

## Solar Mining Technology Options – Techno-economic-ecological datasheet

### Concentrated Solar Power

#### Solar power tower with storage

Authors: Thomas Telsnig, Gustavo Díaz Ferrán

Released on June, 2016



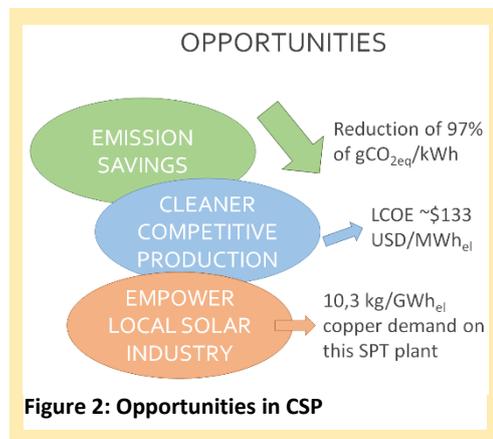
Figure 1: Solar power tower plant [1]

#### I. Description of technology

Solar tower is a type of concentrated solar power (CSP) plant, where an arrangement of reflective mirrors, flat or slightly concave, reflect solar light to a specific region up in a tower and warm up a heat transfer fluid (HTF) which permits to run a Rankine or a Brayton cycle (Not to confuse with Solar updraft tower system [9]). The HTF can be either directly water or indirectly, through heat exchangers, molten salts when running a Rankine cycle [2] and pressurised gas when running a Brayton cycle [3] [4]. Every mirror called heliostat, can move independently with two degrees of freedom, to maintain the position of the reflective focus onto the receiver. Solar power tower (SPT) plant sizes range between 0,5 and 133 MW<sub>el</sub>, principally because the bigger the collector field is, the greater the optical losses are due to atmospheric absorption and angular mirror deviation [5-7]. In comparison with other CSP technologies, solar towers can achieve the greatest solar concentration ratios (150-1500) while cooling water consumption is half the linear Fresnel (LF) or parabolic trough (PT), carrying these to high operating temperatures (300-565 °C) and therefore high thermodynamic efficiency. Nowadays SPT is more expensive than LF and PT but the great possibilities of improvements may project the SPT technology as the cheapest CSP technology by the year 2020 [5]. The worldwide SPT operating capacity is currently around 658 MW<sub>el</sub>, 81% is installed in U.S.A., and 642 MW<sub>el</sub> are under construction [7], whereof 110 MW<sub>el</sub> are located in Chile, under the Abengoa's project Cerro Dominador, which consider a solar tower plus 17.5 hours of thermal energy storage beside a 100 MW<sub>el</sub> photovoltaic power plant [8].

#### ➔ Proposal of a SolarMining-CSP-technology option for the mining industry in Chile

In the arid resource rich regions of Chile an important synergy potential between solar energy and mining exists. Given the intensive energy use of the mining sector, this potential is highly relevant for achieving the country's goal in terms of energy costs, emissions and competitive and sustainable mineral extraction. This paper shows the potential emission savings when electricity from a concentrated solar tower system powered by typical Calama solar conditions supplies mining operations. The concentrated system modelled, based on [16], has 20 MW<sub>el</sub> of rated capacity plus 500 MWh<sub>th</sub> of storage capacity and a diesel co-firing system which ensures operation in times of lower irradiation. Assuming a plant lifetime of 30 years and an interest rate of 10% lead to a saving around to 97% of gCO<sub>2eq</sub>/kWh, while a 133 USD/MWh<sub>el</sub> of levelised cost of electricity. Such a concentrated solar power tower plant demands 10.3 kg/GWh<sub>el</sub> of copper, distributed into its different components.

