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Seasonal Accumulation of Solar Energy in Aquifer for Thermal Conditioning

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Summary

The present work aims to analyze the accumulation of thermal energy in aquifers, using the summer season to extract underground water, heat it by solar collector and inject the hot water into the aquifer, for building heating during the cold season. The first approach to model the behavior of the aquifer is made by an analytical model and then an experimental arrangement is designed and built. The thermal and hydraulic parameters of the aquifer must be known in order to apply accurately analytical and numerical models. In the site of study, the behavior of the aquifer to an injection of hot water, heated by solar collectors is measure and studied. These measures are used to compare, and as inputs to analytical and numerical models for further applications and modeling.

Key-words: UTES, ATES, energy storage, geothermal energy, solar energy

1. Introduction

As the energy demand increases, the conservation and efficient use of energy becomes crucial. Throughout the world, applications of the thermal energy storage system (TES) have proven to be economic and ecological solutions to energy problems and more and more attention has been paid to their use, [Paksy et al. (2004), Dincer and Rosen (2007)]. According to Cruickshank (2009), thermal systems are typically two to four times more efficient than photovoltaic (PV) systems. On the other hand, home heating and water heating are responsible for a large part of the energy needs of residential buildings: around 80% in Canada [NRCan (2011)] and 82% in Europe [Linder and Bahr (2007)]. Therefore, there is great potential in the use of solar thermal technologies to convert solar radiation into sensible heat.

When energy storage is carried out in an aquifer environment it is called (ATES) or "open" systems, where groundwater is extracted or injected into the aquifer through the use of wells to carry thermal energy in and out of the aquifer [Novo et al. (2010)]. Typically, the configuration of the system consists of using two wells to separate the extraction and injection of water, for its storage in the aquifer and its subsequent use in cooling and/or heating processes. These systems have been used successfully and are in operation in Sweden, Germany, the Netherlands, Belgium and other European countries. In Uruguay there are no experiences of this type, so there is potential for development and application of these widely used technologies.

2. Project description

The accumulation of thermal energy in aquifers (ATES) is based on the use of the heat capacity of water and solid media (underground rocks and sand) to accumulate heat. The heat transfer occurs with the extraction of water from the aquifer through one well and re-injecting it in another at a modified temperature.

For the prediction of the thermal behavior of an aquifer accumulation installation, hydrogeological and thermal measurements on site and also modeling must be carried out [Paksy et al. (2004)].

An essential part of an ATES project is the characterization of the aquifer that will act as a medium for the storage of thermal energy. It is necessary to determine properties such as porosity, hydraulic, thermal transmissivity, etc. It is equally important to understand and know the hydraulic behavior of the aquifer in terms of magnitude and direction of the hydraulic gradient, the existence of preferential flow zones, etc.

This project develops and uses numerical models for the prediction of the behavior and design of aquifer accumulation systems and its experimental validation through measurement in the site. Likewise, the use of the models in the evaluation of applicability in Uruguay of such systems is proposed, mainly for seasonal accumulation of solar energy, to be used for thermal conditioning of buildings.

3. Description of system

The experimental facility has two production wells, one forextraction and one for the injection of water from the aquifer. There are a total of 5 monitor wells in the vicinity of the injection well. Piezometric level and temperature monitoring is performed on all wells. In addition, the system working flow rate, water temperature at the inlet and outlet of the solar panels and solar radiation are monitored.

The distribution of the monitoring wells and the quantification of the injection flow rate are carried out using an analytical model, presented in the following section that allows predicting the temperature variations of the aquifer due to the injection of hot water that is extracted and heated by solar panels. The system operates at a flow rate of $1 m^3/h$, increasing the water temperature water from 17ºC to 40ºC. The system is able, in the function of solar radiation, to adjust the water flow to maintain a temperature close to 40°C at the outlet of the solar panels.

The facility is located above the Raigón aquifer in the town of Colonia Wilson, San José, Uruguay. It is a sedimentary aquifer, composed mainly of sand and gravel, with an area of approximately 2300 km^2. In the zone where the experimental essay is installed, the aquifer behaves as free surface and is highly productive, with specific flows of the order of $15 m^3/h/m$. The transmissivity of the medium is in the order of $200 m^2/day$, the saturated thickness is approximately 15m and the Darcy velocity of the underground flow in the area is 0.013m/day. Figure 1 shows the map of the area.

