SOCRATCES

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FINAL INFO DAY

Main project results

24th November 2021

SOCRATCES

Solar Calcium looping integRAtion for Thermo-Chemical Energy Storage

Context

CSP main research lines

- **Cost reduction: equipment CAPEX and/or higher efficiencies**
- **Improving dispatchability**
  - **40%** of current CSP plants with thermal storage
  - CSP under development approx. **80%** with thermal storage
  - At commercial scale based on Molten salts or Ruth steam accumulators

ANDASOL I: 28,500 tons of molten salt. 60% sodium nitrate, 40% potassium nitrate. 1,010 MWh.

- **Environmental sustainability**

This Project has received funding from European Commission by means of Horizon 2020,the EU Framework Programme for Research & Innovation, under Grant Agreement no.727348.

Thermochemical Energy Storage Calcium-Looping (CaL)

Group	Example
Hydrogen systems $MH_n + \Delta H_r \leftrightarrow M + \left(\frac{n}{2}\right) H_2$	$MgH_{2\,(s)} + \Delta H_r \leftrightarrow Mg_{(s)} + H_{2\,(g)}$
Carbonate systems $MCO_{3\,(s)} + \Delta H_r \leftrightarrow MO_{(s)} + CO_{2\,(g)}$	$CaCO_{3\,(s)} + \Delta H_r \leftrightarrow CaO_{(s)} + CO_{2\,(g)}$
	$SrCO_{3\,(s)} + \Delta H_r \leftrightarrow SrO_{(s)} + CO_{2\,(g)}$
Hydroxide systems $M(OH)_{2\,(s)} + \Delta H_r \leftrightarrow MO_{(s)} + H_2O_{\,(g)}$	$Mg(OH)_{2\,(s)} + \Delta H_r \leftrightarrow MgO_{(s)} + H_2O_{\,(g)}$
	$Ca(OH)_{2\,(s)} + \Delta H_r \leftrightarrow CaO_{(s)} + H_2O_{\,(g)}$
Redox systems $M_xO_{y\,(s)} + \Delta H_r \leftrightarrow xM_{(s)} + \left(\frac{y}{2}\right) O_{2\,(g)}$	$2BaO_{2\,(s)} + \Delta H_r \leftrightarrow 2BaO_{(s)} + O_{2\,(g)}$
	$2Co_3O_{4\,(s)} + \Delta H_r \leftrightarrow 6CoO_{(s)} + O_{2\,(g)}$
Ammonia systems	$2NH_{3\,(g)} + \Delta H_r \leftrightarrow N_{2\,(g)} + 3H_{2\,(g)}$
Organic systems	$CH_{4(g)} + H_2O_{(l)} + \Delta H_r \leftrightarrow CO_{(g)} + 3H_{2\,(g)}$ With a side reaction: $CO_{(g)} + H_2O_{(l)} \leftrightarrow CO_{2\,(g)} + H_{2\,(g)} + \Delta H_r$
	$CH_{4(g)} + CO_{2\,(g)} + \Delta H_r \leftrightarrow 2CO_{(g)} + 2H_{2\,(g)}$ With a side reaction: $CO_{2(g)} + H_{2\,(g)} + \Delta H_r \leftrightarrow CO_{(g)} + H_2O_{\,(g)}$
Sulfur systems	$H_2SO_{4(g)} + \Delta H_r \leftrightarrow SO_{2\,(g)} + H_2O_{\,(g)} + \frac{1}{2} O_{2\,(g)}$

Calcium-Looping (CaL)

calcination

$$\boxed{CaCO_{3\,(s)} \longrightarrow CaO_{(s)} + CO_{2\,(g)}}$$

ΔH_r=+178 kJ/mol

carbonation

$$\boxed{CaO_{(s)} + CO_{2\,(g)} \longrightarrow CaCO_{3\,(s)}}$$

ΔH_r=-178 kJ/mol

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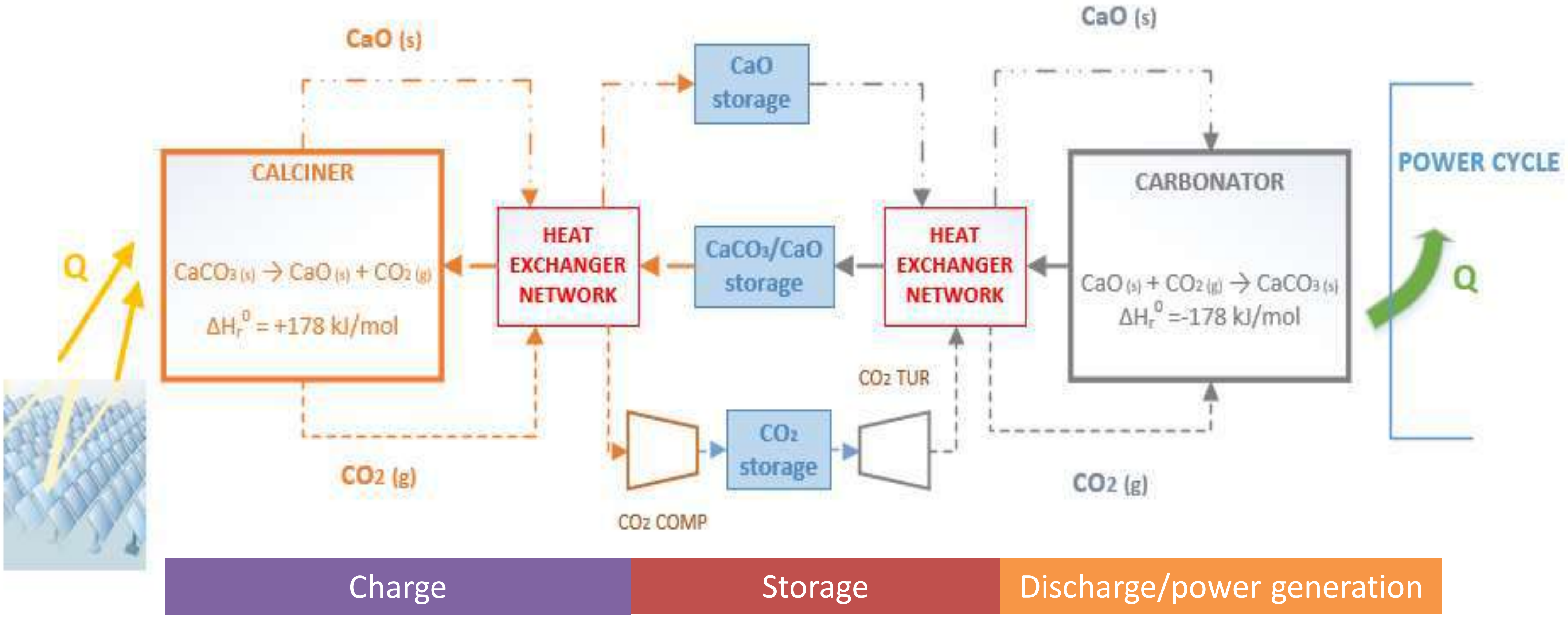
CSP-CaL Concept



R Chacartegui, A Alovisio, C Ortiz, JM Valverde, V Verda, JA Becerra, Thermochemical energy storage of concentrated solar power by integration of the calcium looping process and a CO_2 power cycle, Applied energy 173, 589-605

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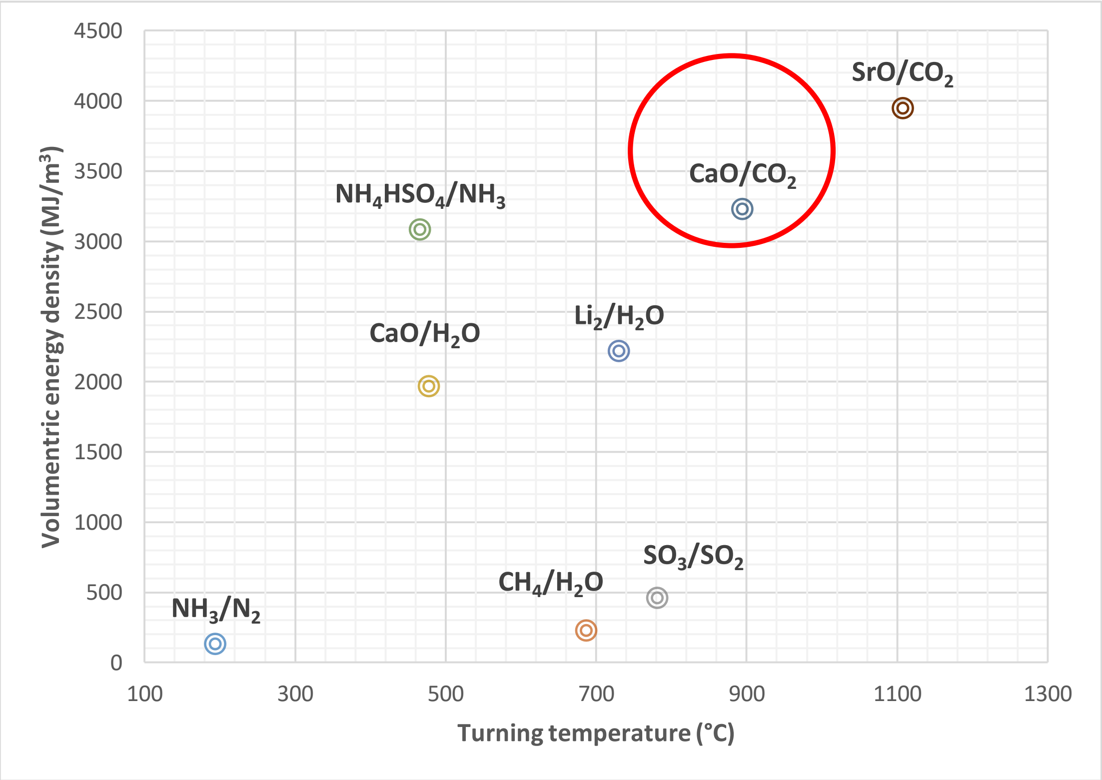
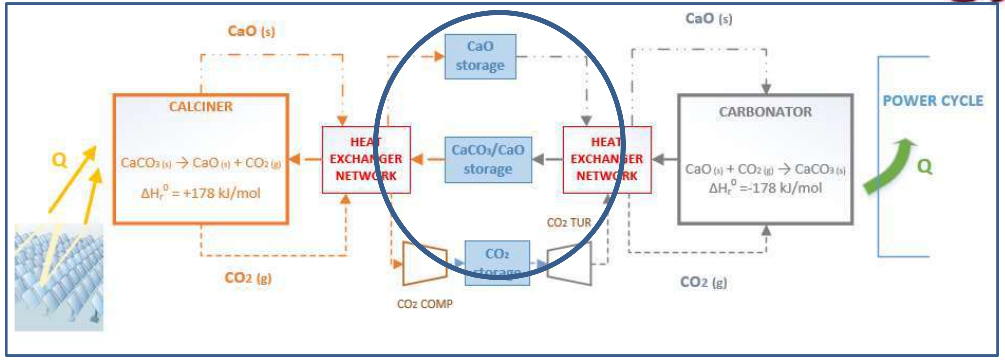
CSP-CaL – Advantages and opportunities

