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Hydrogen Measurement & Extraction at Nevada Solar One

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Abstract. Hydrogen was measured and extracted from the headspace gas of four expansion vessels that are components of the heat transfer fluid (HTF) subsystem in the Nevada Solar One (NSO) power plant, Boulder City, Nevada. Direct, real-time measurements of hydrogen partial pressures in the headspace gas were accomplished using the recently installed hydrogen mitigation process that was developed jointly by the National Renewable Energy Laboratory (NREL) and Acciona Energy, the owner/operator of NSO. This method combines the two functions of extracting hydrogen from the headspace gas and measuring hydrogen partial pressure in the headspace gas. During 2022 and 2023, we operated the process regularly and made real-time measurements of hydrogen partial pressures. In addition, DLR in Germany measured dissolved hydrogen concentration in the circulating HTF. These two measurements were compared via Henry's Law and found to be consistent. Measured values also were compared to model results that were generated by the NSO plant model that was written to predict hydrogen levels in the power plant piping and components. The model predicted hourly hydrogen partial pressures in the expansion tanks for two cases - hydrogen extraction off, and hydrogen extraction on. Real-time hydrogen measurements and sampled HTF measurements were compared to hydrogen levels that were predicted for these two cases. We found good agreement between the hydrogen measurements and the modeled hydrogen for the extraction on case. These results indicate that the extraction process is working properly with its expected performance.

Keywords: Hydrogen, Measurement, Extraction

1. Project history

In 2015, the National Renewable Energy Laboratory (NREL) and Acciona Energy initiated a cooperative research and development agreement to identify and develop a solution to the problem of hydrogen occurrence in the circulating heat transfer fluid (HTF) in parabolic trough power plants. Work was performed from 2015 through 2017 and consisted of plant and process modeling, and laboratory experiments [1]. During this time, we measured and modeled hydrogen permeation in new and in-service receivers [2]. We showed that hydrogen permeation into a receiver annulus is reversible and that reverse permeation can decrease the heat loss of the receiver. We developed computational models that predicted dissolved hydrogen concentrations in the circulating HTF of parabolic trough power plants [3]. We developed a sensor that measures hydrogen partial pressure in the expansion tank headspace gas and demonstrated hydrogen measurements over a wide range of partial pressures from 10 mbar down to 0.003 mbar [4]. Subsequent testing showed that the sensor's performance was not affected when operated at headspace-gas temperature and pressure and when in contact with actual HTF vapor [5]. We developed models and performed experiments to determine mass-transfer rates and corresponding mass-transfer coefficients for hydrogen transport across the HTF liquid/gas interface [6], [7]. We conceived, designed, and demonstrated an integrated sensor/separator that combines hydrogen measurement and extracting functions into a single module [1], [8], [9].

In 2018, NREL and Acciona Energy entered into a commercialization agreement in which the integrated process that was developed in the first cooperative agreement was installed at full scale at Acciona's Nevada Solar One (NSO) power plant. This work was conducted from 2018 through 2021, and consisted of engineering design, procurement, and process installation at the NSO plant [10]. Process installation was completed in December 2019, but commissioning was delayed significantly in 2020 due to the Covid pandemic, and completed in 2021 [11].

In 2022, power plant and process operation was limited due to cloudy weather and persistent smoke from California wildfires. During May and June, we were able to operate the process and make key hydrogen measurements that indicate the process was performing as designed. The year 2023 saw much better operating days for the plant and process. Starting in March 2023, the process operated every day that the power plant operated and demonstrated reliable performance. Measurements that were made regularly in 2023 showed that the process reduced and maintained hydrogen at acceptable levels in the power plant HTF.

2. Objectives

We identified project objectives that served as metrics to track technical and commercial progress during performance of the two agreements between NREL and Acciona Energy. The project objectives were to:

- develop a hydrogen mitigation method that extracts and minimizes dissolved hydrogen in the circulating heat transfer fluid,
- develop a hydrogen sensor that makes real-time measurements of hydrogen partial pressure in the expansion vessel headspace gas,
- design a full-scale, commercial process that measures and extracts hydrogen from the circulating heat transfer fluid of parabolic trough plants,
- install, commission, and operate the process at the Nevada Solar One (NSO) power plant in Boulder City, Nevada,
- verify process performance and determine benefits to the NSO power plant,
- implement a commercialization agreement that offers this technology to other parabolic trough power plants.

