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Flexible Calcium Looping system for CO_2 capture from coal-fired power plants: a comprehensive modelling study on part-load and dynamic performance and economic optimization of the sorbent storage system

Marco Astolfi[a], Edoardo De Lena[a], Francesco Casella[b], Matteo C. Romano[a,*]

[a] *Politecnico di Milano, Dipartimento di Energia, via Lambruschini 4, 20156 Milano, Italy*
[b] *Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Via Ponzio 34/5, 20133 Milano, Italy*

Abstract

In this work, an advanced Calcium looping (CaL) power plant with thermochemical energy storage system is assessed. The CaL system is equipped with two solids storage silos storing calcined solids from the calciner and carbonated solids from the carbonator. The presence of the solids storage allows to design and operate the CaL calciner line (calciner, ASU, CPU) on the average load of the existing power plant, while the carbonator can follow the load of the conventional power plant with air-blown boiler. The economic analysis carried out shows that the optimal size of the storage system from an economic and logistical point of view is on the daily cycle, which shows a cost of CO_2 avoided (CCA) of 31 €/t_{CO2}, about 16% less than the case without storage. In addition, the adoption of the storage system allows the CaL steam cycle to operate with a higher average daily electrical efficiency than without storage, limiting the operation at partial load. Moreover, by exploiting the secondary storage it is possible to have an increase of about 20 MW_e respect to the nominal condition, and a reduction of about 56 MW_e below the minimum load. As demonstrated by studying the dynamics of the system, the increase in power output can be produced in a relatively short time (40% within 40s and the remaining 60% within 300s) by boosting the hot CaO flow through the sorbent cooling line.

Keywords: CCS; Calcium Looping; Energy storage; CO_2 capture; Flexibility; Part-load; Dynamic performance

1. Introduction

Renewable sources in the energy sector are providing new challenges for the electricity system, due to the intermittency of wind and solar energy, whose share in the energy mix is expected to increase in the next years [1–3]. Further, to contain greenhouse gas emissions and their negative effects [3], by 2050 most of fossil fuel fired plants should adopt carbon capture and storage (CCS) systems. Therefore, it is essential to investigate the performance and the control strategies of next generation coal-fired power plants coupled to CCS, to ensure a smooth transition towards a more sustainable power generation sector.

For CCS technologies traditionally proposed for power plants (i.e. post-combustion, pre-combustion and oxyfuel technologies) several process alternatives based on the storage of solvent [4–6], hydrogen [7–9], oxygen [8,10,11] and high temperature solids [12,13], have been proposed to improve their flexibility.

* Corresponding author. *E-mail address:* matteo.romano@polimi.it

Post-combustion system based on Calcium Looping (CaL) technology can also benefit from the thermochemical energy storage potential of the CaO-based sorbent [14,15]. This was the objective of the FlexiCaL project [16]

The main scope of this paper is to summarize the main results of the process engineering study carried out in the FlexiCaL project. A techno-economic analysis was carried out to evaluate the impact of the storage system and of the main operating parameters on the plant performance and on the levelized cost of electricity (LCOE).

Nomenclature

ASU	Air separation unit
CaL	Calcium looping
CaLPP	CaL power plant
CCA	Cost of CO_2 avoided
CPU	CO_2 purification unit
LCOE	Levelized cost of electricity
PCPP	Pulverized coal power plant

2. Plant description

The conceptual plant configuration, studied in this work, is shown in Fig. 1, where the operating conditions of the carbonator and calciner are decoupled by the storage system. This configuration has been discussed in details by Astolfi et al. [15].

