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Tailoring HYSOL: solar energy contribution to reach full Dispatchability and Firmness in target markets

Jorge Servert [a,*], Diego López [b], Eduardo Cerrajero [b], Alberto R. Rocha [c], Daniel Pereira [c], Lucía González [c]

[a] *Industrial Engineering Ph.D., CEO of Investigación, Desarrollo e innovación en energía – IDIE. c/ Segre 27, 1A, 28002 – Madrid (Spain)*
[b] *Investigación, Desarrollo e innovación en energía – IDIE. c/ Segre 27, 1A, 28002 – Madrid (Spain)*
[c] *COBRA Technology & Innovation. c/ Cardenal Marcelo Spínola 10, 28016 – Madrid (Spain)*

Abstract

Renewable energies for electricity generation are traditionally considered a risk for the electricity system due to their lack of dispatchability and firmness. Renewable energies penetration is constrained to strong grids or else its production must be limited to ensure grid stability, which is kept by the usage of hydropower energy or fossil-fueled power plants. CSP technology has an opportunity to arise not only as a dispatchable and firm technology, but also as an alternative that improves grid stability. To achieve that objective, solar hybrid configurations are being developed, HYSOL being the most recent solution. Three reference scenarios have been defined: Kingdom of Saudi Arabia (KSA), Northern Chile (CHL) and Baja California in Mexico (MEX), considering their respective weather conditions and market demand profile. These scenarios have been modelled, simulated and evaluated in terms of dispatchability and firmness defined by the authors. The results show that HYSOL technology has potential to become a reference in providing firm and renewable power, although a detailed design and control system are required.

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Keywords: Hybridization; CSP; dispatchability; firmness; thermal energy storage; gas; biogas; gas turbine

* Corresponding author. Tel.: +34-91-383-5820; fax: +34-91-767-0129.
E-mail address: jservert@idie.es

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Nomenclature

CC	Combined Cycle
CHL	Chile
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
KPI	Key Performance Indicator
KSA	Kingdom of Saudi Arabia
LCOE	Levelized cost of electricity
MD_{95}	Minimum demand coverage ratio for a 95% rated power
MEX	Mexico
MW	Megawatt
PV	Photovoltaics
R&D	Research and Development
S	Ratio of electricity produced using solar energy
TMY	Typical Meteorological Year
η_f	Performance of fossil fuel usage

1. Dispatchability and Firmness: definitions

The objective of this paper is to compare the proposed solar hybrid technology in terms of dispatchability and firmness under several weather and electricity demand variations.

The study will focus on the evaluation of dispatchability and firmness for HYSOL hybrid CSP technology. These concepts are often used to define CSP characteristics but there is no international consensus on their definitions. The following definitions have been agreed between the authors and presented in a previous paper [1]:

- Dispatchability is defined as the capacity of adapting power output to the required levels at any hour of the day without wasting primary energy.
- Firmness definition is being broadly discussed and it can be defined as:
  - Capacity to provide a certain (threshold) power output when it is needed by the grid operator, regardless of previous circumstances. In the present study, the threshold has been defined as 95% of the electricity demand.
  - Ability to provide capacity during the riskiest hours of the year, it is to say, periods when low solar resource coincides with high demand. The selection of the riskiest or “worst week” has been defined as the one with the highest value obtained using Equation 1.

$$R = \frac{\sum_{h=1}^{168} Demand_h}{\sum_{h=1}^{168} DNI_h} \quad (1)$$

Where $Demand_h$ corresponds to the normalized electricity demanded hourly, DNI_h is the Direct Normal Irradiance mean hour value, and 168 is the number of hours in a week.

An important concept not studied in the current analysis is predictability. Predictability is defined as the capacity of forecasting power output of a particular power plant. In the present study, it is assumed that the configurations selected are predictable for at least one day in advance.

To show an example of these concepts, Photovoltaics (PV), Concentrated Solar Power (CSP) and Combined Cycles (CC) can be qualitatively compared:

- PV production is not dispatchable since the electricity production depends directly on solar radiation and no storage media is included in most installations (e.g. batteries), thus resulting in energy curtailment. Regarding firmness, PV installations are not firm since they cannot produce electricity during the night.
- CSP with storage system is dispatchable thanks to its capacity to regulate electricity production. However, firmness of CSP is limited to a negligible portion of its nominal power, as it is capped by the capacity of storage systems conceived and designed for dispatchability.
- Combined Cycle production is dispatchable since it can produce whenever the plant operator schedules without energy dumping (no fuel is consumed), and it is firm because it can work at full load whenever it is required. But they can reach this quality of being dispatchable and firm using 100% of fossil fuel resource.

