Development of Solar Energy in Chile and the World

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***Abstract*—Chile is a country with a huge potential for solar energy. This paper presents an analyses of the global situation of solar energy, identifying the geographical regions with the maximum potential source of solar energy. These areas tend to be in desert locations, since this is where the greatest irradiance is concentrated. A prediction of the potential situation in 2030 is considered. The Chilean desert is considered, identifying the photovoltaic electricity potential and mentioning the current and future projects that will significantly increase the photovoltaic generation of the country.**

***Index Terms*—Concentrated solar power, irradiation, non-conventional renewable energy, photovoltaic, solar energy, world perspective**

I. Introduction

SOLAR energy is a seemingly unlimited flow of energy from the sun. The energy is transmitted through sunlight, which is one of the clear examples of direct solar energy delivered to the Earth. Solar energy has been used since ancient times as a source of light and heat, such for example to light the Olympic torch using the sun's rays concentrated on a mirror [1]. However, the principle of the photoelectric effect and solar collectors were discovered in the 20th century [1]. Solar energy is characterized by being renewable, clean and inexhaustible [2]. This is why the use of this energy has attracted a lot of interest as a sustainable solution to meet energy demand and climate change, as presented in the Paris agreement [3]. Most countries in the world are developing energy policies for the inclusion of Non-Conventional Renewable Energies (NCRE) and in order to reduce the use of fossil fuels to reduce carbon dioxide emissions [4] generated by existing power plants that use fuels such as oil and coal. With the advancement of technology, photovoltaic solar energy is the most attractive solution in many countries, since it reduces energy dependence, increases energy security and allows sustainable development [5]. However, at the time of implementation it is necessary to know the geographical characteristics and the solar resource that each country has, therefore some countries have greater opportunities to incorporate solar technology due to their environmental conditions compared to other countries.

Solar energy is used mainly for the generation of electricity through photovoltaic panels and to heat water through solar thermal collectors [6]. With these two ways of converting solar energy into usable energy, there are a wide variety of applications, such as solar lighting, heating, solar chargers, electricity generation, solar satellite and solar-powered transportation [5].

In Section II this paper presents a world view of solar energy, focusing mainly on the geography necessary for solar energy capture, world irradiance indices and solar energy projections. Section III presents an overview of solar energy in Chile, presenting important data on electricity generation, the photovoltaic electricity potential, in operation and future projects.

II. Solar energy: world scenery

The global outlook has been unfavourable for the market in the generation of electricity by solar energy since the pandemic event overlapped with the shortage of photovoltaic glass that had been afflicting the industry since 2018 [7] but which ended in the last quarter of 2020. After changes in Chinese policy [8], glass production returned strongly and demand for photovoltaic modules is expected to grow by 10% compared to 2020, reaching 153.8 [GW], as shown in Fig. 1 [9]. According to SGKPlanet, by 2021 the five main world producers of solar energy will be China, USA, Japan, India and Germany, where the sum of these countries will reach a total of 358.1 [GW] of power [10]. Although these figures are difficult to validate given that today it is complex to know the number of people who have installed their own solar panel systems and how much energy they collect to inject into the grid. However the data looks similar to the studies carried out by Enerdata [11].

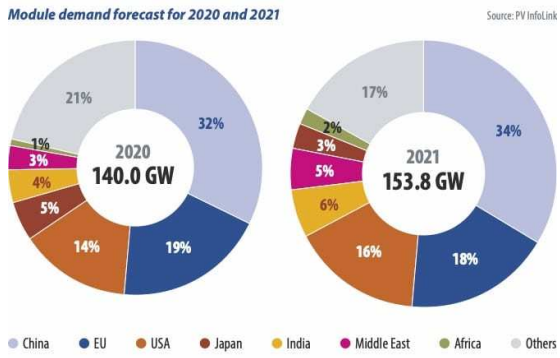

Fig. 1. Comparison of demand for solar modules between 2020 and 2021. Obtained from [9].

