Solar Energy in Chile SXX-SXXI

Mauricio Osses[1,2], Cecilia Ibarra[2], Bárbara Silva[3] and Miriam Roth[1]

[1] Universidad Técnica Federico Santa María, Santiago (Chile)

[2] Center for Climate and Resilience Research, Santiago (Chile)

[3] Universidad Alberto Hurtado, Santiago (Chile)

Abstract

This work attempts to fill in the gaps in the literature by providing a narrative of the development of solar sciences and technologies in Chile during the XX and XXI centuries. It covers scientific activities related to measuring solar irradiance and describes technological trajectories and capacity building. The study shows how Chilean solar energy history has evolved in connection to the world, and as part of an international network of scientists and engineers. It provides a perspective of technological trajectories and capability accumulation, which shows discontinuities and gaps as well as some interesting experiences of success and failure with technological experimentation and diffusion. This work proposes there is a connection between an early and visionary period during the XX Century and the recent and disruptive developments of solar development in Chile.

Keywords: Solar history, solar irradiance, technological trajectories

1. Introduction

Chile's Atacama Desert has been shown to have the highest long-term solar irradiance of any place on Earth, offering unique conditions for solar energy development. This has attracted worldwide attention since the 1900s and several research groups, governmental agencies and private investors have taken various initiatives that attempt to take advantage of this generous resource. However, there are important gaps in the historical documentation of local solar measurements and technological development in the region.

This work summarizes a larger collective effort to recover Chilean history in a book (Osses et al. 2019). The book and this paper attempt to fill in the gaps in the literature by providing a narrative of the development of solar sciences and technologies in Chile during the XX and XXI centuries. It covers scientific activities related to measuring solar irradiance and describes technological trajectories and capacity building. Relevant projects, selected for their innovative approach or future potential, are used as examples. The work used as main sources documents and visual material kept in the Technological University Federico Santa María archive, which includes thesis, papers, projects and institutional reports. It also used interviews with the scientists and engineers who worked in the field.

In the XXI century there are several visions of solar futures for Chile. The paper explores the perspectives for solar science nowcasting and forecasting and the visions of Chile as a solar technology developer and as a solar energy producer.

2. Solar measurements in Chile

Long-term solar measurements in Chile can be separated in three historical stages. The earliest one corresponds to the period 1923-1947, when the Chilean Smithsonian Astrophysical Observatory collected data at Atacama (Calama-Mount Montezuma station). The Observatory was one of three world stations set by the Simthsonian Institute to collect data which was processed in the Unites States. A second period corresponds to the development of a local network with 89 stations measuring along the Chilean territory between 1961 and 1983. The National Solarimetric Archive consisted of surface observations of horizontal global irradiance and

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simulated data from atmospheric models for all the national territory. This information was shared with several international organizations. The third and current stage includes hourly irradiance data collected from 2004 to 2016 at 90 m horizontal resolution over continental Chile. The results have been validated using 140 surface solar irradiance stations throughout the country, providing a solar radiation database for Chile.

Chilean Smithsonian Astrophysical Observatory (1923-1947)

At the beginning of the 20th century, the Atacama region was already considered an optimal solar location. Considering this characteristic, in 1918 the Smithsonian Astrophysical Observatory, led by Samuel Langley, installed a solar observatory in northern Chile, specifically in Calama.

Abbott (1918) briefly comments on the vicissitudes that would conclude with the installation of the Calama station, then Monte Montezuma, indicating that the decision to choose the Atacama region was not strictly scientific, but also weighed reasons associated with international and logistics policy. The Calama-Monte Montezuma station was the longest operating facility of the Smithsonian program, measuring continuously between 1923 and 1947, that is, over a period of 25 years, under the direction of researcher Dr. C. G. Abbot.

The main objective of this observatory was to rigorously measure changes in the solar constant, with the least possible disturbances of particles, clouds or water vapor. Through this study it was possible to establish the solar constant of 1,945 cal/cm^2 per minute that was universally accepted, and also testing the validity of a 273-month periodicity in solar variation assumption. In 1949 a report was published with the conclusions of this investigation (Abbot, 1949). The program ended in 1956, without being able to establish a conclusive connection between solar variability and surface weather conditions (Rondanelli et al., 2015).

An interesting anecdotal fact reported in an interview conducted by Nelson Arellano to the engineer Carlos Espinosa refers to the use of mirrors to transmit information. Comparing the different Smithsonian observatories installed in different locations (United States, Africa, Chile), the data produced worldwide took weeks to months to reach the offices of Washington D.C., with the exception of Chileans. Apparently, given the collaboration of the copper mining company, owned by the Guggeinheim family, it was possible to use the telephone to call the United States every day to give the report. However, the obstacle was to make the data arrive from the Observatory to Calama. To solve this obstacle, mirrors would have been used to make morse code signals and, thus, transmit results almost in real time (Osses et al., 2019).

