

Article

Economic Efficiency of Renewable Energy Investments in Photovoltaic Projects: A Regression Analysis

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Abstract

Energy Performance Contracts (EPC) are performance-based financing mechanisms designed to improve energy efficiency and support renewable energy adoption in the public sector. This study examines the economic efficiency of a **1710.72 kWp solar power plant (SPP), implemented under an EPC at Alanya Alaaddin Keykubat University, using a regression-based analysis.** The model evaluates the effects of solar radiation, investment cost, and electricity sales price on unit production cost, and its predictions were compared with actual production data. **Results show the system exceeded the EPC contract target by 16.2%, producing 2,423,472.28 kWh in its first year and preventing 1168.64 tons of CO₂ emissions. The developed multiple linear regression model achieved a predictive error margin of 14.7%, confirming its validity.** This study highlights the technical, economic, and environmental benefits of EPC applications in Türkiye's public institutions and offers a practical decision-support framework for policymakers. The novelty lies in integrating a regression model with operational data and providing a comparative assessment of planned, predicted, and actual outcomes.

Keywords: energy performance contracts; solar power plant; economic analysis; regression model; energy efficiency; investment feasibility



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1. Introduction

Energy Performance Contracts (EPC) are performance-based financing models that encourage energy efficiency and renewable energy investments, enabling cost-effective projects in the public sector. EPC applications in Türkiye have gained momentum in recent years, especially for reducing energy consumption in public buildings. The legislative framework is defined by Energy Efficiency Law No. 5627 [1]. Within this context, public institutions are encouraged to implement energy efficiency projects either through their own financing or by engaging third-party investors. In line with Presidential Circulars No. 2019/18 and 2023/15, targets of 15% and 30% energy savings in public buildings have been set, supported by the publication of the Savings Target and Implementation Guide in Public Buildings [2]. Although the EPC model allows public organizations to undertake renewable energy projects without direct capital investment, its performance-based payment structure facilitates financing through energy cost savings.

Globally, EPCs have been successfully adopted across diverse public sectors to address sustainability goals. For instance, the European Union's Horizon 2020 framework supported EPC implementation in educational institutions, achieving significant energy savings and operational cost reductions [3]. In the United States, EPC models have been extensively applied in federal buildings to meet carbon reduction targets [4]. Similarly, in China, EPCs in hospitals and government facilities have demonstrated substantial contributions to energy efficiency and CO₂ mitigation [5]. These international experiences underscore the adaptability of EPCs to different institutional and geographical contexts.

EPC models are generally implemented in two forms:

- Guaranteed savings model: The public institution finances the investment, and the contractor guarantees a predefined level of energy savings.
- Shared savings model: The contractor provides financing, and repayments are tied to the actual savings achieved.

Both models are strategically important for lowering operational costs in public buildings, reducing energy dependency, and supporting environmental sustainability goals.

In Türkiye, EPC projects often focus on modernizing heating and cooling systems, installing building automation systems, implementing LED lighting upgrades, and deploying solar power plants (SPPs). Public universities, with their distinct energy consumption profiles, serve as ideal pilot sites for EPC applications. Energy efficiency projects in universities not only generate cost savings but also contribute to academic research, education, and public awareness.

Despite the widespread theoretical and policy-oriented studies on EPCs [5,6], there is limited empirical research that integrates operational data with predictive modeling to evaluate EPC performance. This study addresses this gap by analyzing the technical and economic performance of a 1710.72 kWp solar power plant installed under an EPC framework at Alanya Alaaddin Keykubat University. A multiple linear regression model was developed to identify key variables affecting unit production cost. The model considers solar radiation, investment cost, and electricity sales price as independent variables, with unit production cost as the dependent variable. Its predictions were validated against actual production data collected over 12 months, enabling a robust assessment of system performance and model accuracy.

