Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage

Paul Denholm and Mark Mehos

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-6A20-52978
November 2011

Contract No. DE-AC36-08GO28308

Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage

Paul Denholm and Mark Mehos

Prepared under Task No. SS10.2720

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-6A20-52978
November 2011

Contract No. DE-AC36-08GO28308

NOTICE

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Table of Contents

1 Introduction

Falling cost of solar photovoltaic (PV) generated electricity has led to a rapid increase in the deployment of PV and projections that PV could play a significant role in the future U.S. electric sector. The solar resource itself is virtually unlimited compared to any conceivable demand for energy (Morton 2006); however, the ultimate contribution from PV could be limited by several factors in the current grid. One is the limited coincidence between the solar resource and normal demand patterns (Denholm and Margolis 2007a). A second is the limited flexibility of conventional generators to reduce output and accommodate this variable generation resource. At high penetration of solar generation, increased grid flexibility will be needed to fully utilize the variable and uncertain output from PV generation and shift energy production to periods of high demand or reduced solar output (Denholm and Margolis 2007b).

Energy storage provides an option to increase grid flexibility and there are many storage options available or under development.[1] In this work we consider a technology now beginning to be deployed at scale – thermal energy storage (TES) deployed with concentrating solar power (CSP). PV and CSP are both deployable in areas of high direct normal irradiance such as the U.S. Southwest. From a policy standpoint, a simplistic approach to choosing a generation technology might be based simply on picking the option with the lowest overall levelized cost of electricity (LCOE). However, deployment based simply on lowest LCOE ignores the relative benefits of each technology to the grid, how their value to the grid changes as a function of penetration, and how they may actually work together to increase overall usefulness of the solar resource.

Both PV and CSP use solar energy to generate electricity, although through different conversion processes. A key difference between CSP and PV technologies is the ability of CSP to utilize high-efficiency thermal energy storage (TES) which turns CSP into a partially dispatchable resource.[2] The addition of TES produces additional value by shifting solar energy to periods of peak demand, providing firm capacity and ancillary services, and reducing integration challenges. Given the dispatchability of CSP enabled by thermal energy storage, it is possible that PV and CSP are at least partially complementary. The dispatchability of CSP with TES can enable higher overall penetration of solar energy in two ways. The first is providing solar-generated electricity during periods of cloudy weather or at night. However a potentially important, and less well analyzed benefit of CSP is its ability to provide grid flexibility, enabling greater penetration of PV (and other variable generation sources such as wind) than if deployed without CSP.

In this work we examine the degree to which CSP may be complementary to PV via its use of thermal energy storage. We first review the challenges of PV deployment at scale

---

[1] The only storage technology with large scale deployment to date is pumped hydro, with about 20GW of capacity in the United States. Other storage technologies deployed in the United States include a single 110 MW CAES facility, and a number of relatively small battery and flywheel installations (Denholm et al. 2010).

[2] The degree of dispatchability is based largely on the amount of storage in the plant. For additional discussion see Sioshansi and Denholm (2010).

with a focus on the supply/demand coincidence and limits of grid flexibility. We then perform a series of grid simulations to indicate the general potential of CSP with TES to enable greater use of solar generation, including additional PV. Finally, we use these reduced form simulations to identify the data and modeling needed for more comprehensive analysis of the potential of CSP with TES to provide additional flexibility to the grid as a whole and benefit all variable generation sources.

2 Challenges of Solar Deployment at High Penetration

The benefits and challenges of large scale PV penetration have been described in a number of analyses (Brinkman et al 2011). At low penetration, PV typically displaces the highest cost generation sources (Denholm et al. 2009) and may also provide high levels of reliable capacity to the system (Perez et al 2008). Figure 1 provides a simulated system dispatch for a single summer day in California with PV penetration levels from 0% to 10% (on an annual basis). This figure is from a previous analysis that used a production cost model simulating the western United States (Denholm et al. 2008). It illustrates how PV displaces the highest cost generation, and reduces the need for peaking capacity due to its coincidence with demand patterns.

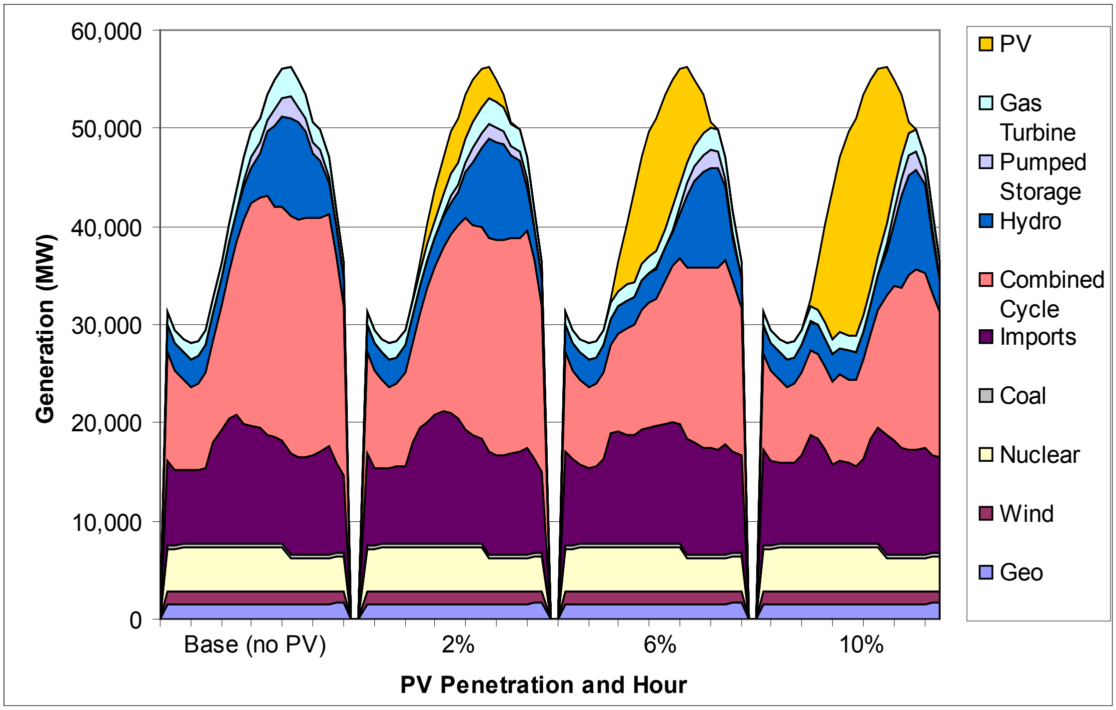

Figure 1. Simulated dispatch in California for a summer day with PV penetration from 0%–10%

Note: Figure is modified from Denholm et al. (2008).

At fairly low penetration (on an energy basis) the value of PV capacity drops. This can be observed in Figure 1 where the peak net load (normal load minus PV) stays the same between the 6% and 10% penetration curves.[3] The net load in this figure is the curve at the top of the "Gas Turbine" area. Beyond this point PV no longer adds significant amounts of firm capacity to the system. Several additional challenges for the economic deployment of solar PV also occur as penetration increases. These are illustrated in Figure 2, which shows the results of the same simulation, except on a spring day. During

---

[3] When evaluating the impact of wind and solar, net loads typically remove both sources from the normal load. We just show the load minus the solar output to isolate the impact.

this day, the lower demand results in PV displacing lower cost baseload energy. At 10% PV penetration in this simulation, PV completely eliminates net imports, and California actually exports energy to neighboring states.

