SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Analysis and Simulation of CSP and Hybridized Systems
https://doi.org/10.52825/solarpaces.v1i.668

Published: 31 Jan. 2024

# Technical-Economic Feasibility Study of Hybrid CSP Plants with Gas in Chile

Catalina Cáceres[1][https://orcid.org/0000-0001-5025-9123], Catalina Hernández[2][https://orcid.org/0000-0003-3901-8446] and Frank Dinter[2][https://orcid.org/0000-0001-5127-3760]

[1] Universidad de Chile, Chile

[2] Fraunhofer Chile Research, Chile

**Abstract.** The Chilean government has presented an accelerated decarbonization plan, proposing the closure of coal-fired power plants by 2025, to combat climate change. Therefore, it is important to migrate to new forms of cleaner generation that are also safe for the electricity system. It is in this context that the motivation arises to study the hybridization of two technologies usually opposed, such as CSP and Gas, to enhance the benefits of each one. The plant to be evaluated has a HYSOL configuration, which consists of a Solar Tower with thermal storage of salt to which is incorporated a gas cycle whose exhaust gases are used to heat the salt when necessary. For this study, SAM was used to model the solar field and EES was used to simulate the thermodynamic components of the Brayton and Rankine cycles. The study is carried out at 3 locations in the Antofagasta Region. Capacity factors close to 90% are obtained, which is higher than most of the Non-Conventional Renewable Energies. Similar $CO_2$ emission factors are obtained in the 3 locations and around 0,12 Ton $CO_2$/ MWh, which is substantially lower than other generators based on conventional fuels. The lowest LCOE occurs in L2 and has a value of 82,9 USD/MWh, being more cost effective than Open Cycle Gas and Nuclear technologies and could become competitive in the future with other technologies if the costs associated with the solar field are reduced as expected. It's concluded that the proposed solution is technically and economically feasible.

**Keywords:** CSP, Hybridization, Gas, Renewable Energy, HYSOL

## 1. Introduction

As a way to combat climate change, Chile plans to close coal-fired power plants by 2025. However, several experts warn about the technical challenges that this means, on the one hand, the amount of energy to be replaced must be considered and, on the other hand, the robustness of the electrical system [1]. The solution of hybridizing Concentrating Solar Power (CSP) technologies with gas-fired technology points to this, since it allows reducing the CO2 emissions of the latter while preserving the inertia provided by the gas turbine. It also allows the incorporation of thermal storage of salt and the use of the gas turbine as a backup.

It is because of this that it was decided to study a HYSOL configuration. This consists of the typical configuration of a Solar Tower with storage to which a Brayton Cycle is integrated between the hot and cold tanks, which allows heating salt with the use of gas if needed, see Figure 1.

## 2. Methodology

A 110 MW power plant is being studied at 3 locations in northern Chile. The Rankine Cycle has a maximum power of 110 MW and the Brayton Cycle of 50 MW. A Solar Multiple configuration equal to 2 and 9 hours of storage is selected, in order to produce electricity 24 hours a day, desirably only with the steam cycle during the day, but production at night can be complemented by power generation with the gas cycle, maintaining an output power between both turbines of 110 MW most of the time possible, following certain operating constraints.