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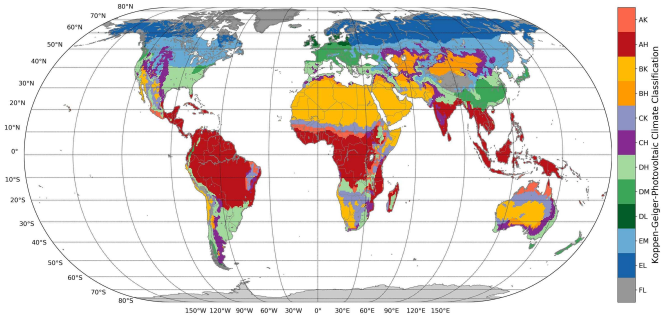

Fig. 2. Climate classification map. Obtained in [14].

A. Geography in the development of solar energy

Almost all of the energy available in the Earth's atmosphere, except geothermal energy, comes from the sun in the form of heat or in the form of radiation. The amount of energy the earth receives from the sun is approximately 1.37 kW per m^2 [12]. Although this is the average energy density that the Earth's surface receives, clearly not all the surface receives the same amount of energy. The irradiance (unit of measurement of the solar radiation that reaches the Earth) depends on certain factors, mainly geographical, that is why the implementation of the generation of electricity through a solar source is more effective in certain places over others. Deserts are places with a large amount of irradiance given the absence of clouds and extensive arid territories. In 2019, the largest solar energy park in the United Arab Emirates was inaugurated [13], making good use of the properties of its geography.

B. Deserts and irradiance indices

Irradiance is the unit that measures the density of radiation from the sun that reaches the earth's surface and is measured in W/m^2. Based on the above, Ascencio-Vásquez [14] using the Köppen-Geiger-Photovoltaic (KGPV) method, designed a world climate classification where he contemplated irradiance in different climates to generate a color map with 24 are identified categories (see Fig. 2). In Fig. 2 the scale on the right consists of two letters, the first indicates the climatic zone (A-Tropical, B-Desert, C-Savanna, D-Temperate, E-Ice and F-Polar) and the second letter corresponds to the irradiance level (L-Low, M-Medium, H-High and K-Very high).

Then, Ascencio-Vásquez generates Table I which indicates the percentage of presence of an irradiance category by climatic zone. From this it is clear that desert areas have greater irradiance compared to other areas. By having a higher concentration of radiation, deserts are potential sources of solar energy. Data from 2009 shows that 6 deserts as the places with the greatest irradiance that could be used for solar energy.

Table II summarizes these conditions [15]. The amount of energy that deserts receive in less than 10 hours is capable of supplying all the energy consumption of humanity for a year, in a utopian scenario. For a case closer to the current technological scope, consider an efficiency ratio of 8% in energy conversion, with covering an area of 1,100 km^2 to be distributed in one of the aforementioned deserts, it would be enough to supply about 20 [TW] of average power [16].

TABLE I
PERCENTAGE OF IRRADIANCE BY CLIMATIC ZONE ACCORDING TO KGVP

Zone	L	M	H	K
Tropical	0.04%	2.80%	11.11%	1.77%
Desert	0.00%	0.17%	3.36%	12.05%
Savanna	0.01%	1.20%	5.25%	4.44%
Temperate	0.76%	4.45%	7.58%	0.84%
Ice	20.24%	10.12%	2.10%	0.10%
Polar	8.95%	1.17%	0.61%	0.80%

TABLE II
DESERTS WITH GREATER IRRADIANCE

Desert	Location	Area	Irradiance
Atacama	South America	139.869 km^2	275 W/m^2
Arabia	Western Asia	2.589.910 Km^2	270 W/m^2
Sáhara	Africa	9.064.960 Km^2	260 W/m^2
Great Basin	North America	492.100 Km^2	220 W/m^2
Greaty Sandy	Australia	388.500 Km^2	210 W/m^2
Takla Makan	Central Asia	271.950 Km^2	210 W/m^2

C. Projections on solar energy

Currently, almost all major environmental policies are promoted by the so-called 2015 Paris agreement, held at the COP21 [17] summit, where the agreement seeks to keep the global temperature rise below $1,5°C$.

That is why the different countries participating in the agreement strive to carry out efforts promoting non-polluting energies, this is how world powers such as the US, Japan, Germany and China, seek to implement more solar installations to cover part of the energy generation and reduce the gap by 2025.

