EVALUATING THE POTENTIAL FOR SOLAR THERMAL ENERGY UTILIZATION IN CHILE

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Abstract. *The Atacama Desert, located in northern Chile, is regarded as one of the regions with the highest solar radiation in the world. However, Chile exploits limited renewable energy resources, currently represented by hydroelectric generation, wood based biomass and incipient wind farms. Thus, the country relies heavily on fuel imports to meet its growing energy demand, making it a growing net importer of energy. Therefore, it is of critical importance for Chile to secure adequate energy supplies, ensuring that imported energy is accessible through international markets in order to satisfy any requirements that cannot be met by its internal production. Renewable energy is emerging as an interesting alternative to fossil fuels, and therefore it is important to evaluate the resource potential of wind, solar, geothermal and other energy sources. Herein, we present an evaluation of the potential for solar thermal energy applications in Chile, obtained through computer simulations using a solar radiation database obtained from the Chile-SR satellite estimation model. The results show that there is good potential for the application of solar technologies throughout the country, with solar fractions for both flat plate and evacuated tube solar thermal collectors being higher than 0.4. CSP plants can achieve up to 50% more electricity production than those in Spain. The high availability of solar radiation in Chile constitutes a good opportunity for the deployment of technologies which could help the country achieve a greater degree of energy independence.*

Key words: *Chile-SR, solar energy utilization, SHC, CSP plants*

1. INTRODUCTION

Chile exhibits a high diversity of geographical features and climates which have a significant influence on the availability of renewable energy sources, particularly solar energy, considering that the Atacama Desert has been described by several authors as one of the regions with the highest solar radiation in the world [1, 2]. However, currently the country exploits limited renewable energy resources, apart from hydroelectric generation, wood based biomass and incipient wind farms. The country relies heavily on fuel imports to meet its growing energy demand, making it a growing net importer of energy. Renewable energy sources accounted for only 34% of primary energy consumption in Chile in 2011, while non-renewable fossil fuels accounted for the remaining 66% [3]. Additionally, in recent decades, the electricity consumption has also steadily increased, as shown in Fig. 1, and it is projected to continue doing so as the country further develops. The energy sector produced around 66,000 GWh in 2012, with 65% of that energy coming from fossil fuel-fired thermoelectric power plants, while the rest was provided mainly by hydroelectricity.
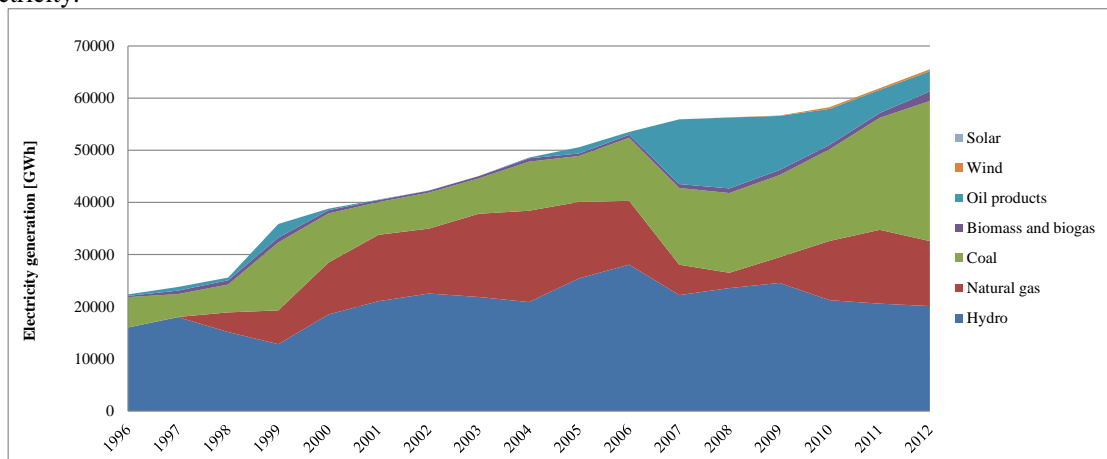

Figure 1 - Historical electricity generation by source in Chile, GWh.