3. NSO plant and mitigation process layout

Process development was based on a method to remove hydrogen from a single location - the power plant expansion vessels. Figure 1 shows a schematic of the NSO plant components that contain circulating HTF. High-temperature HTF returns from the solar field and enters the steam generator heat exchangers where it drops its temperature to generate steam for the plant turbine. Low-temperature HTF exits the steam generators and flows to the four expansion vessels, where it resides until it returns to the solar field via the HTF pumps.

The hydrogen mitigation process was located below the expansion vessels at ground level. Headspace gas is withdrawn from two of the four expansion vessels and passed through the process module that measures and extracts hydrogen from the headspace gas. Headspace gas returns to the two other expansion vessels. Existing piping connects the expansion vessels and completes this internal gas flow loop. Other components that makeup the mitigation process are the headspace gas blower, gate valve, vacuum pumps, and hydrogen catalytic oxidizer.

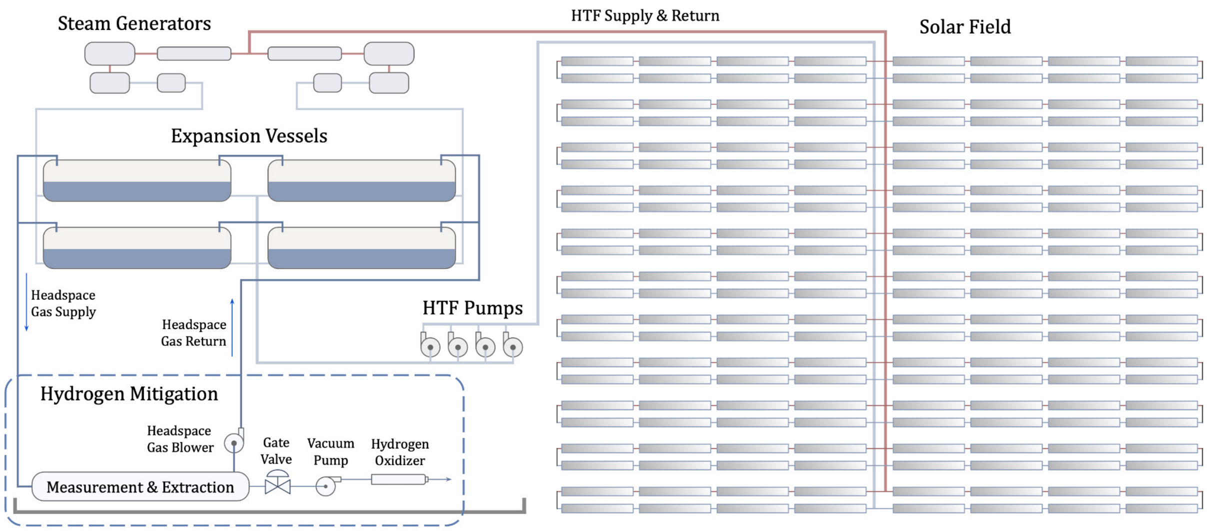

Figure 1. *Hydrogen mitigation process interface with the power plant expansion tanks*

Since hydrogen is generated and resides mostly in the circulating HTF liquid, the equilibrium partitioning of hydrogen between HTF liquid and headspace gas phases in the vessels is important, as is the mass transfer coefficient for hydrogen transfer across the liquid/gas interface. Determining accurate values for the temperature-dependent hydrogen/HTF partitioning and mass transfer coefficients was a key part of our modeling and experimental work at NREL during the development of the process [6], [7].

