Solar Energy Systems in Northern Chile: Application Potential

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Abstract

Northern Chile is well-known for its exceptional solar energy availability. In this paper we compare the solar insolation in Calama and Pozo Almonte with Albuquerque (USA) and Spain. We show that overall energy availability in Calama is 23% higher than in Albuquerque and 44% higher than in Almería. For a two axis tracking system, availability is 17% higher than in Albuquerque and 43% higher than in Almería. In northern Chile the yearly average clearness index is over 0,72 for inland localities. This means over 300 totally clear days a year. In the final part of the paper we analyse possible solar energy applications in this exceptional solar environment.

1. Introduction

Northern Chile is well known for its exceptional solar radiation availability. Late in the XIXth Century, an american engineer, Charles Wilson, built a 5000 m² solar still that operated from around 1878 to 1914 and produced an average of 5000 liters of fresh water a day [1]. This was installed in a place called "Las Salinas", near present day Baquedano, on the road from Antofagasta to Calama. Later, in the early XXth Century, Dr. George Abbott, from the Smithsonian Institution, installed a solar observatory near Calama [2]. In this observatory, measurements of both the solar constant and the spectral distribution of sunshine were systematically made.

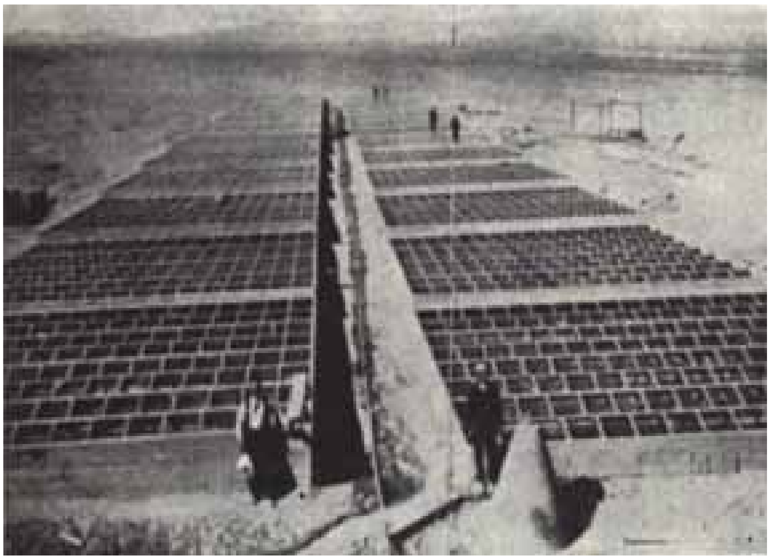

Fig. 1 The Las Salinas Solar Desalination Plant. Photograph from [1], taken around 1912

Today this region is an area of intense mining activity. Chile is one of the premier world copper producers and also nitrates, iodine and lithium salts are important items in our export products. Naturally this intense mining activity needs large amounts of both energy and water. Today, the *Sistema Interconectado Norte Grande (SING* or *Northern Interconnected Grid)* has an installed capacity of 3600 MW with an annual production of 14.900 GWh. Of this total production, over 80% is for the mining sector [3].

New mining activities will mean increased energy needs. Electricity is used for mining, mineral crushing, flotation, electrowinning operation and other tasks. Increasingly electrical energy is needed for water desalination (typically by reverse osmosis) and then the *pumping* of this desalinated sea water to operations that lie at over 3000 meters altitude. In a typical desalination scheme, around 30% of energy use is for actual sea water desalination and the rest is used for pumping it to the mines where it's used.

Today in the *SING,* over 99,5% of the electricity generated is done by fossil fuels, the greatest part by coal fired plants and a small fraction by Combined Cycle power plants that use liquified natural gas.

All of the important mines are well aware of the large carbon footprint of these activities, so that they're looking into ways to reduce the fossil fuel dependence of mining in the North of Chile by the introduction of renewable energy.

In the region, the two best candidates for the replacement of fossil fuels are geothermal and solar energy. In this paper we explore the potential of solar energy, specifically comparing its availability to two other well-known places in the world: Almería in southern Spain and Albuquerque (35,2ºN, 106,5ºW and 1631 meters altitude) in New Mexico. We chose the first because its the place in Europe with one of the best solar potentials and the second one because its in the middle of the Southwestern US, also a place of many solar projects. For Chile, we've used the available data for Calama (-22,5ºS Lat. and 68,9º W Long., 2280 meters altitude) and also Pozo Almonte, a place near Iquique (-20,3ºS Lat. and 69,7º W Long., 1000 meters altitude).