1. High energy density





Technology	Energy density [kWh/m³]	Maturity
sensible	low	high
solid		
liquid		
latent		
sorption		
thermochemical		
	high	low

Kuravi et al. (2013)

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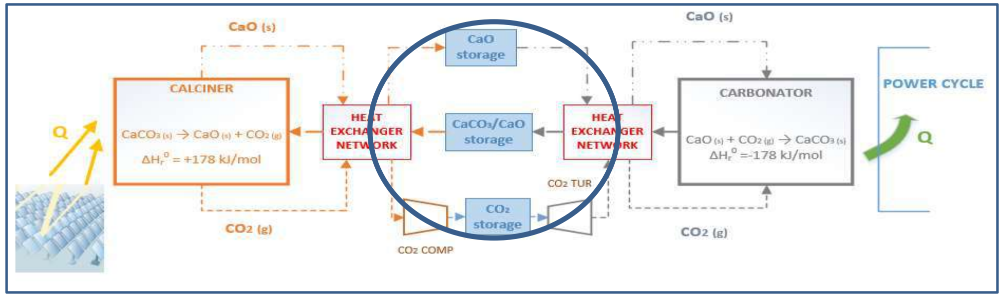
CSP-CaL – Advantages and opportunities

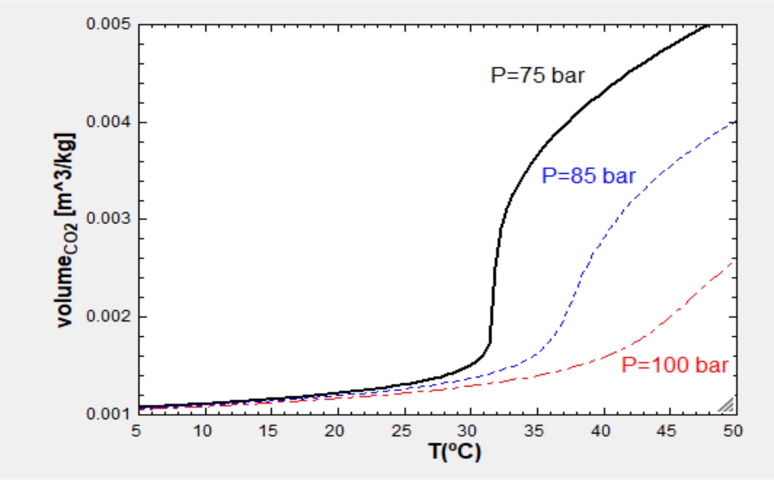
2. Low-temperature energy storage

- ✓ Minimizes thermal losses
- ✓ Reduces parasitic consumption of auxiliaries
- ✓ Capacity for seasonal storage
- ✓ Increases capacity factor

Molten salts → T min Storage ~200ºC



CO_2 storage



Different solids storage strategies

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CSP-CaL – Advantages and opportunities

3. Abundant and stable materials→ limestone, dolomite, etc.

Low-price

Abundant and widely available

Non-hazardous or contaminant

Characteristics for the large scale deployment of an energy storage system

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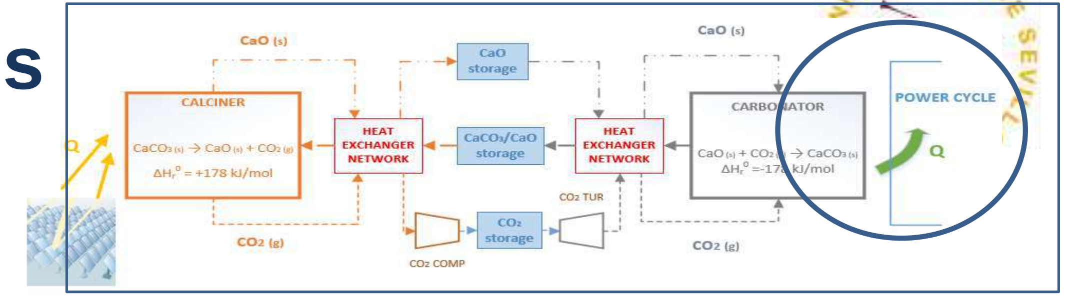
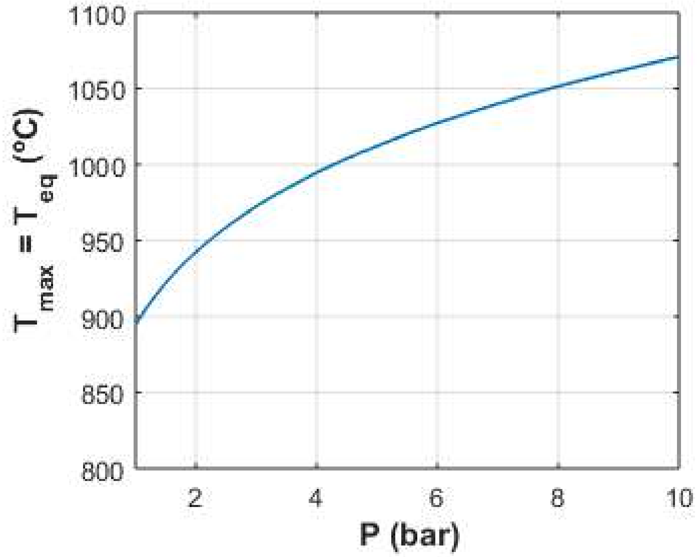
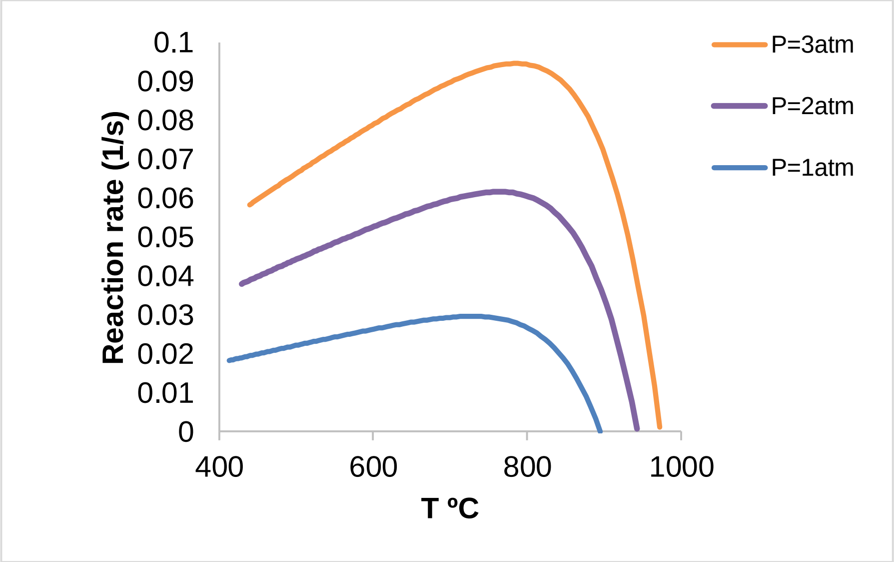
CSP-CaL – Advantages and opportunities



4. High temperature exothermic reaction

- ✓ Energy delivery at high temperature 650-1000ºC as a function of CO_2 partial pressure
- ✓ An advantage compared with molten salts →T máx ~550-600°C due to salts degradation
- ✓ Integration of high-efficiency power cycles





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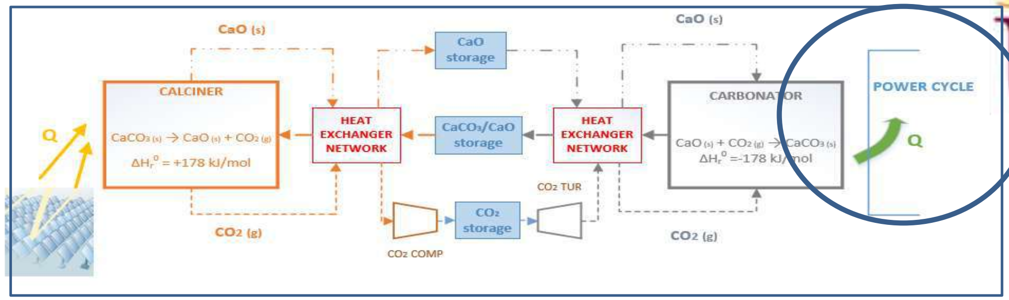
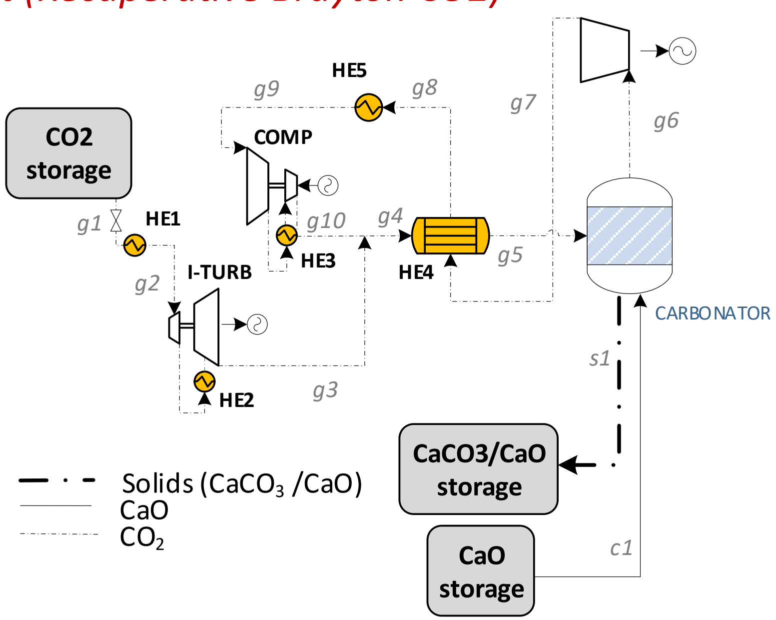
CSP-CaL – Advantages and opportunities



