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Towards the Chilean Solar Thermal Potential Knowledge for Solar Power Tower Plants

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Abstract. The present paper presents a very simple energy yield model fitted using the annual DNI and the latitude as main inputs, considering a solar tower CSP plant, with 100 MW of net energy output and 6 hours of thermal storage. Furthermore, a mask of suitable areas for CSP power tower installations in Chile is also shown. The mapping of solar radiation components has been calculated from multi-regressive models based on ground based measurements, existing maps of solar resources and atmospheric parameters. An analysis of the available data bases in Chile is also done in order to obtain useful information for the development of the work.

INTRODUCTION

In the past, Chile has presented energy difficulties due mainly to its dependency on fossil fuel imports and infrastructure. This fact has contributed to a bad distribution of energy supply and to high energy prices. In order to palliate these problems, the Chilean Government has shown increasing interest in solar energy technologies, as demonstrated on its Energy Agenda seeking to provide a reliable, efficient, sustainable, inclusive, reasonably priced, diversified and equilibrated energy matrix.

Chile has experienced a rapid increase in the implementation of solar energy technologies. According to the Production Development Corporation (CORFO), a Chilean governmental organization, the country's cumulative installed photovoltaic (PV) capacity surpassed a peak power of 1.2 GW in June 2016 with 1.6 GW under construction and a further 12700 MW undergoing environmental evaluation. Concentrated Solar Power (CSP) is also reported, with a 110 MW plant currently under construction and a further 1,085 MW undergoing environmental evaluation. Many of these solar projects are located in the Atacama Desert, due to the level of irradiation, which can reach an annual value of 2500 kWh/m^2 in global horizontal irradiation (GHI) [1].

Detailed knowledge of the solar resources and their spatial distribution along the territory are thus crucial for the solar energy power systems penetration in the energy mix of the country. However, their development for electricity generation in a country also depends on several aspects, e.g., energy policies and technology development. Because of this, Geographic Information Systems (GIS) may help to handle, visualize and analyze the energy resource, the estimated potential and the projects infrastructure in a country, and then effectively contribute to a better deployment of solar technologies. There are many examples in the literature where GIS are widely applied to different renewable energy technologies [2]. There are mainly two different applications of GIS related to solar power projects. One of them is the appropriate site selection for a solar power plant. Site selection studies needs to take into account land, meteorology and infrastructure information with the objective to select the best places for new solar projects. The

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second use is the determination of the solar energy potential at a regional or country level. This application also needs to take into account the same information but the objective is to address the electricity eventually produced by a solar project and its distribution along the country or region.

There are many examples for solar energy potential studies for PV and CSP technologies [3]. These studies englobe different technological options [4–6]. In Chile, the solar power tower industry has had a recent development in comparison with PV or parabolic through technologies. This has led to the fact that most of the studies did not focus on solar power tower plant technologies or, at least, with updated information about the installed power and its prospects for the future [1,5]. In particular, in [1], the authors concluded that the use of irradiation data from the Chile-SR satellite estimation model for system simulation resulted in solar fractions over 80% for residential-sized solar thermal systems in most of the country, with PV systems yielding between 4.5 and 8 kWh/kWpv, and CSP annual yields of up to 240 GW h/year for a 50 MW parabolic trough plant.

Other references such as [7–10] have utilized ground station measured data in order to simulate CSP plants of various configurations, although with specific characteristics such as power block size that are useful as context information without intending to evaluate the solar potential countrywide. Although [7] does present simulation results for CSP plants of the tower type, the results are local and cannot be extended or extrapolated to other locations. Therefore, the present work is related with the potential estimation of CSP power tower technology in Chile in order to close a knowledge gap related to tower systems performance in Chile.

The determination of a specific renewable energy potential in a country need to define three main inputs: (1) a map of the annual resources; (2) a very simple model for the annual energy yield estimation at each map element; (3) the definition of the exclusion areas or areas not suitable for power plant installation. In our work we show the results of the development of these three steps for the CSP power tower potential estimation in Chile. The work starts by the review of some existing solar radiation data and direct normal irradiance (DNI) maps for the generation of an updated DNI map. A very simple energy yield model is also fitted using the annual DNI and the latitude as main inputs. Finally, a mask of suitable areas for CSP power tower installations is also developed.