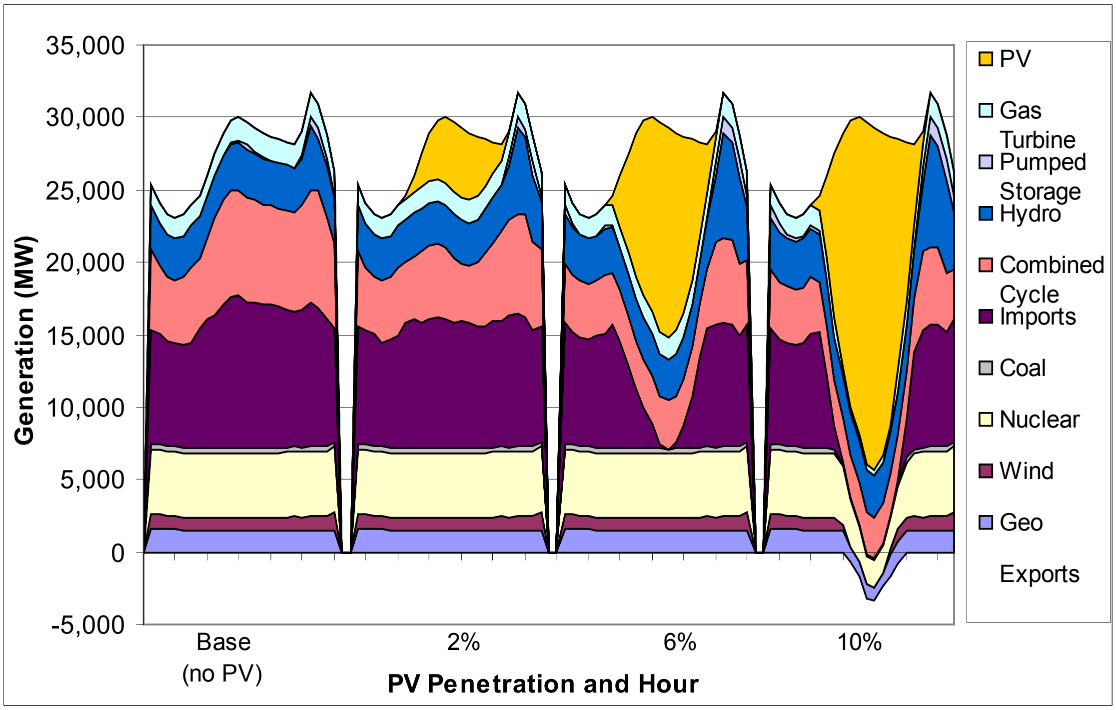

Figure 2. Simulated dispatch in California for a spring day with PV penetration from 0%–10%

Note: Figure is modified from Denholm et al. (2008).

Several factors limit the ability of conventional generators to reduce output to accommodate renewable generation. These include the rate at which generators can change output, particularly in the evening when generators must increase output rapidly in a high PV scenario. This challenge is illustrated in Figure 3, a ramp duration curve for California covering an entire simulated year. This is the net load ramp rate (MW/hour) for all 8,760 hours in the simulated year ordered from high to low. In the no PV case, the maximum load ramp rate is about 5,000 MW/hour and a ramp rate of greater than 4,000 MW/hour occurs less than 100 hours in the simulated year. In the 2% PV case, the hourly ramps are actually smaller since PV effectively removes the peak demand (as seen in Figure 1). However at higher penetration, the ramp rates increase substantially, and in the 10% PV case the net load increases at more than 4,000 MW/hour more than 500 hours per year.

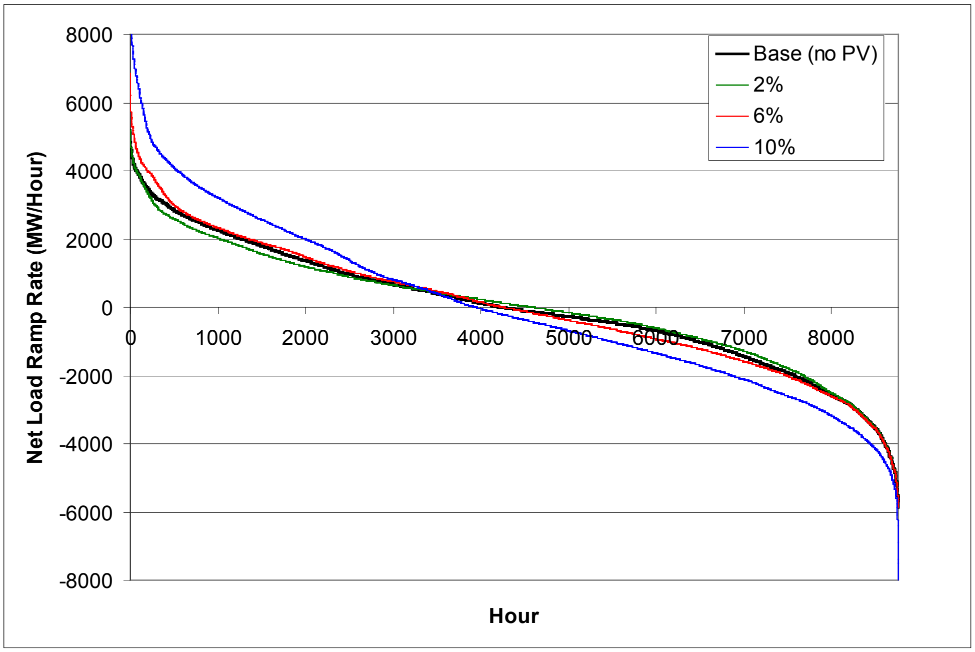

Figure 3. Ramp duration curve in California with PV penetration from 0%–10%

Note: Figure is derived from Denholm et al. (2008).

Another limitation is the overall ramp range, or generator turn-down ratio. This represents the ability of power plants to reduce output, which is typically limited on large coal and nuclear units. Accommodating all of the solar generation as shown in Figure 2 requires nuclear generators to vary output which is not current practice in the U.S. nuclear industry. Most large thermal power plants cannot be turned off for short periods of time (a few hours or less), and brief shutdowns could be required to accommodate all energy generated during the period of peak solar output. The actual minimum load of individual generators is both a technical and economic issue – there are technical limits to how much power plants of all types can be turned down. Large coal plants are often restricted to operating in the range of 50%–100% of full capacity, but there is significant uncertainty about this limit (GE Energy 2010). Many plant operators have limited experience with cycling large coal plants, and extensive cycling could significantly increase maintenance requirements.[4]

The ability to "de-commit" or turn off power plants may also be limited by the need to provide operating reserves from partially loaded power plants. As the amount of PV on the system increases, the need for operating reserves also increases due to the uncertainty of the solar resource, as well as its variability over multiple time scales.

Previous analysis has demonstrated the economic limits of PV penetration due to generator turn-down limits and supply/demand coincidence (Denholm and Margolis

---

[4] "Cycling operations, that include on/off startup/shutdown operations, on-load cycling, and high frequency MW changes for automatic generation control (AGC), can be very damaging to power generation equipment." However, these costs can be very difficult to quantify, especially isolating the additional costs associated with cycling above and beyond normal operations (Lefton and Besuner 2006).

2007a, Nikolakakis and Fthenakis 2011). Because of these factors, at high penetration of solar, increasing amounts of solar may need to be curtailed when its supply exceeds demand, after subtracting the amount of generation met by plants unable to economically reduce output due to ramp rate or range constraints or while providing operating reserves. Generator constraints would likely prevent the use of all PV generation in Figure 2. Nuclear plant operators would be unlikely to reduce output for this short period. Furthermore, PV generation may be offsetting other low or zero carbon sources. In Figure 2, PV sometimes displaces wind and geothermal generation, which provides no real benefit in terms of avoided fuel use or emissions.[5]

While the penetration of solar energy is currently far too small to see significant impacts, curtailment of wind energy is an increasing concern in the United States (Wiser and Bolinger 2010). While a majority of wind curtailments in the United States are due to transmission limitations (Fink et al 2009), curtailments due to excess generation during times of low net load are a significant factor that will increase if grid flexibility is not enhanced. The resulting curtailed energy can substantially increase the levelized cost of energy (LCOE) from variable generators, because their capital costs must be recovered over fewer units of energy actually sold to the grid.

The ability of the aggregated set of generators to rapidly change output at a high rate and over a large range can be described as a grid's overall flexibility. Flexibility depends on many factors, including:

- Generator mix – Hydro and gas-fired generators are generally more flexible than coal or nuclear.
- Grid size – Larger grids are typically more flexible because they share a larger mix of generators and can share operating reserves and a potentially more spatially diverse set of renewable resources.[6]
- Use of forecasting in unit commitment –Accurate forecasts of the wind and solar resources and load reduces the need for operating reserves.
- Market structure – Some grids allow more rapid exchange of energy and can more efficiently balance supply from variable generators and demand.
- Other sources of grid flexibility – Some locations have access to demand response, which can provide an alternative to partially-loaded thermal generators for provision of operating reserves. Other locations may have storage assets such as pumped hydro.

A comprehensive analysis of each flexibility option is needed to evaluate the cost-optimal approach of enhancing the use of variable generation. In this analysis, we consider the

---

[5] We discuss the tradeoff in curtailment in more detail in Section 3.

