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The value of CSP with thermal energy storage in providing grid stability

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Abstract

CSP plants both with and without thermal energy storage are unique renewable resources that provide clean electric power and a range of operational capabilities to support continued reliability of electric power systems. Utilizing stored thermal energy storage to operate a conventional synchronous generator, CSP plants with thermal energy storage can support power and provide ancillary services including voltage support, frequency response, regulation and spinning reserves, and ramping services – services that would otherwise be provided, at least in part, by conventional fossil-fuel generation.

By being available during peak demand in sunlight hours and providing the capability to shift energy to other hours, the addition of thermal energy storage to CSP plants improves their contribution to resource adequacy, or capacity requirements, especially as solar penetration increases. This makes CSP an ideal complement to support greater adaption of intermittent resources such as wind and PV.

To make procurement decisions that include a balance of both solar PV and CSP, utilities need to see reasonable estimates of quantifiable economic benefits. In simulations of the California power system, recent studies by the Lawrence Berkeley National Labs (LBNL) found that the comparative value of CSP with storage increases as the amount of solar on the grid increases. If CSP with six hours of storage and PV with no storage were each providing five percent of the grid’s power, CSP power would have an additional value of $19/MWh (1.9¢/kWh). At grid penetrations of 10 percent each, CSP power would be worth an additional $35/MWh (3.5¢/kWh). The added value results from a calculation of grid integration costs and market benefits.

The author will outline how CSP with storage provides grid stability and its corresponding value to utilities.

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1. Introduction

CSP plants both with and without thermal energy storage – and possibly, hybrid fuel capability – are unique renewable resources that provide not only clean electric power, but also a range of operational capabilities that support the continued reliability of electric power systems. Thermal energy storage allows these plants to store some of the solar energy captured during the daylight hours, and, with some variations among designs, shift energy production into subsequent hours overnight or the next day as needed by the utility or regional system operator. Utilizing the stored thermal energy to operate a conventional synchronous generator, they can also support power quality and provide ancillary services, including voltage support, frequency response, regulation and spinning reserves, and ramping reserves – which would otherwise be provided, at least in part, by conventional fossil-fuel generation. Finally, both by being available during peak demand in sunlight hours and by providing the capability to shift energy to other hours, the addition of thermal energy storage to CSP plants improves their contribution to resource adequacy, or capacity, requirements, especially as solar penetration increases.

The current interest in CSP with thermal energy storage is arising due to the dramatic penetration of renewable energy expected soon in many power systems around the world. Conventional wind and solar plants produce energy on a variable basis and have lower contributions to resource adequacy relative to nameplate capacity than fossil-fuel generation [1]. As more investment is planned in wind and solar generation, utilities and government regulators have sought more sophisticated types of cost-benefit analysis, incorporating scenario-based resource planning, to compare alternative renewable resource portfolios. This has resulted in evolution towards more comprehensive calculation of net system costs on a portfolio basis, due in part to research that has clarified certain elements of value [2-4]. However, in most regions surveyed, this trend has not yet captured the full, long-term benefits of CSP with thermal energy storage, which could result in a procurement bias towards portfolios of lower cost solar projects that also have lower long-term economic and reliability benefits.

To advance valuation of CSP technologies, this report surveys the recent research literature on the economic and reliability benefits of CSP with thermal energy storage, including consideration of system integration costs incurred by other renewable resources. As the valuation of net system costs becomes more precise, the latest generation of CSP plants comes on-line, and the next generation CSP technology shows evidence of cost reductions, utilities and regulators should gain confidence that CSP with thermal energy storage is a desirable investment within a growing renewable resource portfolio when compared to other renewable energy and integration solutions, including other types of storage.

