Grant Agreement No. 727348

Project Acronym:

SOCRATCES

Project title:

SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage.

DELIVERABLE D8.12

Final Innovation Evaluation Report

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INTRODUCTION

This report is framed in ***Task 8.5 Innovation management activities*** of WP8, and it is the Second evaluation made during the project life. The main aim of this task is to define a technology forecasting plan and decision-making mechanisms for innovation management. This mechanism will be used to select and prioritise innovative ideas and project outcomes to implement new features and/or changes that improve the pathway towards commercial exploitation of SOCRATCES concept and linked technology solutions and derived knowledge.

The activities within task 8.5 are strongly linked to other project tasks, mainly within WP1 and WP9.

- **Task 1.3 IP, Exploitation and Innovation management.** This task includes the coordination of knowledge management and exploitation of the project results as well as other innovation-related activities.
- **Task 9.4 IPR management and Exploitation Plan.** It involves the design and agreement of the Exploitation Plan, taking into account the agreements on IPR and Exploitation. The exploitation plan will include the description of the exploitation strategy, its implementation, and market findings of the project. Additionally, the plan will focus on the exploitation opportunities of SOCRATCES, summarising different possible exploitation scenarios that can be applied. The Innovation Manager will handle these aspects together with other partners.

BIOAZUL has been assigned as leader of *task 3.1, task 8.5 and WP9* and is working closely with USE, VERTECH and SPI to encourage and stimulate the use of the consortium creative efforts to build new ideas technical and organisational solutions. BIOAZUL put in place a set of working tools that allow all project partners to cooperate with a common understanding of goals and processes.

The work during the last years of SOCRATCES has allowed obtaining important research results and decisions about the future implementation of the SOCRATCES technology evolution (and derived technologies and knowledge from components development). In this way, the innovations have been described in a detailed way, as well as some new ones have been included in the list. In this stage, the project partners have been able to make a first general evaluation to them and set references to compare with SOCRATCES results.

As a result of the analyses developed, the consortium is determined to move forward in this direction to prepare a new proposal within the European funding program HORIZON EUROPE that will boost the work carried out to higher TLRs and take advantage of some of the technologies. Also, some partners are analysing the formation of a spin-off to develop and commercialise some of the technology developed.

1. SOCRATCES: OBJECTIVES AND IMPACTS.

This section provided general information on the SOCRATCES project, its objectives and how foreseen impacts in the DoA has been achieved. The aim is to have a proper framework for the innovation management done within the project life.

1.1. SOCRATCES project

SOCRATCES "*SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage*" is a research and innovation action (RIA) funded by the European Union's Horizon 2020 programme and coordinated by the University of Seville.

The **general objective** of SOCRATCES is to demonstrate the practical feasibility of this thermochemical energy storage concept, CaL-CSP integration scheme already obtained at laboratory scale, extending the laboratory research in this very promising field by erecting a pilot-scale plant that uses cheap, widely available and non-toxic materials as well as already mature solar and calcination/carbonation reactors technologies. The pilot plant will be validated in a relevant environment to prove it as:

- **Feasible:** SOCRATCES is a combination of a novel integration of systems in CSP/TCES in a configuration that allows using already tested technologies. Therefore, the use of individual technologies and their integration has a controlled risk due to the recent experience of the partners in the consortium.
- **Viable**: SOCRATCES technologies aim to reduce investment and O&M costs drastically. The global integration is expected to reduce the costs on the commercial scale to an LCOE below 7c€/kWh.
- **Sustainable**: SOCRATCES is environmentally sustainable because it is based on the use of non-toxic minerals as reactants in the TCES system. It allows long-term solar energy storage in chemical form. SOCRATCES is economically sustainable with reduced investment costs. SOCRATCES is socially sustainable as it is based on a technological framework currently in use and fully accepted by end-users.

The successful realisation of a pilot plant will give the EU a leading role in the development of cheap, efficient and non-toxic energy storage of CSP in a chemical form.

SOCRATCES main **commercial objective**, linked to R&D objectives, is to introduce a novel technology (and subsystems) into the CSP tower technology market with a relevant reduction of costs at the commercial level (TCES cost <12€/kWh and CSP plant LCOE <7c€/kWh).

SOCRATCES main **social objective** is to provide a new integrated set of affordable, viable and sustainable CSP technology, with outstanding performance and based on renewable sources and abundantly available cheap materials for the cycle.

1.2. SOCRATCES impacts

SOCRATCES is intended to open a new pathway for the next generation of CSP tower plants, technologically feasible, economically viable and sustainable (environmental, social and economic). The roadmap for advancing from the concept to commercial technology is conceived in three stages to be developed in a period of 10 years: $10KW_{th}$ small prototype, $500kW_{th}$-1 MW_{th} scale pilot plant and commercial demonstrator. In SOCRATCES, the small CSP/TCES prototype ($10KW_{th}$) will represent the first step to demonstrate the technology and will serve to identify and solve challenges and opportunities at a small scale.

The expected impacts are included in the table below:

EXPECTED IMPACT	PROPOSAL SOLUTION	OBJECTIVE	ACHIEVED
Reducing the technological risks for the next development stages	Natural CaO sorbents and Ca-rich industry waste materials. Low cost, non-toxic, abundant, stable and sustainable	- Prototype demonstration of capacity for energy storage. - Solids and CO_2 storage. - Solids conveying and system management. - System tested at TRL5.	✓
	Use of mature inexpensive technologies and materials in the solar receiver. Potential for integrating future high-temperature developments	- Solar calcination. Integration of already available technology at receiver. - Systems design - CaL attrition control	✓
	T Carbonation (power cycle loop) > 850ºC. High-efficiency cycles can be integrated (already commercial as steam) and future ones as SCO_2	- Prototype demonstration of high-temperature carbonation >850ºC. Integration of already available technology for the power block. - Carbonator CO_2 closed-loop control development	✓
Significant increased technological performance	- Combination of novel (CaL TCES, solar calciner) and commercial technologies (CSP tower plant, fluidised bed reactors, pneumatic conveying, gas turbine power cycle). - New CSP/CaL integration conditions result in high global system efficiency with two possible power block integrations: indirect and direct.	- Global efficiency: direct integration >46%, indirect integration with high-efficiency power block (SCO_2)>50% - Reduce prices of receivers by new integration concept on solar-calcination - Tcarbonation>850ºC. High efficiency of power cycle	✓
	Optimised energy storage system. Sensible heat storage plus <u>Thermochemical</u> storage due to $CaCO_3$ endothermic decomposition reaction plus <u>mechanical energy</u> employed for CO_2 compression and extracted from the cycle operation.	- High-density energy storage: 3.2 GJ/m3 - Low materials price: <10 €/ton - Highly stable materials: Residual activity >0.5	✓
	Energy management/ storage	System tested at TRL5	✓
Reducing lifecycle environmental impact;	Use of abundant natural CaO precursors and Ca-	System tested at TRL5 LCA/LCC analysis	✓

	rich industry waste materials.		
Nurturing the development of the industrial capacity to produce components and systems and opening of new opportunities;	Development of prototype for technology demonstration	New CSP concept New calcination technology	✓
Contributing to the strengthening the European industrial technology base, thereby creating growth and jobs in Europe	The first step to the next generation of SOCRATCES CSP power plants in Europe fully competitive with future fossil fuel plants under market conditions	System tested at TRL5	✓
Increasing the reliability and lifetime while decreasing operation and maintenance costs, hence creating new business opportunities;	- Moderate temperatures at calciner allow using already available receiver technologies - High-temperature carbonator in closed CO_2 loop allows the integration of already existing technologies in indirect integration (steam/Stirling) and future ones (SCO2). - Ca-based materials yield limited abrasion compared with other solid particles materials (as SiC)	System tested at TRL5	✓
Primary energy and GHG emission reductions the global climate and energy challenges	Optimised integration of several efficient technologies for high-efficiency power production from solar energy sources with relatively low investment costs	System tested at TRL5	✓
Reducing renewable energy technologies installation time and cost and/or operational costs, hence easing the deployment of renewable energy sources within the energy mix	Capacity for long term storage and 24/365 power operation	Operation under different long term energy storage strategies.	✓
	Optimising the economic performance under a global approach to all systems (solar field/heat transfer media/ storage/power block)	SOCRATCES costs at commercial scale: Energy Storage <12€/kWh_{th} LCOE<7c€/kWh	✓

In addition, the following table summarises the impact per partner:

Partner	Expected Publications	Published Publications	R&D installations	New Knowledge in	Product/ Modules
USE	>6	**17**	Prototype Solar field Final Prototype	TCES/reactors / Solids pneumatic conveying/solar integration /Grid integration/ He-Steam calcination/ Solids/gas storage/ heat exchangers	TCES / Power Unit/ control system
POLITO	>4	**22**	NO	Power block integration/solids conveying/ CO2 storage/ Heat exchangers	-
ZAR	>3	**7**	NO	Systems integration/control/ Solids/gas storage/ heat exchangers	-
CERTH	>3	**5**	Prototype carbonator reactor	Carbonator design/control	Carbonator reactor
CLX	>2	**0**	Prototype calciner	Solar conveying/ He calcination/ systems integration/ Solids pneumatic conveying/Grid integration, energy integration	Calciner reactor / Flash Calcination/ He Calcination
CSIC	>5	**9**	NO	TCES/reactors development/ Solids pneumatic conveying/ CaL attrition / He-Steam calcination	TCES
TTZ	>4	**4**	NO	Power block/LCA/ energy integration/ reactors design	Power Unit/ control system/LCA
BIO	NO	**0**	NO	energy integration/ systems management	-
CNR	>3	**5**	NO	CaL attrition control /reactors development/ Solids pneumatic conveying	-
SPI	NO	**0**	NO	SOCRATCES components and global business model	Business Model,
ISI	NO	**0**	NO	Control technology/ integration	control system
AUTH	>3	**8**	NO	Carbonator design/ CaO sorbents	Carbonator reactor
VM	1	**1**	Prototype solar power system	TCES/power cycles,/ Grid integration/ energy integration	Solar power/control

2. INNOVATION MANAGEMENT

This action aims to design a **decision-making mechanism** to select new ideas and project outcomes - INNOVATIONS- for which there is an actual demand for further development.

2.1. SUMMARY OF PREVIOUS EVALUATION REPORTS

The proposal after the **first year** of the project was to develop a multicriteria decision matrix for the evaluation of the innovation degree/innovation potential of the project INNOVATIONS developed in the different WPs. The work done to prepare the matrix was structured in the following steps:

- STEP 1: Select the criteria for comparison.