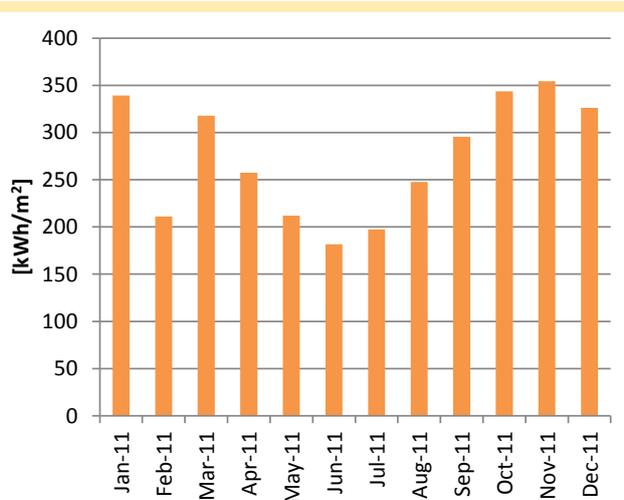


## II. The technical performance

In this section, the assumptions and datasets used to calculate the energy yield of a solar tower power plant with storage at a characteristic plant location in Chile are described.

**Location.** The investigated power plant site is located in vicinity to the Chuquicamata copper mine, north of the city of Calama in the Antofagasta region. The open pit mine operated by state-owned enterprise Codelco is one of the largest open-pit copper mines in the world [10]. The arid climate of the Atacama Desert which is characterised by a high solar irradiance makes this location interesting for solar technologies. This opens an option to integrate this technology into the existing electricity consuming mining processes.

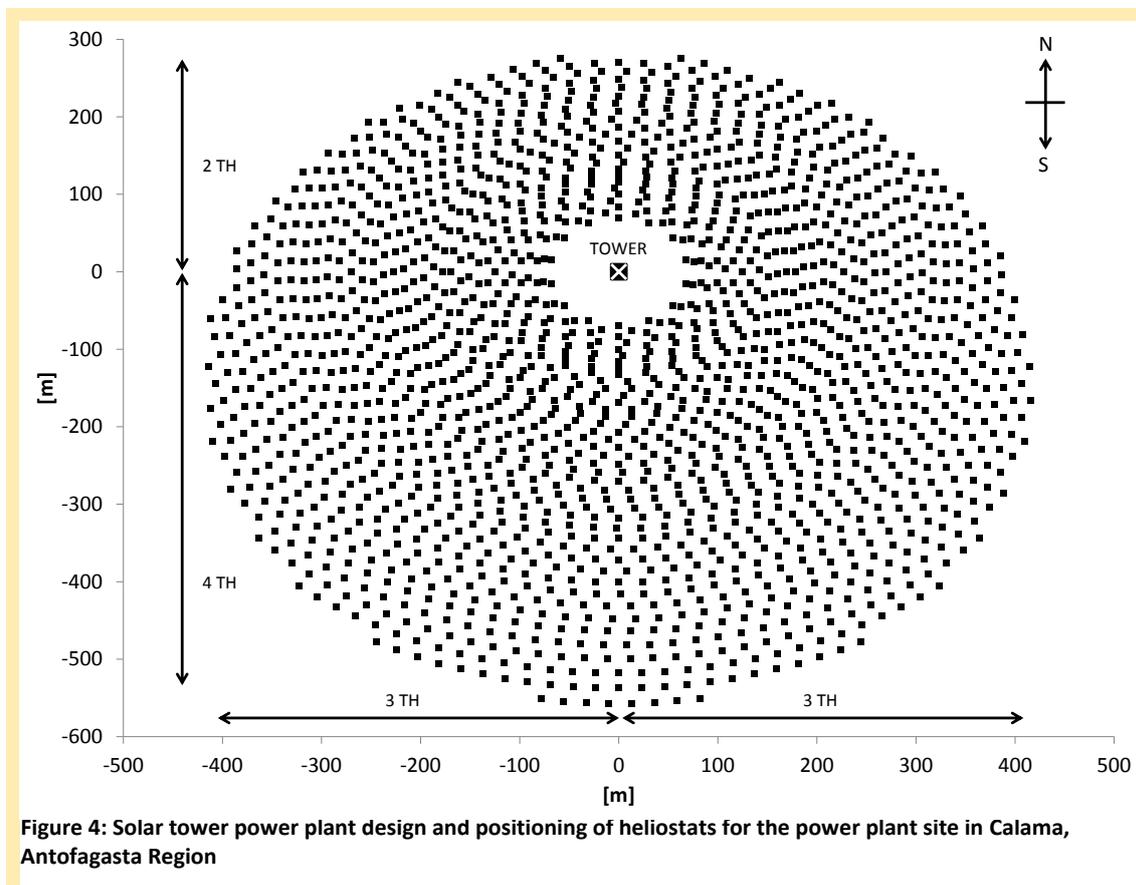
**Weather data.** To estimate the electricity yield of a solar tower power plant with storage detailed information of the direct normal irradiance (DNI) in at least hourly time resolution at the power plant location need to be used. Moreover, the year-to-year variability of the solar resource should be considered by using a typical meteorological year (TMY) or to calculate exceedance probabilities (e.g.: P50, P90) of a long-term dataset. Thus the financial risk of a solar energy project is minimised [11] [12].



