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# LIFE CYCLE ASSESSMENT OF INNOVATIVE CONCENTRATED SOLAR POWER PLANTS USING SUPERCRITICAL CARBON DIOXIDE MIXTURES

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## ABSTRACT

*The SCARABEUS project, funded by the European Commission, is currently investigating the potential gains brought about by the utilization of carbon dioxide mixtures in supercritical power cycles of Concentrated Solar Power plants, in lieu of the common Rankine cycles based on steam turbines or even pure carbon dioxide cycles. The analysis has already confirmed that it is possible to attain thermal efficiencies higher than 51% when ambient temperatures exceed 40ºC, which is unheard of when conventional technology or standard* $CO_2$ *technology is used. Additionally, this extraordinary performance is achieved with simpler cycle layouts, therefore with lower capital costs.*
*The additives considered include organic and inorganic compounds which are added to the raw carbon dioxide in a variable proportion, depending on the composition of the additive and on ambient temperature. Regardless, it is important to assess whether or not there is an additional environmental advantage in terms of carbon dioxide and other potential hazards brought about by the new chemicals in the system. This is presented in this paper where the results obtained so far by the consortium for the carbon footprint from a Life Cycle perspective are discussed. Along with the assumptions and methodology, the results are compared for three reference plants: state-of-the-art CSP plant based on steam turbines, innovative CSP plant using pure supercritical* $CO_2$ *technology, and the SCARABEUS concept using supercritical* $CO_2$ *mixtures. The results are promising as they suggest that it is possible to reduce the carbon footprint of a 110 MWe CSP plant to be significantly less than* $27kg_{CO_2}/MWh$ *from the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5).*

## Nomenclature

| | |
|---|---|
| $\Delta T_{min}$ | HX minimum temperature difference [ºC] |
| $\eta_{is}$ | Isentropic Efficiency [%] |
| $\eta_{PB}$ | Cycle Thermal Efficiency [%] |
| $CSP$ | Concentrated Solar Power |
| $DAC$ | Direct Air Capture |
| $DGS$ | Dry Gas Seal |
| $EOL$ | End of Life |
| $H_{TES}$ | Thermal Energy Storage Capacity [h] |
| $HTF$ | Heat Transfer Fluid |
| $Infr.Imp.$ | Infrastructure Impact |
| $LCA$ | Life Cycle Assessment |
| $LS$ | Labyrinth Seal |
| $M_{salts}$ | Amount of molten salts [kg] |
| $n$ | Number of Heliostats |
| $O\&M$ | Operation and Maintenance |
| $PHX$ | Primary Heat Exchanger |

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|  |  |
|---|---|
| $pp$ | Percentage points |
| $REF$ | Reference Power Plant |
| $sCO_2$ | Supercritical carbon Dioxide |
| $SO_2$ | Sulphur dioxide |
| $SoA$ | State of the Art |
| $TES$ | Thermal Energy Storage |
| $W_{nom}$ | Nominal Power [W] |
| $WF$ | Working Fluid |

## INTRODUCTION

### Current and Future Trends in Concentrated Solar Power Technologies

Electricity production is responsible for around one third of the global greenhouse gas emissions, but its importance in the quest for decarbonisation of the global economy goes further ahead due to the electrification of other sectors (in addition to electricity supply to current consumers): mobility and residential heating/cooling. The relevance of renewable energies to achieve the 1.5ºC Paris Agreement is unquestioned, as these will be instrumental in the transition to a 100% carbon-neutral energy system. The use of variable renewable energies (VRE) like photovoltaic and wind has many advantages in terms of cost, efficiency, and sustainability, but it also represents a risk in terms of reliability of grid operation when deployed at a massive scale. This risk is due to their variability over different time scales, producing less electricity in cloudy days, for example. This makes it necessary (mandatory) to implement additional control and storage systems [1].

Concentrating Solar Power (CSP) technologies can easily be integrated with Thermal Storage Systems (TES) in order to provide economical, $CO_2$-free and dispatchable electricity in locations with appropriate environmental conditions. This capacity allows the system to tailor the production of electricity to the instantaneous energy demand [2–5], therefore compensating for the unpredictability of variable renewable energy sources, from a grid operator standpoint.

Different CSP configurations are currently used (state of the art): parabolic trough collectors, central receiver plants (tower), Fresnel collectors or parabolic dish collectors (usually coupled to Stirling engines). All of them are based on optical technology, concentrating the sunlight on a hot spot (area) where a receiver is used to heat a heat-transfer fluid (HTF). This fluid can be used directly in the process (for instance, water-steam in a steam power cycle) or in a heat exchanger to transfer its thermal energy to the working fluid of the power cycle (for instance, molten salts sent to a steam generator). Even though there are different CSP technologies commercially viable today, solar towers are the most promising configuration due to the high temperatures and high efficiency that can be attained. In a solar CSP tower, energy from the sun is converted into electricity using a large number of sun-tracking mirrors, also called heliostats, which focus direct solar radiation onto a receiver located atop a very high tower [6]. The heat transfer fluid (HTF) that flows inside the receiver (commonly molten salts or water/steam) is heated by this concentrated solar radiation and then used directly or through a conventional steam generator to produce electricity in a power block.

Solar towers are a relatively new technology. So far, there are just eleven solar tower power plants in operation worldwide [7]. Nevertheless, the experience accumulated to date is very relevant, and several other projects are under construction or in the engineering phase. The low number of solar tower power plants currently in operation or in the commissioning phase is in contrast with the large number of operational parabolic trough plants, even though the efficiency of the latter is lower than that of a solar tower plant. This different degree of development is due to some key aspects that the solar tower technology must improve to become fully competitive:

- High costs of key components owing to the few Original Equipment Manufacturers in the market.
- High financial costs, due to the incipient commercial deployment.
- Low reliability as experienced by some of the plants currently in operation.
- Economies of scale not yet achieved and/or fully exploited.

The foregoing bullet points are being tackled by both the industry and the R&D community, yielding promising results and improvements at a very high pace. The sector is in a period of intense development, and the associated electricity prices are decreasing. One of the aspects that are being analysed the most is the cost reduction that could be attained by more efficient cycles. The use of supercritical carbon dioxide ($sCO_2$) cycles in conjunction with high-temperature solar receivers is a promising technology to reduce costs while increasing conversion efficiency. This cycle is a very interesting option to replace the steam Rankine cycle due to its higher efficiency, more compact turbomachinery, and to the possibility to include heat storage and direct heating.

