Life Cycle Sustainability Assessment of a dish-Stirling Concentrating Solar Power Plant in the Mediterranean area

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Abstract

Among the different renewable energy sources, solar energy shows the highest exploitation potential to satisfy a substantial portion of the worlds' future energy demand, guaranteeing at the same time lower emissions than conventional energy providers. Much of this potential is usable thanks to Concentrating Solar Power (CSP) technologies, of which the dish-Stirling concentrator is the most efficient. Nevertheless, the production and installation phases of the dish-Stirling technology can have an environmental impact which motivated the assessment of the plant in the three dimensions of sustainability (environmental, economic and social). The present publication evaluated an existing dish-Stirling plant located in Italy with a Life Cycle Sustainability Assessment. The Life Cycle Assessment resulted in the emission of 35 tons of CO_2e. The main drivers of emissions were the electronic components (16%) and the steel used for the structure (37%). Life Cycle Costing resulted in total costs of 308,467 €. S-LCA resulted in working seconds for skilled and unskilled workers equal to 1,454,400 and 1,713,600 s, respectively. The main challenges that were identified for this work were the data availability for all pillars and the comparability between the actual study and the publications already available in the relevant literature.

Key Words: LCSA, dish-Stirling, Concentrating Solar Power, LCA, renewable energy

Abbreviations

ADPe	elementary Abiotic Depletion Potential
ADPf	fossil Abiotic Depletion Potential
AP	Acidification Potential
BWC	Blue Water Consumption
CED	Cumulated Energy Demand
CML	Name of assessment methodology (Centrum voor Milieukunde)
CRM	Critical Raw Materials
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance
EP	Eutrophication Potential

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EPBT	Energy Payback Time
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HYSOL	Hybrid Solar Energy Technology
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LCSD	Life Cycle Sustainability Dashboard
LCST	Life Cycle Sustainability Triangle
LCWE	Life Cycle Working Environment
ODP	Ozone Layer Depletion Potential
PCU	Power Conversion Unit
PED	Primary Energy Demand
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
SDG	Sustainable Development Goal
SHDB	Social Hotspot DataBase
S-LCA	Social Life Cycle Assessment

1. Introduction

Energy systems are undergoing a worldwide transformation due to their high pollution impacts in terms of carbon and other toxic discharges. The transition towards low carbon emissions and an energy-efficient society are being promoted especially by Goal 7 (Affordable and clean energy), Goal 12 (Responsible consumption and production) and Goal 13 (Climate action) of the Sustainable Development Goals (SDGs) [1]. The concepts such as an increase in energy savings and the development of alternative energy technologies, aimed at reducing greenhouse gas (GHG) emissions, are in the current focus of public debate and hence become key elements of the energy policies of any industrialized country. The ongoing exploitation of non-renewable energy resources is unsustainable in perspective to future generations – across the three dimensions of sustainability: economic, environmental and social. In 2014, the European Union published their targets to significantly increase the use of renewable energy sources for electric energy generation in the 2030 framework for Climate and Energy policies [2]. This strong commitment is essential to achieve the goal of reducing CO_2 emissions related to the generation of electrical energy and to avoid a temperature rise above 2 °C in 2050 [3].

Due to the prevalent use of fossil fuels and the permanent growth in energy demand, the electricity sector is closely linked to global warming related emissions. Among the different renewable energy sources, solar energy represents an abundant source of energy with the highest exploitation potential of all energy sources to satisfy a substantial portion of the worlds' future energy demand [4].

In the last decade, there has been a significant increase in solar-based electricity generation, exemplarily shown by the use of Concentrating Solar Power (CSP) plants. CSP technologies enable indirect conversion of solar radiation into electricity, by first converting thermal energy into mechanical energy using a working fluid that evolves according to a thermodynamic cycle and then transforming the latter energy into electricity using a power generator [5]. The International Energy Agency (IEA) expects the CSP technology to be highly competitive by 2030, assuming exploitation of the full potential of CSP. By 2050, 11.3% of total global electricity could be provided by the mentioned plants, leading to a reduction in CO_2-emission of 2.1 Gt per year [6]. One of the most efficient CSP technologies today is the dish-Stirling system, which is characterized by solar-to-electric conversion efficiency values greater than 30%. The surface of the primary optic is shaped like a paraboloidal dish that concentrates only the incident solar beam radiation into a focal point. The main feature of this plant is the presence of a tracking system, which ensures the continuous and accurate alignment between the focal axis of the dish and the sunlight direction. The receiver system is located at the focal point of the reflector and delivers high-temperature thermal energy to the Stirling engine [7]. The working fluids that can be used in this engine are hydrogen or helium [8]. From the environmental point of view, the CSP technology generates electricity by very few polluting emissions during its use phase. Yet, as most of the common technologies in the renewable energy sector, the dish-Stirling system is responsible for most of the environmental impacts in its production and installation phases. Both steps may involve high energy consumption and the use of raw materials. Considering the social and economic sustainability dimensions, CSP systems could result in further potentially positive effects compared to other technologies using different energy sources. Life Cycle Sustainability Assessment (LCSA) is a framework combining and measuring all three pillars of sustainability. A detailed and careful analysis of the entire life cycle of the CSP system could provide a clear representation of the holistic sustainability performance of the electricity production from solar energy source.

The goal of this publication was to analyze an existing dish-Stirling concentrating solar power plant, supplying energy into the grid, in terms of its sustainability performance. Far more impact indicators than only Global Warming Potential (GWP) were reported for an improved environmental assessment and the explicit description of individual components allows the author and reader to identify the emission hotspots. Additionally, for the first time, critical raw materials used for the dish-Stirling production have been assessed as part of S-LCA.

1.1. Life Cycle Sustainability Assessment

LCSA is a framework combining all three pillars of sustainability. LCSA extends the scope of the analysis from mostly product-related questions to sector-related questions [12]. The LCSA framework being well accepted was developed by Kloepffer and Finkbeiner et al. [13,14]. It can be described with the formal Eq. (1) – being ISO-14040-consistent [15]:

$$LCSA = LCA + LCC + S\text{-}LCA \quad (1)$$

The Life Cycle Assessment (LCA) is the environmental assessment of a product's life cycle [15], Life Cycle Costing (LCC) are the costs of a product's life cycle [16] and S-LCA is the Social Life Cycle Assessment of a product [10,11]. To implement LCSA, a contemporary and complementary implementation of the three techniques LCA, LCC and S-LCA to the same functional unit (FU) and an equivalent system boundary must be carried out. It is a method for sustainability assessment of both, positive and negative impacts, whereby the social pillar, in particular, can have a positive influence on the overall sustainability assessment [9–11]. The framework does not include any weighting between the three pillars and none compensation between the pillars is allowed [14].

The advantage of LCSA is the transparency and the identification of potential trade-offs between the pillars [17]. LCA offers a detailed approach for assessing different processes and systems as well as a quantification of the potential environmental impacts. For the life cycle of a product or service, potential environmental impacts are considered in pre-defined system boundaries based on quantitative data on raw material consumption and emissions of all respective relevant processes. According to the ISO standard 14040, LCA includes a systematic investigation of the environmental impacts for all stages of a product's life cycle [15,18,19].

LCC is a methodology encompassing and assessing all costs related to a product arising in all life cycle stages from cradle-to-grave [20,21]. The LCC methodology is used for various purposes in a high number of different sectors, nevertheless, there is no uniform and distinct definition for LCC except the ISO reference standard for buildings [22].

S-LCA is the most recent of the three sustainability assessment techniques presented. It is not yet available for all products standardized. S-LCA as a complementary evaluation approach to LCA and LCC evaluates the social impact of a product, considering the same functional unit and an equivalent system boundary [9–11].

1.2. Present LCSA studies of dish-Stirling systems

Few publications on LCSA of solar concentrators/dish-Stirling have been published. Further LCSA studies dealt predominantly with photovoltaic systems [23–26] or considered individually one or two of the three named sustainability pillars, not fulfilling the LCSA framework. In detail, Ehtiwesh et al. [27], and Lamnatou and Chemisana [28] analyzed the environmental aspects related to the CSP technology. Two publications, conducted on dish-Stirling systems, were presented by Bravo et al., and Cavallaro and Ciraolo, which respectively illustrated a comparative environmental assessment between the dish-Stirling technology and a photovoltaic (PV) plant with equal power [29] and a preliminary LCA analysis [30]. Benacloche et al. [31] conducted an LCA analysis and a socio-economic Multiregional Input-Output analysis for the estimation of environmental impacts, production services and employment creation, on a parabolic solar concentrator coupled to a biomass system. Corona et al. [32] focused their attention on the social aspect of an LCSA, suggesting a new classification and characterization model based on previous methodological developments. Naves et al. [33] focused their review study on the evaluation of sustainability in the economic domain in the Solar Energy sector.

Three publication dealt with LCSA and CSP technology in detail, whereof two studies published all key factors (e.g., system boundaries, functional unit etc.) – see Tab. 1:

The paper by Corona & San Miguel, published in 2019, investigated a novel hybrid solar energy technology (HYSOL) in Spain [34]. The primary objective of this article was to respond to the need expressed by the scientific community to test the use of LCSA for different products and in different sectors. The focus was not on the sustainability results, as the main goal was on identifying the operationalization of LCSA. The relevant framework conditions such as system boundaries, functional unit and analyzed indicators can be taken from Tab. 1, as can the presentation of results. The LCSA application itself was described in detail. Further, Corona & San Miguel focused on the presentation and visualization of LCSA to support decision-makers. A visualization proposal, named Sustainability Crown was presented [34].

The second study on LCSA for a fictional CSP plant was published by Ko et al. in 2018 [35]. The framework conditions, tools used and main results are shown in Tab. 1.