REVIEW OF THE EXISTING DATA SOURCES

The Chilean Ministry of Energy (MINEN) has made available the Explorador Solar [11] with information of the solar resource in Chile. This web-site provides estimations of solar resource, direct and global radiation derived from atmospheric models, ground and satellite databases for the period between 2004 and 2016. Said ground based campaigns were supported by MINEN in collaboration with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). The main campaign consists of 11 stations distributed mainly along the North of the country, in the Atacama Desert area (FIGURE 1).

The available GHI data of the ground-based campaign were validated by comparison with the extraterrestrial solar radiation. Only the 0.2 % of the data contains errors. However, these are mainly at sunrises and sunset indicating that the errors are due to the cosine error in the instrumentation. Results are shown in TABLE 1. Locations cover a range of 10° of latitudes, from -18° to -27°, but there is an additional one out of this range located at -33° of latitude. Most of the stations have more than 80% of clear sky days, and only three of them are below the 50%. These are the two stations placed further from the Equator and PANG that are placed at the seaside. In fact, only in the CCALA station placed in at -33° has a significant number of overcast days with a 13%.

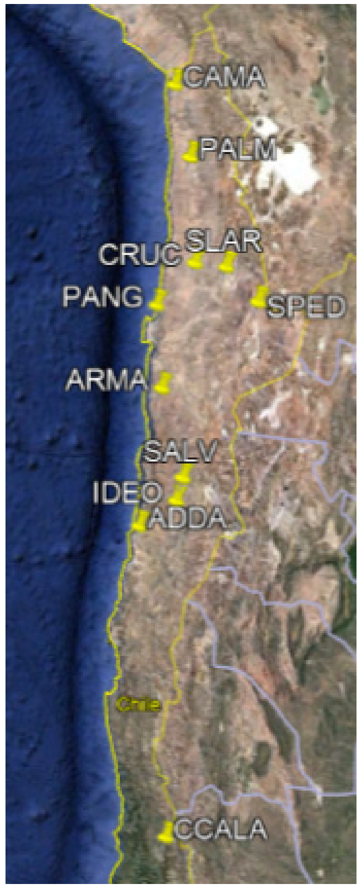


FIGURE 1. Spatial distribution of the ground measurement stations

TABLE 1. Main information of solar radiation at each location. The table shows the name of the station, the location (latitude and longitude), the number of days of measurements, the percentage of missing data (QC), and the number of clear, partly cloudy and overcast days.

N°	Station	Lat. [°]	Long. [°]	N° Days	QC	Clear days	Partly cloudy days	Overcast days
1	CAMA	-18.86	-70.22	2504	0.18%	82%	17%	1%
2	PALM	-20.26	-69.78	2760	0.22%	91%	8%	0%
3	CRUC	-22.27	-69.57	1915	0.00%	95%	5%	0%
3	Crucero2	-22.27	-69.57	1614	0.30%	96%	4%	0%
4	SLAR	-22.34	-68.88	428	0.30%	90%	10%	0%
5	SPED	-22.98	-68.16	1825	0.36%	91%	8%	1%
6	PANG	-23.07	-70.39	1915	0.18%	52%	45%	3%
7	ARMA	-24.63	-70.24	1115	0.25%	97%	2%	0%
8	SALV	-26.31	-69.75	927	0.38%	96%	3%	1%
9	IDEO	-26.75	-69.91	2110	0.34%	94%	5%	1%
10	ADDA	-27.26	-70.78	466	0.05%	40%	53%	7%
11	CCALA	-33.4	-70.54	1244	0.19%	57%	31%	13%

TABLE 2. Main atmospheric parameters and solar resource at each station.

N°	Station	TL [no_unit]	O3 [Dobson]	WV [cm]	BE [no_unit]	GHId [kWh/m^2]	DNId [kWh/m^2]	k_T [no_unit]
1	CAMA	4.1	254	2.28	0.09	6.71	7.59	0.70
2	PALM	3.9	257	1.73	0.08	7.02	8.74	0.73
3	CRUC	3.6	259	1.43	0.06	7.22	9.12	0.77
3	Crucero2	3.6	259	1.43	0.06	5.9	7.47	0.77
4	SLAR	2.3	259	1.04	0.01	7.24	8.83	0.76
5	SPED	2.3	259	1.04	0.01	7.1	9.09	0.76
6	PANG	3.9	260	2.09	0.09	5.85	6.25	0.63
7	ARMA	2.9	262	1.06	0.02	7.65	10.49	0.81
8	SALV	3.0	264	1.29	0.03	7.29	9.8	0.77
9	IDEO	3.1	264	1.31	0.04	6.99	9.19	0.77
10	ADDA	3.0	266	1.81	0.04	5.17	5.32	0.58
11	CCALA	1.8	276	1.41	0.01	5.26	5.91	0.58