### Limitations of Supercritical Carbon Dioxide and Rationale of SCARABEUS

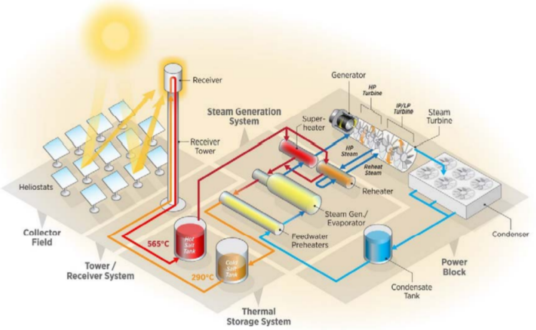
Supercritical carbon dioxide power cycles are the last attempt to reduce CSP cost to yield a cost-effective, dispatchable solar power generation technology. Nevertheless, in spite of the promising features of the cycle highlighted in recent years, the truth is that the thermodynamics of $sCO_2$ systems suffer significantly when ambient temperatures increase. As a consequence, in a practical case, the efficiency gain enabled by this technology with respect to conventional CSP plants based on steam turbine technology is not as large as originally expected. This is because, in order to attain the thermal efficiencies announced by the cycle, it is important that the working fluid achieve low temperatures close to the critical temperature of $CO_2$ ($\approx$ 31ºC), and this is well above ambient temperature in usual CSP sites. In hotter environments, the working fluid departs from the critical point and the main virtues of the concept vanish.

The SCARABEUS concept relies on the addition of certain compounds to the raw flow of carbon dioxide, yielding a working fluid whose critical temperature is higher than that of $CO_2$. Accordingly, even if ambient temperatures increase, the fluid can be taken close to the critical point and this enables higher thermal efficiencies that are well above what the current power block technology (steam turbines) is able to attain. In particular, the work carried out by the consortium in the last years has shown that cycle efficiencies as high as 51% can be achieved when ambient temperature is in the order of 40ºC and turbine inlet temperature is $\approx$700ºC. Moreover, even if the latter temperature were to drop to state-of-the-art values (550ºC), cycle efficiency would still be $\approx$45% [8–11].

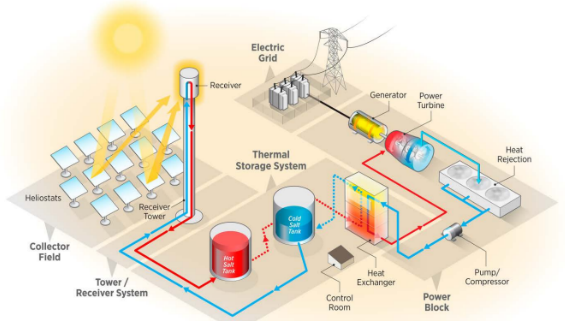
## Scope and Organisation of Work

The dopants considered in the SCARABEUS projects are screened for their thermodynamic characteristics but, of course, they have to also comply with other Key Performance Indicators. Amongst these, environmental impact (i.e., carbon footprint, ozone depletion potential, toxicity) and economic performance (i.e., cost of energy) are the most relevant. The first of these (carbon footprint) is assessed in this paper, which presents the results of the Life Cycle Assessment of the technology. This is done for a reference power plant using state-of-the-art technology, which is presented in the second section of the paper along with a $sCO_2$ plant and the innovative SCARABEUS plant. Next, the fundamentals of the methodology used to carry out the Life Cycle Assessment of these plants is presented, and the main assumptions for the systems are set.

The results are presented in a longer section, where the total carbon footprint of both systems is discussed thoroughly. This is accompanied by a comparison against literature data and a discussion on the impact of uncertainty and the margin for variations of the foreseen Key Performance Indicators. The last section gathers the main conclusions and information about currently ongoing work.



(a) *SoA CSP Plant*



(b) *$sCO_2$-based CSP Plant*

**FIGURE 1**. SoA and $CO_2$-based CSP plants divided by subsystems (retrieved from [12])

## PLANTS DESCRIPTION

Three Concentrated Solar Power plant types are studied in this work, all of them with central receivers: state-of-the-art steam-based (reference case), $sCO_2$ and SCARABEUS. A schematic representation of the plants can be seen in Figure 1, illustrating the main subsystem of a CSP plant: Collector Field, Tower/Receiver System, Thermal Energy Storage and Power Block. The top figure (a) exemplifies a steam-based plant, whereas the bottom figure (b) is valid for both the $sCO_2$ and SCARABEUS ($sCO_2$-based) technologies. To move from the former to the latter, the steam generation system (i.e. Primary Heat Exchanger, PHX) is replaced with a shell-and-tube heat exchanger transferring heat from the Molten Salt stream coming from the solar receiver to the working fluid in the power block (either $sCO_2$ or SCARABEUS blend). The layout of the power block is also largely different in order to exploit the characteristics of each working fluid.

The information about the reference plant has been provided by Abengoa Energía. It is a 110 $MW_e$ (121 $MW_e$ gross) plant using two-tank thermal energy storage with a capacity of 17.5 equivalent hours at nominal conditions. The Heat Transfer Fluid is Solar Salt, stored at 565ºC in the hot tank and at 290ºC in the cold tank. The power block makes use of a reheat steam turbine with multiple feedwater heaters and dry cooling.

CSP plants based on supercritical $CO_2$ (either pure or blended $sCO_2$) have been widely studied by some of the authors of this work [8, 11, 13]. Their main difference with respect to the reference plant is found in the power block. The remaining subsystems employ similar technology and are designed under the same assumptions and boundary conditions (Solar Multiple, storage capacity -hours-, Direct Normal Irradiance, etc.) as the reference plant. The $sCO_2$ case is based on a *Recompression* cycle, the most commonly used cycle layout for its good performance in a variety of applications, in particular CSP. For the innovative SCARABEUS technology, a mixture comprised of 70% $CO_2$ and 30% $SO_2$ is considered, running on a *Recompression* cycle as well. It is to note that the addition of 30% $SO_2$ to carbon dioxide raises critical temperature from 31ºC to 80ºC which translates into a thermal efficiency increase from 42.82 to 44.40%, as illustrated by Table 1. Furthermore, the temperature rise across the solar receiver also increases from 132.6 to 193.3ºC. This is of utmost importance, since this parameter has an impact on the operating temperatures of the hot and cold tanks in the Thermal Energy Storage and, therefore, on the inventory of storage medium (molten salts) needed to store a certain amount of energy. The larger the temperature rise across the solar receiver, the smaller the inventory of storage medium, with a direct impact on footprint, cost and environmental impact of this subsystem of the plant. Yet, it has to be highlighted that this temperature difference between the hot and cold tanks is still well below that of the reference power plant: 275ºC.