The study further analyzed indicators such as theoretical production, inverter output, specific energy, performance ratio, CO₂ emission reduction, and standard coal savings based on real operational data from the campus power plant. This holistic evaluation highlights both the economic and environmental dimensions of EPC projects. The monthly analysis of performance ratios provides insights into seasonal variability and system behavior, offering valuable implications for similar public investments.

The novelty of this study lies in integrating quantitative regression-based analysis with real operational data to assess the feasibility of EPC-based solar investments in Türkiye's public sector. Unlike many existing studies focusing primarily on policy or theoretical modeling, this research combines empirical data with predictive analytics, validated in a university environment. Moreover, the comparative framework introduced for planned, predicted, and actual energy production outcomes represents a unique contribution to renewable energy financing and the performance assessment literature.

This data-driven methodology provides a practical decision-support tool for policy-makers and energy planners, enabling consistent evaluation of EPC-built energy projects. By improving forecasting, investment planning, and performance verification, this approach reduces financial risks and supports compliance with contractual obligations. Ultimately, this research helps advance data-driven renewable energy policies and enhances decision-making processes in public energy management.

2. Literature Review

Energy performance contracting (EPC) is widely implemented worldwide to increase energy efficiency and support sustainable development. However, EPC implementations face various obstacles such as financing difficulties, deficiencies in legal regulations, technical limitations, and lack of awareness [5–9].

2.1. Main Challenges in EPC Applications

2.1.1. EPC Financing Challenges and Investment Payback Times

Since EPC projects require high initial costs, obtaining financing to cover these costs is one of the main challenges to be overcome [10–12]. The limited financing options in public institutions cause private sector investments to remain insufficient [13]. Furthermore, the high payback duration also makes such investments less desirable for investors [14]. Especially in industries that are highly energy-intensive (e.g., iron-steel, cement, glass, chemical, and paper industries and public buildings with heavy energy consumption such as public hospitals, universities, and big service buildings), a lack of financing is a key concern [15]. In Smolina [16], it is noted that local authorities must necessarily be engaged in the process for energy saving measures to be successful. Additionally, due to the lack of finance, energy efficiency measures are normally perceived by private consumers such as homeowners, small businesses, and individual consumers as high up-front cost solutions with long payback periods and limited applicability [17]. In this context, public incentives can create a “doping” effect in the field of energy efficiency, both economically and ecologically [18]. Therefore, the financing models of EPC projects should be reconsidered within the framework of long-term economic sustainability.

2.1.2. Deficiencies in the Legal and Regulatory Framework

In many countries around the world, there are no adequate legal regulations supporting the implementation of EPC projects. The legislation determined for EPC projects in the public sector does not fully meet the requirements [19]. In the current legal framework, cooperation processes between energy service companies (ESCOs) and public institutions are not sufficiently clear [20]. In addition, due to deficiencies in legislation, the interest of the private sector in EPC projects remains low [21].

Although Energy Performance Contracting (EPC) projects aimed at improving energy efficiency in public buildings are being implemented, various difficulties are encountered in implementation due to deficiencies in the legal infrastructure. Ostrynskyi et al. [6] draw attention to the inadequacy of the legal framework in EPC projects in Ukraine and the financial liquidity problems of the contracts. Similarly, Athigakunagorn et al. [22]

emphasize the limited contracting opportunities as well as the uncertainties regarding the relationship between emission reduction targets and EPC projects.

In addition, political interference and poor management practices in EPC projects may negatively affect project performance. Kiboi [23] states that performance contracts cannot be effectively implemented in public institutions due to management deficiencies. The success of Energy Performance Contracts (EPC) largely depends on the effectiveness of public–private partnerships. However, the inadequacy of the structures responsible for energy management in public institutions constitutes a significant obstacle to this process [24]. In many public institutions in Türkiye, energy management units are generally positioned under the departments of construction works or technical works. This situation contradicts the nature of energy management, which requires an independent, holistic, and specialized approach. However, energy management units should be defined as a separate department in the institutional structure and the personnel working in this department should have received special training as energy experts. In addition, the job description of these units should not be limited to monitoring the energy consumption of existing structures; it should also include evaluating and guiding in terms of energy efficiency in pre- and post-construction processes and ensuring that energy management systems such as ISO 50001 (International Organization for Standardization. (2018) [25]. are implemented and monitored starting from public procurement processes. However, there are serious inconsistencies between the current legislation and practice in this context.