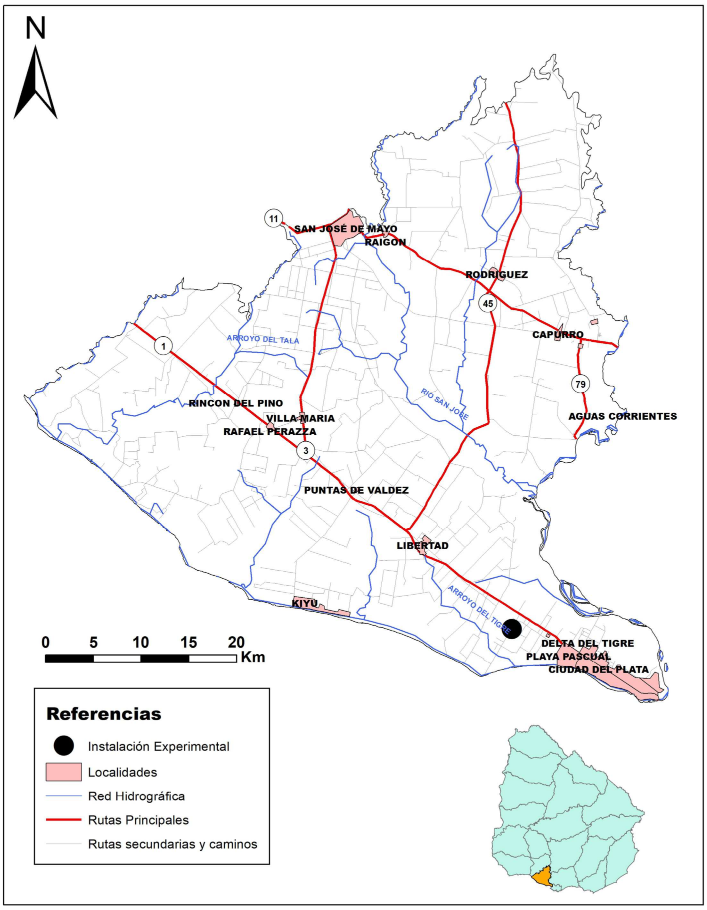

Fig. 1. Location of the experimental facility over Raigón aquifer.

4. Analytical model

Stauffer et al. (2014), analyses several models for the thermal use of underground water systems. Applying the moving source theory to a two dimensional model that considers advection and conduction, yields the analytical solution for the response of a constant line source of infinite length along the vertical direction with a continuous heat flow rate $q_{tb} = J/H$ per unit length of the borehole (injection well). This is called MILS model and can be used to compute the variation in temperature in a plane perpendicular to the infinite line of energy injection/extraction for a given time, t. This model is used to represent temperature variations in a 2D cut of the aquifer, without considering the top and bottom edge effects. The model results in the following equation:

$$T(x,y,t) = T_0 + \frac{q_{tb}}{4\pi C_m\sqrt{D_{t,L}D_{t,T}}}\int_0^t exp\left[\frac{-[x-u_t\cdot(t-t')]^2}{4D_{t,L}\cdot(t-t')} - \frac{y^2}{4D_{t,T}\cdot(t-t')}\right] \times \frac{dt'}{(t-t')} \quad \text{(eq. 1)}$$

where $D_{t,L}$ and $D_{t,T}$ are the longitudinal and transversal thermal diffusivity coefficients, respectively, which include thermal dispersion effects (β_L and β_T) and the thermal velocity of the acuifer u_t.

$$D_{t,L} = D_t + \beta_L u_t \quad \text{(eq. 2)}$$

$$D_{t,T} = D_T + \beta_T u_t \quad \text{(eq. 3)}$$

The thermal speed of the aquifer is defined from the discharge vector of the aquifer (mean aquifer velocity of Darcy velocity, q) and the ratio between the volumetric thermal capacity of the water and the aquifer (C_w and C_m).

$$u_t = qC_w/C_m \quad \text{(eq. 4)}$$

This model is used to predict the behavior of a plane section of the aquifer, when hot water coming from solar water heaters is injected. The results are used to dimension the experimental array that is built in the Raigón aquifer.

For the hot water to be injected, a maximum of 40ºC is stablish to ensure that the aquifer don't suffer unwanted environmental effects. Since the water is taken from a cold zone of the aquifer and reinjected after being heated, there is no environmental impact in this way either.

