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Improved flexibility and economics of Calcium Looping power plants by thermochemical energy storage

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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 the CaL calciner line (calciner, ASU, CPU) on the average load of the power plant, while the carbonator can follow the load of the conventional power plant with air-blown boiler.

Preliminary economic optimization of the system has been performed for a specific case with power plant with weekday capacity factor of 76%, showing that: (i) significant saving (about 20%) of the capital cost of the calciner line can be achieved thanks to the storage system, resulting in a reduction of the total plant Capex of about 5%; (ii) the economic optimal design leads to large storage silos and calciner sized on the average plant load; (iii) reduction of the cost of electricity by almost 3% has been estimated for the best case compared to the baseline CaL case without storage, which can improve if production plan with lower capacity factor is expected.

Keywords: Calcium looping; CCS; CO₂ capture; flexibility; energy storage

1. Introduction

After the first formulation of the concept 20 years ago [1] and significant fundamental research on sorbent properties, reactors design and operation, process integration and economic analyses [2–5], Calcium looping (CaL) technology has been demonstrated in two different 1-1.7 MW_{th} scale facilities [6–8]. A new research field for CaL power plants is the exploitation of the calcined sorbent (CaO) as thermochemical energy storage medium, to improve the flexibility and reduce the cost of electricity of power plants in energy mixes with increasing share of intermittent renewable energy sources [9]. This paper, which derives from the research carried out in the RFCS project FlexiCaL [10], focuses on this topic.

When the capacity factor of power plants is reduced, which may occur in countries with high penetration of intermittent renewable energy sources, the cost of electricity increases, especially for capital intensive power plants. A significant share of the Capex of a CaL system (about 40%) is associated to the calciner line, composed by the calciner and its convective pass, the air separation unit (ASU) and the CO₂ compression and purification unit (CPU). So, the idea assessed in this paper, which was originally proposed for oxyfuel power plants [11,12] and for CaL

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plants [9], is to reduce the Capex associated to the oxyfuel calciner line by means of sorbent storage. According to this principle, the calciner line can be sized and operated at the average load of a target period (e.g. daily average), while sorbent storage allows managing the fluctuations associated to the cycling of the air-blown PC power plant (PCPP). This can be achieved by storing carbonated sorbent when the PCPP and the carbonator operate at a load higher than the average one and storing calcined sorbent when the PCPP and the carbonator operate at a lower load than the average one.

The scope of this work is to perform an economic optimization of a CaL system with solids storage and to find the economic optimal size of the storage vessels. In this paper, preliminary results are presented, which will be completed by coming comprehensive analysis with additional sensitivity analyses.

Nomenclature

ASU	Air separation unit
CaLPP	Calcium Looping power plant
CCA	Cost of CO ₂ avoided
CCE	CO ₂ capture efficiency
CPU	CO ₂ purification unit
LCOE	Levelized cost of electricity
PCPP	Pulverized coal power plant

2. Plant description

In Figure 1, a schematic of the CaL plant is shown. Flue gas from the PCPP (stream #1) is compressed by a fan (b), preheated to 300°C in a Ljungström gas-gas heater (c) and fed to the carbonator (d), which is a cooled circulating fluidized bed (CFB) reactor. After solids separation in a cyclone (g), carbonator off gas is first cooled to 350°C in a convective pass (f) and then in the gas-gas before being emitted at the stack (h). CaO-rich solids (2) are fed to the bottom of the carbonator and reacts with the CO₂ in the flue gases producing CaCO₃ through the exothermic carbonation reaction ($\text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3$).

Carbonated solids (7) are fed to the calciner (i), which is a refractory lined CFB reactor operating at 920°C, where CaCO₃ is converted back to CaO releasing a concentrated stream of CO₂. Heat for endothermic calcination reaction and for heating the solids to the calcination temperature is provided by the oxy-combustion of coal (8). High purity oxygen (9) for combustion is produced in a cryogenic air separation unit (ASU) and diluted with recirculated gas (12) at 350°C to achieve an O₂ concentration of 50%_{vol} at the calciner inlet. Calciner off gas (10) is cooled to 350°C in a convective pass (k) before gas recycle and to nearly ambient temperature in low temperature heat recovery sections (n, o, p), where water and oxygen are preheated. CO₂-rich gas is then compressed and purified in a CO₂ purification unit (CPU) and delivered to a pipeline for CO₂ transport and storage.

