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PROGRESS IN SOLAR ENERGY R&D IN NORTH OF CHILE: SOLAR PLATFORM OF ATACAMA DESERT PROJECT AND ONGOING ACTIVITIES

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Abstract

Chile is now considered one of the highest potential markets for solar energy, due to the very high solar resource existing particularly in the North and the political boosting by means of becoming legislation. In the Atacama Desert highest irradiation levels in the world are achieved, over 8 kWh m^2 per day. In order to take advantage of it, the Chilean government is intended that 20% of the country's energy from renewable sources in 2025. Under this context, PV and solar thermal commercial plants, including CSP, are already operating and others under construction. In order to actively contribute to the solar resource exploitation in North of Chile, new R&D activities are being developed in the last few years by the local universities and research centers. They include the foundations of the Solar Platform of Atacama Desert (PSDA), in the Antofagasta Region, which aims to host R&D pilot-scale solar facilities for demonstrative tests under the natural environment of Atacama Desert. An overview of the related ongoing activities is presented in this work.

Keywords:*North of Chile, Solar Energy Research, Solar Platform, Atacama Desert*

1. Introduction

The Atacama Desert exhibits the highest solar radiation levels in the world with a low frequency of cloudiness in areas apart from the coast. Data showed in Fig. 1 are available in Solargis (Geomodel, 2015) and illustrate the direct normal irradiation (DNI) in the world and global horizontal irradiation (GHI) in Chile. As observed, average annual DNI of 3800 kWh/m^2 is achieved only in the Atacama Desert.

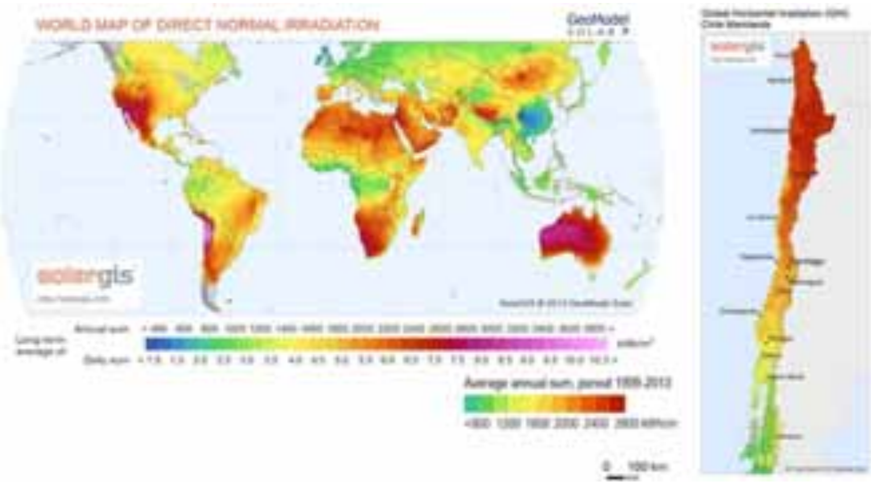

Fig. 1: World DNI and Chile GHI maps taken from Solargis.

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Despite this potential, Chile still imports the 70% of its primary energy and electricity prices have increased significantly in the last decade. Energy sources are mainly fossil fuels (coal, GNL and diesel). Moreover, Chilean industry, mostly mining, has high demands of electricity (90 % of the Northern electric system, SING) and heat (Ministerio de Energía, 2016). Although the current solar contribution to SING is yet only 1.91%, the construction of new commercial PV, solar thermal and CSP plants is ongoing since last few years. In order to contribute to this development, new local R&D activities are also being started. One of them is the PSDA, which is projected as an in-situ pilot plant to demonstrate and test solar energy technologies under the natural environment of the Atacama Desert.