It was selected four kinds of criteria: technical, economic, environmental and social. They consider several aspects, but the ones considered more relevant were **engineering specifications** (technical indicators) and **customer needs** (economic and market issues). They were adapted to the specific innovations when required.

CRITERIA	INDICATORS
Technical innovation	Effectiveness
	Efficiency
	Novelty
	Implementation cost
	Ease of implementation
	Applicability and suitability at a different scale
	Compatibility
	Sensitiveness to changes in operating conditions
	Long term effect and the impact on system complexity
	Reliability
Economic criteria	TCES Investment costs.
	Long term storage / energy.
	Storage capacity.
	Levelized cost of energy (LCOE).
	O&M costs per kWh.
	Quality of service.
Environmental criteria	Cumulative energy demand
	Depletion potential
	Emission values
	Land Use
	Toxicity potential
	Risk potential
Social criteria	Equity

Table 1: Criteria and indicators selected within the 1st Evaluation report

- STEP2: Select the innovations to be compared.

The partners were requested to identify the main innovations as outcomes of their work. In the first report, project partners identified **28 innovations**. The innovations identified were not listed on D8.1 because of the public nature of this deliverable. They should be kept confidential to avoid any conflict of interest related to their commercial exploitation and protection, especially if partners are planning to apply for patents.

- STEP3: Score the selected innovations.

From that moment, **continuous monitoring** of the innovations was proposed to be carried out. To do this, they will be followed up using the indicators defined for the technical, economic, environmental and social criteria.

The second year of the project brought great progress in the development of technologies and the results of the different models proposed. This work has made the consortium reconsider the technical indicators proposed in the previous report.

The variety of innovations that arose during the project requires a regrouping of them, not only under WP criteria but also by the nature of innovation. For that reason, it has changed the strategy for evaluating innovations according to the following scheme:

SOCRATCES partners revised the innovations according to work developed during the project, and the result was the identification and description of **33 innovations** (5 more than in the first report) and grouped them according to the nature of each innovation in order to be able to set suitable references comparable with the innovations as well as an indicator which allows for scoring the innovation of the ideas in a proper way.

In order to maintain confidentiality and at the same time to show the impact of innovations developed within the project, the innovations have been codified and not fully described within this deliverable because of the public nature of the deliverable. These codes are related to the internal confidential documents describing the innovations within the consortium. They are fully available for revision under request and always within the confidential framework of the Grant Agreement. It is planned to update this information related to innovation evaluation in order to change the dissemination level of the next related deliverables to "confidential" according to INEA's indications to maximise possibilities of innovations exploitation.

This is the list and groups of innovations resulting from SOCRATCES:

WP	GROUPS	CODE INNOVATIONS
WP2	Models	01_1; 01_3; 01_5, 04_13
	Equipment	03_10, 03_11, 01_32, 04_12, 04_15
	Studies	10_25, 14_27
WP3	Models	01_1, 06_17, 15_31
	Designs	01_2, 01_32, 05_16, 06_18, 14_28, 14_29, 15_33
	Studies	10_24, 14_27
WP4	Integration	02_6, 08_19
	Carbonator	08_20, 08_21
	Stirling	02_7, 02_8, 08_22, 08_23
WP5	Control	01_4, 03_9, 04_14, 13_26
WP7		15_30

The resulting groups were evaluated separately. In this way, the specific references for each of them were established, and the technical indicators have been revised to show the degree of innovation of each of the ideas.

2.2. FINAL PHASE OF INNOVATION EVALUATION

During the **final phase** of the project (2020 and 2021), the construction, testing and operation of the prototype took place, and the consortium was able to compare initial assumptions with the final results of the technology and verify the hypotheses formulated on the different innovations. This evaluation has led the consortium to identify which solutions are more competitive and promising.

Likewise, SOCRATCES was granted the service "Module C - Assisting projects to improve their existing exploitation strategy" by the Horizon Results Booster that allowed the consortium to make an exhaustive study of the key exploitable results of the project and the possible future development of the innovations. This service has included the following activities:

- Review of the key exploitable results of the project.
- Revise, complement and clarify existing exploitation plans of project results and/or outline exploitation paths of results.
- Techniques to identify all relevant stakeholders in the exploitation value chain.
- Support to perform a risk analysis related to the exploitation of results.

The work carried out together with the Horizon Result Booster was very useful for work packages 8 and 9, specifically for the deliverable D9.6 submitted in November 2021 and for the full evaluation of the Key Exploitable results within the actual deliverable.

To summarise, during the second period of SOCRATCES, the work to manage innovation consisted of periodic reviews of the tables developed by the consortium in the last report. These reviews have consisted of a review of the scores given to each of the technical indicators as well as an update of the reference data that serve as benchmarks for our work.

After the reviews carried out in this second period, there have been 31 innovations that maintain a future projection both for new R&D projects and for possible exploitation in the market by the consortium partners.

GROUPS OF INNOVATIONS RELATED TO…	CODE INNOVATIONS
SPECIFIC MODELS FOR CARBONATION (WP2)	01_1; 01_3; 01_5, 04_13
EQUIPMENT FOR CARBONATION (WP2)	03_10, 03_11, 01_32, 04_12, 04_15
STUDIES FOR CARBONATION (WP2)	10_25, 14_27
MODELS FOR SOLAR CALCINER (WP3)	01_1, 06_17, 15_31
DESIGNS FOR SOLAR CALCINER (WP3)	01_2, 01_32, 05_16, 06_18, 14_28, 14_29
STUDIES FOR SOLAR CALCINER (WP3)	10_24, 14_27
INTEGRATION (WP4)	02_6, 08_19
CARBONATOR (WP4)	08_20, 08_21
STIRLING (WP4)	02_7, 02_8, 08_22, 08_23
CONTROL (WP5)	01_4, 03_9, 04_14, 13_26
VALIDATION (WP7)	15_30

2.2.1. Technical evaluation of the innovations

The following tables show the final technical evaluation carried out by the partners regarding the technical indicators for each of SOCRATCES innovations. These evaluations include:

- Explanations of the state of the innovation and the comparison of the same with the reference data
- Quantitative score: high-medium-low, following the methodology of the previous reports, we have maintained this score to be able to compare with the previous report.
- Qualitative score, using the **range form 5 (best) to 1 (worst)** as **final score** which could be used for the further selection and upgrade of our innovation in future R&D processes or exploitation stages.

INNOVATIONS RELATED TO SPECIFIC MODELS FOR CARBONATION (WP2)						
	Indicators	**BENCHMARKING**	**01_1**	**01_3**	**04_13**	**01_5**
Technical Innovation	Novelty (High/Medium/Low)	REFERENCES [1–4]	Medium. Novel models with specific data for TCES: particle size, reaction kinetics, reactor conditions. The models have been developed before, but not specifically for this application. **FINAL SCORE: 4**	Medium. Novel models with specific data for TCES: particle size, reaction kinetics, reactor conditions. The models have been developed before, but not specifically for this application **FINAL SCORE: 4**	Medium. Novel models with applications in gas-solids reaction systems. Drop-tube reactor models specified in CaL-TCES systems. Reactor kinetics; particle size, reactor conditions, Mass-momentum-energy conservation. The model can be applied in every gas-solid application in a drop-tube reactor **FINAL SCORE: 4**	High. There are no carbonators for fines with the vertical flow as large as in SOCRATCES (around 10 m of vertical falling) for 10 kWth. It means changing typical Fluidized Bed FB reactor technology for Entrained Bed (EB) Reactors. Other reactors have been proposed at lab-scale as in the reference **FINAL SCORE: 5**
	Implementation cost (High/Medium/Low)		Numerical models developed **FINAL SCORE:1**	Numerical models developed **FINAL SCORE:1**	Numerical models developed **FINAL SCORE:1**	High. These are the main reactors of the plant. **FINAL SCORE: 4**
	Ease of implementation (High/Medium/Low)	REFERENCE [5]	Numerical models developed **FINAL SCORE:4**	Numerical models developed **FINAL SCORE:2**	Numerical models developed **FINAL SCORE:4**	Difficult. One important objective of the project is to achieve relevant knowledge about the scaling up of the reactors **FINAL SCORE:2**
	Applicability and suitability at a different scale (High/Medium/Low)	REFERENCE [2]	Models will be validated at lab scale to achieve important parameters for the scale-up of the technology **FINAL SCORE: 5**	Models will be validated at lab scale to achieve important parameters for the scale-up of the technology **FINAL SCORE: 4**	Models will be validated at prototype scale to achieve important parameters for the scale-up of the technology **FINAL SCORE: 5**	Difficult. One important objective of the project is to achieve relevant knowledge about the scaling up of the reactors **FINAL SCORE: 3**
	Compatibility with the project goals (High/Medium/Low)		The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	The approach is 100% compatible with the goals of the project. **FINAL SCORE: 4**
	Sensitiveness to changes in operating conditions (High/Medium/Low)		Highly sensitive, this is the reason for the novelty. There are models focused on specific conditions for TCES **FINAL SCORE: 1**	Highly sensitive, this is the reason for the novelty. There are models focused on specific conditions for TCES **FINAL SCORE: 4**	Highly sensitive, this is the reason for the novelty. There are models focused on specific conditions for TCES **FINAL SCORE: 1**	Highly sensitivity. Along the project will be evaluated operation ranges for the main parameters **FINAL SCORE: 3**
	Reliability (High/Medium/Low)	[5]	Numerical models validated **FINAL SCORE:4**	Numerical models validated **FINAL SCORE:3**	Numerical models validated **FINAL SCORE:4**	High. These reactors are currently used for other industrial applications **FINAL SCORE: 3**