This dependence on fossil fuels constitutes an historical weakness of the country, since they are almost 100% imported. Therefore, it is of critical importance for Chile to achieve adequate energy supplies, in order to pursue economic growth, and to ensure that imported energy is accessible through international markets to satisfy any requirements that cannot be met by its internal production. Furthermore, it is imperative to promote the development of local energy sources at a sufficient rate to satisfy the need for the substitution of imported energy resources, in order to achieve energy security and a degree of energy independence.

Mid-term and long-term energy planning requires reliable information on the available resources. As identified in previous reports by the authors [4, 5] several solar radiation databases for Chile are available. However, these databases have several shortcomings, since a significant deviation exists between sources and the ground station measurements are associated with unknown uncertainty levels. This situation highlights the need for an appropriate, country-wide, long-term resource assessment initiative, since the lack of quality data is partly responsible for solar energy not yet being considered as a major energy source. As a general conclusion, the previous studies demonstrated that although there are several databases of ground measurements, a weather simulation model, and satellite-derived data available for Chile, none of these data sources are completely valid and therefore the need for a nationwide effort to carry out a resource assessment, in order to provide developers with high quality data, has been identified. In this context, the CHILE-SR model [6] constitutes a major advance in the assessment of Chilean solar resources and encourages the deployment of solar energy in Chile. This model was developed as a modification of the existing Brasil-SR model developed by INPE within the SWERA project [7], taking its basic algorithm and modifying it in order to create an adaptation especially suited for the different climate conditions that Chile presents with respect to Brazil. The Atacama Desert is located in the northern region of Chile, and moving southward there is a Mediterranean climate in the central region, which gives way to a cold forest region in southern Chile. The model is able to capture all of these climates and provide accurate estimates, as it has been shown elsewhere [4, 5, 6].

This paper presents an analysis of the potential for the application of solar thermal energy in Chile, derived from the results of the CHILE-SR model. The main goal of this analysis is to evaluate the potential and feasibility of solar thermal energy applications to be used as an input for energy planning. The case studies presented herein aim to aid and encourage policy and decision makers to create energy policies that foster the deployment of solar energy systems throughout the country.

2.   SOLAR ENERGY RESOURCES IN CHILE

The potential for solar energy applications is computed using the solar energy database provided by the radiative transfer model CHILE-SR which uses satellite data from 2010 to 2012 and weather data from meteorological stations as inputs. The CHILE-SR model is a modification of the physical method developed by INPE (Instituto Nacional de Pesquisas Espaciais, Brazil), based on an atmospheric radiative transfer model. Cloud cover data is acquired from geostationary satellite images combined with climate data to parameterize the atmosphere [5, 6, 8]. The results of the CHILE-SR model allow the production of maps showing annual and monthly averages of solar irradiation with a spatial resolution of approximately 1x1 km. Figure 2 presents the annual average for the global daily irradiation incident on a surface tilted at an angle corresponding to the local latitude for a large part of the Chilean territory. It should be noted that the northern territory, above 20° 24" S, is not considered in this analysis, since the images received from the satellite GOES-13 do not cover this area. Also, the Earth's curvature distorts the results for areas south of 45°S.
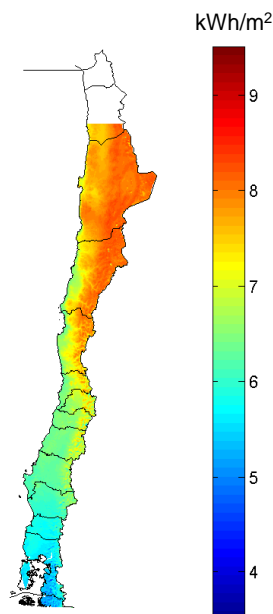

Figure 2 - Annual average for total daily irradiation over a plane tilted in an angle equal to the

As observed in Fig. 2, the highest daily solar irradiation (8.2 kWh/m^2/day) occurs in the Atacama Desert in northern Chile, which presents low precipitation levels (roughly 50 mm per year [8]) and low annual cloud cover. The clear sky conditions have attracted many astronomical observatories, including all of the telescopes and instrumentation of the European Southern Observatory (ESO) [9], among others.

