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Integration of a Thermochemical Energy Storage System in a Rankine Cycle Driven by Concentrating Solar Power: Energy and Exergy Analyses

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Abstract:

This paper proposes and investigates novel concepts on the integration of a thermochemical energy storage (TCS) system in a concentrating solar power (CSP) plant. The TCS material used is calcium oxide reacting with water and the power cycle studied is a Rankine cycle driven by CSP. Firstly, three integration concepts on the coupling of the TCS system with the Rankine cycle are proposed, including the thermal integration concept, the mass integration concept and the double turbine concept. Then, an energy analysis is performed to determine and compare the theoretical overall energy efficiency of the proposed concepts. After that, an exergy analysis is also carried out for the selected integration concepts so as to evaluate and compare the overall exergy efficiency of the installation with TCS integration.

The results show that the turbine integration concept has the highest overall energy efficiency (0.392), followed by the thermal integration concept (0.358) and the mass integration concept (0.349) under ideal conditions with 11 h of charging and 13 h of discharging. The energy storage density using calcium hydroxide as the storage media is estimated to be about 100 kWh_{el}·t⁻¹. Exergy analysis results also indicate that the turbine integration concept seems to be the best option under the tested conditions.

Keywords: Thermal energy storage (TES); Thermochemical; Rankine cycle; Concentrating solar power (CSP); Integration concept; Calcium hydroxide; exergy analysis

Declarations of interest: none

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1. Introduction

The increasing energy demand, the environmental protection issue and the national energy independence all over the world call for researches aiming at more efficient use of renewable energy such as solar energy. Among various solar energy technologies, the Concentrating Solar Power (CSP) plants are expected to play an important role in the energetic scenarios owing to its advantages in terms of high efficiency, low operating cost and good scale-up potential [Cáceres 2013; Zhang 2013; Dunham 2014; Balghouthi 2016]. According to IRENA [2016], the CSP deployment would reach 44 GW in the reference scenario (Remap 2030). It is estimated that the CSP would contribute up to 11.3% of the electricity production in the year 2050, with 954 GW of installed capacity [IEA 2014; del Río 2018].

One of the advantages of CSP technology is the possibility of integrating a thermal energy storage (TES) function, permitting the production of electricity any time when it is the most needed and valuable, whether during the peak hours, nights, or cloudy intervals [Zhang 2016; Dowling 2017; Alva 2018]. To do this, a TES system at high temperature should be designed and installed properly between the solar field and a power cycle. Although adding a TES system usually increases the investment cost of the CSP plant, it improves significantly its adaptability and dispatchability. CSP plants (existing or under construction) having TES systems at high temperature are summarized in recent reviews [e.g., Tian 2013; Kuravi 2013; Pelay 2017a; b]. The storage capacity in terms of discharging time is generally between 3 to 8 hours, and recently up to 15 hours (Gemasolar, Spain) aiming at round-the-clock electricity production driven by solar energy [Dunn 2012].

The most commonly used storage technology is based on the sensible heat storage, in which the thermal energy is stored/released by raising/decreasing the temperature of a storage material. This technology is the most mature and deeply investigated, with a wide variety of both liquid (e.g., pressurized water, molten salt, mineral oil, etc.) and solid (e.g., sand, rock, cast iron, etc.) materials being used for CSP applications [Gil 2010; Tiskatine 2017]. Some recent developments are also reported, such as on the use of industrial wastes or by-products [Ortega-Fernández 2015; Gutierrez 2016], chloride salts [Myers 2016], lithium coupled with molten salts [Cabeza 2015], or solid particles [Zhang 2017a; Calderón 2018]. However, their limited energy density (usually between 60 kWh_{th}·m⁻³ (200 °C-300 °C) for sand, rock and mineral oil, and 150 kWh_{th}·m⁻³ for cast iron (200 °C-400 °C) [Fernandes 2012]) increases significantly the size of TES systems. Latent heat storage materials such as Phase Change Materials (PCMs) are also proposed for CSP applications owing to their higher storage capacity [Gil 2010; Pitié 2013; Sharma 2015; Zhang 2017b; Chirino 2018]. But their small thermal conductivity (commonly 0.2 - 0.8 W·m⁻¹·K⁻¹) usually limits the heat transfer, resulting in very slow charging and discharging processes [Nithyanandam 2015]. Some new advances on the effective encapsulation of PCMs [Zhang 2014; Parrado 2015] as well as the enhancement of thermal conductivity are summarized in recent papers [Xu 2015; Liu 2016; Alva 2018].

Besides the sensible and latent heat storage technologies, the thermochemical storage (TCS) is a promising solution for its highest storage capacity (up to 10 times greater than latent storage [Pardo 2014a]), wide accessible temperature range and long storage duration at ambient temperature [Prieto 2016]. This technology is mainly based on reversible chemical reactions (e.g., gas-solid) involving absorbing or releasing a large amount of reaction heat:

The charging stage uses solar energy for the decomposition of $\{S, nG\}$ associated with the condensation of the gas while the discharging stage brings the solid and gas into contact for heat release by the exothermic reaction. TCS material candidates at a medium or high temperature (300–1000 °C) for CSP application include metallic hydrides, carbonates system, hydroxides system, redox system, ammonia system and organic system [Kuravi 2013]. Their main characteristics, advantages/disadvantages and experimental feedback are reviewed and summarized in [Pelay 2017a].

Beyond the testing of new TCS materials [e.g., Deutsch 2017; Valverde 2017; Bagherisereshki 2018] and proper reactor designs [e.g., Álvarez De Miguel 2013; Schmidt 2017; Wokon 2017; Pan 2017] and pilot scale testing [Tescari 2017a; b], the TCS system must be coupled in a proper way with the vapor generator of the power cycle (e.g., Rankine cycle) in a CSP plant. However, relatively little attention seems to be given to this integration issue. Recently, Cabeza et al. [2017] proposed a new concept of consecutive TCS reactions (either one cycle or two coupled cycles) and its implementation in CSP plants, with the purpose of eliminating reversibility problems and therefore improving the overall efficiency. Ortiz et al. [2017] proposed possible integration schemes of calcium looping (CaO-CaCO₃) for power production by direct or indirect means. Their results showed highest plant efficiencies up to 45–46% using a closed carbon dioxide Brayton power cycle. Noteworthy is the very recent work of Schmidt and Linder [2017], in which an integration option of the TCS system into a CSP plant has been proposed and analyzed. Their analysis showed that a storage efficiency up to 87% might be reached when the required steam production during discharge is thermally integrated into the Rankine steam cycle.