It is important to underline that a configuration that meets predictability and dispatchability conditions may not be able to meet firmness conditions (e.g. even being predictable and capable to adjust the power outputs, they may not be able to provide energy if the energy demand is high, energy storage is empty or the primary resource is too low).

2. Target markets

Three target markets have been selected both for their commercial interest and for their capacity to put HYSOL's capabilities to the test: northern Chile (CHL), Kingdom of Saudi Arabia (KSA) and Mexico (MEX). A Typical Meteorological Year (TMY) was selected for each location, obtained using Meteonorm 7.0 [2].

Northern Chile's (CHL) demand (Figure 1) is characterized by a flat profile throughout the year, as industrial clients demand a majority of the electricity, and operate 24/7. High DNI is found at high altitude; a location at about 1900 m above sea level has been chosen. In this case, HYSOL would act as a baseload plant.

The demand profile in KSA (Figure 1) shows a small daily amplitude (peak-to-valley difference is about 20% of the peak) and little day-to-day variation, but winter average demand is only 55% of summer [3]. In this case, HYSOL would act as a baseload with the capability of addressing small peaks.

The Mexican (MEX) grid demand (Figure 1) shows a deeper daily amplitude of around 30% of the peak, with noticeable differences between weekdays and weekends, and seasonal changes where winter average demand is about 60% of summer [4]. In this case, HYSOL would provide a certain constant power and address higher peaks.

These profiles are addressed with HYSOL by modulating the peak power supplied, as described in next section.

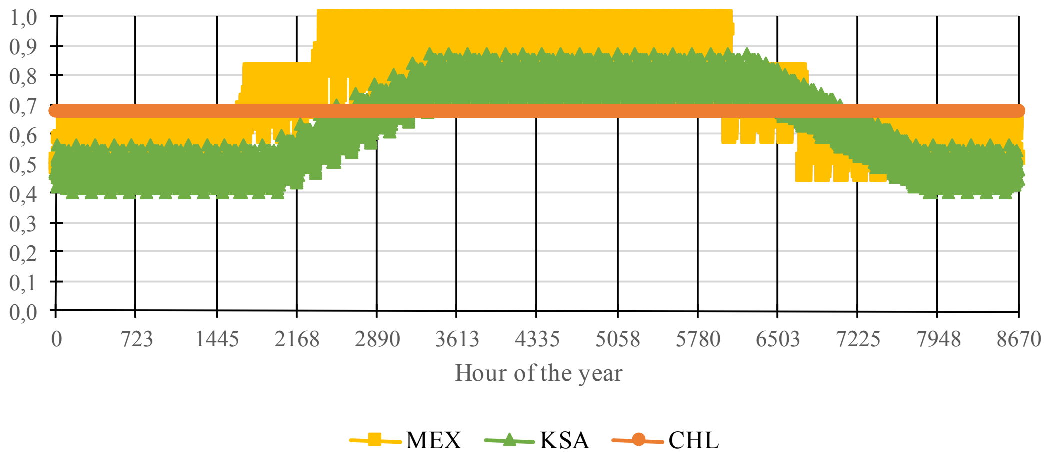

Fig. 1. Demand profiles normalized with the highest peak for comparison.

3. Solar hybrid configuration: HYSOL

HYSOL concept is based on a CSP power plant with molten salts storage (parabolic trough or solar tower systems). HYSOL uses a Brayton cycle in combination with the traditional concept of CSP plant with storage that works only when solar radiation is not enough to provide the desired electrical output (Figure 1). The objective is to maximize the share of electricity produced by solar resource being dispatchable and firm with minimum fuel consumption.