[6] This includes both the size of a balancing authority area (the area in which supply and demand resources are balanced) and the connections between a balancing authority and its neighbors. Larger balancing authority areas can utilize a greater set of generation resources. Absent a large balancing authority area, there is the potential to exchange supply and demand resources with neighboring areas, but requires both the transmission capacity and the market or other regulatory mechanisms to efficiently schedule and exchange resources (King et al. 2011).

use of thermal energy storage. Previous analysis has demonstrated the ability of a wind- and solar-based system to meet a large fraction of system demand when using electricity storage (Denholm and Hand 2011). A number of storage technologies are currently available or under development, but face a number of barriers to deployment including high capital costs[7] efficiency related losses[8], and certain market and regulatory challenges.[9] A number of initiatives are focused on reducing these barriers.[10]

An alternative to storing solar generated electricity is storing solar thermal energy via CSP/TES. Because TES can only store energy from thermal generators such as CSP, it cannot be directly compared to other electricity storage options, which can charge from any source. However, TES provides some potential advantages for bulk energy storage. First, TES offers a significant efficiency advantage, with an estimated round trip efficiency in excess of 95% (Medrano et al. 2010).[11] TES has the potential for low cost, with one estimate for the cost associated with TES added to a CSP power tower design at about $72/kWh-e (after considering the thermal efficiency of the power block).[12]

---

[7] Estimates of storage costs vary widely. However a cost of $2,000/kW for an 8-hour (usable) storage device appears to be on the low end of estimates for commercially available storage technologies with the exception of compressed air energy storage (EPRI 2010).

[8] The AC-AC round trip efficiency of new pumped hydro and some batteries (such as lithium-ion) is expected to exceed 80%, but many battery technologies such as sodium sulfur and most flow batteries have round-trip efficiencies of 75% or below (EPRI 2010).

[9] These include difficulty in valuing and recovering the value for the multiple services that storage can provide. (Denholm et al 2010).

[10] Examples include R&D efforts to reduce costs such as the ARPA-E Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) program with a goal of $100/kWh, or $800/kW for an 8-hour device (Johnson 2011).

[11] This efficiency value represents the ratio of useful energy recovered from the storage system to the amount of energy extracted from the heat source, and is restricted to this application. A more rigorous definition of round-trip efficiency would include the loss of availability associated with a reduction in temperature at the outlet of a thermal storage system This as occurs for indirect storage systems where a temperature drop exists across heat exchangers transferring thermal energy from the solar field working fluid to the storage medium and again from the storage medium to the power block.

[12] Assumes base case total capital cost for storage of $30/kwh (thermal) and 42% Rankine power cycle efficiency. (Kolb et al. 2011)

3 System Model

The purpose of this analysis is to explore the potential of CSP to provide grid flexibility and enable increased solar penetration in the Southwestern United States. To perform this preliminary assessment, we use the REFlex model, which is a reduced form dispatch model designed to examine the general relationship between grid flexibility, variable solar and wind generation, and curtailment (Denholm and Hand 2011). REFlex compares hourly load and renewable resources and calculates the amount of curtailment based on the system's flexibility, defined as the ability for generators to decrease output and accommodate variable generator sources such as solar and wind.

California is a likely candidate for large-scale deployment of both PV and CSP, and has strong solar incentive programs and a renewable portfolio standard. However, modeling California in isolation ignores the fact that California has strong transmission ties to neighboring states, including Arizona and southern Nevada, which have significant potential for solar energy. Currently, power exchanges between neighboring areas in the western United States are accomplished through bilateral contracts, and typically do not occur in real time. This analysis assumes the eventual availability of real-time power and energy exchanges across California, Arizona, New Mexico and Southern Nevada to allow sharing of solar resources. It also assumes that transmission is accessible to all generation sources on a short-term, non-firm basis. This "limiting case" allows for examination of the best technical case for solar deployment without market barriers or transmission constraints.

We began our simulations by evaluating the limits of PV, given flexibility limits of the existing grid. The simulations use solar, wind and load data for the years 2005 and 2006. Load data was derived from FERC Form 714 filings. For hourly PV production, we used the System Advisor Model (SAM), which converts solar insolation and temperature data into hourly PV output (Gilman et al. 2008). Weather data for 2005 and 2006, was obtained from the updated National Solar Radiation Database (NSRDB) (Wilcox and Marion 2008). We assume that PV will be distributed in a mix of rooftop and central systems (both fixed and 1-axis tracking). Additional description of this mix, including geographical distribution is provided in Brinkman et al. (2011).

Because California has significant wind capacity installed and plans for more, we also consider the interaction between solar and wind generation. Simulated wind data for 2005 and 2006 for California/Southwest sites was derived from the datasets generated for the Western Wind and Solar Integration Study (WWSIS) (GE Energy 2010). We started with a base assumption that wind provides 10% of the region's energy based on the "In-Area –10% Wind" scenario from the WWSIS. These data sets were processed through the REFlex model to establish base relationships between grid penetration of PV, curtailment, and grid flexibility. The overall system flexibility was evaluated parametrically, starting with a base assumption that the system is able to accommodate PV over a cycling range of 80% of the annual demand range. This corresponds to a "flexibility factor" of 80%, meaning the aggregated generator fleet can reduce output to 20% of the annual peak demand (Denholm and Hand 2011). This value is based on the WWSIS study and corresponds roughly to the point where all on-line thermal units have reduced output to their minimum generation levels and nuclear units would require cycling. The actual flexibility of the U.S. power system is not well defined, and this value is not intended to be definitive, but is used to represent the challenges of solar and wind integration and the possible flexibility benefits of CSP/TES.[13]

Figure 4 illustrates the framework for this analysis, showing the simulated dispatch over a 4-day period (April 7-10). It demonstrates a case where 10% of the annual demand is met by wind and 20% is met by solar. The figure shows both the simulated solar profile and its contribution to meeting load. Because of relatively low load during this period, PV generation exceeds what can be accommodated using the assumed grid flexibility limits. This typically occurs in the late morning, before the demand increases to its maximum in the afternoon. In these four days about 16% of all PV generation is curtailed and about 5% of the annual PV generation is curtailed.[14]

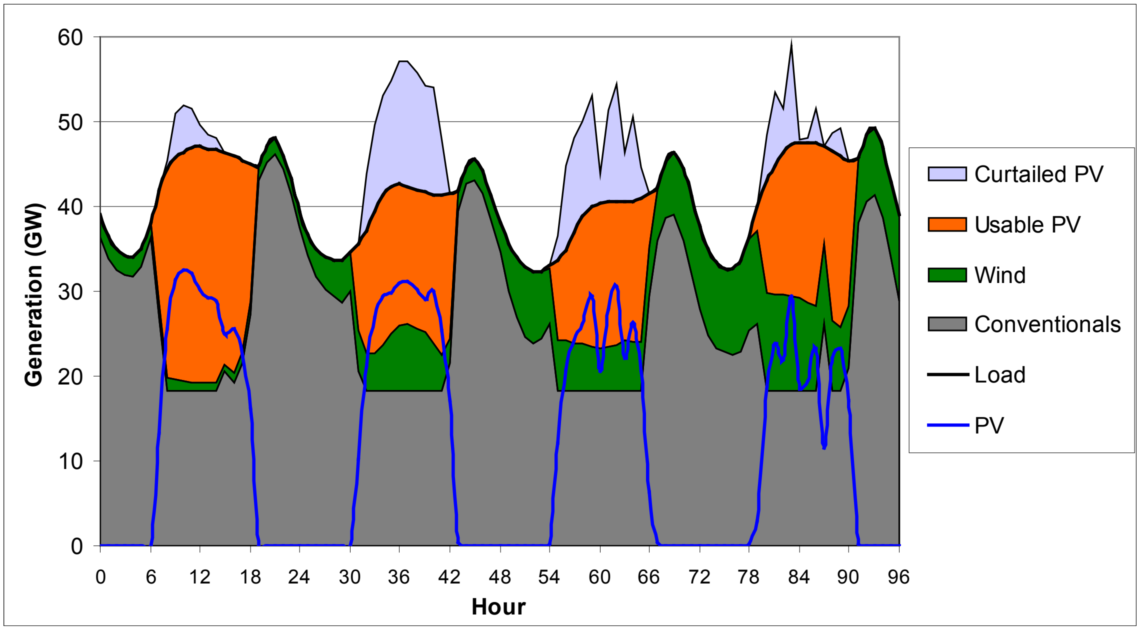

Figure 4. Simulated system dispatch on April 7-10 with 20% contribution from PV generation and resulting curtailment due to grid flexibility constraints

Figure 5 illustrates the average and marginal PV curtailment rates as a function of PV energy penetration for this initial scenario. It should be noted that the *x*-axis shows penetration of only solar PV. Because wind provides 10%, the total penetration of variable generation is 10% plus the penetration of solar. The average curve shows the total curtailment of all PV at a certain generation level. At the overall assumed system flexibility level, by the time PV is providing 22% of total demand, about 6% of all potential PV generation is curtailed.