2. Key categories of utility value and calculation of net system costs

When comparing CSP with thermal energy storage to alternative renewable technologies (including CSP without storage), there are several primary categories of additional benefits provided by thermal energy storage, as well as lower system integration costs when compared to other variable energy resources, as listed below:

- **Energy**
  - Hourly optimization of energy schedules
  - Subhourly energy dispatch
  - Ramping reserves
- **Ancillary Services (for secondary frequency control)**
  - Regulation
  - 10-minute spinning reserves
  - Operating reserves on greater than 10 minute time-frames from synchronized generator
- **Power quality and other ancillary services**
  - Voltage control
  - Frequency response
  - Blackstart
- **Capacity**
  - Generic MW shifted to meet evolving system needs
Operational Attributes

- Integration and curtailment costs compared to solar PV and wind
  - Reduced production forecast error and associated reserve requirements
  - Reduced curtailment due to greater dispatch flexibility without production losses
  - Ramp mitigation

There are also other categories of additional benefits which may arise on a system-specific basis, such as improved long-term reductions in greenhouse gas emissions provided by a flexible, clean resource. Generally, these benefits are converted into a common metric of total economic value per year divided by total energy output from the plant, such as $/MWh or €/MWh. The sum of these values allows for calculation of the net system cost, which is the costs minus the benefits, and can be compared to the net system costs of alternative investments to achieve the same levels of renewable energy production, operational performance and reliability [5-7].

3. Design and operation of CSP with thermal energy storage

There are several viable CSP designs used when simulating market or utility value, some of which are described in this paper. Generally, CSP technology uses reflectors to focus sunlight onto a small area to heat a working fluid. The heat thus captured can then be efficiently converted to mechanical work in a steam turbine, which can then drive a generator to produce electricity. The two prominent commercial designs for a CSP plant are parabolic troughs and power towers, with several other designs in stages of development.

The thermal energy storage systems integrated into the CSP technology consist of a collection method, a reservoir, and a storage medium, for which all the current commercial applications use molten salts. Depending on CSP plant configuration and design, the storage medium may also be the working fluid of the CSP cycle or it can be a separate loop that communicates with the working fluid through a heat exchanger. A key feature is that the thermal storage is not charged at all from the electric power system, but only from the solar field. Hence, there is no or minimal cost for charging during daily operations, but only the decision on how to utilize the stored thermal energy for maximum economic benefit, within the operational constraints of the plant.

While different CSP designs with thermal storage will have different net system costs, this report is focused on the calculation of economic and reliability benefits. For that purpose, the key operational characteristics that need to be modeled include the storage capacity, the minimum and maximum operating levels, start times and the allowable number of starts per day, ramp rates, regulating range, and the plant’s capability to shift between storing and discharging. Not all CSP plants with thermal energy storage in operation or under construction offer equal operational flexibility, but all future designs can be modified to meet system needs. Those needs can range from providing a few hours of stored energy to serve early evening loads, to adding storage until the plant is essentially “base-loaded,” meaning that it operates at relatively stable output throughout the day.

4. Energy and ancillary services

The energy and ancillary services benefits of solar thermal storage are the most straightforward to calculate, as researchers can use historical market prices or utility costs as a baseline [8,9], before analyzing the changes in benefits that may occur under future system conditions [10,11]. All CSP with thermal energy storage provides utilities with the capability to shift energy production from storage to the highest value hours across the operating day, and in principle, with appropriate designs, should also be able to provide energy dispatch in real-time operations as well as spinning reserves and regulation. As the availability of dispatchable energy and ancillary services would in part be a function of solar insolation and storage capacity, provision of these services would also need to be forecast by the system operator for daily operations.

When calculating the economic value that can be obtained by optimally dispatching a CSP plant, the typical benchmark calculation is the average value ($/MWh) of production from a CSP plant without storage – or a solar PV plant – compared to one with storage. The value of the energy from thermal storage is calculated as the plant’s simulated additional wholesale market revenues or power system avoided costs (primarily fuel). Figure 1 summarizes study results on the U.S. markets, using different types of simulation models. The results from models
using historical market data or low renewable energy scenarios are generally in the range of $5-10/MWh for energy and ancillary services.

![Graph showing PV capacity credit estimates with increasing penetration levels](image-url)

**Fig. 1.** Survey of PV capacity credit estimates with increasing penetration levels

As additional solar generation is added to the power system, the progressive displacement of fossil-fired generation actually leads to lower energy value for incremental solar additions without storage, whether CSP or solar PV. However, CSP with thermal storage can continue to shift energy to the highest value hours. In simulations of the California power system conducted by, the marginal energy value of an incremental parabolic trough plant with 6 hours of thermal storage declines at a low rate as solar penetration increases, but when compared to CSP plants without storage which face decreasing revenues during the daylight hours, its revenues are as much as $9/MWh higher by 10% solar energy penetration, $17/MWh by 15%, $20/MWh by 20% and $36/MWh by 30% [12]. Other studies find that solar thermal storage provides $16.70/MWh higher revenues than CSP without storage when modeling the Colorado-Wyoming power system at high renewable penetration of around 34% annual energy from wind and solar [13]. The revenue difference with solar PV in these simulations is similar, but with some differences depending on whether the PV plant has tracking or not.