National Solarimetric Archive (1961-1983)

The Solar Energy Laboratory was funded in 1961, under the initiative of Professor Julio Hirshmann Recht, a pioneer researcher in the field of solar energy, who was its first Director until 1978. The Laboratory was located on top of the Central House tower at the Technical University Federico Santa María (UTFSM) in Valparaiso, Chile, where it had an available area of approximately 800 m^2. Hirschmann was well aware of the unique favourable solar radiation conditions in the north of Chile and had originally established contact with the researchers working on solar measurements in the region. As mentioned earlier, particularly important was the work reported by Charles Abbot, who had carried out radiative measurements from 1923 to 1947 in the interior of Antofagasta, with the support of the Smithonian Institute, who contributed to spreading the solar potential of the Atacama Desert (Abbot, 1951). Other systematic records were made from September 1957 until September 1958 by the Applied Sciences Research Department, DICA (University of Chile, 1967) in the town of Baquedano at the Atacama Desert, being published by Francois Desvignes and German Frick (1959). Nevertheless, despite acknowledging these two relevant initiatives, Hirschmann stated that "*Up to ten years ago, the solar radiation measurements in Chile had been sporadic, were carried out in diverse regions of the country, and were not systematically related*" (Hirschmann, 1973).

Hirschmann had early recognized that having the most accurate data possible was essential to develop technological applications that could compete economically with conventional sources. Not only it was important that the data were obtained with properly calibrated instruments, but also that the elaboration, recording of maximum values, integration to obtain daily solar energy and the determination of monthly average values were made with a common pattern, so that comparisons of data recorded at different stations and by different organizations could be made (Roth, 1997).

Aiming at addressing the above issues, several initiatives were promoted by Hirschmann and his associates in order to create a proper and organised solarimetric datacentre for the whole country. In 1965 the Solar Energy

Laboratory already had 24 instruments for solar and atmospheric measurements, being considered the best assembled in the country. As a result, in 1965 the Meteorological Bureau of Chile and UTFSM signed an agreement to create the National Archive of Solar Evaluations at the Solar Energy Laboratory. On December 5, 1970, this National Solarimetric Archive was inaugurated in the presence of delegates of the Regional Associations of the World Meteorological Organization of the United Nations (Hirschmann, 1973).

The Solar Energy Laboratory contacted all those Chilean institutions already carrying out solar measurements to obtain their cooperation in providing a more complete vision of the solar radiation conditions of incidence or incidental to all regions in Chile. According to Hirschmann (1973), these institutions were the Meteorological Bureau of Chile, the Ministry of Public Works (Department of Hydrology), the national company of electricity ENDESA (Department of Hydrology), University of Chile, Catholic University of Chile, University of Concepcion, State Technical University and the Northern University. Nationwide data was sent to the Solar Energy Laboratory at UTFSM, where it was evaluated and processed by a team of specially trained people with standardized procedures, as requested by the World Meteorological Office. The results were sent back to the organizations of origin.

The first article by Hirschmann reporting coordinated measurements of solar radiation of incidence in Chile was issued in the Solar Energy Journal (Hirschmann, 1962). This publication compared the first measurements carried out by pyranographs in the north of the country with the isopleths over the earth's surface established by J. N. Black (1956). Later on, Hirschmann published his work titled "Records on solar radiation in Chile" (1973), including a summary of Chilean publications regarding this subject and calling attention to the phenomenon of seasonal displacement of maximum solar radiation over the South American continent. Hirschmann mentions the work by Sergio Cuevas Droguett (1963), published in the local journal Scientia, with measurements of solar radiation recorded in 1962 in the northern and central zones of Chile. It is also mentioned the article published by César Caviedes (1967) on solar radiation and temperatures in the center of the desert of the North of Chile. However, Hirschmann states that "*the problem with these first Chilean publications is that they have few trustworthy results in the measurements of solar radiations of incidence (global)*" (Hirschmann, 1973).

Original data sets reported by Bocic (1958), Hirschmann (1962), Dobosi and Ulriksen (1970), basically came from two types of instruments used for solar radiation measurements in Chile. Sunshine duration was obtained by Campbell-Stokes Heliographs and global radiation was measured by Robitsch bimetallic Pyranographs. According to Dobosi and Ulriksen (1970), by 1965 there were 14 stations in the country which had simultaneous measurements of global radiation and sunshine duration, 3 stations had global radiation measurements only and the remaining 25 had sunshine duration measurements only. Radiation data covered the period 1964-66. Available sunshine duration data extended mainly from 1948 to 1957 and from 1964 to 1966.

Hirschmann (1973) describes all available stations reporting to the National Solarimetric Archive in the period 1961-1970, going from Parinacota in the northest part of Chile, run by ENDESA, down to three stations located in the Antartic, run by the Meteorological Bureau of Chile (Centro Meterológico Antártico, Base Pedro Aguirre Cerda, Base Gabriel González Videla). An interesting case were the recordings from Mataveri, Easter Island, taken by an old instrument of non-linear ordinates. In order to use this data, the personnel of the Solar Energy Laboratory changed the diagrams, one by one, to a lineal scale using a specially designed integrator. A total of 81 stations were equipped with heliographs during this period and 54 of them also had pyranographs. Only two of these stations kept continuous recordings during the whole period of 10 years for both instruments: Cerro Moreno in Antofagasta and Quinta Normal in Santiago. The number of stations with available data from heliographs/pyranographs started from 29/6 in 1961, reached a maximum of 61/40 in 1965 and ended up in 55/30 by 1970.