2. Solar Platform of Atacama Desert Project

2.1. Objectives

Solar Platform of Atacama Desert was conceived as a technological project with the following objetives:

- To promote and carry out R&D according to the guidelines emanating from different government agencies.
- To promote collaboration with universities and national and international R&D centers in various technological areas related to solar energy.
- To provide specific knowledge opportunities that can meet the future needs of advanced human capital and technical product specialists.
- To promote collaboration with regional and national companies that allow for adequate transfer and commercialization of the developed technologies.
- To promote the productive chain and the creation of spin-offs.
- To provide technical services, including advice and consultancy services to both public and private institutions.
- To foster scientific and technological diffusion, promoting general public to aware of the advantages and benefits of the solar energy technologies.
- To become a reference center in solar energy technologies, not only in Chile but also in the whole Latin American context.

2.2. Funding and political coordination

Funds invested so far in the PSDA are contributions of the Regional Government and the University of Antofagasta which reached US $ 1.35 Million. Currently, the PSDA is considered as the Chilean Laboratory for Solar Energy Research, defined by the Corporation for promotion of production (CORFO), through the National Center for Innovation and the Sustainable Energy Development (CIFES) who is applying resources to the National Strategic Investment Fund (FIE) to cover the operating costs of the Strategic Solar Programme. It considers promoting the development of the solar industry in Chile between 2015 and 2025. For the PSDA are an approximate amount of US $ 50 Million are being evaluated for facilities, laboratories and physical adjustments. These investments are being proposed through Solar Energy Research Center (SERC Chile) and international centres based in Chile.

2.3. Current status

Currently , the land of PSDA is available and the first studies have been already carried out or are financed for the next future. Such studies are the following.

- Study on the "Structural Design and Operational Research and Development of Solar Energy in Northern Chile." STA-CDEA-UA. 2010

- Framework agreement between Centre for Energy, Environment and Technological Investigations (CIEMAT) of Spain and the University of Antofagasta. 2010
- Award of "Fourth National Competition for Centers of Excellence in Research on Priority Areas FONDAP 2013-2018." Chilean project Solar Energy Research Center (SERC-Chile).
- Award of performance agreement for higher education "Strengthening the University of Antofagasta as Regional and National Reference in Non-Conventional Renewable Energy (ERNC)." 2013-2015.
- FIC-R 2013 (Innovation Fund for Competitiveness) "Implementation, development and diffusion of the Plataforma Solar Atacama Desert inserted into the system of regional technology parks first stage". 2013 - 2014.
- FIC-R 2014 (Innovation Fund for Competitiveness) "Implementation of advanced instrumentation system as technological support of the PSDA project, first stage". 2014 – 2015
- FIC-R 2015 (Innovation Fund for Competitiveness) "Positioning of in-situ solar technology laboratory (PSDA) for the purpose of applied research, extension and training of technicians from the Region of Antofagasta. 2015 – 2017.
- Tender for design and feasibility analysis of a solar platform technology development in northern Chile funded by CORFO. It consist in an update and the business model definition of a study made in 2010

2.3. Future projection

PSDA is projected as an applied research platform in-situ , destined to test new technologies and materials considering the conditions of high radiation. In addition, it will be used to support the productive chain of the solar energy local industry, technical certificates for PV and CSP facilities and certification of products to high radiation. Complementary technologies to supply heat and miners processes of the Atacama Desert will be analyzed.

3. Current R&D Activities

3.1. Radiometry and Calibration Laboratory applied to solar technologies (RCL) and Solar resource

Due to the high levels of solar radiation and the low frequency of cloudiness in areas out from the coast, below the 10% on most sites at north (see fig. 2), the Atacama Desert rises like a promising area for solar power plants implementation.

Accurate solar radiation measurements are necessary for the implementation of solar power plants anywhere. Especially, they are essential for centers which aim research on solar technologies. Precise solar radiation measurements are crucial to determine, e.g. the efficiency of the tested prototypes or the degradation of materials used in solar technologies. Such applications involve a series of records of terrestrial surface radiation components and other meteorological components.