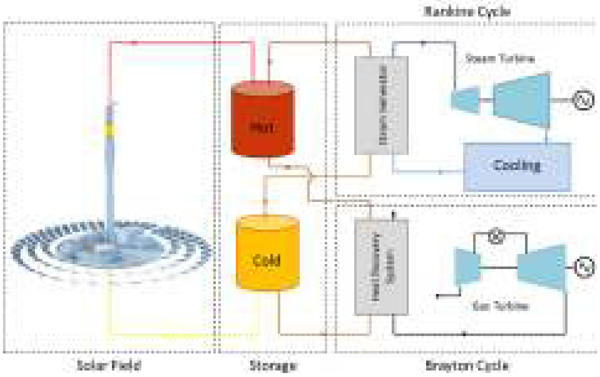

Fig. 2. HYSOL's hybrid CSP configuration considered in the study.

HYSOL is an on-going R&D project that presents a new hybrid configuration for CSP Plants. The design of HYSOL can be adapted to different requirements depending on constraints considered. In this case, a common HYSOL configuration with tailored control parameters has been chosen to address each of the target markets' behavior and available solar resource. Thus, a configuration with 100 MW steam turbine and 80 MW gas turbine is used to address a demand profile proportional to each country's aggregated profile, with a yearly peak demand set to a different value for each market, namely 100 MW in CHL, 130 MW in KSA and 150 MW in MEX. The solar multiple of the solar field is set to 2.47 and the thermal energy storage capacity is 14 hours.

4. Modelling procedure

Solar Field heat production has been modelled with SAM 2014.1.14 [5], and it has been prioritized versus fossil fuel consumption during operation. Therefore, consumption of fossil fuel is adjusted depending on the solar energy input and the electricity demand considered for each hour.

Models defining the Power Block have been developed using Thermoflex 24.1 [6] and integrated in an Excel spreadsheet using VBA for multiple runs. The conditions used to design the Power Block have been the same for all countries: ISO conditions at sea level, so that the selected turbine could not make a difference.

5. Key Performance Indicators (KPIs)

According to the definition of dispatchability, all the plants are qualitatively dispatchable. Solar energy production is prioritized or stored, so there is no dumping of solar energy. In order to quantify the "dispatchability" criteria, a KPI is selected focused on the performance of fossil fuel; it has been defined as the performance of fossil fuel usage (η_f), defined in Equation 2 at Table 1.

Two possible definitions of Firmness have been considered, as described in Section 1. Since both share the requirement of providing capacity, the KPI selected focuses in the evaluation of this capacity, and it has been defined as Minimum demand coverage ratio (*MD95*) in Equation 3 at Table 1.

To evaluate the level of hybridization and the capability of producing electricity using renewable sources, the ratio of energy produced using solar energy (*S*) for total power plant production is provided, as defined in Equation 4 at Table 1. Even if the plant uses biogas to become 100% renewable, the parameter is useful to measure each source's contribution to the final energy output.

Table 1. Key Performance Indicators (KPIs).

	Dispatchability (η_f)	Firmness (MD_{95})	Solar Electricity (S)
Equation	$\eta_f = \frac{\sum_h Ef_h}{\sum_h Qf_h}$ (2)	$MD_{95} = \frac{H_{E>95}}{H}$ (3)	$S = \frac{\sum_h Es_h}{\sum_h E_h}$ (4)

Where, in Equation 2, Ef_h is the electricity produced using auxiliary fuel (hourly value, MWh), Qf_h is the fuel thermal energy input (hourly value, MWh), and h is the number of hours in the period of analysis. The goal is to evaluate the average performance of fossil fuel during the year, since partial load operation required to meet electricity demand leads to penalties in turbine performance (and therefore, a loss on primary energy).

Where, in Equation 3, $H_{E>95}$ is defined as the number of hours with an electricity production higher than 95% of electricity demanded, and H is the number of hours considered in the period of analysis. By these means, the firmness capacity can be evaluated for a whole year (definition 1), or for the riskiest hours of the year (definition 2) which have been defined as the worst week analysis.

Where, in Equation 4, Es_i corresponds to the electricity produced using solar energy (hourly), E_h is the electricity produced by the power plant (hourly), and h is the number of hours in the analysis period.

6. Dispatchability and Firmness results

6.1. Results summary

Table 2. Yearly KPI values.

	Dispatchability (η_f)	Firmness (MD_{95})	Solar Electricity (S)
Chile CHL	52%	74%	72%
Kingdom of Saudi Arabia KSA	50%	88%	67%
Mexico MEX	50%	90%	49%

Table 3. Worst week KPI values.