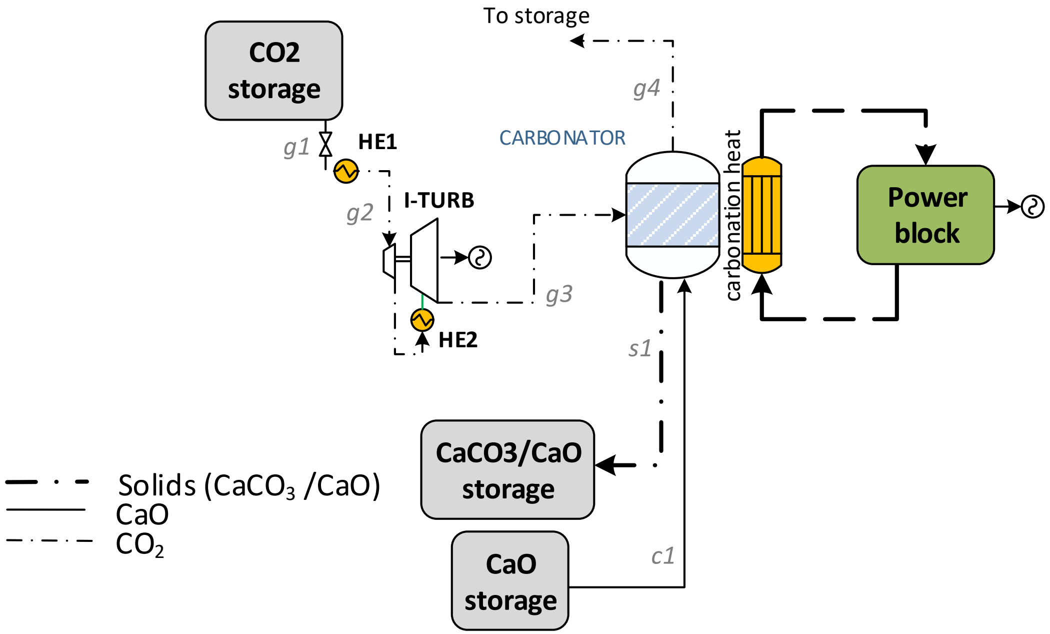
5. Direct and indirect integration of power cycles

- ✓ Flexibility for design and operation
- ✓ Based on the high temperature of the reaction

Direct (Recuperative Brayton CO2)



Indirect



C Ortiz, R Chacartegui, JM Valverde, A Alovisio, JA Becerra, **Power cycles integration in concentrated solar power plants with energy storage based on calcium looping**, Energy Conversion and Management 149, 815-829 2017

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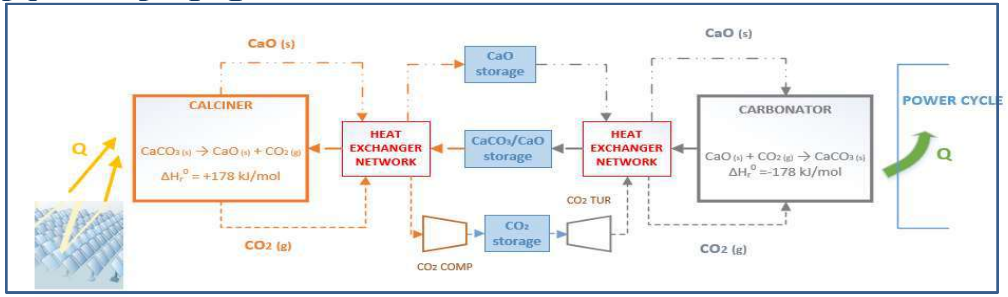
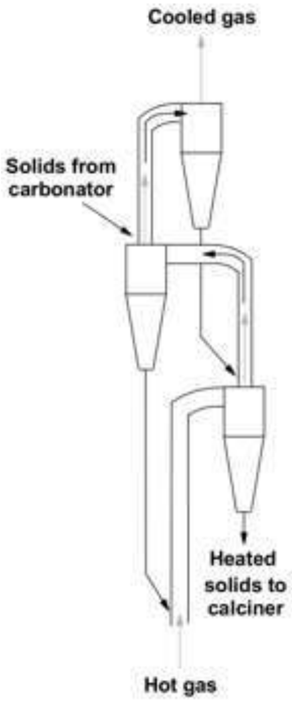
CSP-CaL – Advantages and opportunities

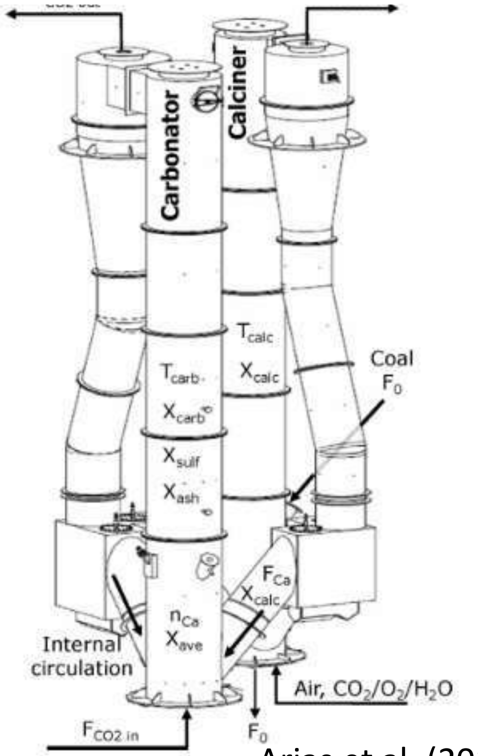


6. Materials y equipment used at an industrial scale

- Proximity with cement industry
- Calciner (solar integration)
- Entrained flow reactors
- Closed CO_2 Brayton cycle
- Solids transport
- Cyclons
- Storage tanks



BAT for cement industry (2013)



Arias et al. (2013)

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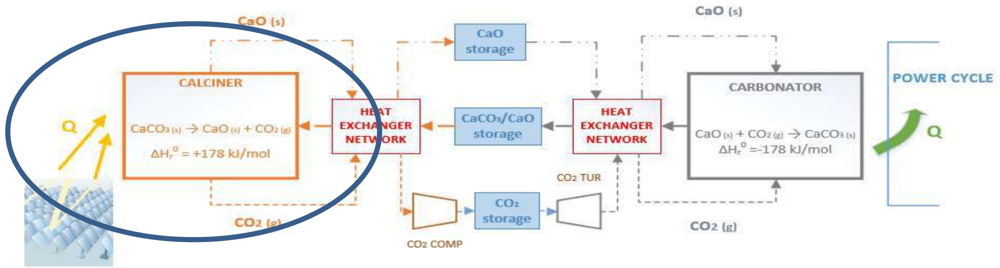
Main Challenges



1. Solar calciner. High-temperature receivers

i) Particles residence time

ii) Particles circulation within the system

iii) Closed CO_2 loop operation

iv) Thermal gradients control

v) Continuous operation for scaling up

Particles solar receivers High-temperature

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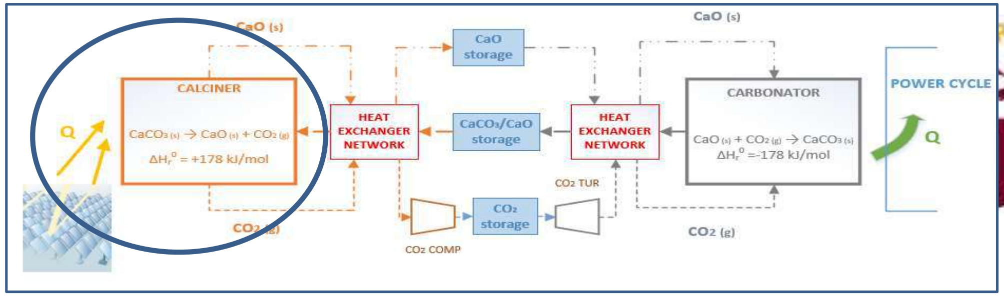
Main Challenges