The PSDA is implementing a meteorological station focused on measuring solar radiation, but also for other generic weather variables, such as temperature, atmospheric pressure and relative humidity, wind speed and direction, etc. The meteo station counts on the most advanced radiometric instrumentation. Within its equipment for solar resource, it has several types of pyranometers based on photo-cells and thermopile with individually optimised temperature compensation for measuring the Global and Diffuse Horizontal and Tilted Radiation, First Class pyrheliometers for measuring Direct Normal Irradiance, UV Radiometers to

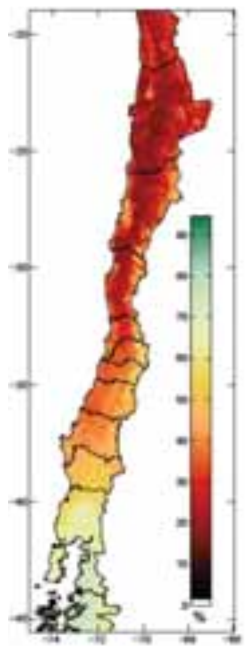


Fig. 2: Annual cloudiness in Chile (Molina Monje and Rondanelli Rojas, 2012)

measure the horizontal UV-A and UV-B horizontal irradiance, several two-axis solar trackers, shadow balls, etc.

Research on solar resource have shown the high radiation levels available in Atacama Desert. For example, in Fig. 3, monthly global horizontal irradiation, H_m [kWh m^{-2}], is compared with three available satellite-derived solar radiation datasets: the 22-year average data from the NASA-SSE (Surface Meteorology and Solar Energy programme) (Stackhouse, 2011), the Solar GIS (Geomodel, 2015) and the Explorador de Energía Solar (EE Solar) model (Ministerio de Energía, 2015; Ministerio de Energía et al., 2015). The total annual irradiation achieved a value of 2554 kWh m^{-2} $year^{-1}$ during the period of measurement. This is a high value that overcomes the values achieved in, e.g., Doha (Qatar) with 2048 kWh m^{-2} $year^{-1}$ (Bachour and Perez-Astudillo, 2014) or the 2190 kWh m^{-2} $year^{-1}$ achieved in Abu Dhabi, the highest one of the Arab state capitals according to Islam (Islam et al., 2010, 2009).

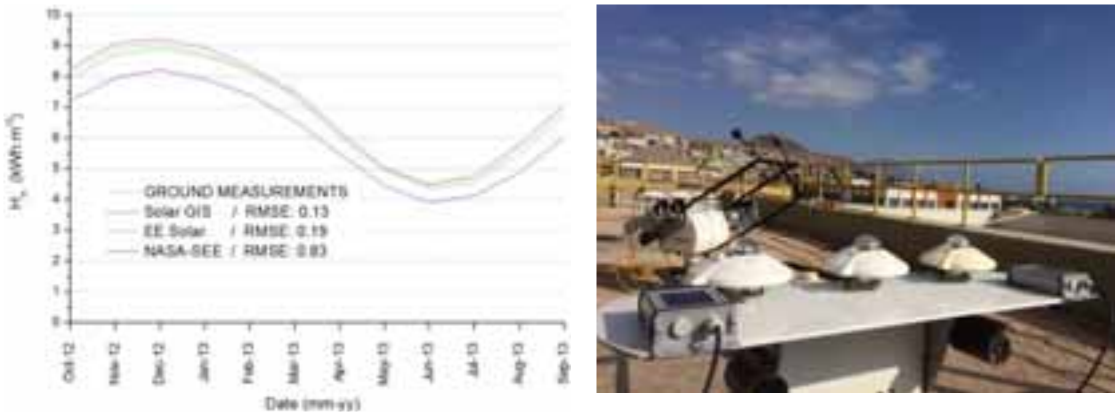


Fig. 3: Left, results of the comparison of monthly average of Global Horizontal Irradiation values derived from ground measurements against three typical years derived from satellite data: Solar GIS, EE Solar and NASA-SEE. This task was developed for a local mining company sited in Atacama Desert. Right , validation of pyranometers and pyrheliometers performance by comparison with reference instrumentetion at Universidad de Antofagasta.