INNOVATIONS RELATED TO EQUIPMENT FOR CARBONATION (WP2)							
	Indicators	**BENCHMARKING**	**03_10**	**03_11**	**01_32**	**04_12**	**04_15**
Technical Innovation	Novelty (High/Medium/Low)	REFERENCE [2,4,6]	High. Typical cyclone operation includes large particles **FINAL SCORE: 5**	High. There is not any carbonator reactor with fins. **FINAL SCORE: 5**	High. It is the main innovation. It is a novel approach for controlling carbonator temperature and enhancing heat transfer **FINAL SCORE: 5**	High. Novel configuration specified for TCES **FINAL SCORE: 5**	High. There are no similar designs in the literature for cooling drop-tube carbonators **FINAL SCORE: 3**
	Collection efficiency by particle size (%)	High. 80% [7]	Increase efficiency up to 85-90% for particle sizes below 5 microns **FINAL SCORE: 4**	Does not apply	Does not apply	Does not apply	Does not apply
	Implementation cost (High/Medium/Low)	Medium. Not yet evaluated at this stage	Medium. Not yet evaluated at this stage **FINAL SCORE: 3**	Medium. Not yet evaluated at this stage **FINAL SCORE: 3**	Medium. Not yet evaluated at this stage **FINAL SCORE: 3**	Medium. Not similar data are available to compare **FINAL SCORE: 3**	Medium. Not similar data are available to compare **FINAL SCORE: 3**
	Compatibility with the project goals (High/Medium/Low)	No compatible with project goals	High. The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	High. The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	High. The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	High. The approach is 100% compatible with the goals of the project. **FINAL SCORE: 3**	High. The approach is 100% compatible with the goals of the project. **FINAL SCORE: 2**
	Dimensions of the carbonator. Length (m2)	High. Not yet evaluated in the scale-up at this stage	N/A	Reduction of 10% of length area due to fins	High. Improves carbonation design **FINAL SCORE: 4**	High. Improves carbonation design and reactions control **FINAL SCORE: 4**	High. Improves carbonation design and reactions control **FINAL SCORE: 4**
	Respond to operational conditions changes (s)	Medium. Not yet evaluated at this stage	Medium. Not yet evaluated at this stage. Few seconds/minutes depending on size	Reduction of the time of transient processes	High. It involves fully novel operation conditions **FINAL SCORE: 5**	High. Flexible construction for flexible operation **FINAL SCORE: 5**	High. Constructed to be flexible in operation **FINAL SCORE: 5**
	Effectiveness (High/Medium/Low)	High. Not yet evaluated in the scale-up at this stage	Medium. Complete separation is near impossible, and system improvements are achieved without a high separation **FINAL SCORE: 3**	High. It enhances heat transfer and facilitates control **FINAL SCORE: 5**	High. It enhances heat transfer and facilitates control **FINAL SCORE: 5**	It is not tested yet. There is only one similar drop-tube carbonator with electric furnaces. Novel configuration specified in TCES conditions **FINAL SCORE: 3**	Medium. Even though it is not tested yet, it is expected to be effective. There are no similar designs in the literature **FINAL SCORE: 3**

INNOVATIONS RELATED TO EQUIPMENT FOR CARBONATION (WP2)							
Criteria	**Indicators**	**BENCHMARKING**	**03_10**	**03_11**	**01_32**	**04_12**	**04_15**
	Sensitiveness to changes in operating conditions (High/Medium/Low)		Low. **FINAL SCORE: 2**	Low.	High sensitivity. The control strategy is developed to allow fast response to operating conditions **FINAL SCORE: 4**	High. Flexible construction for flexible operation **FINAL SCORE: 4**	High. Constructed to be flexible in operation **FINAL SCORE: 4**
	Ease of implementation (High/Medium/Low)		Medium. A new multitubular reactor is necessary **FINAL SCORE: 3**	Low. Small changes in design.	Medium. Not yet evaluated at this stage **FINAL SCORE: 2**	Medium. Not implemented yet **FINAL SCORE: 2**	Low. Not easy to be constructed **FINAL SCORE: 2**
	Applicability and suitability at a different scale (High/Medium/Low)		High. Scale-up rules for cyclones are well established **FINAL SCORE: 4**	High. No problems with scale-up **FINAL SCORE: 4**	High. The CO2 mass flow circulating around the components can be increased with the CSP plant size **FINAL SCORE: 4**	High applicability of the concept at different scales with the adequate redesign. **FINAL SCORE: 5**	High applicability of the concept at different scales with the adequate redesign. **FINAL SCORE: 5**
	Efficiency (High/Medium/Low)		Medium. But system improvements are relevant **FINAL SCORE: 3**	Medium. But system improvements are relevant **FINAL SCORE: 3**	High. Expected a notable efficiency improvement **FINAL SCORE: 4**	High effcienciy of the concept at different scales with the adequate redesign. **FINAL SCORE: 4**	Medium. Even though it is not tested yet, it is expected to be efficient. There are no similar designs in the literature **FINAL SCORE: 3**

INNOVATIONS RELATED TO STUDIES FOR CARBONATION (WP2)				
Criteria	**Indicators**	**BENCHMARKING**	**10_25**	**14_27**
Technical Innovation	Effectiveness (High/Medium/Low)	[8–10]	High. Studies have shown that calcination and carbonation are significantly enhanced in a sound-assisted fluidised bed. **FINAL SCORE: 5**	Medium. A range of sorbents derived from industrial wastes could hold a similar residual carrying capacity to natural limestone. **FINAL SCORE: 2**
	Novelty (High/Medium/Low)	[8–11]	Medium. Sound-assisted tests have been performed on fluidised beds before, but not in a CSP context **FINAL SCORE: 4**	High. Many of these materials have not been studied for this particular use before. **FINAL SCORE: 4**
	Implementation cost (High/Medium/Low)	[8,9]	N/A	High. They are low-cost carbonate materials that can be used as CO_2 sorbents. **FINAL SCORE: 5**
	Ease of implementation (High/Medium/Low)	[10,11]	High. All the equipment (signal generator, audio amplifier, loudspeaker and oscilloscope) required are for sound generation is very easily available on the market and can be easily implemented. **FINAL SCORE: 5**	High. Low costs materials as CO2 sorbents proved and available. **FINAL SCORE: 5**
	Applicability and suitability at a different scale (High/Medium/Low)	[1], [2]: Medium [3],[4]	High. This technology can be easily scalable. **FINAL SCORE: 5**	High. Simply more sorbent is required, and the amounts available are high. **FINAL SCORE: 5**
	Compatibility with the project goals (High/Medium/Low)	SOCRATCES Description of Work	Medium. Although it improves calcination and carbonation, it is relevant to fluidised beds, which are not being used in the project.	High. The project has a specific mandate to study alternatives to limestone. **FINAL SCORE: 5**
	Sensitiveness to changes in operating conditions (High/Medium/Low)	[1], [2]: Medium	N/A	High. These sorbents are generally relevant over the same operating conditions as limestone. **FINAL SCORE: 5**
	Ability to measure a wide range of relevant operating conditions (High/Medium/Low)	[3],[4]	High. The sound frequency and amplitude can be altered depending on different particle and gas properties. **FINAL SCORE: 5**	High. Low costs materials as CO2 sorbents proved in a wide range and are available **FINAL SCORE: 5**
	Relevance to resulting designs/reactions/processes (High/Medium/Low)	[3],[4]	Medium. This is mainly relevant to calcination and carbonation in fluidised beds, but there are some applications in drop tube reactors which, but some applications in drop tube reactors should be studied further. **FINAL SCORE: 3**	High. Low costs materials as CO2 sorbents proved and available. **FINAL SCORE: 5**

INNOVATIONS RELATED TO MODELS FOR SOLAR CALCINER (WP3)					
	Indicators	**BENCHMARKING**	**01_1**	**06_17**	**15_31**
Technical Innovation	Effectiveness (High/Medium/Low)	[12–14]	High. These models have been critical for unit design. **FINAL SCORE: 5**	High. These models have been critical for unit design. **FINAL SCORE: 5**	High. These models have been critical for unit design. **FINAL SCORE: 4**
	Novelty (High/Medium/Low)	[12–15]	Medium. The models have been developed before, but not specifically for this application. **FINAL SCORE: 3**	Medium. We have developed models which are similar to those in general CaL. However, there are some innovations around fast calcination and focusing on CSP-CaL conditions **FINAL SCORE: 3**	High. This kind of calciner (with an irradiating cavity) is new, and so similar simulations have not been made before. **FINAL SCORE: 5**
	Ease of implementation (High/Medium/Low)	Not evaluated yet	High. The models are developed specifically for the calciner and carbonator as designed. **FINAL SCORE: 4**	High. The models are very relevant to SOCRATCES and were developed with implementation within the project. **FINAL SCORE: 5**	High. The models are very relevant to SOCRATCES and were developed with implementation within the project. **FINAL SCORE: 4**
	Applicability and suitability at a different scale (High/Medium/Low)	[12–15]	High. The models have a few geometrical parameters, but these are flexible and can be altered depending on the reactor dimensions. This is more relevant than 1D models. The models are specific for TCES. **FINAL SCORE: 5**	High. The models are fundamental and relevant at all scales, from crystal/grain (some nm) up to full-scale plants (some metres). **FINAL SCORE: 5**	Medium. The models are generally relevant, but scale-up will require some reworking. **FINAL SCORE: 4**
	Compatibility with the project goals (High/Medium/Low)	-	High. These models have been critical for unit design. **FINAL SCORE: 5**	High. The kinetics are crucial to the success of SOCRATCES, and the model is applicable. The models were a key part of D3.2. **FINAL SCORE: 5**	High. The heat transfer inside the calciner is crucial for calcination to occur. The geometry is new, so there are no previous models to fall back on. **FINAL SCORE: 5**
	Ability to be modified and validated with experimental data (High/Medium/Low)	[12–15]	High. These models will use process data to be improved. **FINAL SCORE: 5**	High. The kinetic models are of a flexible format which allows fitting experimental data to modify the 2-3 parameters. These parameter values are then used for predictions. **FINAL SCORE: 5**	High. The model should be modified to take account of real process data when they are available. The model is easily configurable to accommodate these data **FINAL SCORE: 5**
	Long term effect and the impact on system complexity	[12–15]	High. It is necessary for the better design of the process **FINAL SCORE: 4**	High. Although the models themselves are complex, understanding the kinetics reduces the uncertainty elsewhere in the process. **FINAL SCORE: 5**	Medium. Little effect on system complexity, but important for the long-term development of the technology. **FINAL SCORE: 4**
	Reliability (High/Medium/Low)	[12–15]	Numerical models developed. **FINAL SCORE: 4**	Numerical models developed. **FINAL SCORE: 4**	Not validated yet due to calcination temperatures in the solar receiver **FINAL SCORE: 4**