---

[13] For more discussion of grid flexibility and its relationship to minimum generation levels see Denholm et al. (2010)

[14] This "assigns" all curtailment to PV as discussed later in this section.

The actual allocation of curtailment strongly influences the economics of PV and other variable generation. Figure 4 also shows the marginal curtailment rate, or the curtailment rate of the incremental unit of PV installed to meet a given level of PV penetration. If curtailment were assigned on an incremental basis at the point where PV is providing 22% of total demand, only about 50% of this additional PV would be usable, with the rest curtailed.

In this analysis we "assign" all incremental curtailment to solar, partially based on the federal production tax credit which incentivizes wind generation, while the primary federal incentive for solar is an investment tax credit that incentivizes installations but not generation.[15] Curtailment of solar may also occur if wind is installed "first" and a "last in, first curtailed" rule applies. The actual allocation of curtailment is, and is likely to continue to be, a contentious issue. Regardless of allocations rules, increased grid flexibility will be needed to minimize curtailment if solar is expected to play a "primary" role in reducing fossil-fuel use in the electric sector.

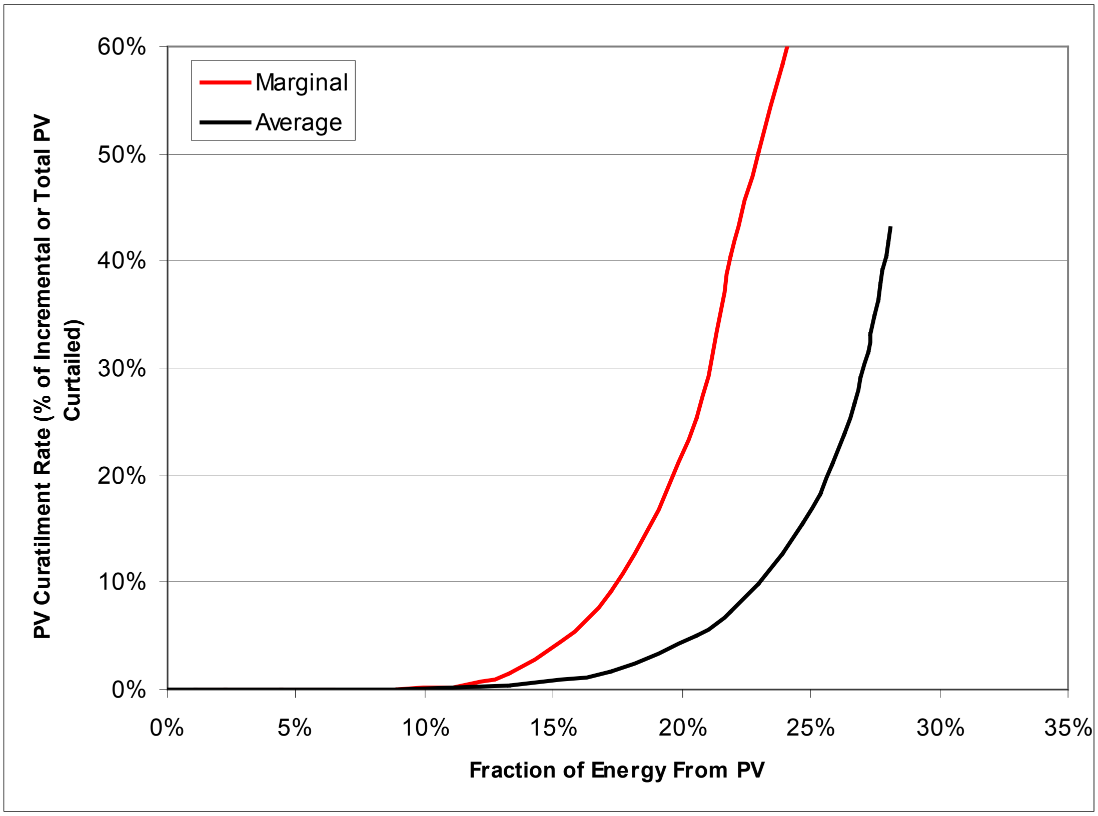

Figure 5. Marginal curtailment rates of PV in a base scenario in the southwestern United States assuming an 80% system flexibility

The estimation of the marginal curtailment rate is important because it helps establish the optimal mix of generators serving various portions of the load. This can be observed in

---

[15] As a result of the production tax credit, wind generators can bid negative values into wholesale markets and still receive positive operating revenues.

Figure 6, which translates curtailment into a cost of energy multiplier. This multiplier—equal to 1/(1-curtailment rate) —can be applied to the "base" LCOE of electricity generation (no curtailment). This represents how much more would need to be charged for electricity based on the impact of curtailment and the corresponding reduction in electricity actually provided to the grid.

Both the average and marginal multipliers are shown in Figure 6. The average multiplier is applied to all PV generators. The marginal multiplier is applied to the incremental generator, and is more important when determining the role of storage or other load-shifting technologies. For example, at the point where PV is providing 25% of the system's energy, the curtailment of all PV (average curtailment) is about 17% and the resulting cost multiplier is 1.2. If the base cost of PV is $0.06/kWh, the overall, system-wide cost of PV would be $0.06 x 1.2 or $0.072/kWh. This overall cost may be acceptable, but the costs are greater at the margin. For example, the last unit of PV installed to reach the 25% threshold has a curtailment rate of about 68% and a cost multiplier of 3.1. At a $0.06/kWh base price, this incremental unit of PV generation would have an effective cost of more than $0.18 per kWh. This would likely result in examining options to both increase grid flexibility (to accommodate more PV with lower curtailment rates) and improve the solar supply/demand coincidence.

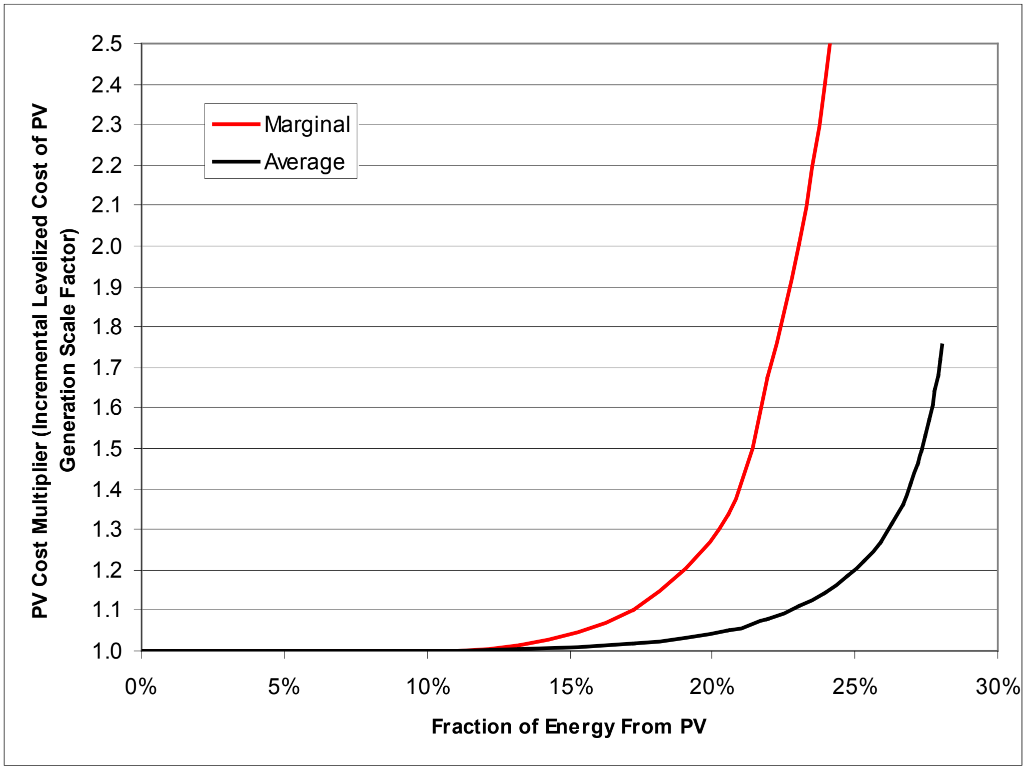

Figure 6. Impact of curtailment on PV LCOE multiplier in a base scenario in the southwestern United States assuming an 80% system flexibility

4 Increasing Solar Deployment Using CSP

While there are many options to increase grid flexibility, in this work we focus on the potential use of CSP with TES. Thermal storage extends the contribution of solar electricity generation by shifting generation to improve its coincidence with normal demand, and by improving system flexibility. The latter is accomplished by reducing constraints of ramping and minimum generation levels.