**TABLE 1**. Key Performance Indicators of the standard and SCARABEUS $CO_2$ power cycles.

| | Steam Rankine | Pure $sCO_2$ | $sCO_2$-$SO_2$ Blend |
|---|---|---|---|
| $\eta_{PB}$ [%] | 36.5 | 42.82 | 44.4 |
| $\Delta T_{solar}$ [ºC] | 275 | 132.6 | 193.3 |

## METHODOLOGY

### Life Cycle Assessment

The assessment of innovative CSP technologies requires taking into consideration its life cycle environmental impact with the same degree of importance as the thermodynamic and economic performances. To this aim, the Life Cycle Assessment presented here follows the ISO 14040 and 14044 standards [14, 15], an internationally recognised methodology to assess the environmental and human health impact associated with products or services through all their lifetime stages. According to these standards, LCA covers the following four phases:

- Goal and scope definition: defining the purpose of the study and the system boundaries.
- Inventory analysis: gathering relevant data about the system, as well as the impact associated with the inventory of materials and energy.
- Impact assessment: using the inventory to quantify the environmental impact of the system.
- Interpretation: analysis of the results.

The main objective of this work is to define a comprehensive methodology to compare the life cycle carbon footprint of the standard $sCO_2$ and SCARABEUS technologies, against the state-of-art technology and benchmark value, as well as to identify the potential promising configurations from a sustainability standpoint. Carbon footprint, measured through global warming potentials (GWPs) from the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5 [16]), is the metric to study and compare the life cycle impact of these innovative CSP plants. The function unit is 1 MWh of net electricity produced by the CSP plant. The activities included in the life cycle of a CSP plant (system boundaries) are raw material production (manufacturing), transportation, construction, operation and maintenance (O&M), and dismantling and End-of-Life (*EOL*), summarised in Figure 2. The processes are divided into foreground (technology-specific primary or design data) and background from existing life cycle inventory (LCI) database as depicted in Figure 2. To model the wastes and recycled content, the Circular Footprint Formula (CFF) is used following the Product Environmental Footprint Category Rules (PEFCR) of the European Commission [17]. The whole methodology is implemented in SimaPro 9 [18].

### Life Cycle Inventories and Data Assumptions

To construct the life cycle inventories of the three systems, the technology-specific data for the foreground processes have been generated from inputs by the different partners of the project. The Life Cycle Inventory associated with the background processes have been mainly obtained from Ecoinvent 3.7.1 [19]. For the reference plant, very detailed data was provided by Abengoa Energía, thoroughly indicating the specific characteristics of each one of the elements existing in the aforedescribed CSP plant, activities required for the construction, information about the operation and maintenance and also about the dismantlement. For the innovative ($sCO_2$) CSP plants, achieving such level of detail based on current engineering practice is not possible, thus the required information has to be generated following a different approach. For those elements that are technologically similar to the reference plant, adjustment factors based on thermodynamic performance and engineering aspects have been defined to scale the original data. This applies to the Collectors Field, the Tower/Receiver system

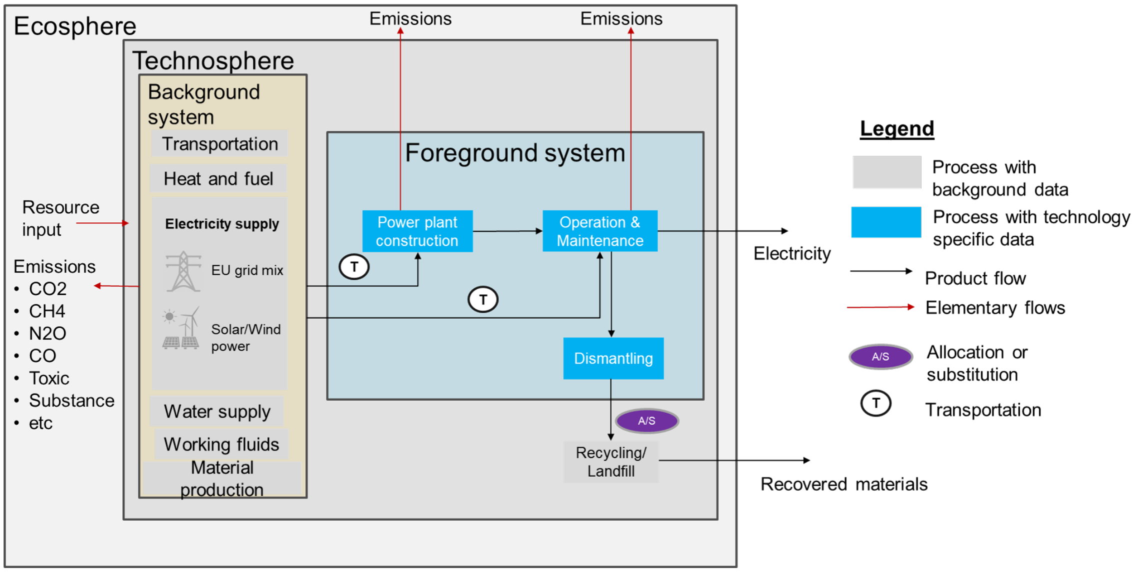


**FIGURE 2**. Activities included in the life cycle of a CSP plant

and the Thermal Energy Storage system, as shown in Figure 1. For those that are specific to the $sCO_2$ and SCARABEUS technologies -the power block elements-, the information was self-produced by means of different preliminary design tools developed by the authors. Additional information regarding working fluid inventory, leakages and electricity consumption has been estimated as described in later sections.