As a third publication, the study by Rodríguez-Serrano et al., a sustainability assessment of a solar thermal power generation facility in Mexico was conducted using the Framework for Integrated Sustainability Assessment (FISA). FISA, like LCSA, considers all three pillars of sustainability [36]. This study did not detail key factors, which is why it was not included in Tab. 1.

	Corona & San Miguel, 2019	Ko et al., 2018
Goal	test the use of life cycle-based sustainability analysis	cradle-to-grave analysis of the environmental performance of a CSP tower plant in selected impact categories
Product	novel type of hybrid concentrating solar power (CSP) plant designed to operate using both solar energy and auxiliary fuels	concentrating solar power (CSP) tower plants
FU	1 MWh of electricity poured into the grid	1 kWh net electricity fed to the grid
System boundaries	cradle-to-gate	cradle-to-grave use phase: use of grid electricity is included
Data assessed by	two engineering companies	primary data from a project is used, combined with manufacturer data GaBi database
Comparison made with other product(s)	yes: CSP PTC	no
Assumed energy production per year	800 GWh/year	585 GWh/year
Assessed lifetime	n.a.	30 years
LCA indicators	Climate change: kg CO_2e /MWh Water stress: m3/MWh	GWP ADP EP net caloric primary energy demand (PED n.-r. and PED r.) blue water consumption (BWC) land occupation
LCA software and database	SimaPro 8.0.3 & ReCiPe	GaBi & CML2001
LCC indicators	**similar system boundaries** Life Cycle Cost: €/MWh (not clear what is part of it) Costs balance per functional unit Net value added Multiplier effect	**cradle-to-use** (personnel costs excluded) NPV
LCC tools	n.a.	n.a.
S-LCA indicators	**similar system boundaries** Employment creation (person-year) (h/MWh) Social Risk (SHBD) Social Performance of the promoter	LCWE (Life Cycle Working Environment) Distribution of working time (s/country) Lethal and non-lethal accidents
S-LCA tools	SHDB	SHDB
Calculation of EPBT	by CED v9 method	n.a.
Recycling considered	yes	yes
LCA Climate Change Results	Climate Change: CSP Bio: 45.9 kg CO_2e /MWh CSP GN: 294 kg CO_2e /MWh	Life Cycle: 24.3g CO_2e /kWh Construction: 12g CO_2e /kWh Use: 15.2g CO_2e /kWh EoL: -2.9 CO_2e /kWh
EPBT Results	CSP Bio: 6.1 months CSP GN: 22 months	n.a.
LCC Results	CSP Bio: 211 €/MWh CSP GN: 154 €/MWh	Construction cost: 478 m€ Annual operation costs: 892 t€ NPV: 43,4 m€ (5 % discount rate, 30 years, 66.5 €/MWh)
S-LCA Results	CSP Bio: 454,090 person-year CSP GN: 158,106 person-year Person-year = employment generated	Total working time: 19,398,646s (5388h; 673d – with 8 h each day)

Table 1 CSP-LCSA-studies

1.3. Delimitation of the present study

The differences between the two studies in Tab. 1 and the present LCSA consist of:

- the actual study refers to a real CSP system located in Italy (Palermo), being produced in Sweden,
- the CSP system transfers energy to the national electric grid,
- the system boundary was defined as cradle-to-use,

- the functional unit was defined to be the CSP system itself and not a definite amount of generated energy,
- use phase and End-of-Life phase were not considered,
- the lifetime of the CSP system was expected to be 25 years, and
- hydrogen as a thermal fluid was used (instead of HYSOL technology or heat transfer fluid).

The LCA results were more detailed (impact assessment as well as results presented) compared to the above-mentioned studies. Explicit descriptions of the components and their contributions to the total emissions were given and more impact indicators rather than just carbon dioxide equivalents were assessed. Regarding LCC, the kind of labor as well as components required to build the CSP plant were given. The S-LCA, based on the Social Hotspot database, was presented with additional details (specific labor hours from real data). The current study is the first to include the European framework for critical raw materials in processes and supply chain.

In the following, the LCSA study for a solar dish-Stirling system is presented, including: a complete LCA case study carried out with the software GaBi [37]; a full LCC carried out in accordance with ISO 14040/44 and considering the production and maintenance costs; and a S-LCA which focuses on the risk analysis of raw materials up until their extraction.

2. The dish-Stirling Concentrating Solar Power Plant of Palermo: a Case Study

A grid-connected dish-Stirling solar concentrator with a nominal power of 33 kW located at the campus of the University of Palermo (Italy) was analyzed. The dish-Stirling system is a CSP technology performing an efficient conversion of Direct Normal Irradiance (DNI) into electricity. Furthermore, it cogenerates thermal energy.

2.1 Description of the dish-Stirling system of Palermo

The main components of the analyzed system are the reflector of paraboloidal dish shape, the solar tracking system, and the power conversion unit (PCU) including: a receiver, a Stirling engine, and an alternator. The concentrator is a paraboloidal dish made up of 104 independent glass mirrors, installed on a steel structure that collects and focuses the incident solar beam radiation to a focal point placed at more than seven meters from its vertex (Fig. 1 and Fig. 2). The mirrors are characterized by a double curvature and a sandwich structure with an extra thin glass upper surface that provides a high reflectivity of 95%. The maximum optical efficiency of the concentrator is assured by a periodical mirror cleaning, which plays a key role among all the maintenance activities of the system. Indeed, the deposition of soiling on the reflective surface affects the electric energy generated by the system [38]. The cavity receiver is located in the focal point and absorbs the concentrated solar rays to supply high-temperature thermal energy to the working fluid. In the examined case study, the solar power plant uses hydrogen, equipped with a tank of 40 liters that needs to be replaced every three months. The geometric concentration ratio of the parabolic dish system is usually higher than other CSP technologies. This system presents a diameter of the aperture area of the dish collector equal to 11.86 meters and a diameter of the aperture area of the receiver equal to 0.2 meters, obtaining a geometric concentration ratio of 3,516 (aperture area of the concentrator divided by the aperture area of the receiver).

The correct operation of the parabolic concentrator requires the perfect alignment between the focal axis of the dish reflector and the direction of the incident solar rays. For this reason, the concentrator tracks the sun during its daily path, thanks to a bi-axial tracking system, also called azimuth-elevation tracking. The latter adjusts the position of the concentrator by allowing two independent rotational motions, one related to the azimuth angle and the other to the elevation angle, which univocally define the position of the sun at a given time of day. The concentrator, driven by electric motors, rotates around a perpendicular axis to the earth surface (azimuth tracking) and around a parallel axis to it (elevation tracking). Fig. 2 shows the PCU that includes the receiver, the Stirling engine, and the alternator. Those components convert the solar thermal energy into mechanical energy and then into electric energy.

Fig. 1 dish-Stirling solar concentrator at Palermo

Fig. 2 Power conversion unit including the cavity receiver, the Stirling engine and the electric generator

The cavity receiver represents a heat exchanger that allows the hydrogen to reach the operating temperature and pressure to evolve in the Stirling engine. The maximum values of hydrogen temperature and pressure are 720 °C and $2x10^7$ Pa respectively. The engine-working is based on the homonymous thermodynamic cycle that consists of four transformations, such as the isothermal expansion with the absorption of heat at the highest temperature of the cycle, the isochoric cooling, the isothermal compression with heat loss at the lowest temperature of the cycle, and the isochoric heating [39,40].

The Stirling engine, installed in the examined case study system, has four double-acting cylinders each consisting of a hot chamber and a cold chamber. The expansion and heating of hydrogen, occurring in the hot chamber, and the compression and cooling, occurring in the cold chamber, activate the alternate movement of the pistons and rotate a crankshaft. Finally, an alternator keyed into the same shaft generates electricity [41]. To increase the efficiency, the Stirling engine is provided with the regenerators that increase the difference of temperature between hot and cold sides of the engine. The regenerator develops two actions: 1) a pre-cooling of the hydrogen that flows to the cold chamber and 2) a pre-heating of the hydrogen that flows to the hot chamber. While the receiver continuously supplies thermal energy to the hot side of the engine, at the same time a cooling system removes a low-temperature heat flow from the cold side. The cooling system consists of a dry-cooler, a circuit for glycol-water flow and a circulator. The support of the dish-Stirling system is made by a steel structure fixed to a reinforced concrete foundation.

The main features of the dish-Stirling solar concentrator are the high reflectivity of mirrors, the paraboloidal shape of the reflector, the precision of the tracking system, and the high conversion efficiency of the Stirling engine, which can reach values higher than 30% with DNI above 900 W/m². The main characteristics of the dish-Stirling system are collected in Tab. 2.

Parameter	Value	Unit
Aperture area of the receiver	0.0314	m²
Average parasitic electric consumption	1,600	W
Clean mirrors optical efficiency	0.85	-
Contemplated Lifetime	25	y
Emissivity of the receiver	0.88	-
Focal length	7.45	m
Geometric concentration ratio	3,516	-
Typical output at solar beam irradiance of 960 W/m²	31.5	kW
Max operating pressure of hydrogen	$2x10^7$	Pa
Net aperture area of the dish collector	106	m²
Reflectivity of a clean mirror	0.95	-
Temperature of the receiver	720	°C

Table 2 Typical parameters of the dish-Stirling system [36]

2.2 Producibility of the dish-Stirling system in Palermo

The electrical producibility of the dish-Stirling system has been analyzed through a numerical model [38] implemented in the TRNSYS environment [42]. According to the reference numerical model, the electrical production of the dish-Stirling system depends essentially on the solar beam radiation and the air temperature that characterize the installation site, as well as the level of cleanliness of the mirrors. Based on the Meteonorm solar database, Palermo is characterized by an annual normal solar irradiation value of 1,932.61 kWh/m²/y. Fig. 3 shows the monthly values of the cumulative solar beam irradiation and the average air temperature [43].

