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First Report on Life Cycle Assessment

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EXECUTIVE SUMMARY

This Deliverable 8.3 gives the first report on the Life Cycle Assessment for the application of the SOCRATCES technology. The most challenging task for WP8 and especially for the Life cycle assessment will be the collection of the actual process data for all different process steps for the SOCRATCES technology but also for comparable and suitable alternative processes. The objectives of this task were only partly achieved in this first LCA analysis. At this stage of the project, the LCA was performed based on the data gathered from the mathematical models by the University of Seville.

Compressed LCIA data is graphically demonstrated in a spider diagram for five environmental impact categories: the consumption of energy, depletion potential, the consumption of raw materials, resulting emissions and the toxicity potential. The chosen LCIA methods used in the software Umberto LCA+ namely: ReCiPe 2008 Midpoint (H) w/o LT and IPCC 2013; represent the most important impacts for this study. With a change of method, a different spectrum of results could be created. Certainly, the general trend would remain the same according to the goal and scope of this study.

The results of the LCA clearly demonstrates that the SOCRATCES technology concept (closed loop with recycling of CaCO_3) has a good ecological impact compared to the alternative battery-storage approach. Nevertheless, it is very important to say, that the values used for the individual products and the generated results are not absolute but only comparative. By changing only a few assumed parameters, the overall calculation can give a different result.

Additional LCA analyses will be developed in next months for a complete LCA framework definition. Deliverable D8.3 will be updated with the results of new analyses with more adjusted data based on the numerical models and the real measurements of the prototype as well as extended reference models.

1. INTRODUCTION

The LCA approach evaluates the environmental impact of a product, process or activity throughout its life cycle. LCA can serve to improve the overall environmental performance of a product, or it can be the basis for communicating achievements of the manufacturer towards sustainable production. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided. It should be mentioned, that LCA is only one of several environmental management techniques (e.g. risk assessment, environmental performance evaluation, environmental auditing, etc.). There is always the possibility of finding a more appropriate technique to use. Nevertheless, LCA can assist in:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle;
- The selection of relevant indicators of environmental performance, including measurement techniques, and
- Marketing (e.g. implementing an eco-labelling scheme, making an environmental claim, or producing an environmental product declaration).

Deliverable 8.3 gives the first report on the Life Cycle Assessment for the application of the SOCRATCES technology. The strategy and the drafts for data collection were created during the first period and described in the deliverable 8.2 “LCA, LCC Scope and system boundaries”. [1] In summary, it can be said that in D8.2 the basic information about the LCA was given. A framework was established with the definition of goal and scope. The inventory analysis (LCI) and the impact assessment (LCIA) were scheduled. It was planned to use generated data from the whole process, starting from calciner through storage reservoirs, carbonator and power block in the ecological and economic assessment. The data used for calculation in this deliverable is explained and shown in chapter 3. The actual process boundary, the LCI and LCIA used for assessment are described in subchapter 1.1 “Fundamentals”.

The most challenging task for WP8 and especially for the Life cycle assessment will be the collection of the actual process data for all different process steps for the SOCRATCES technology but also for comparable and suitable alternative processes.

1.1. Fundamentals for the Life Cycle Assessment

For carrying out the LCA some fundamentals need to be clarified and summarized. At the starting point of the Life Cycle Assessment, the approach and the methodologies should be clear and elaborated. The goal and scope definition are the first phase of any life cycle assessment and different aspects should be addressed during this stage. Generally, these should be clearly defined and be consistent with the intended application. In some cases, the goal and scope of the study may be revised due to unforeseen limitations, constraints or as a result of additional information. The goal is explained as followed for the SOCRATCES technology: The **overall goal** of the LCA is assessing the environmental profile of the

SOCRATCES technology and evaluation of energy and waste flows associated with calcium looping thermal energy storage system over different stages of its life cycle. [2]

When it comes to **the scope** of an LCA, following items should be clearly studied and considered inter alia: functional unit, reference flow and the system boundaries. The **functional unit** is to provide a reference to which the input and output data are normalized (mathematically). It must be clearly defined and measurable. For the definition of the functional unit, a reference flow needs to be specified. The **reference flow** is the measure of product components and materials needed to fulfil the function, as defined by the functional unit. An appropriate selection of the functional unit is crucial, because different functional units can lead to different results for the same product system. In this context, taking into account the previous considerations, the mutual work driven for the environmental assessment and in accordance with the main goals of the SOCRATCES project, the functional unit selected is 1 kWh of thermal energy stored over specific lifetime for the SOCRATCES systems. With the definition of the functional unit, the reference flow of the system must be in accordance. If a different reference should be addressed, the complete system has to be changed. With the set of the functional unit, the reference for all input and output streams must be kWh as well. A mass or molar balance of the calcium looping cannot be considered directly, but must be described in dependency of its energy uptake. So a constant reference flow can be assured.

Furthermore, the system boundaries need to be defined. The **system boundaries** include or exclude technological processes from the system, according to the consistency of the LCA goal. The decision should be made regarding which unit process to include in the study and also the level of detail. The choice of boundaries is quite important, since every additional or deleted in- and output might change the environmental impact drastically. There are main options which can define the system boundaries. Due to present studies and remarks on the literature review it was decided in deliverable 8.2 to use a **cradle-to-grave** approach, which includes the material and energy production chain and all processes from the raw material extraction to the products end of life treatment. For the LCA of the prototype this approach cannot be assured, since the power Block will not be part of the assessment and it stops after the carbonator. For a cradle-to-grave approach, the last step would be the end of life after the use of the thermal energy. This approach will be carried out in the second report on LCA (D8.13 at the end of the

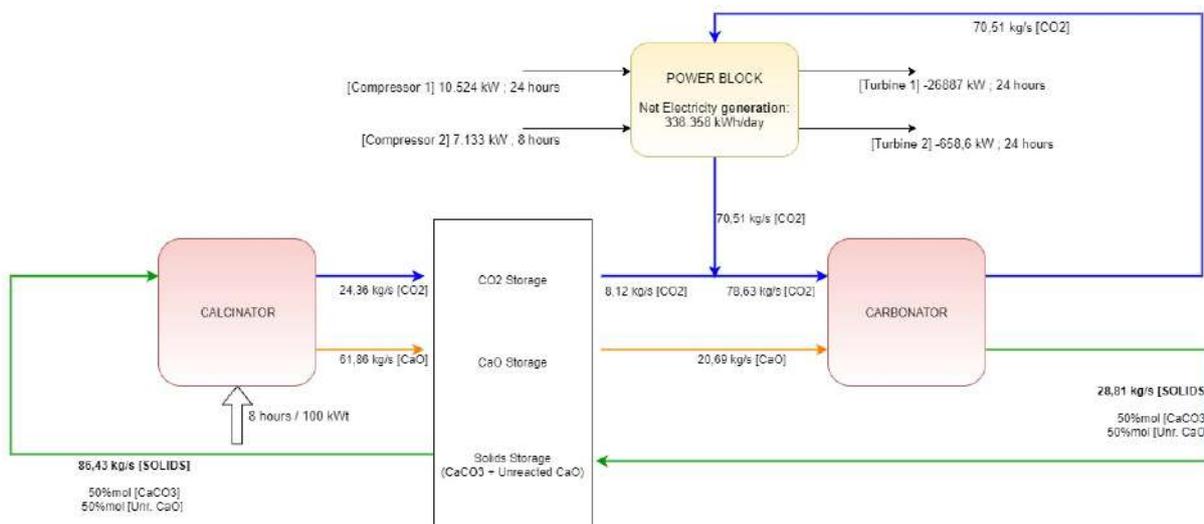


Figure 1: Schematic flow diagram of the SOCRATCES technology, as foundation of the LCA

SOCRATCES project). In addition, the consideration of a “cradle-to-cradle” approach, including the possibility of reuse/recycle of resources should clearly be kept in mind. Then the scope will be adapted accordingly. In figure 1, a process flow diagram shows the simplified relation between the process streams and the fundamentals of the LCA.