**Figure 3: Monthly direct normal irradiation (DNI) for Calama/Antofagasta Region in 2011**

Due to the lack of long-term measurement data of solar radiation, weather data of the recently started and publicly available wind and solar measurement project “Campaña de medición del recurso Eólico y Solar” of the Department of Energy of Chile was used, which offers wind and solar ground measurement data at a 10-minute time resolution [13] [14]. The dataset of the measuring station at Chuquicamata goes from May 2010 to December 2012. As the measurement year 2012 shows significant gaps (measurements from March to October are missing) the only full consecutive year of weather measurements in 2011 was taken as a characteristic year for the calculations. Figure 3 shows this monthly direct normal irradiance (DNI) along the reference year of 2011. According to this dataset, the annual direct normal irradiance was calculated to be at 3280 kWh/(m<sup>2</sup>\*a), which corresponds to reported values of NREL (2015) [15].

**Plant configuration.** The calculation of the energy yield was performed by using the CSP performance model of Telsnig (2015) which simulates the system performance of the solar power plant based on an hourly control logic [16]. The solar tower power plant simulated has a rated capacity of 20 MW<sub>el</sub> and includes a thermal storage with a total storage capacity of 500 MWh<sub>th</sub> resulting in an overall capacity factor of 75% (approximately 6500 full load hours per year). A diesel-fuelled co-firing system ensures system operation in times of lower irradiation during the day to avoid part-load states. The total share of co-firing during the year is limited to 2%. The solar field has a total aperture area of 215520 m<sup>2</sup> and is composed of 1796 heliostats which are positioned around the receiver tower in a surrounding field. The positioning of the heliostats in the field determines the usable heat at the receiver. The optimal spot of each heliostat was calculated by applying the method outlined in Stine and Geyer (2001) and Lipps and Vant-Hull (1978) [17] [18]. Figure 4 shows the calculated position of each heliostat in the field and the total dimensions of the investigated solar tower power plant.