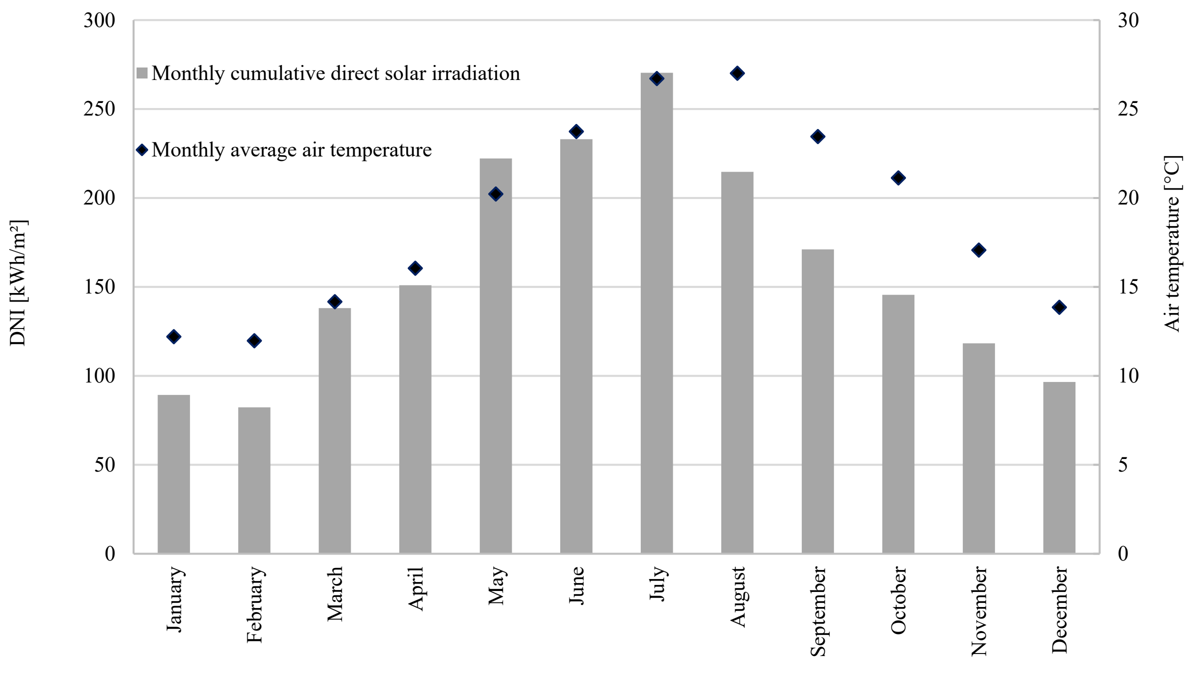

Fig. 3 Monthly cumulative direct solar irradiation and monthly average air temperature of Palermo [43]

Fig. 4 shows the monthly values of the electric energy produced by the dish-Stirling system in Palermo. It shows that the energy production trend closely matches that of the DNI shown in Fig. 3. The annual net electricity production amounts to approximately 46 MWh in Palermo.

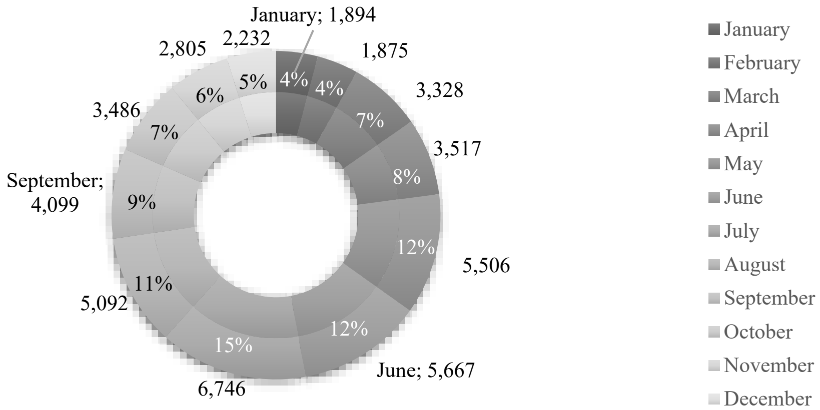

Figure 4 Monthly net electric output energy [kWh]

From Fig. 5, showing the annual net electricity production of the dish-Stirling concentrator distributed per DNI class (DNI intervals of 50 W/m²), it can be observed that the energy production of the concentrator increases as the DNI level enhances, so does the solar-to-electricity conversion efficiency. Excluding the dish reflector optical losses, the highest average value of the conversion efficiency is about 36% for DNI levels between 950 and 1000 W/m² [43].

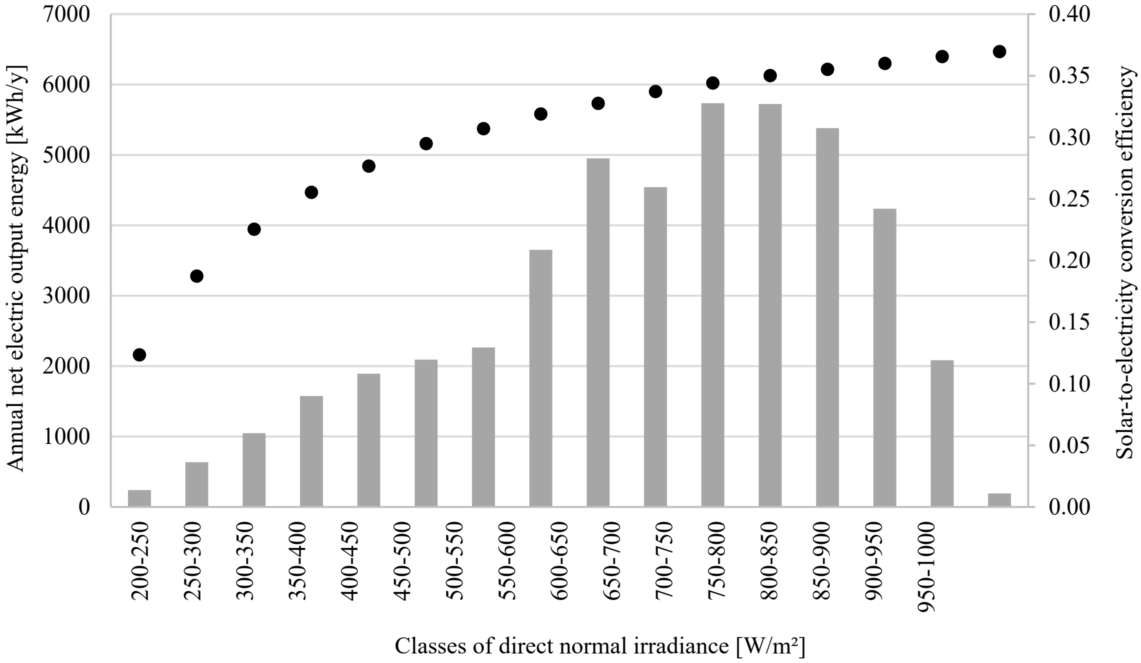

Fig. 5 Annual net electric energy produced (grey pillars) for each class of DNI and corresponding average value of solar-to-electricity conversation efficiency (black dots) [43]

3. Methodology

3.1. Life Cycle Assessment

A Life Cycle Assessment provides a structured approach to evaluate processes and systems and quantify their potential environmental emissions and impacts. LCA was harmonized with the standards ISO 14040 and ISO 14044, which led to a common structure of LCA including four steps:

- the Goal and Scope of the assessment, including the definition of the FU and the system boundaries,
- the Life Cycle Inventory Analysis (LCI),
- the Life Cycle Impact Assessment (LCIA) and finally,
- the Interpretation [15,18,19].

3.1.1. Goal and Scope

The goal of this LCA, as part of LCSA, was to provide a comprehensive and actual LCA for the production (cradle-to-use) of one dish-Stirling concentrating solar power plant located in Palermo. The FU was set to one power plant. The LCA, especially LCI and LCIA were based on primary data and on secondary data from GaBi and Ecoinvent databases. Additional assumptions had to be made in order to obtain the most realistic result possible. During the use phase, a certain amount of hydrogen would have to be added regularly to the dish due to unstoppable leakage of the gas. We assumed that about 95% of all hydrogen was being produced from natural gas and coal [44], inferring the GaBi process *DE: Hydrogen peroxide (100 %; H_2O_2) (Hydrogen from steam cracker) ts* to be suitable. The software GaBi SP40, its professional database and the Ecoinvent database 3.5 were used. Across various plans, for the sake of improved clarity, the complete engine was modeled, shown in the following process diagram (Fig. 6). Fig. 6 distinguishes the following macro-components of the solar concentrator:

- the PCU equipment, comprising the receiver, the Stirling engine and the electric generator positioned inside the power conversion unit;
- the tripod, that is the lattice structure supporting the power conversion unit;
- the mirror, i.e. the dish reflector;
- the circle structure on which all mirrors are fixed;
- the dish-carrier, which is the lattice structure on which the circle structure is fixed; and
- the elevation tracker and the turntable, which constitute the biaxial tracking system.

