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A Statistical Analysis of Critical Success Factors Affecting Utility-Scale Solar Plant Installation in India

Sandeep Pratap Singh

M.Tech. Research Scholar
Industrial Engineering
Takshshila Institute of Engineering and Technology
Jabalpur (M.P.), India
Email: sandeepsingh1442002@gmail.com

Alok Agrawal

Assistant Professor
Department of Mechanical Engineering
Takshshila Institute of Engineering and Technology
Jabalpur (M.P.), India
Email: alokagrawal26318@gmail.com

Abstract— The rapid expansion of utility-scale solar power in India requires rigorous project execution, resource allocation, and risk management from an Industrial Engineering and Management (IEM) perspective. This empirical research paper evaluates 15 Critical Success Factors (CSFs) across 75 solar sector professionals using a structured 58-item Likert-scale questionnaire. Statistical analysis including Cronbach's alpha reliability, Kaiser-Meyer-Olkin (KMO = 0.438) sampling adequacy, Exploratory Factor Analysis (EFA), Pearson correlation, multiple regression ($R^2 = 0.137$, $F = 0.626$, $p = 0.842$), and ANOVA were conducted. Although Safety Management (mean = 3.738) and Quality Management (mean = 3.684) received the highest perceived ratings, inferential testing revealed no statistically significant predictive predictors at $p < 0.05$. These empirical outcomes demonstrate that utility-scale solar installation operates as an integrated system where isolated optimizations fail if system bottlenecks remain. An IEM system-level implementation framework (Measure → Model → Predict → Optimise) is proposed.

Keywords:— Utility-Scale Solar, Critical Success Factors, Industrial Engineering, Multiple Regression, Exploratory Factor Analysis, India.

1. INTRODUCTION

Energy infrastructure forms the backbone of economic and industrial growth. Driven by accelerating global energy demand and decarbonization objectives, the transition toward renewable energy has gained unprecedented momentum in India. Utility-scale solar photovoltaic (PV) power plants—typically ground-mounted facilities with capacities exceeding 5 MW—represent a cornerstone of India's clean energy transition. However, developing, constructing, and commissioning large-scale solar projects involves complex engineering, multi-stakeholder coordination, stringent land acquisition, and severe grid transmission constraints.

From an Industrial Engineering and Management (IEM) perspective, utility-scale solar plant installation is an integrated socio-technical system requiring rigorous planning, scheduling, resource allocation, quality assurance, risk management, and supply chain optimization. Despite optimistic deployment targets, project execution routinely encounters schedule overruns and operational bottlenecks. Prior research frequently examines technical or economic constraints in isolation. This study addresses this research gap by providing a comprehensive, statistically validated empirical evaluation of 15 Critical Success Factors (CSFs) using

primary data collected from 75 practicing solar industry professionals in India.

2. LITERATURE REVIEW

Sustainable infrastructure execution depends on a multi-faceted matrix of managerial, technical, and institutional determinants. Gunduz and Almuajebh (2020) identified project planning, leadership, communication, quality control, and stakeholder coordination as primary determinants of sustainable construction project success. El Touny et al. (2021) highlighted environmental compliance, resource conservation, and economic feasibility within complex infrastructure environments. In renewable energy specifically, Alnaimi et al. (2021) demonstrated that competent project management, financial backing, organizational commitment, and supportive government regulations significantly govern project performance.

Further research underscores the role of digital transformation and operational engineering. Mahmood et al. (2023) and Xu et al. (2024) evaluated the integration of Building Information Modelling (BIM), Internet of Things (IoT), and digital monitoring systems in mitigating schedule delay and improving resource utilization. In the Indian context, Jayanti (2021) and Haldar et al. (2024) emphasized land tenure complexity, grid capacity bottlenecks, and regulatory clearances as major systemic barriers. While existing literature acknowledges these individual factors, empirical studies combining EFA, correlation, and multiple linear regression on primary practitioner data remain scarce.

