Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 69 (2015) 2049 – 2059

Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

High capacity factor CSP-PV hybrid systems

A. Green, C. Diep*, R. Dunn, J. Dent

SolarReserve LLC, 2425 Olympic Blvd., Santa Monica, CA 90404, USA

Abstract

Tower concentrating systems with direct molten salt heat transfer and storage can deploy particularly inexpensive and scalable thermal storage, enabling cost-effective 24-hour generation using only solar energy. While typical capacity factors (CFs) for intermittent renewables are generally between 20% and 40%, the SolarReserve Crescent Dunes project will offer above 50%. This paper discusses how SolarReserve's CSP technology can cost-effectively produce a CF over 80%, and when hybridized with PV, can raise the CF further to roughly 90%. A detailed operational model of a hybrid system in Chile's Atacama Desert was produced, using localized data on weather and interconnection capacity, to illustrate this capability.

Analysis of high CF CSP-PV hybrids leads to three important conclusions. First, it was found that effective configuration of high CF systems supported selection of fixed-tilt PV at a high angle, which is optimized for winter generation in order to minimize seasonal differences. Second, when a dispatch strategy was developed which incorporated multiple priority levels and which dispatched CSP in response to PV output, it enabled higher CF CSP-PV hybrid operations than the CSP accomplished alone. Third, it was found that average annual DNI was not a sufficient metric of solar resource, and that seasonal variability and consolidation of non-optimal days were also important to high CF designs. New metrics for solar resource measurement are proposed and discussed.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

Keywords: CSP-PV Hybrid, High Capacity Factor, Smart Dispatch

---

* Corresponding author. Tel.: +1-310-315-2295
E-mail address: Charles.Diep@SolarReserve.com

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.218

1. Introduction

Tower concentrating systems with direct molten salt heat transfer and storage can deploy particularly inexpensive and scalable thermal storage, enabling cost-effective 24-hour generation using only solar energy. While typical capacity factors (CFs) for intermittent renewables are between 20% and 40%, the SolarReserve Crescent Dunes project will offer above 50%. The Crescent Dunes solar energy project is a 110 MW CSP facility with over 10 hours of molten salt storage located near Tonopah, Nevada; construction is largely complete and the facility is undergoing commissioning [1].

Certain markets support the development of even higher CF design. For example, the energy market in the Atacama Desert in northern Chile is dominated by large mines with relatively steady 24-hour energy demands; with no domestic hydrocarbons, a powerful community of environmental stakeholders, no nearby hydropower opportunities, and abundant suitable land with high solar resources, the market opportunity is ideal for new high CF solar energy projects [2].

SolarReserve's CSP technology employs a molten salt tower receiver, which allows significant flexibility in the relative sizing of the solar field, heliostat selection, storage amount, and power block. The development of a CSP project which operates a high capacity factor is not a major technological leap from Crescent Dunes; rather, it simply entails a relatively larger amount of storage and smaller power block to deliver a day's worth of collected solar energy over a longer time period. While the CF generally increases as the power block size decreases relative to the other components, a smaller power block may not be able to deliver all of the energy that the system is capable of collecting and storing. In other words, increasing the CF past a certain point can reduce the cost-effectiveness of the system. In the case of a plant sited in the Atacama, the high CF can be achieved with a relatively high power block capacity due to the extremely high solar resources in this area.

The levelized cost of energy produced by PV is generally lower than that of CSP. PV can be operationally combined with CSP if the CSP is dispatched in response to the output from the PV; if a baseload output is required or desired, this combination can enable a lower-cost solution for a given high CF objective than what is achievable with CSP alone.

Nomenclature

CF	capacity factor
CSP	concentrating solar-thermal power
DNI	direct normal irradiance (insolation)
DSV	daily solar variability
PL	priority level
PV	photovoltaic
SDMI	standard deviation of monthly irradiance
TMY	typical meteorological year

2. System design

In response to market demand for a high CF solar product, SolarReserve sought to reasonably optimize a hybrid PV-CSP system design, as illustrated below in Figure 1. Three guiding principles were used: first, a relatively low-risk CSP configuration was preferred, so that technical feasibility would not be a question; second, PV capacity was constrained to a small enough size that the CSP could balance it (by operating at part load) without approaching the steam turbine's minimum load; and third, in order to illustrate the performance of the dispatch model in light of transmission constraints, an arbitrary interconnection capacity limit was imposed.