SOLAR RADIATION MAPS

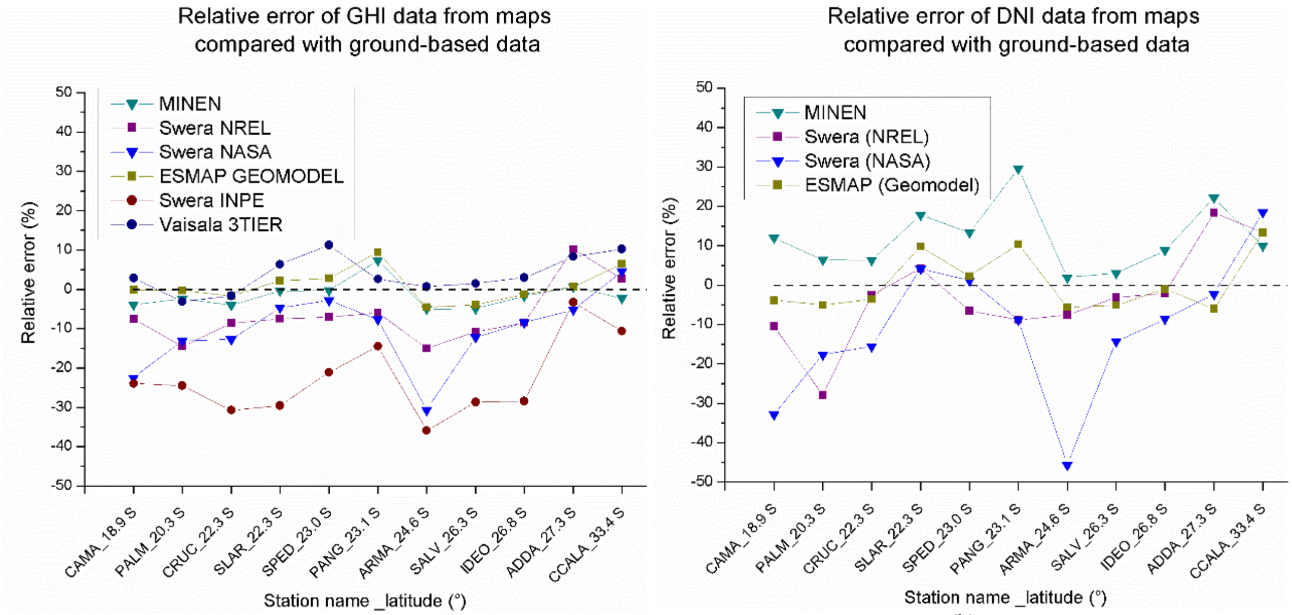
One of the main inputs for any solar energy potential estimation is the availability of an accurate map of solar resources. Even when there are different maps of solar radiation dealing with the global horizontal irradiance, this information is not the main input for the CSP system and a reliable map of DNI is needed. Thus, in this section we are going to test six different maps of solar radiation including the region of interest:

- Solar and Wind Energy Resource Assessment (SWERA) is a project financed by United Nations Environment Programme (UNEP). The data provided have different spatial resolutions and are freely available. In this paper we have tested three different SWERA maps: INPE (Brazilian Institute for Space Research) and NREL maps, both with a 40 km spatial resolution; and the map by NASA with a resolution of 1° x 1°.
- The Renewable Energy Resource Mapping (ESMAP) is a project supported by the World Bank. In this work, we have tested the map provided by Geomodel with a spatial resolution of 1 km.
- Renewable energy forecaster 3TIER has also available solar annual maps through the International Renewable Energy Agency (IRENA)'s Global Renewable Energy Atlas, an open-access online platform. The map used in this study has a spatial resolution of 3 km.
- The Chile-SR satellite estimation model, developed by researchers of Pontificia Universidad Católica de Chile in collaboration with INPE [1].
- Finally, in this work we have also reviewed the solar resource map provided by MINEN in the Explorador Solar [11].