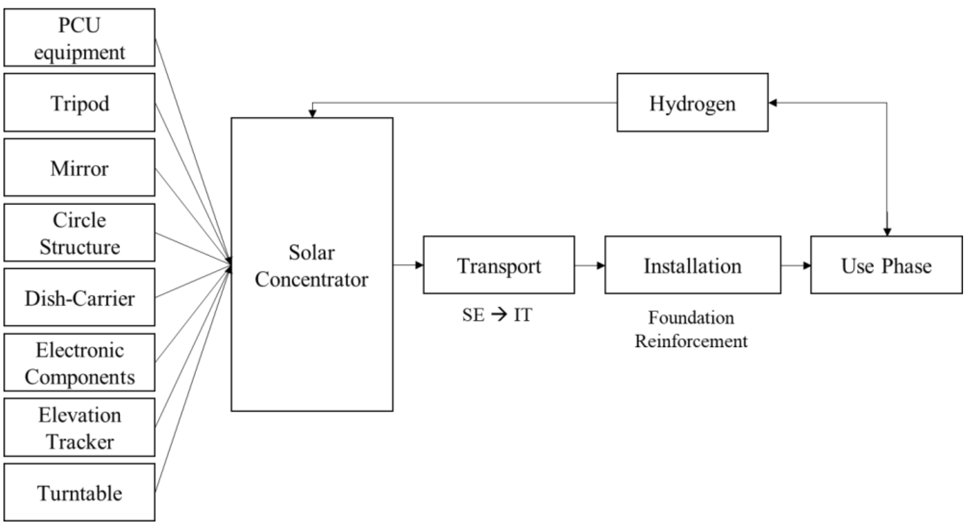

Fig. 6 Simplified Process Diagram - System Boundaries

The solar concentrator was assembled in Sweden and trucked to Italy, Palermo. The transport was calculated and assumed in accordance with the European Automobile Manufacturers Association (2019) [45] and integrated into the model with the GaBi Process *GLO: Truck, Euro 4, 28 - 32t gross weight / 22t payload capacity* virtually driving 10,473 km, fed with 2,297 kg diesel (*EU-28: Diesel mix at refinery*) (Tab. A.1). Up upon arrival in Italy, a foundation, made from concrete and reinforcing steel (Tab. A.2), was cast on-site to securely install the solar concentrator.

3.1.2. Life Cycle Inventory Analysis

Within the LCI quantitative statements about the input and output variables of the components were collected. Raw materials used and energy required to produce the individual components and for the production of the entire solar concentrator were collected and combined. Data about the transport route was included. The attached tables (A.1 – A.10) show the selected databases and processes for the individual components. A brief explanation is given as to why the process was selected and what function it contains.

Additionally, the following assumptions have been made: Since only the main materials from the actual dish-Stirling engine (Tab. 2) were available and no further details of the production, database processes were taken as reference processes. For the Stirling engine the Ecoinvent process *GLO: Stirling heat and power co-generation unit construction, 3kW electrical feature* was selected as general default, initially used by Kuenlin et al. [46]. As the Ecoinvent process described an engine with the power of 3 kW and a total mass of up to 495.96 kg, additional assumptions had to be made to better approach reality: The Stirling engine of the present LCA is characterized by a size of 33 kW, a total mass of 734.1 kg and the presence of four cylinder-piston units. As the total mass difference results in 238.14 kg (Eq. (2)), all further materials must be scaled up accordingly and changed in the Ecoinvent process.

$$734.1\ kg - 495.96\ kg = 238.14\ kg \tag{2}$$

A scaling example: ceramic cavity counts for 19.5 kg of the total 734.1 kg which leads to a share of 2.7 % of the materials used in the Stirling engine (Tab. 3). In the following, each material was added according to its share.

Element	Material	Quantity [kg]	Share in %
Heat exchanger	Nickel alloy	15.6	2.1
Cylinder/piston	Steel	400	54.5
Connecting rods	Steel	130	17.7
Electric generator	Steel	65	8.9
	Copper	65	8.9
Regenerator	Steel	39	5.3
Ceramic cavity	Ceramics	19.5	2.7
Total		**734.1**	

Table 3 Materials used for dish-Stirling at Palermo

The upscaling (Tab. 4) did not fully represent the actual solar concentrator but it was the most appropriate approach since detailed primary production data were not available (Table A.5).

Material	Real mass share [%]	Share of difference [kg]	Assigned to Ecoinvent	New value in GaBi [kg]
Nickel alloy	2.1	5.1	*GLO: nickel, 99,5 %*	5.1
Steel (cylinder/piston, electric generator (steel), regenerator)	68.7	163.5	*GLO: sheet rolling, steel [allocatable product]*	299.5
Steel (connecting rods)	17.7	42.2	*GLO: reinforcing steel [allocatable product]*	178.2
Copper (electric generator)	8.9	21.1	*GLO: copper [allocatable product]*	25.6

Ceramic cavity	2.7	6.3	*GLO: ceramic tile [allocatable product]*	6.8
Other (see Appendix)				218.9
Total				**734.1**

Table 4 Mass upscale

Furthermore, in the actual CSP two axial gear motors are installed. The GaBi process *Manufacturing electric motor (<=10 kW); assembling electric motor; production mix, at plant; <=10 kW (en)* appeared to correspond to reality. Due to the black-box structure of GaBi, this process could not be accessed directly, which was why the following assumptions and modeling have been made:

The percentages given in the GaBi description e.g. motor assembled from electrical steel (45.1 %), mechanical steel sheet (10.7 %) etc. were copied in a "new" model. To a large extent, the processes could be reconstructed and thus rebuilt (Table A.6). However, the original process did not provide any information on the required production energy, hence this must be added as another estimation from further sources, to avoid neglecting emissions. Boughanmi et al. [47] did a LCA for a 10 kW engine, using the same materials as named by the GaBi process *Manufacturing electric motor.* These results could be referred to as a baseline scenario for our calculation of the required production energy.

The production line included materials and transportation, but excluded the energy needed for production. That value needed to be assumed to meet the defined system boundaries and to fully assess the production process. Primary data and exact measurements were not given in that case, so it was necessary to make use of literature data: Boughanmi et al. [47] divided specified environmental impacts, such as the cumulated energy demand (CED) of a 10 kW electric engine regarding to their life cycle emissions – which was quite similar to the actual one assessed. Boughanmi et al. [47] estimated the CED for the production with 3,481 MJ (Tab. 5: Difference) – including already the production energy needed [47].

The actual "Italian" CED represented the energy needed for the production line excluding the energy needed – resulting in 2,161 MJ (Tab. 5: CED excl. electricity). To assume that missing energy aspect, the difference (1,320 MJ) was estimated and inserted in the process "*FR: Electricity grid mix*", since Boughanmi et al. [47] used French data in their study. Re-modelling Boughanmi et al. [47] with the actual Italian-CED-basis, the total production CED (incl. energy needed) resulted in 5,644 MJ (Tab. 5).

Difference	**CED excl. electricity**	**Required production energy**	**CED incl. electricity grid mix**	**Calculated loss factor for the electricity mix in France**	**Energy production**
[MJ]	**[MJ]**	**[MJ]**	**[MJ]**		**[MJ]**
3,483	2,161	1,320	5,644	2.64	500.56

Table 5 Calculation Production Energy [44]

Due to the calculated energy loss factor, the real energy demand for the production of the engine was estimated: Dividing 1,320 MJ by the value of 2.64 (Tab. 5). The value of 2.64 was calculated as the *Difference* divided by the *Required production energy*. A plausibility check of the calculated 500.56 MJ, which represented the required amount of production energy, led to the same CED as given by Boughanmi et al. [47].

With this CED, scaling up the process to two motors with a total weight of 24.6 kg of the actual "Italian" engine, the calculated assumptions could be integrated in the GaBi model (Table A.6).

Further assumptions, based on secondary data, had also been made for the required production energy of the dish. The amount of energy needed in the manufacturing process has not been published due to confidentiality agreements [29,30], therefore assumptions had been made: According to Ordóñez Barreiro et al. [48], the ratio of required energy of different thermal solar systems (dish-Stirling, central power and parabolic trough) throughout the life cycle is seen to be comparable. As only manufacturing data for the object itself was missing, the energy demand in manufacturing was estimated according to Burkhardt et al. [49] with 0.037 MJ/kWh. This amount represented the energy assumed for the manufacturing of the solar plant. With a life expectancy of 25 years and an annual electricity generation of 46 MWh, a total of 1,150 MWh was expected at the end of the use phase. With the given information, the total energy demand for all manufacturing processes of the dish was expected at 42.550 MJ.

Besides the unknown amount of production energy (Tab. 5), the type of energy remained unclear. Within this study, the total energy demand was assumed of being provided by the electricity grid in Sweden (GaBi process: *SE: Electricity grid mix*), as the entire manufacturing operation took place in Sweden. Cut off criteria were applied for few components within the framework of this LCA due to missing process data (Table A.4).

3.1.3. Life Cycle Impact Assessment (LCIA)

The purpose of the LCIA is to classify and characterize the data collected in the inventory with regard to certain environmental effects, so-called impact categories. The CML 2001 (2016) method was selected in this study. The LCI-processes listed in Tab. 3, Tab. 4 and in the Appendix were modeled as cradle-to-use assessment in LCIA with GaBi SP40 (part four of [15,18]). A Global Warming Potential (GWP) of 35 t CO_2e was assessed for the functional unit of one dish Stirling engine (Tab. 6).