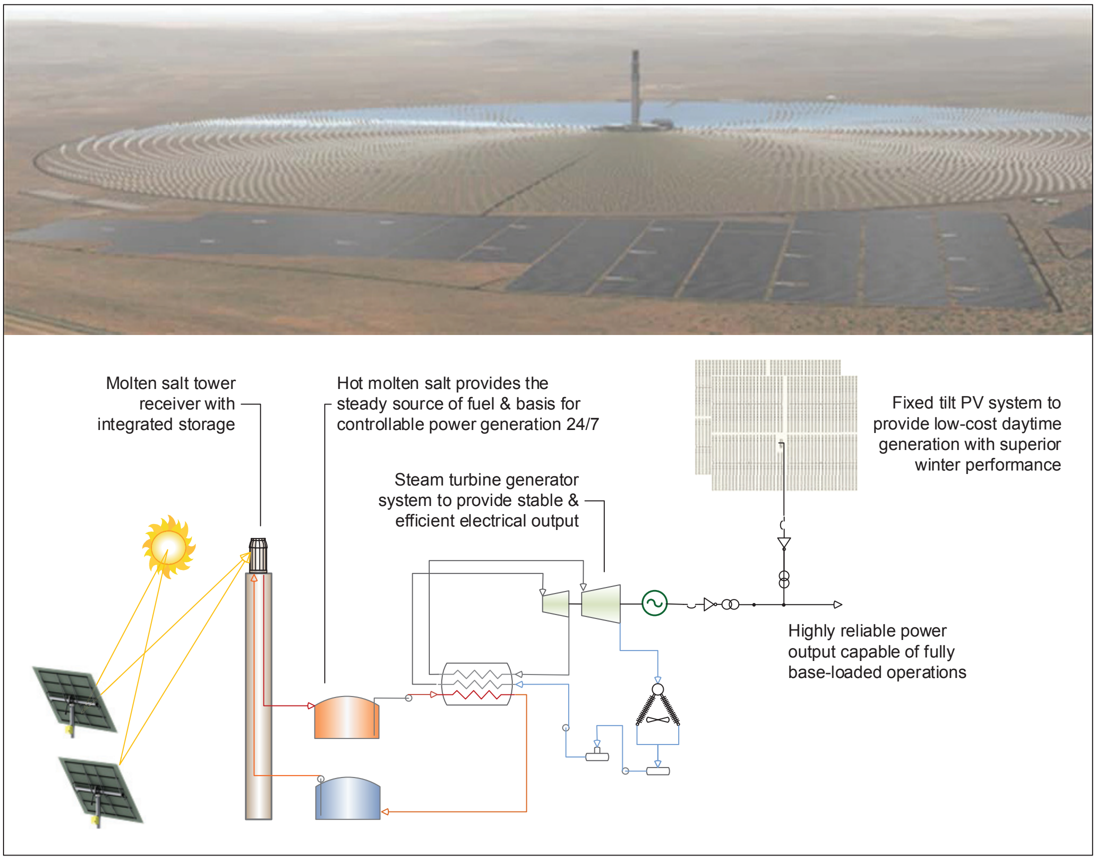

Figure 1 - Conceptual diagram of high CF hybrid facility

The CSP was sized at 100 MWe net, accomplished with a single steam turbine generator, representing the same general asset class as SolarReserve's Crescent Dunes project. The modeled CSP has a heliostat field aperture of 1.3 million m^2, roughly 10% more than Crescent Dunes, which optimally takes advantage of incremental improvements in receiver capacity in the high-DNI location. This system presents a thermal collection capacity to electric power generation multiple (Solar Multiple) of roughly 2.6. In addition, 14 hours of storage (roughly 30% more salt mass than at Crescent Dunes) was found to be the optimal amount.

PV capacity of 60 MWac was chosen. While more PV could have been integrated without requiring CSP to be backed down past its minimum set point, it was found that 60 MW met various technical and commercial objectives. Additional PV has a declining marginal contribution to output; due to the interconnection limit, when the CSP is already operating for 24 hours during most days, incremental PV additions were found to add less and less to the total facility output. PV was optimized for winter output in order to maximize the combined CF of the facility; multiple scenarios were run using PVSyst software, and it was found that a fixed-tilt configuration at 45 degrees would maximize the output during winter months without dramatically reducing annual output. Other PV configurations (using the latitude angle to maximize annual yield, single-axis tracking, etc.) would have contributed incremental energy during non-winter months and during sunnier days, which generally were times when the CSP was already capable of achieving high CF output. By optimizing for winter, the PV configuration focused on providing energy when the overall hybrid system would otherwise have fallen short of its objective.

3. Performance model

A simplified version of SolarReserve's proprietary SmartDispatch program was utilized to simulate the hourly performance of the hybrid system. SmartDispatch is a simulation which optimizes the plant output to meet a hierarchical ordering of multiple energy output Priority Levels ("PLs"). In this example, we modeled the following set of PLs: [50, 100, 130]. Less formally, this signifies that the first priority was to deliver 50 MW at all times, the second priority was to deliver 100 MW whenever possible, and the third priority is to deliver whatever else is possible subject to the interconnection limit. This concept is employed in SmartDispatch as illustrated below in Figure 2 through Figure 4.