The analysis has been performed by comparing map values with the available ground measurement stations in *Explorador Solar* showed in the previous section. Although the spatial coverage of the different maps is not the same, they all contain the radiometric stations used as a reference. For the analysis, all the spatial resolutions have been harmonized to 1km.

The DNI averages provided by MINEN are estimated by using the CLIRAD-SW radiative transfer model for clear skies and by using a calculated empirical function from ground measurements for cloudy days. Thus, because of the lack of available DNI measurements a first analysis of GHI is performed comparing the six GHI maps values with the GHI recorded at the measurement stations. Results are shown in FIGURE 2 a. According to the results of the GHI comparison 3Tier, INPE and NASA maps are far from the general behavior and except for the result at CCALA, MINEN and Geomodel data are similar. In both cases, the major disagreement with the ground measurements appears at PANG station (above 5%).

In FIGURE 2b DNI results are presented. In general, for the DNI comparisons differences are larger than the GHI ones. There are not DNI information provided by 3TIER and INPE and NASA has the largest disagreement with a mean relative error of 13%. Again MINEN and Geomodel data are close to the ground estimations. However, MINEN overestimates more than Geomodel. Regarding MINEN, the greatest disagreement with the recorded data appears at PANG station (~ 30%); while is at CCALA station where Geomodel shows the greatest difference (~ 15%).



(a) (b)

FIGURE 2. (a) Relative error of daily global horizontal irradiation values provided by different GIS maps compared with the ground measurements at each MINEN ground measurement stations in Chile. (b) Relative error of daily direct normal irradiation values compared with the ground measurements.

According these results three multi-regressive models has been proposed. All of them use MINEN and Geomodel data as input variables: MOD_00 also latitude as an additional input variable; MOD_01 also consider latitude and TL as input variable; and MOD_02 an iterative fit (like the MOD_01) has been performed sampling among the existing data set without consider latitude or TL. The best resulting fit for MOD_02 is the function:

$$DNI = 0.82 + 0.69\ Minen + 0.34\ Geomodel \qquad (1)$$

In FIGURE 3 the results of the comparison with the ground measurements are shown. The best fit is represented by MOD_02 and thus this model has been used to calculate the DNI map represented in FIGURE 4.

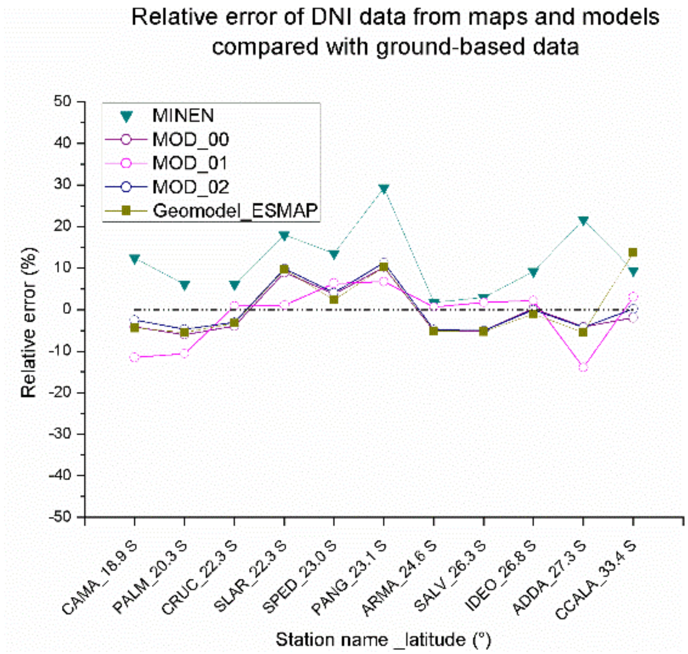


FIGURE 3. Relative error of the DNId data from fitted models and original Geomodel and MINEN estimation, compared with the ground measurements.

Even when differences on the final map can be seen at a zoom level, in the general map color seem to be always over a daily mean of 8,5 kWh/m^2 at the northern part of the country, what agrees with the ground measurement estimations as well.