2. Methodology

The data that we used in this paper comes from two sources. The first one is the extensive data base maintained by the *World Radiation Data Center* [4]. This organization, that operates in Russia under the sponsorship of the World Meteorological Organization (WMO) has gathered an extensive set of solar radiation data from around the world. This includes both daily global insolation and sunshine duration data. For some places there also is both direct, beam and diffuse data. The data sets for Chile are from our National Meteorological Office. In every case the type of instrument is identified. In the case of Chile, the pyranometers are PSP manufactured by Kipp & Zonen and the sunshine duration measurements were done with Campbell Stokes recorders.

A second, smaller data set, comes from measurements that are sponsored by our *Comisión Nacional de Energía* (National Energy Commission) [5]. This is an ongoing project and there's a total of about 18 months of data. These are measurements done on a 10 minute basis both of global horizontal radiation as well as a tracking system that faces the sun and measures both hemispherical radiation and diffuse radiation. The three sensors are Kipp & Zonen CM-5 pyranometers. The diffuse radiation is obtained by placing a shadow band on one of the moving sensors. Due to the non conventional nature of the tracking system, we used the horizontal data as our essential data set.

In the case of the data for Almería and Albuquerque, we had 10 and 9 years of daily data. For the Calama data, we had a total of four years of daily data for solar radiation and ten years of monthly averages for sunshine duration. In the case of Pozo Almonte, we had one year of daily data with 10 minute resolution.

For comparison purposes we decided to use two well-known non dimensional indexes: the *Clearness Index* and the *Sunshine Fraction* index. The clearness index is:

$$K_T = \frac{H_h}{H_0} \quad (1)$$

Where H_h is the horizontal insolation (daily or monthly average) and H_0 is the extraterrestrial insolation for the same period. This second term can be easily calculated if one knows the latitude and day of the year.

The sunshine fraction index is:

$$K_s = \frac{S_h}{S_0} \quad (2)$$

Where S_h is the monthly average of sunshine duration in hours and S_0 is the theoretical sunshine duration calculated from:

$$S_0 = 2 \times \arccos(-\tan(\phi) \cdot \tan(\delta))/15 \quad (3)$$

Where ϕ is the latitude and δ is the average solar declination for that particular month.

So we can conduct the following comparisons on our data sets:

- The direct comparison of horizontal insolation in [MJ/(m^{2}day)] for the localities under study. This can be done with the monthly averages.
- Comparison of the K_T index versus insolation.
- Comparison of the K_T index versus the K_S index for the different localities.

In the first case, our comparison gives energy availability results. For the second and third cases, since we use non dimensional indexes, the data points obtained can clearly show overall differences in solar energy availability in these different locations.

All the previous results were done for either daily values or monthly averages. To get a finer picture of solar energy availability, we also tried to reconstruct the *hourly* values of global and direct radiation. To do this we had the hourly data available from Pozo Almonte and also the daily totals for Calama.

We reconstructed hourly values using the Bird solar radiation model [6]. This is one of the better known clear sky solar radiation models. We decided to use it because it provides a good compromise between ease of use and precision. The input data that's needed is sufficiently detailed to adequately take care of altitude and atmospheric conditions. It's also firmly based in a atmospheric broadband transmission model. Other models, such as the Page [7] relationships, have a more empirical basis, and the more exact Pérez model [8] needs many more parameters to have adequate results. So balancing exactness with simplicity, we decided that the Bird model was a very good compromise.

3. Results and Discussion

To see how well the Bird model fit our data, we had the 10 minute interval measurements conducted in Pozo Almonte. We took days where the clearness index was over 0,72 and then compared the measured daily curve with the curve predicted from the Bird model. We did this for over 20 different days along a year. In figure 2 to 4 we show results for three different days during the year.