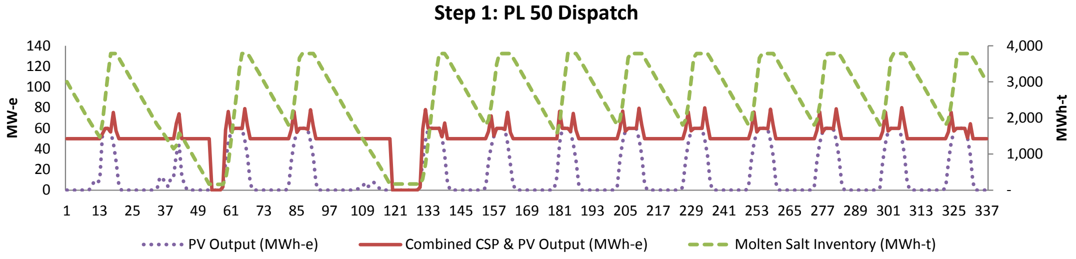
Step 1: PL 50 Dispatch

Figure 2 – Illustrative first step in SmartDispatch logic: model is dispatched at PL 50 MW.

As illustrated above, SmartDispatch begins by dispatching the CSP at the first PL. A fourteen-day period is shown. Solar collection, a reflection of DNI which increases the molten salt inventory, is not shown, but is similar to PV output in timing and relative amount. It can be observed that the hybrid system output exhibits sharp spikes when PV ramps up and down; this is due to the minimum set point on the CSP steam turbine, and they are largely just temporary artifacts of this intermediate first step.

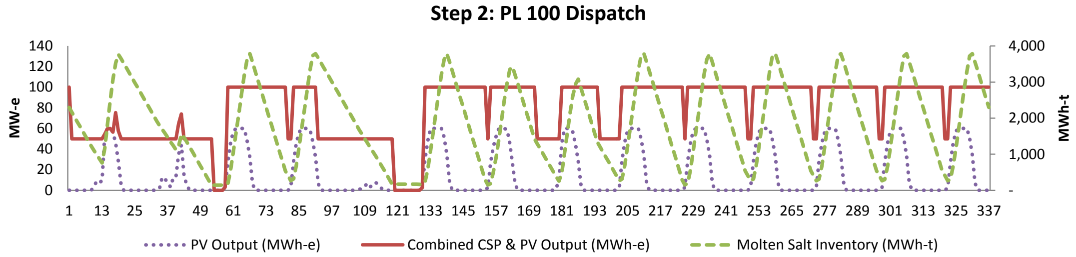
Step 2: PL 100 Dispatch

Figure 3 - Illustrative second step in SmartDispatch logic: model is re-dispatched at PL 100 MW.

As a second step, SmartDispatch is re-run with a PL of 100. CSP output is increased significantly over the results from the first step, but never at the expense of attaining 50 MW net output. It should also be noted that the molten salt inventory is discharged more deeply and the molten salt tanks spend less time being full.

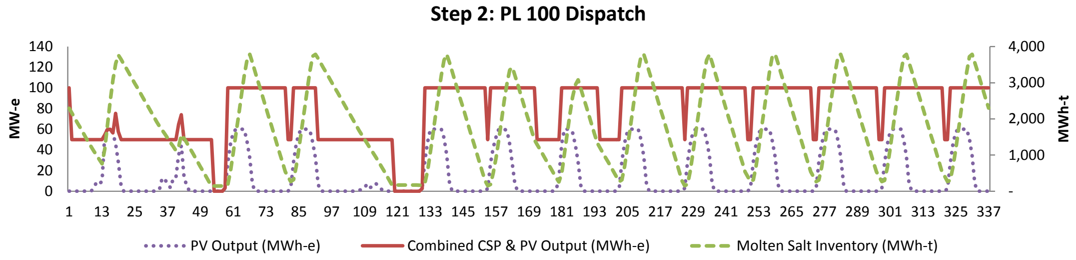
Step 2: PL 100 Dispatch

Figure 4 - Illustrative third step in SmartDispatch logic: model is re-dispatched at PL 130 MW.

For the third step, SmartDispatch is again re-run, this time with a PL of 130. Again, output is increased without sacrificing performance at PL 50 or PL 100. Molten salt is utilized even more fully than in the prior step. We observe spikes of generation from 100 to 130 MW for short periods of time. The sharp spikes can be mitigated by running multiple additional PLs in smaller increments (for example, [50, 100, 105, 110, 115, 120, 125, 130]) which smoothens the output to approximate more realistic plant operations without undermining the performance objectives of the model. Such a strategy was adopted in the year-long simulations discussed elsewhere in this paper.