Ancillary service and other operational flexibility requirements are expected to increase in power systems with increasing penetration of wind and solar [14,15]. There is less convergence in estimates of the value of ancillary services, since these are smaller markets or system requirements, and can be fulfilled by many competing resources. However, simulations by the California ISO have shown that in California, barring introduction of new resources that provide operational flexibility, fossil generation continues to provide the bulk of ancillary services under 33% RPS in 2020 [16]. The opportunity is there for CSP to provide these services and earn revenues [17, 18]. Optimizing against 2005 spinning reserve prices in California and Texas, sales of spinning reserves can comprise 2 – 7% of CSP plant revenues [19]. To advance this research agenda, the CSP industry also needs to clarify the operational capabilities to provide different ancillary services of thermal storage designs.

5. Capacity

A primary economic benefit of solar energy is the correlation of its production with both daily peak demands (depending on the location and season) and annual peak demands. Solar’s daily production pattern thus correspondingly provides a high resource adequacy, or capacity credit.

Different types of solar technologies obtain different capacity credits, depending on their location. Generally, for any particular location, fixed tilt solar PV obtains the lowest capacity credit because its peak output is focused in a few midday hours. Solar PV with single- and dual-axis tracking gets a higher credit, because its production can be better shaped to fit the hours with the highest capacity requirements. CSP without storage obtains a similar or
slightly higher capacity credit to tracking PV. Finally, CSP with thermal storage obtains the highest capacity credit of any solar resource, as a function of location and storage capacity, because its storage capability allows for shifting of additional energy into the highest valued capacity hours [20].

The capacity value of a solar resource is measured as the avoided cost of alternative capacity, whether procured from existing or new generation. In the United States, long-term capacity value is typically based on the avoided costs of combustion turbine generation.

As solar penetration increases, a region’s incremental capacity needs begin to shift to the evening hours [21, 22]. This happens because without storage, solar can only serve demand during the sunlight hours, and as long as demand growth increases capacity requirements within those hours, additional PV and CSP without storage will continue to accrue capacity value. However, when additional demand growth creates capacity needs outside the sunlight hours, conventional solar production – PV or CSP without thermal storage – face diminishing capacity value. Findings of a number of western U.S. and Canadian studies that show the declining capacity credits available to solar PV as penetration increases, as shown in Figure 1 [23]. While the methodologies used in these studies differ, there is consistency in the general finding.

A number of recent studies have examined the comparative capacity value of solar PV and CSP in high solar penetration scenarios. As shown in Figure 2, the value of capacity for the plants with 6 hours of thermal storage ranges from $37/MWh at low penetration (5% annual solar energy) to $15/MWh at high penetration (30% solar energy). In contrast, the capacity value for non-dispatchable solar resources may diminish to almost $0/MWh at such high penetrations. Other research shows Denholm and Mehos (2011) show similar results for a model of California and neighboring states, with PV capacity value diminishing rapidly between 6 – 10% penetration [24].

![Fig. 2.: Marginal Capacity Value ($/MWh) by Penetration of Solar and Wind Technologies – Mills and Wiser (2012b)](image)

A key issue for research is to resolve the differences between regional studies in the rate of change of incremental solar PV capacity value as solar penetration increases. The studies of the California power system appear to agree that major declines take place between 5 – 10% solar PV penetration by annual energy [25, 26], which is within the solar production forecast under the 33% RPS.

Another forthcoming development in capacity valuation is the incorporation of operational attributes as wind and solar penetration increases [27]. Although the designs of such “flexible capacity” requirements and markets are still nascent, they are intended to either set aside quantities of particular needed attributes or provide financial incentives for their provision. Due to the fast ramp rates on the plants, CSP with thermal energy storage, depending on the design, will at least partially qualify as flexible capacity resources.
6. Integration and curtailment costs

Significant penetration by wind and solar generation creates new integration requirements for existing power systems. Both wind and solar generation are variable, meaning that electric power is only produced when the fuel source is available, and have higher forecast errors than conventional generation [28] (NERC 2009). In addition, these technologies generally cannot be actively controlled, or “dispatched,” by system operators without loss of production, often called “curtailment”. As a result, additional reserves are needed, as well as more substantial ramping of the available flexible resources.