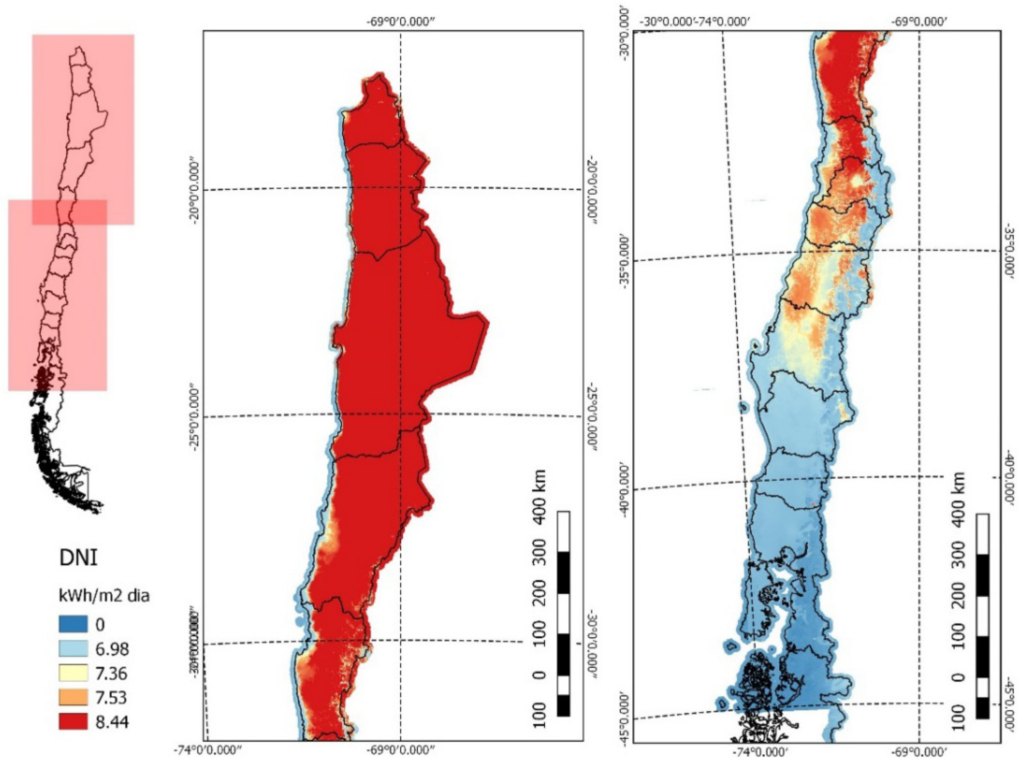


FIGURE 4. Daily direct normal irradiation map calculated with MOD_02.

SOLAR ENERGY YIELD ESTIMATION

In this section we present a preliminary model for the energy yield estimation from a solar power plant at the Chilean country. As it is well known [12], for an appropriate estimation of a solar power plant energy yield two main inputs are needed: the definition of a detailed model of the plant availability for running it at least at hourly basis; the availability of a near-real hourly series of meteorological data at one specific location for the simulation of the model.

When a potential assessment it is performed at country level, a simplification of this methodology has to be applied. The objective is to provide a simple linear model that could predict the amount of energy per square meter, using the direct normal irradiance and the latitude as the only input parameters. This has sense due to the objective is not a feasibility assessment, but only a general estimation of the potential at country level it is expected. Many different examples of these types of simplified models can be seen at the literature [2–4].

For the generation of a simple model the first step is the definition of the plant technology, power output and the size of the thermal storage system. According to ACERA[1] (The Chilean Association for the Renewable Energies), there are at least ten ongoing project related to CSP power plants and seven of them are based on the use of power tower technology (TABLE 3). Thus, based on this information we have defined the base case as a tower CSP plant with 100 MW of net energy output and 6 hours of thermal storage. For the energy yield estimation, System Advisor Model (SAM) from NREL has been used. The plant has been optimized for the Crucero location.

TABLE 3. Main information related to ongoing CSP power plants projects.

Project name	Owner	Gross Energy	Technology	Thermal Storage Systems
Cerro Dominador	Abengoa Solar Chile S.A	110 MW	Tower	17.5 h
Likana Solar	Likana Solar SpA	450 MW	2 towers of 120 MW net power + PV	13 h
Tamarugal Solar	SolarReserve Chile Ltda	450 MW	3 towers of 150 MW	13 h
Camarones	ELECNOR Chile S.A.	105 MW	Tower	10 h
Copiapó Solar	Copiapó Energía Solar SpA	240 MW	2 towers of 120 MW	13h
Atacama 2 CSP	Abengoa Solar Chile SpA.	110 MW	Tower	15 h
María Elena	Ibereólica Solar Atacama S.A.	400 MW	4 towers of 100 MW	10 h
Pedro de Valdivia	Ibereólica Solar Atacama S.A.	360 MW	4 Parabolic Trough Collectors of 90 MW	10 h
CEME1	CEME1 SpA	70 MW	Parabolic Trough Collector	14 h
Minera Centinela	Minera Centinela	7 MW	Parabolic Trough Collector	No