Impact Category	**Result**	**Unit**
Climate Change (Global Warming Potential)	34,772	[kg CO_2e]
Acidification Potential	135	[kg SO_2e]
Eutrophication Potential	42	[kg PO_4e]
Photochemical Ozone Creation Potential	22	[kg C_2H_4e]
Abiotic Depletion Potential (fossil)	0.4	[GJ]
Abiotic Depletion Potential of Resource	369,098	[kg Sbe]
Ozone Layer Depletion Potential	0.00	[kg R11e]

Table 6 LCIA Results

Focusing on the total emissions of 35 t CO_2e, it became evident that 21 % of all emissions were attributable to the elevation tracker. Both the dish-carrier and the electronic components led to 16 % of the total CO_2e-emissions. 12 % were caused by the foundation while a total of 11 % of greenhouse gas emissions were attributable to the PCU equipment (Fig. 17). Similarly, other emissions were broken down in detail to assign the occurring emissions. Thus, it emerged that the three main drivers for all indicators were the

- electronic components,
- the elevation tracker and
- the PCU equipment,

followed by the dish, the turntable and the tripod. When considering materials, 54 % of total GWP emissions and 43 % of the energy needed were caused by the use of steel.

The absolute emissions of the Acidification Potential (AP) were 135 kg SO_2 eq./Solar Dish, 31 % driven by the PCU equipment (42 kg SO_2e) and 26 % by the electronic components (35 kg SO_2e) (Fig. 8). In total, 46 % of the Eutrophication Potential (EP) was driven by electronic components and 34 % by PCU equipment (Fig. 9).

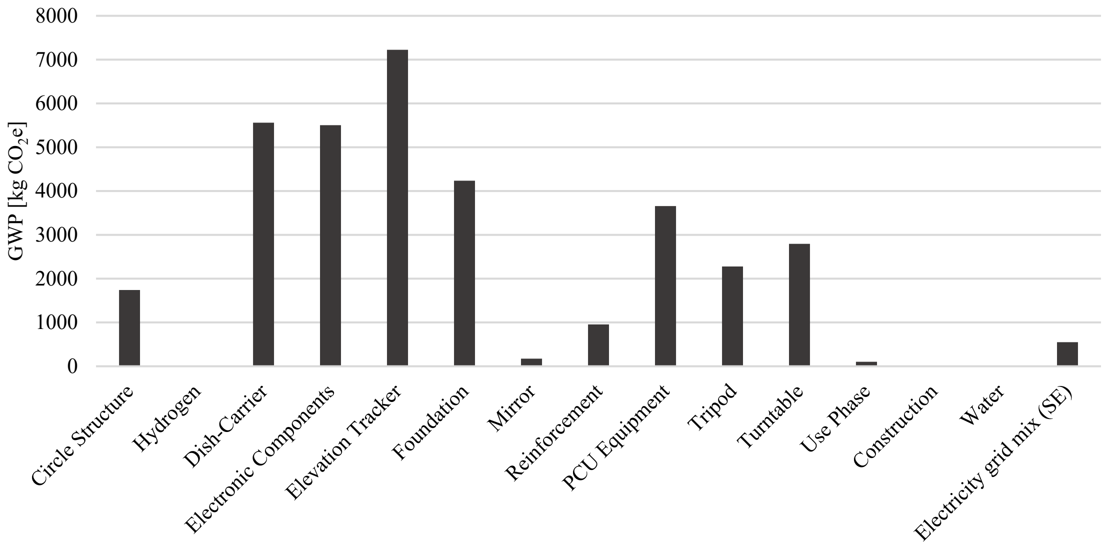

Fig. 7 GWP emissions

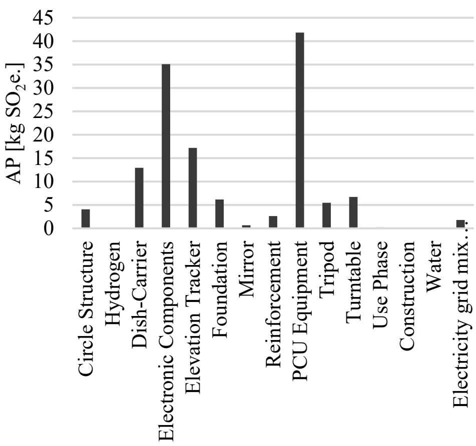

Fig. 8 AP emissions

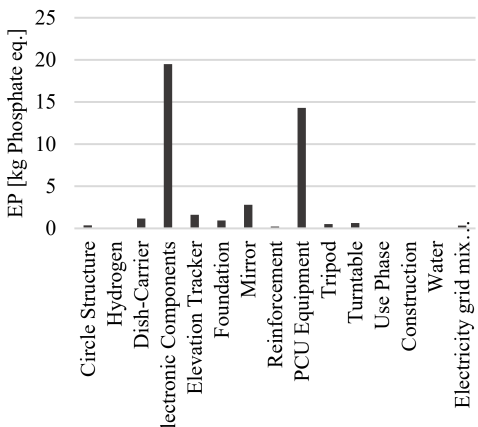

Fig. 9 EP emissions

The Photochemical Ozone Creation Potential (POCP) was influenced by 48 % by the electronic components in its total emissions of 22 kg Ethene eq. (Fig. 10). For the elementary Abiotic Depletion Potential (ADPe) the electronic components accounted for 61 % (Fig. 11) and 54 % for Ozone Layer Depletion Potential (ODP) (Fig. 13). The fossil Abiotic Depletion Potential (ADPf), however, was only influenced by 21 % by the electronic components. A further 21 % was accounted for by the elevation tracker and 13 % was attributable to the PCU equipment (Fig. 12).

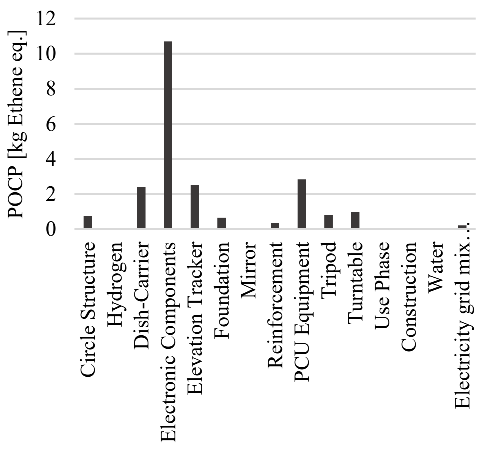

Fig. 10 POCP emissions

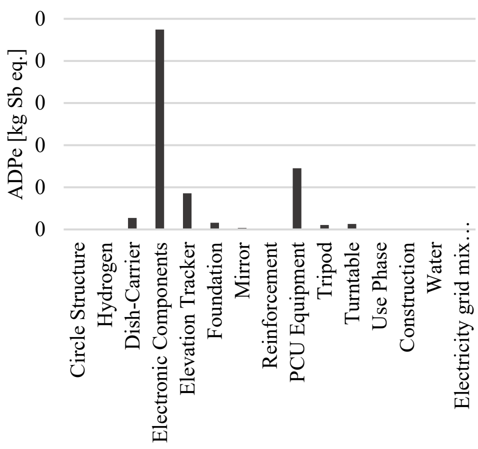

Fig. 11 ADPe emissions

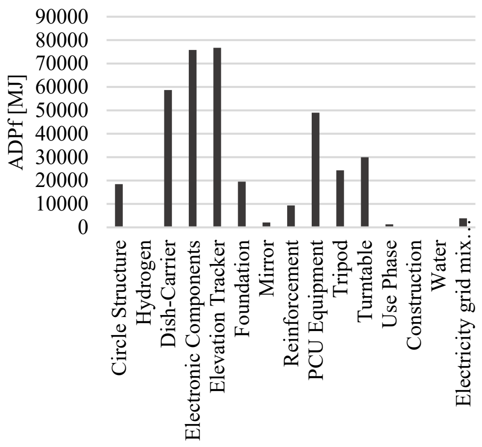

Fig. 12 ADPf emissions

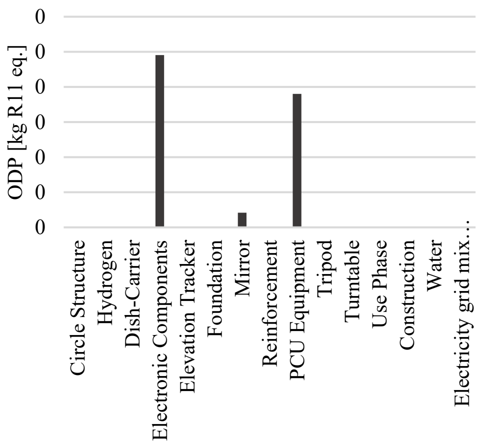

Fig. 13 ODP emissions

Since hydrogen has to be replenished regularly and water is required to ensure frequent cleaning, an explicit LCA for the use phase was conducted, resulting in the following values: The GWP of the use phase was 102 kg CO_2e. All other indicators accounted for only a very small portion of the total emissions of the use phase (AP = 0.2 kg SO_2 eq., EP = 0.1 kg Phosphates eq., POCP = 0.1 kg Ethenes eq., ADPe = 0 kg Sb eq., ADPf = 1,281 MJ, and ODP = 0 kg R11 eq.). For all indicators, water was the driving factor and accounted for at least 95 % of total emissions. If the use phase would be excluded from the emissions and only the cradle-to-gate system boundaries would have been considered, GWP would result in 34,669 kg CO_2e.