4. Integrated sensor/separator function and design

We conceived an integrated module that combines the functions of hydrogen sensing and separating into a single unit [1], [8], [9], [10]. This simple process module was designed to measure and remove hydrogen from the headspace gas without intrusion into the expansion tanks and other power plant components, and was the project's most significant innovation. The design uses a single palladium/silver alloy membrane to measure and extract hydrogen from the headspace gas. Figure 2 shows the integrated module that has cylindrical geometry and two operating volumes. Headspace gas flows continuously through the annulus when the process is operating. The permeate volume is contained inside a palladium membrane that separates it from the headspace gas flow. When operating, hydrogen in the headspace gas permeates through the membrane into the permeate volume. When the module is operating in separator or extraction mode, the permeate valve is open and hydrogen is quickly removed from the permeate volume and sent to the catalytic oxidizer. When operating in sensor or measurement mode, the permeate valve is closed and hydrogen accumulates in the permeate volume until its pressure equals the hydrogen partial pressure in the headspace gas flow. Measuring total pressure in the permeate volume is a direct measure of the hydrogen partial pressure in the headspace gas. Hydrogen molar concentration in the headspace gas is obtained by dividing the permeate pressure by the headspace gas pressure. With this single module, we extract hydrogen from the headspace gas and measure hydrogen partial pressure in the headspace gas. The configuration that is shown in Figure 2 was installed at the NSO power plant.

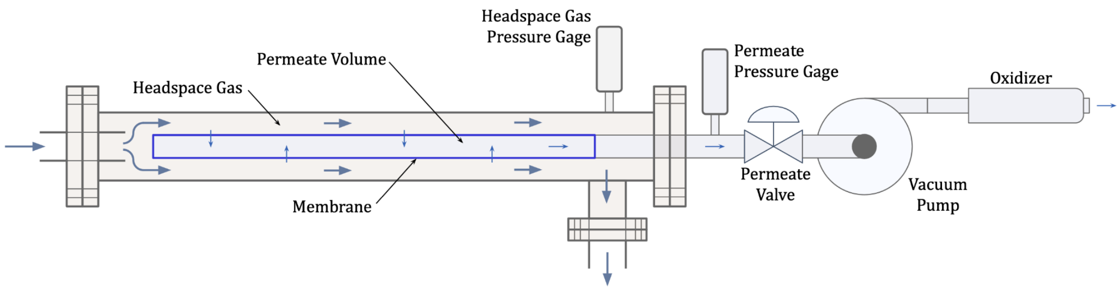

Figure 2. *Integrated sensor/separator design that was installed at the NSO power plant*

5. Integrated sensor/separator laboratory testing

We tested a laboratory-scale version of the module that was based on the cylindrical design shown in Figure 2 [1], [10]. Figure 3 shows laboratory data collected over 20 minutes for a series of gas-mixture total pressures. The gas mixture represented the headspace gas and had a concentration of 0.1% hydrogen in nitrogen (0.001 mole fraction hydrogen). During the test, we set the total pressure of the gas mixture to 2.6, 4.1, 1.6, and 6 bar as shown in Figure 3. When the permeate valve was open, the module operated in extraction mode and the hydrogen pressure was near zero. When the permeate valve was closed, the module operated in sensor mode and the hydrogen partial pressure increased rapidly and leveled to a constant value. Since the hydrogen molar fraction in the supply gas mixture was 1/1000, the hydrogen partial pressure was always 1/1000 of the total gas pressure. In Figure 3, hydrogen partial pressure measurements are plotted in mbar, so the value for each measurement in mbar is the same as the corresponding value of supply gas pressure in bar. There are three measurements for each total pressure. The time needed to make each measurement was about one minute.

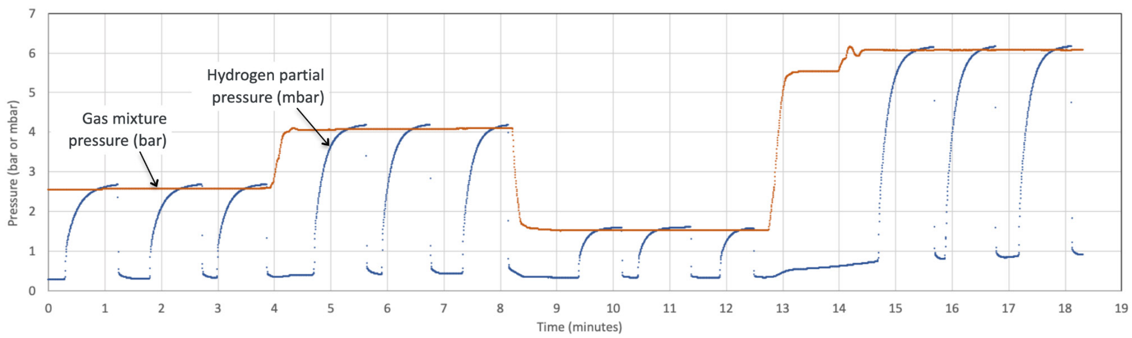

Figure 3. *Permeate-volume pressure response in separation and sensing modes*

These data demonstrated module operation in both sensor and extraction modes. The tests showed that this module can measure hydrogen levels in the headspace gas over the course of an operating day with high resolution. With this module, the power plant can map hydrogen levels in the headspace gas during daily operation and determine how hydrogen levels vary seasonally within the operating year.

