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Modeling the Guaranteed Performance of CSP Plants

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Abstract. Performance models are an essential tool for the development, design optimization, and estimation of the expected performance or yield of concentrating solar power ("**CSP**") plants. It has also become common practice to use performance models to calculate the guaranteed performance of CSP plants for evaluating whether a newly constructed CSP plant has met its performance obligations. Although this would seem to be an obvious approach, actual experience has shown that insufficient thought has gone into how this should be done, and the performance models used have generally not been up to the task. We discuss some of the issues in relation to defining the guaranteed performance of a CSP plant, using a performance model to determine the guaranteed performance, and issues related to assessing whether the plant has met its guaranteed performance. We provide recommendations for how future projects should address these issues.

Keywords: Concentrating Solar Power (CSP), Guaranteed Performance, Performance Model, Project Finance, Financial Model, EPC Contractor, Final Acceptance Test

1. Introduction

Most CSP projects use some form of non-recourse project financing, which implies that the financing relies primarily on the revenue potential of the project, and there is limited recourse by the lenders against the owner if the project underperforms. Thus, the bankability of the power purchase agreement ("PPA") and the expected performance of the plant over the life of the project are the key factors that determine the project's financial viability. A financial cash flow model, referred to as the financial model, is prepared to evaluate the financial feasibility of the project. The financial model includes all the costs to construct the plant, the costs to operate and maintain the plant, payments to the banks and investors, and any other payments (taxes, insurance, etc.). The financial model will also model all revenues to the project for sales of electricity. The revenues established rely upon an assumed plant performance. CSP plants must harvest their fuel from the sun. The overall performance of the plant deals not just with converting a fuel into electricity like a conventional fossil power plant, but also with the efficiency of collecting the fuel. Since CSP plants cycle daily with the solar resource, it is also important that plants efficiently start up each day and manage transients through cloudy periods. Because the performance of the plant will vary seasonally due to changing sun positions, day length, solar intensity, and different weather conditions, it is necessary to use a performance model to estimate the expected performance and revenues of the plant. Many CSP plants also include thermal energy storage ("TES"), which allows plants to collect energy during the day and dispatch power at night or times of low solar resource. Thus, the efficiency and operational strategy for charging and discharging the TES also has an influence on the performance of the plant and needs to be dealt with properly in the model.

The "project finance" structure is good at allocating risk to the party most able to handle the risk. Since the plant performance is largely dependent on the design, efficiency, and quality of the plant constructed, typically it is the engineering, procurement, and construction ("EPC") contractor ("contractor") who is considered most able to address plant performance risk. As a result, most CSP projects require the contractor to provide a full wrap around performance guarantee on the plant. The intent is to make sure that the plant as designed, constructed, and commissioned, can perform as the project assumes in its financial model. A long-term performance test evaluates whether the plant can meet its guaranteed performance.

In the CSP community, it has become a common practice for the contractor to provide the performance model to calculate the "guaranteed performance". This is referred to often as the EPC performance model and this includes all input assumptions used for calculating the guaranteed performance and accounts for the contractor's performance margin or contingencies. The revenues assumed in the financial model are usually based on the plant performance predicted by the EPC performance model using an assumed reference solar resource for the project site.

The EPC contract defines the contractual relationship between the contractor and the owner of the project. The EPC contract defines the scope of the project and the responsibilities of the contractor, including the guarantees. The EPC contract also defines the requirements for performance testing and performance acceptance and how the guaranteed performance calculation is done. Unfortunately, there is inadequate attention given in many EPC contracts as to how the performance model is used for calculating the guaranteed performance of the plant, what adjustments can be made, and whether the contractor's model is even capable to do the evaluation contemplated. If there is a lack of detail in the EPC contract, then this can lead to expensive legal disputes between the parties.

2. Plant Guaranteed Performance

At the completion of the construction and commissioning of the plant, the EPC contractor needs to demonstrate that the plant can operate and meet its performance guarantee. There are typically two stages of plant testing. The first is referred to as the initial or preliminary acceptance tests and must be conducted and passed following the completion of construction and commissioning. Initial acceptance testing typically includes a demonstration of the capability and efficiency of the major systems in the plant: solar field, TES, and power block. This testing is conducted by the EPC contractor to demonstrate to the owner that the plant is ready for delivery to the operation and maintenance ("O&M") contractor (or operator) for initial commercial operation.