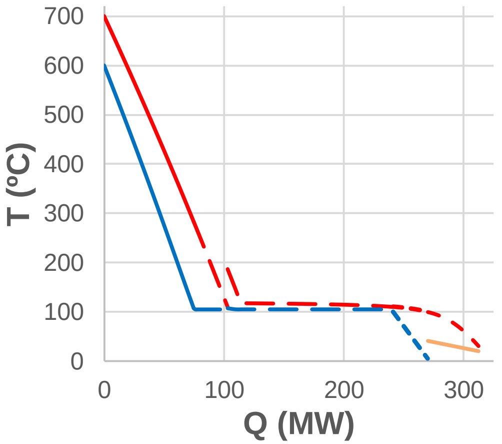


Alternatives for reducing the calcination temperature

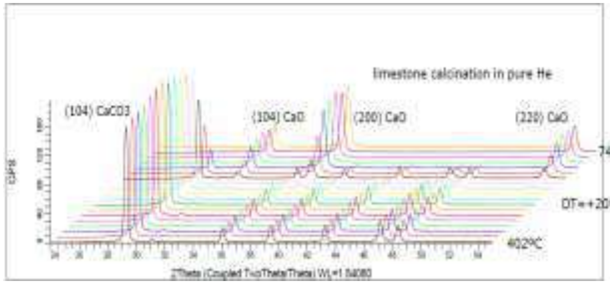
Steam calcination

- Commercial availability
- Closeness to CSP tower
- Separation condensing

➢ **Effects on particles structure**

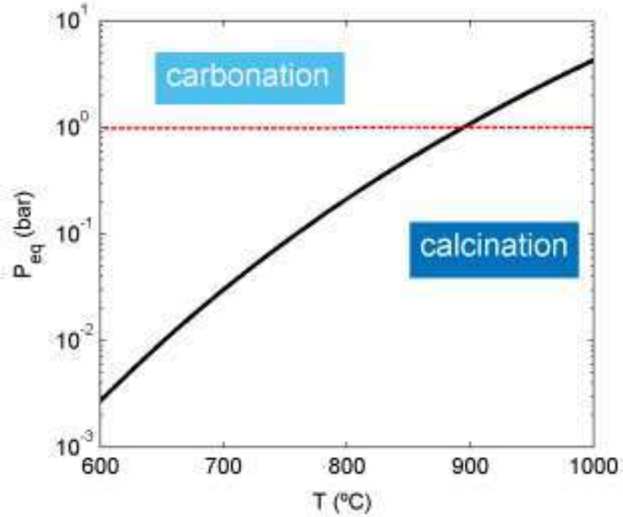


Helium calcination



- Reduced loss of activity with cycles
- **Membranes separation**

Vacuum calcination



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Main Challenges

2. Multicyclic CaO conversion

$$CaO_{(s)} + CO_2 \rightarrow CaCO_{3(s)} \qquad \Delta H_r^0 = -179,2\,\frac{kJ}{mol}$$

Deactivation with the number of cycles

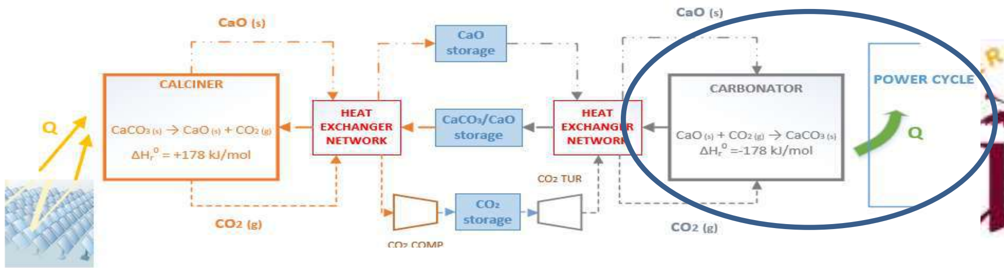
It affects to plant performance

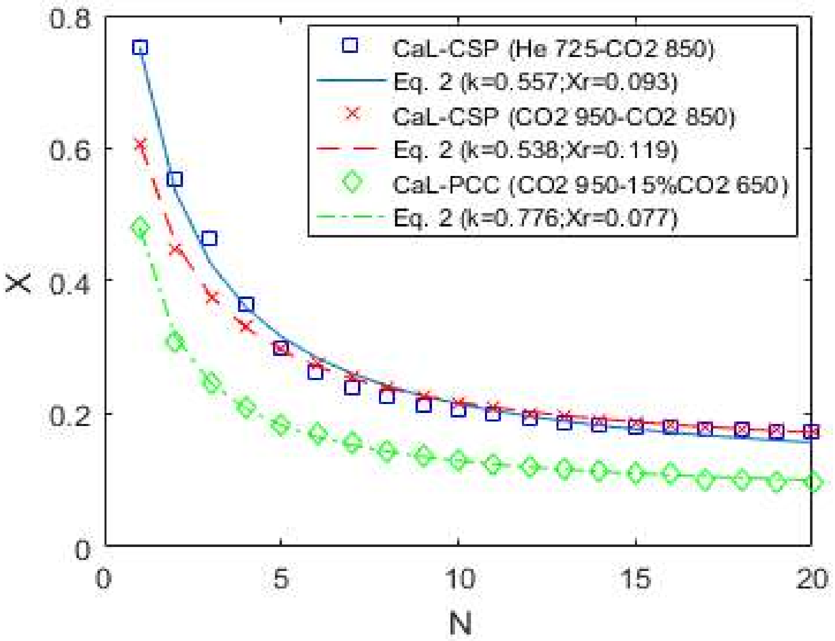
$$X = \frac{mol\ CaO\ reacted}{mol\ CaO\ in} = \frac{mol\ CaCO_3\ produced}{mol\ CaO\ in}$$

$$CO_2\ captured = CaCO_3\ formed = CaO \cdot X$$

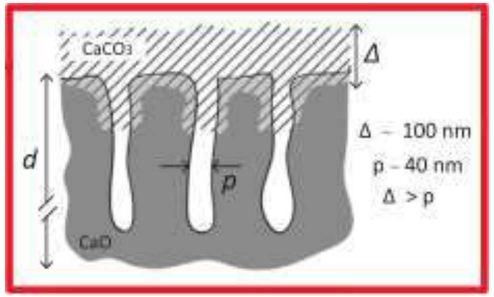
$$(1 - X) = solids\ inerts$$ → **Efficiency penalty**

Deactivation is highly dependent on the design conditions of reactors, material and processes





B Sarrión, A Perejón, PE Sánchez-Jiménez, N Amghar, R Chacartegui, ..., Calcination under low CO2 pressure enhances the calcium Looping performance of limestone for thermochemical energy storage, Chemical Engineering Journal, 127922,2020



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Summary of main benefits of CaL Storage concept (SOCRATCES)

1 CaO precursors:

- ✓ Low price
- ✓ wide availability
- ✓ harmlessness

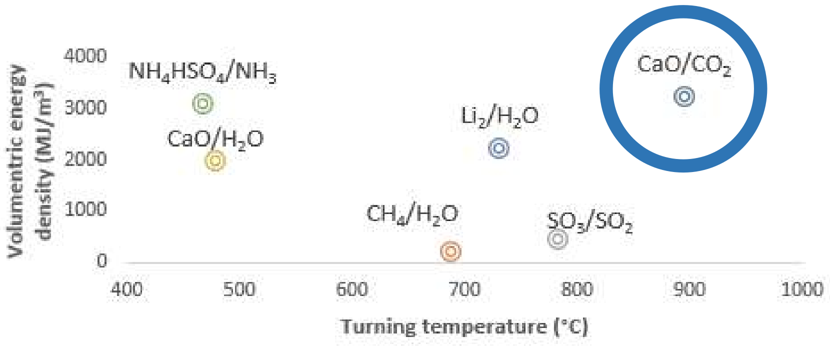
2 Carbonation for generating heat ~650-1000ºC

- ✓ High efficient generation of electricity

3 Reactants and products can be stored at ambient temperature

Ambient temperature

4 High energy density to maximize storage capacity



5 Materials and process equipment

- ✓ Well-known in the cement industry

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SOCRATCES operation conditions

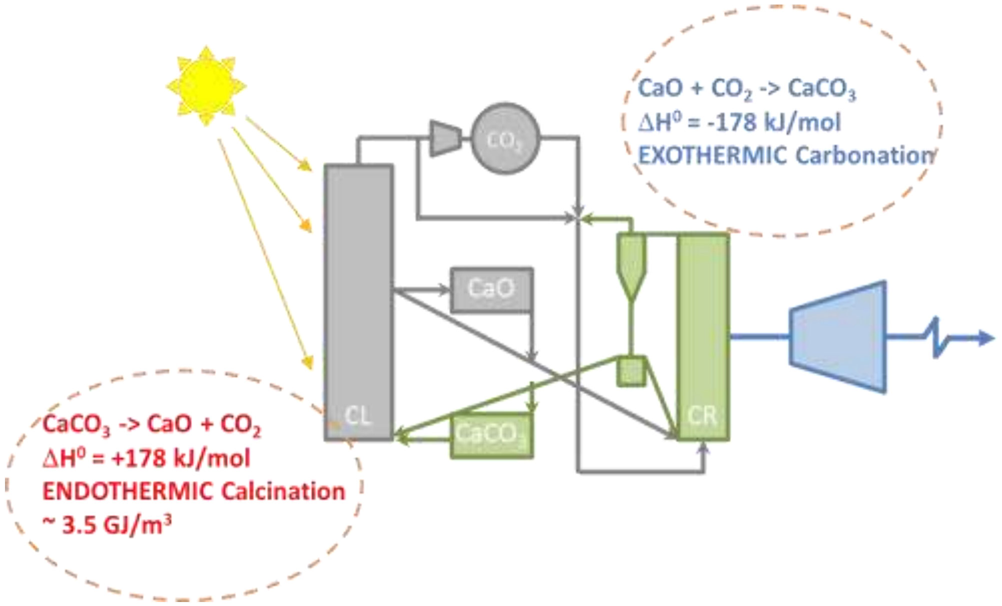


Figure 1: Schematic representation of SOCRATCES.