Several configurations with different flows are simulated using this analytical model and the response of the aquifer is observed. With the hot water flow and its temperature the heat rate injected is computed and this is the input used for the model.

The model returns the temperature increments in the extension of the aquifer and this way, the position of the boreholes to be perforate for temperature monitoring is set. For a flow rate of 1m^3/h with a temperature of 40ºC the variations in temperature show in figure 2 are obtained. It was observed that after three months of injection, the aquifer reaches a steady regimen, and the temperature ceases to rise. The flow rate considered is associated with the area available for the installation of panels and the type of panels, in addition to the scope in project dimensions.

In the figure 2 the temperature increment with the position is presented for a 2D slice of the aquifer, where the natural flow is from west to east.

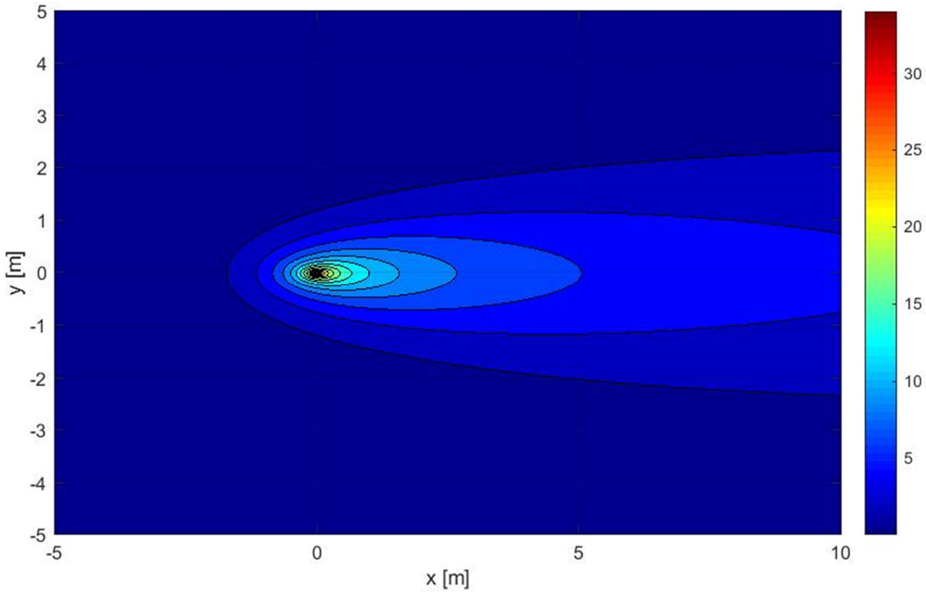

Fig. 2. Temperature increase 2D profile of the aquifer.

5. Experimental description

The analytical model was used to analyze the aquifer response to an injection of hot water. Figure 3 shows schematically the experimental set up that is built.