INNOVATIONS RELATED TO DESIGNS FOR SOLAR CALCINER (WP3)								
	Indicators	**BENCHMARKING**	**01_2**	**05_16**	**06_18**	**14_28**	**14_29**	**01_32**
Technical Innovation	Effectiveness (High/Medium/Low)	[8,9] 96%	High. The design should be effective at calcining, but questions remain about whether the radiation can sufficiently penetrate the bed. **FINAL SCORE: 4**	High. The design should allow flash calcination of sorbent, reducing the time spent at the harsh conditions, which cause annealing and sintering. The small size of the particles reduces the amount and effect of any attrition. **FINAL SCORE: 4**	High. As a result of their being optimum, they will be effective. FINAL SCORE: 4	Successful designs identified **FINAL SCORE: 3**	Medium. Materials deposition on the heat transfer surface could reduce thermal transfer efficiency. Modelling of fouling in the reactors would mitigate risks during operation. **FINAL SCORE: 2**	High. The design should be effective at calcining, but questions remain about whether the high CO_2 mass flow at a high temperature can be conveyed to the reactor. **FINAL SCORE: 4**
	Efficiency (High/Medium/Low)	[8,9] 31%	Medium. While the solar energy can be well distributed, the nature of the bed may cause the top layer to be sintered while the bottom layer is still uncalcined. **FINAL SCORE: 4**	Medium. The concept should provide a cavity wall at a temperature that allows for high heat transfer. Losses out of the cavity aperture have been higher than expected but are manageable on a larger scale. **FINAL SCORE: 4**	High. As a result of their being optimum, they will be efficient. (There may, however, be some trade-off with effectiveness.) **FINAL SCORE: 4**	High. The CaCO3 sorbents have the tendency to agglomerate due to cohesive forces at elevated temperatures. An effective reactor design should reduce this phenomenon, avoiding further risks. **FINAL SCORE: 4**	Medium. The efficiency is not significantly affected as the fouling is controlled. **FINAL SCORE: 4**	Medium. Not yet evaluated at this stage **FINAL SCORE: 3**
	Novelty (High/Medium/Low)	[8,9]	High. This is a new invention that is not seen elsewhere. **FINAL SCORE: 5**	High. This new invention combines two fields (flash calciners and CSP) in a new way. **FINAL SCORE: 5**	Medium. The conditions will be new, but the concept of running at optimum conditions is a long-held approach. **FINAL SCORE: 4**	High. Avoidance of agglomeration of sorbent particles may significantly increase the efficiency due to higher reaction rates in the reactors. **FINAL SCORE: 5**	Medium. Similar CFD studies have been done for different systems, such as fouling in heat exchangers. **FINAL SCORE: 4**	High. No previous solar receivers are based on this technology. **FINAL SCORE: 5**
	Implementation cost (High/Medium/Low)	[2]: 85 € (2018) per tonne lime at 25 MWth scale	Medium. There is a significant cost in installing vibration units, but the rest will be relatively cheap. **FINAL SCORE: 4**	Low. It is a double-walled vessel made of steel. **FINAL SCORE: 2**	Low. There will be some initial outlay to determine these conditions, but after that the cost is zero but the returns could be very large. **FINAL SCORE: 2**	Medium. More complex reactor designs could potentially increase the CAPEX of the unit. **FINAL SCORE: 3**	Low. CFD studies and lab-scale experiments are needed. **FINAL SCORE: 2**	Medium. Not yet evaluated at this stage **FINAL SCORE: 3**

INNOVATIONS RELATED TO DESIGNS FOR SOLAR CALCINER (WP3)							
Indicators	BENCHMARKING	01_2	05_16	06_18	14_28	14_29	01_32
Ease of implementation (High/Medium/Low)	[5][16]	Medium. While the design is theoretically simple, running a vibratory table at high temperature in an airtight environment with powder may present significant operability challenges **FINAL SCORE: 3**	High. It is easy to install, but there is a need to carefully control the CSP beams to spread the energy around the cavity wall **FINAL SCORE: 5**	The optimum conditions have been analysed and tested at a pilot scale. **FINAL SCORE: 4**	Low. CFD studies and lab-scale experiments are needed. **FINAL SCORE: 2**	Medium. Reactor design incorporating fouling effects could be of high complexity. **FINAL SCORE: 3**	Medium. Not yet evaluated at this stage **FINAL SCORE: 2**
Applicability and suitability at a different scale (High/Medium/Low)	https://cordis.europa.eu/project/id/727402/es [17] [5] [18] [19]	Medium. The process is scalable but is modular, i.e. there would be relatively small savings from scaling up. **FINAL SCORE: 2**	High. The design is more suited to larger size systems, where the cavity can be made larger whilst keeping the >900 C temperature required for calcination. This would increase residence time and ensure reasonable calcination levels. **FINAL SCORE: 5**	Medium. Whilst the fundamentals of an optimum condition for calcination are easy to determine, the exact heating rates, powder flow rates per unit area etc. will vary according to scale. Process model validation using pilot-scale data will help to increase the applicability. **FINAL SCORE: 3**	Medium. The complexity of the design could be elevated by increasing the scale. **FINAL SCORE: 5**	High. CFD modelling could be applied at different scales providing reliable results. **FINAL SCORE: 5**	Medium. It seems more appropriate just for large scale systems **FINAL SCORE: 3**
Compatibility with the project goals (High/Medium/Low)	SOCRATCES Description of Work [20]	Medium. While it should calcine, it is not of flash calciner design as per the grant **FINAL SCORE: 3**	High. The design fulfils all requirements of the specification as set out in the grant **FINAL SCORE: 4**	High. Optimal conditions will increase efficiency and thus the relevance of the process to commercial scale-up activities. **FINAL SCORE: 5**	High. Efficient reactor design is essential for demonstrating the viability of thermochemical energy storage via calcium looping. **FINAL SCORE: 5**	Medium. Fouling is not a risk directly related to SOCRATCES. Despite that, the project aims at identifying risks related to higher TRLs. **FINAL SCORE: 3**	Low. Not evaluated yet. Highly related to **FINAL SCORE: 4**

INNOVATIONS RELATED TO DESIGNS FOR SOLAR CALCINER (WP3)							
Indicators	BENCHMARKING	01_2	05_16	06_18	14_28	14_29	01_32
Sensitiveness to changes in operating conditions (High/Medium/Low)	[17][20][21] [19]	Medium. All systems involving high-temperature calcination are sensitive to such changes; 10 C can double (or halve) reaction rates **FINAL SCORE: 3**	Medium. All systems involving high-temperature calcination are sensitive to such changes; 10 C can double (or halve) reaction rates **FINAL SCORE: 3**	Low. The optimum conditions are not affected by non-optimal conditions. **FINAL SCORE: 2**	Low. Limestone should be conveyed without problems from one reactor to the other. **FINAL SCORE: 1**	Medium. Operating conditions are expected to affect fouling. The modelling should be conducted considering different operating conditions. **FINAL SCORE: 2**	High. The control of the different gas injections must allow giving a rapid response to changes in operating conditions **FINAL SCORE: 4**
Long term effect and the impact on system complexity	[5][16] [19]	Medium. If the operability issues become challenging, the system complexity could rapidly increase. **FINAL SCORE: 3**	Medium. Although the calciner will stay relatively simple, there are knock-on effects for the solar field. These should be easier to overcome in a field-scale trial **FINAL SCORE: 3**	High, but in a positive way. **FINAL SCORE: 5**	High. Agglomeration is significantly affected by temperature when the sorbent is in carbonated form. **FINAL SCORE: 5**	Medium Modelling of fouling will give information regarding systems maintenance. **FINAL SCORE: 3**	Medium. If the operability issues become challenging, the system complexity could rapidly increase. **FINAL SCORE: 3**
Reliability (High/Medium/Low)	[5][16] [19]	Medium. The operability of the vibratory tables in a dust-laden, airtight environment will be a challenge. **FINAL SCORE: 3**	Low/Medium. The CSP-cavity interface is the key in this system and must be kept in an operable state **FINAL SCORE: 2**	Not applicable. -	High. It is crucial for the normal operation of the systems. **FINAL SCORE: 4**	Medium/High. CFD models are considered reliable as they have been successfully used in the past. **FINAL SCORE: 3**	Medium. Not yet evaluated at this stage **FINAL SCORE: 3**
Ability to be validated with experimental data (High/Medium/Low)	[19] [22,23]	High. If built, the results could be validated quickly and easily. **FINAL SCORE: 4**	High. When built, the results could be validated quickly and easily. **FINAL SCORE: 4**	High. The fingerprinting exercise (running the calciner at a range of temperatures and flow rates) will quickly validate whether the optimal conditions predicted by modelling are indeed optimal. **FINAL SCORE: 5**	Medium. The agglomeration phenomena have to be tested during the prototype system operation. **FINAL SCORE: 3**	High. The models can be validated in the prototype. **FINAL SCORE: 5**	Low. Not yet evaluated at this stage **FINAL SCORE: 1**

INNOVATIONS RELATED TO STUDIES FOR SOLAR CALCINER (WP3)				
	Indicators	BENCHMARKING	10_24	14_27
Technical Innovation	Effectiveness (High/Medium/Low)	[24,25] [20][26]	High. Studies have shown that calcination and carbonation are significantly faster in a fluidised bed when sound-assisted. **FINAL SCORE: 5**	High. A range of sorbents derived from industrial wastes could hold a similar residual carrying capacity to natural limestone. **FINAL SCORE: 5**
	Novelty (High/Medium/Low)	[24,25][27]	Medium. Sound-assisted trials in FBs have been performed on fluidised beds before, but not in a CSP context. **FINAL SCORE: 3**	High. Many of these materials have not been studied for this particular use before. **FINAL SCORE: 5**
	Relevance to resulting designs/reactions/processes (High/Medium/Low)	[24,25] [28]	Medium. This is mainly relevant to calcination and carbonation in fluidised beds, but some applications in drop tube reactors should be studied further **FINAL SCORE: 3**	High. A range of sorbents derived from industrial wastes could hold a similar residual carrying capacity to natural limestone. **FINAL SCORE: 5**
	Applicability and suitability at a different scale (High/Medium/Low)	[24,25]	High. This technology is easily scalable. **FINAL SCORE: 5**	High. Simply more sorbent is required, and the amounts available are high. **FINAL SCORE: 5**
	Compatibility with the project goals (High/Medium/Low)	SOCRATCES Description of Work	Medium. Application is relevant to fluidised beds, which has been analysed in the project. **FINAL SCORE: 3**	High. The project has a specific mandate to study alternatives to limestone. **FINAL SCORE: 5**
	Ability to measure a wide range of relevant operating conditions (High/Medium/Low)	[24,25] [29]	High. The frequency and amplitude can be altered to account for different particle properties or gas densities. **FINAL SCORE: 4**	High. The project has a specific mandate to study alternatives to limestone at a pilot scale. **FINAL SCORE: 5**