Compared to the two LCSA studies on solar dishes mentioned before [34,35], the following became evident: both studies have selected 1 kWh or 1 MWh of produced energy as FU (Tab. 1). Setting the actually modelled and calculated value of 34,772 kg CO_2e (Fig. 7) in relation to the absolute amount of energy produced over a lifetime of 25 years (1,150 MWh total), we could calculate the GWP per MWh produced (Eq. (3)).

$$\frac{34{,}772\ kg_{CO2\ eq.}}{1{,}150\ MWh} = 30.24\ kg_{CO2\ eq.}/MWh \tag{3}$$

Considering the system boundaries cradle-to-gate, respectively the value would be 30.15 kg CO_2e/MWh. The cradle-to-use figure of 30.24 kg CO_2e/MWh or 30.24 g CO_2e/kWh was quite similar to the values in both comparison studies: Ko et al. [35] obtained 36.3 g CO_2e/kWh for cradle-to-gate and 51.5 g CO_2e/kWh for cradle-to-use. When comparing the cradle-to-use balance, a significant difference became evident (51.5 vs. 20.24 g CO_2e/kWh). The study by Corona & San Miguel (2019) [34] presented two values of 45.9 kg CO_2e/MWh and 294 kg CO_2e/MWh (Tab. 1). The study by Rodriguez-Serrano et al. [36], which had hardly any key factors and thus made comparability much more difficult, showed a GWP value of 24 g CO_2e/kWh.

3.1.4. Energy Payback Time (EPBT)

Any solar concentrator aims to generate electricity. However, energy was also required for the construction and production of the solar concentrator. The Energy Payback Time (EPBT) is defined as the time needed to generate as much electricity as needed throughout the life cycle of the solar concentrator, for production, construction, and demolition. Since this study did not consider the End-of-Life-phase, demolition was not included within the EPBT. Literature, e.g. Lamnatou & Chemisana [28] and Varun et al. [50], showed one year or less as expected EPBT. The estimated EPBT of one year corresponds to the equivalent of 54.188 MWh. The EPBT for the actual dish-Stirling was calculated using the following Eq. (4):

$$EPBT = \frac{Cumulative\ energy\ demand\ (CED)\ for\ the\ system\ boundaries\ (cradle - to - use)\ [MJ]}{Annual\ electricity\ generation\ [\frac{MJ}{a}]} \qquad (4)$$

The cumulative energy demand (CED) was calculated using GaBi SP40, while the annual electricity generation was measured using real-time data (Fig. 4). A calculated CED of $52.08*10^4$ [MJ] and an annual electricity generation of 46 [MWh] (=165,600 [MJ]) led to the calculated EPBT of 3.14 years. Compared to the study mentioned above [34] (Tab. 1) and to other literature values [28,50], the EPBT of 3.14 years is comparatively high.

3.2. Life Cycle Costing

Life Cycle Costing (LCC), as the second pillar of LCSA, belongs to the group of sustainability instruments that focus on the flows related to the production and consumption of goods and services. In contrast to LCA, LCC represents the economic approach, which summarizes the total costs of a product discounted over its entire life cycle. LCC is based on a purely economic assessment that considers different costs associated with a product. External costs are neglected in this approach.

In general, LCC follows the four steps of ISO 14040/44. The definition of objectives and scope is analogous to LCA. It is notable that both assessments (LCA and LCC) focus on a consistent definition of the product system. One challenging aspect of LCC is the proposed capture of all costs over the entire life cycle, while costs are borne by different actors, which can lead to contradictions. In contrast to LCA, there is no comparable phase of impact assessment in LCC, since all inventory data comprise a single unit of measurement: currency. Characterization of the inventory data is therefore not necessary. Aggregated cost data provide a direct measure of the financial impact [16]. LCC differs from the traditional cost accounting system, known in the business, in that the costs and revenues of a cost object are tracked over several calendar periods and not just over one cost period.

To comply with the conventional LCC approach and to follow the ISO 14040/44 standard, the framework of the previously analyzed LCA was adopted: FU was set to one dish-Stirling solar power plant, the system boundaries were classified as cradle-to-use. The LCC was calculated via Excel.

3.2.1. Life Cycle Costing Results

The conventional LCC approach was being applied. External costs were not included in the calculations. The conventional costs explicitly considered the costs of purchased and used components, transportation costs, installation phase costs and maintenance costs (Tab. 7 – 9). In particular, regarding the maintenance phase, it is essential to mention that a life cycle of 25 years or 219,000 operation hours for the dish-Stirling engine was assumed. Due to confidentiality agreements, the individual component costs such as inverters or filters (first column, Tab. 7) could not be broken down and reproduced in detail. The total costs of these components resulted in 180,000 € (Tab. 7).

Costs of each component:	Description	180,000 €
Inverter	Variable Frequency Drive; Pure Sine Wave Inverter	
Rectifier	Active Front End	
Reactor	Standard Reactor	
Filter	Standard Filters	
Energy meter	Direct connected electricity meter	
Actuator	Linear actuator	
Solar instruments	Solar monitoring system; Pyranometer; Pyrheliometer	
Conditioning	Air conditioner cabinet	
Circulator	Water Circulator	
Electric panel fan	Axial fan	
Coaxial gear-motor	Tacking motor	
Alternator	Electric motor	
Dry cooler	Dry cooler	
Costs of components transport (Sweden to Italy)		**10,000 €**
Detailed costs of the installation phase:		**25,525 €**
	Labor and Machines*	18,325 €*
	Concrete	3,200 €
	Iron	3,000 €
	Copper	1,000 €
Weather Station		**15,000 €**
Costs of maintenance phase*		**77,942 €***
Total incl. maintenance		**308,467 €**
Total (cradle-to-use)		**230,525 €**

*Table 7 Costs in Euro (*will be shown in separate tables)*

Including maintenance, the largest driver of the total costs were the components themselves, which accounted for 58 % (180,000 €). Maintenance costs followed by 25 % of total costs over the entire lifetime of 25 years (Fig. 14).

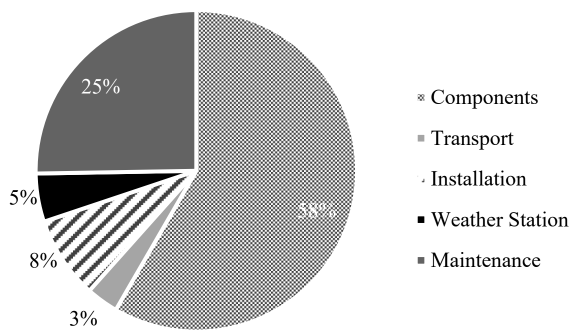

Fig. 14 Costs in % (of total incl. maintenance)

Maintenance costs were broken down in Tab. 9, where it became evident that the upkeep of the Stirling power concentrator accounted for the largest share of maintenance costs. However, over a period of 25 years, the annual maintenance costs were at 3,118 €/year. In total, 8 % of the costs were attributable to the detailed costs of the installation phase. At 18,325 €, the costs for labor and machines accounted for 71 % of this specific cost factor (25,525 €). Splitting up these 71 %, while 74 % of the total amount were personnel costs with 13,525 € and 16 % accounted for installation machinery (Tab. 8). The weather station itself accounted for 5 % of the total costs incl. maintenance (7 % excl. maintenance). Transport expenditure and components filled the remaining 3 % (incl. maintenance; 4 % excl. maintenance). The cost of labor and machinery (total of 18,325 €) were divided into labor and machinery costs. The labor outlay was distinguished between skilled and unskilled workers and furthermore calculated according to the unit expenditure and the number of days worked. Additionally, five different machines were explicitly listed. The total costs were calculated from the unit costs (€ per day) and the number of days of use (Tab. 8).

COSTS	**Unit cost [€/day]**	**n° Days**	**Total [€]**
Skilled labor	150	50.5	7,575
Labor	100	59.5	5,950
Cherry picker	150	14	2,100
Bob cat	100	7	700
Excavator	200	2	400
Mobile cranes	150	4	600
Cranes	1000	1	1,000
Total labor and machines			**18,325**

Table 8 Costs of labor and machines

The total maintenance costs of 77,942 € were depicted in Tab. 9. The information about the calculated lifetime of the dish-Stirling engine was of significant importance (assumed lifetime of 25 years or 219,000 operating hours).

Operating hours	**Components replaced**	**Working hours**	**People employed**	**Qualificat. people**	**Labor cost [€]**	**Component cost [€]**	**Unit cost [€]**	**Times**	**Total [€]**
Stirling power concentrator									
6,000	Engine seals	3.25	1	skilled labor	101.56	720	821.56	36.5	29,987
	Gas valve seats								
	Thermal insolation		1	unskilled labor					
	Oil and oil filters								
42,000	Heater quadrant	7	1	skilled labor	218.75	4,850	5,068.75	5.2	26,430
	Cylinder liners								
	Piston rods								
	Gears		1	unskilled labor					
	Thermal couplers								
	Bearings								
2,000	Yearly corrective maintenance	2.4	1	skilled labor	45	15	60	109.5	6,570
4.54 times per year	Hydrogen bottle (40 liters, 200 bar)	0.15	1	unskilled labor	1.875	55	56.88	112.5	6,398
Mirror									
Every 2 weeks (360 hours)	100 liters water	0.5	1	unskilled labor	6.25			608.3	3,802
Tracker System									
5,000	Yearly corrective maintenance	2.2	1	skilled labor	41.25	50	91.25	43.8	3,997
Preventive maintenance (every 10 years)	Backup batteries	0.25	1	unskilled labor	3.125	300	303.13	2.5	758
									77,942

Table 9 Maintenance costs

The frequency per lifetime considers how often a replacement/cleaning has to be done within the entire lifetime – column 1, line 1 of Tab. 9 shows every 6,000 operating hours the engine seals have to be replaced. Therefore, the second last column was calculated as total operating hours (219,000 h) divided by hours passed before engine seal replacement (6,000 h) (Eq. (5)):

$$\frac{219{,}000}{6{,}000} = 36.5 \quad (5)$$

The last column presents the total summed costs (*Total [€]*) and refers to frequency and outlay per component (Eq. (6)):

$$821.56€ * 36.5 = 29{,}987.03€ \quad (6)$$

The component costs (*Component cost [€]*) were known and given. Data is taken from past invoices as well as empirical values from the operating accounting in Palermo, Italy. The calculation of the labor costs differed, as these were determined from the hourly rates per unskilled and skilled worker. The daily rates from Tab. 8 were divided by an estimated amount of eight working-hours per day and multiplied by the assumed hours required per activity. As shown exemplarily in the first column of Tab. 9 (Eq. (7)):

$$\left(\left(\frac{150}{8h}\right) + \left((\frac{100€}{8h}\right)\right) * 3.25h = 101.56€ \quad (7)$$

