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Second report on LCA

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EXECUTIVE SUMMARY

Sustainability is an essential and increasingly important issue in our society and for future generations. Climate change has become a global problem and has enlarged the research in renewable and sustainable energies to reduce greenhouse gas emissions. Energy storage addresses the issues of a fluctuating energy supply and demand. In order for these energy storage systems (such as SOCRATCES technology) to meet EU environmental standards and contribute to climate neutrality in Europe, the integration of environmental assessments during the development of such new technologies is essential.

The life cycle assessment identifies ecological hot spots in technologies and defines possible optimization points. Life cycle assessment is used to demonstrate transparency and corporate credibility to stakeholders and customers. It is also applied in the research and development of new technologies to use the ecological footprint for marketing and cost structure. LCA tools model the environmental impacts of products and technologies throughout their lifecycle: from raw material extraction to processing, manufacture, distribution, use and disposal or recycling. Instead of optimizing only one indicator, the life cycle assessment offers a holistic view of the environmental impacts to avoid optimizing one environmental indicator without taking the unfavourable effects on other indicators into account.

The Life Cycle Analysis for the SOCRATCES project was performed to assess the environmental impact of the technology. The methodology followed was based on the international standards ISO 14040:2006 and 14044:2006, considering three different scales – the pilot plant and two industrial-scale sizes with 10 and 100 MW.

The data for calculating the environmental impact was compiled by the consortium and the previously developed deliverables in the project. Additional information that was not covered during the work of the project was taken from different literature resources. Data for reference systems was also gathered by literature review. For the calculation of the LCA, the Umberto LCA+ software was utilized, and the methods Recipe 2008 Midpoint (H) w/o LT and IPCC 20013 were applied. The calculations were based on the functional unit of 1 kWh for all calculations.

The results showed that the technology is comparable to alternative energy storage approaches in terms of the environmental impact assessment. It is even located in the lower region of CO_2-Eq output per kWh produced electricity and has significantly lower values for the toxicity impacts. When the eco-efficiency factor is considered, it emerged that the technology is considerably superior to competing alternatives, which comes from the higher storage time than other technologies. The eco-efficiency is merging the results of LCA and LCC (D8.14) and gives an even better understanding of the sustainability and viability of the SOCRATCES technology. Overall, the technology is highly recommendable from an environmental perspective and is expected to help alleviate the ongoing worldwide environmental crisis if used sensibly.

1. INTRODUCTION

In this report, the environmental performance of the SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage (SOCRATCES) was assessed and compared to a competing state-of-the-art storage technology involving the application of molten salts. The environmental impact is analyzed through Life Cycle Analysis (LCA); the economic advantages having already been detailed in D8.14. While fossil-fuel driven energy technologies are characterized by convenience and ease, they have unquestionable deleterious impacts on the environment, emphasizing the need to resort to alternatives. Solar technologies are some of the most attractive solutions among environmentally friendly sources of electricity. However, solar power being available periodically only necessitates the technology's integration with storage systems. Myriad forms of storage technologies have been explored and continue to be explored, one of them being the thermochemical approach adopted in SOCRATCES. The storage allows production and/or release of energy during either peak hours or nighttime.

LCA methodology is a widely used technique to analyze the environmental impact of a process during the course of its life cycle. It starts with the raw material procurement within production, usage, end-of-life treatment, reutilizing and final disposal. LCA in the modern era is performed to ensure that a product or a process does not affect the natural ecosystem and the environment through interference and burdening beyond its perceived or estimated capacity. LCA can assist in the following aspects:

- Identifying areas of potential improvement of environmental performance of e.g. products at numerous stages in their life cycle.
- Supporting decision-makers in industry, government or non-governmental organizations (e.g., strategic planning, priority setting, product or process design or redesign).
- The opportunity of recommending suitable guidelines of operation, together with prescribed evaluation methods, from the perspective of environmental safety and soundness
- LCC can be employed to develop marketing strategies (e.g. to accomplish a plan of action regarding eco-labelling, making an environmental claim, or producing an environmental product declaration).
- Compile an inventory of appropriate inputs and outputs of a scheme to be evaluated
- Assessment of the prospective environmental impacts corresponding with those inputs and outputs.
- Examination of the results in correspondence to the objectives of the study.

The deliverable D8.13 Second Report on Life Cycle Assessment aims to demonstrate the life cycle assessment of the SOCRATCES system and includes the life cycle inventory and life cycle impact assessment comparable to the first report on LCA (D8.3). D8.13 is, as was stipulated in the DoW, a continuation or extension of the work already presented in D8.3. This deliverable presents a more comprehensive, more thorough and detailed analysis. The approach remains primarily to rely on literature data but considers the partial experimental data from the pilot plant were available to some extent for the scaling-up analysis.

2. FUNDAMENTALS OF THE LIFE-CYCLE-APPROACH

The Life Cycle Assessment is carried out principally based on the outcomes of the already submitted first report on LCA and that on LCC. The LCA will focus on the environmental sustainability analysis of the SOCRATCES technology in three different scales. In order to analyze if substantial improvements in terms of environmental performance can be made or not, a comparison between SOCRATCES and a comparable state-of-the-art system energy storage in combination with solar energy capture will be conducted. Furthermore, a detailed Life Cycle Inventory and a Life Cycle Impact Assessment will be carried out to identify, quantify, and assess ecological impacts and estimate indicators of the environmental pressure. Prelaminar information was already gathered in deliverable D8.2 that showed the scope of the LCA and LCC within certain system boundaries. The first report on LCA D8.3 has laid down the methodology and framework, roughly summarized with minor revisions and adjustments based on the knowledge gathered.

The LCA will be carried out according to the international standards ISO 14040:2006 and 14044:2006 [1, 2]. Those standards divide the LCA into four different phases:

1. Goal and Scope Definition: assessing the environmental profile of the SOCRATCES technology and different comparable technologies.
2. Life Cycle Inventory (LCI): Inventories for the input production, e.g. chemicals, energy, water and other influences, coming from the ecoinvent database v2.2 / v3
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation of results
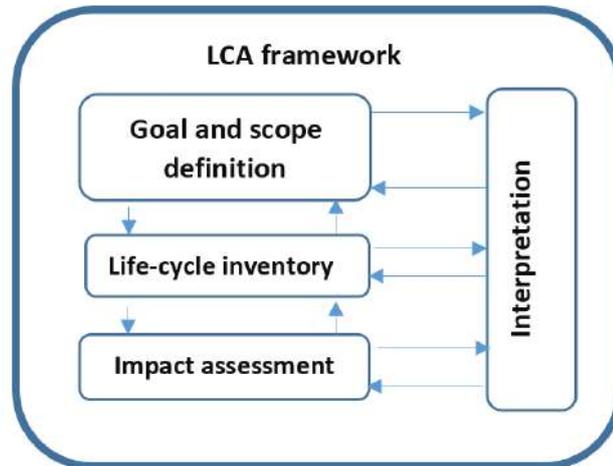
Figure 1: Different phases of the LCA according to ISO 14040:2006 [2]

Figure 1 illustrates the correspondence between the four phases, which are firmly bound to one another. This topic was already mentioned in deliverable 8.2. Nevertheless, these steps are defining goal and scope, doing a Life Cycle Inventory analysis (LCI), and a Life Cycle Impact Assessment (LCIA). The outcome requires a comprehensible evaluation at the end and an ongoing interpretation that can impact every other prior resolution.

It is an iterative process by means of carrying out the four phases. Thus, in the course of LCA, an adaption of phase is very common. The goals and scope of the LCA were already set in

Deliverable 8.3. At present, a question that appears to be pertinent is whether SOCRATCES has a comparatively lower Green-House-Gas balance in contrast with comparable state-of-the-art processes or not. It is worth mentioning that the collaborating teams in the consortium had come to an agreement that the functional unit to be used was 1 kWh electrical energy produced in the power block in evaluating the environmental impacts in LCA. With the definition of the functional unit, the reference flows are determined accordingly. If a different reference should be addressed, the complete system has to be adjusted to accommodate the alteration. All input and output streams are to be specified on the basis of the set functional unit.

After thus defining the goal and scope to demarcate the boundary and limits, the LCA proceeds with examining the Life Cycle Inventory (LCI). This stage includes collecting and evaluating input and output streams for the examined system, assortment and aggregation of available information. Figure 2 shows a step-by-step methodology to perform the LCI. It starts with the accumulation of information, which chiefly is quantitative data of the operation of the plant.
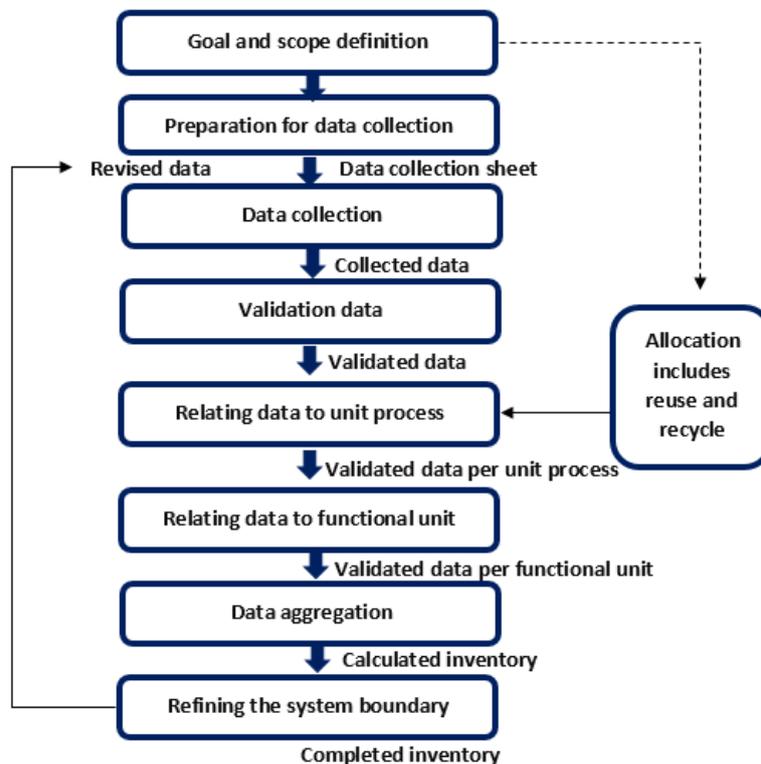
Figure 2: Life Cycle Inventory. Process of data collection according to ISO 14040:2006 [2]

A close examination of the steps outlined in Figure 2 reveals that the preliminary steps were already executed and documented in the first report on LCA, along with system boundaries for the LCA and the LCC. For the second report on LCA, while the data is revised and updated, the computation and the overall approach remains the same.