INNOVATIONS RELATED TO INTEGRATION (WP4)				
Criteria	Indicators	BENCHMARKING	02_6	08_19
Technical Innovation	Efficiency (High/Medium/Low)	8-15 % [30–32]	13-19% efficiency, including solar loses **FINAL SCORE: 4**	18% **FINAL SCORE: 3**
	Novelty (High/Medium/Low)	High [6]	High. The integration is done with a newly proposed approach [7] **FINAL SCORE: 4**	High **FINAL SCORE: 5**
	Implementation cost (High/Medium/Low)	5-15 USD/kW [33,34]	12-18 kUSD /kW **FINAL SCORE: 1**	10-12 USD/kW **FINAL SCORE: 3**
	Ease of implementation (High/Medium/Low)	High [35]	Medium. A heat exchanger network has to be built in order to recover thermal power optimally **FINAL SCORE: 3**	High **FINAL SCORE: 4**
	Applicability and suitability at a different scale (High/Medium/Low)	High [6]	High. The model is scale-independent **FINAL SCORE: 5**	High **FINAL SCORE: 4**
	Sensitiveness to changes in operating conditions (High/Medium/Low)	Low [35]	Low. The model allows taking into account different operating conditions. **FINAL SCORE: 2**	High **FINAL SCORE: 4**

INNOVATIONS RELATED TO CARBONATOR (WP4)				
	Indicators	BENCHMARKING	08_20	08_21
Technical Innovation	Efficiency (High/Medium/Low)	40% at 4 m SOCRATCES Deliverable D2.2	~ 80% at 2 m **FINAL SCORE: 2**	N/A **FINAL SCORE: 2**
	Novelty (High/Medium/Low)	High SOCRATCES Deliverable D2.2	High **FINAL SCORE: 5**	High **FINAL SCORE: 4**
	Ease of implementation (High/Medium/Low)	Low SOCRATCES Deliverable D2.2	High **FINAL SCORE: 4**	Low **FINAL SCORE: 2**
	Applicability and suitability at a different scale (High/Medium/Low)	Medium SOCRATCES Deliverable D2.2	High **FINAL SCORE: 4**	High **FINAL SCORE: 4**
	Sensitiveness to changes in operating conditions (High/Medium/Low)	High SOCRATCES Deliverable D2.2	High **FINAL SCORE: 4**	High **FINAL SCORE: 4**
	Long term effect and the impact on system complexity (High/Medium/Low)	High SOCRATCES Deliverable D2.2	High **FINAL SCORE: 5**	High **FINAL SCORE: 5**

INNOVATIONS RELATED TO STIRLING (WP4)						
	Indicators	BENCHMARKING	02_7	02_8	08_22	08_23
Technical Innovation	Efficiency of the Stirling system (High/Medium/Low)	8-18% SOCRATCES Deliverable 4.3	10-20 % **FINAL SCORE: 3**	10-20 % **FINAL SCORE: 3**	Up to 30% **FINAL SCORE: 3**	Up to 35% **FINAL SCORE: 3**
	Novelty (High/Medium/Low)	Low [36]	Medium. An approach for topology improvement is proposed. **FINAL SCORE: 2**	Medium. **FINAL SCORE: 2**	Medium **FINAL SCORE: 3**	Low **FINAL SCORE: 2**
	Implementation cost of the Stirling system (High/Medium/Low)	28,440€ /1kW engine[1]	15,000-30,000 € /1kW engine **FINAL SCORE: 4**	15,000-30,000 € /1kW engine **FINAL SCORE: 4**	15,000 € /1kW engine **FINAL SCORE: 4**	10,000 € /1kW engine **FINAL SCORE: 4**
	Ease of implementation (High/Medium/Low)	High Deliverable 4.3	Medium. The design of the heat exchanger must be changed **FINAL SCORE: 3**	Medium **FINAL SCORE: 3**	Low **FINAL SCORE: 2**	High **FINAL SCORE: 4**
	Applicability and suitability at a different scale (High/Medium/Low)	Low Deliverable 4.1	Medium. The new design can be applied to different system sizes **FINAL SCORE: 2**	Medium. In the case of the smaller size, it is more difficult to find an absorption chiller. **FINAL SCORE: 2**	Medium **FINAL SCORE: 3**	Low **FINAL SCORE: 2**
	Compatibility in integration (High/Medium/Low)	Low Deliverable 4.1 Deliverable 4.3	High. The heat exchanger can be easily included in a new system design **FINAL SCORE: 4**	High **FINAL SCORE: 4**	Medium **FINAL SCORE: 2**	Medium **FINAL SCORE: 2**
	Sensitivity to changes in operating conditions (High/Medium/Low)	High Deliverable 4.1	Medium. In the case of different operating conditions, the optimal design could be slightly different. **FINAL SCORE: 3**	Medium. **FINAL SCORE: 3**	Medium **FINAL SCORE: 3**	Medium **FINAL SCORE: 3**

[1] G. Lubbers, Quotation for Stirling Engine, Doetinchem: Microgen Engine Corporation, 2019.

INNOVATIONS RELATED TO CONTROL (WP5)					
Indicators	**BENCHMARKING**[2]	**01_4**	**03_9**	**04_14**	**13_26**
Effectiveness (High/Medium/Low)	-	High. Novel control systems are fundamental to improve the performance of the system. **FINAL SCORE: 4**	High. As there is not a control system developed for CSP with CaL and the control system developed works well, this innovation is effective. **FINAL SCORE: 4**	High. In the case of a successful MPC development, it is expected that the effectiveness regarding the efficiency of the plant and regarding the scalability would be very high. **FINAL SCORE: 4**	In the case of successful development, it is expected that the effectiveness regarding the efficiency of the plant and regarding the scalability would be very high. **FINAL SCORE: 5**
Efficiency (High/Medium/Low)	-	High. Novel control systems are fundamental to improve the performance of the system. **FINAL SCORE: 4**	It is expected that the efficiency of the plant is not increased significantly. The main advantage is that the MI program can be used for the different process control task. **FINAL SCORE: 4**	High. MPC strategies will enhance the efficiency of the process and also will optimise the dynamics until a steady-state is reached. **FINAL SCORE: 4**	It is expected that the efficiency of the plant is not increased significantly. The main advantage is that the MI program can be used for the different process control task. **FINAL SCORE: 5**
Novelty (High/Medium/Low)	-	High. The main innovation as there is not a control system developed specifically for these types of installations. **FINAL SCORE: 3**	High. The main innovation as there is not a control system developed specifically for these types of installations. **FINAL SCORE: 3**	High. It is the main innovation. It is a novel approach for controlling the carbonator operation. **FINAL SCORE: 3**	High. The synonym "artificial intelligence "is used for several kinds of methods. Especially in control technics, artificial intelligence like FUZZY logic has been used for a long time, but especially machine learning is quite new for process control. **FINAL SCORE: 4**
Implementation cost (High/Medium/Low)	-	Medium. Not yet evaluated at this stage for similar installations. **FINAL SCORE: 3**	Medium. 50 k€ but it can be higher depending on future improvements in automatic control. **FINAL SCORE: 3**	Medium. It is assumed that the implementation cost of an MPC strategy will require additional costs in PM and computers. **FINAL SCORE: 1**	It is assumed that an additional well-performed computer is needed. Further (hardware) costs are not expected. **FINAL SCORE: 1**
Ease of implementation (High/Medium/Low)	-	The hardware implementation is quite simple. The human effort (programming) cannot be predicted at the actual state. **FINAL SCORE: 4**	The hardware implementation is quite simple. The human effort (programming) cannot be predicted at the actual state. **FINAL SCORE: 3**	Medium. There is no benchmark to compare **FINAL SCORE: 4**	The hardware implementation is quite simple. The human effort (programming) can't be predicted at the actual state. **FINAL SCORE: 3**
Applicability and suitability at a different scale (High/Medium/Low)	-	Applicable at all scales. Once the AI mechanism is set up, it can be used for any scale without changes. **FINAL SCORE: 4**	Applicable at all scales. Once the AI mechanism is set up, it can be used for any scale without changes. **FINAL SCORE: 5**	High. MPC strategies can also be implemented at different scales **FINAL SCORE: 4**	Applicable at all scales. Once the AI mechanism is set up, it can be used for any scale without changes. **FINAL SCORE: 4**

[2] There is not any specific control system for this type of installations.

INNOVATIONS RELATED TO CONTROL (WP5)					
Indicators	**BENCHMARKING[3]**	**01_4**	**03_9**	**04_14**	**13_26**
Compatibility with the project goals (High/Medium/Low)	-	The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	High. The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**	The approach is 100% compatible with the goals of the project. **FINAL SCORE: 5**
Respond to operational conditions changes (High/Medium/Low)	-	**FINAL SCORE: 5**	High. Few seconds **FINAL SCORE: 5**	High. Very sensitive control strategy. **FINAL SCORE: 5**	High. Reduction of the time of transient processes. **FINAL SCORE: 5**
Reliability (High/Medium/Low)	-	**FINAL SCORE: 4**	High. Control working with reliability **FINAL SCORE: 5**	High. MPC strategies can be highly reliable if reactor models are reliable too. **FINAL SCORE: 4**	**FINAL SCORE: 4**

INNOVATIONS RELATED TO VALIDATION (WP7)		
Indicators	**BENCHMARKING**	**15_30**
Effectiveness (High/Medium/Low)	Medium (effective only for large quantities of heliostats) [37]	Low (for the small number of heliostats and relatively high thermal inertia of the receiver, dynamic aim control is not necessary). **FINAL SCORE: 2**
Efficiency (High/Medium/Low)	Low (long travel to standby position) [37]	Medium, as the SOCRATCES heliostat moves faster than larger commercial heliostats. **FINAL SCORE: 4**
Novelty (High/Medium/Low)	Low (typical heliostat control) [37]	Low, this type of control is common in central receiver CSP. **FINAL SCORE: 2**
Implementation cost (High/Medium/Low)	Low (only programming) [37]	Low. **FINAL SCORE: 2**
Ease of implementation (High/Medium/Low)	High (remote programming) [37]	High. **FINAL SCORE: 4**
Applicability and suitability at a different scale (High/Medium/Low)	High (does not change with scale) [37]	High. **FINAL SCORE: 4**
Compatibility (High/Medium/Low)	High (applicable to different receiver types) [37]	High. **FINAL SCORE: 5**
Sensitiveness to changes in operating conditions (High/Medium/Low)	Medium (only full on-full off focusing) [37]	Low, due to the high inertia of the receiver. **FINAL SCORE: 5**
Long term effect and the impact on system complexity (High/Medium/Low)	Low (no impact on system complexity) [37]	Low. **FINAL SCORE: 2**

[3] There is not any specific control system for this type of installations.

2.2.2. Full evaluation of the SOCRATCES Key Exploitable Results

To finalise the evaluation work of the innovations arising within the project, a complete evaluation of the 3 Key Exploitable Results (KERs) has been carried out.

These KERs were identified based on the scientific and technological knowledge exploitable from the SOCRATCES project. The KER's identified under the scope of Deliverable *D1.3 Innovation Management Manual* were updated with information provided under Task 8.7. The results collected were next integrated with the major outcomes of the Exploitation Strategy Seminar from the PDES-C service (Horizon Results Booster Module C) conducted by an external expert appointed by the European Commission, and finally, they were updated within deliverable 9.6 IPR and Exploitation plan including new KER's reflecting partners' main interests and the exploitation potential.

