Analysis on the Value of Photovoltaic Power Plant Engineering Consultant under Constraint Conditions

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Manuscript submitted August 10, 2023; revised September 28, 2023; accepted October 24, 2023; published February 20, 2024.

doi: 10.12720/sgce.13.1.12-18

Abstract: The policy of “Grid-parity” keeps PV power plant and fossil energy power plant at the same bidding level, which is conducive to promoting the transformation of energy consumption to "low-carbon" development; At the same time, it also brings constraints on investment, quality, progress, technical standards, plant engineering consultant budget to the project construction. Taking constraint conditions as the evaluation criteria, the weight ranking of plant engineering consultant values of various PV power generation system equipment is analyzed by the analytic hierarchy process to determine the selection range of supervised equipment. The implementation of the selected scope of consulting services has promoted the realization of multiple objectives of the power station construction project, such as quality, progress and investment, and ensure investment income. It reflects the value of the conventional work of plant engineering consultant. In the 260MW “Grid-parity” fishery-solar complementary photovoltaic project, the value analysis method of plant engineering consultant under constraints was applied to calculate the economic value generated by engineering consultant up to 4.76 million RMB. In additional, based on various quality defects found during the supervision of PV power generation equipment, and based on rejected PV modules, important quality events related to main-transformers, and the detection results of hot-spot defects of PV modules in the whole station, the calculation method of economic value of plant engineering consultant is determined, which brings new ideas to the construction party in evaluating the effectiveness of plant engineering consultant.

Key words: Constraint condition, plant engineering consultant, photovoltaic power plant, gird-parity, Analytic Hierarchy Process (AHP)

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1. Introduction

The PV power generation system is composed of PV modules, PV brackets, combiner boxes, inverters, package transformers (or inverter-transformer integrated machines), cables, main-transformers, gas insulated metal enclosed switchgears (GIS)/Air Insulated Switchgears (AIS), Static Var Generators (SVG), medium & high voltage switchgears, etc. [1]. Since 2019, PV power plants have been gradually constructed in accordance with the policy of “Grid-parity” in China, and their construction investment budget has been prepared according to the benchmark grid price of local desulfurization coal-fired power plant. The new budget mainly reduced the procurement cost of PV power generation equipment compared before, which led to a sharp decline in the quality of equipment supply, thus affecting investment income. In addition, the new policy also puts forward the requirement for the engineering schedule node about full capacity grid-connection. If any important equipment quality defects occur, the project will be delayed in grid-connection, and economic losses may even lead to failure of plant investment [2].

Entrusted by the investor, plant engineering consultant shall supervise and control the whole process of equipment formation and/or the results in accordance with relevant national laws, regulations and technical standards by means of the control technology on quality, investment and schedule, which has great significance in ensuring the investment income of PV power plant [3]. Under the multi-objective constraints brought by "Grid-parity", the plant engineering consulting conventional value needs to be targeted analysis according to the constraints of PV power station construction. Besides it, quantitative evaluation of the economic value of plant engineering consultant will provide an important basis for the investor's management decisions. The purpose of this study is to quantitatively analyze the value of plant engineering consultant under the constraint of Grid-parity, and provide theoretical support for plant engineering consultant decision-making and scope formulation.

2. Analysis the Value of PV Power Plant Engineering Consultant Based on AHP

2.1. Brief introduction to AHP

Analytic Hierarchy Process (AHP) has been widely used in all walks of life by decomposing the elements related to decision-making into target layer, criterion layer and scheme layer; and conducting qualitative and quantitative analysis through pairwise comparison among various factors [4, 5, 6]. The main calculation and analysis steps are as follows.

- Establish hierarchical structure model. The objectives, factors and objects of decision-making are divided into target layer, criterion layer and scheme layer according to their interrelationship.
- Construct judgment matrix. According to Table 1, the judgment matrix is constructed by comparing each scheme in pairs among the factors of the criterion layer and under a certain criterion, and evaluating the grade according to its importance. In the constructed judgment matrix (A), the elements of the judgment matrix should follow $aij = \frac{1}{aji}$.

$$A = (a_{ij})_{n\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

Table 1. Comparison and quantification criteria of AHP

Comparison between factor *i* and factor *j*	Quantized value
Equally important	1
Slightly important	3
Moderately important	5
Strongly important	7
Extremely important	9
Intermediate value of two adjacent judgments	2，4，6，8