3.   SOLAR THERMAL ENERGY APPLICATIONS FOR WATER HEATING

Approximately 91% of houses in Chile use gas heaters for residential water heating. The widespread use of this device is responsible for 18% of the energy consumed by the residential sector. This energy demand can be reduced by increasing the use of solar collectors. Currently, there are approximately 6400 m^2 of solar thermal collectors installed in Chile. However, recent studies have shown that this number should be increased considerably in the next years [10]. In this context, using the detailed information obtained from the CHILE-SR model several simulations were carried out in order to assess the potential of solar thermal systems in relation to meeting the residential energy demand in Chile. The typical solar hot water system considered herein consists of a solar collector, a circulation pump, a thermal storage system and an auxiliary heater, as shown in Fig. 3.
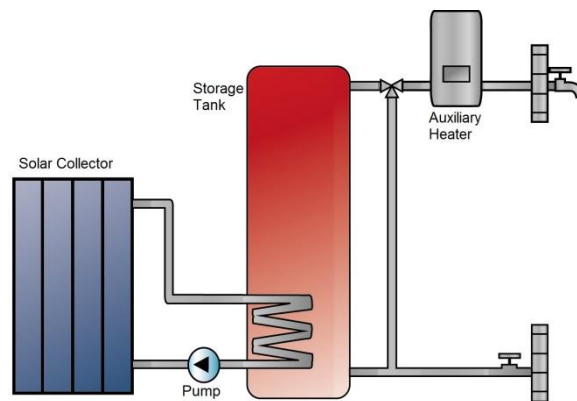

Fig. 3. Solar heating system configuration for residential water consumption

The residential water consumption scenario considers that the compact system in Fig. 3 supplies the energy demand of a family of four people, with a hot water consumption rate of 75 liters per person per day. The collector area is assumed to be 4 m^2, tilted at an angle corresponding to the local latitude. It is also assumed that the storage tank has a total capacity equal to the daily hot water demand. Therefore, the energy load for the system is the energy required to raise the mains water temperature to the temperature required for consumption (40°C). In this context, the mains water temperature for the whole territory was estimated using the algorithm developed by Burch and Christensen [11]. In this algorithm the energy load is dependent on the ambient temperature and the annual thermal amplitude. Regarding this parameter, the energy load can vary according to the climatic features of each location, and the spatial distribution of the energy load for a household is as shown in Fig. 4. The greatest demands are observed at the higher locations, at the proximity of the Andes Mountains, since these areas are characterized by low ambient temperatures. Coastal areas present higher temperatures and low thermal amplitude, and consequently these areas require a lower energy load. The potential contribution of the solar hot water system is then estimated by applying the *f*-chart algorithm [12] for two types of solar collectors: flat plate and evacuated tube.

3.1. Flat plate collectors

In order to evaluate the performance of the system using flat plate collectors with different characteristics, the simulations were carried out considering two types with different efficiency parameters: one of high performance and one of low performance. The efficiency parameters of the flat plate collectors considered herein are summarized in Table 1

Table 1 - Efficiency parameters for the flat plate collectors considered in the simulations

	High Performance Collector	Low Performance Collector
$F_R(\tau\alpha)$	0.789	0.734
$F_R U_L$	4.360	5.250
$K_{(\tau\alpha)}$	0.954	0.855

The spatial distribution of the solar fraction of the solar system operating with high and low performance flat plate collectors is presented in Fig. 4. As expected, it can be observed that the solar fraction in the northern region is higher than the solar fraction in southern areas. It is also observed that the coastal areas present higher solar fractions than the