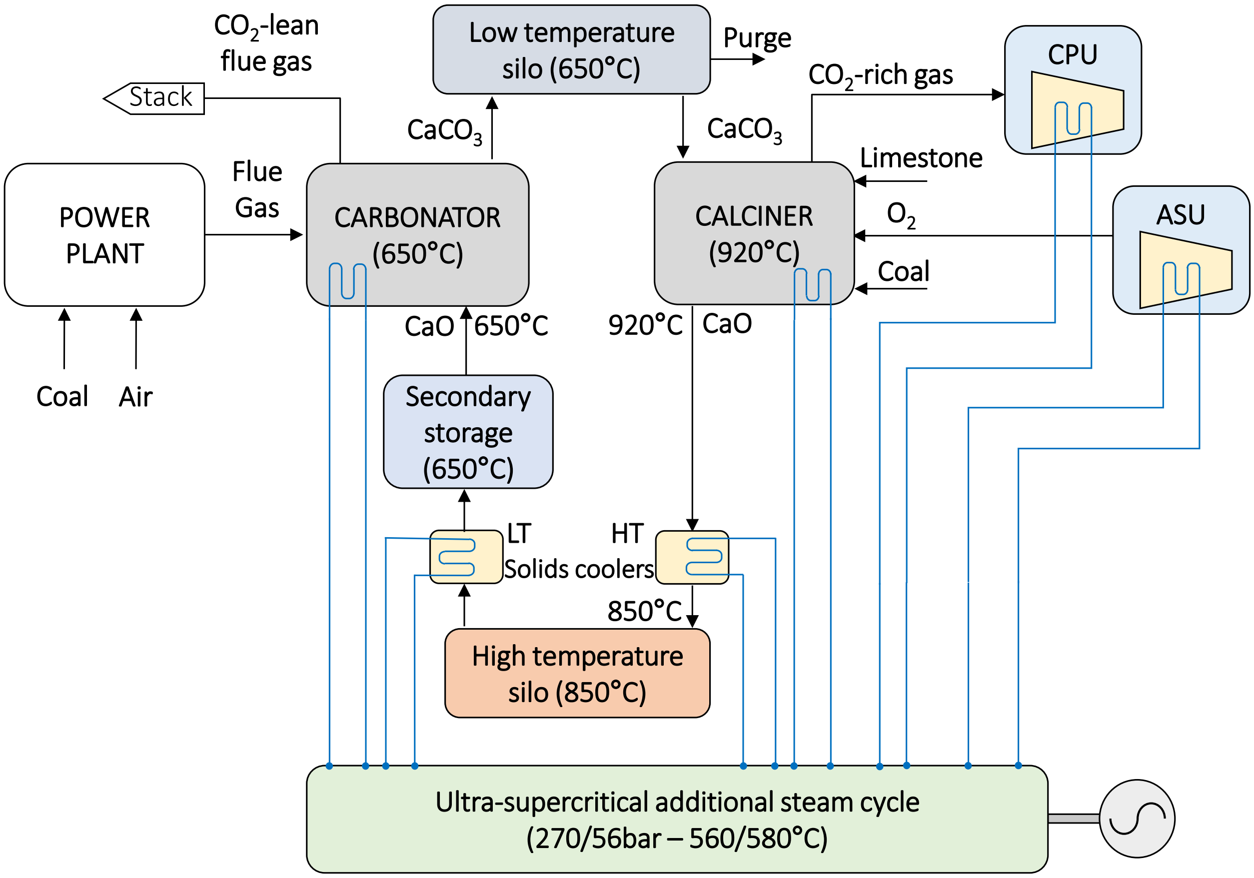

Fig. 1 Conceptual configuration of highly flexible CaL system coupled to coal-fired power plant

The flue gases leaving the pulverized coal power plant (PCPP) are treated in the carbonator, where a large fraction (around 90% in nominal conditions) of the CO_2 is captured by the carbonation reaction ($CaO+CO_2 \rightarrow CaCO_3$). The carbonated solids are fed to the calciner, which is a refractory-lined CFB reactor operating at 920°C, where $CaCO_3$ is converted back to CaO by releasing a concentrated stream of CO_2. Heat needed for the calcination reaction and for heating the solids to calcination temperature is provided by coal oxyfuel combustion. The high purity oxygen (95%vol.) for oxy-combustion is produced in a cryogenic air separation unit (ASU). The calciner off gas is cooled to 350°C in a convective pass. Part of this gas is recirculated to the calciner and the rest cooled in medium and low-temperature heat recovery sections, where water and oxygen are preheated. The CO_2-rich gas is then compressed and purified in a CO_2 purification unit (CPU).