From the above literature survey, one may find that the research on how to integrate the TCS system to the power cycle of the CSP plant is insufficient. Actually, it is an essential issue for the implementation and application of TCS technology, calling for deeper and extensive investigations. The main objectives and originalities of this paper are therefore threefold: (1) to propose various novel integration concepts of TCS system into the Rankine cycle driven by CSP, for both charging and discharging stages; (2) to perform a detailed energy analysis of the proposed integrated concepts and to evaluate impacts of various influencing factors on the overall energy efficiency of the CSP plant; and (3) to discuss and compare the second law efficiency of the proposed integration concepts through an exergy analysis.

This paper is organized as follows. In section 2, the selected gas-solid reaction and material are briefly introduced and the key issue on how to manage the water vapor from the TCS reactor is

identified. Three novel TCS integration concepts (thermal integration, mass integration and turbine integration) are proposed and described in section 3. The performance modelling of the three integration concepts based on energy analysis is presented and discussed in section 4. Section 5 provides an exergy analysis of the integration concepts. Finally, main conclusions and future work are summarized in section 6.

2. Thermochemical reaction and its operation

In this section, we briefly introduce the selected gas-solid reaction and materials, as well as the identified key issues for the integration of TCS unit into the Rankine cycle.

2.1. Reaction used as TCS storage media

Various hydrates and hydroxides have been proposed as potential TCS materials, as summarized in some latest papers [e.g., Aydin 2015; André 2016; Liu 2016; Prieto 2016; Pelay 2017a; Zhang 2016]. Among them, the CaO/H₂O couple has been deeply studied with a great amount of experimental feedback [e.g., Azpiazu 2003; Michel 2012; Schaubé 2013a; b; Pardo 2014b; Yan 2016; 2017; Sakellariou 2017]. It is found to be a pertinent candidate as TCS material for CSP application with various features, including for high-temperature use (450~600 °C), good reversibility, operating pressure close to the atmospheric pressure, low material cost, environment-friendly and high energy density (about 3 GJ·m⁻³), etc. As a result, it is selected *a priori* for this conceptual study. The reaction formula is shown in Eq. (2).

For a reaction temperature at 500 °C, the equilibrium pressure equals to 0.1 MPa (1 bar). Under this condition, the reaction heat (Δh_R) is found to be 104 kJ·mol(CaO)⁻¹=5774.56 kJ·Kg(H₂O)⁻¹ [Schaube, 2011].

2.2. Management of the water vapor from the TCS reactor

The integration of TCS reactor in a solar power plant is a so-called passive concept in which the storage medium (CaO) is kept motionless and heated-up or cooled-down by the circulation of a heat transfer fluid (HTF) [Pelay 2017a]. When used as TCS material in a CSP plant, water vapor at high temperature produced by the decomposition during the charging stage should preferably be condensed to saturated liquid and stored in a separate reservoir at ambient pressure (0.1 MPa). Hence the required volume for the storage unit is greatly reduced. Meanwhile, the superheated steam (500 °C) contains a significant amount of thermal energy, a part of which is possible to be recovered so as to increase the overall efficiency of the whole system, as shown in Fig. 1a. Instead of condensing the water vapor directly at the outlet of the TCS reactor by an additional condenser, alternative energy valorization options are actually available, either to produce extra electricity through an additional turbine or to preheat the steam of the Rankine cycle.

During the discharging stage, the exothermic synthesis happens when CaO and water vapor are in contact. Supposing that the CSP plant is driven only by solar energy, it is necessary to find a heat source to vaporize water stored previously in the liquid form through an evaporator, as shown in Fig. 1b. This heat source should have a higher temperature than that of liquid water to be evaporated (e.g., 100 °C at 1 bar).

As a result, the positioning of TCS reactor in the whole system and the way of managing water vapor are key issues for an energy-efficient integration of TCS unit into the Rankine cycle. Different integration concepts shown in the following section will highlight the options proposed for these key points.

Figure 1. Management of water vapor as a key issue for energy-efficient TCS integrations into the Rankine cycle. (a) charging stage; (b) discharging stage.

3. TCS integration concepts

In this section, we shall firstly present a conventional regenerative Rankine cycle driven by CSP without storage as a reference case [Moran, 2003]. Then, three novel integration concepts of TCS unit into the Rankine cycle are proposed and described, named as thermal integration, mass integration and turbine integration.

3.1. Conventional Rankine cycle without TES

Figure 2 shows a representative schematic view of the conventional regenerative Rankine cycle driven by CSP. The main components in this cycle include a steam generator, a turbine, a condenser, an open feedwater heater and pumping and piping accessories. Solar energy is firstly absorbed by the solar receiver at the top of solar tower and transferred to the HTF. This amount of thermal energy is then utilized in converting water contained in generator (point 6) into superheated steam at the suitable pressure and temperature (point 1). The superheated steam then flows through

the turbine. While doing work in the turbine, the pressure of steam is reduced. The steam leaving the turbine (point 2) passes through the condenser and is condensed into liquid at low pressure for recycling. An open (or direct-contact) feedwater heater serves as a mixing chamber where the steam extracted from the turbine (point 2') mixes with the feedwater leaving the pump (point 4). Ideally, the mixture leaves the heater as the saturated liquid at the heater pressure (point 5). This steam regeneration configuration usually enhances the thermal efficiency of the Rankine cycle at the cost of lower electricity production rate due to steam extraction.