The PSDA Radiometry Area tasks have been defined to provide support to the local industry in different research areas. These tasks may be summarised in four groups:

1. Instrumentation checking: testing, validation and calibration tasks to ensure the accuracy of the measurements;
2. Data evaluation: generating an accurate database and studies related to the physics of the atmosphere and the solar resource assessment;
3. Optics: optical characterisation of surfaces used in solar technologies;
4. Measurement methodologies and instrumentation development: provide tools by developing and/or adapting instrumentation with different applications to solve the measurement problems related with the new research studies to develop on solar energy area.

To achieve said goals, collaboration is ongoing with a number of national and international research centers, such as the Plataforma Solar de Almería (PSA, Spain), Universidad de Almería (UAL, Spain), and the universities belonging to the Solar Energy Research Center (SERC-Chile).

3.2. Solar PV

In collaboration with the PSDA Radiometry Area, there are also developing studies of how the Atacama environment affects the optical properties of mirrors and glasses used for solar technologies. These studies are focused on relating the surface optical degradation with the deposition rate of soiling and dust over the time. With the common aim of studying the effect of soiling on solar technologies efficiency, the performance ratio (PR) is the most used indicator, also at the PSDA, to investigate the degradation at PV plants (IEC, 1998). The goal is to relate and correlate optical degradation of PV glass with the PR and examine the causes for this degradation. Thus, tasks within PV area include:

- Precise inspection of PV plants with current-voltage (IV) curve tracers.
- Characterization of optical properties of PV glass.
- Determination of the physical-chemical properties of accumulated dust.
- Inspection o PV plants with IV tracers, IR cameras and, in the near future, with electroluminescence.
- Study of bifacial PV modules.
- Calculation of the Levelized Cost of Electricity (LCOE)

Currently, PV plants of different technologies are being installed and will be fully operational in 2015. The technologies include mc-Si, monocrystalline Si and HIT (heterostructure with intrinsic thin layer) modules. In total, 6 plants of the size of ≈1.2 kWp each of several features such as potential induced degradation (PID) free, monofacial and bifacial glass to glass will be used to compare in situ the performance and soiling effects. The comparison goes further as the same installations will be available at the coastal zone of the Atacama Desert, in the campus of the Antofagasta University. Examples of such studies at the coastal zone of the Atacama Desert are found in Ferrada et al. (2015). It was pointed out that the maximum PR at these conditions for mc-Si modules of 230 Wp was 85% and that the rate by which PR can degrade was up to 4.5%/month. Studies regarding the resulting levelized cost of electricity (LCOE) for PV plants athe coastal zone of Atacama Desert are addressed in Fuentealba et al. (2015). Since the characteristics of the environment and solar resource may be much different at the PSDA compared to the coastal zone of Atacama Desert, detailed studies under local conditions are required.

In addition, the existing collaboration between the Centro de Desarrollo Energético Antofagasta and SERC with the International Solar Energy Research Center Konstanz (ISC Konstanz) in Germany focuses on the development of AtaMo, the solar module for the Atacama Desert. The project consists on the selection of best materials for the PV module which perform best in the Atacama Desert. Sets of solar cells based on crystalline silicon are constantly fabricated in Konstanz, and then mini modules of 1 to 4 cells are produced. The mini modules are tested in situ at the PSDA by using a current-voltage (IV) curve tracer of same technology and same measurement principle as the indoor sun simulator existing at the laboratories of ISC Konstanz. The solar cells used are monofacial on p-type mono and multi crystalline silicon substrates and bifacial on n-type monocrystalline silicon wafers, both of the size 15.6 by 15.6 cm^2. Mini modules are fabricated with PV glass of several thicknesses (from 3.2 standard down to 2 mm, 1.5 mm and 1 mm), different encapsulants such as Ethylene vinyl acetate (EVA), thermoplastic materials (TM) and low UV light cut-off (U encapsulant). The backsheets (BS) consist of standard (white), transparent and desert type sheets (optimized in terms of hardness and thickness for desert regions), as well as glass (as BS) are employed.