- Calculate the eigenvector. Calculate the eigenvector (w) corresponding to each matrix one by one according to the following formula.

$$w_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n} \Bigg/ \sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n} \qquad i,j = 1,2,\ldots\ldots,n \quad (2)$$

$$w = \begin{Bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{Bmatrix} \quad (3)$$

- Hierarchical single sorting and its consistency check. Calculate the maximum eigenvalue (λ_{max}) of each judgment matrix; Then the consistency index (CI) of the corresponding n-order matrix is calculated; Find the random consistency index in Table 2 to get the standard (RI); Calculate the inspection coefficient (CR). If CR<0.1, the judgment matrix passes the consistency test; If CR≥0.1 or negative, readjust the matrix value. The relevant formula is as follows.

$$CI = \frac{\lambda max - n}{n-1} \tag{4}$$

$$CR = \frac{CI}{RI} \tag{5}$$

Table 2. Average Random Consistency Index (RI)

Size of Matrix	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

- Overall ranking of schemes. The weight of the relative importance of all factors in each level to the highest level was calculated, that is the total ranking.

2.2. The conventional work value analysis on plant engineering consultant

Affected by constraints such as equipment investment, plant engineering consultant budget, grid connection progress, contractor integrity, technical standards, etc. [2], PV power plant engineering consultant needs to achieve the plant engineering value of making the progress meet the project requirements under the condition of controllable cost. Furthermore, it is also needed that the equipment quality meet the relevant national regulations, technical standards and procurement technical requirements.

As shown in Fig. 1, based on AHP, the plant engineering consulting conventional value is taken as the target layer; The constraints are taken as the criterion layer; Take the equipment as the scheme layer, such as PV Modules, PV Brackets, Combiner Boxes, Inverters, Package Transformers (or Inverter-transformer Integrated Machines), Main-transformers, GIS/AIS, SVG, Cables, Medium & High Voltage Switchgears, etc. In this way, the ranking relationship of the consulting values of various equipment can be obtained, which is an important basis for the client and the consultant to determine the scope of plant engineering consultant.

Based on the analysis and calculation of AHP, as shown in Table 3–4, the plant engineering consulting conventional value of individual equipment is ranked as PV Modules, Package transformers (or Inverter-transformer Integrated Machines), PV Brackets, Inverters, Main-transformers, Cables, GIS/AIS, SVG, Combiner Boxes, Medium & High Voltage Switchgears. It is recommended to select the equipment with a total sequencing weight greater than 0.1, that are of outstanding value.

Table 3. Calculation results of characteristic vector of criteria layer

CEI	CBPEC	CGP	CCI	CTS
0.467	0.038	0.073	0.275	0.146

Table 4. Calculation results of consistency inspection of criteria layer

λ_{max}	CI	RI	CR	Pass or No
5.309	0.077	1.12	0.069	YES

Table 5. Calculation results of the consistency test of the total sorting

CI	RI	CR	Pass or No
0.090	1.49	0.060	YES

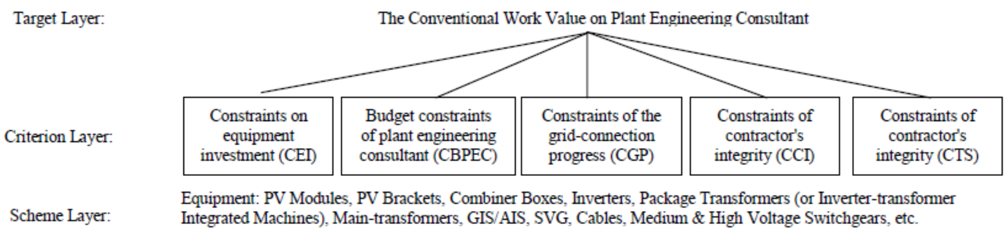


Fig. 1. Hierarchy analysis structure of plant engineering consulting value.

