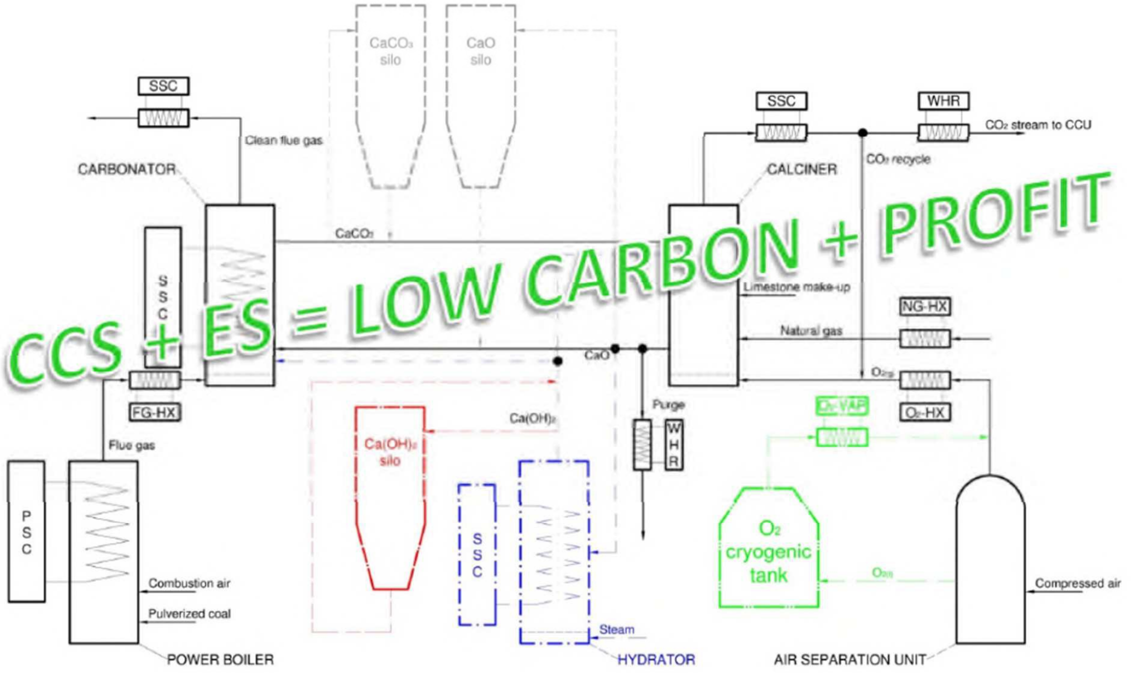
Graphical Abstract

Carbon capture and storage (CCS) with energy storage (ES) systems increase flexibility and profitability of fossil-fuel-fired power systems.



Broader Context:

Fossil fuel power plants with CO_2 capture, nuclear power stations and renewable energy sources have been identified as capable of reducing around 42% of the energy sector's cumulative CO_2 emissions between 2009 and 2050. However, the increasing share of intermittent renewable energy sources in the energy portfolio will be challenge for balance of the energy network. Therefore, the fossil fuel power plants are expected to be decarbonised and to flexibly balance energy supply and demand to avoid energy wastage and shortages. Implementation of energy storage is seen as an alternative option to counterbalance the intermittent nature of renewables. In this study we present a concept of CO_2 capture systems based on calcium looping with inherent energy storage. We demonstrated that such systems, in addition to decarbonisation of power plants, can increase the degree of energy utilisation at very small additional capital costs. In the realistic future energy portfolio/policy scenarios, the fossil fuel energy systems based on the proposed concept can generate higher profit than current fossil fuel power plants without CO_2 capture. In other words, integration of carbon capture and storage with energy storage can enable decarbonisation of power and other carbon-intensive industries with no economic penalties.