Figure 2. Schematic view of a conventional regenerative Rankine cycle driven by CSP without TES [Moran 2003]

3.2. Concept 1: Thermal integration (Thermal Int.)

The Thermal Int. concept is shown in Fig. 3. The added TCS unit comprises of a TCS reactor, a water reservoir, a second condenser and two heat exchangers. There are three fluid circuits in the integrated system: the solar circuit as energy supply, the principal Rankine circuit for power generation and the TCS circuit for energy storage. Note that although the working fluids are identical as pure water or steam, the principal Rankine circuit and the TCS circuit are independent of each other without direct mass contact or exchange. Hence, this concept is named as Thermal Int. because there is only heat exchange between the TCS circuit and the Rankine circuit.

During the charging stage (Fig. 3a), the HTF (e.g., pressurized air or molten salt) from the solar tower offers the steam generator sufficient amount of thermal energy to run the principal Rankine cycle. Meanwhile, it heats the Ca(OH)_2 reactive salts in the TCS reactor up to 500 °C at 1 bar to initiate the decomposition. The water vapor generated in the TCS reactor is partially condensed in the heat exchanger 1, then completely condensed in the condenser 2 and finally be stored as the saturated liquid (100 °C, 1 bar) in a separate water reservoir. The sensible and latent heat released by the water vapor will be used to preheat the working fluid of the principal Rankine circuit via heat exchanger 1. The CaO reaction product (and subsequent reactant) remains in the TCS reactor. This integration concept permits the steady operation of the principal Rankine circuit for power production and the TES in parallel.

During the discharging stage (Fig. 3b) when solar energy is not available, the liquid water stored in the reservoir is firstly heated up and vaporized by the high temperature steam extracted from the turbine of the principal Rankine circuit via the heat exchanger 2. The saturated vapor (100 °C, 1 bar) enters then into the TCS reactor and reacts with the CaO for the synthesis of Ca(OH)₂. The heat released from this exothermic reaction in the TCS reactor runs the principal Rankine cycle steadily under the same operational conditions (temperature, pressure and steam mass flow-rate) as during the charging stage. In this case, the TCS reactor also serves as the steam generator.

The positive aspect of this concept is that it is technically simple to implement whereas the disadvantage is that a separate reservoir is required to store the liquid water resulting from the TCS reaction, implying a higher capital cost.

Figure 3. Schematic view of the thermal integration concept. (a) charging stage; (b) discharging stage [Luo 2016].

3.3. Concept 2: Mass integration (Mass Int.)

The Mass Int. concept is shown in Fig. 4. Compared to the conventional Rankine cycle as shown in Fig. 2, a TCS unit is added including a TCS reactor, a second condenser, a throttle valve, a third pump and two heat exchangers. There are still three fluid circuits in the installation: the solar circuit, the principal Rankine circuit and the TCS circuit. But different from the above-mentioned Thermal Int. concept, the principal Rankine circuit and the TCS circuit are coupled and share the same working fluid (pure water or steam) with mass exchange. As a result, this concept is named as Mass Int.

During the charging stage (Fig. 4a), the water vapor generated in the TCS reactor is partially condensed in the heat exchanger 1, depressurized by the throttle valve, completely condensed in the condenser 2 and finally stored as the saturated water (41 °C, 0.008 MPa) in the water reservoir shared with the principal Rankine circuit. The sensible and latent heat released by the common

water vapor will be used to preheat the working fluid of the Rankine cycle via the heat exchanger 1 located upstream of the steam generator.

During the discharging stage (Fig. 4b), the liquid water stored in the reservoir will be pressurized by pump 3 and then evaporated by exchanging heat with the extracted steam via the heat exchanger 2. The saturated vapor (100 °C, 0.1 MPa) enters the TCS reactor and reacts with the CaO reactive salts stored inside. Again, the TCS reactor serves as the steam generator to run the Rankine cycle steadily under the same operational conditions as during the charging stage.

The Mass Int. concept seems less interesting than the Thermal Int. concept because more components are required for the TCS unit, implying higher capital costs. Moreover, the mixing of working fluids between the principal Rankine circuit and the TCS circuit could bring further technical difficulties because of the massive fines formation. An efficient filtration system (e.g., sintered metal fiber or ceramic filters [Smolders 2000]) may have to be implemented for dust removal to prevent the eventual damage of the turbine. A special design of the TCS reactor coupled with metal filter may also be considered [Schmidt 2017].

Figure 4. Schematic view of the mass integration concept. (a) charging stage; (b) discharging stage [Luo 2016].

3.4. Concept 3: Turbine integration (Turbine Int.)

Figure 5 presents a schematic view of the Turbine Int. concept. Additional components of the TCS unit include a TCS reactor, a second turbine, a second condenser, a third pump, a water reservoir and a heat exchanger. The principal Rankine circuit and the TCS circuit are completely independent of each other during the charging stage (no heat or mass exchange) and thermally coupled during the discharging stage.

During the charging stage (Fig. 5a), the water vapor generated in the TCS reactor passes through the turbine 2, condensed in the condenser 2 and finally stored as the sub-saturated water

(41.5 °C, 0.1 MPa) in a water reservoir. A part of its thermal energy is valorized as power production via the second turbine. The integration concept for the discharging stage (Fig. 5b) is the same as that of Thermal Int. concept, in which water stored in the reservoir will be evaporated by exchanging heat with the extracted steam via the heat exchanger 2.

The main feature of this concept is the additional power production in parallel of the one provided by the principal Rankine circuit during the charging stage. However, the implementation of this second turbine, which is partially used only during the charging stage, implies higher capital cost for the CSP plant.

Figure 5. Schematic view of the turbine integration concept. (a) charging stage; (b) discharging stage [Luo 2016].

4. Energy analysis of different TCS integration concepts

This section presents a detailed energy analysis of three proposed concepts of TCS integration into the Rankine cycle of a CSP plant. Firstly, the performance modelling of each individual components and of the system as a whole will be described under ideal operating conditions (as indicated in Fig. 1). Then a parametric study on various influencing factors will be performed so as to identify appropriate functioning points for different integration concepts towards performance comparison.