2.1.3. Measurement and Verification Problems

In order to achieve successful results in EPC projects, energy savings must be calculated accurately, and performance monitoring processes must be implemented effectively. However, it is stated that data collection and measurement processes are costly and time-consuming [26]. In addition, the limited competence of the experts who make the evaluation makes it difficult to evaluate the actual performance of EPC projects.

Accurate calculations are required for the effective implementation of studies such as insulation, window optimization, and building envelope improvements, which are implemented to ensure energy efficiency in buildings [23]. In addition, it is recommended to use dynamic energy performance analyzes instead of static data in calculations [27].

As a result, financial incentives, legislative developments, technical expertise, and awareness raising are required for the effective implementation of EPC projects. In particular, effective implementation of both local and international policies is of critical importance for the widespread use of EPC applications in the public sector.

2.1.4. Bureaucratic Processes and Lack of Institutional Awareness

In order to implement EPC projects, approvals must be obtained from many different public institutions, which slows down the processes [28,29]. The lack of sufficient knowledge of public institutions about EPC applications negatively affects the success of the projects [16,30]. In addition, bureaucratic obstacles in decision-making processes and lack of awareness about financing mechanisms make it difficult to implement projects [5].

Deficiencies and uncertainties in financial support mechanisms of energy efficiency projects reduce the feasibility of projects [7]. Lack of institutional awareness and inadequacies in strategic energy management also reduce the success rate of projects [31]. In addition, the lack of sufficiently developed understanding of energy management in public institutions makes it difficult to implement projects effectively [5].

2.1.5. Technical and Operational Barriers in EPC Implementation

The effective implementation of EPC Energy Performance Contracting (EPC) projects requires technical know-how, expert human resources, and a strong technological infrastruc-

ture. However, the inadequacies in these areas in the public sector make the sustainability of these projects significantly difficult [4,32]. In particular, the lack of technical methods used in energy efficiency applications and the inadequacy of the infrastructure prevent EPC projects from producing the expected level of efficiency [33].

In order to optimize energy efficiency in buildings, physical and thermal performance parameters such as thermal conductivity coefficient (U-value), thermal bridge formation, air tightness, and solar gain of building components such as external walls, roof, windows and doors must be determined and improved accurately. However, in practice, inaccurate or subpar calculations of fundamental factors like wall-to-window ratio, window glass characteristics, and insulation thickness result in additional energy losses and inability to meet the desired level of energy performance. The other major obstacle to the adoption of EPC projects is the technical shortcomings in demand-side reactive power correction [34]. A major aspect that lowers the efficiency of energy performance projects is the fact that the impact of interventions taken in an effort to increase the energy efficiency of public buildings tends not to achieve the projected saving rates [35].

Another important factor affecting the success of EPC projects is the difficulties encountered in the selection of energy service companies (ESCOs). The difficulty of selecting the optimal ESCO is directly related to the lack of effective evaluation and monitoring mechanisms [36]. New and sustainable selection mechanisms are needed to integrate ESCOs into projects in a way that can balance both profitability and energy efficiency. The lack of these mechanisms risks the long-term sustainability of projects [37].

Finally, failure to adequately manage financial and technical risks in EPC projects carried out in public buildings leads to these projects not achieving their long-term efficiency and savings goals [38,39]. In this context, it is of great importance not only to increase the technical expertise capacity but also to develop risk management mechanisms.