Once the plant achieves initial acceptance, the plant may start its final acceptance testing. This is typically a 12-month or longer performance test where the actual plant performance must achieve an agreed level of performance in relation to the EPC contractor's performance model, often this must be 100%. In many projects, the EPC contractor has 2 or 3 years to achieve 12 continuous months at or above 100% of guaranteed performance. The primary purpose of the EPC contractor's model is to determine the guaranteed performance requirement during the final acceptance test. This is used to evaluate whether the EPC contractor has met its performance guarantee and whether underperformance liquidated damages are payable. The model is typically run using actual solar and meteorological data for the test period. If the actual plant performance is below the guaranteed performance as calculated by the EPC contractor's performance model, then the EPC contractor may owe the owner of the project underperformance liquidated damages. A 1% difference in guaranteed performance, for example, can have significant implications in liquidated damages payable by the EPC contractor.

When we refer to plant operation, this typically includes both the operation and maintenance of the plant. With many independent power projects, the developer or owner of the project may contract with an affiliate or a related company, to operate the plant. Otherwise, the owner must contract a third party to operate the plant. Accordingly, the EPC contractor provides guarantees on a plant operated and maintained by the O&M contractor and who may not be associated with the EPC contractor. Hence, it is in the EPC contractor’s best interest that the operator operates the plant properly. The EPC contract needs to clearly define the performance obligations of the EPC contractor in relation to the O&M contractor. During the final acceptance test, the plant may experience outages and deratings due to the operation or maintenance of the plant. These may be due to mistakes made by the O&M contractor operating or maintaining the plant. Who accepts responsibility for these mistakes that may result in the plant under performing? Often the cause may not be clear whether it is an O&M contractor‘s responsibility or a potential defect in the plant itself. The EPC contractor will also have a responsibility to correct any deficiencies in the plant during some initial period. Thus the question that often arises when there is a problem at a CSP plant is whether it is the responsibility of the O&M contractor or EPC contractor to correct. This can lead to delays in resolving disputes that arise on a CSP plant.

Most CSP projects assume a ramp-up in performance in their financial model over the first few years of operation. The ramp-up should account for the maturity of the technology, the experience of the contractor, the maturity of the market in the country, the location of the plant, and the capability of the owner and operator. An example of a ramp-up scenario is that the plant must achieve 80% of the performance model output in year 1, 90% in year 2, and 100% in year 3. If ramp-up factors are included in the financial model, then they are also likely to be included in the EPC guarantee performance obligations. The ramp-up factors means that the contractor must guarantee a minimum performance of, for example, 80% in the first year, 90% in the second year, and 100% in the third year. Typically, if the plant exceeds 100% performance for any rolling 12-month period prior to the end of the third year, then the EPC contractor meets its performance guarantee for final acceptance of the plant. However, there is often confusion between the ramp-up period of performance obligations and the final acceptance obligations. The EPC contract needs to define clearly what the ramp up factors account for and who “owns” the shortfalls in performance.

3. Plant Performance Models

Performance models are an essential tool for the development and design optimization of CSP plants. They have become an essential part of the performance analysis used to determine the expected performance of a CSP project for financing the project. SolarPACES has developed guidelines that describe many of the important aspects of CSP performance models relevant to conducting the yield analysis for CSP projects [1]. The CSP industry appears to be unique in that it has become common practice for the EPC contractors of CSP plants to provide the performance model used for calculating the guaranteed performance of the plant. This seems to be a deviation from what is done in other industries such as for utility scale photovoltaic (“PV”) projects where an industry accepted model such as “PVsyst” is typically used to evaluate the bankability of the projects [2], [3]. These models determine the performance guarantee obligations for the project during acceptance testing. CSP projects are significantly more complex than PV projects and the performance modeling of CSP plants is more complex. The operation of CSP plants often relies on actions of an operator, which further complicates the modeling of the plant. The inclusion of TES means that solar energy can be stored during the day and dispatched later. The operating strategy of the TES will affect the expected output of the plant.

Sometimes it appears that insufficient attention is given to the quality of the EPC contractor’s performance model and the assumptions used in the model. It is important that the model and its assumptions are authenticated before the EPC contract is signed. Important model assumptions should be stated in the EPC contract. Typically, during the financing of a project, the owners and investors in the project will conduct a due diligence of the performance model and the assumptions used in the financial model. This will include a review of the solar resource file and the project design performance assumptions as well as an independent review of the performance model projections by the project's independent engineer ("IE"). Some important considerations are:

- It should be clear who has responsibility for different assumptions. In some cases, we have seen optimistic plant availability and mirror cleanliness assumptions used, that the operator is expected to meet whereas conservative system efficiencies are used for the assumptions that the EPC contractor is responsible for. This approach if allowed, moves performance risk onto the O&M contract, and by default back to the owner.
- The models are often "black box" models, meaning that the internal logic of the model is not able to be inspected. Many parameters in the model are not accessible to be viewed or changed. In many cases the models are provided by the EPC contractor and there is no indication that the model has been validated to accurately reflect the plant's operation and performance. Other industries use commercial products that have been independently validated for calculation of performance guarantees. We suggest that the CSP industry needs to develop industry standard and validated models to use when calculating guaranteed performance.
- Most models are not designed to be used for the purpose of accurately evaluating the performance of the plant and its components. Many common situations cannot be adequately modelled. Most models cannot be used to model reduced availability of different systems in the plant, for example when only 2 of 3 HTF pumps or TES pumps are available. This means other, less precise methods must be used for adjusting the guaranteed performance of the plant if it is deemed not to be the responsibility of the EPC contractor. If these kinds of corrections are to be allowed the performance model should be designed to allow them.
- Most performance models often do not accurately reflect the actual operation and performance of the plant. This may be because the models are inadequate, for example, many models are empirical rather than physical based models and as a result do not reflect the transient operation that the plant experiences. Often models are run with hourly solar resource input data, which does not allow startups, shutdowns, and cloud transients to be appropriately modeled.
- If the plant includes TES, it is critical that the model be able to implement the correct operation strategy for the TES.
- The EPC contractor often builds contingency factors into the model that results in the model not reflecting the actual expected performance of the plant. We suggest that contingency factors not be built into and hidden inside the performance model, but instead be explicitly accounted for both in the EPC contract and the guaranteed performance calculation.
- It should always be remembered that performance models are a simplification of the real-world operation of a CSP plant. This is especially true on partially cloudy days where we only have an approximate indication of the solar resource conditions seen by the plant at any given time.
- Often the EPC contract does not clearly define the process for calculating the guaranteed performance of the plant. This results in ambiguity concerning possible adjustments, which may be allowed but no clear direction as to the precise circumstances under which such adjustments are permitted and how they are to be applied.

4. Adjustments to the Guaranteed Performance

Many performance guarantees include clauses to protect the EPC contractor from events outside of their control during the performance test. In some cases, these clauses are vague or do not state how the adjustments are to be made. We think the EPC contract should be very clear on any adjustments that are to be made to the guaranteed performance. We believe it is important that the performance model be capable of directly accounting for each of these issues. The following list describes some of the more common issues we have run into.

4.1. Grid Outages

These generally are events where the plant may be available to send energy to the grid, but the grid cannot take the energy. Grid outages will typically be considered outside the control of the EPC contractor unless it was due to an issue caused by the EPC contractor. Adjustments to the performance guarantee will be made for these. The fact that there should be an allowance for grid outages is not the problem. It is important that the model correctly allow the grid outage to be accounted for and correctly reflect the expected operation of the plant in this situation. For example, if the plant includes TES, can the plant continue to operate and charge the TES during the grid outage? If it can, then the guaranteed performance should also account for this.

4.2. Force Majeure Events

These are typically events that prevent the plant from operating that will be considered outside the control of the EPC contractor, such as earthquakes, floods, and strikes. Adjustments to the performance guarantee will be made for these. However, a flood caused by poor grading and drainage engineering of the sites would not be excluded. The same problem as described above arises in respect of grid outages where the performance model should be able to operate in the same manner as the plant. If the plant can store energy in TES during the Force Majeure Event, then the guaranteed performance should also reflect this.

4.3. O&M of the plant

Often the EPC contractor does not operate the plant during the performance test. An issue often arises is whether adjustments should be made to the performance guarantee for abnormal operation or inadequate maintenance of the plant during the performance test. This should be carefully considered and dealt with in the EPC contract and the O&M contract. Operators do make mistakes operating plants, especially during the first years of operation but these should be accounted for in the availability assumptions of the plant. Typically, there are ramp up factors included in the EPC contracts for the first few years, and these should account for this initial learning curve of the O&M team. Uncertainty arises unless the drafting of the EPC contract is clear how operator errors of judgment are to be accounted for. We are of the opinion, that some level of operator errors will always occur in complex power projects such as CSP plants that must start up and shut down daily. The plant availability factors should account for this. The quality of the plant and the level of automation will directly influence the risk of operator mistakes. A well-designed, constructed, and commissioned CSP plant with state-of-the-art automation should have minimal issues with poor operation. Too often the operator is blamed for errors or equipment failures, when the underlying problem is the design, quality of construction, or completion of the building of the plant itself. It is important that the O&M company be prepared to take over the operation of the plant at initial acceptance, but this is not possible unless the EPC contractor is supporting the O&M contractor. It is a best practice for the EPC contractor to support the training of the O&M team and to support the O&M of the plant during the acceptance testing. It is important that the groups work as an integrated team. However, each incident that occurs should be evaluated separately. We have seen a few instances when the operator made mistakes that resulted in outages that we did believe should be considered outside the EPC contractor’s responsibility and would be excluded from the guaranteed performance.