As demonstrated above, SmartDispatch aggregates the highest achievable hourly output based on the PL structured for the hybrid systems. For the case illustrated above, the system is first dispatched to maximize performance at 50 MW; then, it is re-dispatched to also achieve 100 MW without reducing the occurrence of 50 MW net output; finally, it is re-dispatched again up to 130 MW without reducing the occurrence of 50 MW or 100 MW net output. Net output includes both PV output and CSP output.

The meteorological data used for the simulations in the next section was a typical meteorological year (TMY) file of consisting of concurrent hourly DNI, GHI, diffuse radiation and other relevant meteorological data for a location in Chile. Data was procured from a commercial supplier and was correlated with ground station measurements on-site.

4. Performance model results

Using the data described above, an 8,760-hour (one-year) production simulation was run. Excerpted results are shown below.

Figure 5 and Figure 6 (below) illustrate the energy collection and dispatch of the hybrid CSP-PV system over 4 weeks – the first two in November and the second two in June.

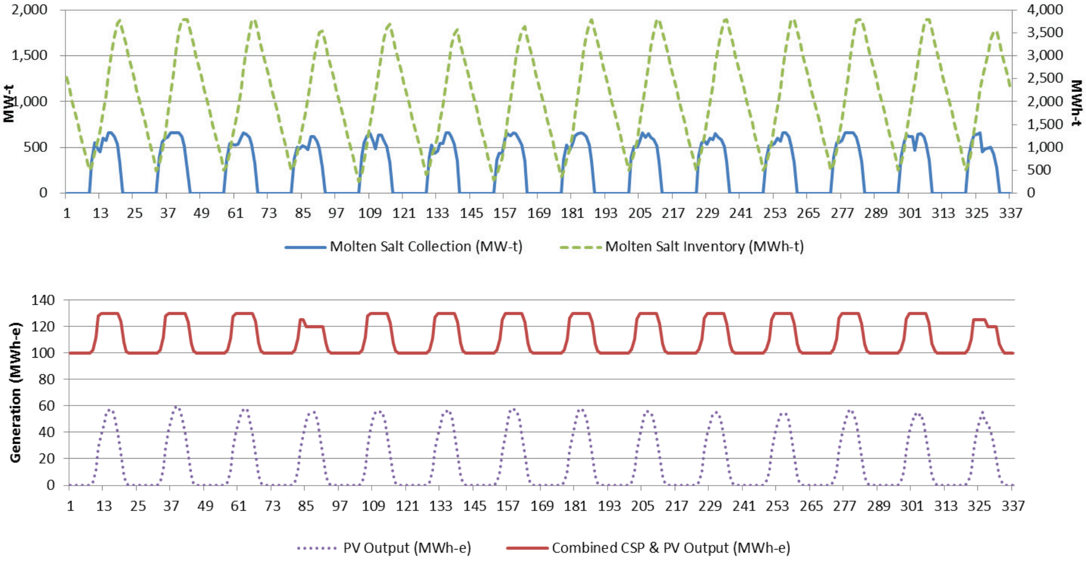

Figure 5 (Above) - Energy collection in the tower storage system (top) and hybrid CSP and PV output (bottom) for 2 weeks in November (summer in Chile). Cumulative hours are marked on the x-axis.