The carbonator is designed as a 20 m-high cooled reactor operating at 650°C directly connected to the PCPP. This reactor has been calculated assuming a gas superficial velocity of 5 m/s, a solids inventory of 1000 kg/m^2, a fresh sorbent make-up ratio (F_0/F_{CO2}) of 0.10 and a sorbent circulation rate (F_{Ca}/F_{CO2}) of 7.0, ensuring a CO_2 capture efficiency in the carbonator of 90%, according to the model described in [17]. Since this reactor is directly connected to the PCPP, it must be sized at its peak load and it must follow its load during the day. On the other hand, the thermochemical energy storage system allows to design the calciner island (i.e. calciner, ASU and CPU) on the average load of the PCPP, instead of the peak load, thus allowing to downsize and reduce the cost of these components compared to a standard CaL case without storage, where the carbonator and calciner are directly connected [18–21].

3. Method

The process evaluation has been initially performed by defining the PCPP coupled to CaL system with and without storage system and calculating mass and energy balances at nominal condition with process simulation software [22] supported by a carbonator model [17]. The economic model of the PCPP integrated with the CaL system was developed using the economic functions presented in [23–25]. The simulations were carried out with 1-hour time step over one week. Coal and $CaCO_3$ consumption, total electricity generation and CO_2 emissions were calculated on an annual basis. The economic analysis allowed to calculate the total plant cost, the LCOE and the cost of CO_2 avoided (CCA). Finally, for a given production plan of the PCPP, techno-economic optimization was carried out by varying the size of the calciner and the storage system.

Once the storage system was designed on the average daily load of PCPP, each heat exchanger was sized in terms of surface and mass of steel, and the partial load performance of the CaL power plant (CaLPP) was evaluated using the commercial software Thermoflex® [26] for several off-design conditions, representing typical plant operating conditions. All the analyses were carried out taking into account (i) the different boundary conditions for each case investigated; (ii) the off-design constraints of each component; (iii) the part-load operation strategy of the components, to ensure the feasibility of the solutions in terms of pressures and temperatures of steam. In order to analyze the potential of the system, it was also considered the case of a secondary storage that allows to decouple the operation of solids heat exchangers from the rest of the system. In this way, it is possible to further increase or reduce the power output and improve the energy trading on the secondary market.

The analysis was then concluded by evaluating the ability of the FlexiCaL system to: (i) operate in a stable way at all load levels, (ii) follow the load changes of the PCPP, and (iii) possibly generate some additional power for brief time intervals, to provide ancillary services such as primary frequency control. To this purpose, a dynamic model of the plant with storage system was built, using the Modelica language [27] and existing reusable component library [28], adding new components for the CaL process. The model comprises the carbonator unit (reactor and convective pass), the calciner convective pass, the solid coolers and the entire steam-side of the plant that supplies extra power besides the PCPP production.

4. Results and discussion

Thanks to the storage system, the calciner line of the FlexiCaL plant is sized on the average weekday load, with a reduction of about 20% of its cost compared to a baseline CaL plant, with a consequent 4-5% reduction in the specific total capital cost of the whole plant.

As shown in Fig. 2 left, the minimum LCOE is obtained for a storage system designed on the weekly cycle of the PCPP, but with very large silos (5 times the volume of the carbonator). The sizing of the storage system on the daily cycle leads to a slightly higher LCOE, but logistically better silos design (about 2.5 times the volume of the carbonator). The selected system with storage shows a CCA of about 31 €/t_{CO2}, about 16% lower than the case without storage (Fig. 2 right).