mountain regions (at the same latitude). This difference is important since in the coastal regions of Chile it is common to observe periods of thick cloud during the morning, which decreases the availability of solar radiation. Nonetheless, the high thermal amplitude observed in the desert and mountain areas increases the energy load significantly. According to the results shown in Fig. 5, the reduction in the efficiency of the collectors greatly affects the energy supplied by the system. In this context, it is crucial to consider the cost of the collector, since the cost of high efficiency collector considered herein is double that of the other collector [13].
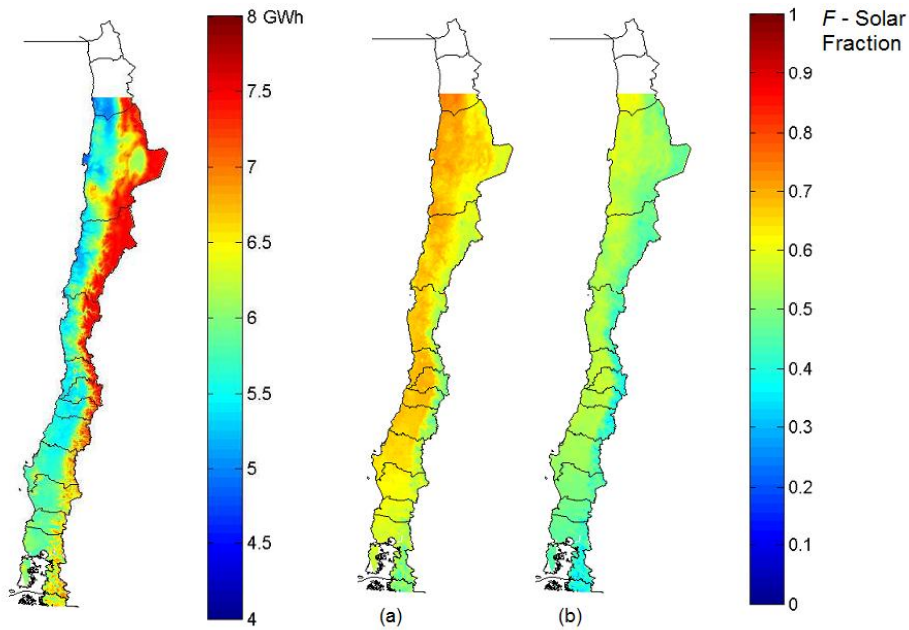

Figure 4 - Annual energy load for residential water heating, as a function of the geographic location, in GWh (left), and annual solar fraction using (a) high performance and (b) low performance solar collectors (right).

3.2. Evacuated tube collectors

The performance of the system using an evacuated tube collector was evaluated applying the same approach described in the last section, that is, two collectors were considered, one of high efficiency and another of low efficiency, as detailed in Table 2.

Table 2 - Efficiency parameters of the evacuated tube collectors considered in the simulations

	High Performance Collector	Low Performance Collector
$F_R(\tau\alpha)$	0.79	0.68
$F_R U_L$	1.58	2.94
$K_{(\tau\alpha)}$	0.95	0.94

The spatial distribution of the solar fraction for the hot water system operating with evacuated tube solar collectors is presented in Fig. 5. It should be noted that the high performance collector allows solar fractions over 65% to be achieved in all populated areas of the country, even in mountain regions. In addition it can be observed that this kind of system can supply almost 90% of the energy load in the northern regions of Chile.
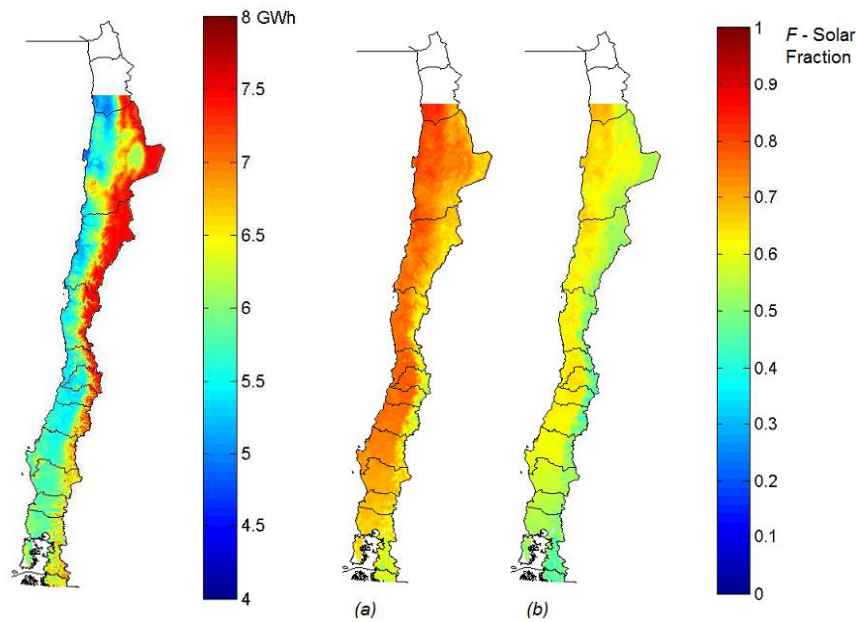
Figure 5 - Annual energy load for residential water heating, as a function of the geographic location, in GWh (left), and annual solar fraction using (a) high performance and (b) low performance evacuated tube solar collectors (right).