CSP was added to REFlex using hourly generation values produced by SAM. SAM uses the direct normal irradiance (DNI) to calculate the hourly electrical output of a wet-cooled trough plant (Wagner and Gilman 2011). The choice of technology was based primarily on data availability at the time of analysis as opposed to any presumption regarding CSP technology or economics. The results should be applicable to any CSP technology able to deploy multiple hours of thermal energy storage. For our base case, we assume 8 hours of storage and that the electrical energy produced by the plant can be dispatched with an effective 95% efficiency. In this initial analysis we did not consider the effects of part loading or multiple starts on plant efficiency. Distribution of locations was based on the study described by Brinkman et al. (2011).

Figure 7 illustrates the importance of dispatchability at high solar penetration. This scenario is identical to Figure 4, except PV provides 15% of annual demand and CSP meets 10% (so the contribution of solar technologies in total is greater in the PV/CSP case in Figure 7). The figure shows two CSP profiles. This first “non-dispatched CSP” is the output of CSP if it did not have thermal storage. It aligns with PV production, and would result in significant solar curtailment. The other curve is the actual dispatched CSP, showing its response to the net demand pattern after wind and PV generation is considered. It shows how a large fraction of the CSP energy is shifted toward the end of the day. In the first day, this ability to shift energy eliminates curtailment. On the other days, the wind and PV resources exceed the “usable” demand for energy in the early part of the day, resulting in curtailed energy even while the CSP plant is storing 100% of thermal energy. However, overall curtailment is greatly reduced. Solar technologies provide an additional 5% of the system’s annual energy compared to the case in Figure 4, but the actual annual curtailment has been reduced to less than 2%, including the losses in thermal storage.

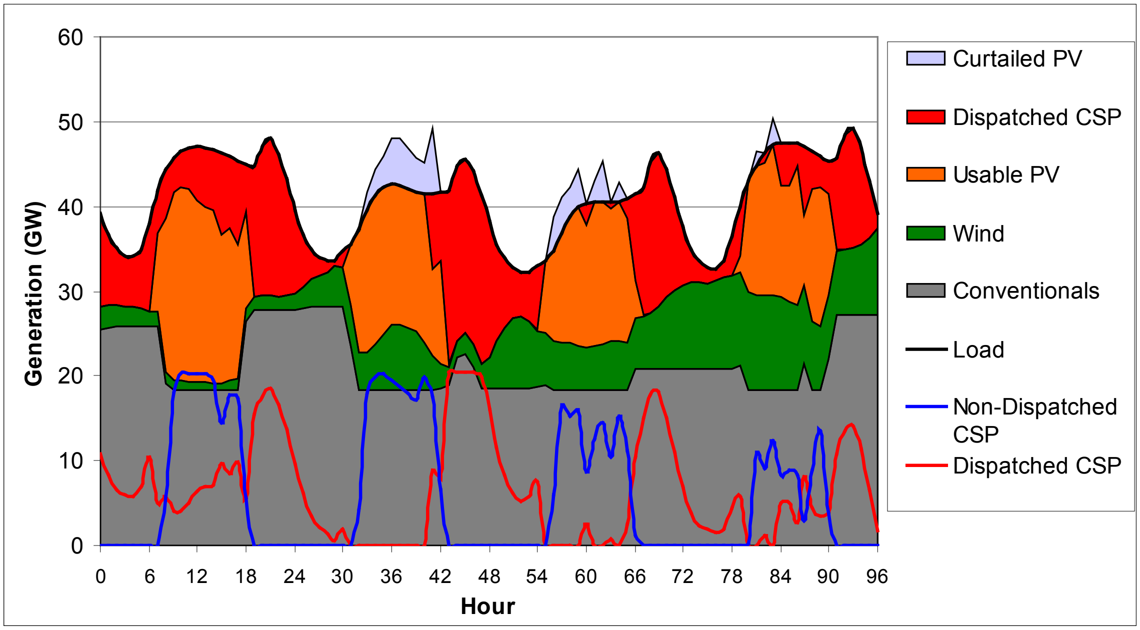

Figure 7. Simulated system dispatch on April 7-10 with 15% contribution from PV and 10% from dispatchable CSP

Figure 8 shows how the addition of CSP/TES can increase the overall penetration of solar by moving energy from periods of low net demand in the middle of the day to morning or evening. In this figure there is an equal mix of CSP and PV on an energy basis and the PV-only curves are identical to those in Figure 5.

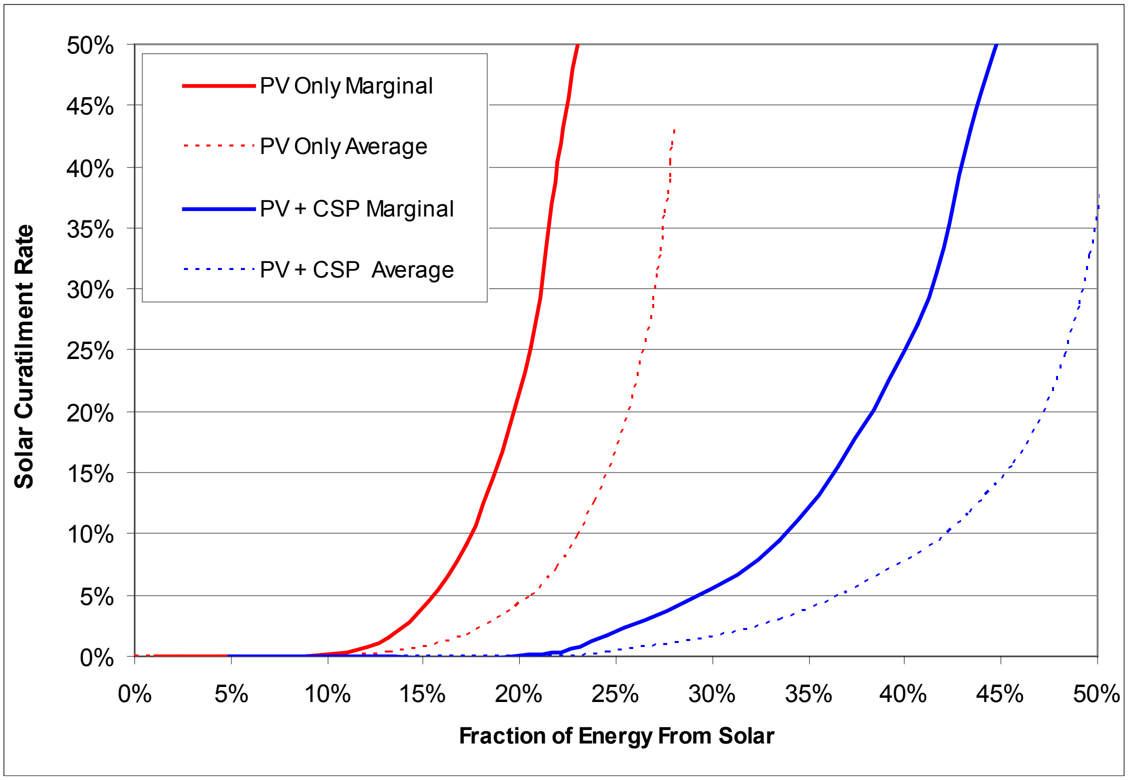

Figure 8. Curtailment of solar assuming an equal mix (on an energy basis) of PV and CSP

Figure 8 demonstrates the importance of dispatchability to reduce curtailment and increase the overall penetration of solar via the ability to shift solar energy over time. However, the analysis to this point assumes that CSP and PV are complementary only in their ability to serve different parts of the demand pattern. We have not yet considered the additional benefits of CSP to provide system flexibility by replacing baseload generators and generators online to provide operating reserves.