The next phase of the LCA is the Life Cycle Impact Assessment (LCIA). LCIA interprets the information gathered in the LCI, translates them into ecologically pertinent indicators such as material depletion, greenhouse potential, ozone consumption potential, acidification potential, photochemical ozone creation, water discharges, solid waste outflow, toxic potential, hazard potential and land use. Contingent upon the technique chosen and utilized in Umberto, an

assortment of these indicators is picked, suited to SOCRATCES. For this analysis, Recipe 2008 Midpoint (H) w/o LT and IPCC 20013 were employed, the justification having already been given in the first report of LCA. For the impact assessment, so-called midpoint category indicators are first estimated, considering problem-oriented effects on the environment and divided into different categories, e.g. acidification, climate change, and eutrophication. The impact resulting from environmental pollution can then be quantified using damage-oriented endpoint methods that are assigned to different classes. According to the ILCD handbook (International Reference Life Cycle Data System), these are human health, the natural environment and natural resources [1].

Deliverable 8.2 was already roughly discussing the environmental impacts and that they will be determined on the basis of six main aspects: the consumption of energy, depletion potential, the consumption of raw materials, resulting emissions, the toxicity potential and the abuse and risk potential. The emission category includes water emissions, waste and air emissions. The air emissions consist of global warming (GWP), ozone depletion (ODP), acidification (AP) and photochemical ozone creation (POCP). Based on these environmental impacts, weaknesses and potentials can be easily described and improved. Data acquisition and calculation will be made according to ISO 14044 emission categories. They can be explained as follows: Cumulative energy demand, Depletion potential (Fossil depletion (FD), reported as kg oil- equivalent, Metal depletion (MD), reported as kg Fe- equivalent, Water depletion (WD) (m^3)). Emission values are initially calculated separately as water, air, and soil emissions. Land Use is an assessment of the environmental impacts on biodiversity through land use and land transformation. The toxicity potential refers to human toxicity and ionizing radiation. The last impact category is the risk potential, which reflects the danger of accidents in manufacturing, using and recycling the product [2, 3].

3. DATA COMPILATION

Due to the complexity and the various links between process factors and the environment, the assessment of all the impacts requires the development of a very complex model. It must be determined which steps of the plant life cycle are included in the considerations. The balancing should extend from the development and extraction of raw materials, through production, the use phase to disposal and recycling ("from the cradle to the grave") in order to record all the impacts associated. With these individual phases of the life cycle, other material flows are connected, which are at least partially included in the life cycle of the primary product. For a complete assessment, all substructures would have to be included in the investigation, for example, the proportionally used traffic areas, the power generation and distribution system, the computers used in the office of the administrative employees, including the associated chip production as well as the software industry – to get everything covered, the whole economy needs to be implemented. In order to be able to carry out an LCA at all, boundary criteria are necessary to determine a balance.

Those boundaries define the process that needs to be analyzed with regard to flows, emissions, materials and work. This approach inevitably leads to the limitation of certain process steps of the system under investigation. On the one hand, the outcome of the analysis depends on the system boundaries; on the other hand, the system boundaries are heavily influenced by the intended application of results and the definition of the goal.
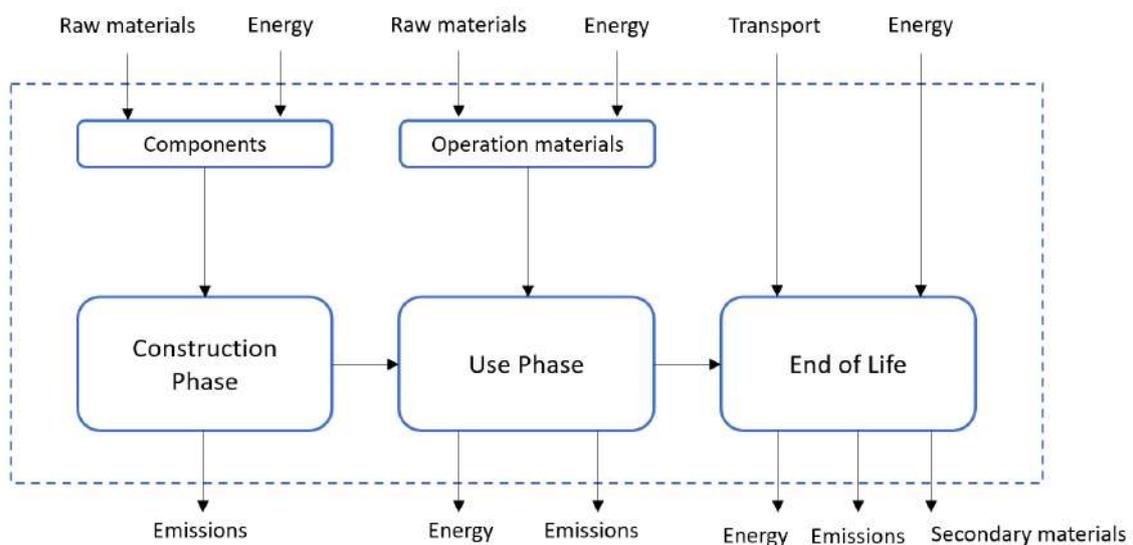
Figure 3: System boundary of the SOCRATCES technology

Figure 3 shows the system boundary for the SOCRATCES technology. Basically, three stages of life will be included in the calculation with the Umberto® software. For the construction phase, the raw materials and the energy consumption for the components are extracted from the database and literature. The data for the operation materials for running the plant and the operation parameters were gathered from the project partners and from the previously submitted deliverables. For the use phase, a time horizon of 25 years is considered. The data for the end of life phase is gathered from different literature resources and the database ecoinvent.

On the basis of those boundaries, a differentiation must be done between direct and indirect emissions over the entire life cycle of the SOCRATCES plant. All emissions that are emitted into the environment directly at the power plant site during the operating phase are direct emissions. All other emissions that are not directly related to the operation of the plant are referred to as indirect emissions.

The disposal phase includes the dismantling, disposal and recycling of usable materials. In general, a distinction is made between materials that have reached the end of their life cycle and are disposed of and materials that can continue to be recycled. It is distinguished between the processes of direct recycling and processes of direct disposal. Direct recycling includes the costs of the demolition at the site as well as the sorting of individual recyclable materials in construction waste containers for further use in a subsequent recycling process (cut-off criterion). Further material recycling concerns are focused on the metallic and glass components of the system. For the solar receiver, data for construction and end of life for the solar side (heliostats and tower) is taken according to state of the art in 2016.

The SOCRATCES plant consists of two types of equipment and materials. The first is off-the-shelf products such as heat exchangers, turbines, compressors, pumps, etc. The second type comprises highly specialized custom-made equipment. Within this second category fall the calciner and carbonator reactors. It is difficult to conceive that the materials used in the construction of the two reactors will not be available for procurement from exclusively European sources, there being an amply developed high-tech industry. It is relevant to mention that this has been the case for the pilot-scale reactors erected in Seville, Spain. The reactor bodies may require the service of fabricating firms with well-equipped machine workshops, but the required capabilities are evaluated as accessible to metal workshops worldwide. The materials and instrumentation required for the rest of the plant, as mentioned already, are primarily available from European manufacturers. For the power block module of the pilot-scale plant, for example, the recuperator heat exchanger and the Stirling engine were procured from Dutch sources, while the piping and other materials were obtained from local sources in Germany where the construction took place. However, it is worth mentioning that the Stirling engine, while it was originally by a Dutch company, was in fact produced in a Chinese facility and had to be shipped from China to Germany. This may well be the case for other equipment as well since the manufacturing of innumerable European industrial producers takes place outside Europe. The list of components considered for the LCA calculation is shown in table 1, as well as the sources for the data used for the modelling in the Umberto software.

The material and substance flows are recorded during the entire construction phase, operation and demolition of the plant, as mentioned in figure 3. The material flows of climate-relevant emissions are balanced for the life cycle. Bauxite, copper, iron and limestone are recorded as mineral resources and hard coal, lignite, crude oil, natural gas and uranium are recorded as energetic resources. The following substances relevant to the construction and operation of solar thermal systems are identified: steel-reinforced concrete, glass, stainless steel, steel, cast iron, electrical sheet, aluminium, copper, zinc, ceramics, paint, plastics and natural gas. Percentages of recycled material are also taken into account. The data are taken from different literature recourses.