UTFSM also carried out comparative simultaneous measurements on different types of instruments for the recording of solar radiation. These instruments were a Robitsch-Fuess bimetallic pyranograph, Kipp thermocouple pyranograph with Kipp recorder and Eppley thermocouple pyranograph with Dynmaster recorder. Small differences between these instruments, plotted on a common scale for a given day, have been reported by Hirschman (1974), presenting the cosine function as a mathematical expression for the processes of solar energy. Aiming at improving the periodic contrast or comparison of different equipment, German Frick built a pyroheliometer of his own design.

In 1974, an Armstrong compensation pyheliometer was acquired, which was for many years the standard instrument for Chile's solarimetric measurements, as it was the most accurate instrument available in Chile and Latin America. In 1997 it was replaced by a cavity radiometer acquired by the Chilean Meteorological Directorate. Subsequently, when the computation was integrated into the procedures, it was recorded on Digital Magnetic Tapes and currently on diskettes.

When the Chilean governmental fund for scientific and technological development (Fondo Nacional de Desarrollo Científico y Tecnológico, FONDECYT) started in the 80s, several projects were presented to modernize and improve the procedures for registering and presenting solar and wind data, adapting it to new possibilities of data registration, proposing a uniform procedure to the national community and making results compatible with what was done in Europe and the United States (Roth, 1997). Pedro Roth, from the Technical University Federico Santa María, conducted two projects titled "Registration and Presentation of Solar and Wind Data" (Fondecyt 0019, Fondecyt 476/82).

Current solar irradiance data (2004-2016)

The growing market of renewable energies in Chile and in the world requires an adequate estimation of natural resources with renewable energy (water, wind and solar), in particular for planning variable operation of power generation plants (wind and solar), with prediction horizons of hours and days. The precise prediction of meteorological variables of the solar and wind resource is a problem that requires the interaction between real-time data (measurements), satellite images, computational models and applications of computational intelligence techniques. The real-time predictions generated are a valuable asset for the operators of the generation systems.

The timely measurement of solar and wind resources is not in itself sufficient to predict the solar radiation received by each collector (thermal, concentrator or photovoltaic) in a solar farm. The situation is similar in a wind farm, since both often occupy several hectares. The solar resource is affected by cloudiness that is not distributed evenly over the solar field. The wind resource is also affected by the topography of the place and the wind conditions of the weather station at the place where each turbine is located are not necessarily replicable. To predict the solar radiation that each panel receives on a solar farm, as well as the wind speed that each turbine receives, sophisticated models with real-time feedback are required to predict resource availability and thus accurately estimate energy production of the systems and thus reduce the financial risk associated with the projects.

The solution for a solar resource prediction that addresses different time scales will combine measurements on the ground, sky cameras, satellite images with forecasting algorithms and machine learning techniques. The objective is that solar energy, which is characterized by being a renewable resource of a variable nature, becomes a predictable and therefore manageable energy resource.

Estimates through satellite images require that methodologies be validated with precision measurements in the field. Pyranometer-based measurements from ground stations typically have lower uncertainty levels that satellite-derived data obtained by radiative transfer models. In Chile, there are currently not enough high-end weather stations with state-of-the-art equipment. On the one hand, there are meteorological stations of different characteristics and for different purposes, very few of them of high range and oriented to scientific research. While some of the data from these stations can be acquired, their specifications do not allow the raw treatment, necessary for calibration and validation of high precision models.

There are three public databases with solar radiation information in Chile. As mentioned earlier, the National Solarimetric Archive collected data on 89 stations between 1961 and 1983, whose information has been made available by Sarmiento (1995), several final year project publications at UTFSM (Cáceres, 1984; Lira, 1986; Ortega, 1989; Guajardo, 1999) and the summary report "Solar irradiance in territories of the Republic of Chile" (CNE/UNDP/UTFSM, 2008). There are claims of discrepancies between the Archive and other sources of information. According to Ortega (2010), "*the data from the Archive might have uncertainties as high as 15% associated to the measurement period, plus the uncertainty which is inherent to the use of actinographs (pyranographs)*". However, these claims have not been properly proven, but the argument has been helpful at justifying fresh funding for modern measurement campaigns.

Since January 1988, the Chilean Meteorological Directorate run several pyranometers located at 18 meteorological stations along the country. However, half of them have been decommissioned due to maintenance costs during 2001-2005, leaving only nine operating stations available on the website until 2010, when the global measurement was reported on a horizontal surface. The data was taken in 10 min intervals, presented as hourly integrated irradiation (Wh/m^2) and can be requested at www.meteochile.cl at a low fee that covers processing costs.