6. Testing the installed process in 2021

NSO operated the process intermittently starting in June 2021. Several problems occurred in the process piping and module that caused delays and needed to be addressed before the process could operate consistently. Management of HTF condensation and liquid pooling downstream of the knockout pot – particularly during process startup – proved to be the most challenging issue. These problems were resolved in June and July, and the process started operating consistently in August 2021. Figure 4 shows permeate volume pressure during measurement of hydrogen partial pressure in the headspace gas. The plot has the fast-rising response and then levels off as expected for these hydrogen measurements. We made many measurements of hydrogen partial pressure that had a similar response and collectively indicated that the measurement function was working as intended.

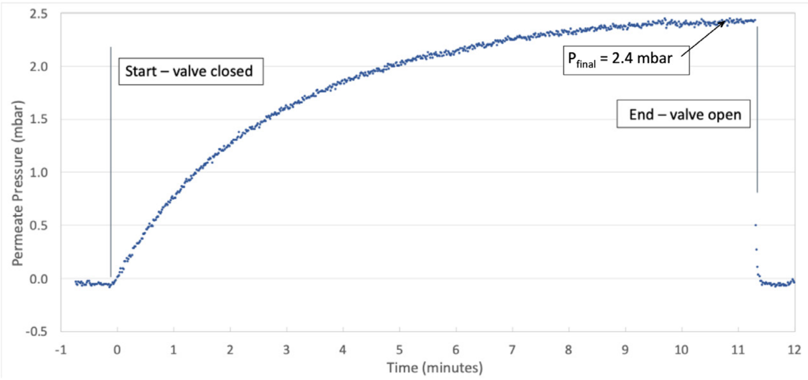

Figure 4. *Permeate pressure versus time for measuring hydrogen in headspace gas*

It is interesting to note that the response time (Figure 4) needed to get to constant pressure was about ten minutes for the installed module, while only one minute for the laboratory-scale module (see Figure 3). We explain this result by comparing the diameters of the installed membrane (3.5”) to the diameter of the laboratory membrane (0.375”). The time needed to get to constant pressure during measurement is proportional to the membrane diameter. Since the ratio of diameters is 9.3, we expected the response time to be about 9.3 minutes, which is the case as shown in Figure 4.

7. Process operation in 2022

During the early months of 2022, NSO operated the process consistently. NSO made several measurements of hydrogen partial pressure that were compared to modeling predictions that used hourly HTF temperatures for the days when the measurements were made. Figure 5 shows modeling predictions and measurements that were made over four days in May. Two operating cases were predicted by the model. The brown diamonds are hourly model results for the case of “process extraction off” during those days. The blue circles are hourly model results for the case of “process extraction on”. The red squares are hydrogen measurements that were made using the sensor function of the installed process. Over the four-day period, the measured hydrogen partial pressures agreed well with the model results for the “extraction on” case.