To actually get a clear overview of all the inputs considered for the SOCRATCES plant, every component listed in table 1 is organized in the construction, use and end-of-life phases. The site where the SOCRATCES plant is assembled and the CSP is located in Seville, Spain. Starting with the solar side, the construction for the tower and the field of heliostats comprises transportation, baseplate, supporting structure, control cabinet, the tower, the concentrator and the heliostat modules themselves. For the tower and the heliostats, the transportation as assembled units is calculated. For a complete assessment of the solar side, raw material transports should also be taken into account. However, these are subject to a wide range of fluctuations, depending on the local delivery share. In order to be able to transfer the results of the balance as simple as possible to the boundary conditions, the assumptions for the necessary transports were chosen so that they only lead to the least possible restriction of general validity.

The following simplifying assumptions are therefore made:

- Only truck transports within the country of installation are considered.
- Transports outside the country for imported components (e.g. by ship) are only taken into account to a limited extent and within Europe.

The assumed transport distance for building materials such as concrete and structural steel is 50 km. For transporting, different lorries are used (Lorry 16-32 metric ton*km, EURo6).

Table 1: List of components considered in the LCA calculation

Location	Component	Further Information and data recourse
Solar side	Heliostats	Build and assembled in Spain/ [4] and consortium
	Central tower	
	Concentrator	
Calciner	Calciner	Build in Europe/ consortium
	Heat exchanger	Manufactured in Europe/ [5]
	Compressor	
	Electric motor	
Storage	3x Storage (CO_2, CaO, $CaCO_3$)	Manufactured in Spain/ consortium
Carbonator	Carbonator	Manufactured in Greece/ consortium
	Heat exchanger	Manufactured in Europe/ [5]
	Turbine	
	Compressor	
	Electric generator	

	Turbine	Manufactured in China/ consortium
Power Block	Compressor	
	Regenerator	
	Cooler	
	Electric generator	
Additional	Concrete fundament	[4]
	Piping and wires	[4]
	Transportation of components	Within Europe (0-3000 km)

The size of the foundation is directly dependent on the size of the heliostat field and the solar tower. Those values can be looked up in the attachment. The foundation consists of concrete and reinforcing steel. To convert the concrete mass into the corresponding volume, a density of $2,1t/m^3$ was assumed. In addition, the running time of the construction machine was compiled. A hydraulic excavator with 50 to 100 kW output is assumed (data is taken from the ecoinvent database).

The concentrators consist of the actual reflecting part and the necessary bracket. There are fundamental differences between metal membrane heliostats and glass/metal heliostats. For the SOCRATCES project, mean values were extracted from different systems from the literature and the ecoinvent database. The heliostat field size is accounted with 350877 m². For corrosion resistance, the steel parts of all heliostats are galvanized. The reflective part consists of thin glass mirrors that are glued to the metal membrane. [6] All heliostats have a control cabinet in which control-electronics, transformers, cables and other small parts are located. The raw material composition of components and electronics can only be estimated. For balancing, it is assumed that they consist of steel, plastic, aluminium and copper. The data is also taken from the database ecoinvent 3.

When accounting for the operation of the solar side (use phase), only maintenance and repair are included. This includes the expenses for replacement mirrors and the mirror cleaning. The replacement over the course of 25 years due to breakage or corrosion is taken into account. These are statistical mean values that have been taken from literature. [7] The cleaning of the mirrors is scheduled at an interval of a maximum of 6 months. This value can vary greatly depending on the weather conditions. The calculations are based on empirical values and are referring to literature that 1l water, 0.002 l of cleaning agent and the use of a small truck-mounted crane is required to clean one square meter of mirror surface [8].

The calciner and carbonator are self-constructed components, whereas not all parts were procured in Europe. Since the data available is for the pilot-scale plant, reference values were estimated for the assessment of the two reactors. Both components were assembled in Europe, and the materials include steel, stainless steel, ceramics, PVC and copper. For sizing the reactors, the data was supplied by consortium partners. (scaling parameters are listed in the appendix)

The data are taken from the database as prefabricated parts for the components heat exchanger, compressor, turbine, and electric motors. In addition, the transport services required to provide these components are limited to an average from Europe. Raw materials for cables, switch cabinets and connectors were drawn from the database. The storage tanks for CaO, $CaCo_3$ and CO_2 were taken from the database, referring to storage tanks with similar modifications and size (scaling parameters were taken from the Deliverable D8.14).

When operating the SOCRATCES system, only working hours (which are not included in the LCA) and spare parts are included in the calculation [9]. For operating the pilot plant, there is also an external electrical heating system with 10kW that ensures the performance of the plant. However, this is not required for the system in large-scale operations and is therefore not included in the calculation.

Since most CSP plants are still in use and not completely disposed of yet, it is not possible to provide reliable data on the demolition and recycling of the complete system. For these reasons, the estimated disposal is limited to the demolition work and the transport of the components to the nearest landfill or recycling facility. It is also assumed that the solar tower plant will continue to be used after the 25-year operating period has expired. The tower, the buildings and the foundations of the heliostats and the heliostats themselves will not be dismantled. The demolition work basically includes the same work that was required for the construction of the SOCRATCES plant. It is expected that 50% of the construction machinery will be used, as less precise work is required. The assumed transport distance to recycling facilities is between 5-50 km. The parts to be scrapped are transported with a 40t truck.

The data given in this chapter refers to the SOCRATCES industrial-scale plant of 10 MW to be able to compare the technology to literature data. In D8.14, the Life-Cycle-Costing was carried out for different sizes of the SOCRATCES technologies with a specific set of system boundaries. Since the LCA and the LCC are closely linked, the LCA should be carried out in a similar way. Nevertheless, the Lifecycle assessment is only of interest for the industrial scale. Three plant scales were modelled and compared to get an idea of plant size on LCA impacts.

3.1. LCA at pilot plant scale

Figure 4 shows the pilot plant of the SOCRATCES technology with indirect CSP-CaL integration and a Stirling cycle. This scale is the first system under investigation. This configuration is based on the indirect CSP-CaL integration of a Stirling cycle operating with CO_2. Deliverable 6.2 -6.5 gives detailed information about the equipment and plant layouts. In the pilot-scale layout, all components of the SOCRATCES project are displayed: the solar receiver, the calciner with its equipment (solar calciner, auxiliary heater), the carbonator block, the storage units for the CaO, CO_2 and solids, heat exchangers, compressor and power block (Stirling engine).
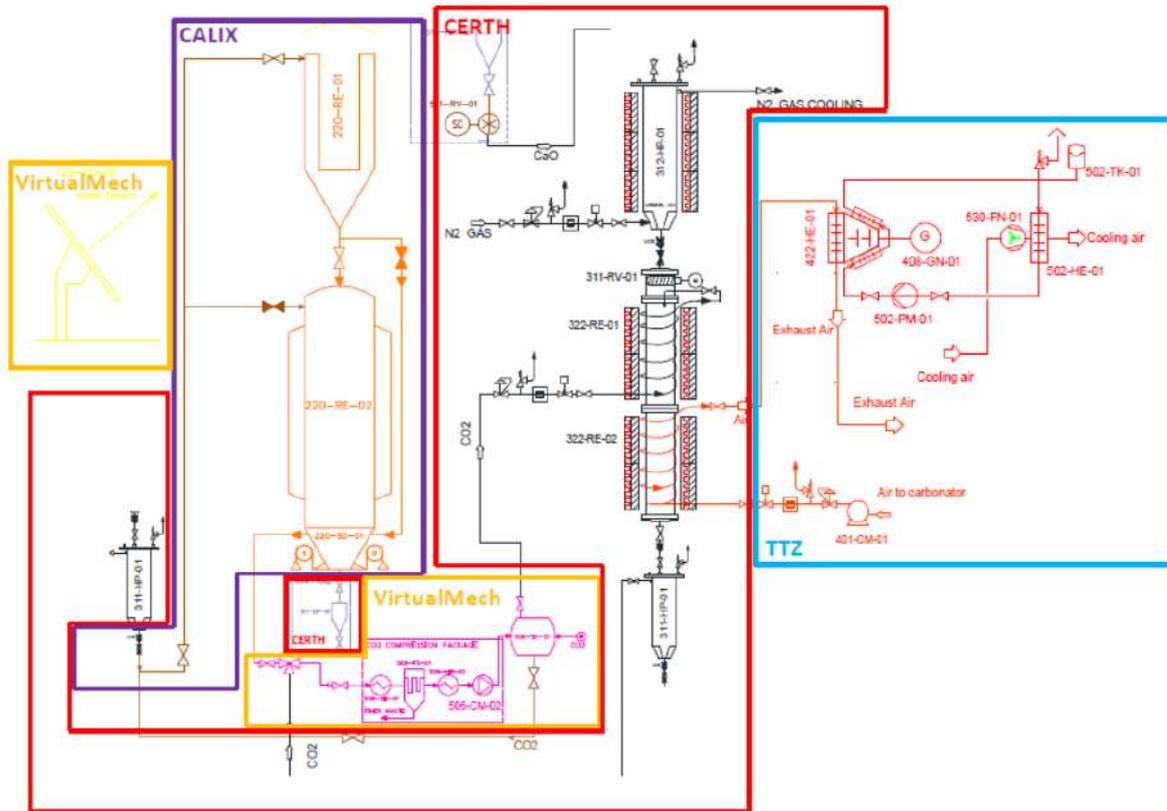
Figure 4: Pilot plant flowsheet diagram of the SOCRATCES technology

The data needed for sizing the components for the LCA were presented in deliverable D8.14, Report on LCC.