3. RESEARCH METHODOLOGY

This study adopts a quantitative, deductive, cross-sectional survey design grounded in a positivist research philosophy. A structured 58-item questionnaire was developed, comprising 8 demographic profile

Respondent Demographics:

Table 1 : Summarizes the demographic profile and organizational distribution of the 75 study respondents.

Demographic Dimension	Category / Sub-group	Frequency (N=75)	Percentage (%)
Primary Work Role	Electrical / Project / Site Engineer	31	41.33%
	Civil / O&M / Procurement / Safety	29	38.67%
	Project Manager / Consultant	15	20.00%
Professional Experience	Less than 5 Years	8	10.67%
	5 to 15 Years	39	52.00%
	More than 15 Years	28	37.33%
Organisation Type	Solar Project Developer	23	30.67%
	EPC Contractor	21	28.00%
	Equipment Supplier / Consultant / Govt	31	41.33%
Largest Project Capacity	Below 50 MW	25	33.34%
	51 MW to 250 MW	33	44.00%
	Above 250 MW	17	22.67%

questions and 50 five-point Likert-scale items (1 = Strongly Disagree to 5 = Strongly Agree). The measurement instrument operationalized 15 independent explanatory constructs (measured via 3 items each) and 1 dependent construct—Successful Installation (SI, measured via 5 items).

Purposive sampling was utilized to target technical and managerial experts directly engaged in Indian utility-scale solar projects. A total of 75 valid responses were gathered. As detailed in Table 1, the sample reflects high professional maturity: 89.33% of respondents possess over 5 years of total professional experience, and 90.67% have more than 2 years of direct solar industry experience across diverse project capacities.

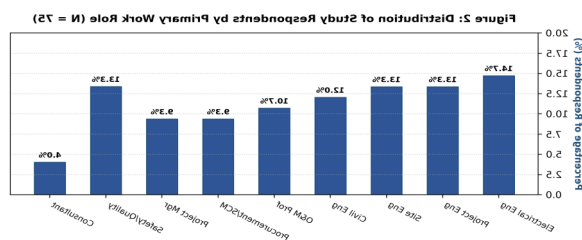


Figure 2: Distribution of Survey Respondents by Primary Work Role (N = 75)

4. Empirical Results & Statistical Analysis

Data analysis was executed using IBM SPSS and Microsoft Excel. The statistical evaluation comprised construct reliability analysis, descriptive ranking, Kaiser-Meyer-Olkin (KMO) test for sampling adequacy, Exploratory Factor Analysis (EFA), Pearson correlation, and multiple linear regression.

Internal consistency was evaluated using Cronbach's Alpha (α). As summarized in Table 2, reliability values across the 15 explanatory constructs ranged from 0.414 to 0.702. Stakeholder Management achieved the highest reliability ($\alpha = 0.702$), whereas Quality Management recorded the lowest ($\alpha = 0.414$). Descriptive mean statistics revealed high practitioner agreement for Safety Management (Mean = 3.738, SD = 0.392, Rank 1), Quality Management (Mean = 3.684, SD = 0.399, Rank 2), and Technical Factors (Mean = 3.640, SD = 0.427, Rank 3). Overall Successful Installation recorded a mean of 3.648 (SD = 0.354).

Table 2 : Reliability coefficients and descriptive statistics for study constructs