The CaL process has been calculated assuming a gas superficial velocity in the CFB reactors of 5 m/s, a solids inventory in the carbonator of 1000 kg/m², a fresh sorbent make-up ratio (F_0/F_{CO_2}) of 0.10 and a sorbent circulation rate ($F_{\text{Ca}}/F_{\text{CO}_2}$) of 7.0, ensuring a CO₂ capture efficiency in the carbonator of 90% according to the model described in [13]. In order to reduce accumulation of ash in the CaL loop, pulverized coal is assumed to be fed in the calciner [14], allowing to selectively separate the coarser sorbent particles from the fine ash in the cyclones, with different efficiencies (assumed equal to 99.9% and 90% for sorbent and ash respectively).

High temperature heat generated by the CaL process is recovered by the CaL power plant (CaLPP), which is also based on an USC steam cycle with reheat and live steam parameters of 560/580°C and 270/56 bar. CaLPP steam cycle also recovers low temperature heat from the intercoolers of the ASU and CO₂ compression trains, by condensate preheating.

From the heat and mass balance calculation of the baseline PCPP+CaL plant without solids storage, about 45% of the total fuel input is consumed in the calciner of the CaL plant. Net electric efficiency is 36.91%, corresponding to an efficiency penalty of 7.66% points with respect to the existing PCPP without CO₂ capture. Specific CO₂

emissions are 80.6 kg/MWh, 89.7% less than the benchmark plant without capture. As a result, the specific primary energy for CO₂ avoided (SPECCA) is 2.24 MJ_{LHV}/kgCO₂.

In the CaL system with solids storage, two silos are added in the plant flowsheet (drawn with dashed lines in Figure 1). The high temperature silo stores calcined solids from the calciner. The low temperature storage collects carbonated solids from the carbonator outlet at 650°C. Thanks to this storage, the load of the calcination line and of the carbonator line can be decoupled, i.e. the calciner can produce a lower flow rate of regenerated sorbent than the instantaneous requirement of the carbonator by emptying the hot storage and vice-versa.