3.2. **LCA at Industrial scale**

For the industrial scale, a 10MW$_{th}$/ 2MW$_{el}$ industrial plant with an indirect CSP-CaL integration and a Brayton cycle and a 100 MW$_{th}$/ 60MW$_e$ industrial plant with direct CSP-CaL integration is viewed. Figure 5 shows the Industrial scale of the SOCRATCES technology, which is extracted from the "thermochemical energy storage of concentrated solar power by integration of the calcium looping process and a CO_2 power cycle" published by the University of Seville in 2016 [4].
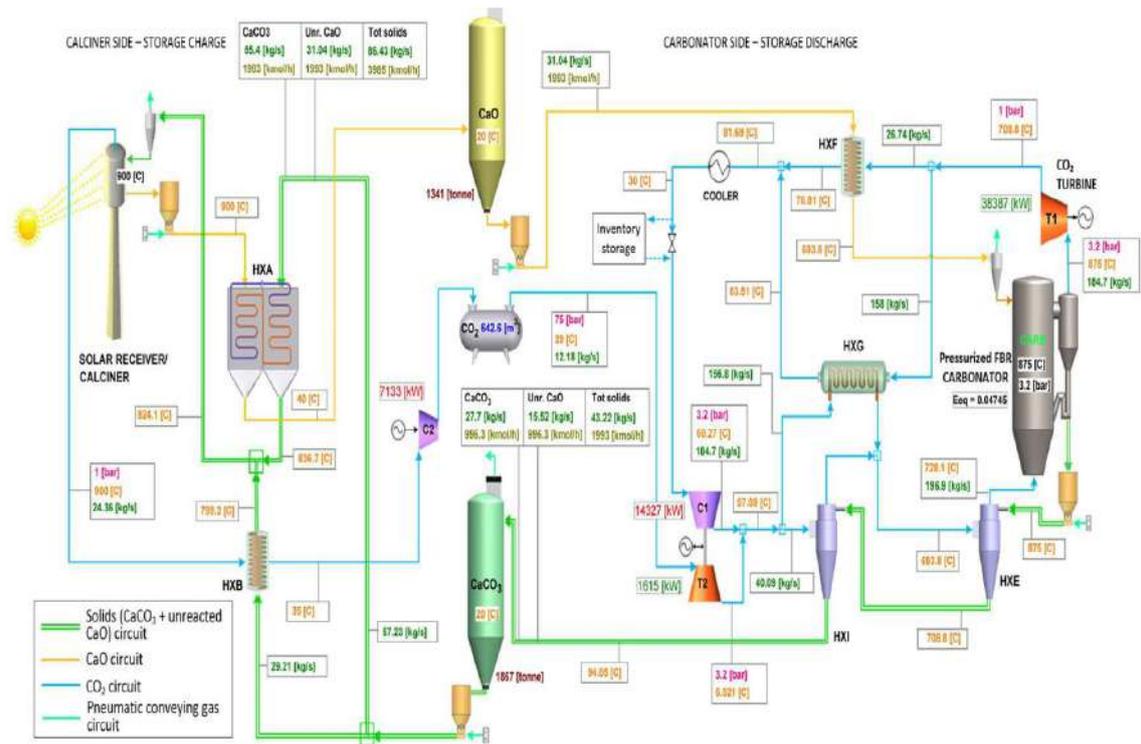
Figure 5. Industrial-scale of the SOCRATCES technology [4]

3.2.1.**2 MW_e industrial plant**

The industrial-scale configuration is based on the indirect CSP-CaL integration of a Brayton cycle, operating with supercritical CO_2. The size of 2 MW_e is referred to the net electrical output of the power block, approximately 10MW_{th}. Since the industrial scale flow diagram is rather complex, a simplified layout is taken into account for the modelling of the technology in the Umberto® software. Figure 6 shows the simplified layout.
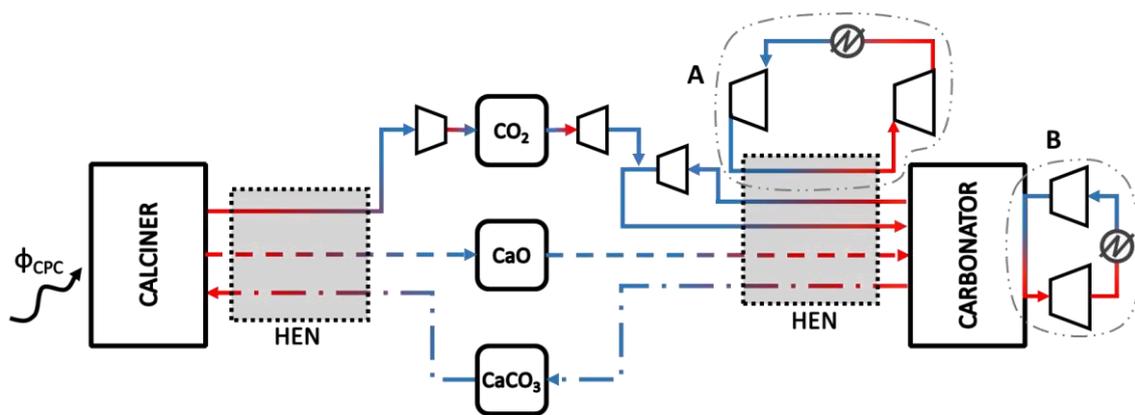
Figure 6: Simplified layout of the 2MW_e industrial plant

The data for the modelling of the industrial 2 MWe is taken from the deliverable D4.2 and D8.14 of the SOCRATCES project. In the appendix, the relevant data basis is displayed. The listed parameters give the fundamentals for calculating the inputs of the Umberto® modelling. For

example, the steel used for building the calciner must resist temperatures up to 950°C. The data shown in the attachment gives all the restrictions for the material of the plant.

The data assumptions used for the LCA calculation come from previous deliverables. It is important to indicate that the operating values are highly dependent on the different operating configurations used for the SOCRATCES plant. For the calculations, the configuration data with the highest environmental impact is applied in the modelling.

3.2.2. **100 MW$_{th}$ industrial plant**

The data used for the input calculation of the 100 MW$_{th}$ industrial-scale plant is listed in the attachment. The configuration is based on the direct CSP-CaL integration (as can be seen in figure 5). The power of 100 MW is referred to as the net thermal flux absorbed in the solar calciner.

3.3. **Comparable Technologies**

To get sufficient comparable data, literature research was carried out to establish an overview of the current state of LCA regarding CSP tower plants. Table 2 provides an overview of some key parameters from different studies. In Lorenz [10], about 120 reports on environmental impact were assessed and compiled. As a result, the mean value was formed, and values of greenhouse gas emissions between 22 and 23 g$_{CO2}$ eq./kWh$_{el}$ were found. This data is considered in the calculation for the comparative Umberto® modelling.

Table 2: Overview of LCA studies for CSP tower plants with key parameters

Reference	Telsing [11]	Lorenz [10]	Mazzaferro [7]	Lorenz [10]	Lechon [12]	Weinrebe [13]
Year	2015	2013	2017	2013	2006	2000
Location	South Africa	Spain	Spain	Israel	Spain	Mediterranean Sea
Power [MW$_{el}$]	20	20	100	130	17	30
Heat transfer fluid	MS: NaNO$_3$, KNO$_3$	MS: unspecified	MS: TES	MS: Ca(NO$_3$)$_2$, KNO$_3$	MS: Ca(NO$_3$)$_2$, NaNO$_3$, KNO$_3$	Air
Storage [h]	-	15	7.5	4	16	-
Life-time [a]	30	25	25	25	25	25
Functional unit	1 kWh$_{el}$	1 kWh$_{el}$	1 kWh$_{el}$	1 kWh$_{el}$	1 kWh$_{el}$	1 kWh$_{el}$
GWP [g$_{CO2}$-eq./kWh]	19.3	14.2	22.7	48.03	202	18-26