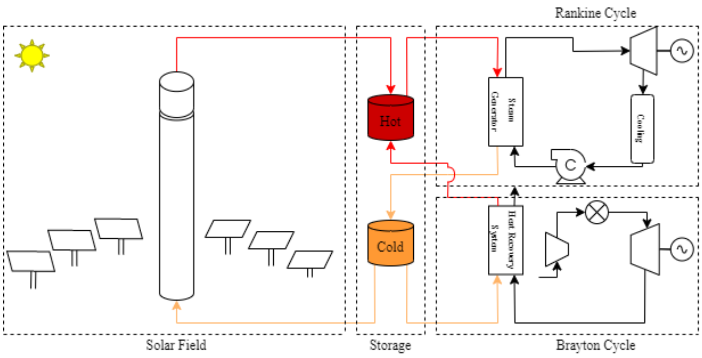


**Figure 1**. HYSOL scheme.

The methodology shown in Figure 2 consists of obtaining from the Solar Explorer [2] the TMY for each selected location, which is used as input in the System Advisor Model (SAM) software [3], where the solar field part of HYSOL is modeled, obtaining the mass flow vector of salt passing through the receiver, with hourly resolution for one year. Then, in the Engineering Equation Solver (EES) program [4] the Rankine and Brayton Cycles are modeled, determining their thermodynamic points through mass and energy balances, allowing to obtain the mass flows of salt flowing from or to them as a function of the operating power of each cycle. In EES the operation logics are arranged to control the operation of the plant according to the filling percentage of the hot tank in terms of volume. As a result of the modeling of the plant operation, the annual power generation with hourly resolution of the plant at each location is obtained. Once the generation is obtained, a post-processing of the data is performed in order to obtain variables such as the CO2 emissions of the plants, the capacity factor, the hours of operation per year at full load, the Levelized Cost of Energy (LCOE), among other results.

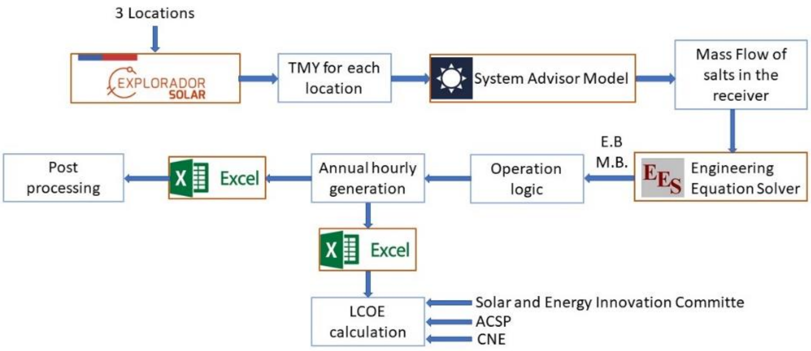


**Figure 2**. Methodology.

### 2.1 Location Selection

For the selection of locations, 5 criteria are taken into account. First, the availability of the solar resource in terms of radiation is considered, so the Atacama Desert (located in the North of Chile) is considered, which has annual Normal Direct Radiation values close to

3300 kWh/year/m$^2$ [5]. Another factor considered is the Atmospheric Attenuation, which is particularly important when having a Solar Tower; in Chile it has values between 2% and 5% [5]. The existence of infrastructure in the area, in terms of gas pipelines and transmission substations, is also considered. On the other hand, the Development Poles [6] defined by the Chilean Ministry of Energy as areas of high development of renewable projects in the coming years are considered, with the aim of including them in the transmission expansion plans. Finally, the energy demands of each region of the country were also considered. In this way, 3 locations (L1, L2 and L3) were selected in the Antofagasta Region as shown in Figure 3.

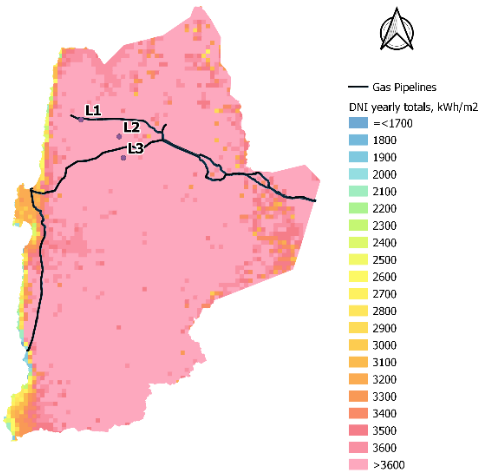


**Figure 3**. Locations studied.

## 2.2 Solar Field Model

The solar field model is performed in the SAM software, which uses as input variable the TMY files of each location. The parameters used in the simulation of the 3 locations are: 110 MW steam cycle power, 9 hours of storage, solar multiple of 2, 565°C hot tank temperature [7], 290°C cold tank temperature [7] and 4% atmospheric attenuation [5].