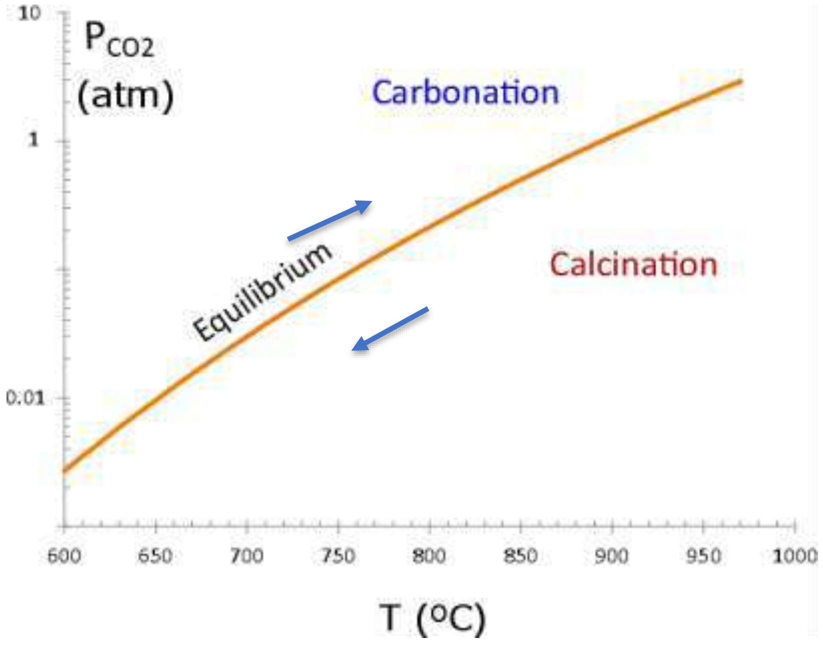
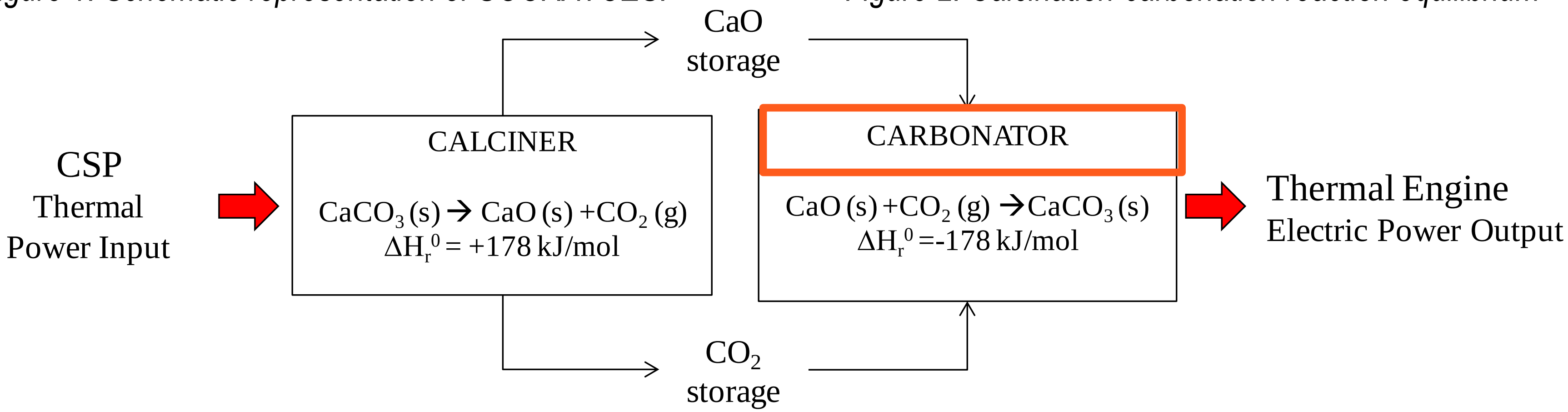


Figure 2. Calcination-carbonation reaction equilibrium



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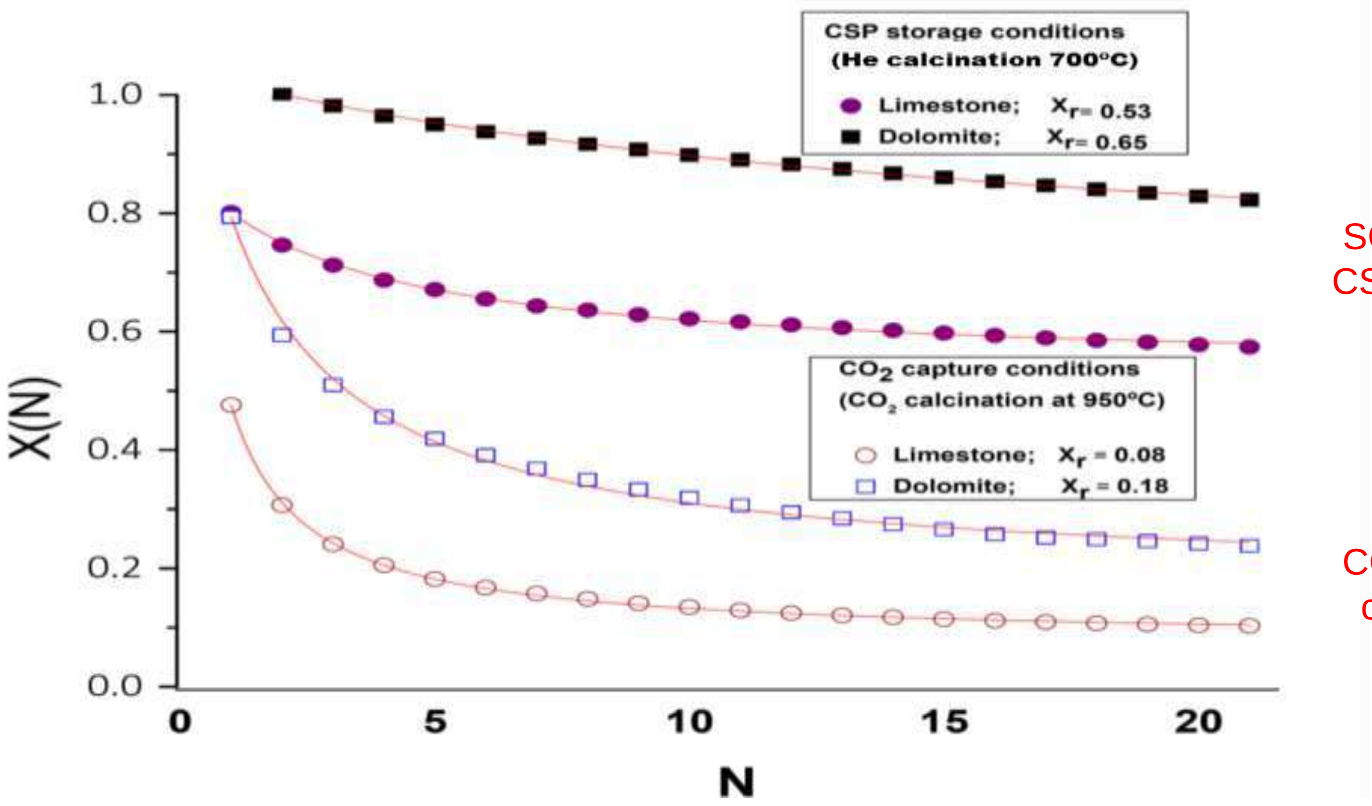
Material behauviour under SOCRATCES operation conditions



SOCRATCES CSP conditions

CO_2 capture conditions

Figure 1: The humble limestone and dolomite show high residual conversion (Xr) at SOCRATCES conditions

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Objectives.

- SOCRATCES global objective is to **advance in the knowledge of the Calcium Looping (CaL) for thermochemical energy storage (TCES)**.

- The project **develops prototypes of the different components and implements their integration in order to reduce the core risks of scaling up** TCES-CaL technology, to identify and to solve challenges; to advance in the understanding of the processes and to optimize the performance of components and global systems with the longer-term goal of enabling highly competitive and sustainable TCES-CSP plants integrating the TCES-CaL technology.

- SOCRATCES is oriented to **generate new knowledge** about the whole CaL process: equipment, materials, reactions, transport, etc. in order **to identify and solve the challenges** for the development of the TCES-CaL system at a commercial scale of MWs.

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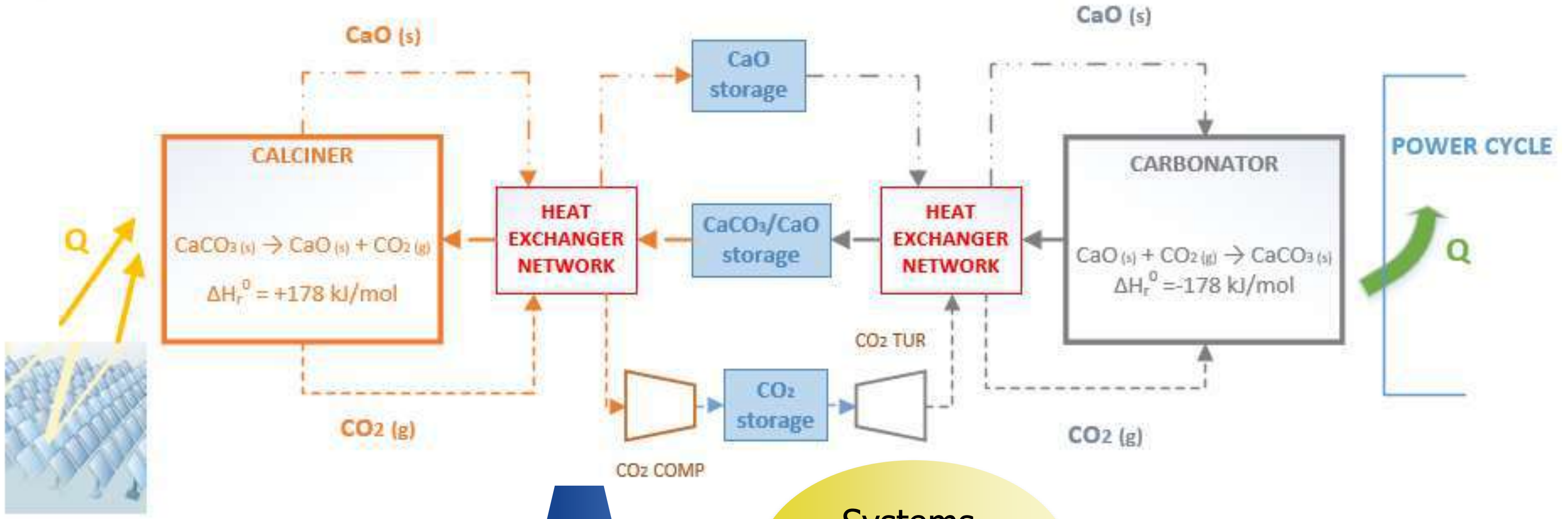
New materials

R & D

Reactions (Ch/Ph)