The importance of system flexibility can be observed in Figure 4, where conventional generators must ramp up rapidly to address the decreased output of PV during peak demand periods. In order to meet this ramp rate and range (along with sufficient operating reserves) a significant number of thermal generators will likely need to be operating a part-load, creating a minimum generation constraint during periods of solar high output. This is represented by the flat line occurring in the middle of each day when the aggregated generator fleet is at their minimum generation point. Comparing the CSP/PV case in Figure 7 to the PV only case in Figure 4, we see that the CSP is dispatched to meet the peak demand in the late afternoon/early evening, and the overall ramp rate and range is substantially reduced. In Figure 4 conventional generators need to ramp from about 18 GW to over 45 GW in just a few hours, while in Figure 7 the generators need to ramp from 18 GW to less than 30 GW.

Adding a highly flexible generator such as CSP/TES can potentially reduce the minimum generation constraint in the system. In the near term, this means that fewer conventional generators will be needed to operate at part load during periods of high solar output. In the longer term, the ability of CSP to provide firm system capacity could replace retiring inflexible baseload generators.

CSP plants with TES add system flexibility because of their large ramp rate and range relative to large baseload generators. Many CSP plants, both existing and proposed, are essentially small steam (Rankine-cycle) plants whose "fuel" is concentrated solar energy. Few of these plants are deployed, so it is not possible to determine their performance with absolute certainty. However, historical performance of the SEGS VI power plant provides some indication of CSP flexibility. Figure 9 provides a heat rate curve based on an hourly simulation model to assess the performance of parabolic trough systems, and validated by comparing the modeled output results with actual plant operating data (Price 2003). It indicates a typical operating range over 75% of capacity, with only a 5% increase in heat rate at 50% load. Figure 9 also provides historical data from small gas-fired steam plants which also indicates high ramp rate and range and fairly small decrease in efficiency at part load (about a 6% increase in heat rate at 50% load).[16] These plants also often operate as low as 25% of capacity, although with lower efficiency.[17] This provides a strong indication that CSP plants should be able to provide high flexibility.

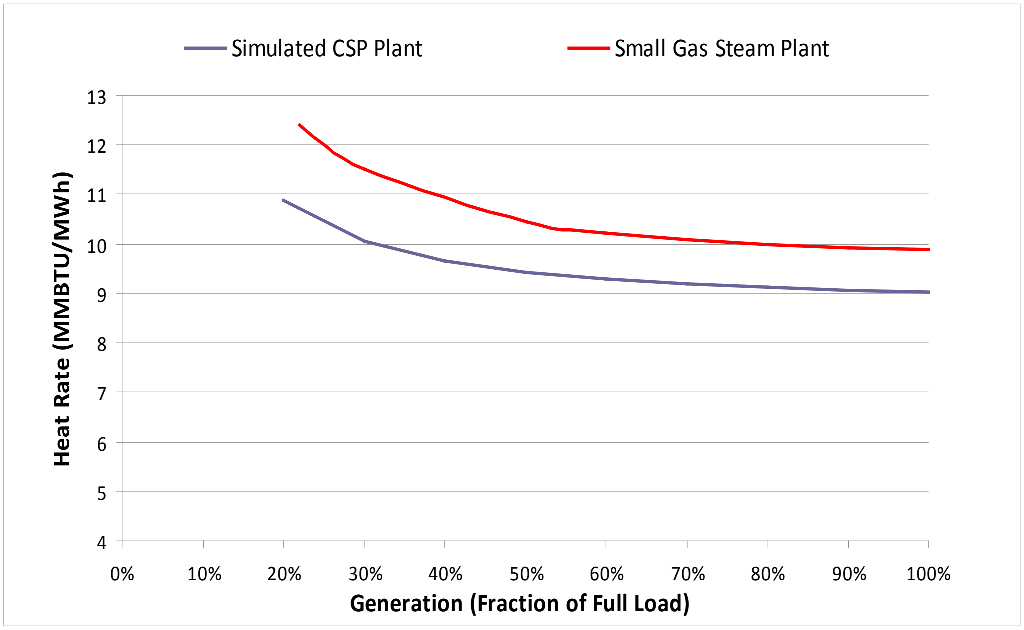

Figure 9. Part load heat rate of a CSP parabolic trough Rankine cycle power block and historic performance of small gas steam plants

---

[16] This curve represents the capacity weighted average of 298 gas steam plants operating in the year 2008. Data is derived from the U.S. Environmental Protection Agency continuous emission monitoring database at www.epa/gov/ttn/emc/cem/html

[17] The difference in heat rates between CSP plants and gas steam plants is likely due to a variety of factors. The steam plant data includes many old plants, including plants constructed before 1960. The CSP curve represents a parabolic trough plant including a power block consisting of a two-stage reheat turbine and multiple feedwater heaters to improve efficiency (Kearney and Miller 1988).

The change in minimum generation constraints is dependent on both the flexibility of CSP plants and the flexibility of generators supplemented or replaced with CSP. As discussed previously, nuclear plants are rarely cycled in the United States, while coal plants are typically operated in the range of 50%-100%. Because it is not possible to determine the exact mix of generators that would be replaced in high renewables scenarios, we consider a range of possible changes in the minimum generation constraints resulting from CSP deployment. For example, deployment of a CSP plant which can operate over 75% of its capacity range could allow the de-commitment of a coal plant which normal operates over 50% of its range. In this scenario each unit of CSP could reduce the minimum generation constraint by 25% of the plant's capacity. This very simplistic assumption illustrates how the dispatchability of a CSP plant should allow for a lower minimum generation constraint. Reducing this constraint should allow for greater use of wind and PV. As a result, as CSP is added, the system can actually accommodate more PV than in a system without CSP.

This is illustrated conceptually in Figure 10, which shows the same 4-day period as in Figures 4 and 7. CSP still provides 10% of the system's annual energy, but now we assume that the use of CSP allows for a decreased minimum generation point, and the decrease is equal to 25% of the installed CSP capacity. In this case about 21 GW of CSP reduces the minimum generation point from about 18 GW to 13 GW. This generation "headroom" allows for greater use of PV, and enough PV has been added to meet 25% of demand (up from 15% in Figure 7).[18] As a result, the total solar contribution is now 35% of demand, significantly greater than the PV-only case shown in Figure 4, and total curtailment is less than the 6% rate seen in Figure 4. By shifting energy over time and increasing grid flexibility, CSP enables greater overall solar penetration AND greater penetration of PV.

---

[18] All additional PV and CSP have the same mix of locations and types. In all cases the hourly solar profiles are simple scaled to obtain the desired penetration.

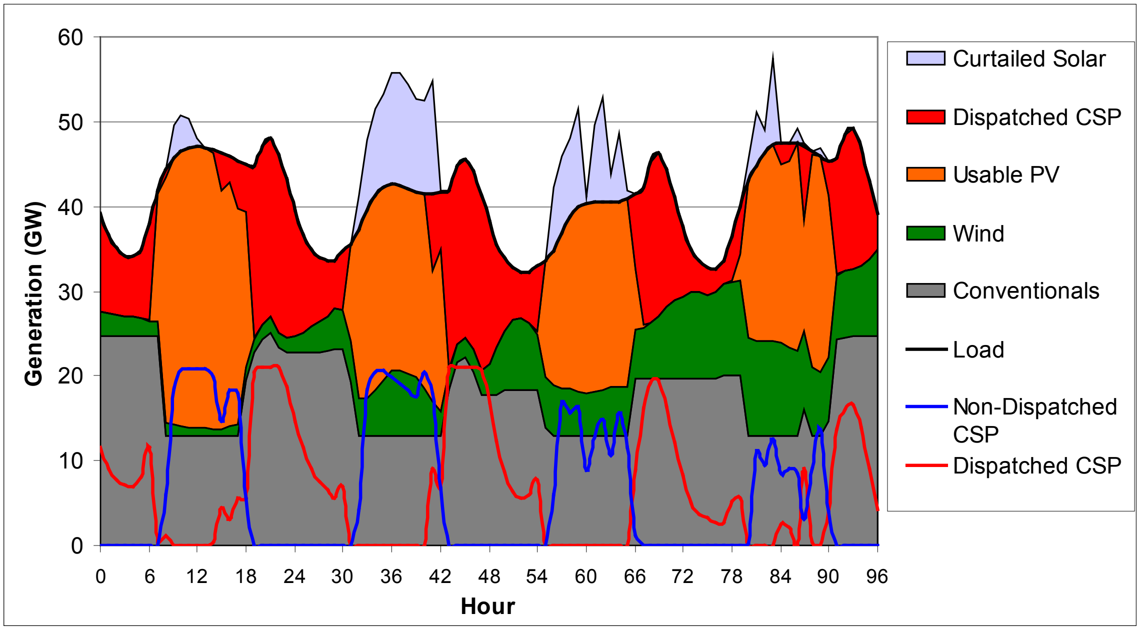

Figure 10. Simulated system dispatch on April 10-13 with 25% contribution from PV and 10% from dispatchable CSP where CSP reduces the minimum generation constraint

Figures 11 and 12 show the potential overall impact of the flexibility introduced by CSP and the corresponding opportunities for increased use of PV. Figure 11 builds on Figure 8 by adding the flexibility benefits of CSP. The figure assumes that each unit of CSP reduces the minimum generation constraint by 25% of its capacity, and an equal mix of PV and CSP on an energy basis. In this case, the addition of CSP allows PV to provide 25% of the system's energy with very low levels of curtailment.