	Dispatchability (η_f)	Firmness (MD_{95})	Solar Electricity (S)
Chile CHL	49%	30%	29%
Kingdom of Saudi Arabia KSA	50%	84%	38%
Mexico MEX	50%	68%	26%

6.2. Yearly results analysis

Figure 3 summarizes the main results obtained in the yearly simulation in terms of demand coverage. Figure (3 a), on the left, shows the distribution of MD_{95} obtained each month. Summer months bring the worst results, as demand is higher and temperature causes the gas turbine to decrease its peak delivered power.

In the Chilean case, altitude is also a factor in the poor results, as the power output predicted for the turbine is lower than obtained. This leads to a poor result despite the fact that Chile has an extraordinary solar resource and the lowest design demand in this study. The use of correction curves in the control equations will improve this result.

Figure (3 b), on the right, shows that, in spite of the relatively low MD95 results, the demand coverage is good with values above 80-85% throughout most of the year. Deviations from the expected production are caused by an imprecise control algorithm, still under development in the research project, and not by a lack of energy available.

Figure 4 shows the results of all KPIs in the three locations, also shown in Table 2. The performance in the use of fuel is in the range of 50% in all cases, with demand coverage above 90% save for the Chilean case, as commented above. The use of solar energy stands between 50 and 75%.

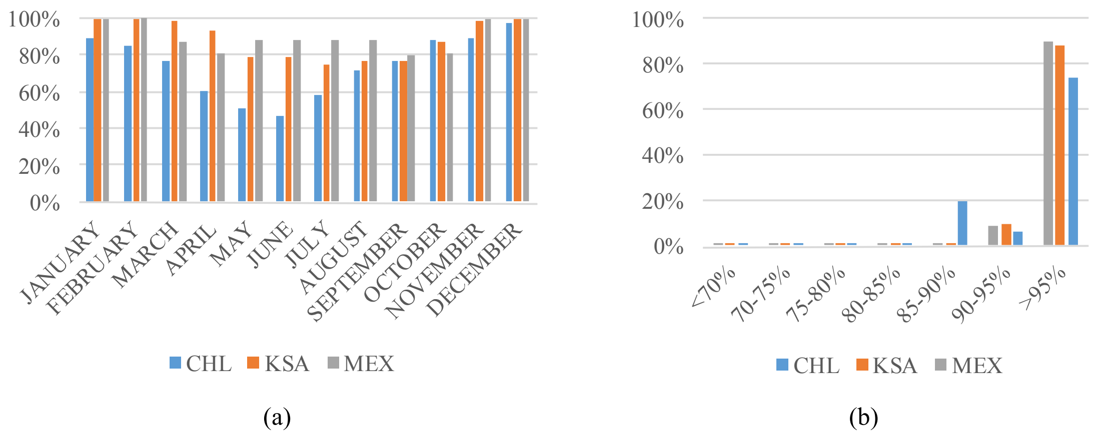

Fig. 3. Yearly simulation results for demand coverage: (a) MD95 monthly values compared with mean monthly demand load, and (b) histogram of % of energy demand covered for different thresholds

6.3. Worst week analysis

Equation 1 has been used to determine the worst week of the year from the point of view of energy balance. The result was week 21 (late in May) for CHL and, coincidentally, week 36 (early in September) for both KSA and MEX. During these weeks, demand is close to the high levels required during summer, but weather instability typical during spring and autumn can strongly reduce the availability of solar energy.

Figure 4 b shows, when compared to Figure 4 a, a sharp decrease in MD95, especially in CHL, and also the expected reduction in solar energy contribution. Numeric values are shown in Table 3.