4.1. Performance modelling

The performance analysis is based on the conservation of mass and energy. To simplify the calculation, the following assumptions are made, while the influences of certain factors will be discussed through the parametric study in the later section. Note that the solar receiver and the solar tower have not been included in the current analysis. It is supposed that the solar field provides

the required amount of thermal energy for the power production of the Rankine cycle and the TES during the charging stage.

- (A1) Steady-state operation;
- (A2) Isentropic compression and expansion processes ($\eta_{isen}=1$);
- (A3) Evaporation and condensation at constant pressure;
- (A4) Negligible heat loss; negligible pressure drop of piping system;
- (A5) During the charging, the water vapor at 500 °C and 0.1 MPa is released from the TCS reactor; during the discharging, the saturated vapor (100 °C, 0.1 MPa) is injected into the TCS reactor; 100% conversion rate of the TCS reactor ($\gamma=1$), no mass leakage during the storage;
- (A6) The power output rate from the turbine of the principal Rankine circuit $W_{T1} = 100 \text{ MW}_{el}$.

Table I. Mass and energy conservation equations for the performance modelling of Rankine cycle with or without TCS integration.

	Component	Reference case	Thermal Int.		Mass Int.		Turbine Int.		Note
			charging	discharging	charging	discharging	charging	discharging	
Principal Rankine circuit	Turbine 1 (T1)		$T_{T1}^{in} = 480\text{ }^{\circ}\text{C}$, $P_{T1}^{in} = 8.0\text{ MPa}$; $P_{T1}^{out} = 0.008\text{ MPa}$; $P_{T1}^{ext} = 0.08\text{ MPa}$ $W_{T1,C(D)} = m_{Rankine,C(D)}[(h_{T1}^{in} - h_{T1}^{ext}) + (1 - y_{C(D)})(h_{T1}^{ext} - h_{T1}^{out})]$ (3) $\eta_{T1,C(D)} = \frac{h_{T1}^{ext} - h_{T1}^{in}}{h_{T1,isen}^{ext} - h_{T1}^{in}} = \frac{h_{T1}^{out} - h_{T1}^{ext}}{h_{T1,isen}^{out} - h_{T1}^{ext}}$ (4)						N1
	Condenser 1 (CON1)		$Q_{CON1,C(D)} = m_{Rankine,C(D)}(1 - y_{C(D)})(h_{CON1}^{in} - h_{CON1}^{out})$ (5) $P_{CON1}^{in} = P_{CON1}^{out}$						N2
	Pump 1 (P1)		$W_{P1,C(D)} = m_{Rankine,C(D)}(1 - y_{C(D)})(h_{P1}^{out} - h_{P1}^{in})$ (6) $\eta_{P1,C(D)} = \frac{h_{P1,isen}^{out} - h_{P1}^{in}}{h_{P1}^{out} - h_{P1}^{in}}$ (7)						N3
	Feedwater heater (FH)		$y_{C(D)}h_{FH}^{in1} + (1 - y_{C(D)})h_{FH}^{in2} = h_{FH}^{out}$ (8) $P_{FH}^{in1} = P_{FH}^{in2} = P_{FH}^{out}$ (9)	-	-	-	(8) (9)	-	
	Pump 2 (P2)		$W_{P2,C(D)} = m_{Rankine,C(D)}(h_{P2}^{out} - h_{P2}^{in})$ (10) $\eta_{P2,C(D)} = \frac{h_{P2,isen}^{out} - h_{P2}^{in}}{h_{P2}^{out} - h_{P2}^{in}}$ (11)						N4
	Steam generator (SG)		$Q_{SG} = m_{Rankine}(h_{SG}^{out} - h_{SG}^{in})$ (12) $P_{SG}^{in} = P_{SG}^{out}$ (13)	-	(12) (13)	-	(12) (13)	-	
TCS circuit	TCS reactor (R)	-	$\gamma Q_{R,C} = m_{TCS,C}\Delta h_R$ (14)	$Q_{R,D} = \gamma m_{TCS,D}(h_{R,D}^{out} - h_{R,D}^{in})$ (15)	(14)	(15)	(14)	(15)	N5
			$m_{TCS,C}H_C = m_{TCS,D}H_D$ (16) $Q_{R,C} = Q_{R,D} + m_{TCS,D}(h_{TCS,steam}^{500^{\circ}\text{C}} - h_{TCS,steam}^{100^{\circ}\text{C}})$ (17)						
	Condenser 2 (CON2)	-	$Q_{CON2} = m_{TCS,C}(h_{CON2}^{in} - h_{CON2}^{out})$ (18) $P_{CON2}^{in} = P_{CON2}^{out} = 0.1\text{ MPa}$ (19)	-	(18) $P_{CON2}^{in} = P_{CON2}^{out} = 0.008\text{ MPa}$ (20)	-	(18) (20)	-	
	Heat exchanger 1 (HX1)	-	$\frac{h_{HX1,Rankine}^{out}}{m_{TCS,C}}(h_{HX1,TCS}^x - h_{HX1,TCS}^y) + h_{HX1,Rankine}^y$ (21) $\frac{h_{HX1,TCS}^{out}}{m_{Rankine,C}}(h_{HX1,Rankine}^x - h_{HX1,Rankine}^y) + h_{HX1,TCS}^x$ (22)	-	(21) (22)	-	-	-	N6
	Heat exchanger 2 (HX2)	-	-	$m_{TCS,D}(h_{HX2,TCS}^{out} - h_{HX2,TCS}^{in}) =$	-	(23)	-	(23)	