4. RESULTS OF THE LCA MODELLING

To maintain the results of the SOCRATCES technology, the process map is shown in figure 7. The system results are either represented by a discrete compilation of the LCIA category indicators for the different impact categories referred to as an LCIA profile. By a set of inventory results that are elementary flows but have not been assigned to impact categories, e.g. due to lack of environmental relevance or by a set of data that does not represent elementary flows. In addition to the elements of LCIA listed in table 3, there could be optional elements and information, as mentioned later, used to meet the goal and scope of the LCA.
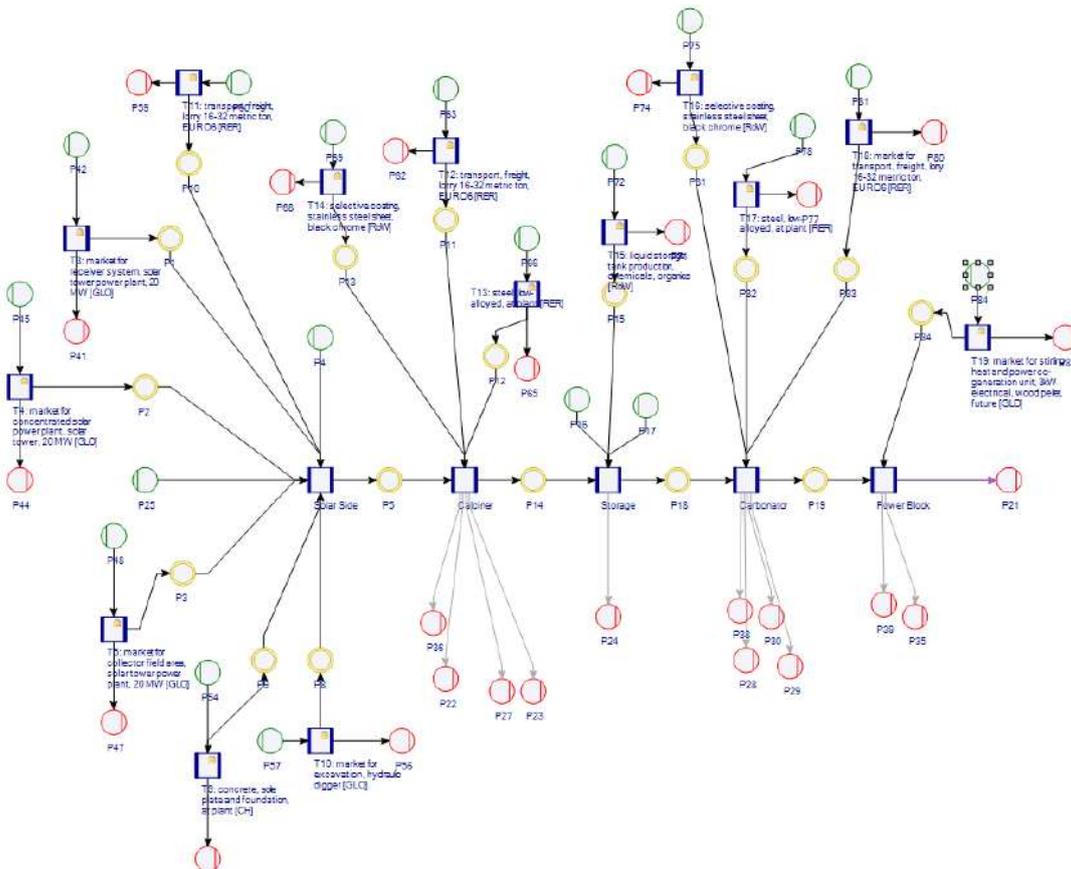

Figure 7: Umberto Process map with the main components of the CSP and the SOCRATCES plant

The Process map modelled in Umberto® shows the different stages of the SOCRATCES plant. The single process steps were already discussed in the previous chapter. For all three models that are reviewed in the LCA, basically, the same map was used. Only for the pilot plant, additional heating was introduced. The map includes all the upstreaming materials that are used during construction, use and dismantling phases. It is important to mention that some upstreaming data are drawn from different plant sizes (e.g. solar tower 20MW). To be able to use the data correctly, it was down- or up-scaled in the calculation process to suit the SOCRATCES technology and the certain plant size (pilot plant and industrial (10MW and 100MW). It also needs to be mentioned that for all up-streaming date cut-off criteria was ensured. Cut-off rules enable to conduct the LCA without having to model 100% of the product system. According to the ILCD Handbook, the cut-off criteria refer to omitting non-relevant life cycle stages, activity types, specific processes and products and elementary flows from the system model [14].

Table 3: List of environmental impact categories provided by UMBERTO LCA+, calculated with the methods ReCiPe 2008 Midpoint (H) w/o LT and IPCC 2013 [15]

Impact category	Impact	SOCRATCES 10 kW	SOCRATCES 10 MW	SOCRATCES 100 MW	Units
Cumulative energy demand	Energy consumption	10	0	0	kWh
Depletion potential	Fossil depletion	0.04	0.00525	0.01	kg-oil – eq.
	Metal depletion	0.08	0.01	0.03	kg Fe – eq.
	Water depletion	0.000456	0.0000582	0.000116	m^3
Emissions	Marine ecotoxicity	0.000333	4.73E-05	9.46E-05	kg 1,4 - DCB – eq.
	Marine eutrophication	0.0000228	1.02E-05	2.03E-05	kg N – eq.
	Fresh water ecotoxicity	0.000119	1.85E-05	3.69E-05	kg 1,4 - DCB – eq.
	Fresh water eutrophication	0.0000194	3.06E-06	6.11E-06	kg P – eq.
	Climate Change	0.17	0.02	0.029	kg CO_2 eq.
	Global warming potential	0.17	0.02	0.003	kg CO_2 eq.
	Photochemical oxidant formation	0.00603	1.11E-04	2.02E-01	kg NMVOC
	Ozone depletion potential	9.34E-09	1.48E-09	2.95E-09	kg GFC
	Particulate matter formation	0.000505	9.30E-05	1.86E-04	kg PM10
	Terrestrial acidification	0.000901	2.18E-04	4.36E-04	kg SO_2 – eq.
	Terrestrial ecotoxicity	0.0000183	4.98E-06	9.96E-06	kg 1,4 - DCB – eq.
Land Use	Agricultural land occupation	0.0000752	0.000912	0.00182	m^2a
	Natural land transformation	0.0000228	3.17E-06	6.33E-06	m^2
	Urban land occupation	0.00424	6.10E-03	1.00E-02	m^2a
Toxicity potential	Human toxicity	0.04	0.0055	0.01	kg 1,4 - DCB – eq.
	Ionising radiation	0.00527	0.000559	0.00112	kg U235 – eq.

Table 3 shows the list of environmental impact categories provided by Umberto® calculated with the methods ReCiPe 2008 Midpoint (H) w/o LT and IPCC 2013 [8]. The data is calculated for the pilot plant (10kW) and the two industrial SOCRATCES plants (10MW and 100MW). The sizing of the technology refers to thermal energy.

With a look at the results, it can already be seen that the environmental impact differs for the three systems, but it is not varying in a wide range. The global warming potential gives the impression that the chosen comparison may not be sufficient since the pilot plant has significantly higher values than the industrial-scale plants. This phenomenon can be explained by the lower efficiency of the system and non-optimized characteristics compared to those expected at commercial-scale plants. Nevertheless, the results can be represented in two ways. Either by a discrete compilation of the LCIA category indicator results for the different impact categories, which refer to an LCIA profile, or by a set of inventory results that are elementary flows. These flows have not been assigned to impact categories, e.g. due to lack of environmental relevance. For better understanding, some general results are shown. In table 4, the energy consumption, fossil and water depletion, human toxicity, and greenhouse gas emissions (GHG) are listed for all systems.

Table 4: Comparable results of the LCIA

Impact	SOCRATCES 10 kW	SOCRATCES 10 MW	SOCRATCES 100 MW
Energy consumption [kWh]	10	0	0
Fossil depletion [kg oil-Eq.]	0.04	0.00525	0.01
Human toxicity [kg 1,4 -DCB – eq.]	0.0000752	0.000912	0.00182
Water depletion [m³]	0.000456	0.0000582	0.000116
Global warming potential [kg CO_2-Eq.]	0.17	0.02	0.029

The LCIA results show that the high environmental impact of the pilot plant can be found in every impact category. Figure 8 shows the global warming potential and the fossil depletion in comparison. The impacts on human toxicity and water depletion are displayed in figure 9. Both figures give an overview of relevant indicative metrics of the SOCRATCES technology with regards to the LCIA. These metrics – fossil depletion, global warming potential, human toxicity and water depletion – should ideally be considered without the values indicated by the 10 kW pilot plant since, in its case, the design and operation were not undertaken with a practical application but feasibility study in mind. The pilot plant design is oriented to generate knowledge about processes and components and not to power production, and its operation is largely an experimental effort. As for the comparison between the 10 MW and the 100 MW plants, carried out using data largely acquired from literature, it must be highlighted how that the metric approximately doubles with the leap from the design of 10 MW to 100 MW, indicating a nonlinear relationship, best approximated by a power-relation of the $y = ax^b$ form. This holds for all four of the metrics considered here.
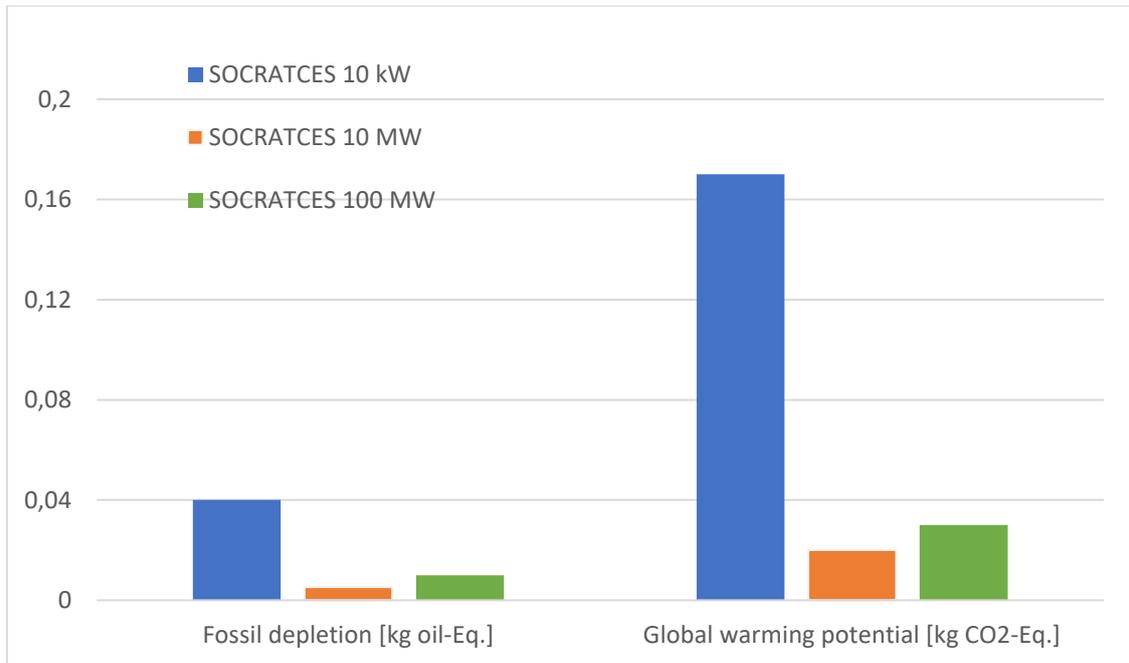
Figure 8: Comparable LCIA results for the three different SOCRATCES sizes for the impacts of global warming potential and fossil depletion
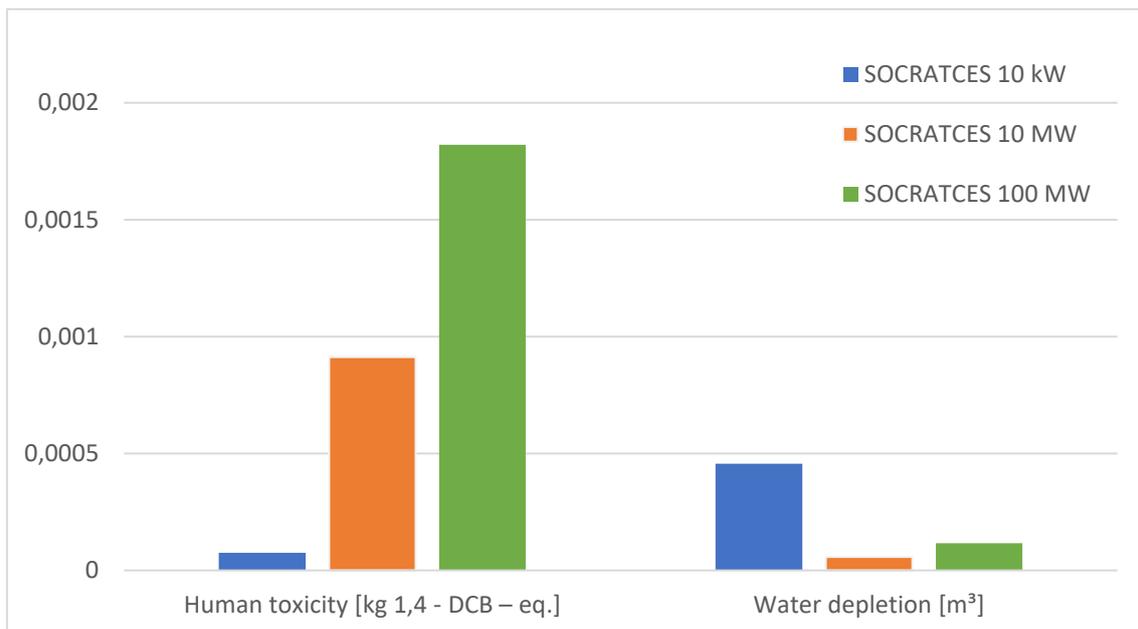