4. CONCENTRATED SOLAR POWER PLANTS

Several studies have demonstrated that concentrated solar power (CSP) technologies are a reliable alternative to meet the higher demand for electricity in the future [14,15]. The energy conversion in these systems relies mainly on four subsystems: the concentrator, receiver, transport/storage and power cycle. The concentrated radiation is absorbed by the receiver, reaching temperatures of up to 600 °C. The heat absorbed by the working fluid is then used to drive a conventional power cycle. Of the CSP technologies available today, the parabolic trough and central receiver are the most developed. Parabolic troughs consist of parabolic mirrors mounted on a 1-axis sun tracking system, in which focus is placed on a pipe which the working fluid flows through. Hence, as the working fluid circulates it absorbs the concentrated radiation increasing its temperature. Central receiver power plants are based on a spatial distribution of heliostats, which reflect solar radiation to a fixed receiver placed at the top of a tower. At the receiver the heat collected is transferred to the working fluid and to the power block.

In relation to these technologies, the main requirements for developing projects is the availability of high levels of direct solar radiation, proximity to the distribution grid and accessibility to relatively flat areas [14,16]. In this context, considering the information obtained by the CHILE-SR model combined with geographical altitude data, it is possible to identify the feasible locations for CSP plants. The locations should meet two main requirements: a slope lower than 3% and an annual direct normal irradiance (DNI) higher than 2100 kWh/m^2, which is the level of direct irradiation in the Andalucia region of southern Spain, where many CSP projects have been developed [17]. The sites that meet the specified conditions are not restricted to the Atacama Desert in the northern region, but extend to other parts of the country up to a latitude of 36° south. However, the highly variable availability of solar resources during the year and the alternative uses of land for agricultural purposes, limit the potential application of CSP plants in central Chile, from 30°S southward.

Aiming to evaluate the performance of CSP plants in some of the locations identified in Fig. 6, several simulation were carried out considering both technologies: parabolic trough and central receiver. In this context, four locations were selected, from different regions of the country: Crucero (22.24°S; 69.5°W; 1200 mamsl), Diego de Almagro (26.4°S; 70°W; 1000 mamsl), Santiago (33.5° S; 70.6°W; 570 mamsl) and Curicó (35° S; 71.23°W; 220 mamsl). The simulations were carried out using the System Advisor Model software [18] and hourly solar radiation data, based on the results of the CHILE-SR model.

4.1 Parabolic trough plant

The analysis presented herein considers the operation of a parabolic trough plant with a configuration analogous to that of the ANDASOL 1 solar power plant located in the proximity of Granada, Spain. This plant has a nominal capacity of 50 MW, 510120 m^2 of aperture area and 7.5 h of thermal energy storage. Figure 7 shows the results of the simulations in terms of the monthly net energy output for the four selected locations. Although Crucero and Diego de Almagro show seasonal variations in the energy generation, they is not as significant as those observed for Santiago and Curicó. It should be noted that the annual net energy generation for the former two locations is 50% higher than the energy output of the reference plant, ANDASOL 1 (158GWh) [15]. Indeed, according to the results obtained, the energy output of ANDASOL is equivalent to those predicted for Santiago and Curicó. From these results it can be