To take an example, the US will have to quadruple the number of photovoltaic installations to reach the nearly 800 [GW] of power required to meet the proposed [18]. In a more general view, the cost of the solar installation is expected to decrease to 340-834 [USD/kW] by 2030, that is, a decrease of between 31 % and 78 % in the best case [19]. By 2030 it is expected that half of the world's energy supply will come from sustainable sources, and that in total 35 % will be solar energy [20].

III. SOLAR ENERGY IN CHILE

Chile is a country located on the South American continent that borders Bolivia, Peru and Argentina. It consists of 16 regions, 56 provinces and 346 communes with a total population of about 18 million [21].

Due to its geographical location, the north of Chile is positioned as one of the areas with the highest concentration of average daily solar radiation in the world. It is possible to satisfy the energy demand of the entire country with the installation of photovoltaic solar panels in an area of 20 km^2 [22].

For this reason, many international and national investors have invested capital in the installation of photovoltaic solar plants and are now concentrating on solar power plants.

TABLE III
STATUS OF ERNC PROJECTS. DATA OBTAINED IN [27].

Technology	Operation [MW]	Under Test [MW]	Building [MW]	EQR Approved
Biomass	466	6	166	0
Wind	2356	327	1958	103939
Geothermal	40	0	33	155
Mini Hidro	596	1	66	750
Solar - PV	3360	375	3116	23641
Solar - CSP	0	0	0	2032
Total	6818	709	5339	37517

TABLE IV
SOLAR ENERGY PROJECTS IN OPERATION IN CHILE.

Project	Technology	Region or city	Installed capacity [MW]	Operation date
San Andrés	Solar photovoltaic	Atacama	50.60	2014
Diego de Almagro	Solar photovoltaic	Atacama	28.05	2014
Pozo Almonte Solar 3	Solar photovoltaic	Tarapacá	16.04	2014
Llanos de Llampos	Solar photovoltaic	Atacama	101.02	2014
Solar Jama	Solar photovoltaic	Antofagasta	52.65	2015
Javiera	Solar photovoltaic	Atacama	69.02	2015
Salvador	Solar photovoltaic	Atacama	68	2015
María Elena	Solar photovoltaic	Antofagasta	68	2015
Luz del Norte	Solar photovoltaic	Atacama	141	2016
Conejo Solar	Solar photovoltaic	Antofagasta	104	2016
Pampa Solar Norte	Solar photovoltaic	Antofagasta	69.39	2016
Carrera Pinto	Solar photovoltaic	Atacama	93	2016
Quilapilún	Solar photovoltaic	Santiago	103.02	2017
Parque El Romero	Solar photovoltaic	Atacama	196	2017
Parque Finis Terrae	Solar photovoltaic	Antofagasta	138	2017
Quilapilún	Solar photovoltaic	Santiago	103.02	2017
Uribe Solar	Solar photovoltaic	Antofagasta	52.8	2017
Doña Carmen Solar	Solar photovoltaic	Valparaíso	34.06	2017
El Bolero	Solar photovoltaic	Antofagasta	135.7	2018
El Pelícano	Solar photovoltaic	Coquimbo	108.1	2018
Santiago Solar	Solar photovoltaic	Santiago	92.73	2018

TABLE V
SOLAR ENERGY PROJECTS THAT CAME INTO OPERATION BETWEEN 2020 AND MARCH 2021.