The cost of wind and solar integration will vary by power system and the scenario being evaluated. When existing power systems are modeled, at low penetration, wind and, more recently, solar PV integration costs are often calculated in the range of $3-5/MWh, while higher penetrations can reach $5-11/MWh [29-32]. If further investment to improve operational flexibility is needed – whether retrofits of existing plants, construction of new generation or storage – then the associated fixed costs could increase substantially over these estimates. Other costs would result from curtailment of solar PV energy at higher penetrations due to periods of surplus solar generation, which could be avoided by dispatching CSP from thermal energy storage [33,34].

CSP with thermal energy storage provides the capability to reduce the variability of its production, and possibly also provide services to integrate other renewable resources, particularly by mitigating system ramps. Recent studies of solar integration into power systems have shown that the major operational impacts take place in the morning and evening solar ramps. As additional solar resources are interconnected, these ramps have higher magnitude and require faster response by other resources. Figure 3 shows that at 33% renewable energy, many of the top power system ramps in California, especially the late afternoon upwards ramps, will be closely correlated with solar production ramps in the morning and evening.

![Fig. 3: Top 10% of upward and downward net load ramp hours in California under 33% RPS, by hour of day (CAISO 33% RPS simulation data-sets, 2011)](image)

Depending on the number of hours of storage, at the very least, a CSP plant should incur greatly reduced or even zero integration costs on a plant level, giving it an average avoided integration cost in the ranges discussed above. Moreover, the energy from thermal storage could be used to mitigate cumulative system impacts – that is, integration impacts not tied to individual plant variability and forecast error but to the cumulative impact on power system operations – in the highest integration cost hours. For example, while formal studies of CSP plants with thermal storage are not yet complete, BrightSource has conducted some simple dispatch simulations with the public...
data provided in California to show how 2500 MW of CSP with different capacities of thermal energy storage could mitigate system ramps in 33% RPS scenarios.

7. Greenhouse gas emissions reductions

A primary objective of renewable energy policies is to reduce greenhouse gas emissions, as well as other air pollutants that can be jointly reduced. For any particular power system, different renewable technologies, and portfolios of those technologies, are likely to result in different patterns of emissions reductions. These patterns will depend on many factors, including the fossil generation mix and how it is operated when integrating renewables, as well as load profiles and the forecast daily renewable profiles. Clearly, solar production without storage will primarily back down fossil generation during the sunlight hours. As solar penetration increases, in some power systems, there may be lower marginal emissions reductions for incremental solar resources, because higher emissions generation has been displaced during those daylight hours [35]. For example, this would appear to be the case for California, where in-state solar generation is primarily displacing natural gas-fired generation.

Whether CSP with thermal energy storage, which tends to shift energy away from the daylight hours, can provide higher marginal emissions reductions than solar resources without storage thus requires region-specific analysis. A flexible solar resource should be better able to shift production to the hours that provide the highest greenhouse gas emissions reductions.

8. Power quality and other reliability services

CSP with thermal energy storage provides a range of power quality and other ancillary services that provide economic value, but which may be difficult to quantify or which need additional analysis. When operating a synchronous generator, CSP with or without storage inherently meets power quality standards that could otherwise, if substituted by solar PV, require investment in more capable inverters, other system controls or transmission equipment, as well as lost production. These services include reactive power support, dynamic voltage support, voltage control, inertia response, primary frequency control, frequency and voltage ride-through, small signal stability damping, fault currents, and the ability to mitigate Sub-Synchronous Resonance (SSR). With the addition of thermal storage, there is the capability to provide these capabilities over a larger number of hours, given that with a full storage charge, the plant can operate at minimum operating limits from sunset to some point in the next operating day. In the near future, some of these services may be valued more explicitly through markets.