Figure 9: Comparable LCIA results for the three different SOCRATCES sizes for the impacts of human toxicity and water depletion

To get a more precise impression of the allocation of the impacts during the life cycle, table 5 shows the global warming impact for the different life cycle phases.

Table 5: Global warming potential impact for the different phases

Impact Global warming potential [kg CO2-Eq.]	SOCRATCES 10 kW	SOCRATCES 10 MW	SOCRATCES 100 MW
Construction	44%	87%	92%
Use Phase	54%	9%	5%
Recycling	2%	5%	3%

Figure 10 displays the values for comparison. It shows that for the industrial scale, the main impact of global warming comes from the construction of the plant. The pilot plant has an almost equal GHG impact on the construction and operation phases, mainly from the additional heating installed and its experimental nature.
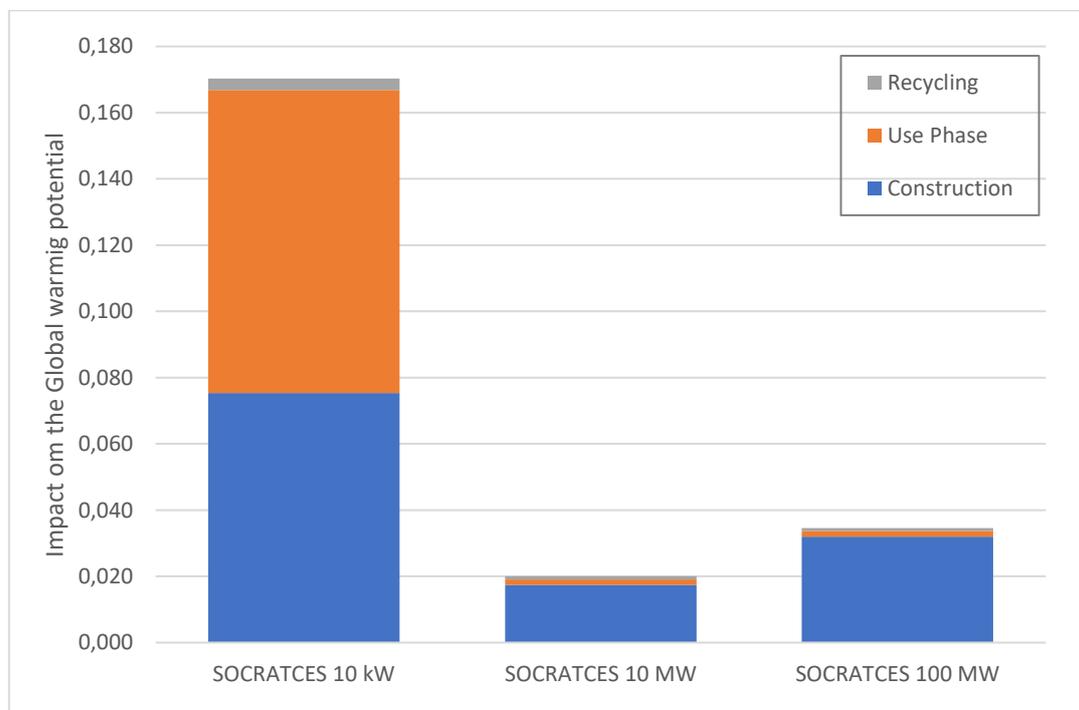

Figure 10: Comparable global warming potential for the different life cycle phases

For a better understanding of the data in general, different evaluation approaches can be applied. In the following these approaches are explained:

1. normalization: where the magnitude of category indicator results is calculated in relation to the reference information;
2. grouping: sorting and possibly ranking of the impact categories;
3. weighting: converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices.

Data prior to the application of one of these approaches should always remain available. In this study, the first step in handling the LCIA data is normalization. Normalization is the calculation of the magnitude of the category indicator results relative to some reference information. The normalization aims to better understand the relative magnitude for each indicator result of the

system under study. The least favourable impact is assigned a value of 1, and the other figures are scaled with reference to that. The risk potential was assumed to be equal for all different systems. As the least favourable impacts were generated with the pilot plant, it was assigned with the value 1, and the two industrial systems were calculated with this reference, as shown in table 6. Therefore, a comparison is possible. Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value choices. It may include aggregation of the weighted indicator results. In this work, the weighting factors were assumed to have an equal share and importance.

Table 6: Normalization of the LCIA data, referring to the pilot plant awarded with the value 1

	SOCRATCES 10 kW	SOCRATCES 10 MW	SOCRATCES 100 MW
Energy consumption	1.00	0.00	0.00
Depletion potential	1.00	0.13	0.33
Emission	1.00	0.12	0.84
Land Use	0.21	1.00	1.00
Toxicity Potential	1.00	0.13	0.25
Risk potential	1.00	1.00	1.00

Following the normalization, the summarized values of the environmental categories result in a spider diagram, shown in figure 11. This spider diagram illustrates a graphical depiction of the ecological pros and cons of the SOCRATCES plant in the different industrial sizes analyzed.
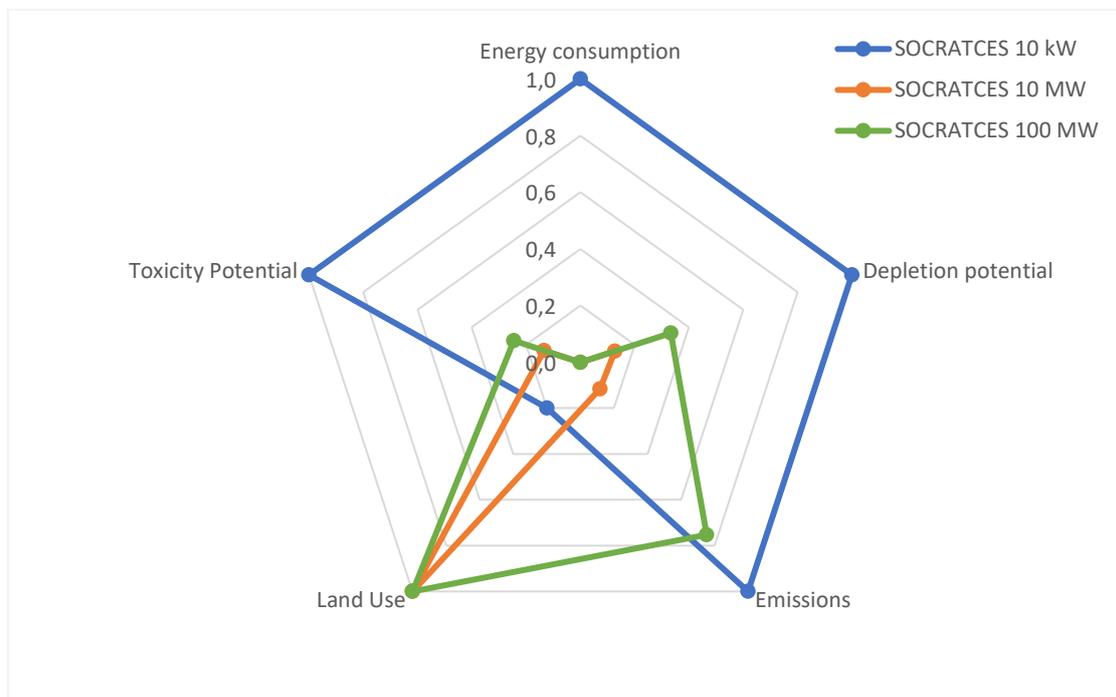