The System boundaries differ slightly from this figure. In figure 2, the system boundaries for the LCA can be seen. Additional energy inputs are described in chapter 4 the modelling of the LCA in the software.

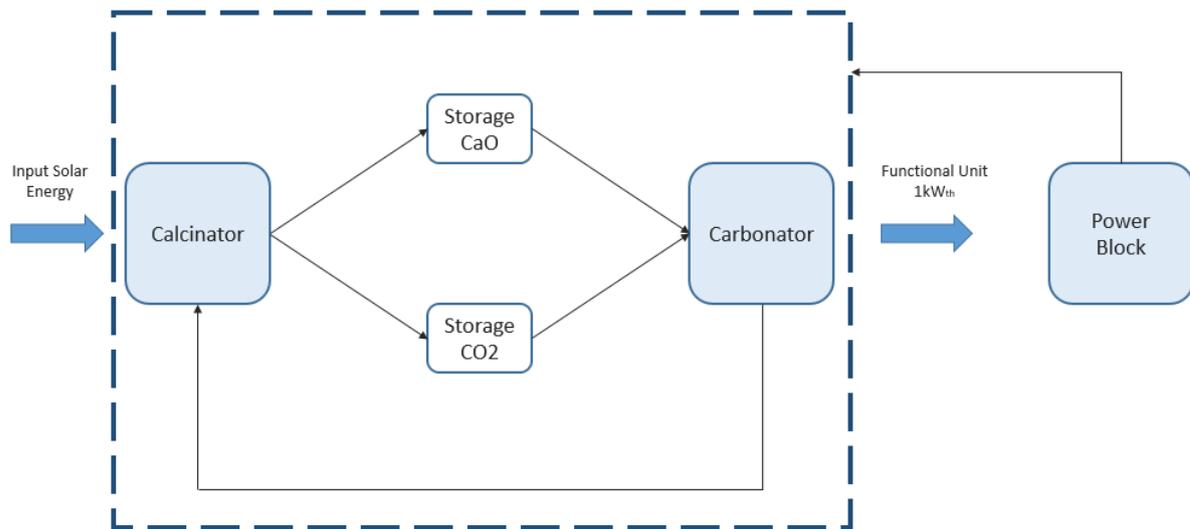


Figure 2: System boundaries of the SOCRATCES technology

Furthermore, to identify and evaluate the amount of significance of the potential impacts, the following impacts groups were chosen: [3, 4]

- **IPCC 2007, Climate Change**
 - GlobalWarminPotential 100a
- **ReCiPe Midpoint (H) w/oLT**
 - Cumulative energy demand
 - Depletion potential
 - Emission values
 - Water emissions
 - Air emissions
 - Solid (waste) emissions
 - Land Use
 - Toxicity potential
 - Risk potential

The evaluation in respect to LCIA factors is different from all other techniques, such as environmental performance evaluation, environmental impact assessment, since it is a relative approach based on a functional unit. The collection of indicator results for different impact categories, which represent the impact profile for the overall system, is most important for the selection of this metrics. Figure 3 shows a first example of how this profile can be displayed.

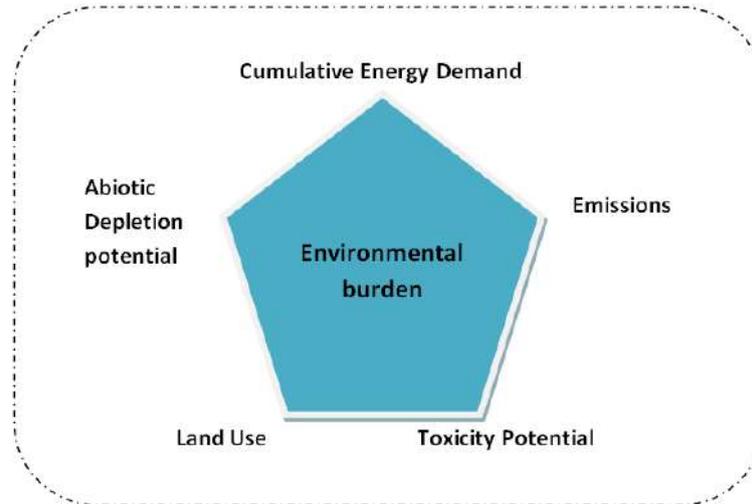


Figure 3: Environmental Burden Metrics [3]

2. ECOLOGICAL FOOTPRINT APPROACH MODEL

The purpose of Eco-Efficiency Analysis is to harmonize economy and ecology. This involves carrying out an overall study of alternative solutions to include a total cost determination (LCC) and the calculation of ecological impact over the entire life cycle. In the development and optimization of products and processes, eco-efficiency analysis makes it possible to consider total costs and ecological impact side by side, to select the most eco-efficient alternative. For the transparency and performance of Eco-Efficiency, the model will include the following: [3, 2]

- LCA for the process and products according to ISO 14040,
- Determination of health impacts (e.g. toxicity) and of risk potentials,
- Determination of dangerous effects for the environment;
- Weighting the LCA results (e.g. the greater the influence of an emission on the total emissions is, the higher a relevance weighting factor will be). It can be done for all relevant aspects, e.g. environment, economy, social aspects, etc.
- Relation between ecology and economy;
- State-of-the-art processes as bench-marks;
- Normalization and use of spider diagram.

For SOCRATCES, the LCA and the LCC are developed independently. In this deliverable the results of the LCA are shown and compared to similar, alternative processes. For this comparison, different factors play an important role: Weighting the LCA results (e.g. the greater the influence of an emission on the total emissions is, the higher a relevance weighting factor will be). It can be done for all relevant aspects, e.g. environment, economy, social aspects, etc. The State-of-the-art processes will play a role as bench-marks, so it can be possible to rank the ecological efficiency of the process. A normalization needs to be done accordingly (the least favourable alternative gets the value 1; all others are set in a relation to

this alternative). The next step is to combine the normalized values via a weighting factors in order to form a total value for the emissions. This weighting factors are based on societal and scientific weighting factors. Relevance factors define the importance of the individual environmental categories particularly for the ecological analysis. The relevance factors automatically indicate the main influences during the calculations. In this work, the weighting factors were assumed to have the equal share and importance. This calculation can be represented best with spider diagrams. This diagram representation will mirror, but not be limited to a certain model. In order to easily visualize the environmentally relevant parameters of processes and compare them, a picture of the relevant environmental impacts can be provided. An example shows six main categories. Those categories can be developed accordingly. [5]

- Raw material utilization
- Surface use
- Energy consumption
- Emissions to air, water and soil
- Toxicity potential
- Risk potential

The following it is an example of what the spider diagram could look like and how it is used to demonstrate the ecological footprint of different products for comparison purposes:

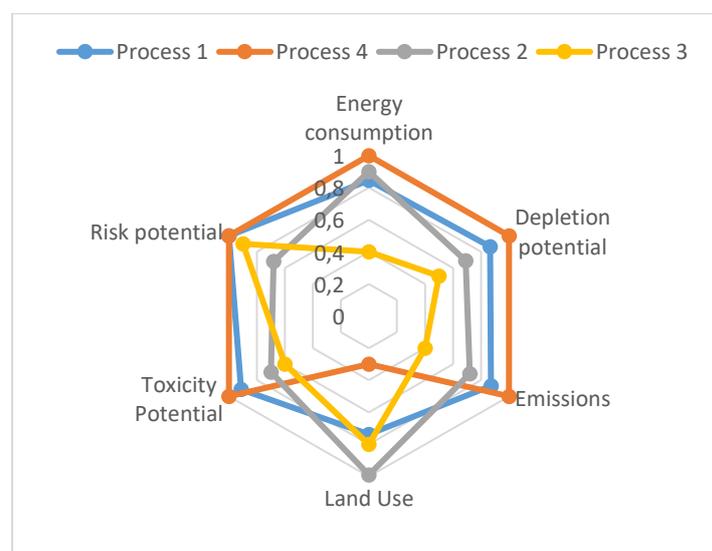


Figure 4: Exemplary ecological footprint of four systems

For the SOCRATCES model, the diagram might include other relevant categories not included here. For a more detailed list of environmental impacts, the following could be considered:

1. Atmospheric emissions

- Reported by unit of weight of input and output
- Usually only regulated materials required by the government are monitored
- Common air emissions: particulates, nitrogen oxides, volatile organic compounds, sulphur oxides, carbon monoxide, aldehydes, ammonia, and lead

- Water vapour and carbon monoxide are generally not included

2. Waterborne waste

- Reported by unit of weight
- Includes emissions from fuel combustion and processes
- Common waterborne wastes includes biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, dissolved solids, oil, grease, sulphides, iron, chromium, tin, metal ions, cyanide, fluorides, phenol, phosphates, and ammonia

3. Solid waste

- Includes all solid material disposed within sources of the system
- Reported by unit of weight
- Types of solid waste:
 - Industrial: Waste generated during production
 - Process: Waste generated within a process and not recycled
 - Fuel-related: Waste produced from combustion and product production (includes transportation and operating processes)
 - Post-consumer: Product and packaging waste which is discarded purchase
 - Hazardous vs. non-hazardous
 - Hazard classification of waste

This data analysis will enable a classification of the SOCRATCES technology with the current state of art processes. Later on, this method could be used together with the LCC to give an overall eco-efficiency. [3, 2]

3. DATA PROCESSING AND COMPARIBLE APPLICATION

3.1. Data used for the LCA

In deliverable 8.2 the inventory analysis was explained. It involves the compilation and quantification of input and output for the analysed system, collection and compilation of the data. The data selected for an LCA study depends highly on the fundamentals as definition of goal and scope. Such data should be measured on the production site in association with the system boundaries or obtained and calculated from other sources. The acquisition of data was already explained in the previous deliverable D8.2. In practice, it always is a mixture of measured, calculated and estimated data. Data quality requirements should always be specified for reaching the goal. The accuracy of the LCA depends on the quality of the data, the best results of the LCA can only be achieved when measured data from the process itself are integrated. At this stage of the project, the data collection sheets were prepared, but could not be filled with experimental data. The University of Seville generated the information used for the LCA calculation with mathematical models. The mathematical models are adjusted to fit the simulation of the LCA.

Two different approaches could be applied for this study. The first model, with the objective of obtaining results that can give a preliminary view of the technology, and in order to carry out a first simulation, a solar energy input of 10 kWh is considered (equivalent to 1 hour of

operation of the prototype calcinator - 10 kW_{th} of power). To get a clearer view on the function of the overall process, this simulation is shown in two different ways:

- Closed loop: shows the process as it is, with the recycling of the CaCO₃ and the simulation is done in energy up takes.
- Open loop: the process has an in- and outgoing stream of the CaCO₃, whereas the functional unit is represented by the mass of the needed carrier material CaCO₃. [6]

The second model should display a larger plant with an input stream of 100 MW of solar energy. Table 1 gives an overview of the data for the pilot scale model, corresponding to the functional unit of 1 kWh of energy

Table 1: Data for the LCA

Streams per unit process	Calciner	Carbonator
Open Loop		
Input:		
Solids	3,151 kg (2,02 kg CaCO ₃ + 1,132 kg CaO)	-
Solar Energy stored	1 kWh	-
CaO	-	2,26 kg
CO ₂	-	0,89 kg
Output:		
Solids	-	3,151 kg
CaO	2,26 kg	-
CO ₂	0,89 kg	-
Closed Loop		
Input:		
Solids	0,005045 kmol/h	-
Thermal Power in calciner	0,125 kW	-
CaO	-	0,001682 kmol/h
CO ₂	-	0,0008408 kmol/h
Output:		
Solids	-	0,001682 kmol/h
CaO	0,002523 kmol/h	-
CO ₂	0,002523 kmol/h	-

Note that this flow rate entails 0,125 kW of thermal energy in the calciner, which, associated with an operating period of 8 hours, means 1 kWh of thermal energy (functional unit).

Since the functional unit for the LCA is defined to be energy (1 kWh_{thermal energy}), the mass balance of the chemicals in the system can be put in the background. Nevertheless, for the

overall LCA the chemicals need to be considered, but not as a constant flow due to its reusability. Therefore, the open loop is calculating the LCA of the used chemicals representative for one kWh energy. The difference of open and closed loop LCA is describing the environmental impact of the CaCO₃. The data for this calculation is extracted from the databank ecoinvent 3.

To meet the goal definition of the reference flow in model two (scale up), the energy uptake of the chemicals is most important for the calculation of the LCA. The feedstock compositions are given in table 2. The energy uptake is then calculated according to Hess's law. The calculation was carried out with the enthalpy of formation at standard state conditions. This calculation probably holds a lot of inaccuracies and gives a rough result of the LCA.

Table 2: Feedstock compositions used for the LCA model two (scale up)

	Calcinator	Carbonator
Input:	1993 kmol/h CaCO ₃ + 1993 kmol/h CaO	1328 kmol/h CaO + 664,2 kmol/h CO ₂ + 70,51 kg/s CO ₂
Output:	3986 kmol/h CaO + 1993 kmol/h CO ₂	664,2 kmol/h CaCO ₃ + 664,2 kmol/h CaO + 70,51 kg/s CO ₂

For calculating the energy flows, the enthalpy of formation were used according to table 3:

Table 3: Enthalpy of formation

Chemical	$\Delta H / \text{kJ mol}^{-1}$
CO ₂	-393,36
CaO	-635,09
CaO ₃	-1206,9

All values used in the LCA were only generated with the mathematical models from the USE. Therefore, the significance of the LCA is very low.

3.2. Comparable Technologies

In order to demonstrate the ecological footprint and environmental efficiency of the SOCRATCES technology, the following examples for further comparison could be used: Photovoltaic system in combination with batteries, molten salts technologies or other storage systems. For some of these alternative processes, a LCA will be performed the same way as for the LCA of SOCRATCES. The main challenge is, to collect proper data for these processes. All comparable technologies must have the equivalent functional unit as the SOCRATCES technology, to give an accurate comparison. For each alternative, a new model needs to be developed in Umberto.