### III. The ecological performance

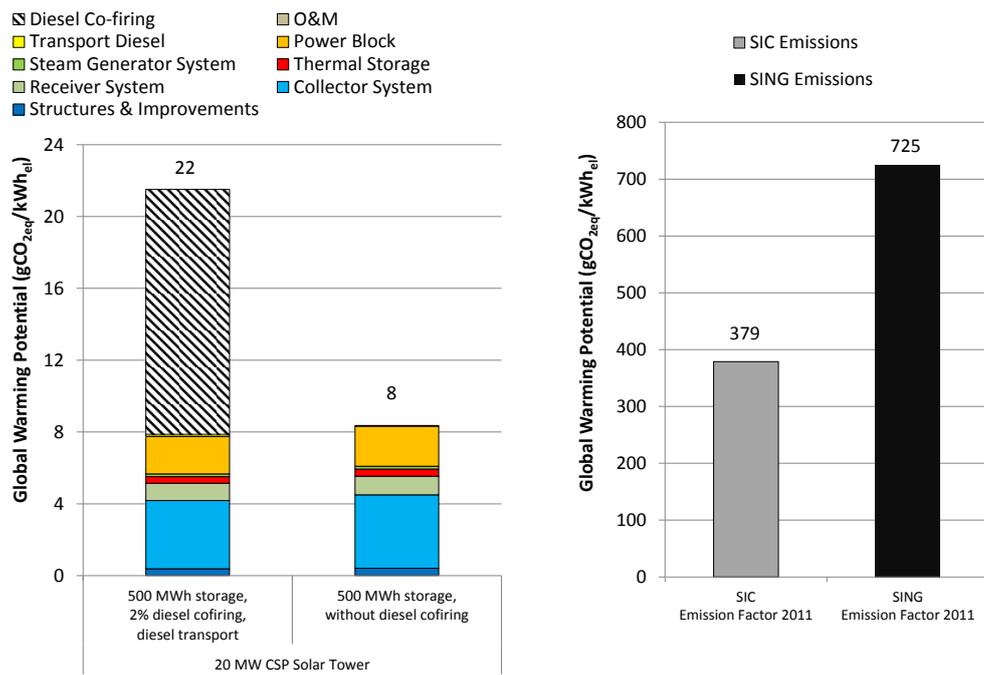
**Methodological approach.** To quantify the environmental impacts of the proposed 'SolarMining' technology options a Life Cycle Assessment (LCA) is performed. The LCA is carried out in close accordance with the general principles and the framework of the international standards ISO 14040 and ISO 14044 [19] [20]. This framework comprises four phases:

- the goal and scope definition
- the inventory analysis
- the impact assessment
- and the interpretation of results

**Goal and scope definition.** The scope of this analysis is to quantify the environmental impacts of a solar tower power plant with thermal storage used to provide electricity for copper mining. Moreover, it is investigated to which extent the production cycle of the mining operation can be closed by evaluating the resource requirements for copper in the solar tower plant. The reference value or ‘functional unit’ to which all inputs and outputs are related is defined at 1 kWh<sub>el</sub>. The system boundaries of the LCA include all major system components of the power plant. The investigated life cycle stages range from the construction of the power plant components to the decommissioning and disposal of the materials at the end of the lifetime. The geographic reference is Calama/Antofagasta Region in Chile and the time reference is 2015. The lifetime of the power plant is defined at 30 years. The data quality requirements were met by using actual solar measurement data in a high temporal resolution. This was based on the estimation of the energy yield of the plant and through the use of a detailed life cycle inventory lists of the different system components of previous LCA studies [16].

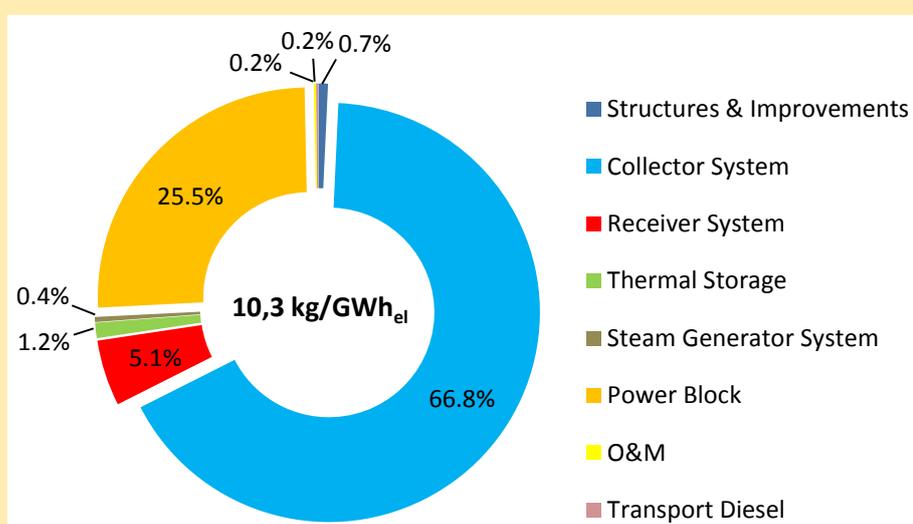
**Inventory analysis.** The life cycle inventory (LCI) analysis involves the data collection and estimation of all inputs and outputs of the investigated product system. We used the life cycle inventory data and parameterised LCA model reported in Telsnig (2015) and adjusted it to Chilean conditions, taking into account changes of the sizing of the different power plant components and transport distances. Transport distances for the construction phase of the power plant were assumed as 220 km which represents the road distance between the harbour of Antofagasta and Calama. Transport distances of the materials to a disposal or recycling facility were assumed to be 100 km. Data of the LCA database ECOINVENT V2.2 was used to consider emissions of pre-processes and raw material extraction [16][21]. The emissions resulting from co-firing of diesel in the co-firing system of the power plant were calculated by the assumption that 2% of the plant’s electricity production is delivered by co-firing, which is reported as the minimum co-firing rate in current CSP plants [22]. The emission factor for diesel was obtained from IPCC (2006) and accounts for 72.6 gCO<sub>2eq</sub>/MJ<sub>diesel</sub> [23]. Auxiliary electricity is generated within the CSP plant.