Figure 11: Spider diagram of the environmental categories comparing different sizes of the SOCRATCES technology

It is possible to identify the location in terms of the environmental impact categories. The blue line describes the pilot plant system with 10kW. It was used as the reference since the values of the Umberto® calculation were the highest. The diagram clearly demonstrates that the industrial scale of the SOCRATCES technology has better values than the pilot plant. In the spider diagram, the land use for the industrial scale is normalized to one since, for the pilot plant, the size of the solar side components was simulated on a very small scale. Nevertheless, it needs to be said that both industrial scales are in normalization to the pilot plant and not to each other. The values for the 100 MW industrial scale are overall slightly higher than the 10 MW plant, which is all in the range of the upscaling factor. When comparing the industrial scale to comparable technologies stated in literature (see table 2), the SOCRATCES technology can keep up in any way. Most of the data available in the literature are not shown in detail to compare every single impact category. Therefore, the comparison is only carried out for the global warming potential. Figure 12 shows the comparison with some data conceived from literature.
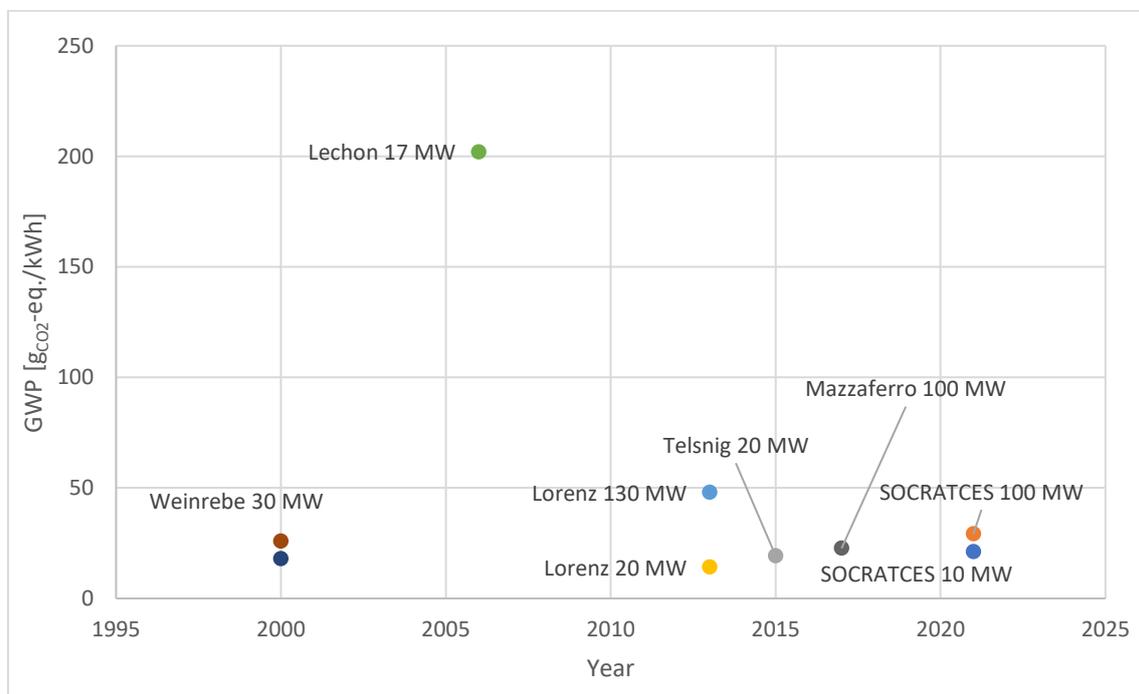

Figure 12: Comparable data for Global Warming Potential

Figure 12 shows the comparison of the industrial SOCRATCES technology in the size of 10 MW and 100 MW to data that was extracted from literature. Especially when comparing the 100 MW SOCRATCES scale with the plants referred to in Mazzaferro with 100 MW and 7.5h storage time and in Lorenz with a size of 130 MW and four hours of storage time, the technology of SOCRATCES seems beneficial. Nevertheless, the SOCRATCES technology can keep up with comparable systems regarding the Life-Cycle-Assessment within the system boundaries. It is very important to always refer to the boundaries of the system and that the generated results are not absolute but only comparative.

5. ECO-EFFICIENCY APPROACH

The purpose of an Eco-Efficiency analysis is to harmonize economy and ecology. This involves carrying out an overall study of an alternative solution to include a total cost determination and the calculation of ecological impact over the entire life cycle. The eco- and cost-analysis results will be demonstrated in a diagram, similar to it displayed in figure 13. It shows the comparison of the overall ecological footprint with the total costs of different processes. The overall ecological footprint can be calculated by the LCIA results. All impacts together will be used in the eco-efficiency analysis.
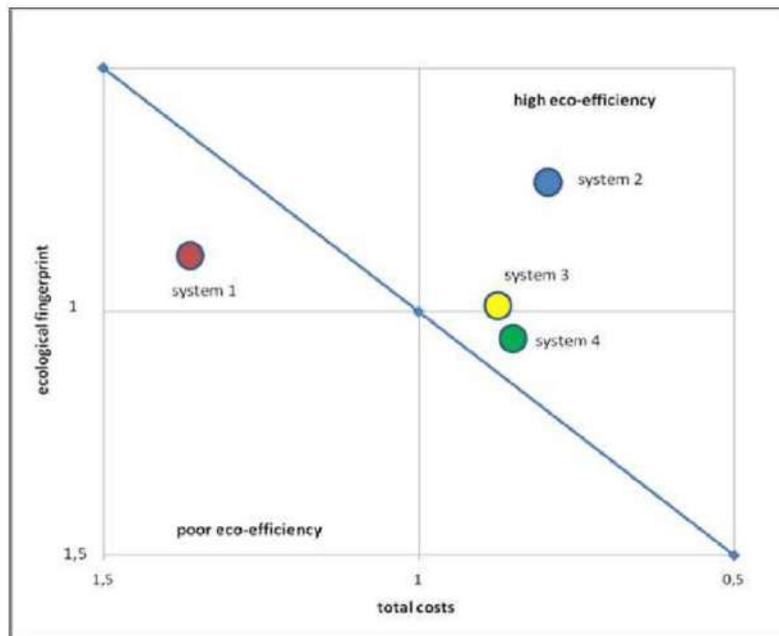

Figure 13: Visualization of the Eco- and Cost-Efficiency [BASF-Method]

The graph above is used as an example. System 2 shows a certain low ecological impact and low specific costs compared to all other systems. It would be an ideal situation to show the efficiency of the system compared to other processes, visualizing the most eco- /cost-efficient process for the targeted application directly. The calculation of total costs and estimation of the environmental footprint are independent calculations of the economic and ecological aspects of a system. On the assumption that ecology and economics have the same importance in a sustainability assessment, a technology less economical can compensate for this disadvantage with a better ecological assessment and vice versa. With the eco-efficiency approach, different alternative processes or technologies are comparable. Costs are calculated against environmental categories and plotted together in a diagram.

The calculation of total costs and the calculation of the environmental footprint are independent calculations of the economic and ecological aspects of the SOCRATCES technology. The economic data was extracted from the deliverable D8.14 Second report on LCC. The weighing factors were set equal on the assumption that ecology and economics have the same importance in a sustainability assessment. In all calculations, no absolute values are considered, only comparative once. Costs are calculated and compared to environmental positions and