Only for a photovoltaic system in combination with a battery storage, appropriate data were found. So far, just one reference system is used. The solar energy input is set equally to the

input stream of the SOCRATCES technology and the size of the battery is adapted to the functional unit of 1 kWh. It is reported in literature, that a lithium-ion battery can store 140-200 Wh/kg. [7]

A better reference process would be the molten salt technology. This technology has a huge variety of applications. Molten salts (fluoride, chloride, and nitrate) can also be used as heat transfer fluids as well as for thermal storage. This application is highly comparable with the SOCRATCES technology.

4. MODELLING AND RESULTS OF THE LIFE CYCLE ASSESSMENT

The LCA is carried out by using the software “Umberto LCA+” incl. “ecoinvent v3 and v2.2”. In the previous deliverable 8.2 a different version of the Umberto software was planned to use. Umberto LCA+ is an updated version to the previous announced one (Umberto NXT). The software Umberto LCA+ uses graphic modelling of the product/process life cycle, and allows analysing, assessing and visualizing the environmental impacts in different impact categories in the same manner. The main difference is the advanced integrated databases: ecoinvent v2.2 and v3. It can be given a large variety of internationally collected and verified data on different products, materials and services. It can be used to model raw material and energy supply chains or end-of-life treatment paths.

All mass flows are related to a defined target product and automatically are allocated to this product. Costs and revenues can be defined for all materials used, also for marketable by-products or side streams that need to be disposed. The LCA software automatically uses the database ecoinvent v.3 that includes a large variety of eco-assessments already been performed and evaluated by recognized institutions. For many relevant process streams (e.g. electricity, chemicals etc.) the upstream emissions during the production are already given. In Umberto, the topmost data structure is a project file. A project file is a database where the models and materials are stored. Several models can be created in one project file. For example the different technologies (SOCRATCES and a state of the art technology). A model typically contains one network for calculation. Every material defined in a project can be used for every model within the same project. All the changes made while working on a project are instantly written in the project database. The first step is drawing the life cycle model or process map. Before the calculation of material and energy flows, as well as the calculation of the life cycle impact assessment can be launched. Specification of the process and activities need to be stated. The results are displayed graphically and in tables. The life cycle model can also be displayed as Sankey diagrams, both for material and energy flows, as well as for weighted “impact flows”, i.e. the environmental impact loads cumulated along the stages of the life cycle. In figure 5, a first version of the SOCRATCES model is displayed. The blue boxes represent the processes itself. Those process steps are used to specify the in- and outputs. Every input is displayed by a green symbol and the process outputs by red symbols. The yellow icons represent the connection points between the single process steps. All data used from the databank is labeled with a specific symbol to distinguish between the processes itself and the data extracted from the databank. In the following figures 6-8 the Umberto LCA+ models of the closed and open calcium carbonate looping, as well as the solar system with the battery storage are displayed.

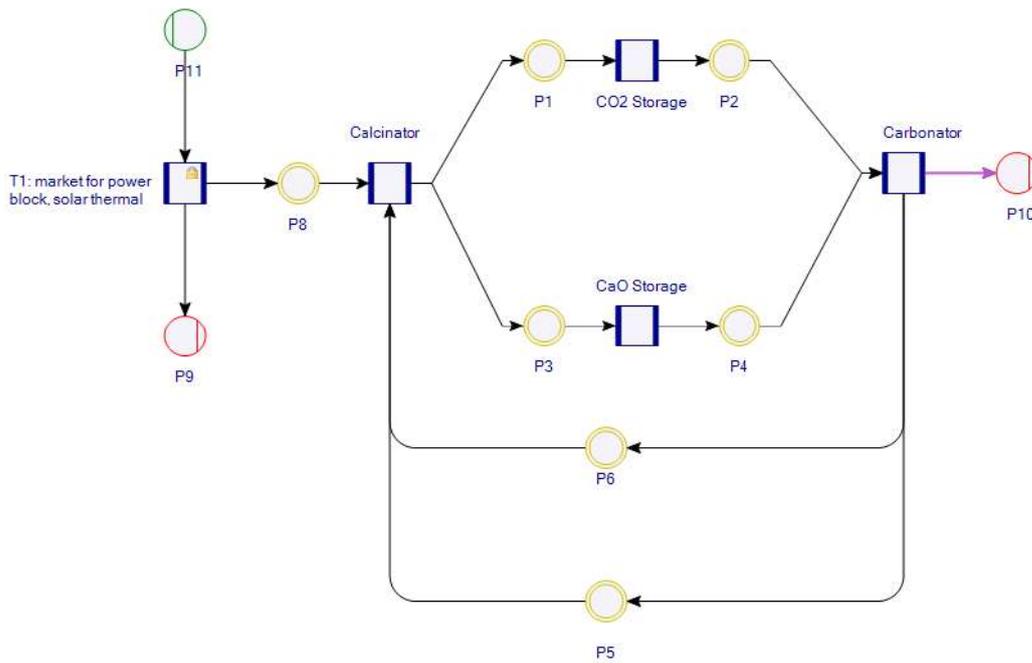


Figure 5: Umberto LCA+ model of the closed calcium carbonate looping from the SOCRATCES technology

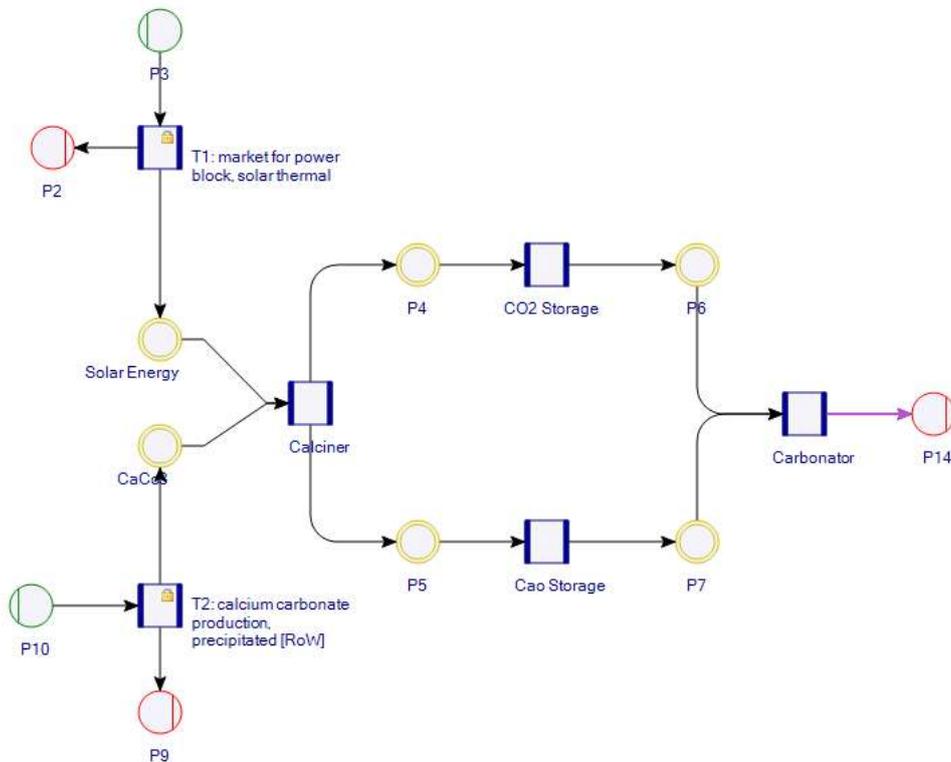


Figure 6: Umberto LCA+ model for the open calcium carbonate looping from the SOCRATCES technology