Table 6. Total ranking weights and consistency test calculation of AHP

Criterion layer Scheme layer	**CEI**	**CBPEC**	**CGP**	**CCI**	**CTS**	**Total sorting weight**
PV Brackets	0.191	0.130	0.015	0.165	0.050	0.148
PV Modules	0.325	0.344	0.039	0.125	0.214	0.233
Combiner Boxes	0.030	0.021	0.035	0.018	0.021	0.025
Inverters	0.104	0.094	0.084	0.187	0.117	0.127
Package Transformers (or Inverter-transformer Integrated Machines)	0.121	0.102	0.128	0.280	0.153	0.169
Main-transformers	0.025	0.140	0.281	0.082	0.284	0.102
GIS/AIS	0.013	0.065	0.225	0.062	0.081	0.054
SVG	0.020	0.052	0.028	0.036	0.014	0.026
Cables	0.154	0.028	0.131	0.024	0.041	0.095
Medium & High voltage Switchgears	0.017	0.025	0.035	0.020	0.026	0.021
λ_{max}	10.868	10.844	10.854	10.670	10.830	
CI	0.096	0.094	0.095	0.074	0.092	
RI	1.49	1.49	1.49	1.49	1.49	
CR	0.065	0.063	0.064	0.050	0.062	

3. Quantitative Analysis of the Economic Value of PV Power Plant Engineering Consultant

The consultants of PV power plant engineering shall check according to laws, regulations, standards and procurement technical specifications on the design rationality of PV power plant's equipment, the correctness of raw materials/components selection, the completeness and feasibility of the procedure scheme, the accuracy of process implementation, the feasibility of the testing work and the authenticity of data logging. The problems in quality and progress are provided to the contractors, who are pushed forward to provide qualified equipment/systems in time [1, 5]. It reflects the value of the conventional work of plant engineering consultant. Because of plant engineering consultant, the main economic values of PV power plant engineering consultant can be reflected from the following aspects.

- The rejection of photovoltaic modules with quality defects, which are the core components of power generation, enhances the reliability of power system and directly avoids the loss of power production. As the equipment supervision process is a sampling inspection, a certain proportion of non-conformities are allowed during the inspection process. In addition, the impact of batch loss should be considered in the condition of the rejection to the batch with quality defects, when the number of non-conformities exceeds the standard range. The economic value (E_1) of this work can be directly calculated by the corresponding power production loss of the rejected equipment.
- It will be illustrated that the equipment quality meets the requirements and the milestone node of the plant engineering is successfully completed, While the PV power plant is successfully started in one go. The quality of the main- transformers are key factors. In case of an important quality defect, the equipment quality will not meet the technical requirements of the contract, the requirements of national laws & regulations, or mandatory standards; Or it will delay the progress of the equipment engineering more than one month or affect the completion of the project milestone node. The economic value (E_2) of this work can be calculated by the number of important quality defects, the treatment cycle of the defect, and its affection of the plant grid-connection.
- As PV power generation system is composed of series and parallel connection PV modules, the existence of defective PV modules will lead to series and parallel mismatch losses, which will lead to the reduction of power generation efficiency and the loss of power production [7, 8]. The hot-spot detection of PV modules in the whole station is also an inspection work of the consultants [9–11]. The corresponding economic value (E_3) of this work can be calculated by the hot-spot detection data of PV modules in the whole station.

The above main economic values (E) provided by the PV power plant engineering consultant to the client can be calculated by the following formula:

$$\begin{aligned} E &= E_1 + E_2 + E_3 \\ &= (m_1 \times P_1 + \sum_{i=1}^{m_2} \mu_i \times P_{2i}) \times h_1 \times Q + m_3 \times P_3 \times h_2 \times Q + \sum_{j=1}^{m_4} \mu_j \times P_{4j} \times h_1 \times Q \end{aligned} \tag{6}$$

Including:
m_1 = Number of defective PV modules rejected; m_2 = Number of inspection batches of rejected PV modules. While the inspection batch is rejected, the quantity of corresponding defective PV modules is not included in m1; m_3 =Number of quality defects of transformer; m_4 = Number of defective sub-strings of PV modules; μ_i = Sensitivity coefficient. It is suggested that the value shall be 5 times of the defect rate of sampling inspection, and the maximum value shall not exceed 0.3; μ_j = Sensitivity coefficient. It is composed of the coefficient of series connection in the sub-string of PV modules (μ_{j1}) and the coefficient of influence of parallel connection between the sub-strings of PV modules (μ_{j2}). In the case of non-extreme hot-spot defect ratio of the power station, the simplified calculation method recommended from the detection statistics is shown in Table 7; P_1 = Nominal power of a single PV module; P_{2i} = Total rated power of the i^{th} inspection batch of rejected PV modules; P_3 = Rated power of the main-transformer; P_{4j} = Rated power of the j^{th} sub-string of PV modules; h_1, h_2: Average utilization hours loss of generation for defect elimination, which calculated by annual utilization hours and defect elimination waiting time. In h_1, it is recommended that the waiting time for defect elimination of PV modules be counted as 1 year, and in h_2, it is recommended that the waiting time for defect elimination of main-transformer is 1 month; Q: Feed-in tariff of the power plant.