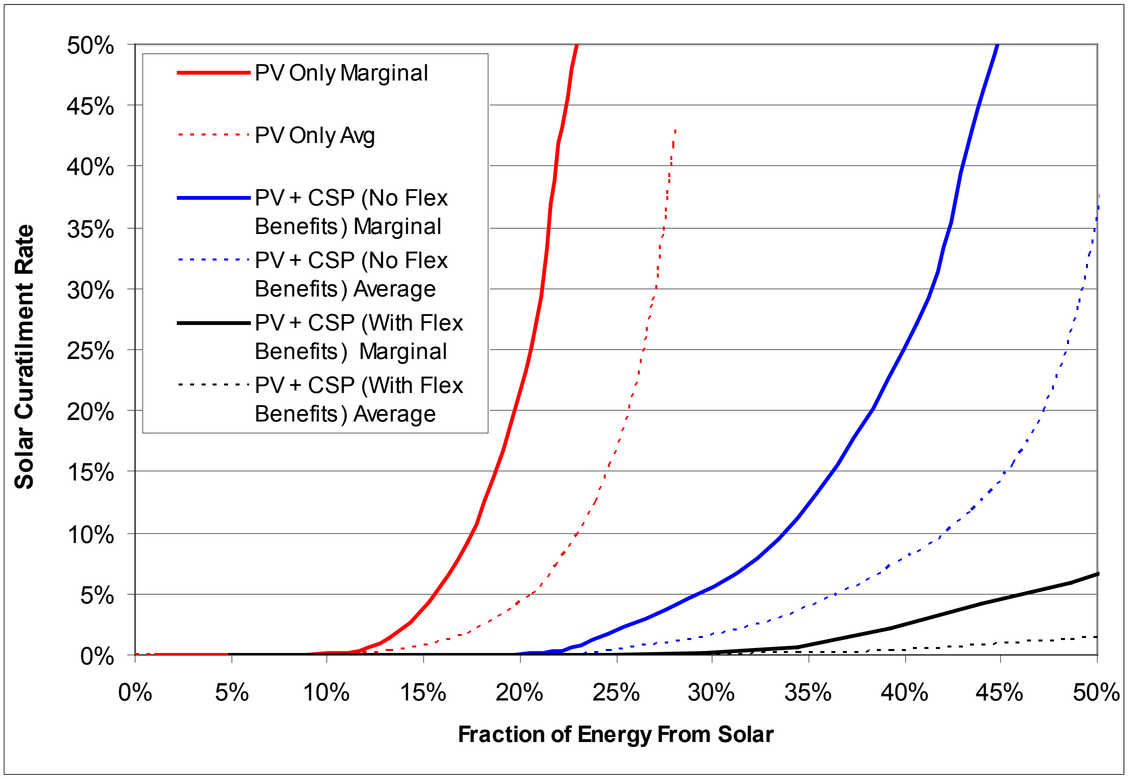

Figure 11. Curtailment of solar assuming an equal mix (on an energy basis) of PV and CSP and impact of CSP grid flexibility

Figure 12 more directly illustrates the relationship between the reduction in minimum generation constraint and potential increase in PV penetration. The figure shows how much more PV could be incorporated at a constant marginal curtailment rate of 20% when CSP is added. In this scenario, the *x*-axis represents the fraction of annual system energy provided by CSP. Increased penetration of CSP results in a linear decrease in minimum generation constraints. The figure illustrates two CSP flexibility cases. In one, each unit of CSP reduces the minimum generation constraint by 20% of its capacity; in the other, the rate of reduction is 40%. These amounts are not meant to be definitive, but represent a possible impact of CSP in reducing minimum generation constraints.

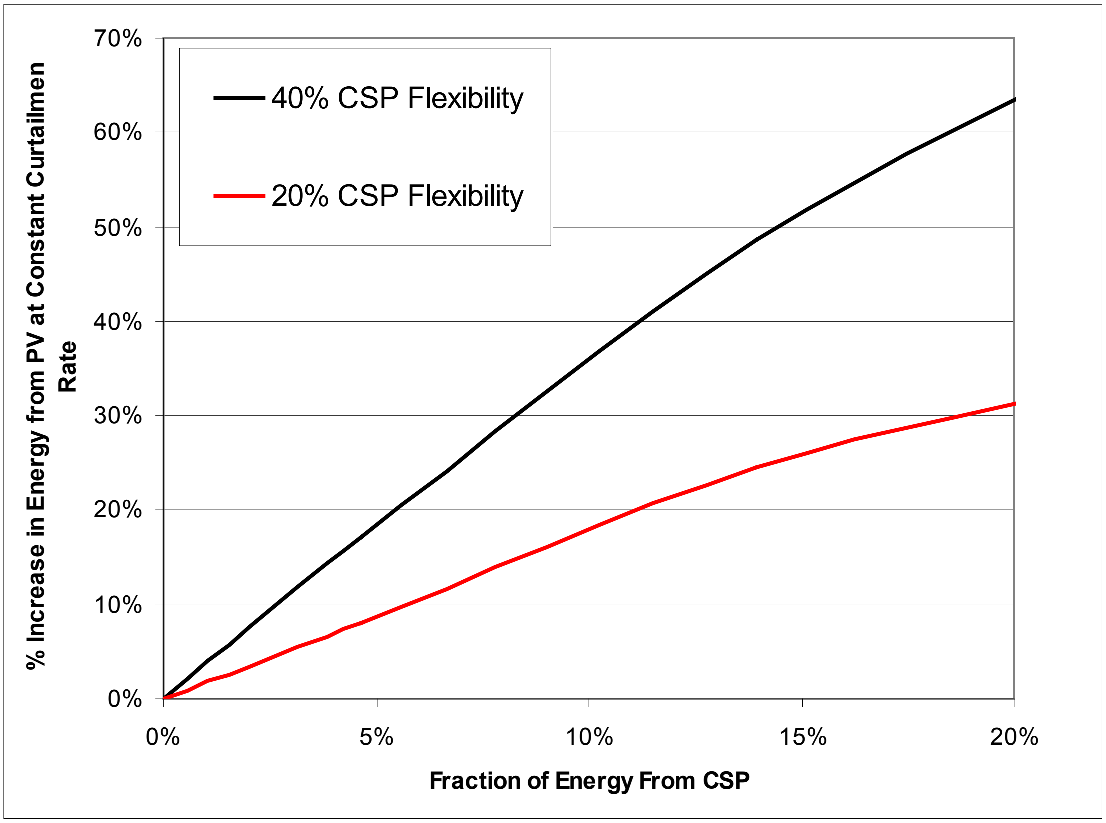

Figure 12. Increase in PV penetration as a function of CSP penetration assuming a maximum PV marginal curtailment rate of 20%. CSP flexibility is defined as the fraction of the CSP rated capacity that is assumed to reduce the system minimum generation constraint.

Overall, this analysis suggests that CSP can significantly increase grid flexibility by providing firm system capacity with a high ramp rate and range and acceptable part-load operation. Greater grid flexibility could increase the contribution of renewable resources like solar and wind. This demonstrates that CSP can actually be complementary to PV, not only by adding solar generation during periods of low sun, but by actually enabling more PV generation during the day. This analysis also suggests a pathway to more definitively assess the ability of CSP to act as an "enabling" technology for wind and solar generation.

5 Further Quantifying the Benefits of CSP Deployment

This analysis is a preliminary assessment of the potential benefits of CSP in providing grid flexibility using reduced form simulations with limited geographical scope and many simplifying assumptions. Gaining a more thorough understanding of how CSP can enable greater PV and wind penetration will require detailed production simulations using security-constrained unit commitment and economic dispatch models currently used by utilities and system operators. These simulations should consider the operation of the entire power plant fleet including individual generator characteristics and constraints, and the operation of the transmission system. The geographical footprint should cover the entire Western interconnect including possible transmission expansion to take advantage of greater spatial diversity of the wind and solar resources as well conventional generators.