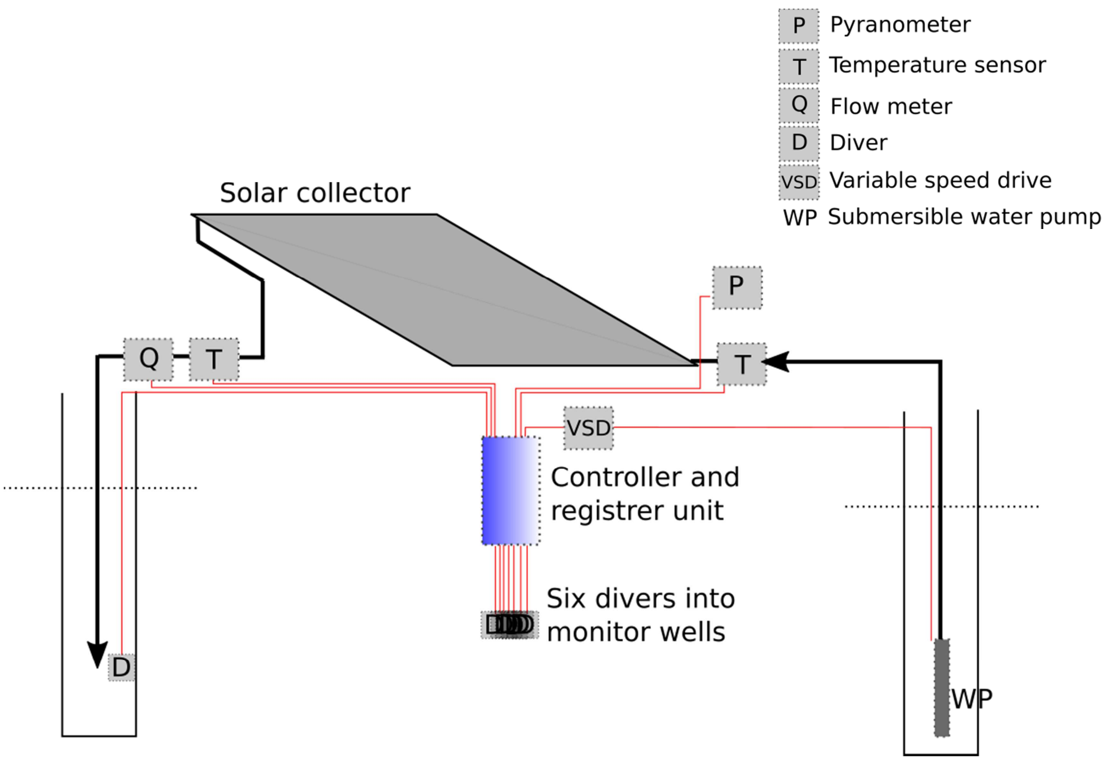

Fig. 3. Experimental array scheme

The water is extracted from the aquifer, circulated by solar heaters, while the temperature is seen at the inlet and outlet, and then injected into the area of the aqueous that is being heated. Divers are used to sense the temperature of the water and the height of the aquifer. One is placed in the injection well, and other 5 are placed in the monitor wells around the injection, specifically perforated to make these measurements. A pyranometer and flow meter complete the measure instrumental. A script is developed to control the system; it takes temperatures and radiation as an input and command the VSD (variable speed drive) to actuate on the submersible water pump. The flow rate is adjusted to assure that the hot water injected is in the acceptable range around the set point (40ºC).

Figures 4 and 5 shows part of the experimental array, which is mostly underground. The solar collectors are an arrangement of plastic tubes, and the cabinet with the monitoring system is shown in the picture.

Fig. 4

Fig. 5

The extraction well is located far enough from the injection zone, to do not alter the area that is heated and to avoid the recirculation effects of hot water in the aquifer. Based on the characteristics of the aquifer, the extension of the land available for the implementation of the experiment, and the operating flow, the extraction well was located 70 m from the injection well.

The nominal water flow is set at $1m^3/h$ and passes through uncovered plastic solar collectors that extends over an area of $35m^2$, to achieve a temperature of approximately 40ºC at the outlet of the collector when the solar radiation is maximum.

From the previous analysis, the distribution of the monitoring wells where the temperature of the aquifer is measured is also determined. 5 wells were perforated, surrounding the injection well. In all of them, water level and temperature are sense.

This is an experimental set up that aims to evaluate the potential of seasonal heating and storage, and demands more instrumentation and monitor wells that make the project more expensive. In further applications that only seeks for the use of the technology but no its evaluation an analysis, some of these components could be saved.

Fig. 6. Installation overview and component scheme

The system is monitored and controlled with a telemetry system, which to have the measurements online in real time, keeping the measurement history and modifying the control logic that operates on the system.

All recorded measures allow analyzing the behavior of the aquifer against the injection of hot water, and later, during the winter season, the behavior when extracting the accumulated hot water for use in heating, and finally determine the efficiency of the storage.

Also, the measurements of radiation, flow and temperatures at the entrance and exit of the collectors, will give other variables of interest such as the efficiency of the collectors and the energy injected and extracted.

6. Results and discussion

The experimental arrangement is currently adjusted and operative, but is has to work for hole summer season to determine the impact on the aquifer. It has been operative for a part of the last summer season in Uruguay, and an increase in the temperature of the aquifer has been observed. Some of the measured points, a temperature increases up to 5ºC is observed. The temperature in the injection well is very sensitive to the flow rates and temperatures injected at each moment.