Table 7. Influence coefficient of hot-spot defect in PV power plant

Sensitivity coefficient	Dirty or Battery Failure	Occlusion	Diode Fault	Open Circuit	Short Circuit	Falling-off
μ_{j1}	5%×n/N	5%×n/N	33%×n/N	1	1	1
μ_{j2}	0.5%×k×n/N	0.5%×k×n/N	2%×k×n/N	0	0	0

Notes：
n = Number of defective PV modules; N = Total number of PV modules in the sub-string; k = Number of PV sub-strings connected in parallel to a single MPPT (Maximum Power Point Tracking);When several kinds of defects coexist, the priority order is Open Circuit, Falling-off, Short Circuit, Diode Fault, Others. Furthermore, only the influence of defects with the highest priority needs to be calculated.

4. Case Study on Calculation of Economic Value of PV Power Plant Engineering Consultant

Taking a "Grip-parity" Fishery-PV complementary project with a capacity of 260 MW as an example, the average annual utilization hours of PV power generation equipment in the area is about 1062.5 h from 2019 to 2021, the total investment of the project will be 1.3 billion RMB, and the total amount of actual survey and design, equipment procurement, and Engineering Construction Procurement (EPC) will be only 935 million RMB; The grid-parity price approved is 0.3844 RMB /kWh; The actual engineering period of the power station shall not exceed 100 days.

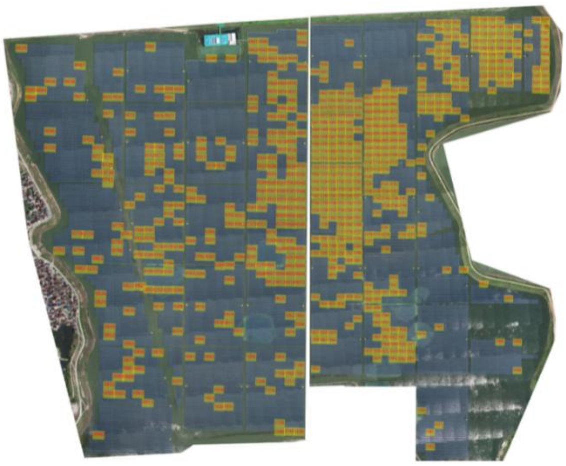
According to the value analysis results under the constraints brought by the policy of "Grid-parity", it is determined that the implementation scope of equipment supervision includes PV Modules, PV Brackets, Inverters, Package Transformers and Main-transformers. In addition to the conventional value of PV power plant engineering consultant, the main economic value generated accumulatively is 4,806,857.87 RMB. The specific calculation is as follows:

- During the sampling inspection of the manufacturing process of 817400 polycrystalline PV modules, 123 modules were rejected, 6 modules were accepted under concession, and 62 modules were accepted after rectification. The nominal power of a single PV module is 330 W. During the sampling inspection of the installation process of photovoltaic modules, 41 PV modules with defects exceeding the standard, such as scratches on the backplane and hidden cracks, were rejected. During the above sampling inspection, the inspection lot is qualified. According to the formula *f*, E_1 is 22,103.96 RMB.

- 10 quality defects were found in the manufacturing process of two main-transformers, its voltage level is 220 kV, and the capacity is 130 MVA, including one important quality defect involving in one main-transformer. According to the formula *f*, E_2 is 4,424,604.17 RMB.
- Due to the sampling inspection of PV modules in the manufacturing stage, some defective components have not been rejected, and the modules are not thoroughly cleaned before operation, which will cause occlusion or dirt. As an effective means of equipment supervision, UAV full-station hot-spot inspection can check the operation status of the components of the power station after operation. Through the hot-spot inspection of the whole station, it was found that 3972 sub-strings had defects, including the Defect or Dirt of the battery, Open Circuit, Short Circuit, Diode Fault, etc. Each MPPT has 6 parallel sub-strings, and each sub-string is composed of 20 PV modules. Details and Distribution of defects is showed in Fig. 2 and Table 8. According to the formula *f*, E_3 is 360,149.74 RMB.