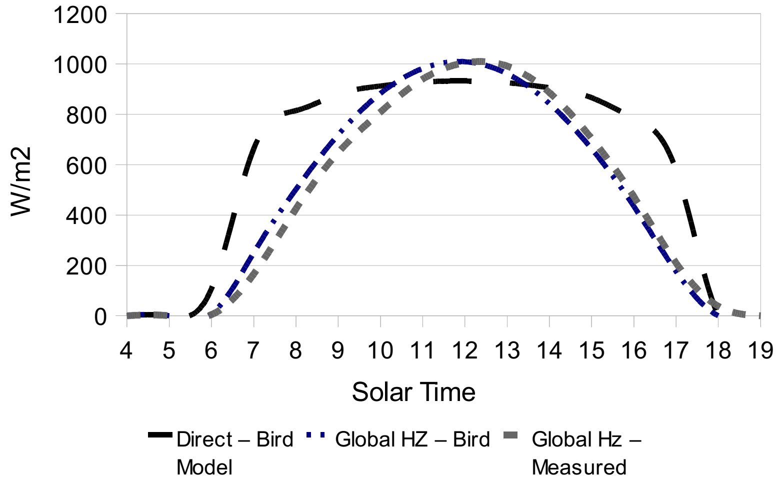

Fig. 2 Comparison of Bird and Measurements for Pozo Almonte, March 22

When one analyzes these days, the average error was less than 1% between the measured data and that obtained from the Bird clear sky model.

In Figure 5 we present the average horizontal insolation for the four places under study: Almería (Spain), Albuquerque (NM, USA), Pozo Almonte (Chile) and Calama (Chile). These monthly averages are for data sets of four years in Calama, 9 years in Almería and 10 years in Albuquerque. In the case of Pozo Almonte, we only had 12 months of data. For greater clarity, we *"matched"* the seasons. This means spring with spring, winter with winter and so on. This facilitates comprehension of the data.