Scaling-Up **A**ssessment



Systems integration & control

Engineering **C**onstruction

Systems development

Power Systems technologies

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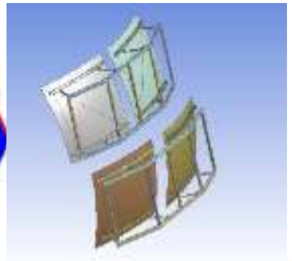
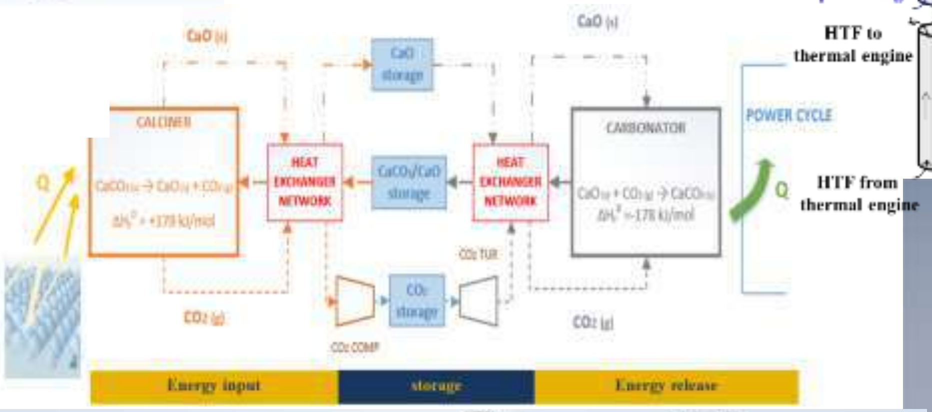
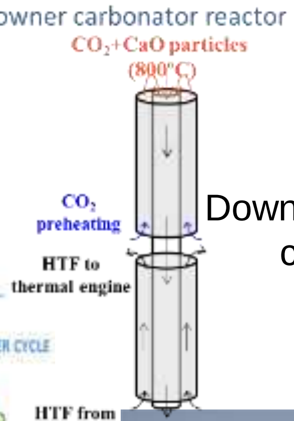
SOCRATCES Prototypes. First of their kinds



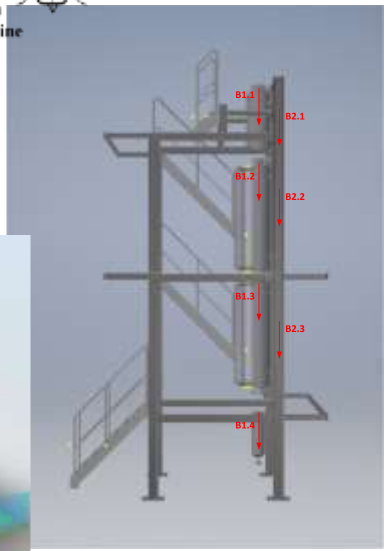
Secondary
reflector/reactor

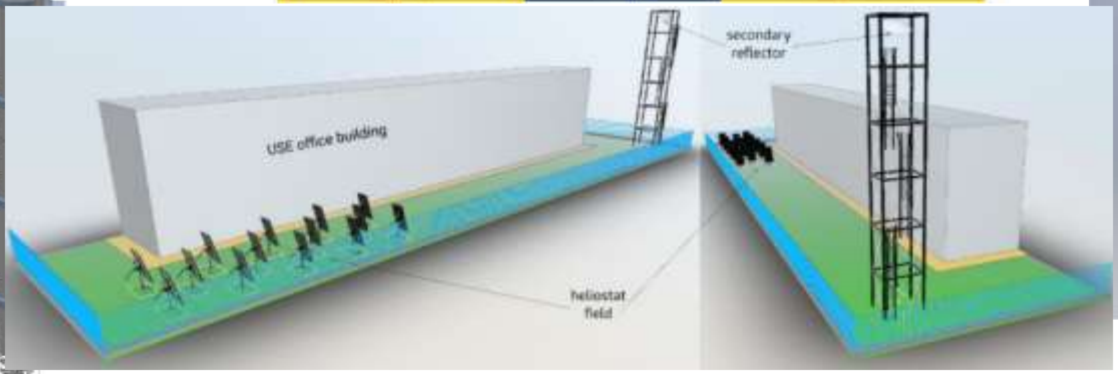
Solar cyclone
calciner





Downer closed loop
carbonator





Downer gravity closed
loop calciner

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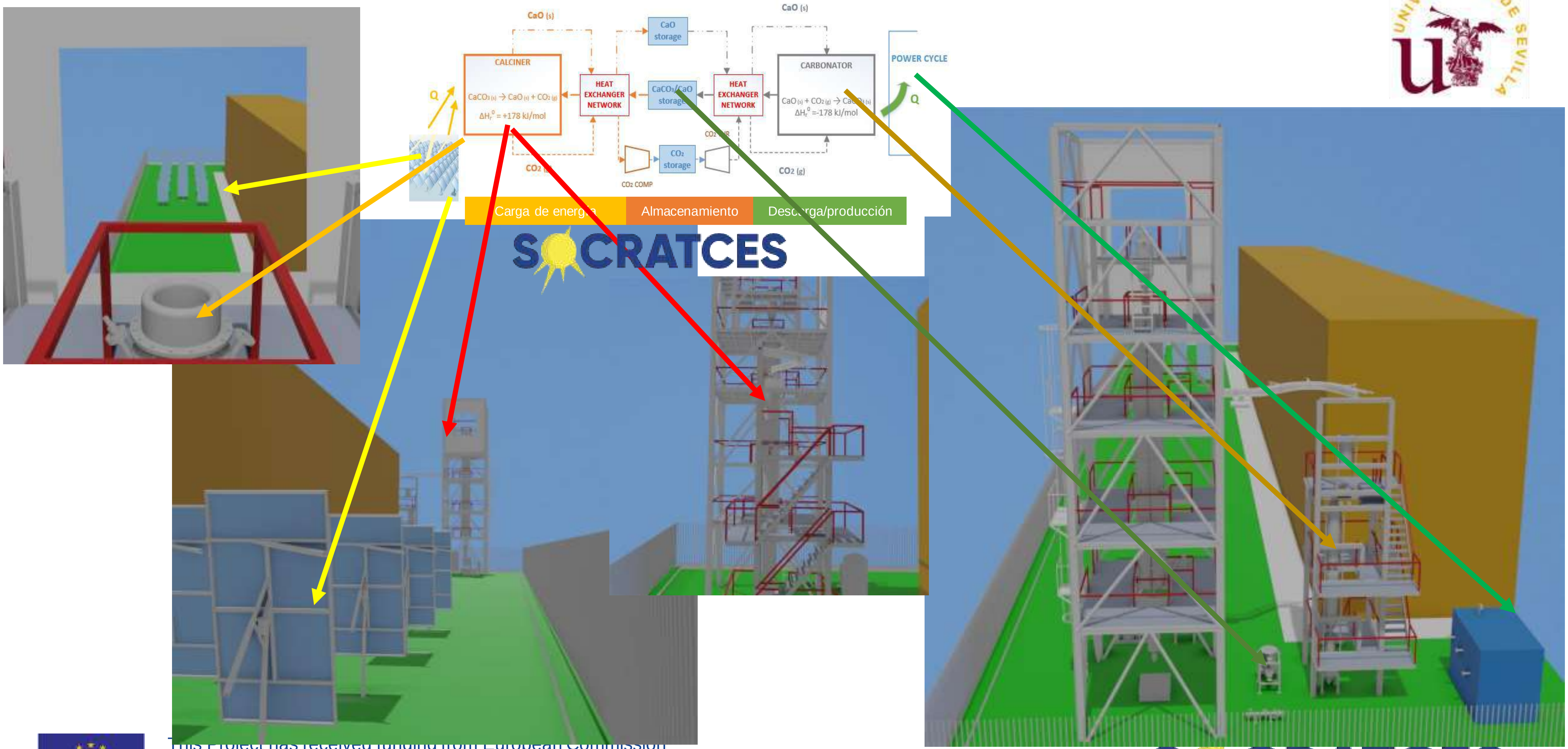