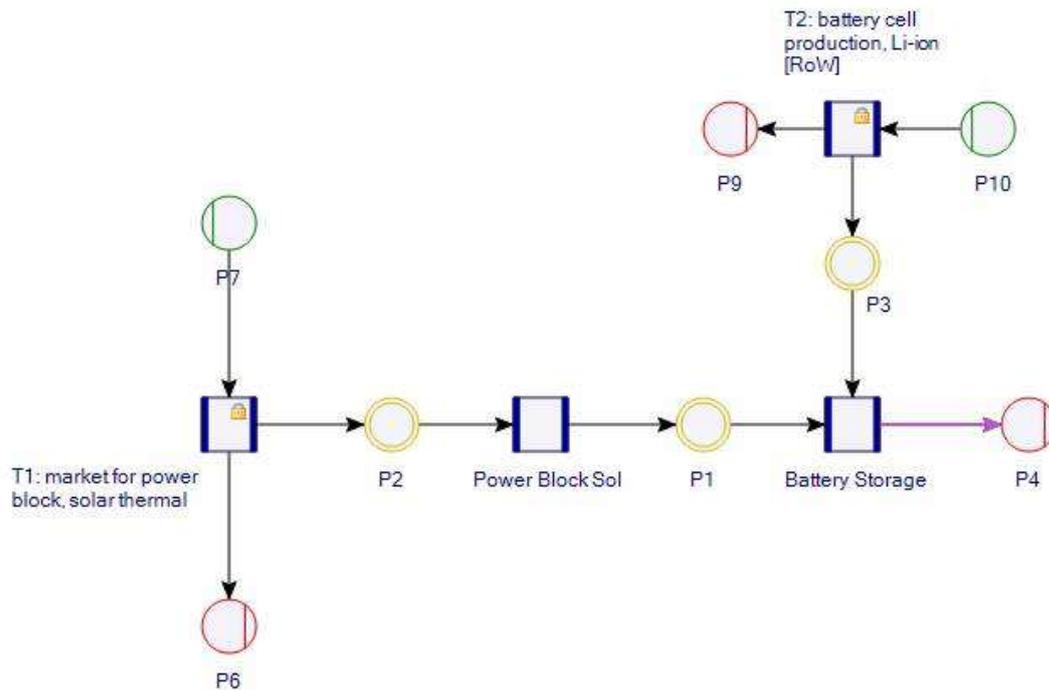


Figure 7: Umberto LCA+ model for the photovoltaic system with a battery as energy storage

The Umberto models give an overview on the process and calculation steps. It is very important to always have a clear and well-arranged process map. Thus it can be assured, that everybody can read and understand it. Furthermore, it is possible to define the Life Cycle Phases additionally. In Umberto it is just possible to calculate the carbon footprint of materials which are flowing into the system boundaries. If materials are just intermediates, their CO₂-equivalent backpack will not be included into the results.

With the use of the databanks v2.2 and v3 the environmental impacts can be calculated according to the chosen methods. The impacts are aggregated and summed to obtain an overall impact amount. Individual impact categories can be chosen throughout all available models and show environmental impacts of the different processes. In Table 4, the environmental impact categories are listed.

The results of the system are represented, either by a discrete compilation of the LCIA category indicator results 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 4, there could be optional elements and information as mentioned later, which are used for meeting the goal and scope of the LCA:

Table 5, gives real calculated data, without a normalization carried out. The data gives a clear statement about the actual environmental impact.

Table 4: List of environmental impact categories provided by UMBERTO LCA+, calculated with the methods ReCiPe 2008 Midpoint (H) w/o LT and IPCC 2013 [8]

Impact category	Impact	Open Loop	Closed Loop	Battery Storag	Units
Cumulative energy demand	Energy consumption	10	10	10	kWh
Depletion potential	Fossil depletion	2,75	1,76	10,39	kg-oil – eq.
	Metal depletion	2,62	2,24	124,95	kg Fe – eq.
	Water depletion	0,05	0,03	0,31	m ³
Emissions	Marine ecotoxicity	2,00E-02	2,00E-02	8,80E-01	kg 1,4 - DCB – eq.
	Marine eutrophication	1,85E-03	1,23E-03	1,00E-02	kg N – eq.
	Fresh water ecotoxicity	8,19E-03	4,70E-03	8,00E-02	kg 1,4 - DCB – eq.
	Fresh water eutrophication	3,95E-04	2,67E-04	6,22E-03	kg P – eq.
	Climate Change	11,27	5,88	34,23	kg CO ₂ eq.
	Global warming potential	11,2	6,06	35,05	kg CO ₂ eq.
	Photochemical oxidant formation	3,00E-02	2,00E-02	2,20E-01	kg NMVOC
	Ozone depletion potential	5,41E-07	2,67E-07	2,26E-06	kg GFC
	Particulate matter formation	2,00E-02	1,00E-02	2,20E-01	kg PM10
	Terrestrial acidification	5,00E-02	3,00E-02	6,10E-01	kg SO ₂ – eq.
Terrestrial ecotoxicity	2,33E-03	1,70E-03	2,00E-02	kg 1,4 - DCB – eq.	
Land Use	Land occupation	0,42	0,18	1,64	m ² a
	Natural land transformation	1,26E-03	5,24E-04	6,10E-03	m ²
	Urban land occupation	1,40E-01	9,00E-02	8,90E-01	m ² a
Toxicity potential	Human toxicity	2,15	1,62	86,53	kg 1,4 - DCB – eq.
	Ionising radiation	0,29	0,15	1,16	kg U235 – eq.

Table 5: Actual impacts generated with Umberto LCA+

Impact	Open Loop	Closed Loop	Battery Storage
Energy consumption [kWh]	10	10	10
Fossil depletion [kg oil-Eq.]	2,75	1,76	10,39
Human toxicity [kg 1,4 - DCB – eq.]	2,15	1,62	86,53
Metal depletion [kg Fe – eq.]	2,62	2,24	124,95
Global warming potential [kg CO ₂ -Eq.]	11,2	6,06	35,05

Based on the models calculations, environmental impacts were estimated and demonstrated on the Figure below. Energy consumption, global warming potential, human toxicity as well as fossil and metal depletion were the most considerable among the others.