Rank	Code	Construct Name	Items	Cronbach's α	Mean (SD)
1	SA	Safety Management	3	0.641	3.738 (0.392)
2	QM	Quality Management	3	0.414	3.684 (0.399)
3	TF	Technical Factors	3	0.601	3.640 (0.427)
4	CM	Communication Management	3	0.656	3.631 (0.401)
5	HR	Human Resources	3	0.587	3.627 (0.403)
6	SCH	Schedule Management	3	0.564	3.618 (0.405)
7	TI	Transmission Infrastructure	3	0.578	3.613 (0.399)
8	EA	Equipment Availability	3	0.591	3.609 (0.408)
9	CP	Contractor Performance	3	0.517	3.578 (0.373)
10	GP	Government Policy	3	0.557	3.569 (0.387)
11	SM	Stakeholder Management	3	0.702	3.564 (0.442)
12	FF	Financial Factors	3	0.552	3.529 (0.384)
13	LA	Land Acquisition	3	0.493	3.493 (0.400)
14	EF	Environmental Factors	3	0.619	3.458 (0.444)
15	WC	Weather Conditions	3	0.674	3.404 (0.479)
—	SI	Successful Installation (DV)	5	0.634	3.648 (0.354)

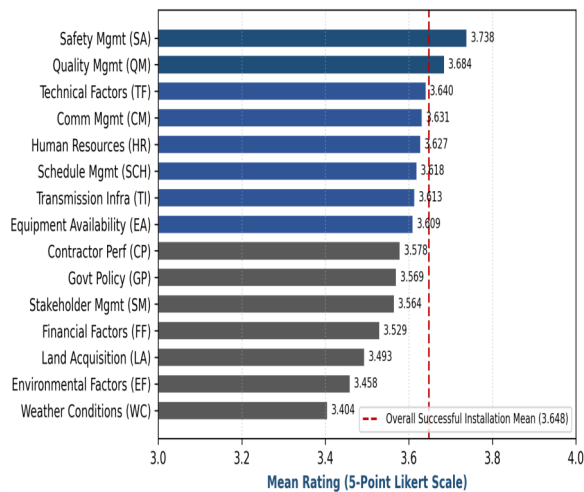


Figure 1: Mean Ranking of Evaluated Critical Success Factors (N = 75)

Sampling adequacy was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. As detailed in Table 3, the overall KMO measure was 0.438. In standard psychometric criteria, KMO values below 0.50 are deemed inadequate for factor extraction. However, Bartlett's Test yielded an Approx. Chi-Square of 1,686.502

(df = 1,225, $p < 0.001$), confirming significant multivariate inter-correlations among items. Principal Axis Factoring extracted an 18-factor solution explaining 74.82% of cumulative variance, with Factor 1 accounting for 16.45%.

Table 3: Statistical Tests of Sampling Adequacy and Factor Structure Validity

Statistical Test	Metric Value	Empirical Interpretation
Kaiser-Meyer-Olkin (KMO) Measure	0.438	Inadequate for robust factor structure (< 0.50)
Bartlett's Test Approx. Chi-Square (χ^2)	1,686.502	Statistically significant (df = 1,225)
Bartlett's Test Significance (p-value)	< 0.001	Rejects identity matrix assumption ($p < 0.05$)
Cumulative Variance Explained (18 Factors)	74.82%	Exploratory factorial baseline established

Table 4 : Pearson's Correlation Analysis of Explanatory CSF Dimensions with Project Performance, Ranked by Correlation Strength

Factor Rank	Explanatory CSF Dimension	Pearson's r	p-value	Statistical Significance
1	Quality Management (QM)	+0.198	0.088	Not Significant
2	Contractor Performance (CP)	+0.190	0.103	Not Significant
3	Transmission Infrastructure (TI)	+0.178	0.127	Not Significant
4	Government Policy (GP)	+0.153	0.189	Not Significant
5	Communication Management (CM)	+0.152	0.194	Not Significant
6	Schedule Management (SCH)	+0.148	0.204	Not Significant
7	Equipment Availability (EA)	+0.144	0.217	Not Significant
8	Human Resources (HR)	+0.090	0.445	Not Significant
9	Environmental Factors (EF)	+0.082	0.485	Not Significant
10	Weather Conditions (WC)	+0.059	0.613	Not Significant
11	Financial Factors (FF)	+0.056	0.633	Not Significant
12	Safety Management (SA)	+0.040	0.734	Not Significant
13	Stakeholder Management (SM)	+0.032	0.786	Not Significant
14	Land Acquisition (LA)	+0.028	0.813	Not Significant
15	Technical Factors (TF)	-0.015	0.897	Not Significant