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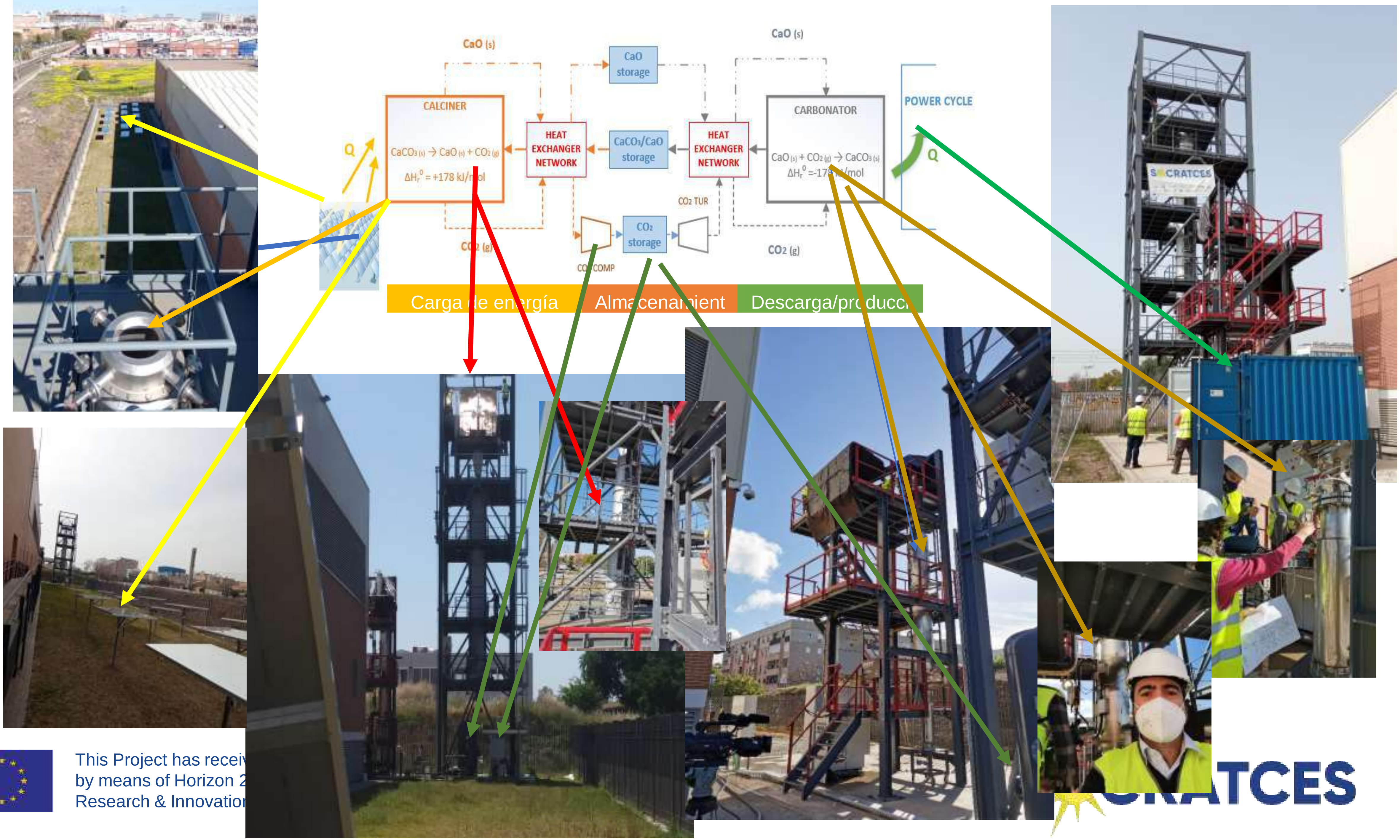
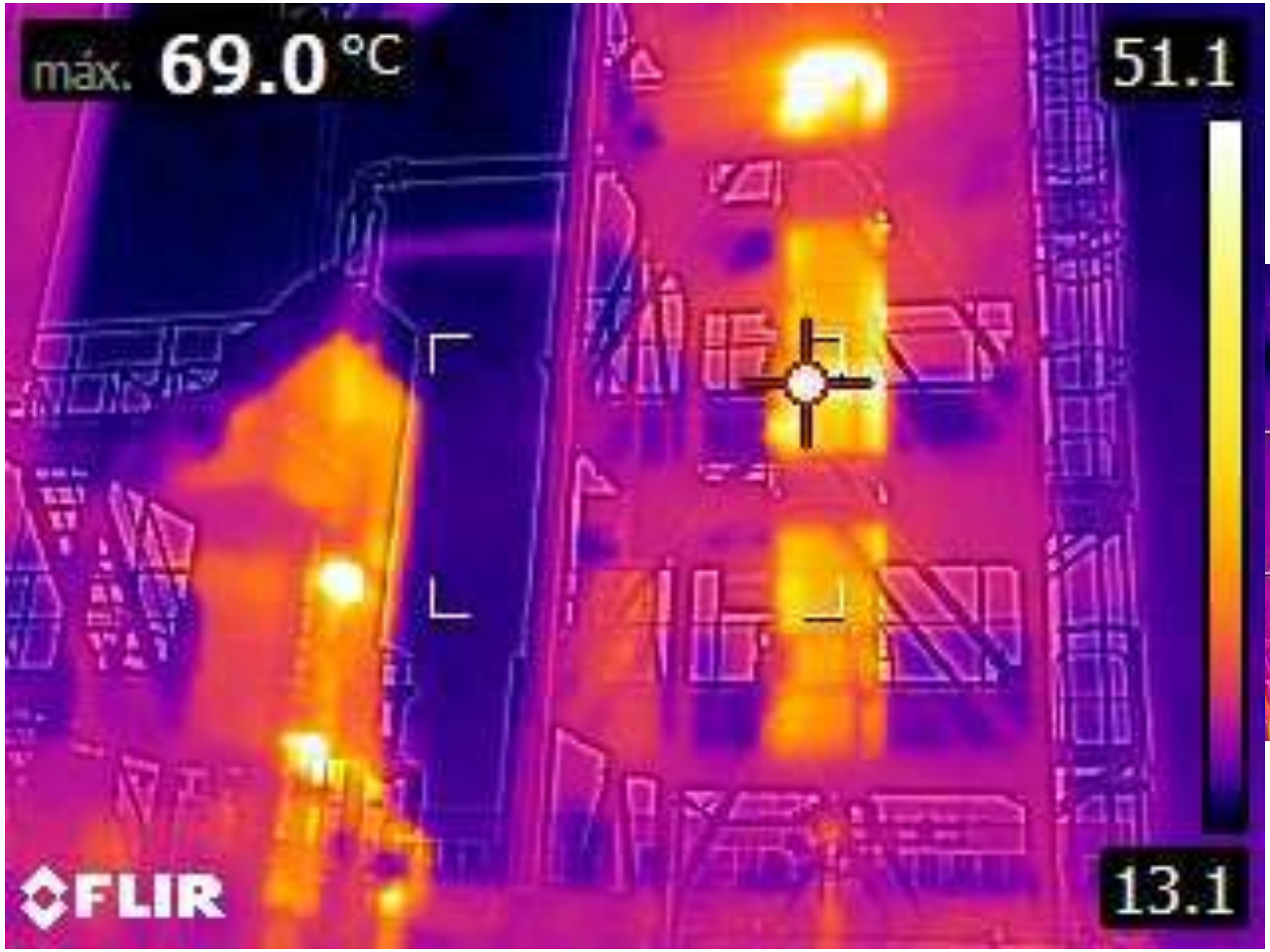
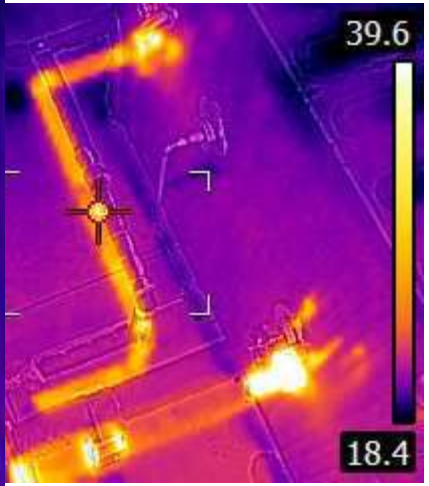
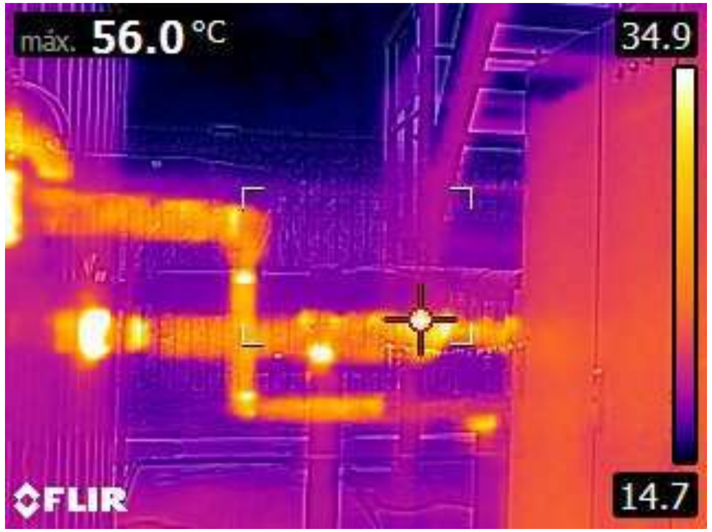


This Project has recei
by means of Horizon 2
Research & Innovatio

And the pilot plant operates ….







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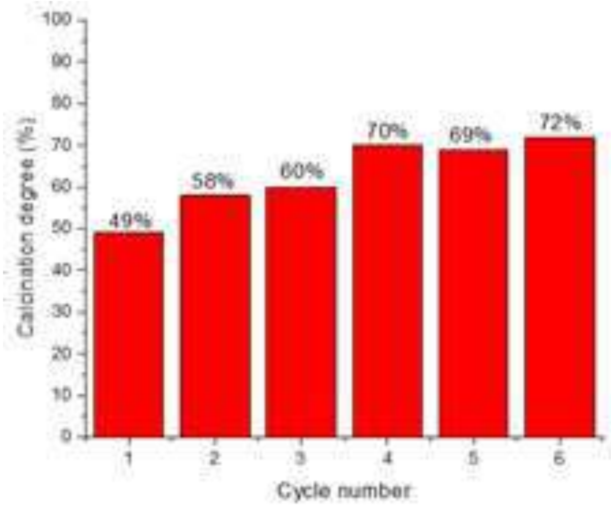
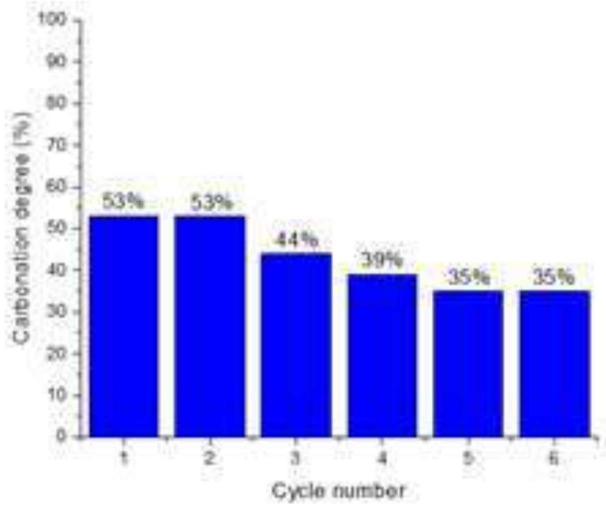
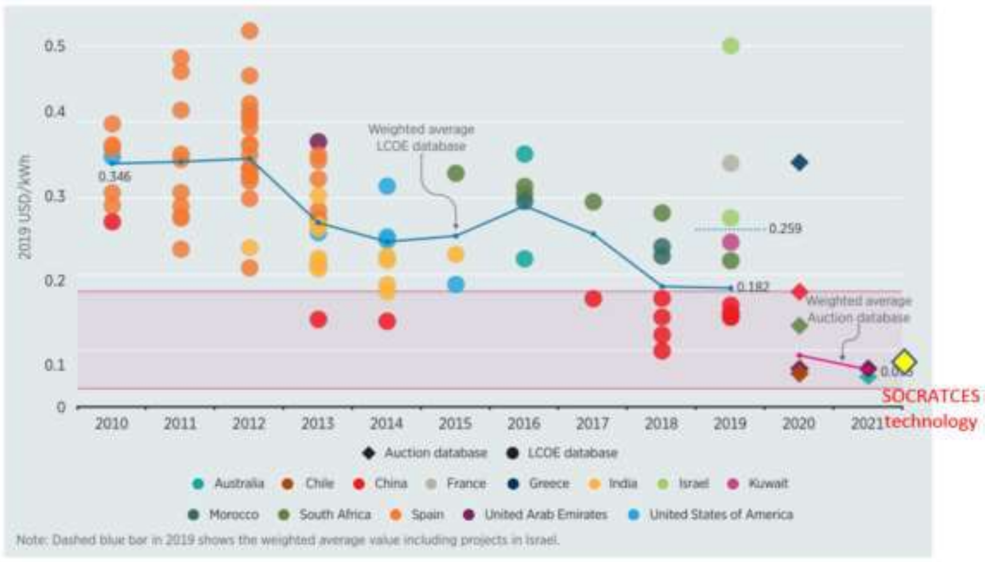
And it provides results…





That combined with models, they predict a good performance at other scales



Source: IRENA Renewable Cost Database and IRENA Auction and PPA Database.