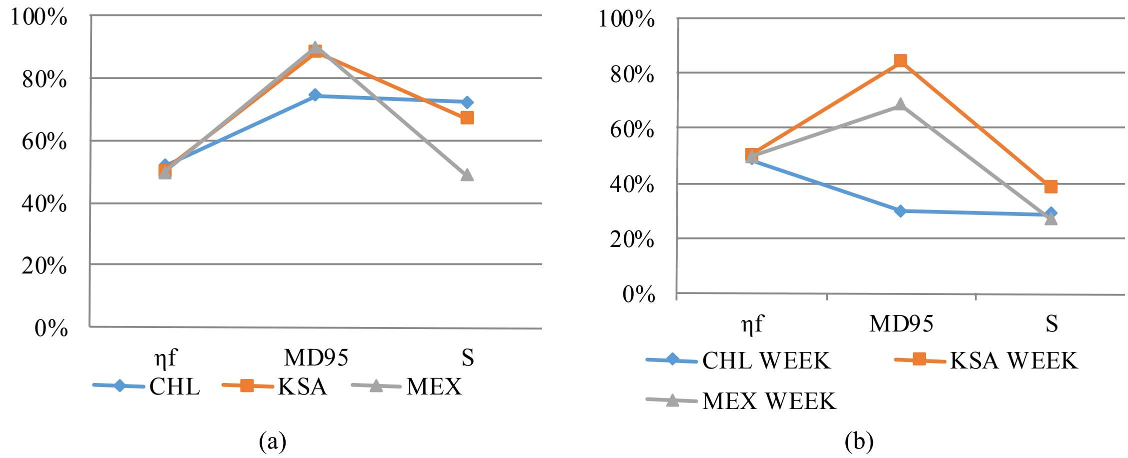

Fig. 4. KPI results for yearly simulation (a) and for Worst week analysis (b)

Figure 6 provides a better insight of these results. KSA case (Figure 6 b) shows very little effect in comparison with the yearly simulation: three days in a row with a low irradiation are not enough to deplete the thermal energy storage, and the demand is met efficiently with small gaps caused by the imperfect control.

Figure 6 a illustrates the Chilean situation described before: despite having plenty of energy stored, even after three days with nearly zero solar irradiation, the control system fails at predicting the output of the gas turbine and demand is systematically not covered.

Finally, Mexico (figure 6 c) shows the only case when demand is not met for a few hours due to actual lack of energy available: after three days with hardly any solar input, demand peaks above 120 MW for more than 24 hours. An economic assessment must be carried out to decide if investing in a larger gas turbine to fill the gap is justified.