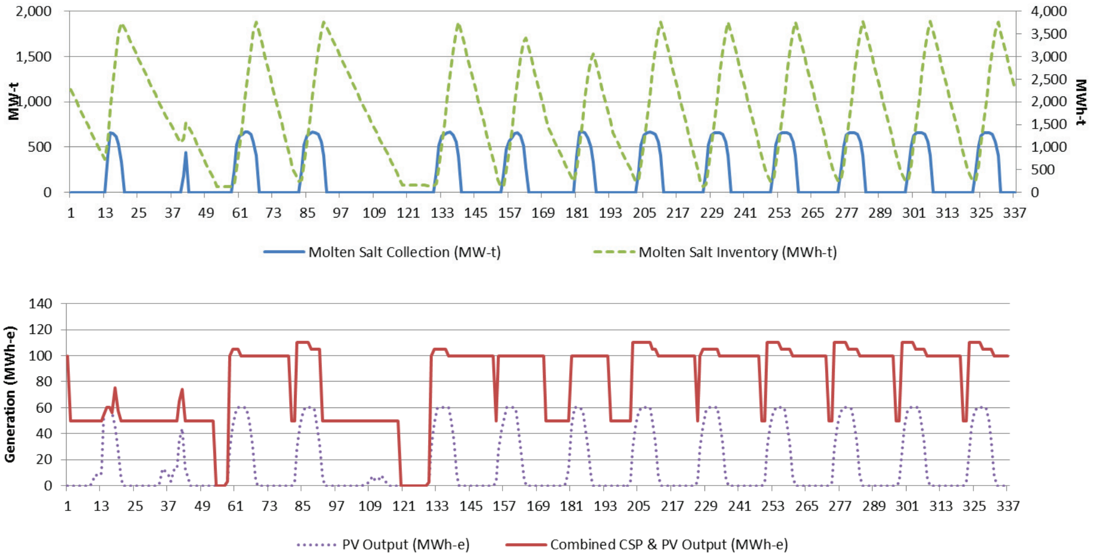

Figure 6 (Above) - Energy collection in the tower storage system (top) and hybrid CSP and PV output (bottom) for 2 weeks in June (winter in Chile.) Cumulative are marked on the x-axis.

These results illustrate how the highest-priority output (the 50 MW PL) is almost always achieved even on cloudy days, and the 100 MW target is even achieved throughout most of the winter period.

These observations are confirmed in Table 1, showing that 50 MW or more is achieved 98.5% of the year, and 100 MW or more is achieved for 84.8% of the year. Table 1 also illustrates the base-loaded nature of the hybrid output, as the number of start-ups over the course of the year is just 34.

Table 1: A summary of annual generation from the hybrid CSP-PV system.

	Molten Salt Collection (GWh-t)	**PV Output (GWh-e)**	**Combined CSP & PV Output (net, GWh-e)**	**Time at 50+ MW**	**Time at 100+ MW**	**Turbine Starts**
Annual Total	1,863	152.4	860.9	98.5%	84.8%	34

To illustrate the effectiveness of using SmartDispatch to integrate CSP with PV, the model was re-run with the same CSP configuration, but without PV. Results are displayed in Table 2 below, and show substantially reduced ability to achieve the 100 MW target over the course of a year.

Table 2: A summary of annual generation from non-hybridized CSP.

	Molten Salt Collection (GWh-t)	**PV Output (GWh-e)**	**Combined CSP & PV Output (net, GWh-e)**	**Time at 50+ MW**	**Time at 100+ MW**	**Turbine Starts**
Annual Total	1,863	0	714.4	98.0%	65.1%	19

5. Discussion of performance results

The results of the SmartDispatch performance model are representative of the capabilities of a hybrid system designed for high CF operation. Different project requirements and proposed locations may have different solar resource patterns, PLs, capacities, interconnection limitations, etc., which may in turn lead to different configuration decisions. However, these results do indicate high CF operation is technically feasible and would be suitable for a commercial structure such as a Power Purchase Agreement which reflects the “base-load” nature of the technology.

The PLs used here were static values, i.e., a certain MW target for all hours of the year. SmartDispatch can also incorporate PLs which vary in MW level from hour to hour. This would enable a CSP facility to prioritize serving a specific customer’s needs (e.g., a particular mine or other industrial user) to the greatest extent possible, and then to accurately model what additional energy could be sold to other customers or on the spot market.

6. Impact of meteorological data characteristics

Simulation of high CF dispatch provides insights into the desirable features of meteorological data to optimize high CF performance. While average annual DNI is a commonly used metric, we find that, when used in isolation, it can be insufficient or even misleading for high CF designs. Furthermore, certain assumptions made in compiling typical meteorological year (TMY) files can damage the validity of a high CF model’s results; in particular, if those assumptions distort the distribution of suboptimal solar days, results of a high CF model can be misleading.

Based on the experience of modeling many high CF configurations, we propose three additional concepts which could be incorporated into measurements of solar resources for high CF applications:

1. the consolidation of optimal days, i.e., to what degree sunny days are consecutive;
2. day-to-day solar variability; and
3. the degree of seasonal variability, i.e., between summer conditions and winter conditions.

Three time series – 2010, 2005 and TMYb – for the same location in Chile were analyzed with respect to these measures. In order to control for the effect of annual DNI, the 2005 and TMYb (different TMY file to that used in Section 5) time series were scaled to meet the same annual DNI as the 2010 time series. The following analysis shows simple metrics for each of the three measures shown above. While it is possible that other more complex constructs might be more accurate, these simple metrics illustrate the key concepts most clearly.

The consolidation of optimal days can be characterized by the average number of days running before the daily DNI falls below a certain threshold – for example, a threshold of half the average daily DNI, which we have chosen for simplicity. For the three time series analyzed here (scaled to meet the same annual DNI), the average daily DNI was 8.96 kWh/m2/day. The dates on which the DNI fell below half the daily average in the 2010 time series are given in Table 3 below, along with the average stretch of days until the daily DNI fell below this threshold.

Table 3: The consolidation of suboptimal days for the 2010 time series.