Bivariate Pearson correlation analysis was conducted to evaluate the linear relationship between each CSF and Successful Installation. As presented in Table 4, the strongest positive associations were recorded for Quality Management ($r = 0.198$, $p = 0.088$), Contractor Performance ($r = 0.190$, $p = 0.103$), and Transmission Infrastructure ($r = 0.178$, $p = 0.127$). However, at the strict 5% significance threshold ($p < 0.05$), none of the 15 CSFs demonstrated a statistically significant linear correlation with project success.

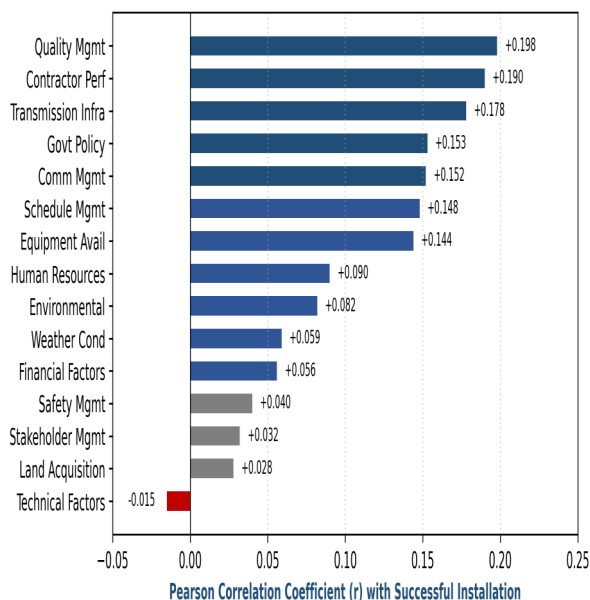


Figure 3: Pearson Correlation Strengths across CSFs with Successful Installation

A multiple linear regression equation was specified to evaluate the combined predictive capability of the 15 CSFs on Successful Installation: $SI = \beta_0 + \beta_1 TF + \beta_2 FF + \dots + \beta_{15} CM + \epsilon$. As detailed in Table 5, the model yielded a correlation coefficient $R = 0.370$ and $R^2 = 0.137$, indicating that the 15 factors collectively explain 13.7% of the variance in installation success. However, adjusting for the 15 predictors resulted in an Adjusted R^2 of -0.082 . The overall ANOVA test proved statistically insignificant ($F(15, 59) = 0.626$, $p = 0.842$), and no individual predictor achieved statistical significance (standardized β coefficients ranged from -0.207 to $+0.197$, all $p > 0.20$).

Table 4. Ranking of Explanatory CSF Dimensions Based on Pearson's Correlation with Project Performance and Statistical Significance

Regression Metric	Value	ANOVA Parameter	Value / Statistic
Multiple R	0.370	Regression Sum of Squares	3.025 (df = 15)
R Square (R^2)	0.137	Residual Sum of Squares	19.008 (df = 59)
Adjusted R^2	-0.082	Total Sum of Squares	22.033 (df = 74)
Std. Error of Estimate	0.566	F-Statistic	0.626
Sample Size (N)	75	Overall Model p-value	0.842 (Not Significant)

5. DISCUSSION AND IEM SYSTEM MANAGEMENT FRAMEWORK

A critical empirical paradox emerges from this research: while practitioners perceive Safety, Quality, and Technical factors as essential (mean scores > 3.60), statistical testing shows no direct predictive relationship with project installation success. This outcome does not imply that these factors are practically irrelevant. Rather, it demonstrates that utility-scale solar plant installation is a complex, integrated engineering system. In such systems, individual factors act as non-linear, interdependent constraints.