To date, production simulations have not considered CSP operations in detail. Both the WWSIS and the first phase of the California 33% Renewable Portfolio Standard integration studies (CAISO 2011) included CSP, but assumed fixed schedules for CSP dispatch. This assumption limits CSP's ability to shift generation to when needed most and to provide grid flexibility to enable PV and wind. Future and ongoing studies, including the second phase of both the California study and the WWSIS will evaluate the benefits of TES in more detail. To perform these simulations, production cost models will need to include the ability of CSP to optimally dispatch the solar energy resource, and not rely on heuristics or schedules often used to estimate the operation of conventional storage plants such as pumped hydro. However, the ability to optimize CSP, including scheduling both its energy and ability to provide operating reserves, is limited by lack of certain data sets needed for a more detailed simulation. A greater understanding of the predictability and variability of the solar resource, including the sub-hourly variation and the effects of spatial diversity in mitigating variability, is needed. This data will also be needed to determine any required increase in operating reserves over various time scales as a function of solar penetration. In addition, more data is needed on the actual characteristics of CSP plants—those now being deployed and under development—including ramp rates, turn-down ratio, part-load efficiency, and start times under various conditions.

6 Conclusions

While it will be some time until solar technologies achieve very high penetrations in the U.S. grid, international experience in wind deployment demonstrates the importance of increasing overall grid flexibility. Key factors in improving grid flexibility include increasing the ramp range and rate of all generation sources and the ability to better match the supply of renewable resources with demand via increased spatial diversity, shiftable load, or energy storage. The use of thermal energy storage in concentrating solar power plants provides one option for increased grid flexibility in two primary ways. First, TES allows shifting of the solar resource to periods of reduced solar output with relatively high efficiency. Second is the inherent flexibility of CSP/TES plants, which offer higher ramp rates and ranges than large thermal plants currently used to meet a large fraction of electric demand. Given the high capacity value of CSP/TES, this technology could potentially replace a fraction of the conventional generator fleet and provide a more flexible generation mix. This could result in greater use of non-dispatchable solar PV and wind meaning CSP and PV may actually be complementary technologies, especially at higher penetrations.

The preliminary analysis performed in this work requires advanced grid simulations to verify the actual ability of CSP to act as an enabling technology for other variable generation sources. Complete production simulations using utility-grade software, considering the realistic performance of the generation fleet, transmission constraints, and actual CSP operation will be an important next step in evaluating the benefits of multiple solar generation technologies.

References

Brinkman, G.L.; Denholm, P.; Drury, E.; Margolis, R.; Mowers, M. (2011). "Toward a Solar-Powered Grid—Operational Impacts of Solar Electricity Generation." *IEEE Power and Energy* (9); pp. 24–32.

California Independent System Operator (CAISO) (2011). "Track I Direct Testimony of Mark Rothleder on Behalf of the California Independent System Operator Corporation." Testimony for the Public Utilities Commission of the State of California, Order Instituting Rulemaking to Integrate and Refine Procurement Policies and Consider Long-Term Procurement Plans, Rulemaking 10-05-006, Submitted July 11.

Denholm, P.; Hand, M. (2011). "Grid Flexibility and Storage Required to Achieve Very High Penetration of Variable Renewable Electricity." *Energy Policy* (39); pp. 1817–1830.

Denholm, P.; Ela, E.; Kirby, B.; Milligan, M. (2010). *The Role of Energy Storage with Renewable Electricity Generation*. NREL/TP-6A2-47187. Golden, CO: National Renewable Energy Laboratory.

Denholm, P.; Margolis, R.M.; Milford, J. (2009). "Quantifying Avoided Fuel Use and Emissions from Photovoltaic Generation in the Western United States." *Environmental Science and Technology* (43); pp. 226–232.

Denholm, P.; Margolis, R.M.; Milford, J. (2008). *Production Cost Modeling for High Levels of Photovoltaics Penetration.* NREL/TP-581-42305. Golden, CO: National Renewable Energy Laboratory.

Denholm, P.; Margolis, R.M. (2008). "Land Use Requirements and the Per-Capita Solar Footprint for Photovoltaic Generation in the United States." *Energy Policy* (36); pp. 3531–3543.

Denholm, P.; Margolis, R.M. (2007a). "Evaluating the Limits of Solar Photovoltaics (PV) in Traditional Electric Power Systems." *Energy Policy* (35); pp. 2852–2861.

Denholm, P.; Margolis, R.M. (2007b). "Evaluating the Limits of Solar Photovoltaics (PV) in Electric Power Systems Utilizing Energy Storage and Other Enabling Technologies." *Energy Policy* (35); pp. 4424–4433.

Electric Power Research Institute (EPRI). (December 2010). "Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits." 1020676. Palo Alto, CA: EPRI.

Fink, S.; Mudd, C.; Porter, K.; Morgenstern, B. (2009). *Wind Energy Curtailment Case Studies: May 2008 - May 2009*. SR-550-46716. Golden, CO: National Renewable Energy Laboratory.

GE Energy. (2010). *Western Wind and Solar Integration Study*. SR-550-47434. Golden, CO: National Renewable Energy Laboratory.

Gilman, P.; Blair, N.; Mehos, M.; Christensen, C.; Janzou, S.; Cameron, C. (2008). *Solar Advisor Model User Guide for Version 2.0.* TP-670-43704. Golden, CO: National Renewable Energy Laboratory.

Johnson, M. (2 March 2011). "Overview of Gridscale Rampable Intermittent Dispatchable Storage (GRIDS) Program." Washington, DC: U.S. Department of Energy.

Kearney, D.; Miller, C. (15 January 1998). "Solar Electric Generating System VI - Technical Evaluation of Project Feasibility." Los Angeles, CA: LUZ Partnership Management, Inc.

Kolb, G.; Ho, C.; Mancini, T.; Gary, J. (2011). *Power Tower Technology Roadmap and Cost Reduction Plan*. SAND2011-2419. Albuquerque, NM: Sandia National Laboratories.

King, J.; Kirby, B.; Milligan, M.; Beuning, S. (2011) *Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection.* NREL/TP-5500-5233. Golden, CO: National Renewable Energy Laboratory.

Lefton, S.A.; Besuner, P. (2006). "The Cost of Cycling Coal Fired Power Plants." *Coal Power Magazine*, Winter 2006.

Medrano, M.; Gil, A.; Martorell, I.; Potau, X.; Cabeza, F. (2010). "State of the Art on High-Temperature Thermal Energy Storage for Power Generation. Part 2 – Case Studies." *Renewable and Sustainable Energy Reviews* (14); pp. 56–72.

Morton, O. (2006). "Solar Energy: A New Day Dawning?: Silicon Valley Sunrise." *Nature* (443); pp. 19–22.

Nikolakakis, T.; Fthenakis, V. "The Optimum Mix of Electricity from Wind- and Solar-Sources in Conventional Power Systems: Evaluating the Case for New York State." *Energy Policy,* (39); 6972-6980.

Perez, R.; Taylor, M.; Hoff, T.; Ross, J.P. (2008). "Reaching Consensus in the Definition of Photovoltaic Capacity Credit in the USA: A Practical Application of Satellite-Derived Solar Resource Data." *IEEE Journal of Selected Topics In Applied Earth Observations And Remote Sensing* (1:1); pp. 28–33.

Price, H. (2003). *A Parabolic Trough Solar Power Plant Simulation Model*. CP-550-33209. Golden, CO: National Renewable Energy Laboratory.

Sioshansi, R.; Denholm, P. (2010). "The Value of Concentrating Solar Power and Thermal Energy Storage." *IEEE Transactions on Sustainable Energy* (1:3); pp. 173–183.

Wagner, M. J.; Gilman, P. (2011). *Technical Manual for the SAM Physical Trough Model*. TP-5500-51825. Golden, CO: National Renewable Energy Laboratory.

Wilcox, S.; Marion, W. (2008). *Users Manual for TMY3 Data Sets*. NREL/TP-581-43156. Golden, CO: National Renewable Energy Laboratory.

Wiser, R.; Bolinger, M. (August 2010). *2009 Wind Technologies Market Report*. LBNL-3716E. Berkeley, CA: Lawrence Berkeley National Laboratory.