The German Cooperation Agency (GTZ) together with the National Energy Commission (Comisión Nacional de Energía CNE) started a measurement campaign in 2008 whose objective was to provide the general public with integrated and comfortable access to the data obtained to date from a network of three ground stations located at Pozo Almonte, San Pedro de Atacama and Crucero, northern part of Chile in the Atacama Desert (available at http://walker.dgf.uchile.cl/Mediciones/). The measurement campaign comprised a wind and solar energy survey in a wide area to better understand the characteristics of these resources in the country, it was not intended to offer scientific precision, but reliable, consistent and comparable data. Many of the stations installed by GTZ have stopped operating. In the case of wind, there are stations of the Meteorological Directorate of Chile and stations installed by GTZ report wind resource measurements, which do not have online access. The only public precision station in Chile, is installed in María Elena and has been operational since 2012. This station called Crucero II is the only one that registers Direct Normal Radiation (DNI).

Two efforts have been made in the estimation of solar radiation from geostationary satellite images in Chile. One of them is the Solar Explorer, developed by the Department of Geophysics of the University of Chile. The Solar Explorer presents the estimation of solar resources in Chile and these data have been generated from atmospheric models and satellite data, for the period between 2004 and 2016 at 90 m horizontal resolution over continental Chile and the results have been validated using 140 surface solar irradiance stations throughout the country (Molina et al., 2017). Another similar initiative was the Chile-SR model, developed by the Pontifical Catholic University of Chile, specifically suited for the conditions of Chile by including updated altitude-corrected weather data (temperature, relative humidity, and atmospheric pressure), topography, and surface albedo (Escobar et al., 2014). The output data from the Chile-SR model is composed of global horizontal radiation and direct horizontal radiation in hourly basis. Both initiatives, solar explorer and Chile-SR model, are currently discontinued. Although the solar explorer does not provide a real-time estimate of solar radiation, one of the great values it has is that it is a tool that is available online and allows users to estimate the type meteorological year (TMY) for each point in the country.

3. Solar technological development

Technological development in Chile shows richness in variety of applications and experimentation, such as desalination, water heating, photovoltaic cells and solar energy storage systems. The projects used local capacities together with international collaboration. The role of the Solar Laboratory of the Technological University Federico Santa Maria was of particular relevance in this area. There was capability accumulation through international collaboration, formal teaching, mentoring and research and development projects. However, there are several discontinuities along time, which impacted capabilities development and technology diffusion. There is scarce formal documentation of the projects undertaken, the available documentation is dispersed on libraries and personal references throughout the world.

Solar desalination

At the beginning of the 19th century, the process of great economic acceleration incorporated the Atacama Desert into its maps as part of the global nitrate supply network. In the first phase of nitrate expansion between 1864 and 1928, the problems of non-metallic mining operations found an important barrier in a demand for water higher than that available. The use of coal machinery for distillation of seawater and inland waters was one of the first measures, with high mineralization rates, so solar desalination rose as an alternative process.

In 1872 the desalination industry of Las Salinas was built and operated until 1910. One of the key actors of this initiative is Charles Wilson, who was born in Stockholm, lived in Brooklyn and arrived in Chile along with the construction of the Chañaral railways. Wilson would have devised a greenhouse system of wooden drawers covered with glass and interconnected by pipes that distilled the underground water of the Sierra Gorda aquifer, which was pumped thanks to windmills. However, it has not yet been credited how it came to this desalination design (Arellano, 2019).

These drawers articulated an area of almost half a hectare, which was capable of producing about 18 thousand liters of distilled water on a summer day (Frick, 1973). This productivity was explained both by the solar radiation harvested, and by the cold wind of the Atacama Desert, which managed to maintain the outside temperature of the glass sufficiently cold. According to the testimony of the mining engineer Alejandro Bertrand, the internal steam condensed and generated water that was accumulated in large underground ponds.

The existence of Las Salinas was known in the northern hemisphere since 1883, 11 years after it was built, thanks to publications in London, New York, Oklahoma and Madrid. This experience was recovered in the 1950s by Dr. Maria Telkes in the United States, who gave information about its existence to the engineer Julio Hirschmann, from the Technical University Federico Santa María at Valparaíso. From that moment on, Las Salinas became an icon for those initiated in solar energy technologies. However, the existence of the other industries of the nineteenth century - Sierra Gorda and Domeyko - was quite unknown.

Sierra Gorda desalination plant belonged to Juan Oliveira, located in the town of Sierra Gorda, 50 kilometers east of Las Salinas. This second solar industry was active between 1886 and 1894. The distiller of Sierra Gorda apparently had a supply of 40 thousand deciliters for every 24 hours. This would have made it twice as productive as Las Salinas, but there is no detailed history of its operation that allows establishing a performance (Arellano, 2019).