**Life Cycle Impact Assessment (LCIA).** The material and energy demand which is outlined in the LCI are used to calculate the environmental impacts during the LCIA. The LCIA involves the connection of the inventory data with appropriate impact categories and category indicators. In this assessment, we want to quantify the impact category “climate change” which is calculated by its indicator “Global Warming Potential (GWP)”. As a second impact category the “depletion of mineral resources” is assessed by quantifying the amount of copper used for the different sections and services of the power plant. In this way, an estimate is given to what extent copper production cycles can be closed by implementing solar technologies in the copper mining processes. Results show that the GWP during the life cycle of the investigated solar tower power plant with storage ranges between 8 gCO<sub>2eq</sub>/kWh<sub>el</sub> and 22 gCO<sub>2eq</sub>/kWh<sub>el</sub> (upper limit at a 2% diesel co-firing rate). This means a significant reduction potential of GHG emissions in comparison to the emissions caused from electricity provided by the Southern Electricity Grid (SIC) or Northern Electricity Grid (SING) which are reported with 379 gCO<sub>2eq</sub>/kWh<sub>el</sub> and 725 gCO<sub>2eq</sub>/kWh<sub>el</sub>, respectively [24] (see Figure 5).



**Figure 5: Global Warming Potential of a solar tower power plant with storage (left-hand side) and GWP emission factors from the SIC and SING electricity mix (right-hand side).**

The assessment of the copper demand for the different sections and services of the CSP plant identifies the collector system (67%), the power block (26%) and the receiver system (5%) as main copper containing components. Especially the wiring, transformers, generators, compressors electrical components require larger shares of copper. The copper demand of all other components and services in the pre-processes of the life cycle or of the raw material extraction is negligible. Based on this assessment a specific copper demand for solar energy generation with a solar tower power plant of 10 kg/GWh<sub>el</sub> was calculated.



**Figure 6: Copper demand of different components of a CSP solar tower power plant**

#### IV. The economic performance

The economic assessment is performed by calculating the levelised costs of electricity (LCOE) of the solar tower power plant according to the methodology described in IEA/NEA (2010) [25]. A stable interest rate of 10% and a plant lifetime of 30 years was assumed. All costs are given in US Dollar (US\$<sub>2010</sub>), 1 US\$ corresponding to 508 CLP. Based on the configuration a total land area requirement of 55 ha was assumed.

The investment costs were estimated from Telsnig (2015) and include the specific investment costs for the main power plant components, subdivided into investment costs of the solar field, the power block, the molten salt storage and the receiver system. Moreover EPC costs (engineering, contracting and procurement) and owner's costs are considered in this calculation.

Operating costs include fixed operating costs (FOM) considering the overall manpower and insurance costs during operation and variable operating costs resulting from the co-firing of diesel in the co-firing system of the power plant.