4.4. Plant availability and breakdown of components or of the plant

The performance guarantee typically assumes a power plant availability. The question is what does this factor include? Does it include both forced and scheduled outages and de-ratings of the plant? Does it include the annual maintenance outages and extended overhauls? During the performance tests, is the EPC contractor responsible for unexpected mechanical breakdown and whether any breakdowns during the warranty period for the plant gives rise to an entitlement to adjust availability or the performance guarantee? EPC contracts are often unclear on whether there are carve-outs to component or plant breakdown and precisely what is permitted under a carve-out. We believe the EPC contractor should guarantee the assumptions used in the performance model. All equipment failures and outages during the guaranteed performance period should be under the EPC contractor's responsibility unless they can be demonstrated to be the owner's responsibility. A well-designed, constructed, and commissioned plant will have fewer outages than a poorly implemented plant. Where things get difficult is that in practice multiple issues can be occurring at the same time that are the responsibility of different parties (the EPC Contractor, the O&M contractor, or the owner). In some cases, multiple parties may share responsibility for a problem. The EPC contract can help address how these problems be resolved by providing clarity on different issues. A model that has the flexibility to model problems that affect the availability and efficiency of the different systems in the plant will allow many complex problems to be solved.

4.5. Solar Resource

In most cases, the actual solar resource during the test period is used to calculate the guaranteed performance. However, insufficient attention is paid to the measurement of the solar resource during the final acceptance test. It is essential that a good solar monitoring station be located at the site and be maintained during performance testing. Some points to consider:

- During testing, we recommend daily cleaning of solar instruments and a check of the alignment of the instrument trackers periodically both in the morning and afternoon. It is not uncommon for an instrument alignment to appear to be good in the morning but the alignment to drift in the afternoon.
- It is important that the solar resource data be quality checked during the performance test so low-quality data can be identified quickly and any issues be resolved.
- Good solar monitoring stations will use high quality instruments and trackers for direct normal irradiance ("DNI") measurement and include redundancy of measurement of the DNI. Large scale CSP projects should invest in quality pyrheliometers and trackers for measurement of the DNI. With multiple instruments, better quality control of the instruments is ensured. Although it seems to be common practice to use two pyranometers, one with a shadow band, as the redundancy for a pyrheliometer, we recommend two separate pyrheliometers and trackers. This way it is easier to detect both tracking and instrument calibration problems.
- Many plants have multiple weather stations, which is good to avoid localized problems that may shadow the DNI instruments, for example tall structures or steam plumes in the power block. Multiple stations can also help provide better DNI averaging across the solar field on partially cloudy days. Multiple stations should not be an alternative to instrument redundancy. Instrument redundancy should be included at each station.
- It is important to ensure the solar data measured during the test be used correctly into the performance model, such that the data is aligned with the solar angle calculations in the model.
- The plan for checking and sharing of solar data between parties and the resolution of disputes should be contained in the EPC contract.

4.6. Mirror Cleanliness

Mirror cleanliness has an important effect on plant performance.

- It is important that mirror cleanliness assumptions are reasonable for the specific plant site. Different sites have significantly different mirror soiling rates. Example, a site near the Sahara Desert in Morocco will likely have much higher soiling rates than plants in Spain. Whilst a 98% mirror cleanliness assumption could be appropriate for a plant in Spain, it is not a reasonable assumption for a plant near the Sahara Desert. Performance models should allow for monthly, if not daily, input of mirror cleanliness.
- During the guaranteed performance test the O&M contractor is often responsible for cleaning the mirrors. The question is: should the guaranteed performance be adjusted for the actual mirror cleanliness during the test? If it is, then how is the actual mirror cleanliness determined? The common approach of sampling even a relatively large number of mirrors in the solar field is approximate and can have a large uncertainty, especially if mirrors are relatively dirty. We have seen large differences in the average calculated field cleanliness when two groups are taking independent measurements. The industry needs better methods and standards for estimating average field cleanliness. Typically, the guaranteed performance is adjusted for mirror cleanliness, but what if there are design or construction issues, which limit access to all or parts of the solar field for cleaning. It is important that plants are designed for rapid cleaning if high mirror cleanliness is assumed in the financial model.
- Achieving a mature mirror cleaning effort is often a challenge for new plants. This should be dealt with in the project financial model and should not assume unrealistically high mirror cleanliness during the first year or two of plant operation. We believe the ramp up in the mirror cleaning effort is also part of the overall ramp up factors in the first years of operation of the CSP plant. Maintaining specialty mirror cleaning equipment is a complex effort, this is especially true for plants in remote areas.
- Receiver cleanliness is affected by soiling but there is no data that has been published to show this. Many EPC contractors assume the same level of soiling that is occurring on the mirrors is also occurring on the glass receiver tubes. We do not think this is a reasonable assumption. There are now instruments that can be used to measure receiver glass transmittance. We recommend that actual receiver cleanliness is measured if there is to be an adjustment to be made during the test.