For about 80 years it was believed that a photograph of a solar desalination plant in the Atacama Desert dated 1908 corresponded to Las Salinas. However, the comparison of the description of 1883 elaborated by Harding with the photograph of 1908 left in evidence differences that could only mean significant changes in the design or that they were different installations. In 1907 and, probably in 1908, the solar desalination plant of Domeyko Office was photographed in what appears to have been the process of starting operations. The publication of these photographs in Antofagasta and London may have several interpretations; One of them is the interest of the owners Ottorino and Nicolás Zanelli in selling all the facilities and exploitation rights to Casa Gibbs Ltd. (Arellano, 2019).

No evidence of Domeyko’s closure has been found and it is not possible to indicate the operating time span. It was reported that it had 20,000 square feet (approximately 2,000 square meters) of glass and was capable of producing 950 British imperial gallons, just over 4,300 liters, of fresh water daily (Arellano, 2019).

All desalination plants built between 1872 and 1907 disappeared without knowing its design process or the cessation of operations, which, due to their size, should have involved administrative procedures. There is no evidence to establish whether there was any kind of connection or social agent that connected the three experiences. However, its territorial location, in the Atacama Desert, speaks of the interest of engineering in harvesting solar radiation and tame thermodynamic processes.

The sun and the salt industry

In the evolution of the uses of solar energy in the industry in Chile there were applications in several technical lines, but in the mid-twentieth century one was incorporated that has definitely had a development of continuity and expansion like no other: the solar evaporation ponds.

The Atacama Desert seems to have been the third site in the world where this technique was implemented. The fractional crystallization process allowed the production of saltpeter by-products and this began to be studied in the 1930s, apparently, by the engineer M. E. Martínez in the Los Dones Office. It was not until the end of the 1940s that the design of engineer Stanley Freed was finalized, who managed to see four of the first ten planned solar evaporation pools built. Between 1948 - when the first four solar evaporation pools were built - and today, the use of this technique increased in surface area and production on an exponential scale (Arellano, 2019).

The case of evaporation ponds is very interesting in relation to the elaboration of the history of technology in Chile and the modes of memory management in the local culture. It should be noted that this technical development was disclosed through the local press and that its existence was highlighted even by the candidate for the presidency of the Republic Eduardo Frei Montalva in the 1958 campaign (Arellano, 2019).

However, the memory around this milestone was diluted to the point that the complexity of the technical contribution has not obtained significant attention. Solar evaporation ponds are artifacts that require sophisticated management in the Atacama Desert: they must deal with the astrophysical phenomena of solar radiation, the atmospheric of large outdoor installations, the hydrogeology of the world's most arid place and the seismicity of the area. To this it should be added that the critical observation regarding the total thermodynamic loss in the evaporation process, made by Julio Hirschmann in the 1960s, must be studied with a sustainability perspective that in the 21st century has a different connotation in role of recent knowledge of anthropic effects (Hirschmann, 1961a).

The 1950s were decisive for the emergence of solar energy as a field of exploration and development in the world and, also, in Chile. Julio Hirschmann learned about Harold Heywood's research work at Imperial College London and made the decision to focus his study on applied solar energy. That converged with the commission of the rector of the USM of the time, Francisco Cereceda Cisternas, to investigate alternatives in the energy supply for Chile (Arellano, 2018).

In 1958, Víctor Bocic Arzic graduated as a Mechanical Engineer at the Technical University Federico Santa María, with the report “General background about solar energy and its use”. The 219 pages of Víctor Bocic’s thesis materialize the evaluation that Julio Hirschmann had considered as optimal for the development of Chile. This thesis is divided into three parts: general background about solar energy and its use; conversion of salt water into fresh water; preliminary draft of a plant for the simultaneous obtaining of electrical energy and fresh water from seawater, using solar energy. This work dominates in an integral way an engineering that provides a forceful chapter of historical antecedents of solar energy technologies, and a study of evaluation of alternatives for the simultaneous solution of two problems: energy and access to water.

Solar energy research at the UTFSM

In order to relate the history of solar energy in Chile with the worldwide development of the different technologies linked to it, the thesis works found in the UTFSM library were analyzed, considering that they partially reflect the interests at the country level on the development and integration of solar technologies. A universe of 535 title and degree works related to solar energy were found, which are divided according to professional level among technicians, engineers (execution and civilians), magister and doctorates. It is noted that not only research in technology itself, but also in its implementation in our society, considering geography, social challenges, government policies, economics, etc. The database includes 60 years of thesis work, from 1958 to 2018 (Roth, 2019).

An 11% of the thesis developed in the UTFSM correspond to the area of theoretical and general studies of solar energy (TEO). Most relate to radiation measurements and solar trackers. This also includes maps and studies on the intensity of solar radiation over the national territory and the appropriate measurement procedures. The most studied areas in thesis works, however, are the use of photovoltaic energy (39%) (great boom since 2008) and active thermal technology (35%) to use solar energy through solar collectors. There are three main areas: collector technologies, applications and energy storage methods. Six jobs in this technology are related to solar cooling. The use of passive solar thermal energy (10% of the total) has been of constant importance throughout the years, where studies on desalination applications, greenhouses and architecture (thermal mass behavior) stand out. In the 80s, works on the concentration of solar energy at high temperatures for the purpose of electricity generation (CSP) appear, however, the great growth of this area has been appreciated since 2008 (Roth et al., 2019).