				$y_D m_{Rankine,D} (h_{HX2,Rankine}^{in} - h_{HX2,Rankine}^{out})$ (23)					
Water reservoir (WS)	-		Saturated water at 0.1 MPa		Saturated water at 0.008 MPa		Sub-saturated water (41.5 °C) at 0.1 MPa		N7
Throttle valve (TV)	-	-	-	-	$h_{TV}^{in} = h_{TV}^{out}$ $P_{TV}^{in} = 0.1$ MPa; $P_{TV}^{out} = 0.008$ MPa (24)	-	-	-	
Pump 3 (P3)	-	-	-	-	-	$P_{P3}^{in} = 0.008$ MPa; $P_{P3}^{out} = 0.1$ MPa $W_{P3,C(D)} = m_{TCS,C(D)} (h_{P3}^{out} - h_{P3}^{in})$ (25) $\eta_{P3,C(D)} = \frac{h_{P3,isen}^{out} - h_{P3}^{in}}{h_{P3}^{out} - h_{P3}^{in}}$ (26)	-	-	
Turbine 2 (T2)	-	-	-	-	-	-	$P_{T2}^{out} = 0.008$ MPa $W_{T2} = m_{TCS} (h_{T2}^{in} - h_{T2}^{out})$ (27) $\eta_{T2} = \frac{h_{T2}^{out} - h_{T2}^{in}}{h_{T2,isen}^{out} - h_{T2}^{in}}$ (28)	-	
Overall energy efficiency of the installation	$\eta_o = \frac{W_{T1} - W_{P1} - W_{P2}}{Q_{SG}}$ (29)	$\eta_o = \frac{(W_{T1,C} - W_{P1,C} - W_{P2,C})H_C + (W_{T1,D} - W_{P1,D} - W_{P2,D})H_D}{(Q_{SG} + Q_{R,C})H_C}$ (30)		$\eta_o = \frac{(W_{T1,C} - W_{P1,C} - W_{P2,C})H_C + (W_{T1,D} - W_{P1,D} - W_{P2,D} - W_{P3,D})H_D}{(Q_{SG} + Q_{R,C})H_C}$ (31)		$\eta_o = \frac{(W_{T1,C} + W_{T2,C} - W_{P1,C} - W_{P2,C} - W_{P3,C})H_C + (W_{T1,D} - W_{P1,D} - W_{P2,D})H_D}{(Q_{SG} + Q_{R,C})H_C}$ (32)			N8
<p>N1: saturated steam at the turbine extraction; $y_C=0$ for Mass Int. concept.</p> <p>N2: $y_C=0$ for Mass Int. concept.</p> <p>N3: saturated water at the inlet of P1; $y_C=0$ for Mass Int. concept.</p> <p>N4: $T_{P2}^{in} = 41.6$ °C for the discharging stage of Thermal Int. and Mass Int.; saturated water for the rest of concepts.</p> <p>N5: H_C and H_D are the number of operating hours for charging and for discharging, respectively; γ is the conversion rate of the TCS reactor; Eq. (15) implies that a portion of reaction heat is consumed to heat the saturated vapor (100 °C 0.1 MPa) to the equilibrium temperature of reaction (500 °C 0.1 MPa).</p> <p>N6: X and Y are intermediate points located at the hot side (TCS) and cold side (Rankine) of the HX1, respectively; saturated steam at X point; $T_{HX1,TCS}^{out} - T_{HX1,Rankine}^Y = 5$ °C (pinch point of HX1).</p> <p>N7: no thermal losses during the storage period.</p> <p>N8: Q_{SG} and $Q_{R,C}$ are the amount of heat provided by the HTF; the solar field (solar receiver) is not included in the analysis.</p>									

Mass and energy conservation equations for the individual components and for the whole system of different concepts are listed in Table 1. Values of thermodynamic properties of water and steam are determined referring to NIST-JANAF Thermochemical Tables [Chase, 1998]. Detailed values of main status points of the Rankine cycle with or without TCS integration may be found in the supplementary material of this paper.

Following this modeling procedure, the global performance of three proposed integration concepts is analyzed and compared with that of conventional Rankine cycle without storage (reference case). The charging/discharging scenarios examined cover a large variety of operation possibilities, for the charging time (H_C) varying from 1 hour to 12 hours and the discharging time (H_D) varying from 0 hour to 13 hours.

Figure 6 shows the overall energy efficiency of the installation (η_o) for different integration concepts under the above-mentioned ideal operational conditions, for various charging (Fig. 6b) and discharging (Fig. 6a) scenarios. η_o is defined as the total net output work of the Rankine cycle (during charging and discharging) divided by all the energy absorbed from the HTF of the solar circuit (during charging), as indicated in Eqs. 29-32.

It can be observed from Fig. 6a that for a given charging time ($H_C=11$ h), the values of η_o with TCS integration are lower than that of the reference case ($\eta_{o,ref}=0.42$) without TCS. This can be explained by the loss of a part of the energy contained in the superheated vapor produced by the TCS reactor during the charging hours. A large part of the energy is recovered/valorized via the heat exchanger 1 (Thermal Int. and Mass Int.) and via the turbine 2 (Turbine Int.). But still, a small part is lost in the condenser 2. It can also be observed in Fig. 6a that the Turbine Int. has the highest η_o while the Mass Int. has the lowest. This difference becomes more important with the increasing number of discharging hours. Figure 6b shows that for a given discharging time ($H_D=12$ h), the η_o of all concepts of TCS integration increases when the number of charging hours (H_C) increases. It seems that a low H_D/H_C ratio is favorable to achieve high values η_o when TCS unit is integrated into the CSP plant.

Figure 6. Overall energy efficiency of the installation (η_o) for different integration concepts under ideal operational conditions. (a) different number of discharging hours ($H_c=11$ h); (b) different number of charging hours ($H_b=12$ h).

However, longer discharging shows clear advantages in terms of higher dispatchability and higher total power output. As shown in Fig. 7, the daily power output of Turbine Int. could reach 3010 MWh_{el} for 11 hours of charging and 13 hours of discharging (round-the-clock operation), which is augmented by a factor of 2.7 compared to that of the reference case without storage (only 11 hours daily production). The benefits of TCS integration into the CSP plant are therefore highlighted. In real world practice, the operation strategy of the TCS unit certainly deserves detailed investigations by taking various influencing factors into account (e.g., climate condition for charging hour, electricity demand profile for the discharging hour, hourly electricity price for techno-economic consideration, etc.).