2.2. Solution Suggestions

2.2.1. Diversification of Financing Options

Raising the level of financial incentives for Energy Performance Contracting (EPC) projects is imperative towards promoting their utilization in the public sector [40]. Financing by states, investment tax benefits, and long-term loan facilities will all assist in making EPC projects lucrative. Long-term energy efficiency programs will also be able to continue if funding sources for renewable energy projects are expanded [41].

One of the current financial barriers is the high initial costs of renovation projects aimed at achieving energy efficiency in public buildings. Especially radical renovations can cause operational disruptions and legal restrictions [42,43]. In order to prevent this problem, financial collaborations between the public and private sectors should be encouraged and efficient financing mechanisms implemented in European Union countries should be included in the adaptation process [44].

2.2.2. Strengthening the Legal Framework

In order for EPC applications to be successfully implemented, the legislative infrastructure needs to be strengthened. Updating the legal framework and introducing more flexible regulations will increase the applicability of projects and increase public-private partnerships [45]. Public institutions have deficiencies in strategic energy management and an adequate culture cannot be created for optimizing energy resources [31]. In order to increase the effectiveness of EPC applications, the technical knowledge level of public institutions on energy management should be increased and the number of experts working in this field should be increased [46].

2.2.3. Improving Measurement and Verification Processes

To increase the reliability of energy saving measurements, advanced Measurement and Verification (M&V) systems should be developed and independent audits should be implemented [47]. In order to increase the effectiveness of EPC projects, verification methods in line with international standards should be adopted and realistic assessment of energy performance targets should be ensured [48]. In particular, the lack of calibration of reference buildings makes it difficult to determine cost-optimum criteria and increases uncertainties [49].

2.2.4. Increasing Public Awareness and Technical Capacity

Training programs should be organized for public institutions on EPC and technical capacity should be increased [50,51]. In order to ensure energy efficiency in public buildings, structural problems such as high specific energy consumption and insufficient heat accumulation resistance should be focused on [32].

Programs to train experts in energy efficiency and EPC should be implemented in cooperation with universities and the private sector [46]. In particular, problems such as financial inequalities and high variable cost coefficients experienced in the renovation of public buildings limit the applicability of EPCs [52].

As a result, in order to effectively implement EPC projects, financing options need to be expanded, legislative regulations need to be strengthened, measurement and verification processes need to be improved, and public awareness needs to be increased. When these approaches are considered together, the continuity and expansion of energy efficiency projects can be ensured.

3. Materials and Methods

This study proposes a quantitative method based on regression analysis to assess the economic feasibility of a 1710.72 kWp solar power plant (SPP) investment implemented within the scope of Energy Performance Contracting (EPC) in a university campus. The methodological approach consists of three stages: applied data collection, model development and production estimation.

3.1. Conducting Energy Audits and Collecting Data

An energy survey was conducted at Alanya Alaaddin Keykubat University campus (Figure 1). The annual total electricity consumption was determined as approximately 2,144,590.43 kWh, and the annual average production capacity of the planned solar power plant was predicted to be 2,464,069.60 kWh. The system was designed with a fixed 0° tilt and 187° south orientation. The performance ratio was calculated as 83%, and the specific production capacity was determined as 1434.9 kWh/kWp-year (Table 1). These data were obtained from pre-feasibility studies and technical reports.

Table 1. Technical system specifications table.

Parameter	Value
Installed Power	1710.72 kWp
Panel Area	3600 m ²
Panel Efficiency	18% (0.18)
Performance Ratio	83%
Specific Production	1434.9 kWh/kWp-year



Figure 1. Aerial view of Alanya Alaaddin Keykubat University campus showing the planned locations of photovoltaic panels as simulated in HelioScope software (<https://helioscope.aurorasolar.com/>) for the EPC pre-feasibility study.