In addition to the thesis work, since 1964 the Department of Mechanical Engineering of the UTFSM includes optional subjects related to solar energy in the curriculum of the career. The general course of Heliotechnics began in 1978 and has been maintained since then, adding a laboratory applied since 1990. Laboratory activities include the determination and study of characteristic curves of different solar technologies, for example for a photovoltaic panel or a flat collector to heat water, as well as the determination of typical temperatures and the thermal behavior of different applications, such as a Trombe wall or a greenhouse (Roth et al., 2019).

4. Institutional networking and capacity building

The development of solar energy in Chile has been characterized by associative efforts and multidisciplinary teams that worked in collaboration with other groups distributed throughout the country and abroad. The creation of the National Solar Energy Committee in 1957 can be considered a milestone in the early stages of solar energy development in Chile. In the fifties there was already interest in the subject, as well as at the University of Chile and the Universidad Católica del Norte (Román and Ibarra, 2019). In addition, the favourable and exceptional solar radiation conditions of the north of the country were already known in Chile and in the world. Abbot's measurements, referred to in Section 2, had contributed to spreading the solar potential of the Atacama Desert.

The National Solar Energy Committee was established on September 14, 1957, at the Faculty of Engineering of the University of Chile. The headquarters of the University of Chile in the north zone convened a scientific and technological meeting of specialists in solar energy, attended by representatives of the University of Chile, the UTFSM, the Catholic University of the North (at that time PUCV subsidiary), and of the Pontifical Catholic University of Chile (Roman and Ibarra 2019).

At an international level, solar energy summoned various researchers and engineers who began to organize around collaborative work. In 1954 - just three years before the creation of the Chilean Committee - in Arizona, the United States, an association for applied solar energy was formed, which later gave rise to the International Solar Energy Society, ISES, which is currently the most important society in the area. Since its inception, ISES has welcomed researchers, engineers, industrialists and government agents from around the world and has established biannual meetings that bring together its partners, also open to new participants. In 1957 ISES published the first volume of its scientific journal, which today is called Solar Energy, which has become a reference publication.

The United Nations promoted the development of solar energy, supported the formation of a network of scientific collaboration in the area, and organized scientific meetings from which it published works. Within this framework are the Solar and Wind Energy Symposium of New Delhi and the First World Congress of Renewable Energies in Rome in 1961. This congress was the first to address the issue of renewable energy worldwide. Hirschmann attended this Conference as Chairman (UN, 1962), where he met Maria Telkes and Felix Trombe, among others.

In Chile, the National Solar Energy Committee met periodically to discuss technical aspects around publications and trends in solar science and technology in the world and about the work being done in the country. This Committee allowed for the establishment of lasting working relationships over time, which laid the foundations for collaboration between universities, in particular UTFSM, the University of Chile and the Universidad Católica del Norte. The collaboration was reinforced by the circulation of the engineers, among which it is worth noting the trajectory of the engineer Germán Frick who began his work in the Committee as an IDIEM official. The following year he moved as Director of the Applied Sciences Research Department -DICA- (University of Chile, 1967) of the Northern Zone of the University of Chile in Antofagasta, where he worked closely with Carlos Espinosa. Later, Frick moved to the UTFSM (1964 to 1978) where he joined Julio Hirschmann, subsequently moved at the Catholic University of Valparaíso and then to the University of Santiago, always working in research and development of solar technology (Román and Ibarra, 2019).

In July 1960, UTFSM was visited by Professor Farrington Daniels, Vice President of the United States Academy of Sciences and recognized worldwide as a leading researcher in solar energy. Professor Hirschmann accompanied Professor Daniels on a tour of the Antofagasta region, where the maximum terrestrial solar radiation is located. The privileged conditions of the area for the industrial use of solar energy impressed Professor Daniels, who offered the visit of other American researchers. Professors Duffie and Bliss returned to Chile the following year and announced that Professor Hirschmann would be granted a scholarship by UNESCO to conduct a study tour of the solar energy research centers in the United States, Israel and France, and also attend the First World Conference on Energy Sources organized by the United Nations in August 1961 in Rome. Professor Hirschmann, recommended by his American colleagues, was one of the five expositors who closed the conference with presentations on the use of solar energy (Roth et al., 2019).

In its first decade, the Solar Energy Laboratory received leading international researchers who had participated in the Rome Conference, including professors G.T. Ward of Canada, Ichimatsu Tanishita of Japan, Felix Trombe of France, Zoltán Dobosi of Hungary, R. Sobotka of Israel and UNESCO expert Dr. Johannes Dannies. Raquel Coo Wilson also visited the laboratory, granddaughter of Carlos Wilson, the engineer who developed the world's first solar distillation plant in 1872 in northern Chile (Roth et al., 2019).