Table 8. Data of Hot-spot Inspection of the PV power plant

Defect Type	Dirty or Battery Failure	Occlusion	Diode Fault	Open Circuit	Short Circuit	Subtotal
Defect quantity (piece)	7,013	315	101	960	180	8,569
Number of defective sub-strings (piece)	3,553	261	101	48	9	3,972
Series loss (RMB)	71,280.25	3,201.67	6,775.33	195,149.12	36,590.46	312,996.83
Parallel loss (RMB)	42,768.15	1,921.00	2,463.76	0.00	0.00	47,152.91



Note: The yellow block is the distribution position of defective PV modules.

Fig. 2. Orthophoto of PV power station and defect distribution.

5. Conclusion

The value of plant engineering consultant consists of the conventional work value of equipment supervision and the additional economic value.

Based on the analysis and calculation of AHP, the conventional work value of individual equipment supervision is ranked as PV Modules, Package Transformers (or Inverter-transformer Integrated Machines), PV Brackets, Inverters, Main-transformers, Cables, GIS/AIS, SVG, Combiner Boxes, Medium & High Voltage Switch-gears. It is recommended to select those with a total ranking weight greater than 0.1 as the scope of plant engineering consultant.

The economic value can be calculated through various quality defects found in the process of PV power engineering consultant. Taking a 260 MW "Grid-parity" fishery-solar complementary photovoltaic project as an example, the value of plant engineering consultant was analyzed under constraints, and the economic value generated exceeded 4.76 million RMB.

However, the influence coefficient of defective PV modules in the series and parallel loss calculation is defined according to the detection statistics of hot-spot defect proportion under the non-extreme situation, which has certain limitations, but has the advantage of convenient calculation. If supported by intelligence data handling system, the influence of one or several components on series or parallel mismatch loss can also be further studied and analyzed.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Gang Li, Zhaolin Wang, Xin Wang analyzed the data and wrote the paper; Pingguo Zou, Xin Zhang, Zhentao Zhang provided guidance and revised the paper. All authors had approved the final version.

References

[1] Li, A. D., Lv, Q. Y. (2012). *Photovoltaic Power Generation System Project*. Chemical Industry Press, pp. 71–98.

[2] Zou, P. G., Zhang, Z. T., Li, G, etc. (2021). Research and application of pv power generation equipment supervision under constant conditions. *Solar Energy*, 321(1): 11–17.

[3] Zhang, L. Y. (2017). *Advanced Course of Plant Engineering Consultant*. Tsinghua University Press. pp. 4–9.

[4] Kamal, M. Al-Subhi, Al-Harbi. (2001). Application of the AHP in project management. *International Journal of Project Management*, 19(1): 19–27

[5] Seda, O., Gokhan, S. (2018). Multi-criteria Decision-making in the location selection for a solar PV power plant using AHP. *Measurement*, 129(3):218–226.

[6] Figen, B., Lütfü, Ş. (2016). The selection of the best solar panel for the photovoltaic system design by using AHP. *Energy Procedia*, 100(2): 50–53.

[7] Skomedal, Å. F., Aarseth, B. L., Haug, H. etc. (2020).How much power is lost in a hot-spot? A case study quantifying the effect of thermal anomalies in two utility scale PV power plants. *Solar Energy*, 211: 1255–1262.

[8] Wang, A., Xuan, Y. (2020). Multiscale prediction of localized hot-spot phenomena in solar cells. *Renewable Energy*, 146(9):1292–1300.

[9] Waqar, A. M., Li, G. Q., Jin, Y., etc. (2020). *Study of manufacturing and hotspot formation in cut cell and full cell PV modules*. *Solar Energy*, 203: 247–259.

[10] Lorente, D. G., Pedrazzi, S., Zini, G., Dalla R. A. (Feb. 2014). Mismatch losses in PV power plants. *Solar Energy*, 100: 42–49.

[11] Kaushika, N. D., Rai, A. K. (2007). An investigation of mismatch losses in solar photovoltaic cell networks. *Energy*, 32(5):766–759.