From an Industrial Engineering perspective, optimizing an isolated activity—such as procurement or safety protocols—will fail to yield measurable project success if upstream or downstream bottlenecks remain unaddressed (e.g., right-of-way land disputes or grid substation readiness). To operationalize these insights, an IEM implementation framework is proposed in Figure 4, structured around four continuous improvement stages:

1. **Measure:** Establish empirical baseline measurements using standardized KPIs across safety, schedule, cost, and quality.

2. **Model:** Map systemic interdependencies among supply chain, land, and technical factors using FMEA and Cause-and-Effect diagrams.

3. **Predict:** Deploy predictive lead-time analytics and risk models to anticipate grid curtailments and equipment lead-time variances.

4. **Optimise:** Apply Lean Construction, Work Study, and PDCA cycles to systematically eliminate front-line bottlenecks.

6. LIMITATIONS, FUTURE RESEARCH AND CONCLUSION

This study has limitations that frame its scope and highlight opportunities for future research. First, the sample size of 75 respondents, while appropriate for an M.Tech exploratory investigation, provides limited statistical power when evaluating 15 simultaneous predictors in multiple regression. Second, the use of subjective, perception-based Likert scales may introduce response bias. Third, the cross-sectional design captures a single snapshot in time rather than tracking dynamic project execution.

Future research should extend this foundation by: (1) expanding sampling across multi-regional state jurisdictions in India; (2) integrating objective project metrics (e.g., actual cost overruns, schedule variance in days, MW commissioning rates); (3) employing Structural Equation Modelling (SEM) and Confirmatory Factor Analysis (CFA) to model latent mediation pathways; and (4) developing a Project Readiness Index to evaluate pre-construction maturity.

In conclusion, this empirical paper establishes that successful utility-scale solar plant installation cannot be achieved through

piecemeal factor management. By bridging Industrial Engineering principles with solar project execution, the study provides a robust empirical foundation for industry practitioners and researchers working toward efficient, resilient renewable energy infrastructure development in India.

REFERENCES:

- [1] Ahmad, M., et al. (2021). Organizational capabilities and renewable energy project performance: A structural equation modelling approach. *Energy Strategy Reviews*, 38, 100756.
- [2] Ajmi, A., et al. (2022). Project success factors in renewable energy infrastructure: A quantitative assessment. *Renewable Energy*, 188, 1205–1218.
- [3] Alnaimi, F., et al. (2021). Project management practices and renewable energy project success in developing economies. *Sustainability*, 13(18), 10135.
- [4] Bolarinwa, S., & Udensi, L. (2024). Institutional and policy determinants of renewable energy project success in emerging economies. *Energy Policy*, 186, 113972.
- [5] Cheng, Y., et al. (2025). Integrated management framework for renewable energy project success using statistical modeling. *Renewable and Sustainable Energy Reviews*, 201, 115084.
- [6] El Touny, A. S., Ibrahim, A. H., & Mohamed, H. H. (2021). An integrated sustainable construction project's critical success factors. *Sustainability*, 13(15), 8629.
- [7] Gunduz, M., & Almuajebh, M. (2020). Critical success factors for sustainable construction project

- management. *Sustainability*, 12(5), 1990.
- [8] Haldar, S., et al. (2024). Reimagining energy infrastructure for justice: Power, politics, and institutional work in India's 2.05 GW Pavagada solar park. *Energy Research & Social Science*, 116, 103645.
- [9] Jayanti, S. (2021). A land-use-constrained, generation–transmission model for electricity generation through solar photovoltaic technology. *Clean Technologies and Environmental Policy*, 23, 2757–2774.
- [10] Kumar, R., et al. (2022). Influence of project management practices on renewable energy project performance. *Journal of Cleaner Production*, 347, 131298.
- [11] Mahmood, A., et al. (2023). Digital transformation in renewable energy project management: An SEM approach. *Technological Forecasting and Social Change*, 190, 122419.
- [12] Xu, H., et al. (2024). Digital project management systems for renewable energy infrastructure development. *Renewable Energy*, 226, 120935.