observed that with the radiation conditions of Northern Chile it is possible to reduce the investment costs associated with the solar field, since smaller collection areas are needed for an equivalent power production capacity.
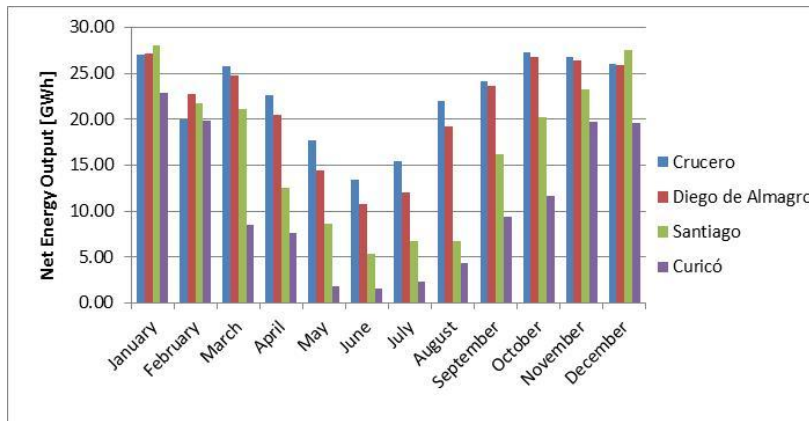

Figure 7 - Monthly net energy output of a parabolic trough plant for the selected locations.

4.2   Central receiver plants

Several simulations were carried out aiming to evaluate the energy output of a plant in a configuration analogous to that of GEMASOLAR, located near Seville, Spain. This plant has a nominal capacity of 20 MW, 304450 m^2 of aperture area and 15 h of thermal energy storage capacity. Figure 8 shows the results obtained from the simulations, in terms of the monthly energy output. It can be observed that the net energy output is stable throughout the year for Crucero and Diego de Almagro. For Santiago and Curicó, the energy production presents a significant decrease as these regions are characterized by a higher latitude and frequent cloud cover during the winter. It was noted that the annual net electric generation is 51% higher than the net energy produced by the reference plant. Consequently, it could also be inferred that these results indicate lower investment costs for installing a CSP plant with these features in Northern Chile. Indeed, the simulations showed that during the summer a plant located in the northern region could operate continuously 24 hours a day, by means of the thermal energy storage system. This finding is of crucial importance since the higher dispatchability achieved enables the signing PPA contracts with one of the several copper mining companies located in that region, which are intensive energy consumers.
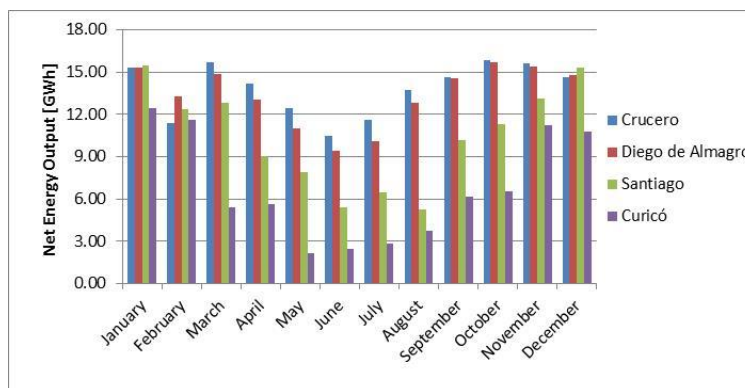

Fig. 8. Monthly net energy output of a central receiver plant for the selected locations

5.   CONCLUSIONS

This paper describes the potential for solar thermal energy applications in Chile, using solar radiation results obtained from the CHILE-SR model as inputs for water heating and power production simulations. The solar powered water heating systems showed high solar fractions for northern and central Chile. If current government incentives are maintained the total area of solar collectors should increase significantly over the next few years. This deployment of the technology could induce a meaningful reduction in energy production required for use in residential homes. The sites appropriate for the development of CSP projects in Chile cover an area stretching from the far north of the country to the central region. This area fulfills two main requirements: slope lower than 3% and annual DNI levels higher than 2.1 MWh/m^2. Simulations were carried out for four locations which satisfy these two requirements and the results showed that locations in northern Chile can supply 50% more energy than the reference plants located in Andalucía, Spain.

Acknowledgements

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