In December 1960, the rector of the UTFSM, Carlos Ceruti, authorized the funds for the creation of the Solar

Energy Laboratory proposed by Professor Hirschmann. The Laboratory, founded in 1961, formed the largest and most projected work team in the country. His work was developed in the area of solar radiation measurement and the creation of the National Solarimetric Archive (see section 3), and in the development of technological applications (see section 4). Professor Julio Hirschmann initiated the UTFSM laboratory together with the engineers Germán Frick and Johan von Sommerfeld.

A working group on solar energy was also created at the Universidad Católica del Norte, led by Professor Carlos Espinosa. There, researchers were trained, among which Orlayer Alcayaga, who did his doctorate in solar energy in France in the 1960s. This team worked with the camanchacas (dense early morning fogs in Atacama) and solar distillation, performed solarimetric measurements and experimented in various applications of solar energy. In the fifties they worked on the development of photovoltaic cells and their adaptation to the particular radiation conditions of northern Chile. This work was carried out in collaboration with international research missions, instances in which the potential of the Atacama Desert was valued (Román and Ibarra, 2019).

At the University of Chile, work on solar energy managed to summon researchers from different departments in the Faculty of Engineering (geothermal, geophysical and mechanical). Since its founding, the Department of Mechanical Engineering worked closely with French researchers, who promoted solar energy research. Dr. Jacques Fournier, Director of the Thermo-fluid area, obtained the concurrence of the General Water Directorate and the Ministry of Public Works for desalination research programs. Fournier worked with Professor Sergio Alvarado and colleagues from the Department of Mechanical Engineering (Román and Ibarra, 2019).

Later, research groups were formed in other universities in the country. At the beginning of the seventies, Professor Aldo Moisan, from the Department of Mechanical Engineering of the University of Concepción, began experimenting with the application of solar engineering to housing construction. Later, the University of Magallanes formed a team dedicated to wind energy, which collaborated with the solar community, joining forces in the promotion of renewable energy (Román and Ibarra, 2019).

University research centres maintained a permanent dialogue and exchange. The National Solar Energy Committee resulted in a broader organization, created in tune with the various international organizations that were grouped around ISES (International Solar Energy Society). Julio Hirschmann was the Director of the Chilean Association of Applied Solar Energy, ACHESA, from its creation in 1963 until 1974. However, ACHESA remained a de facto organization until the beginning of the 1990s, and had regional committees in Santiago, Arica, Antofagasta, La Serena, Valparaíso and Concepción. ISES began as an American organization that soon added international sections. Although there is no chapter dedicated to the Chilean section in commemoration of the 50 years of ISES, Duffie and Tabor mention that the Chilean section, chaired by Julio Hirschmann, was the second international group, after the joint section of Australia and New Zealand. The international sections developed in a model in which their activities were independent, but with strong ties between them (Román and Ibarra, 2019).

In the 1950s and 1960s, water was the problem that mobilized solar energy work, both internationally and in Chile. The provision of fresh and clean water was an especially critical need in the north of the country, and university research groups organized to work on this problem. There was a natural coordination, in which each university team specialized in the research and development of a technological approach to the solution of the water problem. Carlos Espinosa, at the Universidad Católica del Norte in Antofagasta, developed the fog trap catcher by taking advantage of the "camanchaca" characteristic of the region (Arellano, 2019). The UTFSM Solar Laboratory, led by Julio Hirschmann, specialized in evaporation desalination, which somehow continued the work of Charles Wilson, which Hirschmann admired (Román and Ibarra, 2019).

Finally, the team from the University of Chile developed research into a purification technology by freezing brackish water with terrestrial radiation (night cooling), a method known as natural freezing desalination. This was an interdisciplinary work of several departments of the Faculty of Engineering. Jacques Fournier, led one of the groups participating in the research, basing his work on the advances made previously by his department colleague Sergio Alvarado and the publications of the French expert Felix Trombe. Roberto Román began his career in the area as an undergraduate student, interested in renewable energy issues, and hired as a research assistant by Fournier. The project managed to install a pilot desalination plant in Calama and supply the irrigation for a vegetable greenhouse. The interest and collaboration generated by these projects convened various organizations, often due to the enthusiasm of a professional who could provide support. For example, transfers to the Calama pilot plant were made in vans of the Ministry of Public Works and there was also some relationship with CORFO (Román and Ibarra, 2019).

Later, the motivation for obtaining fresh water was combined with interest in solar furnaces and other applications. The renowned French solar researcher, Felix Trombe, began his work in solar ovens in the mid-1940s. According to Carlos Espinosa, in one of the interviews with Roberto Román, Trombe wanted to visit the area towards the interior of Antofagasta, in which he had been interested in Abbot's writings. Trombe and Espinoza visited Montezuma and Chiu-Chiu. Montezuma - the place of maximum solar radiation, as explained in section 3-, was not suitable for Trombe furnaces, probably due to access difficulties. On the other hand, Chiu-Chiu was an ideal place both in terms of radiation and connectivity, and there were periliometric measurements of direct radiation (Román and Ibarra, 2019).