**Solar field:** the information from the reference plant has been scaled with the *Solar Field Adjustment Factor*, see Eq.(1), accounting for the number of heliostats in the new power plant relative to the old one. Provided that the Solar Multiple, the Direct Normal Irradiance and the aperture area of each individual heliostat are the same for both plants, and under the assumption, that solar field and receiver efficiencies are constant, the number of heliostats is inversely proportional to the thermal efficiency of the power block.

$$\text{Solar Field Adjustment Factor} = \frac{n}{n_{REF}} = \frac{\eta_{PB,REF}}{\eta_{PB}} \quad (1)$$

**Tower:** the tower of the reference plant has been scaled through the *Solar Field Adjustment Factor*, which assumes that tower size is proportional to the number of heliostats.

**Receiver:** the receiver of the reference plant has been scaled through the *Molten Salt Adjustment Factor*, see Eq.(2). This is defined as the relative mass flow rate of Molten Salts in the $sCO_2$ case with respect to the reference case. This allows to account simultaneously for the reduction in the receiver duty, driven by the thermal efficiency gains in the power block, and for the temperature difference between the hot and cold storage tanks.

$$\text{Molten Salt Adjustment Factor} = \frac{\dot{m}}{\dot{m}_{REF}} = \frac{\eta_{PB,REF} \cdot \Delta T_{solar,REF}}{\eta_{PB} \cdot \Delta T_{solar}} \quad (2)$$

**Thermal Energy Storage:** the total inventory of stored Molten Salts has been selected as the relevant figure of merit to scale the reference Thermal Energy Storage system. It can be estimated through Eq.(3).

$$M_{salts}[kg] = \frac{\dot{W}_{nom}[W] \cdot H_{TES}[hours] \cdot 3600J/Wh}{\eta_{PB} \cdot C_P[J/kgK] \cdot \Delta T_{solar}[K]} \quad (3)$$

**Power Block:** this item is comprised of several components. These are technology specific, and hence the relevant information required for LCA (breakdown of mass and material) has to be estimated using different design tools, as shown in Table 2.

**Balance of Plant:** given the preliminary nature of this study, accurate information about this item is not available for the innovative CSP plants. Nevertheless, it is safe to assume, based on the partners' experience, that wiring is the main contributor to the environmental impact of the Balance of Plant. Accordingly, provided that wiring is mostly found in the solar field (collectors), it has been decided to scale the adjustment factor for Balance of Plant of the reference plant with the *Solar Field Adjustment Factor*, as a first guess.

**Electricity taken from the grid:** this refers to parasitic consumption occurring mostly during the startup procedures. The information from the reference plant is divided in four concepts: 1) preparation of solar field, 2) pumping of molten salts, 3) sealing of turbomachinery and 4) start-up of power block. The *Solar Field Adjustment Factor* and the *Molten Salt Flow Adjustment Factor* can be used to scale the two first items, respectively, whereas the other two are kept constant with respect to the reference plant due to the lack of clear procedures to perform the extrapolation at this stage of the project.

**Inventory (amount of working fluid)**: loading the system prior to first operation involves a twofold environmental effect: i) production and transportation of the working fluid to the site, and ii) compression to supercritical state, what implies consumption of electricity. The total inventory of fluid has been estimated based on a similar analysis for a MW-scale demonstration plant performed recently by some of the authors, which has then been scaled with multiple coefficients to account for the different output scale, cycle specific work and layout complexity. This information is not disclosed in detail in this paper out of confidentiality restrictions.

**Leakages:** the environmental impact of leakages is threefold: i) impact associated with working fluid makeup, ii) reduction in the annual energy yield due to compression of the makeup $CO_2$, acting as an additional parasitic loss, and iii) impact of the fluid itself when released to the atmosphere. A two-step approach is adopted to take into account this contribution. Firstly, a leakage rate around 0.5% of the mass flow entering the turbine is considered, value consistent with the adoption of labyrinth seals at turbine shaft ends [20]. Labyrinth seals are widely employed in steam-based Rankine cycle and, hence, are representative of the state of art of CSP technology; nevertheless, this choice leads to an unrealistic scenario in which leakages turn out to be the main driver of the carbon footprint of the entire plant. Based on this, the adoption of an advanced sealing technologies seems mandatory.

According to private communications with the industrial partners of SCARABEUS, the leakage rate could be drastically reduced to a value of approximately 0.001% if Dry Gas Seals (DGS) were adopted, hence enabling a much lower overall carbon footprint. This is a more effective technology for very high pressure sealing but has the shortcoming of requiring a cooling system[1] to withstand the turbine inlet temperature considered in SCARABEUS. Cooling of the DGS is accomplished thanks to a certain amount of the working fluid (around 0.5% of mass flow at turbine inlet), extracted from the cycle, sent to the DGS and successively mixed with the remainder of the circulating mass flow. Therefore, this fraction of working fluid is not expanded in the turbine, bringing about a slight drop in cycle efficiency. This is nevertheless not exclusive of DGA since the leakage flow through the high-pressure shaft-end seal of a labyrinth seal also causes performance losses.

**TABLE 2**. Type and source of information categorised by components.

| Component | Type of information | Source of information |
|---|---|---|
| Field | Adj. Factor | In-house Estimate |
| Tower | Adj. Factor | In-house Estimate |
| Receiver | Adj. Factor | In-house Estimate |
| TES | Mass and material | In-house Software |
| Turbine | Mass and material | In-house Software |
| Compressors | Mass and material | Estimated with Thermoflex |
| Pumps | Mass and material | Estimated with Thermoflex |
| PCHE | Mass and material | In-house software |
| PHX | Mass and material | Estimated with Thermoflex |
| HRU | Mass and material | In-house software |
| BoP | Adj. Factor | In-house Estimate |

## Scenarios of $CO_2$ and $SO_2$ sourcing

Two different sources for carbon dioxide, gas process or in-situ direct air capture with wind energy are studied in this work. Table 3 summarises the main assumptions to calculate the carbon footprint for both sources. Based on this, the carbon footprint of the supply of 1 kg of sulphur dioxide is estimated at 0.35 $kg_{CO_2,eq}$.

## Uncertainty Analysis

The hypotheses lying behind both the adjustment factors and the component design tools are prone to a high degree of uncertainty. For such reasons, it is mandatory to perform an uncertainty analysis to account for the variability of the data

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[1] The complete characterisation of this cooling system (point of extraction/reinsertion, mixing pressure, etc.) has not been fully detailed yet and it will be addressed by the consortium in the next months.