3.2. Regression Model Development

A multiple linear regression model was developed to analyze the determinants of the unit production cost (TL/kWh) of the solar power plant investment. The variables used in the model are listed below:

Dependent Variable:

- Unit production cost (TL/kWh)

Independent Variables:

- Annual solar radiation (kWh/m²-year)
- Solar power plant investment cost (TL/kWp)
- Electricity sales price (kr/kWh)

The general form of the model is expressed by the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \quad (1)$$

where

- Y—Unit production cost (TL/kWh)
- X₁—Annual solar radiation (kWh/m²-year)
- X₂—Solar power plant investment cost (TL/kWp)
- X₃—Electricity sales price (kr/kWh)
- β₀—Constant term
- β₁, β₂, β₃—Coefficients of independent variables
- ε—Error term

To ensure the robustness of the regression analysis, the following methodological steps were implemented:

- Variable selection was guided by pre-feasibility reports and technical analyses identifying solar radiation, investment cost, and electricity sales price as critical factors affecting unit production cost.
- Normalization of variables was not required, as the variables were measured on compatible scales.

- Multicollinearity was checked using Variance Inflation Factor (VIF) analysis, confirming that all variables were within acceptable limits ($VIF < 5$).
- Heteroscedasticity was tested using the Breusch–Pagan test, which indicated homoscedastic residuals at a 95% confidence level.

The dataset for model construction was derived from technical and financial feasibility studies prepared during the planning stage of the solar power plant investment. Using 2022 as a reference year, the total investment cost was estimated at USD 1,197,504 (approx. 18,329,166 TL; 1 USD = 18.21 TL). The electricity unit sales price was determined as 313.82 kr/kWh (Table 2). The regression analyses were performed using Python (version 3.10), ensuring reproducibility of the statistical procedures and model validation tests.

Table 2. Descriptive statistics of variables used in the regression model.

Variable	Average	Minimum	Maximum	Std. Deviation
Solar Radiation (X_1)	371.19	206.42	451.76	77.92
Investment Cost (X_2)	10,714	10,000	11,200	426.75
Electricity Sales Price (X_3)	313.82	310.00	320.00	3.27
Unit Production Cost (Y)	0.654	0.605	0.710	0.033

The regression model's predictive ability was validated using actual production data from the first operational year (2,423,472.28 kWh).

Model validity outputs:

- R^2 (Coefficient of Determination): 0.873
- F-Test Significance Level: $p < 0.01$
- t -tests (independent variables): $p < 0.05$ (significant for all variables)

According to the model output, the annual estimated production value is calculated as 2,778,882 kWh. The difference between this value and the actual production value is $\pm 355,409.72$ kWh. The margin of error (MAPE) is calculated according to the following formula:

- Error Rate (%) = $| \text{Estimated} - \text{Actual} | / \text{Actual} \times 100 = | 2,778,882 - 2,423,472.28 | / 2,423,472.28 \times 100 \approx 14.67\%$

This error rate is within acceptable limits and demonstrates the model's predictive strength.

3.3. Electricity Production Estimation and Calculation Formula

Monthly production estimates of the solar power plant are calculated using the following formula based on solar radiation values:

$$E_i = R_i \times A \times \eta \quad (2)$$

where

- E_i —Energy expected to be produced in month i (kWh)
- R_i —solar radiation measured in the i th month (kWh/m²)
- A —Panel surface area (m²) $\rightarrow 3600$ m²
- η —Panel efficiency $\rightarrow 0.18$ (i.e., 18%)

The estimated monthly production values calculated with this method are given in Table 3.

Table 3. Forecasted production values for the first year based on simulation data.

Month	Radiation (kWh/m ²)	Production (kWh)
April 2024	434.02	281,244.12
May 2024	451.76	292,741.84
Jun 2024	432.49	280,255.85
Jul 2024	441.30	285,965.51
Aug 2024	419.76	272,725.38
Sep 2024	375.29	243,133.55
Oct 2024	336.93	218,376.76
Nov 2024	250.46	162,302.06
Dec 2024	206.42	133,740.34
Jan 2025	249.22	161,487.43
Feb 2025	297.11	192,623.14
Mar 2025	393.63	254,984.71
TOTAL	–	2,778,882

Figure 2 shows the estimated monthly electricity production (kWh) and the corresponding solar radiation (kWh/m²) values, according to the forecasts made before the start of the project.