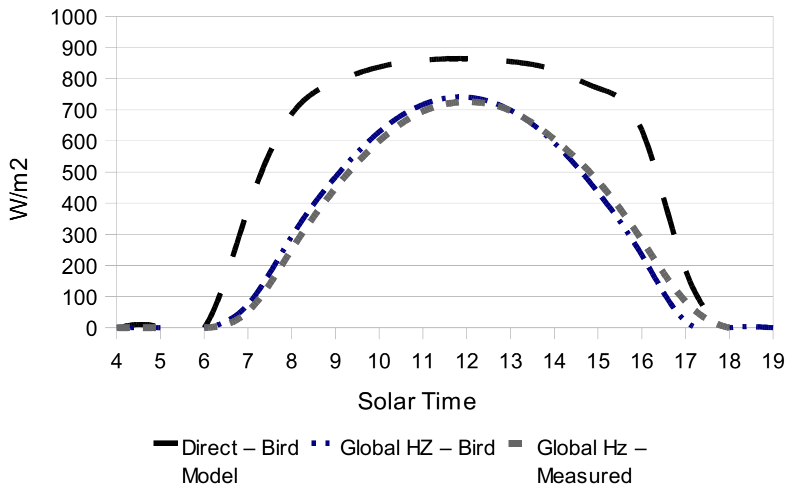

Fig. 3 Comparison of Bird and Measurements for Pozo Almonte, June 15

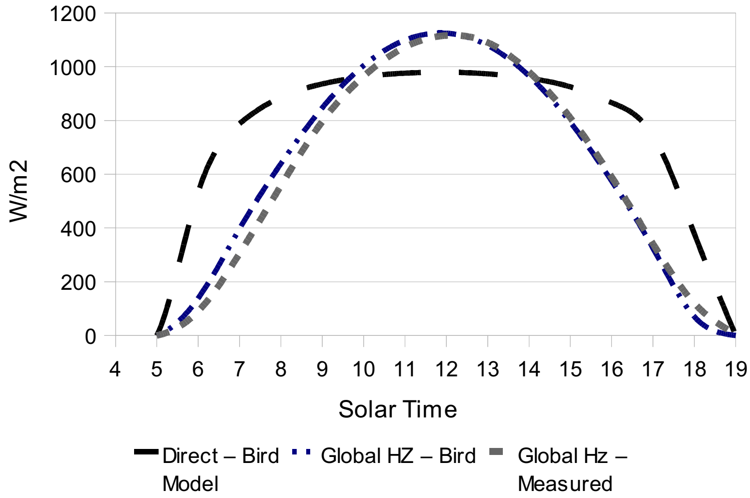

Fig. 4 Comparison of Bird and Measurements for Pozo Almonte, December 27

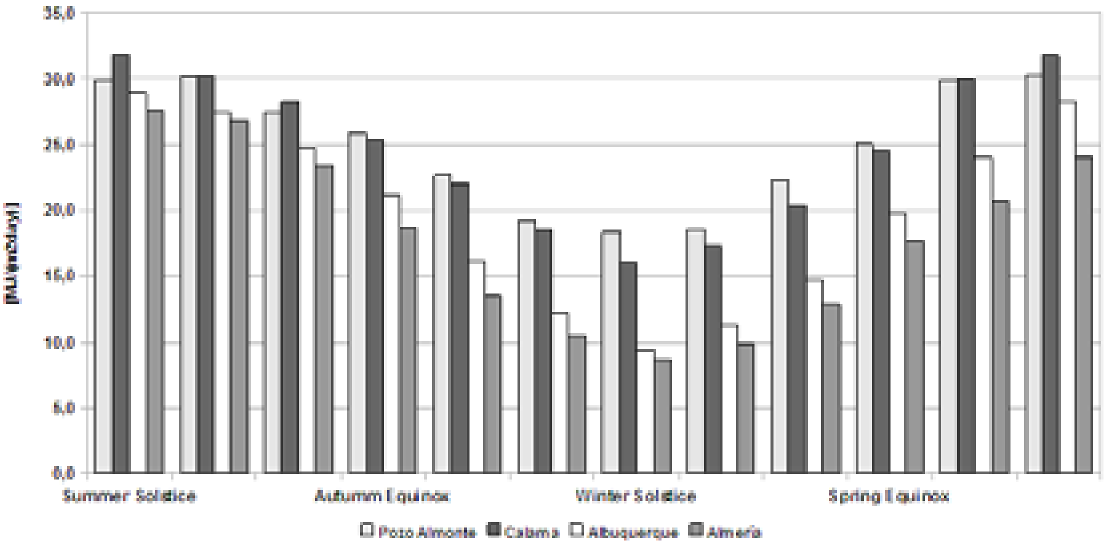

Fig. 5 Monthly average horizontal insolation for Pozo Almonte, Calama, Albuquerque and Almería

From the results it's quite obvious of the large advantage that both Chilean localities have over those in Spain or the US. This can in part be explained by the fact that both Calama and Pozo Almonte lie closer to the equator than both Albuquerque and Almería. But also both places in Chile have much higher clearness indexes than Albuquerque or Almería. This is shown in figure 6.

In this figure its quite clear that average K_T values for both Pozo Almonte and Calama are consistently higher than for Albuquerque and Almería.

We only had sunshine duration data for Almería and Calama. This information is compared in Figure 8. In it we compare K_t versus K_s , that is Clearness Index versus Sunshine Fraction.

Again the significant advantage of the localities in Chile are quite evident. Clearness Index lies consistently above 0,70 *on average;* and for Calama nearly half the time the sunshine fraction is over 0,90. This in fact means 300 or more totally clear days a year. This is due to the fact that the Campbell Stokes sunshine recorder needs a minimum direct beam radiation of over 250 [W/m²] to start burning the paper band. Thus even on a totally clear day, the amount of sunshine recorded is around 95% of the theoretical maximum.