Project	Technology	Region or city	Net power [MW]	Operation date
PV park San Pedro	Solar photovoltaic	Antofagasta	106	18-02-2021
PMGD Berrueco	Solar photovoltaic	de Ñuble	9	06-02-2021
Venturada	Solar photovoltaic	de Ñuble	9	13-02-2021
PMGD Lumbreras	Solar photovoltaic	Metropolitana	3	Feb.-2021
PMGD FV El Membrillo	Solar photovoltaic	O´Higgins	2.5	Feb.-2021
Sonnedix Atacama Solar II	Solar photovoltaic	Atacama	170	Jan.-2021
PMGD Ciprés	Solar photovoltaic	del Maule	9	19-01-2021
PMGD Quinantu Solar	Solar photovoltaic	del Maule	9	15-01-2021
PMGD PFV EL Romeral	Solar photovoltaic	O´Higgins	8	Jan.-2021
PMGD PFV Los Perales I	Solar photovoltaic	Valparaiso	3	Jan.-2021
PMGD PFV santa Carolina	Solar photovoltaic	O´Higgins	3	Jan.-2021
PMGD PFV Don Jorge	Solar photovoltaic	O´Higgins	3	Jan.-2021
PMGD PFV Caimi	Solar photovoltaic	Valparaiso	0.2	Jan.-2021
USYA	Solar photovoltaic	Antofagasta	52.4	07-12-2020
Andes Solar IIA	Solar photovoltaic	Antofagasta	69.4	13-08-2020
Pepa Solar	Solar photovoltaic	Metropolitana	9	12-08-2020
Granja Solar	Solar photovoltaic	Tarapacá	105	30-06-2020
Parque FV Victoria	Solar photovoltaic	Antofagasta	9	11-06-2020
LLanos del Potroso	Solar photovoltaic	Coquimbo	9	07-05-2020
Almeyda	Solar photovoltaic	Atacama	52	05-05-2020
Solar park Villa Alegre	Solar photovoltaic	del Maule	9	31-03-2021

Due to the Paris agreement in 2015, Chile is committing to combat climate change through environmental policies that allow a sustainable future with low carbon dioxide emissions. From the energy point of view, Chile's goal is that by 2050, 70 % of the energy consumed will come from non-conventional renewable energies [23]. Therefore Chile wants to become a world leader in clean energy. It also has the goal of decarbonization or carbon-neutrality for the year 2050 and to obtain an efficient, sustainable and safe energy matrix. Therefore the use of energy from clean sources plays an important role.

TABLE VI
FUTURE SOLAR ENERGY PROJECTS UNDER EVALUATION AND UNDER CONSTRUCTION IN CHILE.

Project	Technology	RegionCity	Power [MW]	Datea	Stage
PV solar park Nuevo Quillagua	Solar photovoltaic	Antofagasta	100	Feb.-2021	Under test
Photovoltaic project Azabache	Solar photovoltaic	Antofagasta	59	Feb.-2021	Under test
PMGD PFV Rauquén	Solar photovoltaic	Maule	9	Feb.-2021	Under test
New solar PV plant Casabermeja	Solar photovoltaic	Metropolitana	9	Feb.-2021	Under test
PMGD PFV Paine	Solar fotovoltaica	Antofagasta	9	Feb.-2021	Under test
PMGD Chillán Solar	Solar photovoltaic	Ñuble	9	Feb.-2021	Under test
PV park Torcazas	Solar photovoltaic	O´Higgins	3	Feb.-2021	Under test
Solar Malinke	Solar photovoltaic	Metropolitana	3	Feb.-2021	Under test
Solar Concentration Plant Cerro Dominador	CSP	Antofagasta	110	Mar.-2021 (Operation)	Under construction
PV park la Huella	Solar photovoltaic	Coquimbo	84	Mar.-2021 (Operation)	Under construction
Caracas plant	Solar photovoltaic	Coquimbo	18	May.-2021 (Operation)	Under construction
Teno uno plant	Solar photovoltaic	Maule	9	May.-2021 (Operation)	Under construction
Machicura park	Solar photovoltaic	Maule	9	May.-2021 (Operation)	Under construction
Los Corrales del Verano park	Solar photovoltaic	Metropolitana	9	May.-2021 (Operation)	Under construction
Sol de Lila park	Solar photovoltaic	Antofagasta	163	Jun.-2020 (Operation)	Under construction
Sol del Desierto park - fases I y II	Solar fotovoltaica	Antofagasta	230	Jun.-2021 (Operation)	Under construction
PMGD PV Los Molinos	Solar photovoltaic	Metropolitana	9	Jun.-2021 (Operation)	Under construction
Domeyko 2 project	Solar photovoltaic	Antofagasta	204	Jul.-2021 (Operation)	Under construction
Sol de los Andes	Solar photovoltaic	Atacama	89.4	Jul.-2021 (Operation)	Under construction
Extension Finis Terrae stage 1	Solar photovoltaic	Antofagasta	126.2	Aug.-2021 (Operation)	Under construction
Valle del Sol project	Solar photovoltaic	Antofagasta	163	Aug.-2021 (Operation)	Under construction
PMGD PV QUetena	Solar photovoltaic	Antofagasta	9	Sep.-2021 (Operation)	Under construction
Diego de Almagro project 1 y 2	Solar photovoltaic	Atacama	104	Sep.-2021 (Operation)	Under construction
PV projectCoya	Solar photovoltaic	Antofagasta	192	Dec.-2021 (Operation)	Under construction
Pampa Tigre park	Solar photovoltaic	Antofagasta	100	Dec.-2021 (Operation)	Under construction
Solar project Valle Escondido	Solar photovoltaic	Atacama	105	Dec.-2021 (Operation)	Under construction
Andes II B	Solar photovoltaic	Antofagasta	180	Feb.-2022 (Operation)	Under construction