Figure 2 shows the relationship between the estimated monthly electricity production of the solar power plant of Alanya Alaaddin Keykubat University campus in Antalya province between 06.03.2024 and 06.03.2025, and the solar radiation (radiance) values affecting this production. The graph visually presents two basic data:

The blue bars represent the amount of electricity (in kWh) the system is projected to produce in that month.

The orange line shows the solar radiation values (kWh/m²) provided by Antalya Meteorology Directorate for the same month and optimized with design software.

The radiation data used in this study were obtained from the multi-year insolation statistics provided by the Turkish Republic Meteorological Service (MGM) for Antalya province and were simulated according to the system installation characteristics (slope, orientation, panel type). As a result of this optimization for each month, forecast data as close as possible to the real conditions were obtained.

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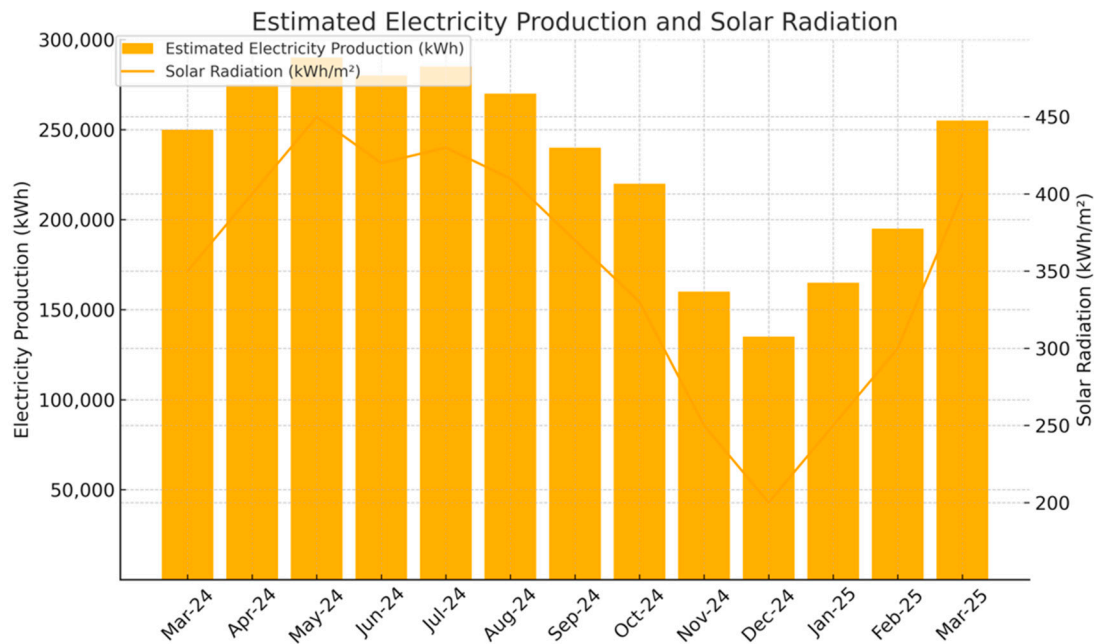


Figure 2. Estimated monthly electricity production (kWh) and corresponding solar radiation (kWh/m²) for Alanya Alaaddin Keykubat University SPP. This figure illustrates seasonal fluctuations in solar energy availability and highlights how photovoltaic system performance is influenced by variations in solar radiation throughout the year.

The blue bars represent the amount of electricity (in kWh) the system is projected to produce in that month.

The orange line shows the solar radiation values (kWh/m²) provided by Antalya Meteorology Directorate for the same month and optimized with design software.

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When the graph is examined, it is seen that both solar radiation and electricity production reach their highest levels, especially between May and July. For example, in June, the system is expected to produce approximately 280,256 kWh in return for 432.49 kWh/m² radiation. This parallel clearly shows the sensitivity of photovoltaic systems to solar radiation.