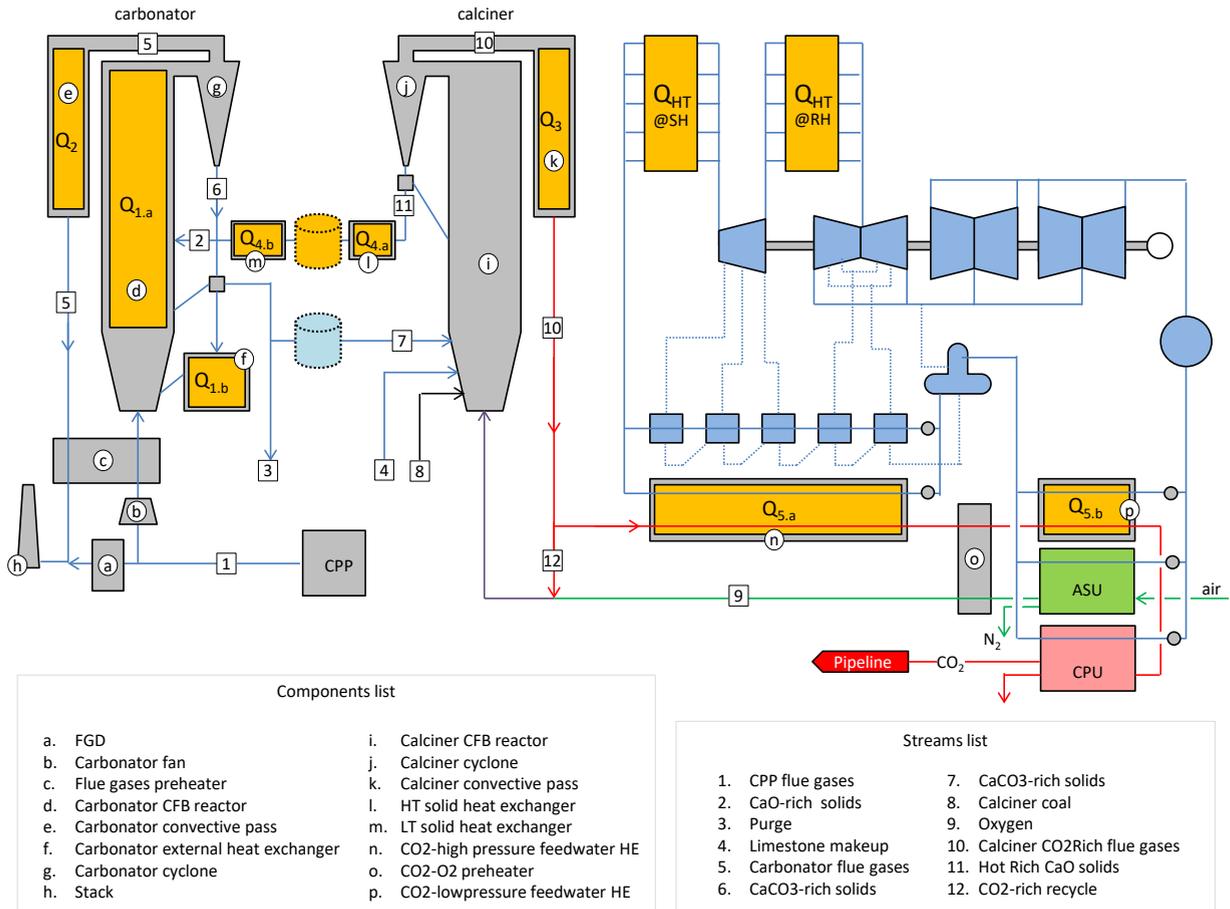


Figure 1. Calcium looping plant for CO₂ capture from an existing PCPP. Silos for solids storage are drawn with dashed lines.

In Figure 2, a representative trend of significant variables during a given operation period is shown for a CaL system with the calcination line with a size equal to 75% of the reference CaL system without storage. The following operating modes can occur:

1. The load of the PCPP is lower than the maximum load of the calciner, therefore the flow rate of hot regenerated sorbent produced in the calciner is more than the flow rate of CaCO₃-rich sorbent formed in the carbonator. The following two conditions may occur under such circumstances:
 - 1a. The high temperature storage is full and the storage capacity of calcined sorbent is completely exploited (Figure 2b): the load of the calcination line reduces (Figure 2a) to match the carbonator load and produce the exact amount of calcined sorbent needed for CO₂ capture in the carbonator.
 - 1b. The high temperature silo has storage capacity available: the calcination line operates at its design load Figure 4a) and calcined sorbent is accumulated in the HT silo, while carbonated sorbent is removed from the LT silo (Figure 4b).

2. The load of the PCPP is higher than the maximum load of the calciner (Figure 4a), therefore the flow rate of hot regenerated sorbent produced in the calciner is less than the flow rate required in the carbonator for CO₂ capture. The following two conditions may occur under such circumstances:

- 2a. The high temperature storage is empty and the low temperature storage is full (Figure 4b): the sorbent flow rate to the carbonator reduces, matching the sorbent flow rate produced in the calciner. In this condition, CO₂ emissions increase and CO₂ capture efficiency reduces (Figure 4c).
- 2b. The low temperature silo has storage capacity available: the carbonator and the calciner operate at their design load (Figure 4a), calcined sorbent is extracted from the HT silo while carbonated sorbent is accumulated in the LT silo (Figure 4b).

3. Methodology

A model of the integrated PCPP+CaL plant with solids storage is developed in Excel and Visual Basic to perform annual simulations. Simulations are carried out with 1-hour time step over one week and results are prorated for the whole year considering annual availability of 90% corresponding to 47 weeks of operation. Identical weeks have been considered, assuming an average daily load of the PCPP of 76% in the weekdays and of 50% in the weekend. Coal and CaCO₃ consumption, total electric energy output and CO₂ emission are calculated on a yearly basis. The mass and energy balance of the plant at part-load has been calculated with a simplified approach, by correcting the nominal efficiency of the steam cycle with: (i) a first parameter taking into account the different proportions of high temperature heat (Q_1, Q_2, Q_3, Q_4 in Figure 1) and low temperature heat (Q_5, Q_{ASU}, Q_{CPU}) inputs to the steam cycle and (ii) a second parameter taking into account the reduced efficiency of the steam cycle at part load.

An economic model has been also defined to estimate the capital and operating costs of the system and the levelized cost of electricity. Capital costs are estimated with exponential scaling methodology, using data from NETL/DOE reports [15–17], Thermoflex software and personal communications with industrial manufacturers.

Economic analysis allows calculating the levelized cost of electricity (LCOE) and the cost of CO₂ avoided (CCA). For a given production plan of the PCPP, provided as input, techno-economic optimization can be carried out by grid search method by varying the size of the calciner and of the storage system.