Figure 5 shows the behavior of temperatures in one day of operation. It is observed that at the beginning of the day the temperatures oscillate, which is due to the behavior of the system that when starts up and seeks that the outlet temperature, *tempOut*, rise to an acceptable minimum value, otherwise, the system stops to start again after a set period of time. The difference between *tempIn* and *tempOut* is the result of solar energy captured by the solar collectors. The temperature in the injection well is represented by *t3* in the graph (fig 5). It is observed how it responds almost immediately to the injected water, and when the system stops, it slowly decreases indicating that the energy disperses, heating the aquifer in the surrounding area. The temperatures of the monitoring wells are between 20 and 22ºC. The unaltered temperature of the Raigón aquifer is 17ºC.

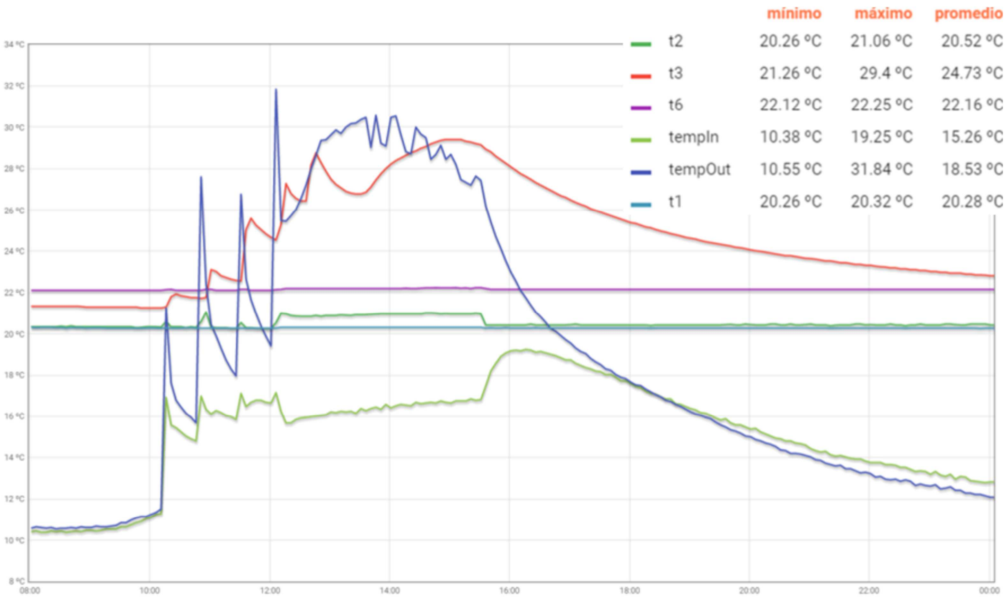

Fig. 7. Temperature measurements for a day of operation.

The data presented in figure 5 correspond to a day in May, where, using the measured flow values, a total energy of 16.4 kWh was injected, and a solar collector efficiency of 18% is reached. It is expected that the energy injected on a summer day will far exceed the calculated for this autumn day. On the one hand, the collectors efficiency increases significantly when the ambient temperature is higher. A maximum of 58% was registered for a summer day. The solar collector used are and economic type that has no cover, what makes them very sensitive to ambient conditions.

To predict the operation of the system during the summer season, we consider the radiation data presented in figure 6, obtained directly from the “Laboratorio de Energía Solar” in Uruguay (LES). These radiation data in the place of interest arise from the work [Alonso-Suárez, 2014], where the methodology is detailed.

Radiation in the month of May is two to three times less than radiation in summer. With this, it is projected that the energy to be injected through the system will be close to 100 kWh per day in the hot season. According to [Rosen and Koohi-Fayegh, 2017] the efficiency of this energy storage could reach 50%, meaning that 1500 kWh per month will be available for heating. On the other hand, the thermal energy demand of a house with standard structure and materials is calculated, resulting that that this experimental array could supply the energy for heating 120m^2.