An AAA class solar simulator is used to measure the IV characteristics indoor at standard testing conditions (STC) before and after the lamination step to determine the cell to module losses (CTM). For the last experiment a total of 37 groups were fabricated, from which 14 groups were based on mc-Si cells for damp heat (DH), humidity freeze (HF) and ultraviolet (UV) degradation test, and 23 groups based on bifacial n-type cell for thermos cycling (TC) test and outdoor measurements at the PSDA. Fig. 4 illustrates a measurement campaign at the PSDA.

Fig. 4. Left: Set of mini modules and testing configuration at the PSDA. Right: Albedometer to quantify solar resource for mini modules.

A first evaluation of results point out to the optimum combination of materials. It consists of the use of thinner glass-glass module (1.0 to 2.0 mm thickness) showing better resistivity against thermal stress compared to glass-transparent back sheet. The encapsulant shall be used as due to its high robustness against long-term humidity exposure and higher transmissivity expected in the UV-B range. Modules with halved cells resulted to perform better in the field due to lower electrical power losses at high irradiation conditions. For full details, refer to Cabrera et al. (2015). A very preliminary estimation based on a maximum PR value of 85% for conventional mc-Si modules, bifacial AtaMo modules could generate between 29% to 32% more energy compared to mc-Si modules utilizing 23% to 33% less area, both assuming a 1 MWp PV plant.

3.3. Solar thermal and CSP systems

In the field of solar thermal technologies, several plants have been installed in the North of Chile in the last few years. Flat and parabolic trough collectors were mounted to provide heat for mining processes, mainly, where the energy consumption has reached 161.716 TJ in 2014 (including electricity and fuel). Currently, analyses of all the possible applications of solar energy in mining are being investigated. In particular, attention is paid to that processes which require the use of heat. In Fig. 5, several applications to processes sulfides and oxides are highligthed. In particular, electro-winning and anodes washing present high heat consumption and temperatures below 100°C in copper production processes.

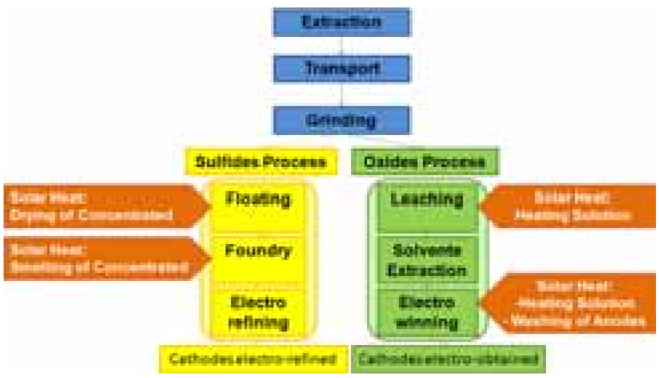


Fig. 5: Possibility for solar heat applications in copper mining processes

Researchers at University of Antofagasta are having the opportunity to collaborate with the most important local mines and to monitor the proper working of those solar facilities. Some studies have been carried out: in one case it was analysed the behaviour of the solar plant (Ushak et al., 2014) and in another one, a TRNSYS model is compared with a solar thermal pilot plant (Gallo et al., 2015). The next scheduled study concerns a parabolic trough system for heating the electrolyte in another mining company.

In Gallo et al. (2014) the integration of thermal collectors with an absorption machine was proposed for the air-conditioning of container in mining camps of the Atacama Desert. At Energy Development Center of Antofagasta, a demonstrative solar thermal plant for hot water heating is currently under installation and it is planned to install another one in the PSDA to study the effect of soiling on such systems with different environmental conditions.