**TABLE 3**. Options considered for $CO_2$ sourcing: $CO_2$ from processed gas [21], $CO_2$ from direct air capture [22]. Several scenarios are differentiated by technology efficiency, heat source (waste/heat pump) and the assumed DAC infrastructure impact.

| **$CO_2$ from processed gas** (data from [21]) | | | | |
|---|---|---|---|---|
| Electricity grid [MJ] | 0.4 | | | |
| Heat from natural gas [MJ] | 0.1 | | | |
| Transport [km] | 500 | | | |
| **$CO_2$ from Direct Air Capture** (data from [22]) | | | | |
| Efficiency | Future | Future | Current | Current |
| Heat source | Waste | Waste | Waste | Heat pump |
| DAC Infr. Imp. | High | Low | Low | Low |
| Electricity wind [MJ] | 1.8 | 1.8 | 2.52 | 2.52 |
| Heat from heat pump [MJ] | | | | 11.9 |
| Waste Heat [MJ] | 11.9 | 11.9 | 11.9 | |
| High DAC Infr. Imp. [g/kg$_{CO_2,eq}$] | 60 | | | |
| Low DAC Infr. Imp. [g/kg$_{CO_2,eq}$] | | 16 | 16 | 16 |

produced. The Monte Carlo simulation method is selected in this study.

Given that the adjustment factors are mostly driven by the thermodynamic performance of the innovative power blocks, pessimistic and optimistic scenarios of the cycle modelling assumptions have been defined, see Table 4. This yields to sets of adjustment factors (pessimistic and optimistic) which are then used to build a triangular probability density distribution, assigned to those items scaling with the said adjustment factors. The uncertainty in the data obtained through component design is on the other hand estimated with a uniform distribution -30%/+50% with respect to the reference value, so as to reflect a larger uncertainty.

**TABLE 4**. Reference, optimistic and pessimistic cases for thermodynamic cycle modelling.

| Component Performance | Reference | Optimistic | Pessimistic |
|---|---|---|---|
| $\eta_{is,Turb}$ [%] | 90 | 93 | 87 |
| $\eta_{is,Pump}$ [%] | 88 | 90 | 85 |
| $\eta_{is,Compr}$ [%] | 89 | 91 | 86 |
| $\Delta T_{min}$ [ºC] | 5 | 3 | 10 |
| Leakage Rate (DGS) [%] | 0.001 | 0.0005 | 0.01 |
| Component efficiency [%] | ±0 | -30 | +50 |

## RESULTS

This section begins with the breakdown of carbon footprint into its different contributions for the three CSP technologies, considering the $CO_2$ sourcing cases and the two different sealing technologies described in the previous section. Then, an uncertainty analysis is performed for the best scenario. Finally, a discussion and bench-marking of results is provided.

### Carbon Footprint Comparison with SoA Labyrinth Seals

In this first step of the analysis, the carbon footprint of the three CSP technologies is assessed considering labyrinth seals (LS), representative of SoA CSP plant, and carbon dioxide captured from processed gas [21]. The results are presented in Table 5 (columns 2, 5 and 6), showing that the carbon footprints are 8.39, 40.38 and 51.19 kg$_{CO_2,eq}$/MWh, for SoA, s$CO_2$ and SCARABEUS case respectively. The main contributors of the s$CO_2$ and SCARABEUS systems are the supply of working fluids ($CO_2$ and, for SCARABEUS, $SO_2$), brought by the adoption of LS characterised by a default leakage rate of 0.5% [20]. This is a fairly unrealistic scenario, for which leakage flow offsets any potential environmental improvement brought about by the better thermodynamic performance of the innovative power cycles (with respect to conventional steam cycles). Sixty percent of the carbon footprint associated to the working fluid in blended s$CO_2$ systems is contributed by liquid sulphur dioxide, 14% by liquid $CO_2$, 25% by transportation of the gases and 0.3% by on-site processing of liquid heat transfer fluids into supercritical states. For pure s$CO_2$ system, on the other hand, this is dominated by the $CO_2$ capture (44%) and transportation (55%) processes.

Excluding Operation and Maintenance (O&M), the carbon footprint of the three technologies are 7.67, 8.09 and 7.00 kg$_{CO_2,eq}$/MWh, respectively. The main contributors to these figures are collector field, transport of materials and thermal storage systems, followed by tower, power block and receiver. As said, it is shown that s$CO_2$ technology cannot compete against state-of-art steam power plants because the benefits of the higher thermal energy efficiency is more than offset by the increased carbon footprint related to the thermal storage system, as a consequence of the lower temperate rise across the solar receiver of s$CO_2$ power cycles. From an environmental standpoint, this comes to emphasise that CSP plants need to explore alternative closed-cycle layouts, such as the *Partial Cooling* cycle, yielding a better balance of the trade-offs between thermal efficiency and integration with the heat source, which may also bring about better techno-economic performance [23].

For the sake of comparison, $CO_2$ sourced in-situ through Direct Air Capture (DAC) powered by wind power is also considered in this section. Additionally, several scenarios of technology efficiency, heat type and assumed DAC infrastructure impact are screened [22]. Table 6 shows the results of this study. The table presents the results for the Total and Working Fluid Supply categories only, given that the other categories remain unaltered with respect to Table 5. The pure $sCO_2$ system experiences a large reduction in carbon footprint, especially when the heat required is provided by waste heat and when the infrastructure impact of the DAC system is low; numerically, carbon footprint decreases from 40.38 to 15.12 $kg_{CO_2,eq}$/MWh. Hence, in general, a carbon footprint similar or lower than the median value reported in literature for CSP plants (27 $kg_{CO_2,eq}$/MWh, [16]) is attainable. Moreover, this is true even without considering the most optimistic scenario (resulting from the most favourable combination of future efficiency, waste heat and low DAC infrastructure impact), but with contemporary efficiencies and heat provided by a heat pump (as a matter of fact, waste heat is not always available and, thus, the heat pump assumption is more realistic). It also has to be highlighted how important the DAC infrastructure impact can be for LCA since carbon footprint almost doubles (from 15.12 to 27.41 $kg_{CO_2,eq}$/MWh) when this impact is changed from low to high.

On the contrary, the change in carbon dioxide sourcing has a weak impact on the results of the SCARABEUS system, even in the best-case scenario, with a small reduction from 51.19 to 42.97 $kg_{CO_2,eq}$/MWh. This comes to confirm that, if labyrinth seals are taken into account, the carbon footprint of these systems is strongly dominated by the production and transportation of liquid sulphur dioxide and, thus, a reduction in the leakage rate is the only way to make the technology environmentally competitive against other technologies.