Technology	CSP Solar Tower with Storage	
<b>Technical data</b>		
Aperture Area Solar Field	[m <sup>2</sup> ]	215520
Number of heliostats	[#]	1796
Solar field concept		Surrounding solar field
Tower Height	[m]	140
Land Area (Estimate)	[ha]	55
Capacity	[MW <sub>el</sub> ]	20
Storage capacity	[MWh <sub>th</sub> ]	500
Storage concept		2-tank direct molten salt
Full load hours	[h/a]	6500
Co-firing fuel		Diesel
Diesel demand	[TJ/a]	22
<b>Economic data</b>		
Specific investment costs	[US\$ <sub>2010</sub> /kW <sub>el</sub> ]	6594
FOM	[US\$ <sub>2010</sub> /kW <sub>el</sub> /a]	95
VOM	[US\$ <sub>2010</sub> /kW <sub>el</sub> /a]	31
Interest rate	[%]	10%
Life time	[a]	30
<b>LCOE</b>	<b>[US\$<sub>2010</sub>/MWh<sub>el</sub>]</b>	<b>133</b>

## V. References

- [1] SNL 1996: Solar Two Tower System. Sandia National Laboratories, Barstow, California, [https://www.eeremultimedia.energy.gov/solar//photographs/solar\\_two\\_tower\\_system](https://www.eeremultimedia.energy.gov/solar//photographs/solar_two_tower_system) (accessed 03.06.2016)
- [2] NREL/Solarpaces 2016: Concentrating Solar Power Projects, Tower technology, NREL website [http://www.nrel.gov/csp/solarpaces/power\\_tower.cfm](http://www.nrel.gov/csp/solarpaces/power_tower.cfm) (accessed 25.05. 2016), 2016
- [3] R. Buck 2008: Solare Turmtechnologie – Stand und Potenzial
- [4] PROMES, Pégase project. PROMES website <http://www.promes.cnrs.fr/index.php?page=pegase-informations> (accessed 30.05.2016), 2016
- [5] H.L. Zhang et al. 2013: CSP plants: Review and design methodology
- [6] Middle East and North Africa region, Assessment of local manufacturing potential for CSP projects, January 2011
- [7] CSP Today 2016: CSP Today Global Tracker, CSP Today website <http://social.csptoday.com/tracker/projects/table?world-region%5B%5D=149&country%5B%5D=Chile&technology%5B%5D=ParabolicTrough> (accessed 25.05. 2016), 2016
- [8] Environmental assessment Chilean service, website [http://seia.sea.gob.cl/expediente/ficha/fichaPrincipal.php?modo=ficha&id\\_expediente=2128879352](http://seia.sea.gob.cl/expediente/ficha/fichaPrincipal.php?modo=ficha&id_expediente=2128879352) (accessed 30.05.2016), 2016
- [9] J. Schlaich, R. Bergemann, W. Schiel, G. Weinrebe 2005: Design of commercial solar updraft tower systems – Utilization of solar induced convective flows for power generation
- [10] CODELCO 2015: Operations – Chuquicamata, Codelco website, [https://www.codelco.com/chuquicamata/prontus\\_codelco/2011-06-21/183718.html](https://www.codelco.com/chuquicamata/prontus_codelco/2011-06-21/183718.html), (accessed 01.12. 2015), 2015.
- [11] NREL 2012: Dobos, A.; Gilman, P.; Kasberg, M.: P50/P90 Analysis for Solar Energy Systems Using the System Advisor Model. Conference paper presented at the 2012 World Renewable Energy Forum Denver, Colorado May 13-17, 2012, NREL/CP-6A20-54488, June 2012.
- [12] Röttlinger, N.; Remann, F.; Meyer, R.; Telsnig, T.: Calculation of CSP Yields with Probabilistic Meteorological Data Sets: A Case Study in Brazil, Energy Procedia, Volume 69, May 2015, Pages 2009-2018, ISSN 1876-6102, <http://dx.doi.org/10.1016/j.egypro.2015.03.210>.
- [13] MoE 2015: Campaña de medición del recurso Eólico y Solar, Ministerio de Energía Gobierno de Chile website <http://walker.dgf.uchile.cl/Mediciones/> (accessed 01.12. 2015), 2015.