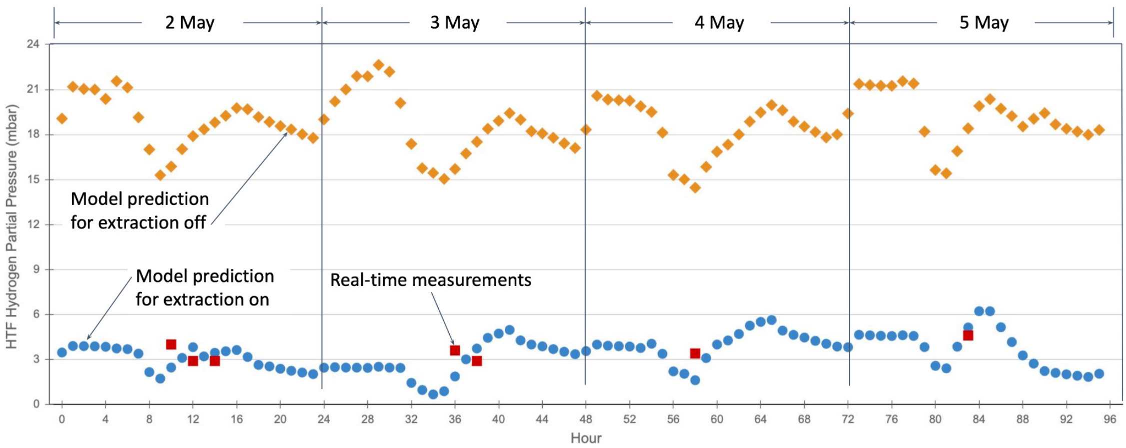

Figure 5. *Expansion vessel headspace gas hydrogen measurements and modeled data*

Figure 6 shows modeling predictions and measurements that were made 2 June 2022. The brown diamonds are hourly model results for the “extraction off” case, and the blue circles are hourly model results for the “extraction on” case. The red squares points are real-time hydrogen measurements that were made using the sensor or measurement function of the process.

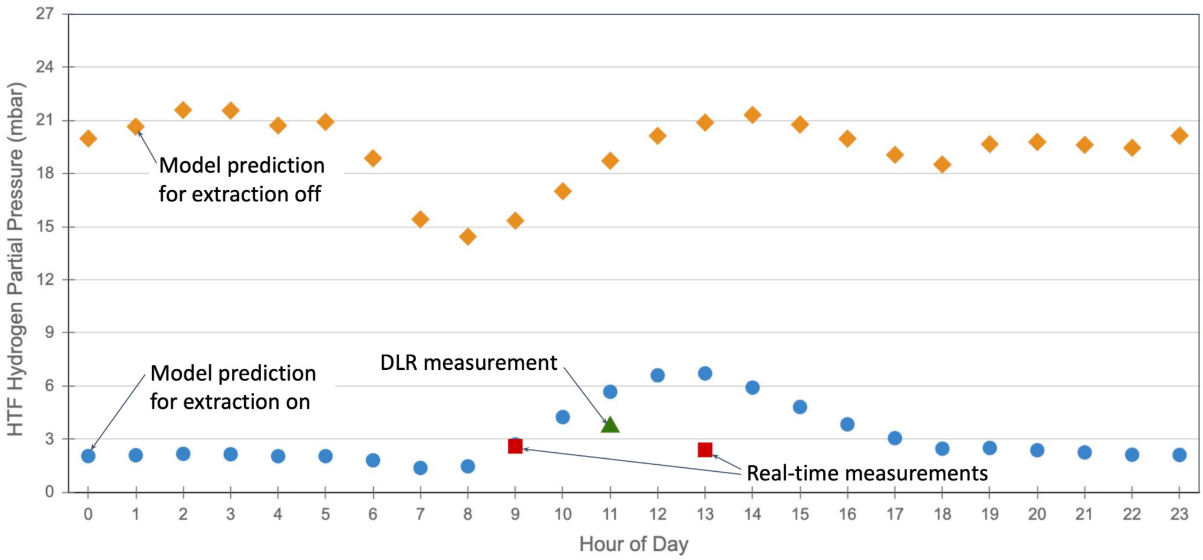

Figure 6. *Expansion vessel headspace gas hydrogen measurements and modeled data*

The green data point is derived from a measurement of dissolved hydrogen concentration in the HTF. NSO sampled the HTF and sent the sample to DLR in Germany for analysis. DLR reported the dissolved hydrogen concentration and we used Henry’s Law coefficient to determine the corresponding gas-phase hydrogen partial pressure. The DLR result agreed quite well with the real-time measurements that were made by the process. Both measurements agreed with model results for the “extraction on” case.

8. Process operation in 2023

Process operation was very consistent in 2023. Process extraction started in mid March and continues until mid November. The process operated without incident every day that the power plant operated. NSO made hydrogen measurements at regular times from March through September. Modeling and measurement results are shown in Figure 7. The brown dashed line is the model prediction for the “extraction off” case. The blue solid line is the model prediction for the “extraction on” case. The red squares are measurements that were made by NSO using the process sensor function.