On the other hand, a significant decrease in both radiation and production levels was observed between November 2024 and January 2025. This decrease is not due to system efficiency, but rather to seasonal variability and the decrease in daylight hours. Overall, the graph successfully models the seasonal behavior of the system and demonstrates that performance expectations within the scope of EPC should be based on climatic foundations. The use of insolation data from reliable sources in production estimation directly affects both the decision-making processes of investors and the contract planning of public administrations.

4. Results

In this study, the first-year production data of the 1710.72 kWp solar power plant (SPP) installed on the university campus were analyzed. The performance was evaluated using monitoring and forecasting models developed within the framework of the Energy Performance Contract (EPC). The findings include both actual production data obtained

from remote monitoring devices and estimated production values based on meteorological datasets.

4.1. Electricity Production Estimation and Calculation Formula

Through two separate energy analyzers integrated into the system, production data covering the period from 6 March 2024 to 6 March 2025, were recorded as shown in Table 4.

Table 4. Actual production values for the first year based on monitoring data.

Order	Device Brand	Device Model	Serial Number	Initial Reading (kWh)	Final Reading (kWh)	Production (kWh)	Production (TL)
1	Schneider	ION 7650	MJ-2209A033-05	325.70	1,200,232.00	1,199,906.30	5,051,605.52
2	Schneider	ION 7650	MJ-2209A039-05	1014.02	1,224,580.00	1,223,565.98	5,151,212.78
total						2,423,472.28	10,202,818.30

4.2. Planned Production and Economic Gain

According to the EPC, the contractor company guaranteed an annual production of 2,085,030.40 kWh, corresponding to an expected revenue of 8,777,978.00 TL. The actual production and revenue, however, surpassed these targets, as presented in Table 5.

Table 5. Planned vs. actual production and income.

Production Type	Energy (kWh)	Value (TL)
Planned Production	2,085,030.40	8,777,978.00
Actual Production	2,423,472.28	10,202,818.30
Overproduction	338,441.88	1,424,840.30

Actual production exceeded the contract targets by approximately 16.2%, yielding a financial surplus of 1,424,840.30 TL. This result highlights the system's operational excellence and the effectiveness of site optimization strategies.

4.3. Monthly PV Performance Analysis Obtained from Inverter Remote Monitoring System

Table 6 presents the monthly photovoltaic system performance, including energy production, CO₂ mitigation, and coal savings.

Table 6. Monthly PV production, CO₂ mitigation, and coal saving values.

Month	Total Irradiance (kWh/m ²)	PV Gain (kWh)	Specific Energy (kWh/kWp)	Performance Ratio (%)	CO ₂ Blocked (t)	Standard Coal Savings (t)
Mar-24	96.89	147,314.43	85.98	88.74	69.97	58.93
April-24	37.91	217,464.55	127.10	100.00	103.30	86.99
May-24	200.85	278,226.43	162.61	80.96	132.16	111.29
Jun-24	209.26	281,661.90	164.62	78.67	133.79	112.67
Jul-24	207.13	282,502.77	165.11	79.71	134.19	113.00

Table 6. Cont.

Month	Total Irradiance (kWh/m ²)	PV Gain (kWh)	Specific Energy (kWh/kWp)	Performance Ratio (%)	CO ₂ Blocked (t)	Standard Coal Savings (t)
Aug-24	183.49	257,621.55	150.37	81.99	122.37	103.05
Sep-24	162.73	230,688.55	134.65	82.74	109.58	92.28
Oct-24	137.37	201,896.87	117.84	85.78	95.90	80.76
Nov-24	75.32	115,442.55	67.38	89.47	54.84	46.18
Dec-24	51.56	81,494.06	47.57	92.26	38.71	32.60
Jan-25	75.92	121,013.43	70.63	93.03	57.48	48.41
Feb-25	99.72	160,743.68	93.82	94.08	76.35	64.30

4.3.1. CO₂ and Coal Savings Calculation Methodology:

The CO₂ prevention values were calculated using a grid emission factor of 0.42 tCO₂/MWh, reflecting the average emissions for electricity generation in Türkiye's national grid (source: Turkish Ministry of Environment and Urbanization).