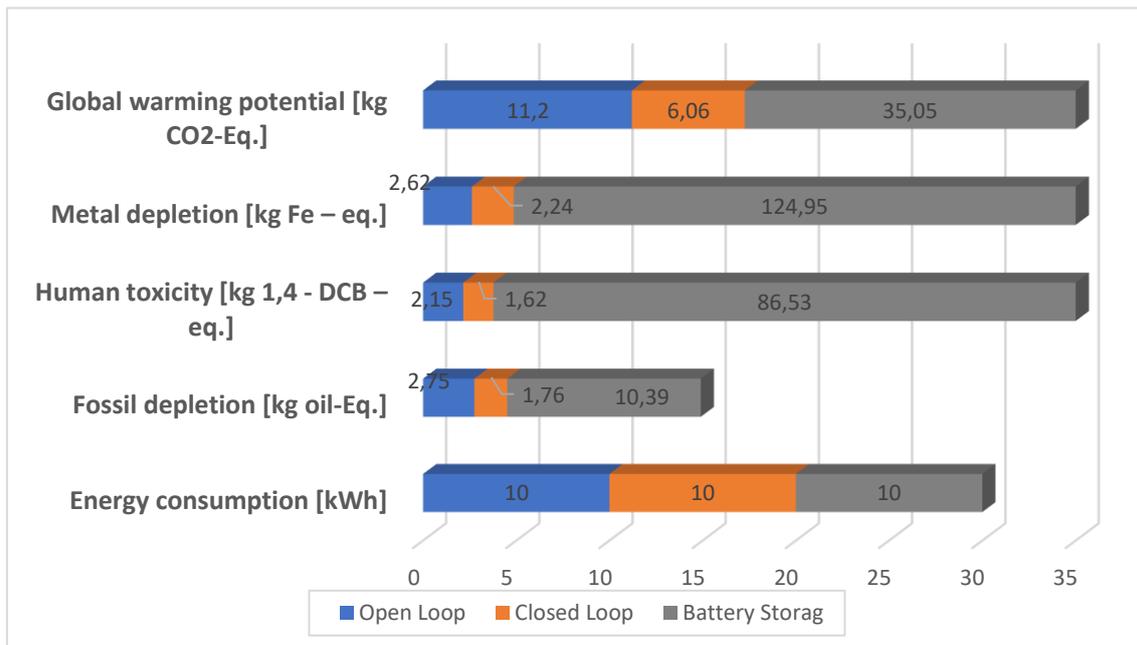


Figure 8: Comparison of some environment impact categories estimated by Umberto LCA+

In table 6, the normalized data is presented. With the normalization, a relation between the different processes is generated. As the battery storage has the highest values in its environmental impacts, it is chosen to be the reference process. Nevertheless it must be said, that the focus lies on the energy storage, since the materials used in the calciner and carbonator are mainly neglected. Furthermore, the ecological impact of the solar field is calculated concerning the functional unit.

Table 6: Normalization of the LCA data, referring to the photovoltaic system with battery storage

	Open Loop	Closed Loop	Battery Storage
Energy consumption	0,00	0,00	1,00
Depletion potential	0,04	0,03	1,00
Emissions	0,32	0,17	1,00
Land Use	0,22	0,11	1,00
Toxicity Potential	0,03	0,02	1,00
Risk potential	1,00	1,00	1,00

Following normalization, the summarized values of environmental categories are resulted in a spider diagram, which can be seen in Figure 9.

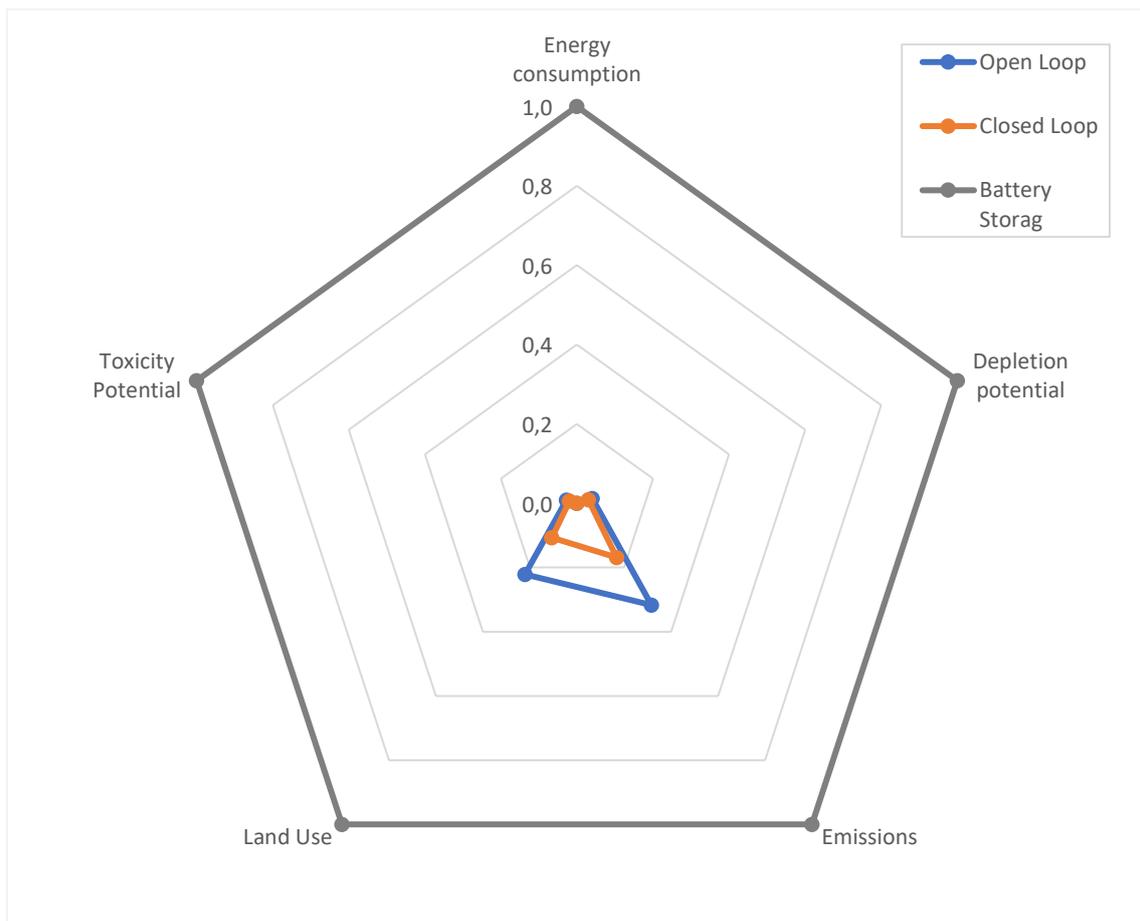


Figure 9: Spider diagram of the environmental categories and the three different methods

For better understanding of the values, the reference value is left out of the diagram. This can be seen in figure 10.