The consortium decided to develop a full evaluation including technical, economic, and environmental indicators about the KERs should be thoroughly evaluated as they are the ones with the most direct application in the market during the following years.

- Evaluation of SOCRATCES Technology as Energy Storage System (KER1):

Criteria	Indicators	REFERENCE DATA	KER1 SOCRATCES Technology as Energy Storage System
Technical Innovation	Novelty (High/Medium/Low)	[20,38]	SOCRATCES concept is a fully novel approach to current TES systems (molten salts)
	Implementation cost (High/Medium/Low)	[20,39]	SOCRATCES-based energy storage systems have an implementation cost similar to molten salts systems. Further cost reduction for SOCRATCES technology is expected
	Ease of Implementation (High/Medium/Low)	[40,41]	SOCRATCES technology is fully novel, and it requires novel designs that should be optimised in the next stages of the technology (currently TL5). Similarities with the cement industry could ease the implementation of the SOCRATCES technology
	Applicability and suitability at a different scale (High/Medium/Low)	[42]	The system is applicable for energy storage in renewable plants but also as energy storage in industrial applications. Scales: 0,5kW_{th}- 100 MW_{th}
	Compatibility with the project goals (High/Medium/Low)	https://cordis.europa.eu/project/id/727348/es	SOCRATCES is aimed at demonstrating the feasibility of the CSP-CaL integration by erecting a pilot-scale plant
	Sensitiveness to changes in operating conditions (High/Medium/Low)	[20]	SOCRATCES concept is a flexible technology that can operate under different operation conditions and even under different integration with technologies for energy storage CO2 capture, H_2 production, etc.
	Reliability (High/Medium/Low)	https://cordis.europa.eu/project/id/727348/es	SOCRATCES technology is fully novel, and it requires novel designs that should be optimised in the next stages of the technology (currently TL5).
Economic Innovation	TCES Investment costs	26.4 $/kWh for Ca(OH2) [43]	10 €/kWh (Deliverable D8.14)
	Long term storage / energy	up to 15h for molten salts [42]	Days-Months (10.1016/j.rser.2019.109252)
	Storage capacity	200-350 kWh/m^3 [42]	200-1000 kWh/m^3 (1016/j.rser.2019.109252)
	Levelized cost of energy (LCOE)	(100-150 €/MWh) for molten salts [44]	80-130 €/MWh (10.1016/j.apenergy.2020.116257, Deliverable 8.14)
	O&M costs per MWh	3.5 $ for molten salts [45]	3.45€ (Deliverable D8.14)
Environmental Innovation	Cumulative energy demand	170 MJ/MWh [46]	360 MJ/MWh
	Emission values	for molten salts 32-42 gCO^2-eq/MWh [46]	20-35 gCO^2-eq/MWh (Deliverable D8.13)
	Land Use	Higher for molten salts case due to the lower energy density [42]	0.01182633 m^2/MWh (Deliverable D8.13)
	(Human) Toxicity potential	-	kg 1,4 - DCB – eq. (Deliverable D8.13)
	Risk potential (qualitative)	-	Acceptable. Reactors are the main risky systems. (10.3390/en14196013)

- Evaluation of Solar and/or Electric Calciner Reactor (KER2):

Criteria	Indicators	REFERNCE DATA	KER2 Solar and/or Electric Calciner Reactor
Technical Innovation	Novelty (High/Medium/Low)	[5,7]	SOCRATCES calciner is a fully novel approach to current state-of-the-art calciner reactors
	Implementation cost (High/Medium/Low)	[47]	SOCRATCES calciners are like those typical coal-fired calciners used in lime or cement industries. Novel designs are required to integrate solar energy
	Ease of Implementation (High/Medium/Low)	[5,40,41]	SOCRATCES calciners are like those typical coal-fired calciners used in lime or cement industries. Novel designs are required to integrate solar energy
	Applicability and suitability at a different scale (High/Medium/Low)	[5,20]	SOCRATCES calciner is highly scalable, which is an advantage regarding typical calciners found in large scale cement plants
	Compatibility with the project goals (High/Medium/Low)	https://cordis.europa.eu/project/id/727348/es	SOCRATCES global objective is to develop a prototype that will reduce the core risks of scaling up the technology and solve challenges
	Sensitiveness to changes in operating conditions (High/Medium/Low)	[5,48]	SOCRATCES calciner design is a flexible technology, which can operate under different operation conditions. Calcination amount can be controlled by the inlet mass flow of material, so the calciner can follow a certain solar radiation pattern.
	Reliability (High/Medium/Low)	https://cordis.europa.eu/project/id/727348/es	SOCRATCES technology is fully novel, and it requires novel designs to integrate efficiently solar energy (currently TL5).
Techno-economic Innovation	TCES Investment costs	290 €/kW for Fluidized Bed reactors [49]	93.7 €/kW (100 MWth) (Deliverable D8.14)
	Thermal to calcination efficiency	31% [8,9]	>60% Expected
	Overall Heat transfer coefficient	500–800 W/m^2K for Fluidized Bed (FB) reactors [50]	100-200 W/m^2K [5]

- Evaluation of Carbonator reactor (KER3):

Criteria	Indicators	REFERENCE DATA	KER3 Carbonator reactor
Technical Innovation	Novelty (High/Medium/Low)	[5]	SOCRATCES carbonator is a full approach to current state-of-the-art carbonator reactors, mainly based on FB
	Implementation cost (High/Medium/Low)	[5,51]	SOCRATCES carbonators are based on entrained flow technology, which is a well-knowledge technology in the industry (cracking, i.e. cracking process)
	Ease of Implementation (High/Medium/Low)	[5]	SOCRATCES carbonators are based on entrained flow technology, which is a well-knowledge technology in the industry (cracking, i.e. cracking process)
	Applicability and suitability at a different scale (High/Medium/Low)	[5]	SOCRATCES carbonator, based on entrained flow technology, is highly scalable. The H/D ratio is fundamental to achieving an optimised design
	Compatibility with the project goals (High/Medium/Low)	https://cordis.europa.eu/project/id/727348/es	SOCRATCES global objective is to develop a prototype that will reduce the core risks of scaling up the technology and solve challenges
	Sensitiveness to changes in operating conditions (High/Medium/Low)	[40]	SOCRATCES carbonator design is a flexible technology that can operate under different operating conditions. The inlet mass flow of material can control carbonation thermal power so that the power cycle can operate under a variable pattern. Additional storage vessels for $CaO/CaCO_3$ allows increasing the flexibility of the system
	Reliability (High/Medium/Low)	https://cordis.europa.eu/project/id/727348/es	SOCRATCES technology is entirely novel, and it requires novel designs to integrate the power block TL5 efficiently).
Techno-economic Innovation	TCES Investment costs	290 €/kW for Fluidized Bed reactors [49]	12 €/kW (100 MWth) (Deliverable D8.14)
	Carbonation efficiency	80-90% [52]	80-90% Expected
	Overall Heat transfer coefficient	500–800 W/m^2K for Fluidized Bed reactors [50][53]	100-200 W/m^2K [5]

2.3. ONLINE INNOVATIONS QUESTIONNAIRES

The European Commission constantly tries to gather and analyse the innovations obtained within the R&D projects of its different financing framework programs. In this context, **The Innovation Radar** (IR) support initiative was running by **DG Connect** / **JRC-IPTS a**s part of the EURIPIDIS2 project, a 3-year joint project run jointly by DG Connect and JRC-IPTS and launched in August 2013.

The Innovation Radar initiative was a tool that accompanies the standard reviews of the ICT 7th Framework Programme and Competitiveness and Innovation Framework Policy Support Programme (CIP ICT PSP) projects and in the H2020 projects. During their lifecycle, the methodology used by the reviewers and the panel of independent evaluators was developed the Innovation Radar Questionnaire and applied to ongoing projects.

The aim of the Innovation Radar initiative was the identification of high-potential innovations in the **FP7**, **CIP** and **H2020** projects and the key organisation in delivering these innovations to the market. The main elements of the Innovation Radar involve:

- Assessing the maturity of innovations developed within the FP7, CIP and H2020 projects and identifying high potential innovators and innovations.
- Providing guidance during the project on the most appropriate steps to reach the market.
- Supporting innovators through EU-(and non-EU-)funded entrepreneurship initiatives to cover specific needs concerning networking, access to finance, Intellectual Property Rights (IPR), etc.

At SOCRATCES, we have used these questionnaires in the final phase of our project, adapting them to our circumstances and trying to make them a complement to the work carried out both in the preparation of the innovation evaluation tables (Section XX) and the work done with the KERs at BOOSTER seminars.

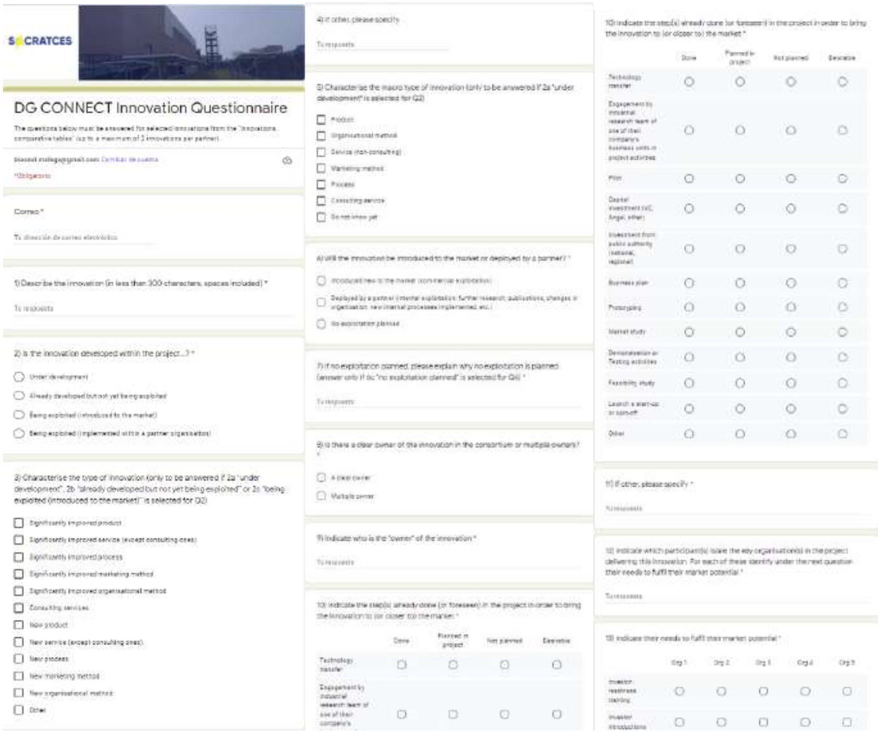


Figure 1: Screenshots of the SOCRATCES Online Innovation Questionnaire

The aim was to obtain consolidated results about the raised innovations after the development and implementation of the prototype. The online questionnaire allows us to assess the maturity of innovations developed within the project and identify high potential innovations, furthermore, we get the information more comprehensive in a visual way.