Date	**Days running until daily DNI fell below 4.48 kWh/m^2**	**Consecutive days below 4.48 kWh/m^2**
Feb 4th	35	1
May 14th	99	5
May 28th	10	1
Jun 11th	14	1
Jun 18th	7	1
Jun 23rd	5	1
July 17th	24	1
Aug 11th	25	1
Sept 2nd	22	1
Average stretch of days until daily DNI fell below 4.48 kWh/m2	**26.8**	

In a similar fashion, the average stretch of days until the daily DNI fell below this threshold is summarized for the three time series in Table 4. The proper DNI threshold may be specific to each plant. In our practical experience, the important question is whether a prior day's sunlight was enough to carry a current day if the current day is cloudy. The importance of a prior day's cloudiness introduces a hysteresis effect that is not otherwise captured by statistical metrics such as the standard deviation. Figure 7 illustrates different scenarios for the average stretch of acceptable DNI days.

Table 4: A summary of the DNI threshold achievement for three hourly time series.

	2010	**2005 scaled**	**TMYb scaled**
Average days before DNI drops below half of average DNI	26.8	18.6	8.2

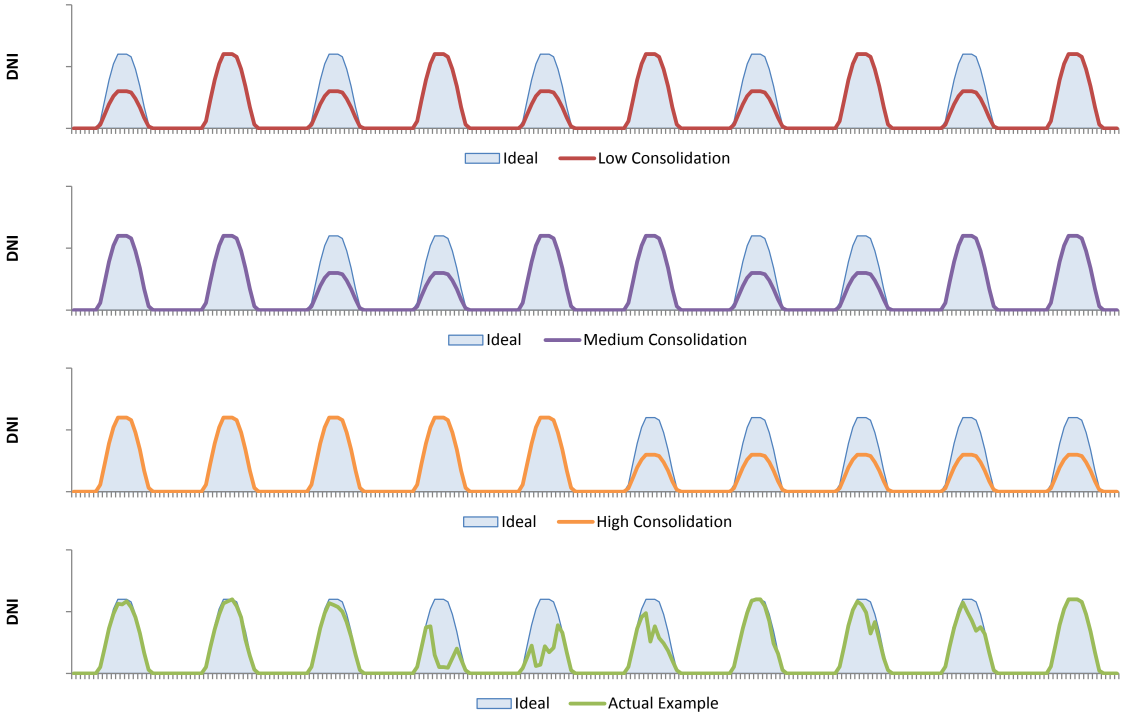

Figure 7 - Illustration of consolidation patterns

The day-to-day (inter-daily) solar variability of the three time series is analyzed below – first as an annual sum, and then as a histogram. As an annual sum, "Daily Solar Variability" (DSV) is defined here as the sum of the absolute value of one day's DNI less the prior day's DNI, as per Equation 1. The DSV values for the three time series are given in Table 5.

$$DSV = \sum_{d=2}^{365} \left| DNI_d - DNI_{d-1} \right| \tag{1}$$

Table 5: A summary of the Daily Solar Variability (DSV) for three hourly time series.

	2010	2005 scaled	TMYb scaled
DSV (MWh)	292.8	548.7	1,102.1

Figure 8 shows another method of illustrating the degree of daily solar variation with a histogram of the number of days that fall into each bin for difference to the proceeding day. Time series with higher DSV values (2005 and TMYb) have a greater frequency of days towards the right of the graph where differences between the DNI on day (d) and day (d-1) are higher.