- [14] CENMA 2015: INFORME DE INSTALACIÓN, CENTRO NACIONAL DEL MEDIO AMBIENTE, Ministerio de Energía Gobierno de Chile website <http://walker.dgf.uchile.cl/Mediciones/> (accessed 01.12. 2015), 2015. <http://walker.dgf.uchile.cl/Mediciones/>
- [15] NREL 2007: Heimiller, D.: South America Direct Normal Solar Radiation. Annual Direct Normal Irradiation map. <http://en.openei.org/w/index.php?title=File:NREL-sam-dir.jpg> (accessed 03.12.2015)
- [16] Telsnig, T. 2015: Standortabhängige Analyse und Bewertung solarthermischer Kraftwerke am Beispiel Südafrikas. Dissertation, Institut für Energiewirtschaft und Rationelle Energieanwendung, ISSN 0938-1228, Universität Stuttgart, 2015.
- [17] Stine, W.B.; Geyer, M. 2001: Power from the sun. Online Book. 2001, <http://www.powerfromthesun.net/>, 20.02.2013.
- [18] Lipps, F. W., Vant-Hull L. L. 1978, "A Cellwise Method for the Optimization of Large Central Receiver Systems," Solar Energy 30(6), 505.
- [19] ISO 2006a DIN EN ISO 14040: Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006), Europäische Norm ISO 14040, DIN Deutsches Institut für Normung e.V. Berlin, 2006.
- [20] ISO 2006b DIN EN ISO 14044: Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044:2006), Europäische Norm ISO 14044, DIN Deutsches Institut für Normung e.V. Berlin, 2006.
- [21] EcoInvent 2010 Swiss Center for Life Cycle Inventories. EcoInvent v2.2, Duebendorf, Switzerland, 2010.
- [22] Geyer, M.: Concentrated Solar Power Plants for South Africa. Conference Presentation, Third Southern African Solar Energy Conference, Port Elizabeth, January 2014.
- [23] IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Published: IGES, Japan.
- [24] MoE 2012, Las Energías Renovables No Convencionales en el mercado eléctrico chileno, Ministerio de Energía, División Energías Renovables, GIZ, Centro de Energía, Universidad de Chile, Centro de Energías Renovables (CER), Comité CORFO, ISBN: 978-956-8066-13-0, Santiago der Chile, mayo 2012.
- [25] IEA/NEA 2010 Projected Costs of Generating Electricity – 2010 Edition. International Energy Agency / Nuclear Energy Agency, 2010.

**Corresponding Author:** Dr. Thomas Telsnig, University of Stuttgart, Institute for Energy Economics and the Rational Use of Energy (IER), Dept. “System analysis and Renewable Energies (SEE)”, [tt@ier.uni-stuttgart.de](mailto:tt@ier.uni-stuttgart.de)

The “Solar Mining Chile” project is funded by the German Ministry of Education and Research (BMBF) and Comisión Nacional de Investigación Científica y Tecnológica (CONICYT).

For more information see: <http://www.ier.uni-stuttgart.de/forschung/laufendeprojekte/index.html>

<http://serc.cl/solar-mining/>

#### **Project Consortium**

Chile: Universidad de Chile, Department of Electrical Engineering, Energy Center (CE), Solar Energy Research Center (SERC), Project manager: Dr. Rodrigo Palma, [rodpalma@cec.uchile.cl](mailto:rodpalma@cec.uchile.cl)

Germany: University of Stuttgart, Institute for Energy Economics and the Rational Use of Energy (IER), Dept. “System analysis and Renewable Energies (SEE)”, Project manager: Dr. Ludger Eltrop, [le@ier.uni-stuttgart.de](mailto:le@ier.uni-stuttgart.de)