For the SAM simulation series of hourly meteorological data have been generated at the testing locations. The relative monthly distribution of GHI has been addressed using the TMY initially provided by Meteonorm. This monthly distribution has been modified in order to match with the expected annual values of GHI. Using this new monthly GHI values in the same Meteonorm tool, new TMY adapted to the local ground data have been obtained. In

TABLE 4 TABLE 4, details of the GHI and DNI outputs from the second Meteonorm TMY at each location are presented. In addition, SAM outputs are also shown. PANG station has been removed due to its special characteristics.

[1] http://www.acera.cl/

TABLE 4. Details of the TMY generated using modified Meteonorm inputs, and SAM results at each location.

	METEONORM ORIGINAL (kWh/m^2)		MODIFIED (kWh/m^2)		SAM OUTPUTS	
Name	***GHI***	***DNI***	***GHI***	***DNI***	**ANNUAL ENERGY YIELD** (GWh)	**Capacity factor (-)**
CAMA	2398	2745	2400	2746	486	55.50
PALM	2174	2253	2511	3066	560	64.00
CRUC	2294	2606	2583	3344	577	65.90
SLAR	2427	2836	2643	3297	569	65.10
SPED	2325	2645	2592	3222	563	64.40
ARMA	2275	2511	2792	3415	587	67.10
SALV	2238	2571	2661	3442	587	67.10
IDEO	2271	2686	2551	3343	575	65.70
ADDA	1944	1823	1963	1883	344	39.30
CCALA	1723	1696	1958	2210	385	44.00

Using the annual energy yield from SAM, and the DNI and latitude at each location, a linear model model is proposed. The obtained regression is presented in the following equation:

$$Ee = 0.0288\,DNI - 0.0612\,Lat \qquad (2)$$

where *Ee* means the annual energy yield per m^2 generated in the case of that m^2 were part of a power tower plant of 100 MW and 6 hours of thermal storage. DNI and *Ee* are in kWh/m^2 and Lat in decimal degrees. This expression is ready to be applied in the updated DNI map described in the previous section and using the developed mask described in the next section, the electricity potential of CSP power tower could be finally estimated.

POTENTIAL AREA FOR THE DEVELOPMENT OF CSP IN CHILE

As shown in the previous sections, Chile has a large territory with great potential for the development of solar energy due to its high irradiation values. However, other factors must be taken into account when evaluation the real potential of solar energy electricity. A restriction map defining the areas where it is not possible to install a power plant or where the costs would be too high can help for the determination of this real potential. For creating this map, an exclusion analysis is carried out and a Boolean map - also called a mask filter – is obtained. In this Boolean map the pixel's value define if that spot is exploitable (1) or not (0). The variables taken into account are:

- Only the areas with an annual DNI average of at least 1800 kWh/m^2 day are selected.
- Slopes are one of the more important factors when selecting a site for a CSP power plant. If the slope is too steep, the costs of leveling the terrain increase and it can make the inversion not profitable. The Digital Elevation Model (DEM) was used to derive the terrain slope. The threshold value for this slope is less than 3%.
- Constricted land is the part of the territory where is not possible to build a solar power plant. This includes waterways and water bodies (with a buffer of 50 m), roads (with also a buffer of 50 m), urban areas (with a buffer of 500 m), train lines (with a buffer of 70 m) and protected areas. Moreover, only areas within 80.46 km (50 miles) of the grid lines are considered.