### Carbon Footprint Comparison with Dry Gas Seals

The scenario changes drastically if Dry Gas Seals are considered, as illustrated by the results in Table 5 under label DGS (columns 3 and 4). It is observed that the carbon footprints of pure $sCO_2$ and SCARABEUS systems are largely reduced from the cases with labyrinth seals (LS), resulting in 9.49 and 8.26 $kg_{CO_2,eq}$/MWh respectively. This large reduction is driven by the impact of the Working fluid supply, which is reduced to the same order of magnitude of SoA steam-based systems thanks to the the significantly lower leak rates ensured by the use of DGS technology. A weak, negative impact of DGS cooling flow on cycle efficiency is to be expected, as already mentioned in a previous section. Nevertheless, despite this lower $\eta_{th}$, both technologies ($sCO_2$ and SCARABEUS) are still more efficient than SoA Rankine cycles and, therefore, the carbon footprint of the collector field (main contributor) is lower for these systems.

**TABLE 5**. Carbon footprint ($kg_{CO_2,eq}$/MWh) of the three CSP technologies when $CO_2$ is sourced from process gas.

| **System** | **SoA** | **$sCO_2$** | **$sCO_2$-$SO_2$** | **$sCO_2$** | **$sCO_2$-$SO_2$** |
|---|---|---|---|---|---|
| **Sealing Technology** | LS | DGS | DGS | LS | LS |
| **Total** | **8.39** | **9.49** | **8.26** | **40.38** | **51.19** |
| **Manufacturing** | | | | | |
| Collector field | 6.01 | 5.33 | 5.08 | 5.05 | 4.87 |
| Receiver system | 0.17 | 0.34 | 0.22 | 0.31 | 0.20 |
| Tower | 0.53 | 0.45 | 0.45 | 0.43 | 0.43 |
| Primary HX | 0.05 | 0.2 | 0.16 | 0.20 | 0.16 |
| Power block | 0.26 | 0.4 | 0.35 | 0.39 | 0.34 |
| TES | 1.24 | 2.41 | 1.58 | 2.20 | 1.46 |
| Water treatment | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 |
| Found. & aux. build. | 0.20 | 0.18 | 0.17 | 0.17 | 0.16 |
| Wires | 0.31 | 0.28 | 0.26 | 0.26 | 0.25 |
| Piping | 0.09 | 0.08 | 0.08 | 0.08 | 0.08 |
| **Transport** | 1.59 | 1.41 | 1.35 | 1.34 | 1.29 |
| **Construction** | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 |
| **O&M** | | | | | |
| Working fluid supply | 0.01 | 0.07 | 0.09 | 31.49 | 43.40 |
| Water use | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 |
| Comp. replacement | 0.1 | 0.09 | 0.08 | 0.08 | 0.08 |
| Maintenance | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 |
| Grid el. consumption | 0.47 | 0.60 | 0.60 | 0.60 | 0.60 |
| **EOL** | -2.86 | -2.54 | -2.42 | -2.40 | -2.32 |

**TABLE 6**. Carbon footprint ($kg_{CO_2,eq}$/MWh) of the $sCO_2$-based CSP technologies when $CO_2$ is sourced from Direct Air Capture and labyrinth seals are considered. Carbon footprint values for manufacturing, transport, construction, remaining items in O&M and EOL are similar to Table 5.

| **System** | **$sCO_2$-$SO_2$** | **$sCO_2$** | **$sCO_2$** | **$sCO_2$** | **$sCO_2$** |
|---|---|---|---|---|---|
| Efficiency | Future | Future | Future | Current | Current |
| Heat source | Waste | Waste | Waste | Waste | Heat pump |
| DAC infr. imp. | Low | High | Low | Low | Low |
| **Total** | **42.97** | **27.41** | **15.12** | **15.82** | **20.59** |
| WF supply **(O&M)** | 35.18 | 18.52 | 6.23 | 6.92 | 11.70 |

It is worth noting that the overall scenario is very similar to that observed in the previous section discussing the carbon footprints without the contribution of O&M. The $sCO_2$ case still has a (slightly) higher carbon footprint than SoA Rankine, due to the higher impact of the receiver and, more importantly, the thermal energy storage (TES), exacerbated by the lower thermal efficiency with respect to the LS case. On the other hand, the SCARABEUS technology yields carbon footprint impact similar to SoA. Interestingly, the contribution of the power block represents only 4% of the total carbon footprint for both systems; this is very interesting as it means that the high uncertainty inherent to the design of the innovative components in $sCO_2$ closed cycles has a weak impact on carbon footprint.

Given the very limited contribution of the working fluid supply, the results for $CO_2$ in-situ sourcing through DAC powered by wind power are not reported in this section. On the other hand, the aggregated summary of data inventory is provided in Table 7, showing an estimate of the amount of material and energy & water consumption needed for each of the three CSP technologies under analysis.

**TABLE 7**. Aggregated summary of data inventory.

| | Item | SoA | $sCO_2$ | $sCO_2$-$SO_2$ |
|---|---|---|---|---|
| **Bill of Materials** | Steel [tonne] | 57352 | 58043 | 52272 |
| | Glass [tonne] | 10621 | 9409 | 8979 |
| | Oil [tonne] | 604 | 535 | 511 |
| | Concrete [tonne] | 317016 | 280844 | 268005 |
| | Polymer [tonne] | 564 | 510 | 484 |
| | Electronics [tonne] | 148 | 131 | 125 |
| | Ceramic [tonne] | 262 | 518 | 314 |
| | Mineral [tonne] | 677 | 1273 | 857 |
| | Iron [tonne] | 215 | 14 | 17 |
| | Copper [tonne] | 553 | 327 | 312 |
| | Aluminium [tonne] | 725 | 396 | 401 |
| | Nitrate salts [tonne] *(TES)* | 46000 | 89477 | 58665 |
| | Chemicals [tonne] *(Water Treatment)* | 2123 | 1881 | 1795 |
| | Wood [tonne] | 33 | 29 | 28 |
| **Energy & Water** | Machine use (diesel) [MJ] *(Dismantle)* | 39100000 | 34638690 | 33055140 |
| | Diesel [tonne] *(Water washing trucks)* | 2974 | 2634 | 2514 |
| | Grid electricity [MWh/yr] *(Backing from the grid)* | 901 | 1159 | 946 |
| | Water [$m^3$/yr] | 64250 | 39201 | 37409 |
| | Gasoline [tonne] (General maintenance) | 18 | 16 | 15 |
| | $CO_2$ [tonne] *(WF)* | - | 14285 | 4994 |
| | $SO_2$ [tonne] *(WF)* | - | - | 1925 |