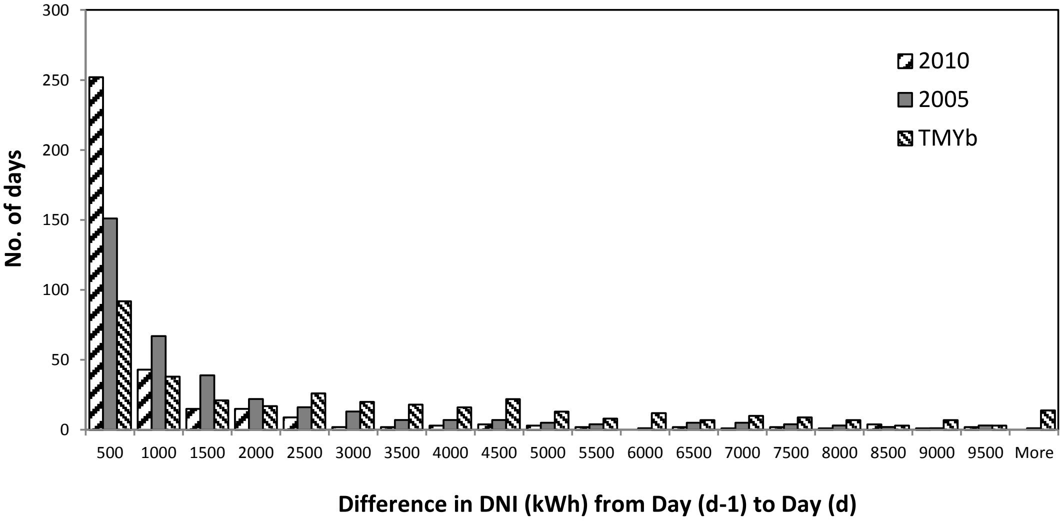

Figure 8 - The frequency of differences between the DNI on day (d) and day (d-1) for three time series.

To capture seasonal variability, employing a similar metric to DSV was considered but discarded due to the lack of a comparable hysteresis effect. Instead, it was found that standard deviation is a satisfactory measure of variability in this context. Specifically, we propose taking the standard deviation of the average daily DNI for each month – hence "Standard Deviation of Monthly Irradiance" (SDMI). Measuring the average daily DNI rather than the monthly total DNI controls for differences in the lengths of months. SDMI is therefore a simple metric which encapsulates the degree of variability on a monthly basis, which roughly approximates effects on a seasonal timescale (effects which may not constrain themselves to calendar definitions of "seasons"). The SDMI values for the 2010, 2005 and TMYb time series are shown in Table 6 below, with the daily average DNI for each month plotted in Figure 9. Generally, a greater difference in SDMI would be expected between different locations with different latitudes and weather patterns, however a difference is still observable between the TMYb and 2010/2005 times series.

Table 6: A summary of the standard deviation of the average daily DNI for each month (SDMI) for three hourly time series.

	2010	2005 scaled	TMYb scaled
SDMI (kWh)	1,020.5	868.8	1,918.3

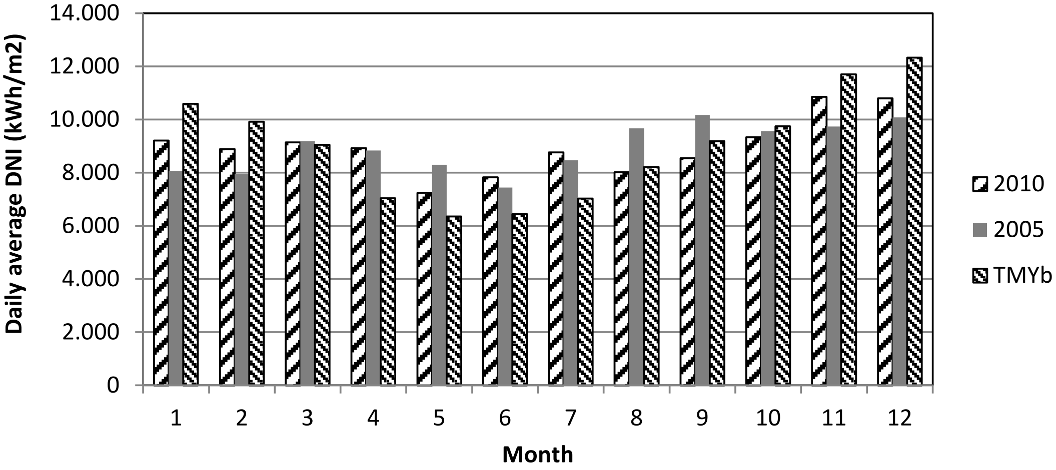

Figure 9 – Seasonal variation in daily DNI for three hourly time series.