Figure 7. Power production of CSP plants as a function of the number of discharging hours ($H_c=11$ h).

4.2. Parametric study

It should be noted that in section 4.1, the overall energy efficiency is estimated under ideal conditions, neglecting all the losses. From the viewpoint of real-world engineering, it is necessary to evaluate the real performances when actual operational conditions differ from the ideal one. In this section, the impacts of various influencing factors on the overall energy efficiency of the plant are analyzed and discussed. The studied parameters include the isentropic efficiency of turbomachines (turbines and pumps), the steam temperature at the inlet of turbine 1 and the global efficiency of the TCS reactor. Note that to evaluate the separate effect of a certain parameter, only the concerned parameter is varied while others are kept as the ideal operational conditions used for performance modelling in section 4.1.

- *Isentropic efficiency of turbomachines η_{isen}*

We define the parameter η_{isen} as the isentropic efficiency of turbine or pumps, to represent non-isentropic compression or expansion processes. Different values of η_{isen} from 0.5 to 1.0 are tested and added to the relevant energy conservation equations for turbines and pumps to determine the values of main status points of the cycle. Note that for simplification purpose, the equal value of η_{isen} is assumed for all turbomachines.

Figure 8 represents the variation of η_o values for different concepts as a function of the isentropic efficiency of turbomachines. The negative effect of non-isentropic compression/expansion of turbines and pumps can be clearly observed. Each 10% decrement of η_{isen} results in about 4.2-4.5% reduction in the η_o .

Figure 8. Overall energy efficiency (η_o) as a function of the isentropic efficiency (η_{isen}) of turbines and pumps ($H_c=11$ h; $H_D=13$ h).

- *Steam temperature at the inlet of turbine 1*

Increasing the steam temperature at the inlet of turbine 1 (T_{T1}^{in}) means the increased temperature of the superheated steam at the outlet of the steam generator (during charging) and the TCS reactor (during discharging). This usually leads to the augmented turbine work output. It may be observed from Fig. 9 that the η_o value increases almost linearly with the increasing T_{T1}^{in} for all the studied concepts.

Figure 9. Overall energy efficiency (η_o) as a function of the steam inlet temperature of the turbine T1 ($H_C=11$ h; $H_D=13$ h).

However, an excessive increase of T_{T1}^{in} may cause the turbine damage. Moreover, higher T_{T1}^{in} requires higher HTF temperature of the solar circuit during the charging and the higher reaction temperature of the TCS reactor during the discharging. Since the equilibrium temperature of Ca(OH)_2 synthesis is related to the pressure (e.g., 540 °C at 0.2 MPa) [Schaube 2012; Zhang 2016], the TCS reactor may have to be pressurized to render higher reaction temperature. This imposes a higher requirement on the TCS reactor design and operation as well as the more complicated control strategy for the whole installation. As a result, $T_{T1}^{in} = 480$ °C (500 °C, 0.1 MPa for the TCS reactor) is selected as an appropriate operational parameter.

- *TCS reactor efficiency γ*

Another influencing factor is the reactor's efficiency, which is defined as the ratio of the effective heat released to the theoretical reaction heat for discharging, or the ratio of the theoretical heat needed to the effective heat absorbed for charging. This factor is closely linked with various aspects including the structure and size of the reactor, the reversibility of the TCS reaction and the chemical stability of the stored materials. Since it is difficult at this stage to quantify the respective impact of each aspect, we introduce the parameter γ as the *global TCS reactor efficiency* taking all

the related effects into account. We also assume identical γ for charging and for discharging, as indicated in Table 1. Note that the assumption of constant and identical γ values may not be appropriate in real practice, since the reversibility of the $\text{CaO}/\text{Ca}(\text{OH})_2$ pair will decrease with the increasing number of operation cycles.

Figure 10 shows the calculated results of η_o as a function of the global TCS reactor efficiency γ . It can be observed that the η_o value decreases with the reduced global reactor efficiency. When γ of the TCS reactor drops from 1.0 to 0.8, the η_o value decreases about 5% for Turbine Int., and about 7% for Mass Int. and for Thermal Int. Turbine Int. concept still has the best overall energy efficiency.

Figure 10. Overall energy efficiency (η_o) as a function of the TCS reactor efficiency γ ($H_C=11$ h; $H_D=13$ h).

Besides the negative impact on the overall energy efficiency, the losses that we studied will also increase the amount of storage materials needed, thus requiring a larger size of the TCS reactor for their storage and operation. In real world engineering, special attention should be given to avoid or minimize the losses to a lower limit.

4.3. Comparison of 3 proposed integration concepts

The parametric study carried out in section 4.2 permits evaluating the impacts of some influencing factors on the overall energy efficiency and determining more realistic operational conditions with respect to the ideal conditions used for performance modelling in section 4.1. Based on the results obtained, a comparison of the three proposed integration concepts under more realistic operational conditional is presented in Table 2. Note that detailed values of various parameters are obtained under the assumptions of $\eta_{isen}=0.85$, $T_{T1}^{in}=480$ °C, $\gamma=0.95$, $W_{T1,C(D)}=100$ MW and round-clock operation ($H_C=11$ h; $H_D=13$ h).

A size estimation of the TCS unit has been made and the results are recapitulated in Table 2. It is shown that the Thermal Int. concept needs a smaller quantity of TCS material (9571 t) than the Mass Int. (10013 t) and the Turbine Int. (9998 t) for 13 hours discharging time. It is because the water vapor from the TCS reactor is stored as saturated liquid (100 °C, 0.1 MPa) for the Thermal Int. whereas for Mass Int. and Turbine Int. concepts, the water is stored at 41.5 °C. Therefore, a bit more quantity of TCS materials is needed for the latter two concepts to compensate this temperature difference.