Figure 15: Levelised cost of electricity and auction price trends for CSP, 2010-2021[23]. Socratces technology positioning.

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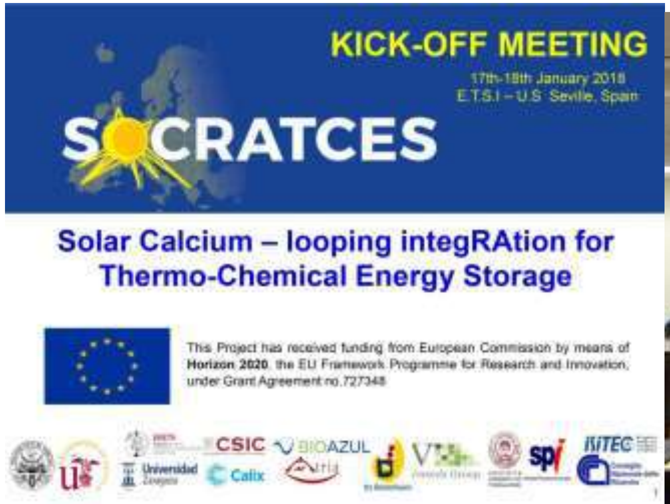
SOCRATCES a 4 years journey



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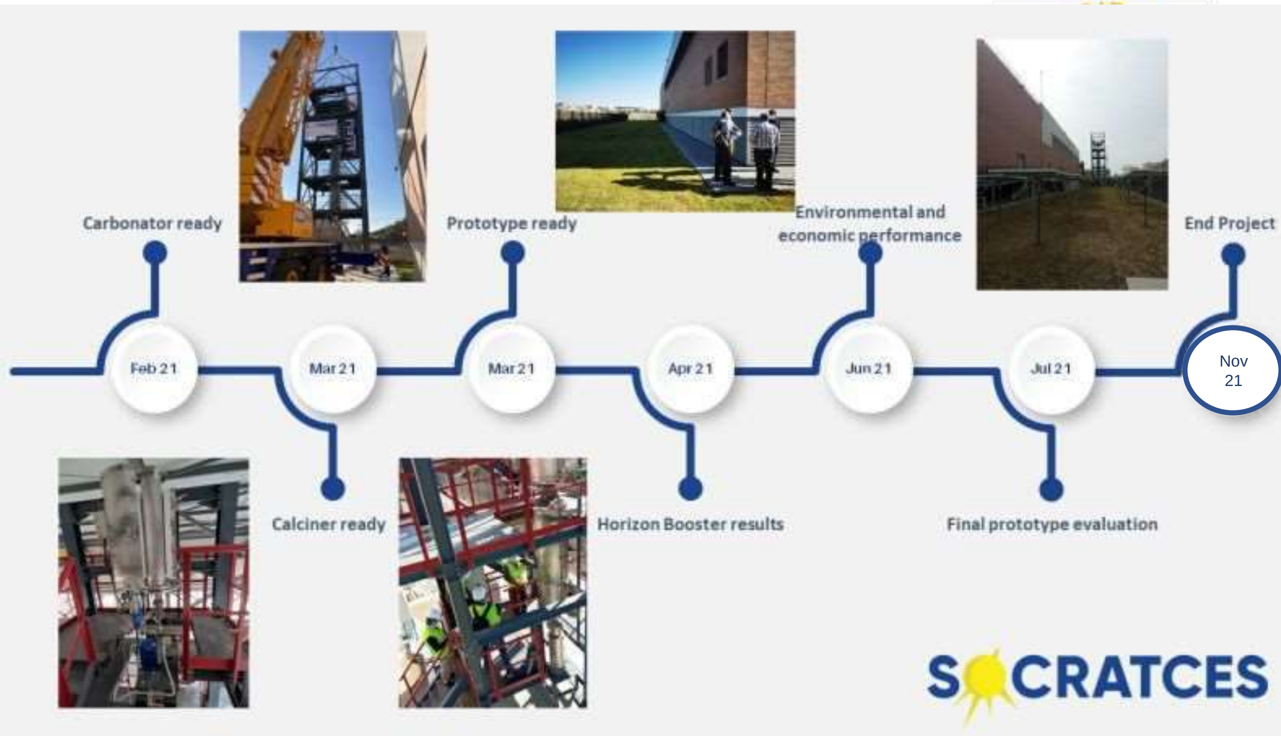

https://socratces.eu/

Nov 21

https://www.linkedin.com/company/socratces/

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Published results, analysis, data (a non complete sample)

Integrations and processes

- R Chacartegui, A Alovisio, C Ortiz, JM Valverde, V Verda, JA Becerra, **Thermochemical energy storage of concentrated solar power by integration of the calcium looping process and a CO2 power cycle,** Applied energy 173, 589-605 First publication
- A Alovisio, R Chacartegui, C Ortiz, JM Valverde, V Verda, **Optimizing the CSP-calcium looping integration for thermochemical energy storage**, Energy Conversion and Management 136, 85-98 2017 Seasonal storage
- C Ortiz, MC Romano, JM Valverde, M Binotti, R Chacartegui, **Process integration of Calcium-Looping thermochemical energy storage system in concentrating solar power plants**, Energy 155, 535-551 2018 Hot storage
- C Ortiz, R Chacartegui, JM Valverde, A Alovisio, JA Becerra, **Power cycles integration in concentrated solar power plants with energy storage based on calcium looping**, Energy Conversion and Management 149, 815-829 2017 Power cycles analysis
- C Ortiz, M Binotti, MC Romano, JM Valverde, R Chacartegui, **Off-design model of concentrating solar power plant with thermochemical energy storage based on calcium-looping**, AIP Conference Proceedings 2126 (1), 210006 2019 Off design

Materials

- C Ortiz, JM Valverde, R Chacartegui, LA Perez-Maqueda, **Carbonation of limestone derived CaO for thermochemical energy storage: from kinetics to process integration in concentrating solar plants**, ACS Sustainable Chemistry & Engineering 6 (5), 6404-6417 2018 Scales impact
- C Ortiz, JM Valverde, R Chacartegui, **Energy Consumption for CO2 Capture by means of the Calcium Looping Process: A Comparative Analysis using Limestone, Dolomite, and Steel Slag**, Energy Technology 4 (10), 1317-1327 Effect of different materials

  Biomineralized materials
- J Arcenegui-Troya, PE Sánchez-Jiménez, A Perejón, JM Valverde, ...**Calcium-Looping Performance of Biomineralized CaCO3 for CO2 Capture and Thermochemical Energy Storage**, Industrial & Engineering Chemistry Research 59 (29), 12924-12933, 2020 Biominerals
- B Sarrión, A Perejón, PE Sánchez-Jiménez, N Amghar, R Chacartegui, ..., **Calcination under low CO2 pressure enhances the calcium Looping performance of limestone for thermochemical energy storag**e, Chemical Engineering Journal, 127922,2020 Low-Pressure Calcination

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Published results, analysis, data (a non complete sample)

Components

- B Sarrión, A Perejón, PE Sánchez-Jiménez, N Amghar, R Chacartegui, ..., **Calcination under low CO2 pressure enhances the calcium Looping performance of limestone for thermochemical energy storage**, Chemical Engineering Journal, 127922,2020

Calciner Effect of Low pressure calcination

- U Tesio, E Guelpa, C Ortiz, R Chacartegui, V Verda, **Optimized synthesis/design of the carbonator side for direct integration of thermochemical energy storage in small size Concentrated Solar Power**, Energy Conversion and Management: X 4, 100025, 2019

Carbonator

CaL Perspectives and challenges

- C Ortiz, JM Valverde, R Chacartegui, LA Pérez-Maqueda, ..., **Scaling-up the Calcium-Looping Process for CO2 Capture and Energy Storage**, KONA Powder and Particle Journal 38, 189-208, 2021

Reviews

- C Ortiz, JM Valverde, R Chacartegui, LA Perez-Maqueda, P Giménez, **The calcium-looping (CaCO3/CaO) process for thermochemical energy storage in concentrating solar power plants**, Renewable and Sustainable Energy Reviews 113, 109252 2019

Hybrid CaL CSP/PV

- R Bravo, C Ortiz, R Chacartegui, D Friedrich, **Multi-objective optimisation and guidelines for the design of dispatchable hybri solar power plants with thermochemical energy storage**, Applied Energy 282, 116257, 2021

Data clustering

- R Bravo, C Ortiz, R Chacartegui, D Friedrich, **Hybrid solar power plant with thermochemical energy storage: A multi-objective operational optimization**, Energy Conversion and Management 205, 112421, 2020

Optimization operation

- R Fernández, C Ortiz, R Chacartegui, JM Valverde, JA Becerra, **Dispatchability of solar photovoltaics from thermochemical energy storage**, Energy Conversion and Management 191, 237-246 2019

Concept

CaL Combined Cycle

- C Ortiz, R Chacartegui, JM Valverde, A Carro, C Tejada, J Valverde , **Increasing the solar share in combined cycles through thermochemical energy storage,** , Energy Conversion and Management 229, 113730, 2021

Novel Concept. More recent approach. An alternative pathway?

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