Figure 7 shows that the measurements agreed well with the model’s “extraction on” case from the start of extraction in late March through mid May. For the rest of May, June, July, and early August, the measurements were higher than model predictions for the “extraction on” case. During this period, NSO reviewed the process operating record and potential equipment problems. We determined that the higher than expected hydrogen measurements were due to decreased membrane performance that was caused by oxides or other fouling substances that formed on the headspace gas surface of the palladium membrane. NSO treated the membrane with 5% hydrogen in nitrogen on day 195 in Figure 7, which brought the measurements back in line with the model predictions. Membrane treatment is a standard maintenance function that was written into the Programmable Logic Controller (PLC) operating routine and is easy to execute. Since then, NSO adopted the schedule of treating the membrane once every two weeks.

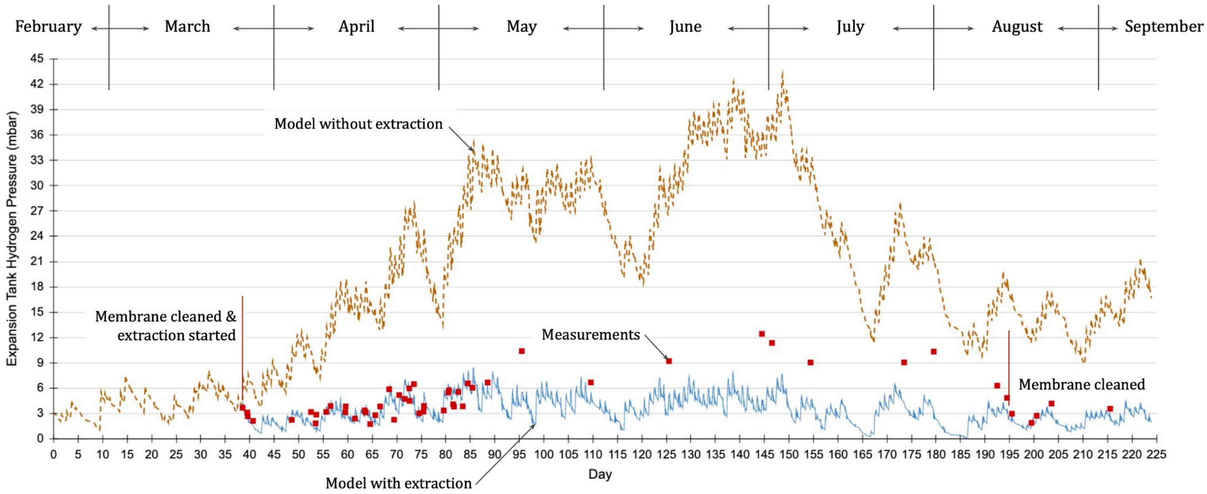

Figure 7. *Headspace gas hydrogen measurements and modeled data for 2023*

9. Project summary and status

All project objectives listed at the beginning of this manuscript were met. Starting in March 2023, NSO operated the process every day the plant operated. The process was operated in both extraction and measurement modes without any problems. Real-time measurements that were made using the process sensor function agreed with plant model predictions for the "extraction on" case and indicated that the process is operating with its expected performance. Independent measurements that were made by DLR that measured dissolved hydrogen in the circulating HTF agreed with the hydrogen partial pressure measurements that were made at the same time using the process sensor function. These outcomes provide a high level of confidence that the process extraction and measurement functions are operating properly.

NSO is conducting a solar field IR drone survey in September 2023 to determine changes to the solar field receiver performance compared to the same survey that was conducted in September 2022. At the time of this writing, the drone survey was complete, but the data need to be evaluated and compared to the 2022 receiver performance data. These data will show the benefits of process extraction to the solar field receiver performance, which is the ultimate performance metric for this process and project.

The final project objective was to implement a commercialization agreement that offers this technology to other parabolic trough power plants. In 2022, NREL licensed the technology to CSP Services, who are located in Cologne, Germany and Almeria, Spain. CSP Services is offering the technology as a turn-key process installation to other parabolic trough power plants. Greg Glatzmaier, the author of this manuscript and project leader, retired from NREL in February 2022, entered into a long-term work agreement with CSP Services, and is supporting their efforts to implement this technology in other parabolic trough plants worldwide.

Data availability statement

Supporting data for results that are reported in this manuscript are owned and restricted by Acciona Energy, and can be accessed only with their expressed permission.

Author contributions

The author's contributions are conceptualization, methodology, measurements, software development, modeling, data analysis, and writing.

Competing interests

The author declares that he has no competing interests.

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