A 7 kW_e solar simulator has been recently acquired in the Energy Development Center at Antofagasta University and will be shortly implemented together with a flux measurement system. Such a device will be employed as high flux radiation source until a real solar system is developed in the Solar Platform of Atacama Desert. Studies at high temperature are programmed to be addressed using the solar simulator. Most of them are focused on the solar energy usage in copper mining. Since copper extraction involves metallurgical processes at 1200 ºC they are being analysed from the point of view of their integration with concentrating solar energy systems. On the future development axis of the Solar Platform will be the proof of concept of these solar mining processes for what pre-industrial scale facilities are planned.

3.4 Thermal storage of concentrating solar energy

Chilean salt deposits have the potential to be exploited to obtain new molten fluids with the possibility to improve the properties currently associated to the solar binary salt (60% $NaNO_3$ + 40% KNO_3) used for Thermal Energy Storage (TES) in CSP plants. In this line, research and development in the solar energy sector is focussed on reducing the high cost of the operation and maintenance of these plants. One of the most important research lines in this context is the study, design and characterisation of salts that are used as energy storage fluids.

Binary mixtures of alkali molten nitrates/nitrites present phase diagrams with simple eutectic point and byadding one or more components, it is expected that the resulting mixture will have a lower melting point compared to the initial eutectic binary mixture. The design of multicomponent mixtures by the addition ofalkali/alkaline earth nitrates could extend the working temperature range of thermal energy storage (Bauer et al., 2014; Cordaro et al., 2011; Fernández et al., 2012; Gil et al., 2010; Mantha et al., 2012; Medrano et al., 2010; Olivares, 2012; Peng et al., 2010; Raade and Padowitz, 2011). The additives that present greater potential to be used for solar energy storage are $Ca(NO_3)_2$ and $LiNO_3$ as these salts decrease the melting point and improve the thermal stability, respectively.

Tab. 1: Thermophysical properties of Chilean lithium/calcium nitrate containing molten salts.

Molten salt mixture (wt.%)	Work temp. range (°C)	Viscosity at 250°C (cP)	Corrosion rate of A516 Steel at 390°C (mm/year)	Electrical conductivity at 390°C (Ω-1m-1)	Energy density (MJ/m3)	Salt Price (US$/Ton)	Two-tanks system cost/stored energy (US$/kWhth)
Solar Salt	221–589	5.51	0.97	0.37	550	893	11.67
20 $LiNO_3$ – 52 KNO_3 – 28 $NaNO_3$	130–600	6.3	0.31	0.67	513	1161	16.35
30 $LiNO_3$ – 10 $Ca(NO_3)_2$ – 60 KNO_3	134–567	5.72	0.027	0.56	607	1274	15.07
10 $LiNO_3$ – 10 $Ca(NO_3)_2$ – 60 KNO_3 – 20 $NaNO_3$	132–580	5.78	0.013	0.45	680	1038	10.98

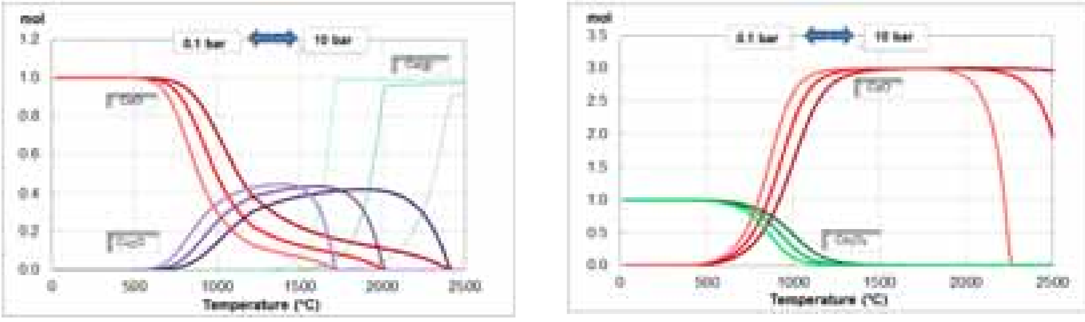
Some researches leading by Antofagasta University (Fernández et al., 2015, 2014) have proposed the study of molten salts of more than three components as a new possibility, showing a higher energy density, based on the heat capacity, which represents an important improvement over the solar salt currently used. It is important to note that based on this parameter, a smaller amount of salt could be used to store the same amount of energy.Results obtained for the new molten salts developed at Antofagasta University were compared to baseline Solar Salt (60wt.% $NaNO_3$ – 40wt.% KNO_3) properties found in the literature (Fernández et al., 2015, 2014).