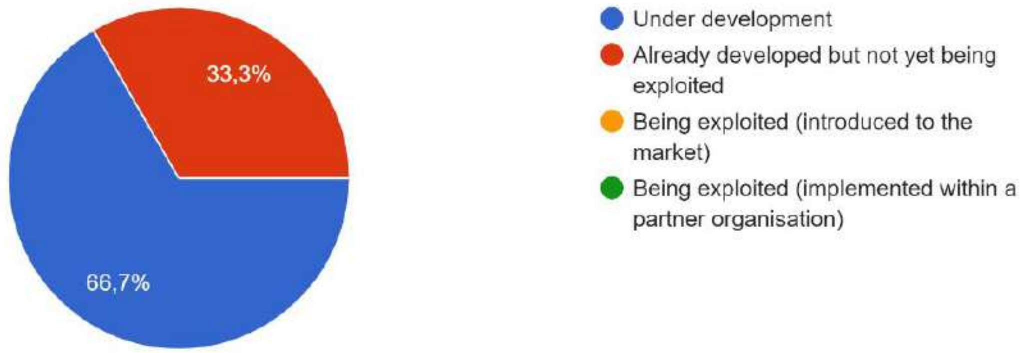
- **RESULTS**

The results of the questionnaires are described below. It is noteworthy that the partners have selected the most promising innovations according to the commercial and research interests of each of their institutions.

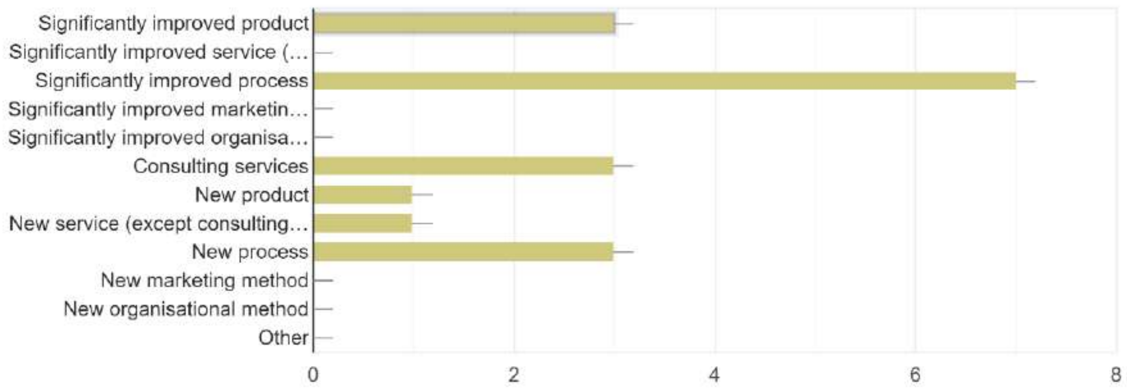
1) Describe the innovation:

- Sound assisted fluidisation: effect on agglomeration and carbonation/calcination reactions
- The technique proposed has the aim of finding the best design variables and the best configuration of the heat exchanger network while integrating various types of power cycles with thermochemical energy storage.
- The objective is to separate $CaCO_3$ and CaO after the Carbonation. If the carbonation reaction is not complete, part of the $CaCO_3$ storage volume is occupied by CaO, and the energy storage is reduced (or the storage volume increases and also the costs). The separation by the density of $CaCO_3$ and CaO will reduce the storage volume and enhance the utilisation of the solids in the proposed process,
- Development of specific calciner and carbonator models for energy storage applications for different scales
- Novel reactors concept for fines applications. From the knowledge gained in the construction and operation of SOCRATCES, new reactors and processes will be developed that can be applied to the large scale management of fines.
- An accurate heat transfer model that analyses the potential heat release in the carbonator for power production. The model can be applied for other solid-gas systems, which enhances the potential interest of development
- Electrically heated drop-tube carbonator based on entrained flow reactor technology.
- "In exploring the concept of extracting heat from an exothermic reactor (the carbonator), a modified reactor with external fins contained within a jacket was proposed under WP6. Such a reactor would undoubtedly be able to extract heat with higher efficiency, and this is more likely to be true when its performance is compared to that of the case when the reactor is loaded with a spirally wound metallic pipe around the external surface.
- To allow the HTF sufficient time to exchange heat with the surface of the carbonator's wall, innovative strategies can be used to enhance residence time."
- Solar-calciner based on a vibratory table. Solar calcination remains the major technological challenge in the CSP-CaL process. Small $CaCO_3$ particles (<45 um) notably enhanced the process's kinetics and multicyclic performance, although these particles cannot be handled in traditional Fluidised Bed reactors. Entrained Flow reactors gain attention in this regard, although the residence time of the particles in the reactor may not be sufficient to complete the reaction.
- Carbonator heat transfer model development
- Innovative control systems and depreciation for thermochemical systems
- Entrained flow reactors with gas injections (nozzles)
- "Solar calciner based on entrained flow reactor technology.
- This is an innovative concept proposed by CALIX within the SOCRATCES project to carry out the calcination of fine particles using concentrated solar energy. The reactor was a drop-down tube calciner constructed (WP6) and validated (WP7) in SOCRATCES."
- Solar Calciner based on a variation of Calix Technology
- Heliostat solar field control algorithm of incident power to the receiver

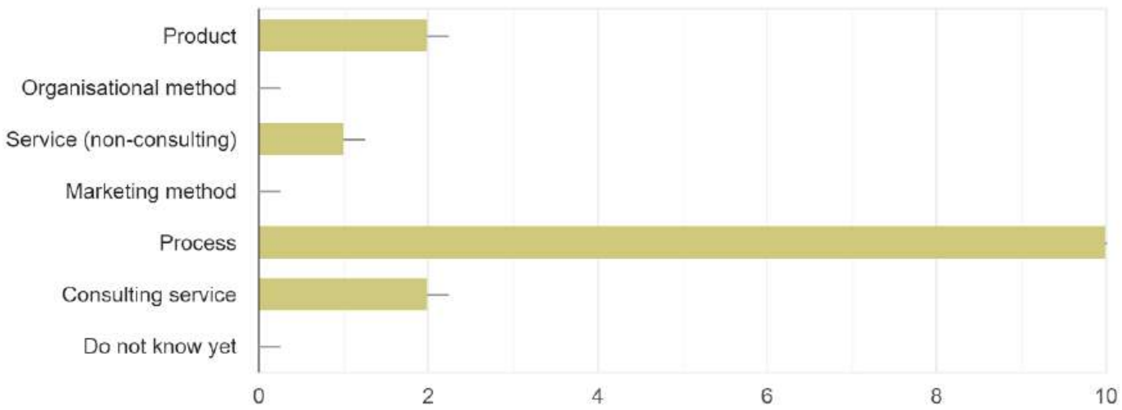
2) Is the innovation developed within the project…:



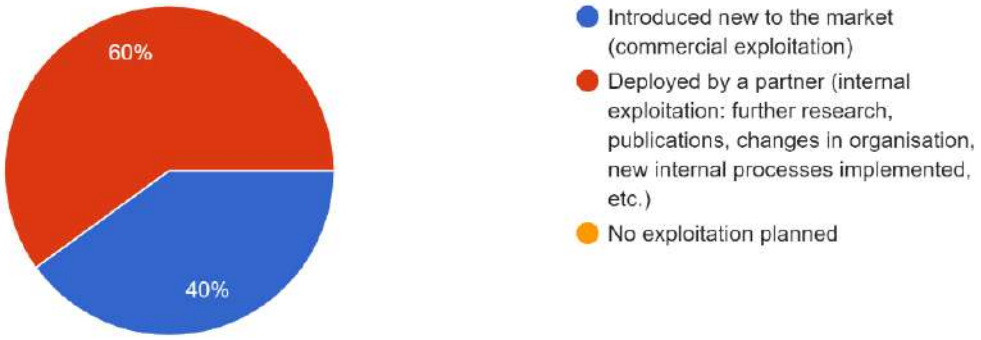
3) Characterise the type of innovation (only to be answered if 2a, 2b, or 2c is selected)



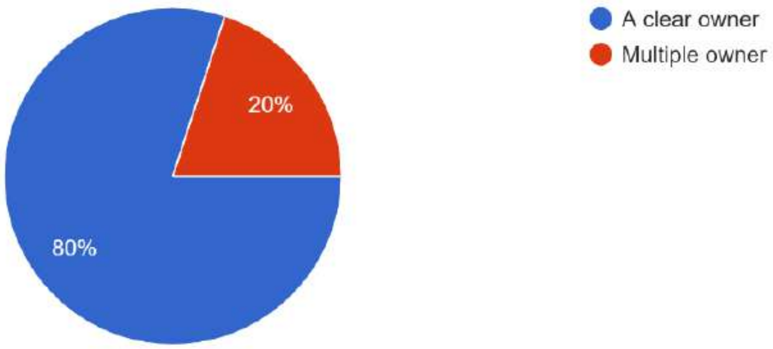
4) Characterise the macro type of innovation (only to be answered if "under development" is selected for Q2):



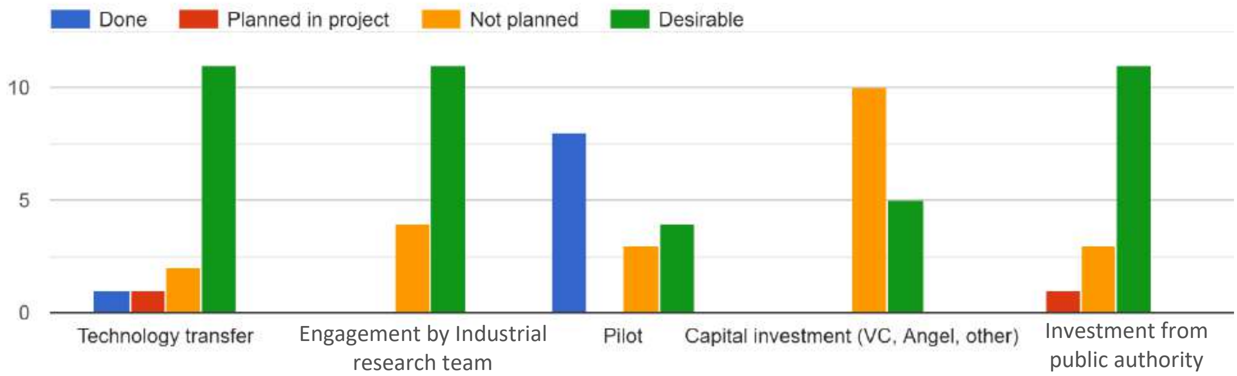
5) Will the innovation be introduced to the market or deployed within a partner:

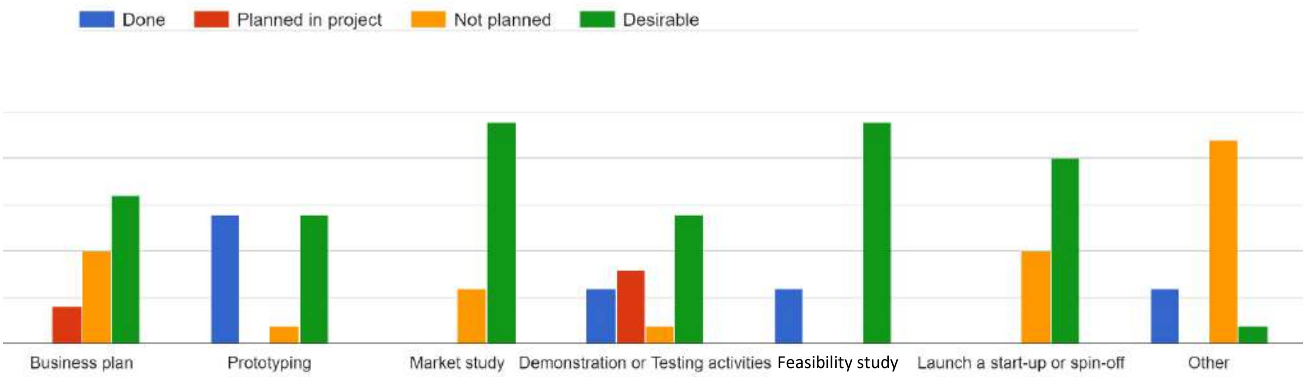


6) Is there a clear owner of the innovation in the consortium or multiple owners?

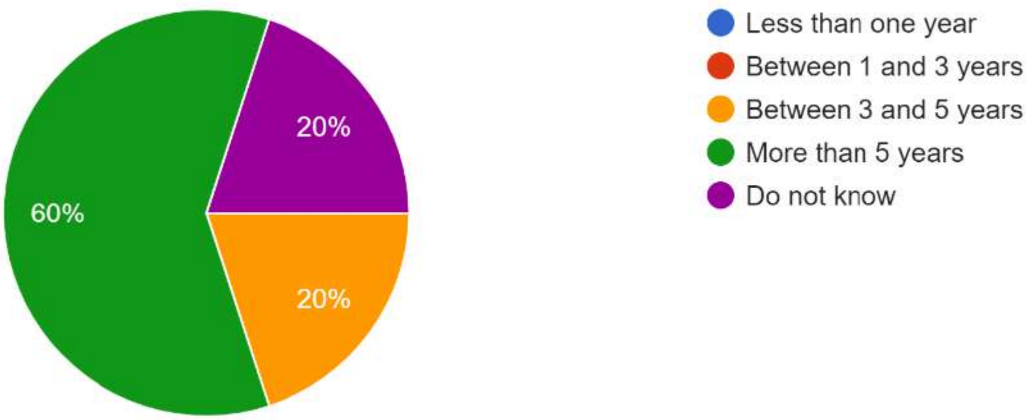


7) Indicate the step(s) already done or are foreseen in the project in order to bring the innovation to (or closer to) the market: Technology transfer, Engagement by Industrial research team of one of their company's business units in project activities, Pilot, Capital investment (VC, Angel, other), Investment from a public authority (national, regional), Business plan, Prototyping, Market study, Demonstration or Testing activities, Feasibility study, Launch a start-up or spin-off, Other.

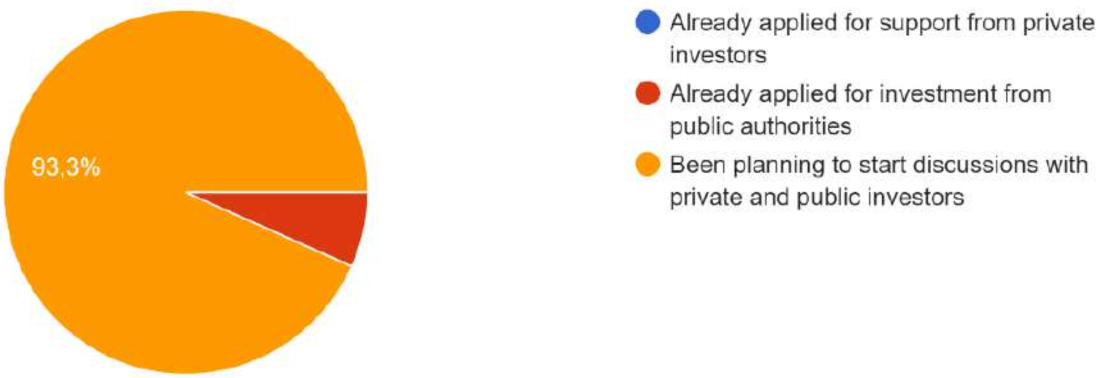




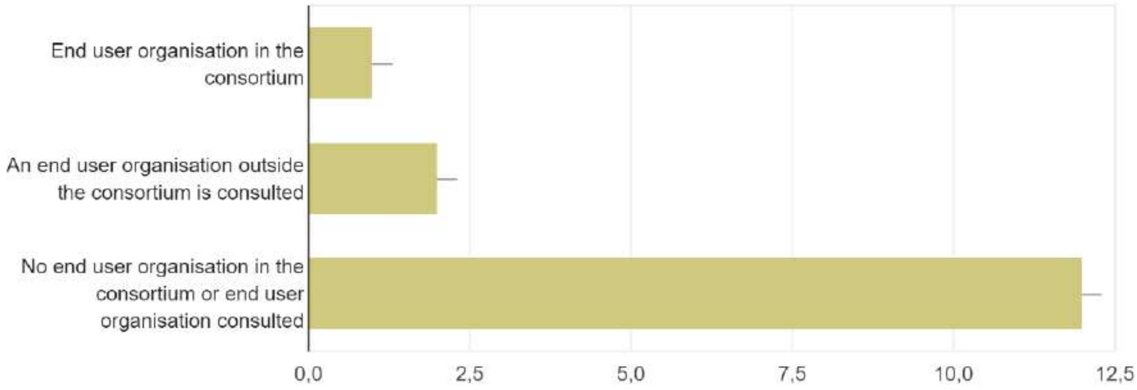
8) When do you expect that such innovation could be commercialised? (Answered only if 5a "introduced new to the market (commercial exploitation)" is selected for Q5)



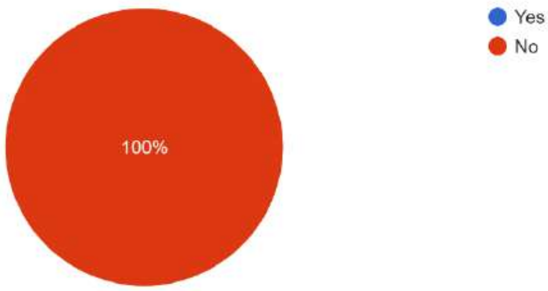
9) Have any of the project partners… (only to be answered if "Done" or "Planned in Project" is chosen for 7.5 "Investment from public authority")



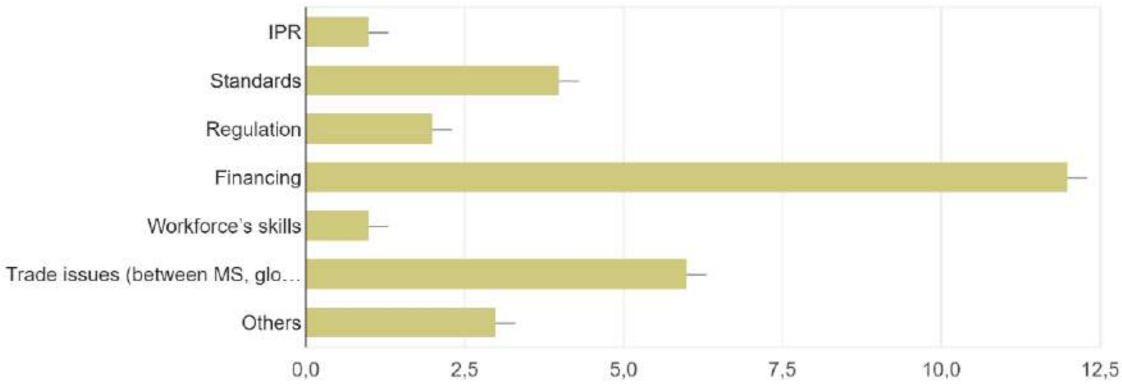
10) How does the consortium engage end-users?



11) Are there in the consortium internal IPR issues that could compromise the ability of a project partner to exploit new products/solutions/services, internally or in the marketplace?



12) Which are the external bottlenecks that compromise the ability of project partners to exploit new products, solutions or services, internally or in the marketplace?



3. NEXT STEPS

As a result of the analyses developed, the consortium is determined to move forward in this direction of exploiting the new knowledge and technologies developed within the SOCRATCES approach to thermochemical energy storage. The closest step to advance is to prepare a new proposal within the European funding program HORIZON EUROPE that will boost the work carried out to higher TLRs and take advantage of some of the technologies. Also, some partners are analysing and discussing the formation of a spin-off to develop and commercialise some of the knowledge generated and the technologies developed.

4. CONCLUSIONS

The innovation management work throughout the SOCRATCES project has added great value to the technical work of the consortium since it has highlighted the possibilities of continuing the research and development of new knowledge, different modules and variations of technology, novel studies and equipment in the field of CSPs.

The consortium has completed the project with **31 innovations** that would allow continuing research and development work in future projects and even technological exploitation of some of them. The work carried out for the technical evaluation of each one of them, based on the comparison with the most recent technologies on the market and the latest published studies, may allow the partners to develop them further, placing the work of SOCRATCES as a leading reference, above many of the current references.

In fact, the consortium is determined to move forward in this direction to prepare a new proposal within the European funding program HORIZON EUROPE that will boost the work carried out to higher TLRs. Also, some partners are analysing the formation of a spin-off to develop and commercialise the technology developed.

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