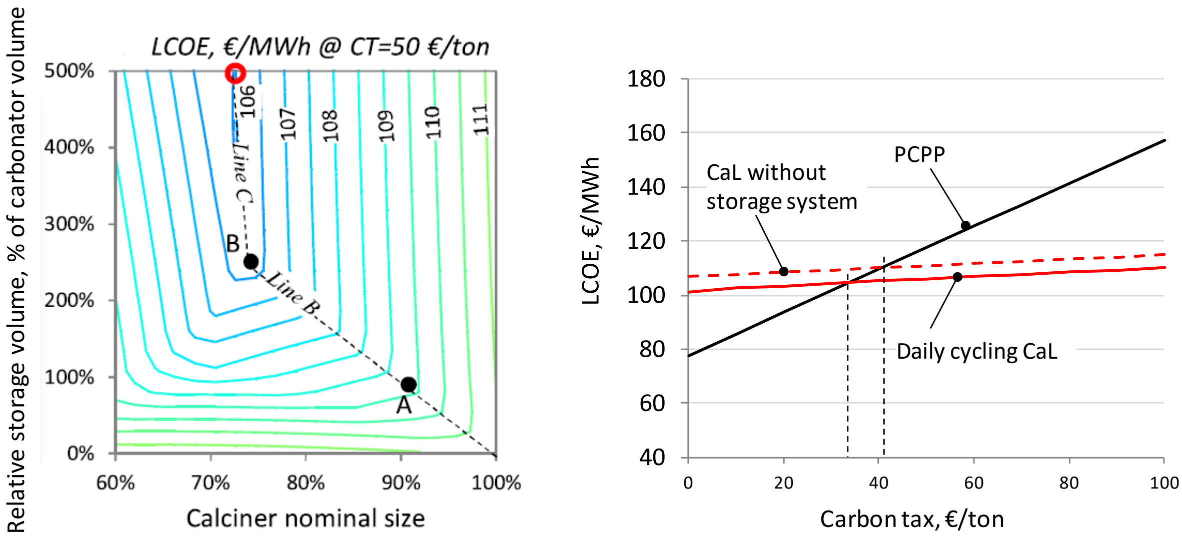

Fig. 2 (left) LCOE as a function of calciner size and the total storage volume; (right) LCOE vs carbon tax for the PCPP (solid black line), the CaL system without storage system (dashed red line) and designed on the daily cycling (solid red line)

As shown in Fig. 3 left, both the gross and net power of the CaLPP decrease almost linearly with the load of the PCPP, in both cases with and without storage. At nominal load, both of these quantities are higher for the baseline CaL case without storage (P_{gross} 642 vs 581 MW_e, P_{net} 376 vs 370 MW_e) while, at minimum load, they are higher for the FlexiCaL case with storage system (P_{gross} 262 vs 149 MW_e, P_{net} 351 vs 163 MW_e). Therefore, the case with storage is on average more efficient on a weekly basis than the case without storage. In fact, in the case with storage, thanks to the constant heat input from the calciner island, the CaLPP receives a more stable heat input, resulting in higher part-load efficiency than the case without storage, even when the PCPP load is low, as shown in Fig. 3 right.

Furthermore, the adoption of a secondary storage allows increased operativity of the flexible system on the balancing market, with variation of +2% (i.e. +20 MW_e for the assumed plant size) power output compared to the nominal load and -12.8% (i.e. -54 MW_e) power output compared to the minimum load.