4.7. High Wind Speeds

There is clearly a disconnect between what is assumed in performance models and how plants are operated in relation to high wind speed conditions. Many models use hourly average data, or even 10-minute average data to decide if the wind conditions are too high to operate the solar field. Solar fields typically stow based on peak or 3-second gust wind-speed data. As a result, most performance model projections underestimate the performance losses due to high wind conditions. We have seen annual performance reduced by 1% or 2% when actual wind stow conditions are used. Performance models need to use a peak wind speed for stowing and the average wind speed for thermal losses. Performance models should also reflect the actual operating plan for how the plant operates during a high wind speed stow event. Normally, there is a period that the plant will wait until it is put back into operation after a high wind speed stow alarm. A careful wind assessment should be conducted at the site to understand how quickly wind speeds may increase and at what wind speed the solar field should be stowed to make sure it is adequately protected.

4.8. Operating strategy

A complex part of the performance model is the control logic: this is the part of the model that must make all the decisions for how the facility will operate. This gets more complex for plants with TES. Decisions are required when to store energy and when to produce power. The first CSP plants with TES used it to maximize power generation over the day. The basic strategy that the O&M contractor would follow is to produce power from solar energy whenever possible and any excess energy will be stored. The stored energy is then used to extend the generation of energy when there is insufficient sunlight to operate the power plant, either during cloudy periods or to extend generation into and potentially all the way through the night until the next day. This common operating strategy is relatively simple to program into a performance model. The operating strategy becomes more complex when the goal is to store energy for later dispatch during a peak or higher tariff period. Then the operator of the plant must decide when to store energy and when to produce energy. The challenge for the operator comes from needing to avoid storing energy too quickly such that the TES fills up too quickly and causes the dumping of energy from the solar field and not storing sufficient energy so that there is not enough energy available in the TES to maximize generation during the peak or higher tariff period. Since the operator does not know how much solar resource there will be on any given day, some level of judgement is required as to when to start charging TES to maximize revenues. As a result, the performance model also needs to have an operating strategy built into it to help optimize revenues in the same manner as the operator would do. In our experience, this has not been done well in many EPC performance models, typically resulting in reduced performance obligations for the contractor. Because the models are black box models the problem manifests later when calculating the guaranteed performance and it becomes clear that the model is inaccurate.

5. Summary Comments

The CSP industry has evolved to include detailed final acceptance testing procedures that rely on a performance model to determine the guaranteed performance obligation of the EPC contractor. In general, we believe the performance models used have not been up to the task and often unfairly treat one party or the other. The CSP industry needs to develop transparent and validated models for performance guarantees.

Lenders to projects and owners usually require an EPC contractor to provide a full performance guarantee to protect projects from the risk of under-performing. Under-performance liquidated damages are paid for under-performance. Many projects experience lawsuits between the EPC contractor and the owner over issues related to final acceptance tests and under-performance. To avoid or at least limit disputes requires experience and clarity of thinking at the time the EPC contract is prepared. An important issue for CSP plants has been plant availability. It may be best to have a plant availability guarantee and an energy guarantee. If an EPC contract includes an availability guarantee and liquidated damages payable for unavailability and under-performance care will need to be taken that there is no duplication of liquidated damages. In our view if more care is taken on the drafting of the EPC contract concerning the long-term performance test less disputes will arise. If disputes do occur, a more sophisticated model than we have seen will significantly assist.

Data availability statement

Detailed questions about performance models or the assumptions that should be used, can be requested from the authors.

Author contributions

Hank Price prepared the original draft of the paper. Gary Rademeyer also contributed to the original draft and provided detailed review and editing of the paper.

Competing interests

The authors have attempted to provide a balanced prospective on the issues associated with the calculation of the guaranteed performance during the final acceptance testing of CSP plants, however, the authors acknowledge that they have represented the owners of several CSP plants in legal cases that deal with calculation of the guaranteed performance. Solar Dynamics also acknowledges that it is a developer of CSP performance models.

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