The factors that has allowed Chile to position itself as an example of the use of energy from renewable sources is due to established environmental policies, established energy policies, regulatory framework [24] and favourable environmental conditions for the use of renewable energy. Among the main laws are Law 20,571 for distributed generation, Law 20,365 that establishes the tax exemption with respect to solar thermal systems and Law 20,698 of expansion of the energy matrix through non-conventional renewable sources (NCRE) [25].

The distribution of electricity generation by non-conventional renewable sources is presented in Table III. It can be seen that the installed capacity of ERNC is 6,818 MW until April 2021 and photovoltaic solar energy leads the way with 3,360 MW of operation (equivalent to 12.88 % of the country's total installed capacity in electricity generation sources [26]). However, the projects that have most approved the environmental rating (RCA) are related to photovoltaic solar energy. Also the solar power concentration (csp) has a relevant number of 2032 MW in the environmental rating. The figures reveal that the use of solar energy in Chile is taking a lot of interest, due to the great potential of the solar resource that the country contains. In [28], the geographically distributed photovoltaic electric potential is presented, where in the north of Chile (Arica, Iquique and Antofagasta) they contemplate the highest annual photovoltaic electric potential between approximately 2118 and 2410 kWh/kWp. On the other hand, further south, in the cities of Temuco and Valdivia they have a potential between 1241 and 1534 kWh/kWp. As a result of this, most of the large photovoltaic solar generation projects are located in the north of Chile.

The photovoltaic electric potential is due to the amount of solar radiation that affects certain geographical places in Chile, being the north where there is greater normal direct irradiance of about 3652 kWhm^2 (in [28]). Further south in the cities of Valdivia and Temuco they have a normal direct irradiance of approximately between 1095 and 1241 kWhm^2. Therefore, Chile is one of the countries with the highest solar irradiance indices in the world, a product of which it is considered a country with high solar energy capacity. Due to the large solar potential that exists in Chile, there are a large number of projects associated with photovoltaic solar generation. In Table IV some projects already in operation in the generation of electricity in Chile are presented. Table V shows some projects that came into operation between 2020 and March 2021 installed in Chile. The acronym PMGD corresponds to Small Means of Distributed Generation, which are projects that in recent times have been incorporated for the generation of electricity. Additionally, in Table VI presents some comming project which are under different stages to be installed in Chile

IV. CONCLUSIONS

Talking about environmental policies today is synonymous with talking about the 2015 Paris agreement, and this work is an example. The largest current projects in solar energy are driven by this agreement, both globally and locally. This is because, so far, the most promising way to deliver is to promote renewable energy facilities. This study shows that despite the pandemic situation, the solar energy market has not decreased in demand, even, against all expectations, it increased demand by 10 % this year compared to the previous one.

Relevant geographical factors in energy potential were also analysed, where it was observed that desert places have the most favourable conditions for electricity generation since they have the highest irradiance indices, followed by tropical areas. In global terms, everything indicates that in 2030 more than a third of the energy consumed will be produced by solar energy. As for Chile, it has the highest irradiance indices in the world, which makes it a country with the potential to be pioneers in the matter. This is why it set itself the goal of achieving energy production almost entirely from solar energy. In the last year, 21 projects came into operation, so in this time the total number of solar energy projects that have projects in the accounts doubled since 2014, which indicates a future for renewable energy in the country.

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