In simulations, the heliostat field and the dimensions of the tower are optimized, obtaining as a result the mass flow of salt in a year that passes through the tower receiver, with hourly resolution. In addition, the dimensions of each plant are obtained for subsequent economic analysis.

## 2.3 Brayton and Rankine Cycle Models

Brayton and Rankine cycles are modeled component by component on EES software, calculating the thermodynamic points corresponding to the inlets and outlets of each equipment. The gas cycle has a 50 MW turbine power, while the steam cycle turbine has 110 MW power.

What is obtained from this model in the case of the Brayton Cycle is the amount of salt that can be heated with its operation at maximum power. While in the case of the Rankine Cycle, the amount of salt required for its operation at different powers is obtained.

## 2.4 Generation simulation Model

The power generation simulations are performed on EES software, using a mass balance in the hot tank, because the availability of hot salt is what will determine the energy production in each cycle, since on the one hand the Rankine Cycle contributes to empty the hot tank, and on the other hand the Brayton Cycle helps to fill the hot tank. In general terms, the operating criteria is that the Brayton Cycle is used as a backup for the operation of the Solar Tower, providing power and heating salt when the percentage of hot tank filling is less than 25%. Otherwise, the gas cycle will be shut down and energy production with the steam cycle will be privileged. In addition, it is included the criteria that the gas cycle cannot be turned on if it has been on in the last 4 hours, in order to avoid damaging the useful life of the equipment.

Figure 4 shows a simplified form of the operation of the plant control strategy. The minimum hot tank level is set at 12% so that the salt pumps are submerged, if the level is below that only the gas cycle can run to fill the tank. Between 12% and 18% the gas cycle continues to run to increase the salt level and the steam cycle can be turned on at low power (40 MW) so as not to significantly affect the hot tank level. Between 18% and 25% the Brayton Cycle continues to run at full power and the Rankine Cycle can run at 60 MW, completing the expected power output of 110 MW. Finally, in the event that the hot tank level is above 25%, then the gas cycle shuts down and all power output is taken over by the steam cycle.

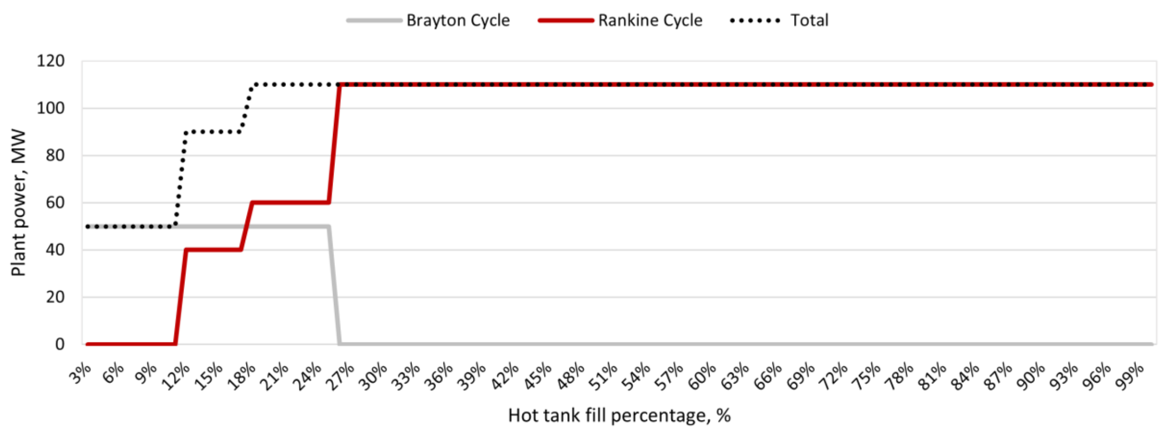


**Figure 4**. Operating power according to the percentage of hot tank filling.

## 3. Results

The simulation of the HYSOL solar fields in SAM allows obtaining the mass flow rates of salt that circulate through the solar receivers of each plant, which on average are around 1 190 kg/s. In addition, the dimensions of the plants are obtained in order to estimate their costs, obtaining that the height of the tower in the three locations is close to 174 meters and approximately 6 400 heliostats are required, using an area of approximately 700 Ha.