## Uncertainty Analysis

A Monte Carlo analysis has been carried out for the SCARABEUS system with $CO_2$ captured from processed gas and using DGS technology. Figure 3 shows that the values of the 95% confidence interval range from 6.02 to 13.51 kg$_{CO_2,eq}$/MWh, with a mean value of 9.08 and a median of 8.90 kg$_{CO_2,eq}$/MWh. Both values are slightly higher than the design point value (8.26 kg$_{CO_2,eq}$/MWh) but still well below the average value of the IPCC AR5 report (27 kg$_{CO_2,eq}$/MWh).

## Discussion

The life cycle carbon footprint of CSP power systems varies broadly from 14.2 to 203 kg$_{CO_2,eq}$/MWh depending on the technology used [16, 24–33]. The very low carbon footprint of SoA technology in this analysis, 8.43 kg$_{CO_2,eq}$/MWh, comes about because of the large thermal energy storage capacity which enables minimal (almost null) consumption of natural gas for daily startup. The results for the $sCO_2$ and SCARABEUS systems reveal a great sensitivity to working fluid leakages. With conventional Labyrinth Seals, a carbon footprint of 15.12 kg$_{CO_2,eq}$/MWh can be achieved by the $sCO_2$ system if the $CO_2$ source is changed from process gas (reference case) to Direct Air Capture with wind energy. Moreover, the carbon footprint of pure $sCO_2$ systems is sensitive to the assumptions regarding impact of DAC infrastructure (adsorbents and the construction of the DAC plant). For the SCARABEUS plant with LS, a lower impact than the median value reported by IPCC AR5 cannot be achieved and this requires utilising advanced sealing technology.

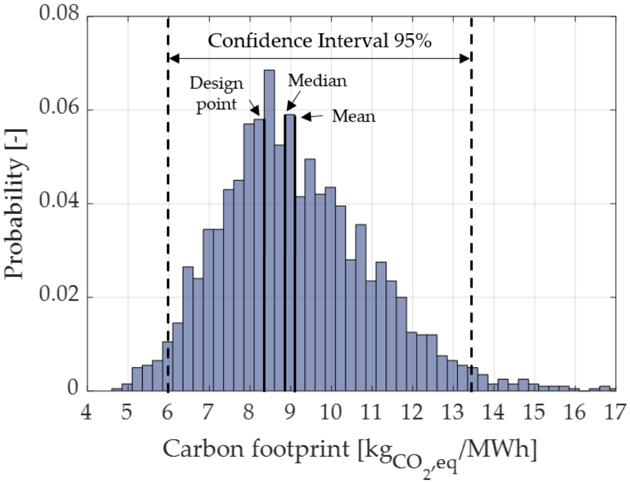

**FIGURE 3**. Uncertainty Analysis of the carbon footprint of SCARABEUS CSP power plants with $CO_2$ from processed gas and DGS technology.

The adoption of Dry Gas Seals enables carbon footprints of 9.49 and 8.26 kg$_{CO_2,eq}$/MWh for the $sCO_2$ and SCARABEUS systems, respectively. For $sCO_2$ systems, this carbon footprint is still higher than SoA Rankine due to the larger TES size. For SCARABEUS, an uncertainty analysis showed that, within a 95% confidence interval, the carbon footprint ranges from 6 to 13.5 kg$_{CO_2,eq}$/MWh.

## CONCLUSIONS

This work addresses the Life Cycle Environmental Assessment of Concentrated Solar Power plants using tower technology (central receiver), based on either pure $sCO_2$ or $sCO_2$-$SO_2$ mixtures (SCARABEUS). This is compared against state-of-art CSP plants based on steam turbine technology. The main conclusions of this work follow:

- The carbon footprint of CSP systems is highly influenced by the working fluid of choice, leakage rate and $CO_2$ sourcing.

- A systematic approach is needed to evaluate the carbon footprint of CSP technologies beyond thermal efficiency, considering additional figures of merits such as the temperature rise across the solar receiver.
- The carbon footprint of state-of-the-art CSP plants is estimated at $\approx$8.4 $kg_{CO_2,eq}$/MWh.
- The carbon footprint of $sCO_2$-based CSP plants is very sensitive to the sealing technology adopted. With SoA labyrinth seals, the carbon footprint of either $sCO_2$ technology can be as high as 40-50 $kg_{CO_2,eq}$/MWh. On the contrary, if Dry Gas Seals are considered, carbon footprint is largely reduced to 8-10 $kg_{CO_2,eq}$/MWh, which is in the range of the reference plant.
- The plant based on pure $sCO_2$ could have a lower impact than the benchmark value from IPCC AR5, if $CO_2$ were captured on-site with a system powered by renewable electricity. This result is nevertheless sensitive to the assumption of the DAC infrastructure impact (adsorbents and the construction of the DAC plant).
- An uncertainty analysis with respect to possible variations of the adjustment factors reveals that, with 95% confidence, the carbon footprint of the SCARABEUS technology ranges from 6 to 13.5 $kg_{CO_2,eq}$/MWh.

Overall, the results presented in this paper show that the environmental performance of the new SCARABEUS technology is on a pair with SoA steam-based technology and certainly below the values reported by the IPCC AR5 report. This is very relevant because both $sCO_2$ technologies have the potential to operate at much higher temperatures than steam turbines (approximately 700ºC), what means that further carbon footprint reductions are possible. This will be explored in future works, also incorporating innovative solar receiver technology. Future research for the innovative $sCO_2$ technology will also focus on optimising the management of waste heat from the CSP system, to be integrated into the $CO_2$ capture system. Additionally, a balance between the trade-offs of thermal efficiency and induced carbon footprint associated with the choice of working fluid and leakage rate will be investigated.

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## REFERENCES

[1] IEA (International Energy Agency). World Energy Outlook Special Report 2018: Energy and Climate change - executive summary.