To conclude the subject matter, the total costs for maintenance could thus be added up (Tab. 7). Further, the cost (total incl. maintenance, Tab. 7) per energy produced (1,150 MWh), were considered and accounted with 268 € per MWh (0.268€/kWh) of generated energy (Eq. (8)).

$$\frac{308{,}467€}{1{,}150MWh} = 268€/MWh \quad (8)$$

This value is comparably higher than the one calculated by Corona & San Miguel [34] (211 €/MWh) and significantly higher than the one reported by Ko et al. [35] (Tab. 1 and Tab. 14). Considering average energy prices for private households in the EU or exclusively Italy or Germany, the published values differ: Eurostat (2020) [52], and IEA (2020) [53] indicated around 280 €/MWh (Italy) and 353 €/MWh (Germany) in 2018. For the first half of 2020, Germany and Italy charged comparatively high prices in comparison to other EU states. The average value for the EU in the first half-year of 2020 was defined at 213 €/MWh [52,53]. No explicit prices for green energy were given, thus no accurate comparison could have been made.

3.3. Social Life Cycle Assessment

S-LCA is the most recent of the three sustainability assessment instruments presented. The use of the same functional unit and similar system boundaries are of critical weight. Again, the assessment should follow the four steps of LCA according to ISO 14040/44 [15,18].

Despite this common assessment framework, there are differences between LCA and S-LCA assessments: The definition and selection of stakeholders is a relevant aspect as the results of the S-LCA depend heavily on these stakeholders. Moreover, the S-LCA allows assessments of both negative and positive impacts, whereas LCA shows emissions, mostly negative. In addition, S-LCA is strongly dependent on local conditions and company behavior, less on the production process itself [10,11,54,55]. In the context of this study, a complete S-LCA according to UNEP guidelines [10,11] was not conducted.

To quantify the social impacts of the dish-Stirling engine a detailed risk analysis of critical raw materials via the Social Hotspot Database (SHDB) [56] was prepared for individual components and their respective raw material and mining countries, manufacture and assembly.

The database aims to foster collaboration to improve social conditions worldwide. The SHDB provides data and tools needed to improve the visibility of social hotspots in product supply chains of products. It contains a comprehensive list of indicators on e.g. labor rights and community infrastructure. The database covers 140 countries and regions and 57 economic sectors [56]. This allows identifying increased risks to the community and human health, as well as other categories of relevance. Results are presented in the following sub-chapter.

In addition to the risk analysis, the work environment of the installation phase was closely examined. The installation of the dish-Stirling system took a total of 46.5 days, which equals 372 hours (1,339,200 seconds), assuming each working day accounted for eight hours. These approximately 1.5 months of full-time work could be divided into work steps (Tab. 10), such as the casting of the foundation, the assembly of the dish-Stirling system, the commissioning of the system and the calibration of the mirrors. The assembly of the system was close to a full working month while the foundation took nine days to be completed. The work was arranged to be outdoors. Both skilled and unskilled employees have worked on the construction (Tab. 10). Skilled workers have spent 50.5 days of 8 hours on the construction site (404 hours or 1,454,400 seconds), unskilled workers have spent 59.5 days of 8 hours on the construction (476 hours or 1,713,600 seconds). The wage costs were considered which had already been processed in LCC, so 150 € per skilled labor force or 100 € for the unskilled employee per working day and worker were calculated. Resulting in an hourly wage of 18.75 €/h (skilled) or 12.5 €/h (unskilled) for an eight-hour day.

In Italy there is no minimum wage [58]. The wage of 12.5 €/h for unskilled workers in the construction of the dish-Stirling engine was above the highest European minimum wage. In 2019, the average weekly working time in Italy was 40.7 h. This corresponds to 8.14 h/d/worker in a five-day week. The applied 8 h/d/worker for the installation of the dish-Stirling were slightly below the 2019-average for Italy, which is positive to note. Comparing these results with the other two LCSA studies mentioned, the present result is significantly lower (fewer working seconds). However, in the case of working days, in particular, reference must be made to the narrower system boundaries, which explains the lower total working days.

Phase	Days	Sub-phase	Days	Type of work	Days	Skilled worker	man/days	Unskilled worker	man/days
Foundation	9		9						
				Excavation	1	1	1	1	1
				Foundation floor	1	1	1	1	1
				Shuttering	2	1	2	2	4
				Concrete reinforcement	3	1	3	2	6
				Concrete casting	1	1	1	1	1
				Earthing system	1	1	1	1	1
Assembly of the dish Stirling system	31.5								
		Dish	17						
				Preparation and pre-assembly	1	1	1	2	2
				Welding of the structure	5	1	5	1	5
				Welding of rings and brackets	5	1	5	1	5
				Finishing and painting of welds	1			1	1
				Mirrors assembly	3	1	3	2	6
				Mirrors calibration	2			2	4
		Arches and cage	5.5						
				Welding of arches	1	2	2	1	1
				Assembly of turntable	1	1	1	2	2
				Assembly of turntable and arches	1	1	1	2	2
				Installation of cooler	0.5	1	0.5	2	1
				Laying of the track	0.5	1	0.5	1	0.5
				Installation of pre-assembled electric panels	0.5	1	0.5	2	1
				Installation of azimuth and elevation motors	1	1	1	2	2
		Elevation	2						
				Installation of engine on the tripod	1	1	1	2	2
				Assembly of dish and tripod - before its elevation					
				Elevation of dish with engine					
				Installation of platforms and fairleads	1	1	1	2	2
		Electrical system	5						
				Installation of sensors	1	1	1	1	1
				Wiring	3	1	3	1	3
				Installation of weather station	1	1	1		
		Water system	2						
				Installation of the cooling system	1	1	1	1	1
				Installation of the hydrogen supply system	1	1	1	1	1
Commissioning of the system	4		4						
				Calibration	2	1	2	1	2
				Testing the movement of the parts	1	3	3		
				Filling and testing the water system					
				Commissioning of Stirling engine					
				Testing the hydrogen system					
				Removal of films	1	1	1	1	1
Calibration of the mirrors	2		2		2	3	6		0
Total days	**46.5**		**46.5**		**46.5**		**50.5**		**59.5**

Table 10 Labor installation phase

3.3.1. Social Hotspot Analysis of critical raw materials involved

The most economically important raw materials with a simultaneous high supply risk were referred to as critical raw materials. There are warnings that Europe's transition to climate neutrality could shift the current dependence on fossil fuels to raw materials. These raw materials are largely sourced abroad and imported. Every three years the list of critical raw materials is revised and published. In 2020, 83 materials were examined, with economic importance and supply risk being relevant parameters, leading to a list of 30 critical raw materials (CRM) [61]. Based on the previous LCA of the dish-Stirling, relevant and also critical input raw materials were defined based on the EU report [61]:

- magnesium: magnesium oxide used for parts of the mirror;
- bauxite: aluminum oxide used for mirror parts and
- coking coal: needed in the steel process, used for the turntable and final assembly.

Further, one could assume the need of:

- beryllium for electronic components and
- fluorspar for the steel production.

Even it can be said for a fact whether these commodities were actually included in the dish-Stirling system, the authors made this assumption to estimate additional risks.

The main producer and supplier countries for the EU could be defined [61]. Since the dish-Stirling was produced in Sweden and constructed in Italy, the authors assumed the purchase entirely from outside of the EU. The main producers were not necessarily considered the same as the main suppliers for the EU: This was the case with Bauxite, while the EU obtains the largest share from Guinea, even this country is not one of the largest Bauxite producers worldwide. In the case of Beryllium, there was no information on the EU's main supplier country [61] (Tab. 11).

	Main Producer			Main Supplier EU		
CRM	1	2	3	1	2	**Main sector**
Magnesium	China (89 %)	US (4 %)	-	**China (93 %)**		Electro. Equipm.
Bauxite	Australia (28 %)	China (20 %)	Brazil (13 %)	**Guinea (64 %)**	**Brazil (10 %)**	Electro. Equipm.
Coking Coal	China (55 %)	Australia (16 %)	Russia (7 %)	**Australia (24 %)**		Ferrous Metals
Beryllium	**US (88 %)**	China (8 %)	Madagascar (2 %)	-	-	Electro. Equipm.
Fluorspar	China (65 %)	Mexico (15 %)	Mongolia (5 %)	**Mexico (25 %)**		Ferrous Metals

Table 11 CRM dish-Stirling - Relevant Countries

The Social Hotspot Analysis for the five critical raw materials was performed via the SHDB (access and analysis in January 2021). In case the EU main supplier was one of the main producers in the world, this country has been assumed to be the country of origin for the raw materials. In the case of Bauxite, this didn't apply – so Guinea and Brazil were analyzed as the main supplier countries. In the case of Beryllium, there was no explicit information on supplier countries. The US has been assumed to be the main supplier for the required materials (Tab. 12: written in bold).

Within the SHDB the search could not be conducted directly, as for raw materials and products themselves, sectors had to be selected [56]. The classification of the five identified CRM resulted in two main sectors:

- electronic equipment and
- ferrous metals (Tab. 12).