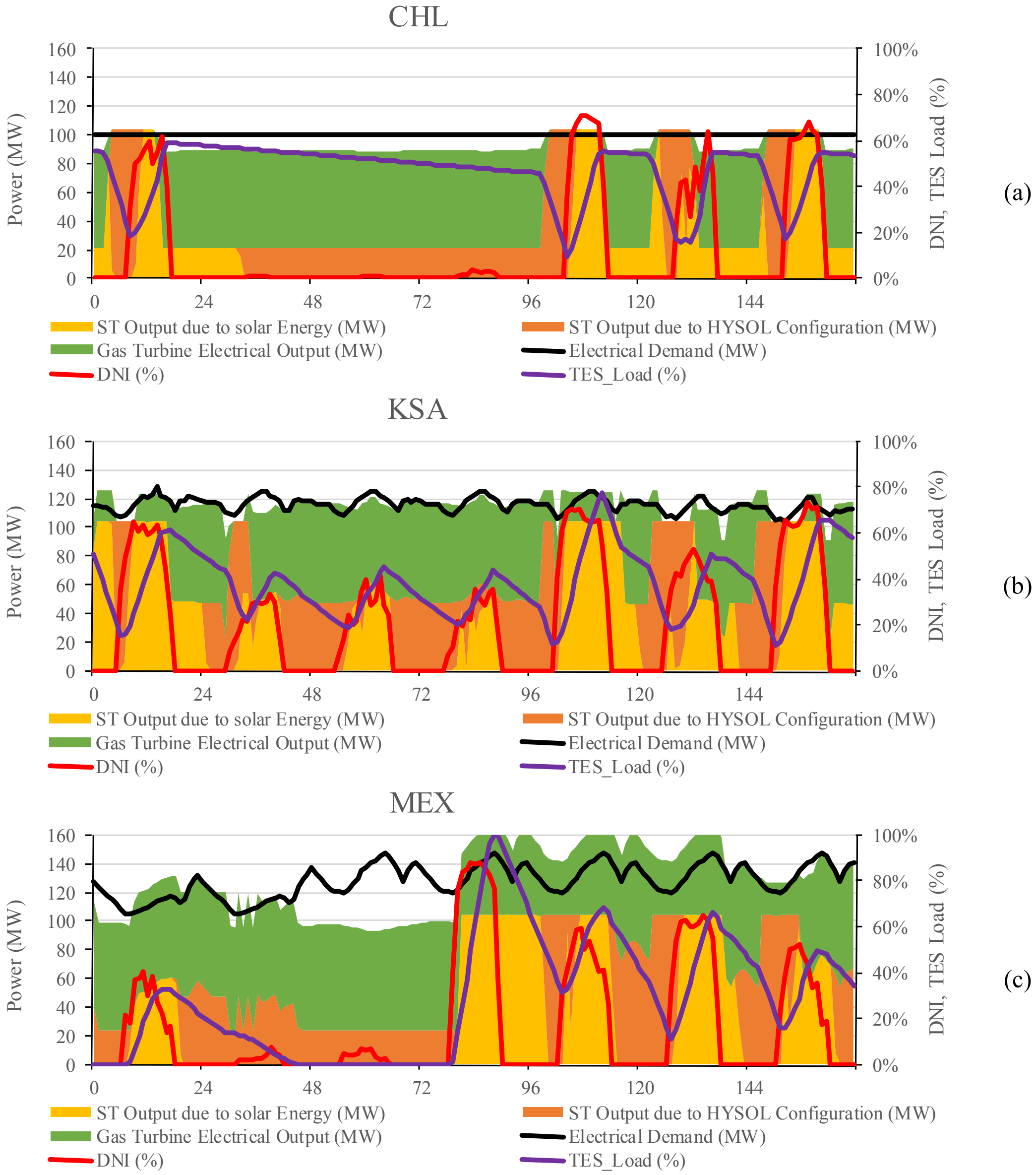

Fig. 6. Power production profile during the worst week for (a) CHL, (b) KSA and (c) MEX.

7. Dispatchability and Firmness: conclusions

Regarding **Dispatchability**, all of the locations present reasonable values for η_f, around 50%. The slightly higher result obtained in Chile can be explained by its lower peak demand, that allows the turbines to operate at their nominal rate much more frequently, whilst reaching KSA's or MEX's peak power forcefully requires one or both turbines to operate at partial loads. This situation shows during the worst week analysis, when the steam turbine in the Chilean case remains at minimum load for several days and, consequently, the dispatchability falls below 50%.

In terms of **Firmness**, yearly simulations show favorable values between 74 and 90% depending on the location. A detailed analysis during the worst week scenario reveals that the majority of demand not met derives from a still imperfect control, with very few hours actually lacking energy availability.

Finally, the **solar fraction** obtained with HYSOL is high, between 50 and 75%, despite operating as baseload and providing peak power above the rated solar output. The results show that HYSOL configuration can provide dispatchable and firm energy in large-scale (>100MWe) applications, just in similar conditions as other configurations heavily based on fossil fuel combustion.

The results obtained show that there is a way to use solar energy to obtain firm and dispatchable energy and not only as an add-on to fossil fuel power plants, although an improved control is required to obtain better results. Additionally, the reduction of auxiliary fuel needs would allow biogas use, resulting in a 100% firm and dispatchable renewable energy supply.

These results are not final, but have provided the authors with an overview of the capabilities of the technology and potential improvements. In terms of techno-economic analysis, it is soon to provide a reliable estimation of costs, since HYSOL configuration has not been optimized. Holistic feasibility comparison is on-going within the project, and the optimization will depend on external constraints, such as legislation, financing, production schedule prioritization, auxiliary fuel costs and real case needs. These constraints will lead to tailor-made HYSOL configurations for different locations and applications. However, since HYSOL technology is an investment-intensive technology where auxiliary fuel consumption is reduced, authors estimate that Levelized Cost Of Electricity (LCOE) will be lower than including CSP and CC separately in a system. Finally, a regulatory framework to evaluate and put in value dispatchability and firmness is urgently needed. HYSOL technology can be adapted to different configurations according to different requirements and criteria, but they need to be settled down to select final HYSOL configuration. HYSOL has shown potential to meet the firmness definition shown in this paper, but due to its high solar contribution, traditional criteria previously used for other technologies (such as fuel storage requirements) could not be applied. Now is time for the stakeholders to define these criteria and their objectives for solar technology in terms of dispatchability and firmness.

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