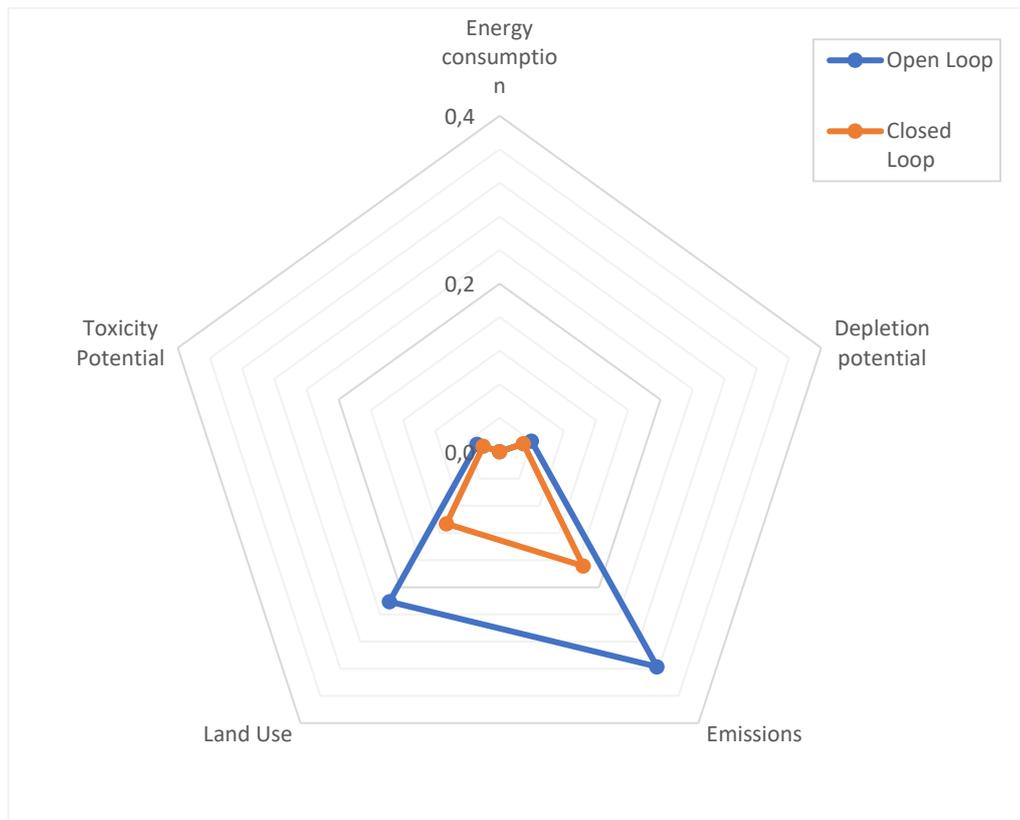


Figure 10: Spider diagram of the environmental categories and the closed and open calcium looping

This diagram demonstrates a graphical depiction of the ecological pros and cons of the two calcium-looping systems for the storage of solar energy and the system with a lithium ion battery. The diagram makes it possible to identify the location in terms of ecological impact categories. As the battery-storage has the highest values for most categories, the grey line describes the reference method (figure 9). The diagram clearly demonstrates that the SOCRATCES technology can compete with another storage-system in terms of ecological aspects (energy consumption, land use, toxicity, depletion potential and emissions into air water and soil).

First, it must be said that the energy consumption is the same for all process, since only the solar energy is considered. All additional heating or added electricity should not be necessary under normal operation conditions. Batteries have their own burden to the environment, which does not count to the impact category “energy demand”. With a change of energy source, the whole LCA changes accordingly and the spider diagram would show the differences. Figure 10 already shows only the open and the closed CaCO₃ looping, where the difference is the environmental impact of the calcium carbonate. With the recycling of it, all impacts are lower. Especially talking about emissions and land use.

Regarding the environmental impacts, it can be seen that the battery-storage system has quite high values in human toxicity and also in its depletion potential. Which primarily comes from the manufacturing of the batteries. The depletion potential is influenced by the use of

resources (fossils, water or metal), which increase significantly with the use of batteries for example.

5. CONCLUSION

The deliverable D8.3 First Report of the Life Cycle Assessment is a result of WP 8 in the project SOCRATCES. The final objectives of this task were only partly achieved in accordance with the project proposal as a preliminary LCA analysis was carried out to assess environmental performance of the system, in order to enable comparison with competing solutions. The LCA can serve to improve the overall environmental performance, or it can be the basis for communicating achievements. In the upcoming months the LCA analyses will be further developed and extended for a complete overview of the SOCRATCES technology

The LCA was performed based on the data gathered from a mathematical model created by the University of Seville. The process maps were built very simplified compared to the actual process plant and the impact categories were calculated. Compressed LCIA data is graphically demonstrated in a spider diagram for five environmental impact categories: the consumption of energy, depletion potential, the consumption of raw materials, resulting emissions and the toxicity potential. The chosen LCIA methods used in the software Umberto LCA+ namely: ReCiPe 2008 Midpoint (H) w/o LT and IPCC 2013; represent the most important impacts for this study. With a change of method, a different spectrum of results could be created. Certainly, the general trend would remain the same according to the goal and scope of this study.

The results of the preliminary LCA analysis clearly demonstrate that the SOCRATCES method (closed loop with recycling of CaCO₃) has a good ecological impact compared to the alternative battery-storage approach. It is very important to say, that the values used for the individual products and the generated results are not absolute but only comparative and data will be adjusted in the successive analyses. For this study all given data were set equally, so a comparison is possible to a certain extent. The data used have been based on results generated in mathematical models. In next months the deliverable will be updated with more accurate data obtained from pilot plant tests to verify or modify the numerical models this first LCA approach is based so far. This will be reported in the deliverable 8.13 by the end of the SOCRATCES project. In the upcoming months new LCA analyses will be developed with more accurate - i.e. experiment based - data of the actual process as well as for the standard state of the art technologies as reference values. Therefore the literature research needs to be continued and extended.

For the interpretation of LCA results it is always important to know the meaning of the applied approaches. Ranking and weighing factors are left out in the LCA, but could be applied in combination with LCC. Ranking and weighing is based on value-choices. Different individuals, organizations and societies may have different preferences; therefore, it is possible that different parties will reach different ranking results based on the same indicator results or normalized results. The normalization of the indicator results can change the conclusions drawn from the LCIA phase. Their integration will be considered when preparing the final LCA deliverable in month 36...

6. OUTLOOK

This deliverable Deliverable D8.3 will be updated along next months extending the analyses with more accurate data, integrating the results from verified numerical models and based on real measurements obtained in the pilot plant. It would improve data quality and reliability of the LCA analysis which is at the moment pre-mature due to the absence of experimental data. Along the development of a more robust LCA analysis, different approaches for interpretation will be applied. In this analysis several reference systems will be considered to show the consequence on the outcome of elements during the LCIA phase. A sensitivity analysis will be included to provide additional information about the most suitable set of reference data.

Adjustable parameters could be detected to a greater extent to reach the overall goal of this LCA. The goal is the identification of opportunities to improve the environmental performance of products at various points in their life cycle, the selection of relevant indicators of environmental performance, including measurement techniques, and marketing. At this time of the project, a preliminary LCA analysis has been developed and it will be updated in next months incorporating refined and more accurate data based and reference values, combining test results and adjusted numerical methods, in order to give the basis for communicating achievements towards a sustainable production. Therefore, the option for updating the Life Cycle Assessment is a good way to further improving reliability of the information, but the necessary headstone is set by this deliverable.