plotted together in a diagram. For the LCA data in the literature, the costing was assessed with the IRENA renewable cost databank [16]. In order to illustrate the concept of eco-efficiency, the eco-efficiency portfolio was applied.
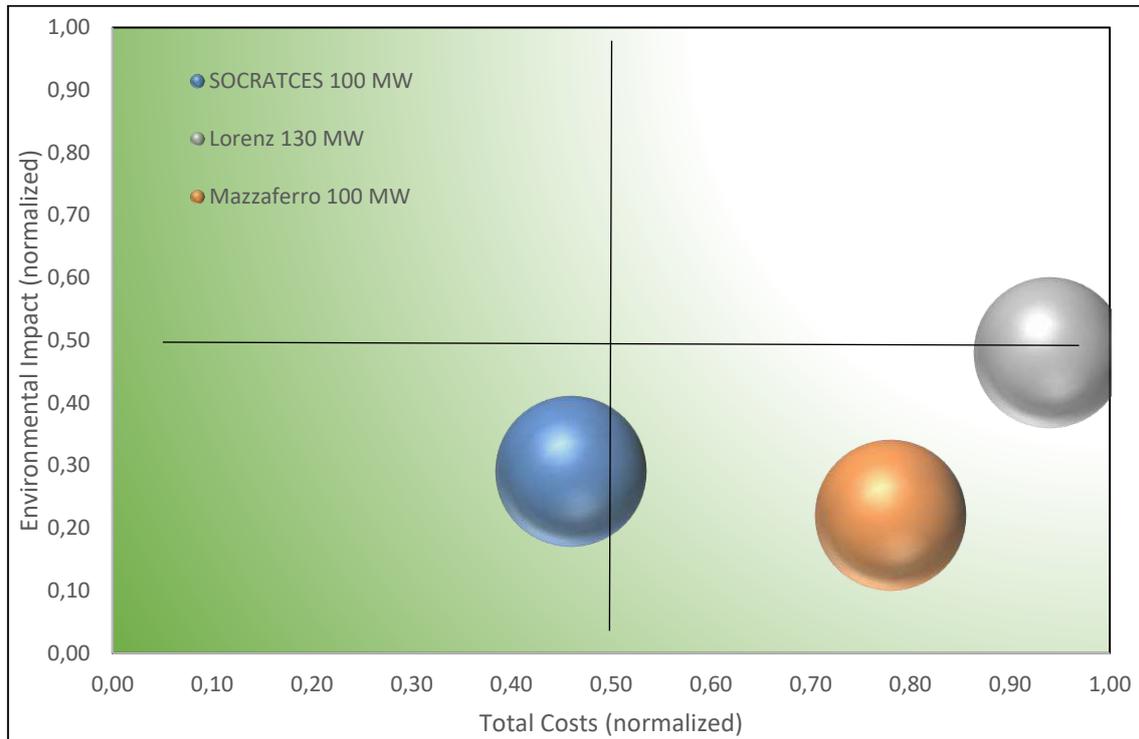

Figure 14: Eco-efficiency portfolio of the SOCRATCES technology in comparison with literature data

The costs are shown on the horizontal axis, and the environmental impact is shown on the vertical axis. The graph reveals the eco-efficiency of the SOCRATCES technology 100 MW scale with various systems from literature. Such results allow a look into the future since Eco-efficiency analysis is utilized in making strategic decisions, and it helps detect and exploit potential ecological and economic improvements. This approach demonstrates that the most favourable technology is located bottom left, the less favourable one - top right. The distance of the individual processes to the portfolio diagonal is a measure of the respective eco-efficiency. Figure 14 shows that the SOCRATCES technology in the industrial scale of 100 MW and storage duration of 8+ hours is most favourable to the two comparing systems. The Lorenz 130 MW plant has a storage capacity of 4 hours, which is increasing the costs per kWh drastically. Also, for the plant referred to in Mazzaferro with 100 MW and a storage capacity of 7.5 hours applies the same. Even though the ecological impact is stated insignificantly lower than the SOCRATCES technology, it is important to mention that the system boundaries could vary significantly and are not known in detail for the reference system.

6. DISCUSSION AND CONCLUSION

Work package 8 shows the economic assessment, business development, risk analyses and technology watch of the solar calcium-looping integration for thermochemical energy storage. Deliverable D8.13, according to the Description of Work, is the second report on life cycle

assessment. In this task, the environmental performance of the SOCRATCES technology was evaluated using a state of the art life cycle approach. The principal goal was to evaluate the potential impacts of the SOCRATCES plant on an industrial scale and interpretation of the results helping to establish this innovative technology. The objectives were achieved in accordance with the project proposal. The performed LCA can serve to improve the overall environmental performance through the development of guidelines and can be the basis for communicating achievements. It was performed based on the data gathered from the project consortium, the use of database and literature. The process map was built in the Umberto LCA+® software, and the impact categories were calculated. Compressed LCIA data were graphically demonstrated on a spider diagram for five environmental impact categories: the consumption of energy, depletion potential, the consumption of raw materials, resulting in emissions, and the toxicity potential as well as the risk potential.

The SOCRATCES technology proposes a novel energy storage technique and is entirely green. It captures solar energy using a conventional array of heliostats. Solar energy is used in real-time to perform an endothermic reaction in a novel reactor with no fuel or external electric consumption. The products of this reaction are stored so that they can be brought together in a vigorously exothermic reaction to power an electricity generation cycle whenever required. The own nature of the system, non-dependent on fossil fuels, makes the technology profoundly green. Its environmental compatibility is conspicuously reflected in the metrics studied in the LCA results presented in this report. With this technology, the system of thermo-chemical energy storage has the potential to contribute to climate protection and reduce the GHG-emission.

Comparing the technology with molten salts storage systems, the SOCRATCES system has a significantly superior eco-efficiency. For example, the global warming potential for the industrial scale of 100 MWth has a value of 39 gCO_2-Eq per kWh produced electricity for the SOCRATCES technology, whereas the state-of-the-art system contributes with values between 20 - 200 gCO_2-Eq /kWh. The calculation clearly demonstrates that the technology developed in the project can compete with alternative methods in terms of ecological aspects, especially in terms of toxicity. When compared to the CSP 100 MW plant in Mazzaferno [7], all values for freshwater aquatic ecotoxicity, human toxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity are significantly higher than the impact values for the SOCRATCES technology. The comparison of the SOCRATCES technology on an industrial scale and the pilot plant are not fully comparable since a pilot plant is an experimental facility non oriented for economic exploitation and optimized ecological impact. Additionally, the external heating installed in the pilot plant affects the result. Nevertheless, the results for the pilot plant is shown as well.

The values used for the analysis of the individual processes and also the derived results are not absolute but only comparative. By adjusting only parameters, the overall calculation can give a different result. The LCIA methods used in the software Umberto LCA+ namely: ReCiPe 2008 Midpoint (H) w/o LT and IPCC 2013; could be changed, and a different set of results would be generated, but, for sure, the general trends would remain the same. According to the goal and scope of this study, the chosen methods collects the critical environmental impacts adequately.

For a better understanding of the results, different approaches for interpretation were applied. The normalization of the indicator results can be a factor of interpretation. It may be desirable

to use several reference systems to show the consequence on the outcome of mandatory elements of the LCIA phase. For the interpretation of LCA results, it is always important to know the meaning of the applied approaches. Ranking and weighing is based on value-choices but is left out in this comparison since the goal was identified and compared to the environmental impact of the SOCRATCES technology. Different individuals, organizations and societies may have different preferences and weighting factors; therefore, it is possible that other parties will reach different ranking results based on the same indicators or normalized indicator results. Still, an average CO_2 equivalent can be given. The process map with all its in- and outputs was calculated by Umberto LCA+. The databanks ecoinvent v2.2 and v3 were used. The results of this show the SOCRATCES technology positive environmental impact and, from this point of view, the interest in further advances in the development of this technology.

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ATTACHMENT

Table 7: Data assumptions for the LCA calculations of the 2MW$_e$ industrial scale

Parameter	Component/stream	Value
Operating temperature	Calciner	950°C
Cut-in power	Calciner	20% of calciner design power
Operation time	Carbonator side	24 h
CaO conversion	CaO	0.5
Thermal losses	Carbonator	1% of reaction heat
Isentropic efficiency	Storage turbine	0.8
	Blower/Compressors	0.8
Electrical efficiency	Electric generator/motor	0.98
Storage temperature	Storage vessels	20°C
CO_2 storage pressure	CO_2 vessel	75 bar
Solid conveying electrical consumption	CaO, $CaCO_3$	10 kJ/(kg*100m)
Minimum ΔT	Gas-gas HEXs	15°C
	Gas-solid HEXs	
	HTF-solid HEXs	
Isentropic efficiency	Turbine CO_2 Cycle	0.92
	Compressor CO_2 Cycle	0.88
Electrical efficiency	Electric generator CO_2 Cycle	0.98
Ambient temperature	Air CO_2 Cycle	20°C
Minimum ΔT	Heater CO_2 Cycle	20°C
	Cooler CO_2 Cycle	15°C
Compressor inlet pressure	Compressor Power Block	75 - 95 bar
Turbine inlet pressure	Turbine Power Block	180-250 bar
Turbine inlet temperature	Turbine Power Block	500° - 700°C
Outlet Temperature (cold side)	Turbine Power Block	100° - 450°

Table 8: Data assumptions for the LCA calculations of the 100MW$_{th}$ industrial scale

Parameter	Component/stream	Value
Operating temperature	Calciner	900°C
Operating pressure	Calciner	1 bar
Operation time	Calciner side	8 h
Operation time	Carbonator side	24 h

CaO conversion	CaO	0.5
Thermal losses	Carbonator	10% of reaction heat
Operating temperature	Carbonator	920°C
Operating pressure	Carbonator	9 bars
Outlet pressure	Power cycle turbine	1 bar
Isentropic efficiency	Turbines and compressors	0.89
Electrical efficiency	Electric generator/motor	0.98
Storage temperature	Storage vessels	20°C
CO_2 storage pressure	CO_2 vessel	75 bar
Solid conveying electrical consumption	CaO, $CaCO_3$	10 kJ/(kg*100m)
Minimum ΔT	Air cooler	15°C
	Gas-solid HEXs	
	Solid-solid HEXs	20°C

Table 9: Scaling parameters for the calculation in Umberto® for the industrial scale of 100 MW

Equipment	Scaling parameter
Solar tower	100 MW
Heliostat field	350 877 m²
Solar Receiver	200 MW
Calciner	54 m³/s (entrained flow)
Carbonator	116,5 m³/s
CO_2 vessel	571,2 m³
CaO storage tank	3350 m³
$HX_{A,B,E,F,I}$	Solid-Fluid (48 MW_{th}, 23 MW_{th}, 15 MW_{th}, 2x10 MW_{th})
HXG	Fluid-Fluid (30 MW_{th})
Cooler	3 MW_{th}