From modeling the Brayton Cycle in EES it is obtained that 3,49 kg/s of gas is required for its operation and allows heating 230,4 kg/s of salt. On the other hand, from the Rankine Cycle model it is obtained that for its operation at 40 MW it requires 274 kg/s of salt, for 60 MW it requires 411,1 kg/s and for maximum power (110 MW) it requires 768,7 kg/s of solar salt.

The results of the HYSOL power generation simulation at the 3 locations (L1, L2 and L3) are shown in Table 1. It can be observed that in the 3 locations the capacity factor is close to 90% (without considering maintenance shutdowns). When comparing the capacity factor (CF) of HYSOL with other forms of power generation, it can be observed that it is a very competitive technology. HYSOL has a higher CF than most renewable energies (Solar PV 25%, Wind 30%, Hydroelectric <40MW 60%) [17] [18], only comparable with geothermal (90%), biomass (85%) and nuclear (85-95%) [17] [18]. Moreover, in terms of conventional technologies, it outperforms combined cycle (60-75%) [17] [18] in this aspect and competes with coal-fired thermoelectric (80-90%) [17] [18].

**Table 1.** Generation simulation results in HYSOL.

| Item | Unit | L1 | L2 | L3 |
|---|---|---|---|---|
| Average hours of daily operation of the plant at maximum power | h/day | 13,6 | 14,0 | 13,9 |
| Plant operating hours | h/year | 8760 | 8750 | 8745 |
| Capacity Factor | % | 89,77 | 90,10 | 89,98 |
| Total annual energy | GWh/year | 865,07 | 868,17 | 867,06 |

Table 2 shows the capacity factor, the annual energy generated and the participation of each cycle in the energy generated by HYSOL in the 3 locations. The gas cycle has an energy generation close to 186 GWh/year in the 3 locations, which, considering the installed capacity of this cycle, results in a capacity factor for the Brayton Cycle of approximately 42%. On the other hand, the steam cycle, in addition to generating more energy per year, has a higher capacity factor. This means that the gas cycle has a participation close to 21% of the annual energy generation, consistent with its operation as a backup.

**Table 2.** Capacity Factor, Total annual energy and participation of each cycle at the 3 locations.

| Item | Unit | Brayton Cycle L1 | Brayton Cycle L2 | Brayton Cycle L3 | Rankine Cycle L1 | Rankine Cycle L2 | Rankine Cycle L3 |
|---|---|---|---|---|---|---|---|
| Capacity Factor | % | 43,6 | 41,7 | 42,5 | 70,0 | 71,2 | 70,7 |
| Total annual energy | GWh/year | 191,1 | 182,6 | 186,2 | 674,0 | 685,6 | 680,9 |
| Participation of the cycle in plant generation | % | 22,1 | 21,0 | 21,5 | 77,9 | 79,0 | 78,5 |

Observing the behavior of the gas and steam turbines throughout the days, it can be seen that their operation is complementary, both in the hours of the day and in the months of the year. The steam cycle has greater operation in the hours of sunshine, starting at approximately 13:00, when the tanks are filled with hot salt that allow the production of steam, and the storage allows the operation of this cycle until the early morning, hours in which the output power of HYSOL begins to be supplemented with the gas cycle. It is also observed that in the winter months more hours of operation of the gas turbine are required to supplement the fewer hours of sunshine.