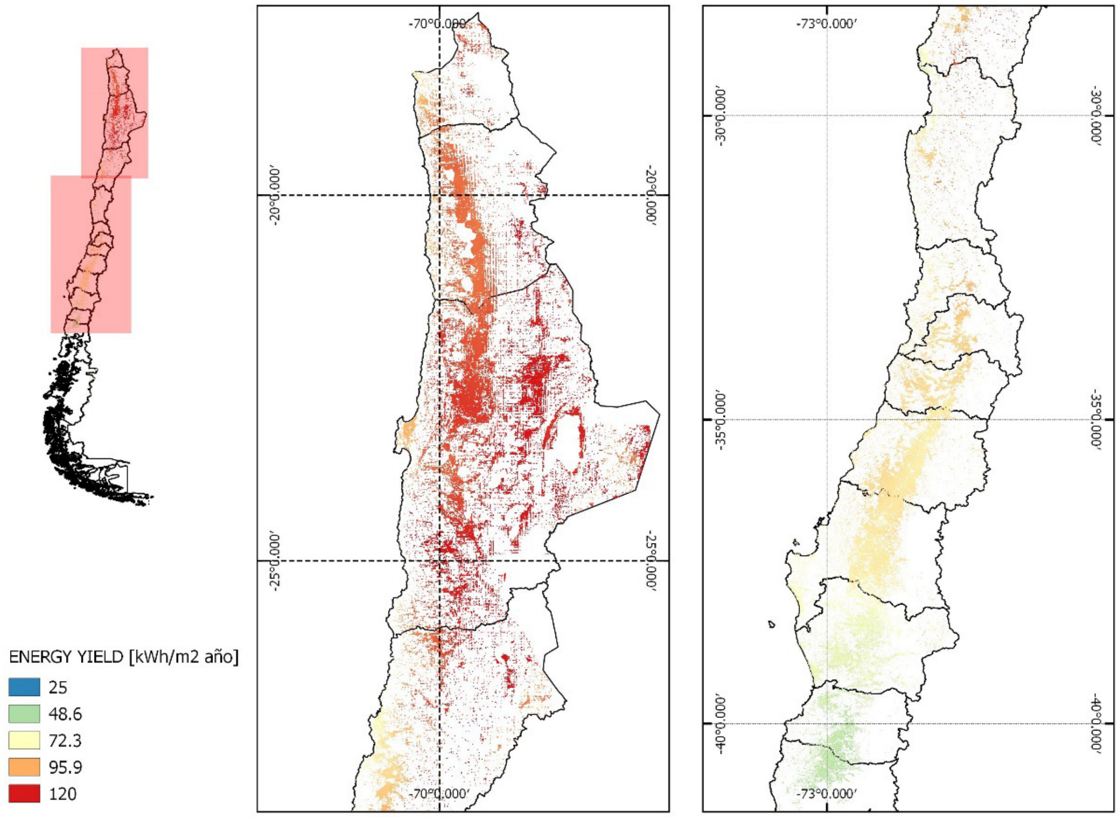


FIGURE 5. Potential of a power tower plant of 100 MW and 6 hours of thermal storage in Chile

The resulting mask filter allows the identification of the areas that should be excluded from the potential calculations. Along with these mask, the DNI values presented in section 3 and the model presented in section 4 were used in the determination of the potential of a power tower plant of 100 MW and 6 hours of thermal storage in Chile. The results of this analysis are shown in FIGURE 5. The areas with greater potential are located mostly in the north of the country, due to the combination of high irradiation values and large suitable areas.

CONCLUSIONS

In this paper, six maps of solar resources including the region of interest have been analyzed by comparing map values with the ground measurement stations available in *Explorador Solar*. All the spatial resolutions have been standardized to 1km for the analysis. According to the results of the GHI comparison, the best results are for MINEN and Geomodel data. The mean relative error compared with the ground measurements is around 3% in both cases. In general, for the DNI comparisons differences are larger than the GHI ones. Again MINEN and Geomodel data are close to the ground estimations with relative errors equal to 12 % and 6%, respectively.

According these results three multi-regressive models has been proposed to estimate DNI values. The best resulting fit uses MINEN and Geomodel maps as main inputs obtaining a reduced relative error of 4.5%. Finally, in the estimated solar resource map values of 8.5 kWh/m^2 are usually achieved at the northern part of the country. These values agree with the ground measurement estimations.

A preliminary model for the solar power plant energy yield estimation in Chile has been calculated. For that purpose, we have defined the base case as a tower CSP plant with 100 MW of net energy output and 6 hours of thermal storage. For the energy yield estimation the NREL's System Advisor Model has been used. The power plant model has been simulated using hourly meteorological series generated by Meteonorm considering as well the annual values of ground measurements. The resulting model has been applied to the estimated DNI map.

A geographic analysis of the territory has been carried out. Using the irradiation values and the production model proposed in this work, the potential of a power tower plant of 100 MW and 6 hours of storage in Chile has been determined. The best areas for the development of this technology are located in the north, and particularly in Antofagasta, due to high irradiation values.

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