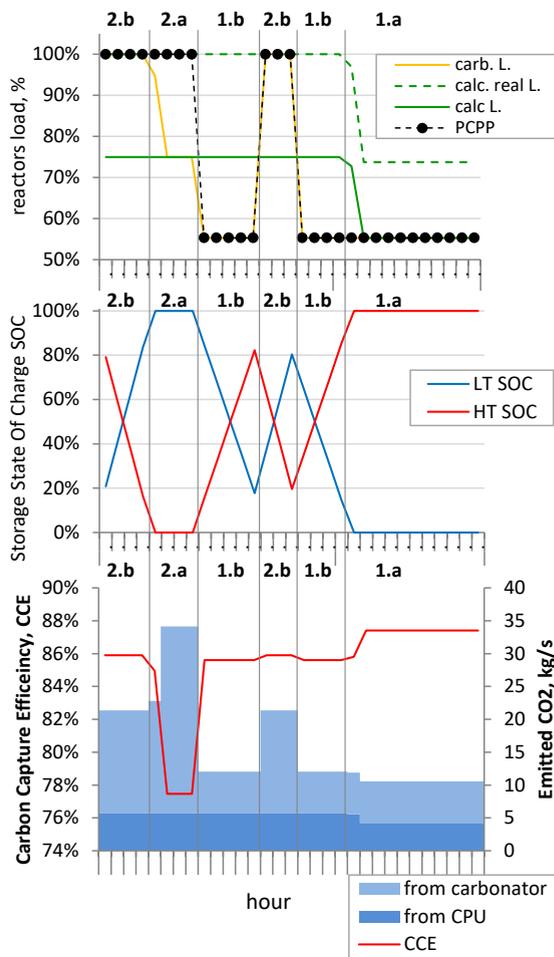


Figure 2. Representative quantities during the possible operating modes of the CaL system with solids storage: a) PCPP, carbonator and calciner load b) State Of Charge of hot and cold storage vessels, c) CO₂ emissions and CO₂ capture efficiency

4. Results and discussion

If storage is adopted and the calciner line is sized on the average weekday load, a reduction of about 20% of the cost of the calciner line (calciner, convective pass, ASU and CPU) was estimated, compared to the baseline CaL plan without solids storage. The specific capital cost reduction of the whole PCPP+CaL plant reduces by about 5%.

In Figure 3, the variation of the LCOE compared to the baseline CaL plant without solids storage, as function of the calciner nominal size and of the relative storage volume is shown. Relative storage volume is defined as the ratio between the total volume of the two silos and the volume of the carbonator.

Based on this figure, the following considerations can be done:

- The economic optimal design of the system involves storage silos with large total volume (about four times the volume of the carbonator) and size of the calciner line close to the average weekday load. This results from the much lower cost of the silos compared to the calcination line equipment. The maximum size of the solids storage system may however be limited by logistical, site-specific issues.
- With the optimal system design, a reduction of the LCOE of almost 3% has been obtained compared to the baseline case. Lower LCOE can be obtained for lower capacity factors, where the competitiveness of the CaL system with solids storage will increase.

Acknowledgements

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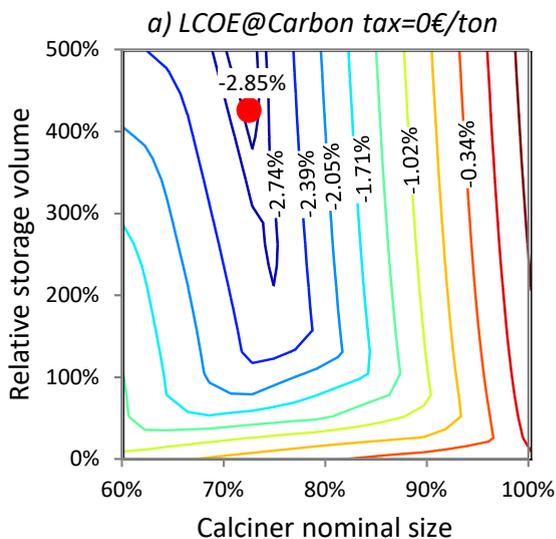


Figure 3. Variation of the LCOE compared to the baseline CaL plant without solids storage, as function of the calciner nominal size and of the relative storage volume (total volume of the two silos compared to the volume of the carbonator).

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