All five categories:

- Labor Rights and Decent Work,
- Health and Safety,

- Human Rights,
- Governance and
- Community,

including all subcategories and one exemplary indicator, each had been selected in the SHDB. The CRM was evaluated for six producing and supplying countries (Tab. 13). The assessed risk has been classified from low (light grey, almost white) to very high (dark grey, almost black) and subjectively rated from low (1) to high (4). The categories *no data* and *no evidence* are shown without color and numerical values.

In order to finally obtain a general country impression per category, we calculated an average value across the given data: as an example, the category Health and Safety showed two indicators for the US which were given as risk factors. Summed to a total of six and in the following divided by the total number of indicators, this led to a mean of three – high risk (Eq. 9; Tab. 12). The detailed analyses are shown in the Appendix: Table A.1-A.10.

$$\frac{2\ (US\ DALYs) + 4\ (US\ Fatal\ Injuries\ by\ sector)}{2\ (Number\ of\ Indicators)} = 3\ \text{(Mean)} \quad (9)$$

CRM	Sector	Country	Health & Safety		
			Occupational Toxics & Hazards	Injuries and Fatalities	Mean
			Overall Occupational Cancer Risk - loss of life (DALYs)	Fatal injuries by sector	
Magnesium	Electro. Equip.	China	4		4
Bauxite	Electro. Equip.	Guinea			
Bauxite	Electro. Equip.	Brazil	2		2
Beryllium	Electro. Equip.	US	2	4	3
Coking Coal	Ferrous Metals	Australia	1	2	2
Fluor Spar	Ferrous Metals	Mexico	2	3	3

Table 12 Health & Safety Social Risk

Considering the summary from the individual analyses, it became evident that no country, no sector and no category could be rated low risk with regard to social hotspots. All risks considered were rated medium to high. China and Guinea in particular posed high risks for the social factors at the country level, with Governance and Health & Safety being considered critical in both countries. These two categories were generally considered to be of high risk (Tab. 13).

CRM	Sector	Country	Labor Rights & Decent Work	Health & Safety	Human Rights	Governance	Community	Overall Mean
Magnesium	Electro. Equip.	China	3	4	2	3	2	3
Bauxite	Electro. Equip.	Guinea	3	-	3	4	3	3
Bauxite	Electro. Equip.	Brazil	2	2	2	3	2	2
Beryllium	Electro. Equip.	US	2	3	2	2	2	2
Coking Coal	Ferrous Metals	Australia	2	2	1	2	2	2
Fluor Spar	Ferrous Metals	Mexico	3	3	1	4	2	2
		Overall Mean	2	3	2	3	2	

Table 13 Overall Social Risk

4. Discussion, Limitation and Future Outlook

The objective of this study was to conduct an outright LCSA of a dish-Stirling Concentrating Solar Power Plant located in Palermo:

LCA

The data reflected a challenge in the present study: For this project, there was little or no primary data on raw materials or production steps. Assumptions had to be made for modeling the LCA. However, these assumptions were cross-checked with indicators such as the EPBT or further g CO_2e/kWh results from other studies. The results of the present study are comparable (Tab. 14 & 3.1.1.), which indicates reliable data and assumptions.

	Corona & San Miguel, 2019	**Ko et al., 2018**	**Actual Study**
Product	novel type of hybrid CSP plant	CSP tower plants	CSP plant
FU	1 MWh of electricity poured into grid	1 kWh net electricity fed to the grid	1 CSP plant
System boundaries (LCA)	cradle-to-gate	cradle-to-grave	cradle-to-gate
Data assessed by	two engineering companies	primary data & GaBi database	few primary data, literature & GaBi
Assumed energy production/year	800 GWh/year	585 GWh/year	46 MWh/year
Assessed lifetime	n.a.	30 years	25 years
LCA indicators	**2** indicators: Climate change Water stress	**6** indicators: GWP ADP EP PED BWC land occupation	**7** indicators: GWP ADPf ADPe EP AP POCP ODP
LCA software and database	SimaPro 8.0.3 & ReCiPe	GaBi & CML2001	GaBi & CML2001
LCC tools	n.a.	n.a.	Excel
S-LCA tools	SHDB	SHDB	SHDB & EU critical raw materials
EPBT	CSP Bio: 6.1 months CSP GN: 22 months	-	3.14 years
Recycling considered	Yes	yes	no
LCA GWP Results	**cradle-to-gate** CSP Bio: 45.9 kg CO_2e/MWh CSP GN: 294 kg CO_2e /MWh **cradle-to-use** -	**cradle-to-gate** 36.3 g CO_2e /kWh **cradle-to-use** 51.5 g CO_2e /kWh	**cradle-to-gate** 30.15 g CO_2e /kWh **cradle-to-use** 30.24 g CO_2e /kWh
LCC Results	**cradle-to-gate** CSP Bio: 211 €/MWh CSP GN: 154 €/MWh	**cradle-to-use** 66.5 €/MWh	**cradle-to-gate** 268 €/MWh
S-LCA Results	**cradle-to-gate** Employment creation CSP Bio: 454,090 person-year CSP GN: 158,106 person-year	**cradle-to-use** Total working time 19,398,646s	**cradle-to-use** Total working time Skilled Worker 1,454,400 s Unskilled Worker 1,713,600 s
Visualization used	-	-	-

Table 14 Comparison with existing LCSA studies

The actual study reported seven midpoint indicators, which was more detailed than in comparative studies. Further, all seven indicators were given for two system-boundary-versions. The assessed GWP was determined lower than the ones calculated in comparative studies (Tab. 14). All assumptions have been explained in detail including the processes used.

LCC

For LCC, the conventional cost approach was chosen, which is utterly similar to business administration approaches. Costs are not considered for a period of one year, but over the entire lifetime: in this case 25 years. Detailed life cycle-assumptions were not given in comparative studies. The costs per MWh could anyhow be compared, whereof the actual costs per MWh were comparatively high. Externalities were not included in this model, which could be seen as a limitation. Regarding LCC and S-LCA, the system boundaries were defined as equivalent to the ones used for LCA – which was not given by both comparative studies (Tab. 14). A comparison of results was attempted; it should be noted that assumptions about system boundaries and calculated data had to be made for comparison. This makes reliable and completely valid analogy difficult (Tab. 14).

S-LCA

It was not possible to perform a full S-LCA due to a lack of information. However, an analysis of wages and working hours and the risk analysis provided an alternative solution. Both, the working hours per day and the wages in Italy for the installation of the dish-Stirling showed positive values, compared to other European countries. Moreover, the values were compared to the values given by one of the comparative studies (Tab. 14). The results of the risk analysis gave a detailed idea of the social risk of producing and supplying countries. None of the indicators could be assigned with low risks; reliable data still remains an obstacle. For the social pillar, it should be pointed out that data and even contacts were limiting factors, which influenced the implementation of a detailed survey and the complete tracking of the full supply chain. Without a sufficient timeframe and contact with all relevant stakeholders, a comprehensive S-LCA is rather imprecise.

LCSA

Even though the most relevant limitation was the data, a complete LCSA has been conducted. According to the approach by Finkbeiner and Kloepffer [13,14], no weighting of the individual pillars is allowed, nor can any of the pillars affect the performance of another pillar with its performance. The LCSA-results are independent of each other and can only be reported individually. At this point, further challenges of LCSA emerged, namely interpretation and communication. There are various visualization tools or approximation approaches to make the LCSA more understandable to non-experts – such as the Life Cycle Sustainability Triangle (LCST) [13], the Life Cycle Sustainability Dashboard (LCSD) [62], the Sustainability Crowns [34] or the Tiered Approach [17]. None of these approaches was used (Tab. 14), as it was difficult to relate the results of the individual pillars. Finally, it was not possible to conclude how the columns relate to each other and to what extent the social component could have an impact on the environmental or economic part and whether an improvement of any kind could be achieved at certain levels, such as wages or lower production costs. The mentioned limitations of the general LCSA led to the conclusion that a general and optimized interpretation and communication approach must be found in a timely manner. In this way, the results of these analyses no longer stand for themselves but lead to general understanding and contribute to the optimization of all sustainability dimensions of products and services.

5. Conclusion

Among different renewable energy sources, solar energy represents an abundant source of energy with the highest future potential to satisfy a substantial portion of the worlds' energy demand. In the field of solar electricity generation, the Concentrating Solar Power plants are called a highly competitive technology [4,6]. Yet, the dish-Stirling is responsible for environmental impacts caused during its production and installation. The LCSA system boundary was defined as cradle-to-use, the functional unit was the CSP plant itself. The LCA is based on data available in GaBi (SP40) and Ecoinvent 3.5 resulting in seven midpoint indicators using the CML2001 methodology. In terms of greenhouse gas emissions, 35 t CO_2e were calculated. Other emission indicators than CO_2e and a detailed split up concerning driving process steps were given in the actual study. The three main drivers for all indicators were the electronic components, the elevation tracker and the PCU equipment – mainly driven by steel as material. The conventional LCC resulted in 308,467.00 € as total costs, which lead to 268.00 € per

MWh (0.268 €/kWh) of generated energy (Tab. 14). The European average energy prices verified the result calculated and represented their plausibility. For S-LCA, workdays, wages, and a risk analysis via the SHDB were assessed. The wage of 12.5 €/h for unskilled workers was slightly above the highest European minimum wage. Based on LCA, relevant and critical input raw materials were defined, following the EU report [61]. No country, no sector and no category could be with low risk for this technology. The LCSA-pillar-results stand on their own, interpretation and communication remain challenging. Limitations further were data availability, uniform system boundaries and comparability of results. A holistic statement about the sustainability performance of the dish-Stirling engine could not be defined, resulting in the future need for a general and optimized interpretation and communication approach for LCSA.

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