The production of $LiNO_3$ at industrial scale is the current challenge in northern Chile and could be the key for a successful development of the new generation of CSP plants but it is necessary to perform storage tests in a bigger scale and real conditions.

In this respect, the Energy Development Center at Antofagasta University is equipped with a loop of molten salts with a working range of 130-500ºC, to test the performance of new raw materials potentially suitable for its use as solar storage in the existing solar technologies using molten salt storage. In addition, the current facilities also include systems for testing the dynamic corrosion produced by the molten salts on different carbon steels, stainless steels and other coated steels, under different flow rates. Results obtained and lessons learned will be applied in the molten salt loop to be build in the Atacama Solar Platform.

A different approach to thermal storage using materials widely available in Northern Chile is based on thermochemical redox cycles of metals oxides. The interest is significant because Chile produces 34% of the global mined copper, what means that it is the larger producer in the world. The impact of copper industry in the Chilean economy is very high: it represents more than 12% of the Chilean GDP.

The redox pair CuO/Cu_2O was proposed by Wong et al. (2010, 2011) as a possible candidate for thermochemical storage of solar energy. Its viability was demonstrated in a solar rotary reactor where the reduction from CuO into Cu_2O was achieved at temperature up to 1000 ºC (Alonso et al., 2015). This study was carried out in the framework of a colaboration between the Energy Development Center at Antofagasta University and the Renewable Energy Institute of Universidad Autónoma de México (UNAM). The solar furnace at Institue of Renewable Enrgy (HoSIER) of UNAM was employed as radiation source. The progress of the reduction was monitored by recording the amount of oxygen delivered inside the solar reactor. 10 g of CuO were introduced in batch mode into the reactor as starting reactant. Gas flow was 10 Nl/min and pressure was very close to atmospheric during all the experiments. 80% of the starting CuO could be reduced into Cu_2O. Also, several cycles of reduction and oxidation were achieved. However, chemical conversion for both, reduction and oxidation was not complete. Different improvements are currently under study and development to be applied to the experimental procedure with the objective of increasing the fraction of active material. Firstly, a theoretical analysis of the operation parameters influence on the thermodynamic equilibrium was realized. As an example of this work, Fig. 6 shows the effect of the total pressure and the atmosphere composition in the equilibrium of the copper oxides system. The lower the pressure, the lower the temperature at which the reduction of CuO starts as expected according to Le Chatelier principle. The maximum conversion of CuO into Cu_2O (87.7%) occurred at 1600ºC at 1 bar of total pressure. By decreasing the pressure to 0.1 bar, the maximum conversion rises to 89.9% and it is achieved at 1400 ºC. On the contrary, the higher the pressure, the higher the temperature at which the maximum conversion is reached. At 10 bar, the maximum conversion is achieved at 1875 ºC and has a value of 84.6%. When applied for TCS, these redox processes are proposed in air because of economic reasons. However, it could be assessed to carry out the reduction stage in inert atmosphere since it would benefit the reaction. In Fig. 6b the graphs indicate that the lower the O_2 concentration the lower the equilibrium temperature. For copper oxides, the maximum conversions are 89.2% at 1575 ºC and 90.4% at 1550 ºC for 10/90 and 5/95 O_2/N_2 relations respectively. The advantages compared to air composition are not very significant in terms of conversion increasing and temperature decreasing. However, if the carrier gas is pure N_2, conversion can be increased to 93.4% at 1475 ºC, what represents an augmentation of 5.7% in the maximum conversion value at temperature 125 ºC lower than the process in air. More details can be found in Alonso et al. (2016).