Table 2. Comparison on the energy performance of three proposed integration concepts under more realistic operating conditions ($\eta_{isen}=0.85$, $T_{T1}^{in} = 480$ °C, $\gamma=0.95$, $W_{T1,C(D)} = 100$ MW and round-clock operation ($H_C=11$ h; $H_D=13$ h).

		η_o	Operational data			Heat exchange rate						Work exchange rate			Size of storage unit	
			$m_{Rankine}$ (kg·s ⁻¹)	m_{TCS} (kg·s ⁻¹)	γ	SG (MW)	CON1 (MW)	CON2 (MW)	HX2 (MW)	HX1 (MW)	R (MW)	T1 (MW)	T2 (MW)	P1+2+3 (MW)	Mass of water stored (t)	Mass of CaO stored (t)
Thermal Int.	Discharging	0.295	144	80	0.67	-	78.0	-	181.4	-	378.7	100	-	1.0	3079	9571
	Charging		91	95	0	190.8	188.7	194.4	-	97.3	548.3	100	-	0.6		
Mass Int.	Discharging	0.286	151	84	0.72	-	87.0	-	210.3	-	396.2	100	-	1.0	3221	10013
	Charging		91	99	0	187.1	188.8	228.3	-	121.2	573.7	100	-	0.6		
Turbine Int.	Discharging	0.327	151	84	0.72	-	87.1	-	210.0	-	395.6	100	-	1.50	3217	9998
	Charging		102	92	0.20	268.3	169.4	251.4	-	-	531.6	100	53.7	1.0		

The energy storage density is roughly estimated to be about $100 \text{ kWh}_{\text{el}} \cdot \text{t}^{-1}$. This value is about seven times higher than that of existing CSP plants using molten salt as energy storage media (eg. for Andasol1 Spain, the heat reservoir consists of two tanks measuring 14 m in height and 36 m in diameter and containing 28500 tons of molten salts, enough to run the turbine for about 7.5 hours at $50 \text{ MW}_{\text{el}}$ [Pelay 2017b]). The energy storage density is calculated to be $13.1 \text{ kWh}_{\text{el}} \cdot \text{t}^{-1}$). Higher energy storage density implies more compact storage unit and less heat loss of the storage reservoirs.

A first comparison between the three proposed integration concepts can then be made. Firstly, the Turbine Int. concept is the most interesting ($\eta_o=0.327$) in terms of overall energy efficiency. However, a second turbine is needed, implying the higher initial cost. Particular attention should be given to the purity of steam leaving the TCS reactor that may cause the mechanical failure of the second turbine. Efficient filtration measures are indispensable for dust removal as has been discussed above. Secondly, the Mass Int. concept is the least attractive ($\eta_o=0.286$). In fact, the mixing of working fluids between principal Rankine circuit and the TCS circuit may not be a good option again due to the purity issue that could be vital to the turbine. Finally, the Thermal Int. concept does not possess the highest overall energy efficiency, but its simple and robust design makes it relatively easy towards implementation. Moreover, relatively small volumes of reservoirs are required based on the size estimation reported above.

5. Exergy analysis of different TCS integration concepts

The previous section presents a comparison of the three proposed integration concepts based on the energy analysis (first law of thermodynamics). Meanwhile, an exergy balance will also be beneficial by providing supplemental insights on the quality of the energy, taking the irreversibility notion of the processes into account [Dincer 2002; Rosen 2003; Kang 2018]. The main purpose of this section is hence to evaluate and compare the overall exergy efficiency of the three proposed integration concepts through an exergy analysis. Note that the exergy analysis and the modelling results presented hereafter are obtained under realistic operating conditions ($\eta_{\text{isen}}=0.85$ and $\gamma=0.95$) as specified in sections 4.3.

5.1. Performance modelling for the exergy analysis

Exergy as a thermodynamic notion means the maximum work extracted from a stream as the stream reaches the dead state [Bejan, 1988]. The total exergy of a system Ex includes four components, namely physical exergy, kinetic exergy, potential exergy and chemical exergy [Rosen 2003]. Neglecting the potential and kinetic exergy changes, the exergy balance of different components may be modelled as follows.

- *Turbine or pump*

$$\dot{l} = mT_0 \cdot \Delta s \quad (33)$$

$$\varepsilon = 1 - \dot{l}/(\dot{E}x_{in} + m\Delta h) \quad (34)$$

- *Heat exchanger*

$$\dot{l} = -(\Delta \dot{E}x_{hot} + \Delta \dot{E}x_{cold}) \quad (35)$$

$$\varepsilon = 1 - \dot{l}/(\dot{E}x_{hot_{in}} + \dot{E}x_{cold_{in}}) \quad (36)$$

- *Steam generator or condenser*

$$\dot{l} = mT_0\Delta s + \frac{T_0}{T}Q \quad (37)$$

$$\varepsilon = 1 - \dot{l}/\dot{E}x_{in} \quad (38)$$

- *TCS reactor*

$$\dot{l}_R = \sum \dot{E}x_{in_{tot}} - \sum \dot{E}x_{out_{tot}} - \left(\sum \dot{l}_{tot} - \dot{l}_R \right) \quad (39)$$

Where h (J·kg⁻¹) is the specific enthalpy, $\dot{E}x$ (W) the exergy and s (J·K⁻¹·kg⁻¹) the specific entropy. $\dot{l}$ (W) is the exergy destruction of the component and ε is the exergy efficiency of the component. The overall exergy efficiency of the CSP plant η_{ex} is defined as the ratio of the exergy extracted by turbine(s) to the amount of exergy provided by the HTF of the solar circuit.

$$\eta_{ex} = \frac{\sum \dot{E}x_{out}}{\sum \dot{E}x_{in}} \quad (40)$$

5.2. Results and discussion

An exergy analysis has been performed for the three proposed integration concepts. Figure 11 shows the exergy flow-chart for each integration concept comprising of both the charging and the discharging stages. Note that the reference temperature T_0 was chosen as 5 °C, a value lower than those of the whole system. It allows an easier reading and interpretation of the results obtained.