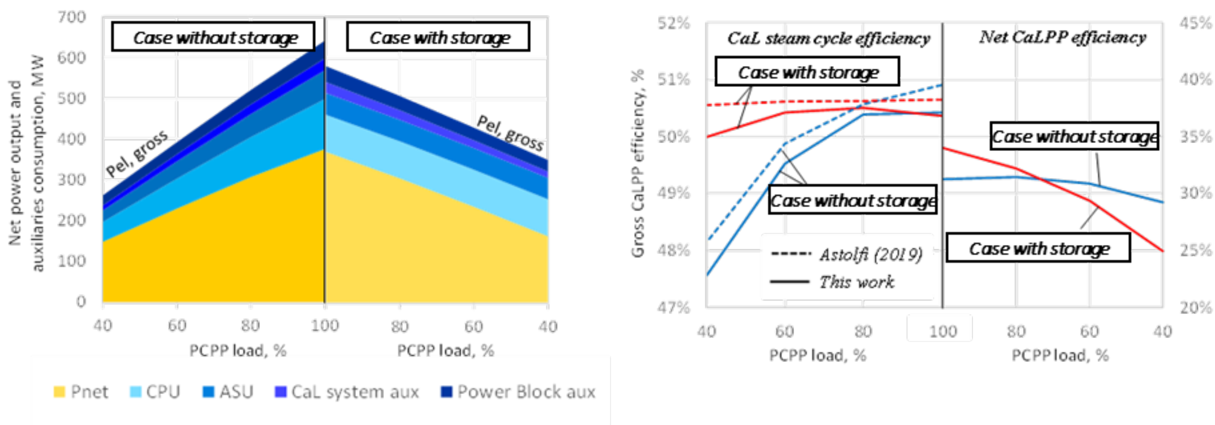

Fig. 3 (left) power output and auxiliary consumption; (right) CaL steam cycle and net CaLPP efficiencies vs. PCPP load. Steam cycle efficiency curves from Astolfi et al.

Based on the CaLPP design data, the dynamic model of the system was developed in Modelica. The model allowed to analyse the plant dynamics and to design a simple control strategy, based in part of decentralized PID control, and in part on feed-forward actions. The performance of the control system was then tested in three scenarios. In the first one, the CaL plant follows a load change from 100% to 60% and back to 100%, with a ramping rate of 1%/min; it was demonstrated that the simple proposed control strategy can control all the important process variables within acceptable limits; for example, Fig. 4 shows the superheater outlet temperatures during the transient. In the second one, it was demonstrated that extra power can be produced within a few seconds and maintained for a few minutes by means of turbine bleed valve throttling, exploiting the heat stored in the feedwater train. In the third one, it was demonstrated how is it possible to provide some additional power in a relatively short time (40% within 40s and the remaining 60% within 300s) by boosting the hot CaO flow through the HT solid coolers.

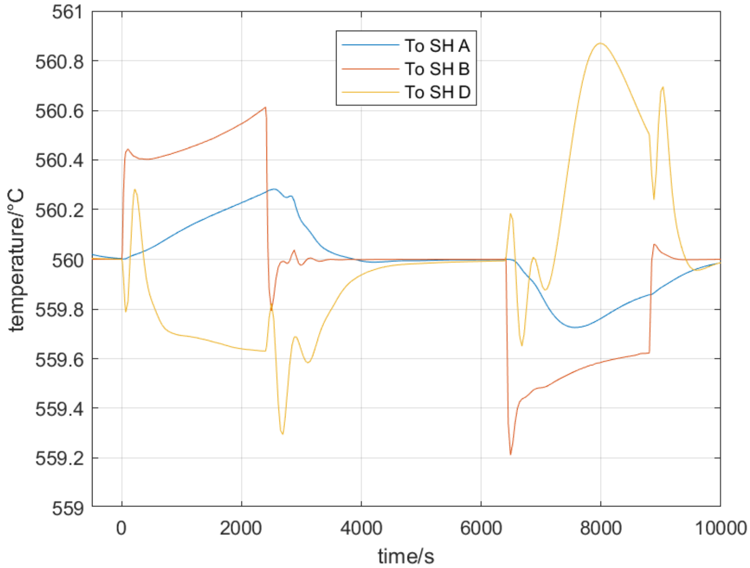

Fig. 4 Superheater outlet temperatures during the main PCPP load ramp changes

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