(a) (b)

Fig. 6: Effect of (a) total pressure on the thermodynamic equilibrium with a ratio air/reactant of 30. b) CuO/Cu_2O and b) gas composition in the thermodynamic equilibrium with 1 bar of total pressure and gas/solid molar ratio of 30

Experimental investigations of this system are currently under development. A lab scale facility based in a solar reactor is being constructed to be coupled with the solar simulator. The reactor consists on a rotary ceramic cavity provided with a transparent window and a gas inlet and outlet (Fig. 7). This prototype is designed to optimize the redox reactions for thermochemical storage with direct absorption of solar radiation.

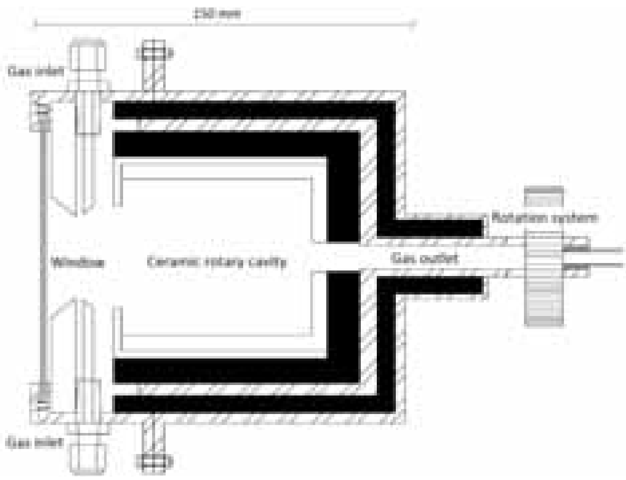


Fig. 7:Lab scale solar reactor sketch for thermochemical storage based on metal oxides based with direct radiation absorption.

In parallel to the design of the reactor, a numerical model to study the thermal behavior of the cavity was carried out. The aim of the work was to analyze how the use of different concentrators affects the cavity wall temperature. To do that, different flux distributions obtained with a ray tracing software were integrated in a CFD model. The first case was a flat profile radiation that impinged on the rear part of the reactor. Then, flux distributions generated by a solar simulator composed of an elliptical mirror and a high power lamp and by a multi-faceted concentrator was considered for the analysis. It was found a relation between the flux profile and the temperature distribution. In particular, higher temperatures were achieved at the back side of the cavity, where the most part of the radiation impinged. The most homogeneous temperature distribution was achieved for the multi-faceted concentrator case. More details can be found in Gallo et al. (2016). For the future, a more accurate model, which includes the solid phase, will be added and it will be validated with experimental tests.

With respect to the Solar Platform, future plans include the development of a scaled-up realistic facility to work under the local solar conditions. Thus current works are focused to study the performance and optimize a directly irradiated thermochemical solar energy storage system based on metal oxide particles.

4. Conclusions

Chile has a great opportunity to participate in the development and future trends of concentrated solar technology due to its potential for exploiting existing raw materials for solar energy storage and the great solar resource in the north of the country.

The proposal of new storage material using by-products and the consolidation of pilot plants in the Atacama Solar Platform, in order to obtain potential TES material is a growing trend in the institutional and private research initiatives in Chile. However, the lack of reliable and accurate data related to this topic requires a reinforcement of the relationship between Chilean institutions and solar market companies.

Due to the high demand of energy associate to mining industry, solar energy explotation in North of Chile has a special focus on this sector. In fact, mining energy demand is the most important of the country and a part of it is the form of heat. The application of solar heat is being evaluated for different stages of the cupper extraction process: floating, leaching and electrowining are examples of low temperature processes while foundry could be addressed with concentrated solar energy. R&D studies are being started in both directions and some of them count with the support of mining companies. Finally, electricy production by PV or CSP (with different types of thermal storage) is also expected to has a significant contribution to the electricity demand flat curve that characterize the mining zones of Northem Chile.

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