[2] L. F. Cabeza, E. Galindo, C. Prieto, C. Barreneche, and A.I. Fernández. Key performance indicators in thermal energy storage: Survey and assessment. *Renewable Energy*, 83:820 – 827, 2015.

[3] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, and L.F. Cabeza. State of the art on high temperature thermal energy storage for power generation. part 1—concepts, materials and modellization. *Renewable and Sustainable Energy Reviews*, 14(1):31 – 55, 2010.

[4] S.J. Wagner and E.S. Rubin. Economic implications of thermal energy storage for concentrated solar thermal power. *Renewable Energy*, 61:81 – 95, 2014. World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden.

[5] J. Hernández-Moro and J.M. Martínez-Duart. CSP electricity cost evolution and grid parities based on the IEA roadmaps. *Energy Policy*, 41:184 – 192, 2012. Modeling Transport (Energy) Demand and Policies.

[6] Solar Paces website CSP technology description. Visited November 2021.

[7] NREL database, 16/12/2021, https://solarpaces.nrel.gov.

[8] F. Crespi, P. Rodríguez de Arriba, D. Sánchez, A. Ayub, G. Di Marcoberardino, C.M. Invernizzi, G.S. Martínez, P. Iora, D. Di Bona, M. Binotti, and G. Manzolini. Thermal efficiency gains enabled by using $CO_2$ mixtures in supercritical power cycles. *Energy*, 238:121899, 2022.

[9] F. Crespi, G.S. Martínez, P. Rodriguez de Arriba, D. Sánchez, and F. Jiménez-Espadafor. Influence of working fluid composition on the optimum characteristics of blended supercritical carbon dioxide cycles. In *ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition*. American Society of Mechanical Engineers Digital Collection.

[10] F. Crespi, P. Rodríguez de Arriba, D. Sánchez, A. Muñoz, and T. Sánchez. The potential of supercritical cycles based on $CO_2$ mixtures in concentrated solar power plants: An exergy-based analysis. In *Proceedings of the 6th International Seminar on ORC Power Systems*, 2021.

[11] F. Crespi, P. Rodríguez de Arriba, D. Sánchez, and A. Muñoz. Preliminary investigation on the adoption of $CO_2$-$SO_2$ working mixtures in a transcritical Recompression cycle. *Applied Thermal Engineering*, 2022.

[12] M. Mehos, C. Turchi, J. Vidal, M. Wagner, Z. Ma, C. Ho, W. Kolb, C. Andraka, and A. Kruizenga. Concentrating solar power gen3 demonstration roadmap. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.

[13] F. Crespi, D. Sánchez, G.S. Martínez, T. Sánchez-Lencero,

and F. Jiménez-Espadafor. Potential of Supercritical Carbon Dioxide Power Cycles to Reduce the Levelised Cost of Electricity of Contemporary Concentrated Solar Power Plants. *Applied Sciences*, 10(15):5049, 2020.

[14] ISO 14040:2006, Environmental Management - Life Cycle Assessment - principles and framework, 2006.

[15] ISO 14044:2006, Environmental Managemente - Life Cycle Assessment - requirements and guidelines, 2006.

[16] S. Schlömer, T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, et al. Annex iii: Technology-specific cost and performance parameters. In *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 1329–1356. Cambridge University Press, 2014.

[17] European Commission. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3, December 15 2017.

[18] SimaPro 9. https://simapro.com/. Retrieved December $21^{th}$ 2021.

[19] Ecoinvent 3.6. Cut-off system model 2020. https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html. Retrieved September $21^{th}$ 2020 .

[20] R.A. Bidkar, E. Sevincer, J. Wang, A.M. Thatte, A. Mann, M. Peter, G. Musgrove, T. Allison, and J. Moore. Low-leakage shaft-end seals for utility-scale supercritical $CO_2$ turboexpanders. *Journal of Engineering for Gas Turbines and Power*, 139(2), 2017.

[21] N. von der Assen, L.J. Muller, A. Steingrube, P. Voll, and A. Bardow. Selecting $CO_2$ sources for $CO_2$ utilization by environmental-merit-order curves. *Environmental science & technology*, 50(3):1093–1101, 2016.

[22] S. Deutz and A. Bardow. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nature Energy*, 6(2):203–213, 2021.

[23] T. Neises and C. Turchi. Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650° c. *Solar Energy*, 181:27–36, 2019.

[24] P. Viebahn, Y. Lechon, and F. Trieb. The potential role of concentrated solar power (csp) in africa and europe—a dynamic assessment of technology development, cost development and life cycle inventories until 2050. *Energy Policy*, 39(8):4420–4430, 2011.

[25] J.J. Burkhardt III, Ga.A. Heath, and C.S. Turchi. Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives. *Environmental science & technology*, 45(6):2457–2464, 2011.

[26] J.J. Burkhardt III, G. Heath, and E. Cohen. Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation: Systematic review and harmonization. *Journal of Industrial Ecology*, 16:S93–S109, 2012.

[27] E.G. Hertwich, T. Gibon, E.A. Bouman, A. Arvesen, S. Suh, G.A. Heath, J.D. Bergesen, A. Ramirez, M.I. Vega, and L. Shi. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences*, 112(20):6277–6282, 2015.

[28] G. Weinrebe, M. Böhnke, and F. Trieb. Life cycle assessment of an 80 mw segs plant and a 30 mw phoebus power tower. *Solar Engineering*, pages 417–424, 1998.

[29] M.B. Whitaker, G.A. Heath, J.J. Burkhardt III, and C.S. Turchi. Life cycle assessment of a power tower concentrating solar plant and the impacts of key design alternatives. *Environmental science & technology*, 47(11):5896–5903, 2013.

[30] T. Telsnig. Standortabhängige analyse und bewertung solarthermischer kraftwerke am beispiel südafrikas. 2015.

[31] F. Asdrubali, G. Baldinelli, F. D'Alessandro, and F. Scrucca. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. *Renewable and Sustainable Energy Reviews*, 42:1113–1122, 2015.

[32] B. Corona, D. Ruiz, and G. San Miguel. Life cycle assessment of a hysol concentrated solar power plant: analyzing the effect of geographic location. *Energies*, 9(6):413, 2016.

[33] F. Cavallaro, D. Marino, and D. Streimikiene. Environmental assessment of a solar tower using the life cycle assessment (lca). In *International Symposium on New Metropolitan Perspectives*, pages 621–628. Springer, 2018.