As a metric for comparing electricity generation technologies, the Levelized Cost of Energy (LCOE) is calculated at each location. The following items are considered for the cost estimation: Gas Cycle, Solar Cycle, heat exchanger (between thermal cycles) and transmission (lines and substations). The costs are estimated from data from the Association of Concentrating Solar Power (ACSP) [8], the National Energy Commission (CNE) [9] [10], Solar Committee & CORFO [11] [12], Ministry of Energy [13] [14], Ministry of National Assets [15] and Zhou et al [16].

As a result of the LCOE calculation, the following values are obtained for L1, L2 and L3: 84,5 USD/MWh, 82,9 USD/MWh and 83,1 USD/MWh, respectively. Thus, in all locations it is higher than the one calculated for the Solar Tower (73 USD/MWh) and significantly lower than the LCOE calculated for the gas Open Cycle plant (162 USD/MWh). However, it is expected to become competitive with other renewables if the costs associated with the solar field are reduced, as expected.

Regarding HYSOL's CO2 emissions, these are close to 110 000 Tons CO2/year in the 3 locations, while the emissions savings are close to 400 000 Tons CO2/year. This translates into an emissions factor of 0,12 Ton CO2/MWh, generating considerably less CO2 emissions than other forms of generation that emit this pollutant, being about 35% of the emissions generated by a combined cycle power plant.

## 4. Conclusions

Power generation in HYSOL's Brayton Cycle has a cycle capacity factor close to 42%. Regarding the Rankine Cycle operation, it has a capacity factor close to 70%, so considering that it has a higher installed power, the participation of the steam cycle in the total generation is close to 78% in all cases. L2 is the location that allows a lower operation of the gas cycle and a higher operation of the steam cycle. In addition, for the HYSOL plant, L2 is the one that allows greater total energy generation (between both turbines), with a value of 868,17 GWh/year and a capacity factor of 90%, competitive with most forms of electricity generation, only below nuclear energy in terms of capacity factor, which is not currently part of the Chilean energy matrix.

In terms of emissions per energy generated, there are no relevant differences between locations, with a value close to 0,12 Ton $CO_2$/MWh, significantly lower than other forms of energy generation through fuels.

Regarding the economic aspect of the study, the lowest LCOE of HYSOL was obtained in L2, with a value of 82,9 USD/MWh. The LCOE of HYSOL is higher than the one of the Solar Tower, but lower than the one of the Open Cycle with gas as fuel, it is competitive with generation technologies such as geothermal energy, coal and nuclear power plants. Although LCOE is not extremely competitive with current forms of generation, the costs of the plant, especially those related to the Solar Tower, are decreasing significantly year by year, which is why it is concluded that HYSOL is economically feasible.

Although L2 is the best performer in terms of energy generation, emissions and $CO_2$ emissions savings and LCOE, the difference in all items is less than 5%, it may be attributable to inaccuracies in the estimates, so the preponderance of this location over the others cannot be stated.

As future work, it is proposed to include the energy demand in the area in the generation model and the sale of energy (allowing for a more in-depth economic analysis), to optimize HYSOL's operating logic to make more efficient use of the stored thermal energy, to study the incorporation of other equipment to the Rankine and Brayton Cycles to increase their efficiency, to conduct a study of HYSOL with biomethane as fuel, and to conduct a technical-economic evaluation of the energy transport voltage, considering investment/maintenance costs and energy loss costs.

## Data availability statement

More information of this work can be found at https://repositorio.uchile.cl/handle/2250/184905.

## Author contributions

Conceptualization, C.C. and C.H., investigation, C.C., methodology C.C., writing – original draft C.C. and C.H., writing – review & editing, C.H., Supervision F.D and C.H.

## Funding

Authors C.H and F.D acknowledge the generous financial support provided by CORFO under project 13CEI2-21803.

## Acknowledgement

We are grateful for the support and contribution of Álvaro Valencia and the Universidad de Chile.

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