The exergy flow-chart for the Thermal Int. concept is shown in Fig. 11a, indicating that the overall exergy efficiency (η_{ex}) equals to 0.49. It can be observed that the highest exergy destructions happen in the TCS reactor and in the heat exchanger (HX2) during discharging whereas in the steam generator, in the TCS reactor and in the condenser (CON2) during charging. These exergy destructions are mainly due to the irreversibilities caused by the large amount of heat transfer in these components. Note that exergy destructions in the reservoir and in pumps are negligible. A close look at each component indicates that the CON2 with a very low exergy efficiency ($\varepsilon_{CON2}=0.19$) during charging stage is the main cause of exergy destruction.

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Figure 11. Exergy flow-chart and overall exergy efficiency (η_{ex}) for three proposed integration concepts. (a) Thermal integration concept; (b) Mass integration concept; (c) Turbine integration concept.

The Mass Int. concept has a slightly lower η_{ex} value (0.48). It can be observed from Fig. 11b that the TCS reactor is the main component of exergy destruction during charging and discharging. The HX2 during discharging, the SG and throttle valve (TV) during charging also have high exergy destructions compared to those in reservoirs or pumps. Similar to the Thermal Int. concept, these losses are mainly due to the irreversibilities caused by the large amount of heat transfer in these components. An option to improve the ε_{TV} is to release the fluid at a pressure higher than 0.008 MPa. Nevertheless, the condensed water should be stored separately instead of sharing a common reservoir which is the distinguishing feature of the Mass Int. concept.

The Turbine Int. concept has the highest exergy efficiency ($\eta_{ex}=0.52$) among the three. Figure 11c indicates that the highest exergy destructions happen in the TCS reactor and in the HX2 during discharging whereas in the TCS reactor, in the SG and in the CON2 during charging. The TCS reactor represents the highest exergy destruction of the system while the CON2 has the lowest exergy efficiency ($\varepsilon_{CON2}=0.27$).

In brief, the exergy analysis of the three proposed integration concepts confirms that, in terms of overall exergy efficiency of the installation, the Turbine Int. concept is the most attractive ($\eta_{ex}=0.52$), followed by the Thermal Int. concept ($\eta_{ex}=0.49$) and then the Mass Int. concept ($\eta_{ex}=0.48$).

6. Conclusion and prospects

This paper presents a conceptual study of three different TCS integration concepts in a Rankine cycle driven by CSP. The TCS material used in this study is the CaO/Ca(OH)₂ couple. Based on the energy and exergy analyses, main conclusions could be reached as follows.

- Different integration concepts are feasible by coupling the TCS system with a Rankine cycle and by carefully determining flow circuit configurations and working conditions for charging and discharging stages.
- The overall energy efficiency of the installation under ideal conditions is evaluated to be 0.358 for the Thermal Int. concept, 0.349 for the Mass Int. concept and 0.392 for the Turbine Int. concept, respectively ($H_C=11$; $H_D=13$). Compared to the reference case without storage, the TCS integration decreases the overall energy efficiency but improves the adaptability and dispatchability of CSP plants with the increased power production.
- The energy storage density using calcium hydroxide as storage media is roughly estimated to be about 100 kWh_{el}·t⁻¹; this value is about seven times higher than that of existing CSP plant with a sensible heat storage using molten salt (about 13.1 kWh_{el}·t⁻¹).

- Different types of losses would cause a reduced overall energy efficiency of the installation. Non-isentropic compression/expansion and poor efficiency of the TCS reactor would have significant negative impacts on the overall energy efficiency.
- Among the three proposed integration concepts, the Turbine Int. concept seems to be the best option with the highest overall energy and exergy efficiencies under the tested conditions.

It should be noted that this study has focused on the integration conception issue, and promising findings have been obtained for this essential step. Nevertheless, a number of scientific & technological barriers remain to be overcome for the real implementation of TCS systems in CSP plants. Our ongoing work includes the dynamic simulation of each individual components (including the solar receiver and the TCS reactor) and the whole installation under real conditions. The techno-economic considerations in TCS evaluation are also our study focus, so as to assess the feasibility of such TCS integration into a real CSP plant. The results obtained on these remaining issues will be presented in future papers.

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Nomenclature

Latin letters

$\dot{E}x$	exergy, W
H	charging or discharging time, h
h	specific enthalpy, kJ·kg ⁻¹
$\dot{I}$	exergy destruction, W
$\dot{m}$	mass flowrate, kg·s ⁻¹
n	number of mole
P	pressure, Pa
Q	heat exchange rate, W
s	specific entropy, kJ·kg ⁻¹ ·K ⁻¹
T	temperature, °C
T_0	reference temperature, 5°C
$\dot{W}$	work exchange rate, W
x	mass fraction of vapor

629	y	fraction of extracted steam
630	X, Y	intermediate points for the modeling of HX1
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632		
633	<i>Greek symbols</i>	
634	γ	global reactor efficiency
635	ε	exergy efficiency of component
636	Δh_R	reaction heat, $\text{kJ}\cdot\text{kg}^{-1}$
637	η_o	overall energy efficiency
638	η_{isen}	isentropic efficiency of turbine and pumps
639	η_{ex}	overall exergy efficiency
640		
641		
642	<i>Subscripts/superscripts</i>	
643	C	charging stage
644	D	discharging stage
645	el	electricity
646	ext	extraction
647	in	inlet
648	isen	isentropic
649	out	outlet
650	steam	steam
651	th	thermal
652	tot	total
653		
654		
655	<i>Abbreviation</i>	
656	CON	condenser
657	CSP	concentrating solar power
658	FH	feedwater heater
659	HTF	heat transfer fluid
660	HX	heat exchanger
661	Int.	integration
662	P	pump
663	PCM	phase change material
664	R	reactor
665	Rankine	Rankine circuit
666	SG	steam generator
667	T	turbine
668	TCS	thermochemical energy storage
669	TES	thermal energy storage
670	TV	throttle valve
671	WS	water reservoir

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