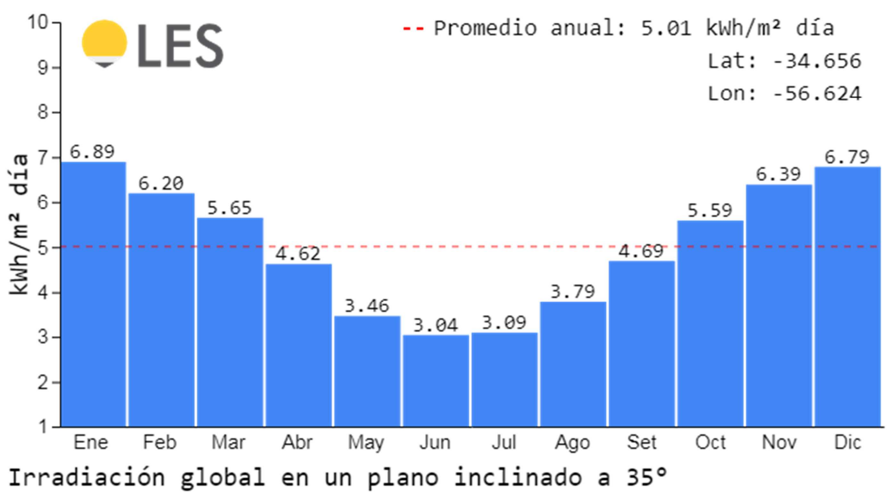

Fig. 8. Monthly radiation at the place where experimental installation is located (LES, 2019).

The system worked intermittently in the summer period, since it was still in the period of set-up and adjustment. The arrangement is neither conventional from hydraulic point of view, nor electrical and data logging, resulting in several instances problems, unforeseen, and delays with respect to the initial schedule. To effectively determine the operation and accumulation capacity during the summer period, the system must be operated in the next season in order to achieve a complete evaluation of the system. Then, in the winter season, water must be extracted from the hot zone of the aquifer to finally determine the accumulation efficiency and the performance of the seasonal accumulation of solar energy in the aquifer.

7. Further work

Since the installation is operational, a full summer season has not been completed. It is necessary to achieve an injection of hot water throughout the whole season to assess temperature increases in the aquifer.

It is seek to compare the injected energy with the energy that can be stored in the aquifer for later use in thermal conditioning by heat pump or direct use. In parallel, we are working with numerical models to simulate the behavior of the system, using the experimental measurements for comparison and calibration of the models.

Once an injection summer cycle is completed, an extraction cycle is carried out in winter, in order to quantify the energy that can be extracted and determine the efficiency and viability of the system.

8. Acknowledgements

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9. References

Paksoy, H.O.; Gurbuz, Z.; Turgut, B.; Dikici, D.; Evliya, H. Aquifer thermal storage (ATES) for air-conditioning of supermarket in Turkey. Renew. Energy 2004, 29, 1991-1996.

Dincer, I.; Rosen, M.A. Energetic, exergetic, environmental and sustainability aspects of thermal energy storage systems. In Thermal Energy Storage for Sustainable Energy Consumption; Paksoy, H.O., Ed.; Springer: Dordrecht, The Netherlands, 2007; pp. 23-46.

Cruickshank CA. Evaluation of a stratified multi-tank thermal storage for solar heating applications. PhD Thesis. Queen's University; 2009.

Nielsen, K. Thermal energy storage: A state-of-the-art. A report within the research program Smart Energy-Efficient Buildings at the Norwegian University of Science and Technology and SINTEF; 2003.

Hooper, F. C. Possibility of complete solar heating of Canadian buildings. *Eng. J.(NY);(United States)*, *38*(11); 1955.

Natural resources Canada (NRCan). Survey of household energy use—summary report. Available from: http://oee.nrcan.gc.ca/Publications/statistics/sheu-summary/pdf/sheusummary.pdf [accessed January 2011].

Linder S, Bhar R. Space conditioning in the residential sector in Europe. Deliverable 1—Ground Reach EU project. Ecofys; 2007.

Novo, A.V.; Bayon, J.R.; Castro-Fresno, D.; Rodriguez-Hernandez, J. Review of seasonal heat storage in large basins: Water tanks and gravel-water pits. Appl. Energy 2010, 87, 390-397.

Stauffer, F., Bayer, P., Blum, P., Molina-Giraldo, N., and Kinzelbach, W.. Thermal Use of Shallow Groundwater. CRC Press, Taylor & Francis Group, 2014.

Alonso-Suárez, R., Abal, G., Siri, R., Muse, P.. Satellite-derived solar irradiation map for Uruguay. Energy Procedia 57:1237-1246, 10.1016/j.egypro.2014.10.072; 2014.

Rosen, M. A., & Koohi-Fayegh, S. (2017). Geothermal energy: Sustainable heating and cooling using the ground. John Wiley & Sons.

Web references:

LES, 2019. Solar map of Uruguay. Laboratorio de Energía Solar. Accesed on august 2019 http://les.edu.uy/online/msuv2/