7. REFERENCES

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Color	Product	Value	Unit	Share
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - freshwater ecotoxicity w/o LT, FETPinf w/o LT: 8.76E-03 kg 1,4-DCB-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	8.76E-03kg	1,4-DCB-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - limoniac acidification w/o LT, TAP100 w/o LT: 0.04 kg SO2-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.04kg	SO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - human toxicity w/o LT, HTPinf w/o LT: 2.21 kg 1,4-DCB-Eq			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	2.21kg	1,4-DCB-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - photochemical oxidant formation w/o LT, POPP w/o LT: 0.03 kg NMVOC			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.03kg	NMVOC	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - freshwater eutrophication w/o LT, FEP w/o LT: 3.02E-04 kg P-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	3.02E-04kg	P-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - climate change w/o LT, GWP100 w/o LT: 10.71 kg CO2-Eq			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	10.71kg	CO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - urban land occupation w/o LT, ULOP w/o LT: 0.13 m2a			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.13m2a		
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - marine eutrophication w/o LT, MEP w/o LT: 1.53E-03 kg N-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	1.53E-03kg	N-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - particulate matter formation w/o LT, PMFP w/o LT: 0.02 kg PM10-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.02kg	PM10-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - natural land transformation w/o LT, NLTP w/o LT: 1.21E-03 m2			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	1.21E-03m2		
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - ozone depletion w/o LT, ODPinf w/o LT: 5.25E-07 kg CFC-11-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	5.25E-07kg	CFC-11-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - ionizing radiation w/o LT, IRP_HE w/o LT: 0.27 kg U235-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.27kg	U235-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - terrestrial ecotoxicity w/o LT, TETPinf w/o LT: 2.52E-03 kg 1,4-DCB-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	2.52E-03kg	1,4-DCB-Eq	
	LCIA Method: IPCC 2007 - climate change, GWP 100a: 11.02 kg CO2-Eq			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	11.02kg	CO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - agricultural land occupation w/o LT, ALOP w/o LT: 0.47 m2a			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.47m2a		
	LCIA Method: IPCC 2007 (obsolete) - climate change, GWP 100a: 10.77 kg CO2-Eq			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	10.77kg	CO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - marine ecotoxicity w/o LT, METPinf w/o LT: 0.02 kg 1,4-DCB-Eq			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.02kg	1,4-DCB-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - metal depletion w/o LT, MDP w/o LT: 5.76 kg Fe-Eq			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	5.76kg	Fe-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - water depletion w/o LT, WDP w/o LT: 0.05 m3			
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	0.05m3		
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - fossil depletion w/o LT, FDP w/o LT: 2.56 kg oil-Eq			100 %
	calcium carbonate, precipitated (LCarbonator -> P14) (1,10)	2.56kg	oil-Eq	

Figure 12: Umberto LCA+ open loop impact data

Color	Product	Value	Unit	Share
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - freshwater ecotoxicity w/o LT, FETPinf w/o LT: 5.30E-03 kg 1,4-DCB-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	5.30E-03kg	1,4-DCB-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - limoniac acidification w/o LT, TAP100 w/o LT: 0.03 kg SO2-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.03kg	SO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - human toxicity w/o LT, HTPinf w/o LT: 1.71 kg 1,4-DCB-Eq			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	1.71kg	1,4-DCB-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - photochemical oxidant formation w/o LT, POPP w/o LT: 0.02 kg NMVOC			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.02kg	NMVOC	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - freshwater eutrophication w/o LT, FEP w/o LT: 2.56E-04 kg P-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	2.56E-04kg	P-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - climate change w/o LT, GWP100 w/o LT: 5.53 kg CO2-Eq			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	5.53kg	CO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - urban land occupation w/o LT, ULOP w/o LT: 0.09 m2a			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.09m2a		
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - marine eutrophication w/o LT, MEP w/o LT: 1.34E-03 kg N-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	1.34E-03kg	N-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - particulate matter formation w/o LT, PMFP w/o LT: 0.01 kg PM10-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.01kg	PM10-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - natural land transformation w/o LT, NLTP w/o LT: 5.30E-04 m2			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	5.30E-04m2		
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - ozone depletion w/o LT, ODPinf w/o LT: 2.68E-07 kg CFC-11-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	2.68E-07kg	CFC-11-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - ionizing radiation w/o LT, IRP_HE w/o LT: 0.14 kg U235-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.14kg	U235-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - terrestrial ecotoxicity w/o LT, TETPinf w/o LT: 1.88E-03 kg 1,4-DCB-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	1.88E-03kg	1,4-DCB-Eq	
	LCIA Method: IPCC 2007 - climate change, GWP 100a: 5.68 kg CO2-Eq			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	5.68kg	CO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - agricultural land occupation w/o LT, ALOP w/o LT: 0.23 m2a			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.23m2a		
	LCIA Method: IPCC 2007 (obsolete) - climate change, GWP 100a: 5.56 kg CO2-Eq			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	5.56kg	CO2-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - marine ecotoxicity w/o LT, METPinf w/o LT: 0.02 kg 1,4-DCB-Eq			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.02kg	1,4-DCB-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - metal depletion w/o LT, MDP w/o LT: 5.39 kg Fe-Eq			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	5.39kg	Fe-Eq	
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - water depletion w/o LT, WDP w/o LT: 0.03 m3			
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	0.03m3		
	LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (obsolete) - fossil depletion w/o LT, FDP w/o LT: 1.62 kg oil-Eq			100 %
	energy [A17 (Carbonator -> P10)] (1,00 kWh)	1.62kg	oil-Eq	

Figure 13: Umberto LCA+ closed loop impact data

Code	Product	Value	Unit	Share
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - freshwater ecosystem w/o LT, FETP w/o LT	0.89 kg 1.4-DCB-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.89 kg 1.4-DCB-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - terrestrial acidification w/o LT, TAP100 w/o LT	6.60 kg SO2-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	6.60 kg SO2-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - human toxicity w/o LT, HTPr w/o LT	81.54 kg 1.4-DCB-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	81.54 kg 1.4-DCB-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - photochemical oxidant formation w/o LT, POFP w/o LT	0.22 kg NMVOC			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.22 kg NMVOC	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - freshwater eutrophication w/o LT, FEP w/o LT	6.04E-03 kg P-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	6.04E-03 kg P-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - climate change w/o LT, GWP100 w/o LT	35.96 kg CO2-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	35.96 kg CO2-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - urban land occupation w/o LT, ULCP w/o LT	0.96 m2a			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.96 m2a	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - marine eutrophication w/o LT, MEP w/o LT	0.02 kg N-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.02 kg N-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - particulate matter formation w/o LT, PMFP w/o LT	0.22 kg PM10-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.22 kg PM10-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - mineral land transformation w/o LT, RLTP w/o LT	7.21E-03 m2			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	7.21E-03 m2	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - ozone depletion w/o LT, ODP w/o LT	4.07E-06 kg CFC-11-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	4.07E-06 kg CFC-11-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - ionizing radiation w/o LT, RP_IHE w/o LT	1.85 kg U235-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	1.85 kg U235-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - nonrenewable resources w/o LT, TETPr w/o LT	0.03 kg 1.4-DCB-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.03 kg 1.4-DCB-Eq	100 %		
LCIA Method: IPCC 2007 - climate change, GWP 100w	36.16 kg CO2-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	36.16 kg CO2-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - agricultural land occupation w/o LT, ALOP w/o LT	4.06 m2a			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	4.06 m2a	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - marine ecosystem w/o LT, METPr w/o LT	6.85 kg 1.4-DCB-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	6.85 kg 1.4-DCB-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - metal depletion w/o LT, MDP w/o LT	122.89 kg Fe-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	122.89 kg Fe-Eq	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - water depletion w/o LT, WDP w/o LT	0.43 m3			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	0.43 m3	100 %		
LCIA Method: ReCiPe 2008 Midpoint (H) w/o LT (abiotic) - fossil depletion w/o LT, FDP w/o LT	10.97 kg oil-Eq			
Energy, solar, converted (natural resource in) (AS (Water) Storage -> H) (3.80)	10.97 kg oil-Eq	100 %		

Figure 14: Umberto LCA+ battery-storage system impact data