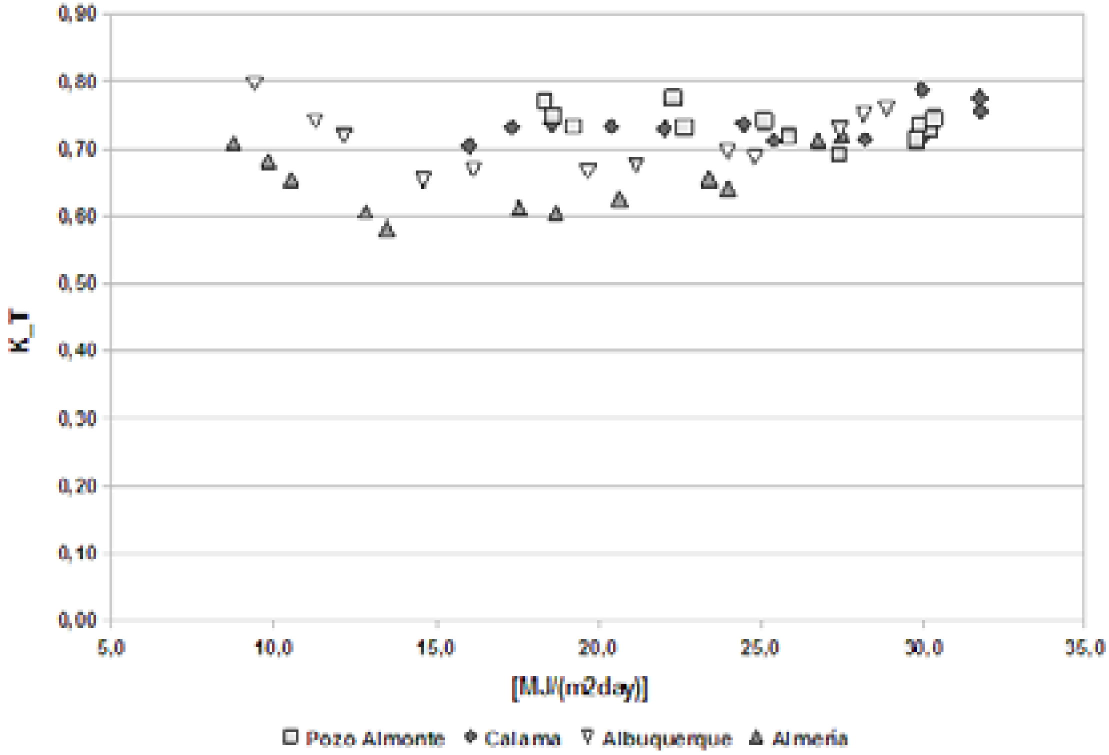

Fig. 6 Comparison of Horizontal Insolation vs Clearness Index for localities under study

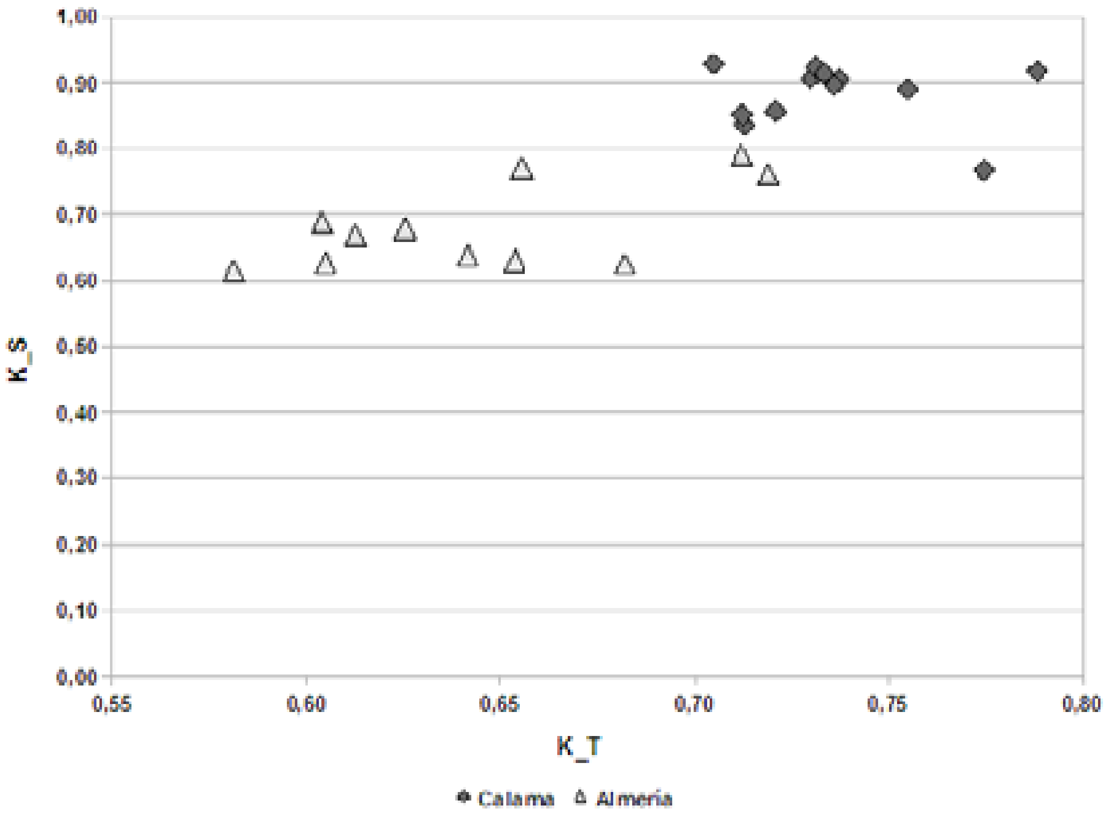

Fig. 7 Comparison of Clearness Index versus Sunshine Fraction for Calama and Almería