The results of performing SmartDispatch for the 2010, 2005 and TMYb time series, all with the same annual DNI but different consolidation of optimal days, DSV, and SDMI values are given in Table 7 below. While these results are not intended to be conclusive, they nonetheless suggest that even with the same annual DNI, sites with high consolidation of optimal days, low DSV and low SDMI give higher annual plant output, and hence higher CFs. This is due both to the absolute collection of energy, and also to the efficient dispatch of that energy.

Table 7: A summary of annual generation and capacity factors achieved from the three time series.

Annual Totals	Molten Salt Collection (GWh-t)	PV Output (GWh-e)	Total Plant Output (GWh-e)	Time at 50+ MW	Time at 100+ MW	Turbine Starts
2010	2,043.5	159.0	907.0	98.0%	91.2%	15
2005 scaled	1,989.4	158.3	874.7	96.9%	84.7%	30
TMYb scaled	1,877.9	152.3	790.0	94.8%	68.8%	78

In general, this analysis indicates that a high consolidation of optimal days, a low DSV, and a low SDMI will support cost-effective high CF output by allowing the facility to operate at a steady state for a higher proportion of the year. These metrics should not be taken in isolation, but rather should be used to complement an understanding of annual DNI. We suggest that providers of solar prospecting tools and resource assessments should take these factors (or similar factors) into account when supporting high CF solar applications. Similarly, typical values for consolidation of optimal days, DSV, and SDMI for a given site, or similar metrics, merit consideration for being conserved during the formulation of typical meteorological year time series. Without incorporating an understanding of the needs of high CF systems, current methods may instead be misleading and counterproductive.

Until new metrics are developed and propagated, we find that the most effective way to assess the high CF potential for a given location is to obtain accurate long-term time series of DNI and to run full SmartDispatch simulations.

7. Summary

There has been much discussion on the dispatchability of CSP with storage systems relative to PV and other renewable energy sources such as wind. However, there has been no known work published on the approach and methodology of dispatch for such a CSP system. With the advent of hybrid systems, mostly in CSP integration into new or existing fossil based generation plants, the manner in which a CSP plant is integrated and dispatched will become more important. This is also true with feed-in-tariffs structured to recognize the beneficial dispatchability features of CSP systems.

The work for this paper utilizes a hybrid system consisting of CSP and PV to achieve high plant capacity factor comparable to traditionally base-loaded generation plants. The focus of the work is a dispatch strategy that maximizes the fulfillment of specific electrical output objectives. The strategy layers on previously unpublished work by SolarReserve that optimizes dispatch of its two-tank molten salt central tower receiver system. This advanced dispatch strategy further considers complementary generation systems such as a utility-scale PV plant, interconnection constraints, customer demands and market opportunities into the optimization algorithm. The approach is based on first assigning a priority to each of these competing requirements. Then an algorithm which considers available power and constraints from one or more generation assets/systems (e.g. CSP, PV, etc.) is dispatched to satisfied each prioritized requirement level sequentially. The key idea in this approach is to ensure that the highest customer/project demand is met, while the lower-priority requirements are also met when the system opportunity exists, and finally, all remaining potential energy is dispatched for useful purposes. A project in the Atacama Desert, Chile configured and dispatched in this manner has been shown to have high capacity factor (energy yield) while meeting all the objectives and constraints set for the project.

Since such dispatch algorithms are inherently complex and time consuming to implement, the work also examines certain potential metrics that developers or general industry participants can readily determine the feasibility of such project configuration at a proposed site. For this purpose, a metric that characterizes the day-to-day solar variability (DSV) and another that characterizes the month-to-month solar deviation can be adopted. An approach is proposed and discussed in this paper, but such implementation can be standardized to potentially benefit other CSP hybrid solutions. It is determined in the assessment that the average annual DNI and these two variability metrics can enable an interested party to quickly evaluate different project sites for high capacity factor hybrid solutions.

While the process and results were not fully presented and discussed in this paper, the dispatch approach and methodology discussed above revealed that a fixed-tilt PV system optimized for higher winter and earlier morning production are most favorable in the configuration of a high capacity factor CSP-PV hybrid system.

References

[1] Mary Grikas. (2014, Febaruary 12). *Next Generation of Solar Energy Storage Advances as Nevada Project Begins Commissioning.* Retrieved from SolarReserve.com: http://www.solarreserve.com/wp-content/uploads/2014/02/Crescent-Dunes-Commissioning-FINAL-12Feb20141.pdf

[2] Andrew Slavin. (2014, September 17). CSP-PV Hybrid to Deliver 90% of Mine's Energy Needs. *Energy and Mines.*