At this time there was a discontinuity in solar records. This is stated in the World Radiation Data Center (year), in which there is a gap in information from Chile between September 1973 and 1976. In addition, one of the most immediate measures of the dictatorship was the prohibition of form associations of any kind, which prevented ACHESA from formalizing its organization. In June 1974, the president of ACHESA, Germán Frick, called to integrate new partners and strengthen the association, even considering that it was not a formal organization. They had to spend some years to resume the dissemination and meeting activities of the Chilean solar community (Román and Ibarra, 2019).

UNESCO continued its support work in the development of solar energy and, in 1974, together with the World Astronomy Organization (IAU), conducted a course in San Miguel, Argentina, attended by engineers and academics from all over Latin America and that gave rise to the formation of the Argentine Solar Energy Association (ASADES). The course allowed to establish bonds between solar engineers in the region. Among other Chileans, Roberto Román, Wilfredo Jimenez, Olayader Alcayaga, Eloísa Terrazas attended. There they established ties not only with Argentine colleagues, but also with Peruvians Ricardo Zuleta and Roberto Acevedo, as well as with the Spanish organization CYTED. Possibly, there was established some contact for the visit to Chile of a UNESCO commission in 1976, in which the national solar installations were toured (Román and Ibarra, 2019).

In 1978, under the direction of German Frick, ACHESA edited its first newsletter and organized the first Solar and Wind Energy Seminar, SENESE. The board decided to prioritize the formalization of ACHESA as a scientific society and continued work on the creation of statutes, initiated in 1974 during the presidency of Julio Hirschmann and which continued in the Gastón de Goyeneche period (1976-1978). On July 3, 1980, they obtained a document that was notarized and entered for the registration of the competent government authority. The dictatorship did not encourage the creation of societies or community groups and the statutes never got official. the absence of legal personality was a recurring theme in the minutes of the ACHESA board, because it prevented the association from representing itself and the country before international organizations. However, the Office of National Planning, ODEPLAN, sponsored the completion of the first SENESE, which was held at the Lo Contador campus of the Pontifical Catholic University between July 31 and August 4, 1978. Architect Ximena Ibáñez led the Event organization. Ibáñez had specialized in helioarchitecture in France in 1977, where he coincided with Roberto Román and Olayader Alcayaga (Román and Ibarra 2019).

The SENESE became the meeting place of the academic community in the different venues of the participating universities. ACHESA had more than one hundred members who participated in the SENESE along with other solar professionals and academics. In those years, it was a mostly male community: in the list of partners from 1978 to 1980 only one woman appears, the architect Graciana Parodi of the University of Chile. Later, in a list of researchers linked to solar energy carried out by ACHESA in 1980, which lists 164 researchers, in addition to Graciana Parodi and Ximena Ibañez (from UC Architecture), María Elena Cuzmar of the Universidad del Norte is registered, Marcela Jiliberto and Eleonor Carmendia of Food Technology of the University of La Serena, Myriam Pérez de Endesa and Viviana Arce of the CADE-IDEPE consultancy (Román and Ibarra 2019)..

SENESE insisted on the need to strengthen collaboration between the different working groups. The solar community promised to maintain and share outreach, research, teaching and development activities and to attract the support of the state, for example in the realization of pilot projects in public buildings (schools, hospitals, social housing, among others) and in the creation of regulatory standards.

5. Conclusions

The study shows how Chilean solar energy history has evolved in connection to the world, and as part of an international network of scientists and engineers. It provides a perspective of technological trajectories and capability accumulation, which shows discontinuities and gaps as well as some interesting experiences of success and failure with technological experimentation and diffusion. This work proposes there is a connection between an early and visionary period during the XX Century and the recent and disruptive developments of solar development in Chile.

The investigations carried out in Chile have used different approaches, using both experimental and computational means, models and simulations. In addition, investigations and applications were often carried out in collaboration or alliance with other institutions, including public and private organizations. Capacity building was also addressed with awareness of its importance for technological diffusion.

The journey through the potential applications of solar energy and the history of the developments carried out at the UTFSM, which are a sample of everything that has been done in Chile, leads to conclude that there has been no lack of talent, nor the ability to interact as peers with other technology centers in the world. Nor has the researchers and developers lacked vision, and new generations of solar engineers have been prepared. So, what can explain the slow and humble development of the Chilean solar industry? We return to the conclusion of the IPCC (2011) on the dependence of the diffusion of solar energy on energy policies, the contribution of the state, the stability of public policies and technological improvements. We would have to add that technological improvements also include the development of local capacities, knowledge of the country's own conditions and the behavior of solar radiation in its geography, as well as the ability to develop and adapt technology. Learning from the past should be useful to better understand and further develop this natural and generous resource of energy, history matters.

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