Finally, using the *Retscreen* software [9] we calculated the solar energy availability on a surface tilted towards the equator at an angle equal to its latitude; with single axis tracking on a north south axis and a two axis tracking system. This was done for the four localities. The overall results are shown in Table 1.

Table 1: Yearly Comparisons of Solar Energy Availability for the four locations under study. The percentages are the gain in Calama versus other localities

		Calama	Pozo Almonte	Albuquerque	Almería
Insolation on horizontal surface	[MJ/m² year]	9026,6	9109,9	7320,4	6255,1
	%		-0,9	23,3	44,3
Insolation on tilted surface	[MJ/m² year]	9516,6	9523,5	8225,0	6964,2
	%		-0,1	15,7	36,7
Insolation on 1 axis tracking surface	[MJ/m² year]	12496,2	12530,2	10243,8	8411,8
	%		-0,3	22,0	32,7
Insolation on 2 axis tracking surface	[MJ/m² year]	13388,1	13323,1	11407,0	9317,4
	%		0,5	17,4	43,7

The differences between Calama and Pozo Almonte are negligible, but both Chilean localities have a consistent advantage over either Southwestern USA or Spain. In the first case solar energy availability is 16% or better for the Atacama desert region of Chile than for the USA. In the case of Southern Spain, the advantage is Chile is over 33%. The results are consistent and clearly demonstrate the very large solar energy potential that exists in northern Chile.

4. Possible Applications

The Chilean mining sector needs both low and medium grade heat for different processes. The most common of them is the electrowinning of copper. Copper ore is leached using a sulfuric acid solution. Then the solution is heated to about 42ºC and passed to the electrowinning facilities, where (using electricity) copper is directly deposited on stainless steel cathodes. This is a common operation in almost all copper mines and each plant has a thermal demand of around 5 to 20 MWth, plus electrical demand. The nitrate and lithium salt industry also has a demand for low to medium grade heat.

In every case solar energy could provide a very competitive source because the conversion efficiency is much higher than with CSP plants. Typically over 50% of available solar energy can be harvested for thermal conversion.

The demand for energy also provides good opportunities for combined heating and power solar systems. In this way the heat rejected by a CSP plant could be used in an industrial process.

In the case of electrical power generation using CSP systems, the main barrier is the scarcity of cooling water. We used the Solar Advisor Model (SAM) from NREL [10] to do preliminary evaluations of parabolic trough systems, and the largest obstacle was water. So dry cooling systems would be mandatory.

From a practical point of view, its obvious that one should first establish solar systems to provide heat for mining processes on a large scale. The minimum scale should be a size to cover at least 30% of the total power demand. This way one can actually measure the performance and the integration with the conventional system. As size increases, one can also incorporate thermal storage.

In the case of the production of electricity, due to the scarcity of water, one should first conduct experiments using either PV or concentrating PV systems. In both cases tracking should be used.

For conventional PV, the best tracking system for the latitudes involved are one axis with the rotation axis on a north-south direction and the tracking from east to west. As more experience is gathered in actual field operations, and solar energy systems evolve, the opportunity to utilize this resource in Northern Chile is truly exceptional.

5. Conclusions

Northern Chile, especially the Atacama desert region, has a truly exceptional solar climate. Average year round clearness indexes exceed 0,70 and solar energy availability is 20 to 30% better than what exists either in southern Europe or the Southwestern USA.

Besides the exceptional solar resource, this is an industrially very dynamic region, with huge mining complexes and a large (and rising) demand for both electrical and thermal energy. The companies that operate in the region are well aware of the need for them to reduce their carbon footprint.

These circumstances provide an exceptional opportunity to start large scale solar projects in this region of the World.

6. References

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