9. Incorporating economic and reliability valuation into CSP plant design

Historically, the types of economic and reliability valuation reviewed in this report were not direct inputs into the design processes of CSP firms. However, recent studies have shown how both plant-level and system level studies can guide alignment between CSP plant design and evolving system needs. For example, valuating a parabolic trough plant by varying the solar multiple and number of hours of storage, and then assessing which design options could allow the plant to break-even using historical market prices (and using estimates of CSP capital costs) [36]. Other research dispatches CSP with thermal storage in power system models that do capture a range of value components, including integration of other renewables, but only evaluates 0 and 6 hours of storage [37,38]. Hence, further research is needed into the incorporation of valuation in CSP plant design. The CSP industry also needs to engage utilities and regional system operators in a more detailed discussion about plant attributes and potential value.

10. CSP with thermal storage and solar PV in renewable energy portfolios

Over the past few years, declines in the price of solar PV have led to conversion of several large-scale CSP projects to PV. At the same time, significant new CSP projects are coming on-line in the western United States in 2013-16 and elsewhere, and those with thermal storage will demonstrate the capability for solar energy that also provides utilities and system operators with substantial operational flexibility. In the interim, the studies cited in this
paper have clarified the short-term and long-term value of CSP with thermal energy storage, allowing for greater confidence in the range of quantifiable and qualitative benefits, particularly as solar penetrations increase.

Moreover, several studies have pointed to the prospects for increasing solar PV curtailment as penetrations increase, due to physical constraints on the power system [39-41]. Denholm and Mehos (2011) have further concluded that a solar portfolio which includes both PV and CSP with thermal energy storage would support less curtailment of aggregate solar production [42]. Mills and Wiser (2012b), while not modeling solar portfolios that mix technologies, corroborate most of these findings [43]. These results suggest the value of a diverse solar portfolio, which includes both PV and CSP as complementary solar resources. Further analysis is needed to refine the appropriate resource mix.

11. Conclusions

Even as solar PV costs have declined, CSP with thermal storage offers significant quantifiable economic and reliability benefits in regions of the world with sufficient direct normal irradiation, particularly at higher solar penetrations – including operational benefits that have not been sufficiently assessed, such as the capability to mitigate system ramps. The result is that CSP with storage needs to be assessed comprehensively on a net system cost basis.

The sum of these economic benefits is significant at higher solar penetrations [44,45]. For example, Mills and Wiser calculate that in California, the benefits of CSP with 6 hours of storage exceed the benefits of solar PV by $19/MWh at 5% penetration of solar energy, and exceed the benefits by $35/MWh at 10% penetration – roughly the penetration levels currently being planned towards in California under the 33% RPS.

Simulation studies of CSP with thermal storage to date have not determined a high value for avoided integration costs, and accurate analysis of these costs is difficult [46]. But studies of integration costs, and other estimates used by utilities, have suggested values for wind and solar integration costs in the range of $5-10/MWh for higher penetration scenarios [47]. Calculations done by BrightSource Energy based on California ISO simulation data suggest that the avoided costs of integration in the late afternoon and early evening hours may be significantly higher than in other hours of the day, providing greater value to resources that can mitigate the system ramps in those hours. Curtailment of solar PV energy due to constraints in power system operations could also increase at higher solar penetrations, and there is the potential for CSP with thermal energy storage to reduce overall solar energy curtailment. Studies suggest that these avoided integration and curtailment costs should be considered when comparing CSP with thermal energy storage to other renewable technologies.

This survey of methods and results leads to two key conclusions. First, there is a reasonable degree of convergence in the results of quantitative studies of the system costs and benefits of CSP with thermal energy storage, and alternative solar technologies, under a range of power system conditions. This result suggests that utilities and regulators should give credence to the basic findings of the studies surveyed in this report, and aim to resolve remaining differences. Second, utilities and regulators around the world are beginning to calculate net system costs when valuing alternative renewable resources, but more comprehensive, scenario-based methods are needed.

The early phases of renewable procurement around the world have tended to focus primarily on rapid deployment of available technologies at the lowest levelized cost of energy (LCOE), and less so on planning towards long-term, reliable clean power systems. There is wide recognition that LCOE is an incomplete and misleading metric for comparison of alternative renewable technologies. The study findings reviewed here demonstrate that a more comprehensive approach to resource valuation is needed for a cost-benefit comparison of CSP with thermal energy storage with other renewable technologies and integration solutions. These studies also highlight the need for simulations of changing power system conditions to guide investment decisions. Without conducting such analysis, CSP with thermal energy storage could be significantly under-valued in renewable procurement.
References