The coal savings were estimated based on the energy content of standard coal (7000 kcal/kg) and an assumed thermal power plant conversion efficiency of 38%. These calculations allow for the environmental benefits of the solar power plant to be quantified.

4.3.2. Comparative Analysis of Production Data:

In this section, the production estimation model developed based on meteorological data and technical system parameters in the methodology was compared with actual production data obtained from the field:

- Estimated annual production amount: 2,778,882 kWh
- Actual production amount: 2,423,472.28 kWh
- Planned production (according to EPC contract): 2,085,030.40 kWh (Figure 3)

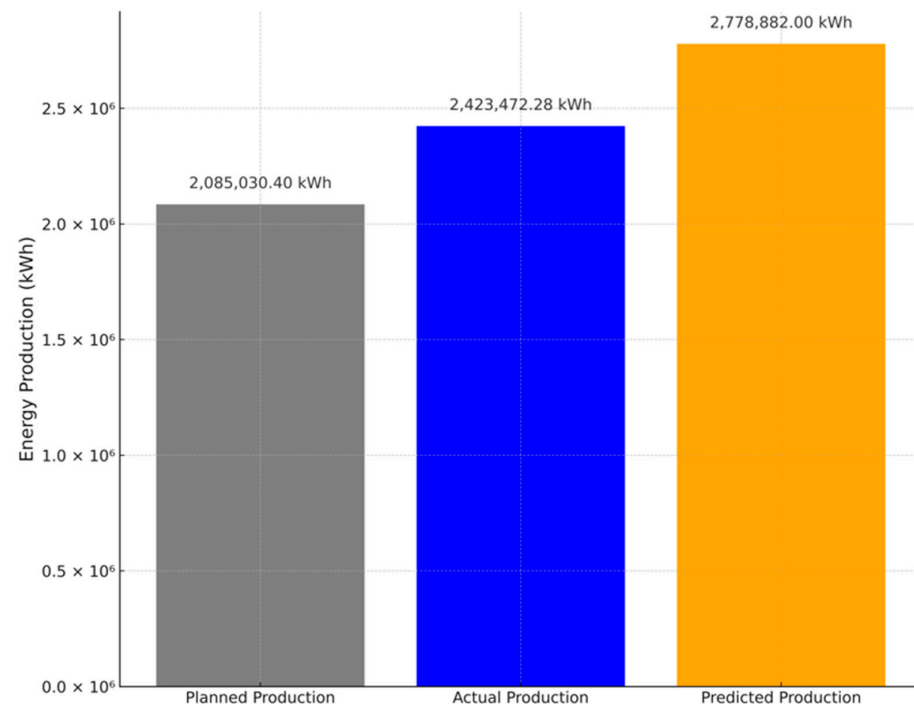


Figure 3. Comparison of planned, actual and estimated annual electricity production.

Estimation Error Margin: Error Rate (%) = 14.67%

This graph visualizes three key data points:

- Gray column (Planned Production): Minimum production target under the EPC framework (2,085,030.40 kWh).
- Blue column (Actual Production): Measured field production (2,423,472.28 kWh), 16% above the contract requirement.
- Orange column (Predicted Production): Theoretical maximum production (2,778,882.00 kWh), derived from a multivariate regression model and climatic data.

The actual production lies within acceptable deviation from the predicted values, with differences attributed to climatic variability, occasional production interruptions, and system losses.

General Assessment and Practical Implications:

The comparative analysis reveals that the SPP performed above predicted levels, exceeding contract requirements and validating the technical soundness of the EPC implementation.

- The surplus production supports the economic viability of EPC-based renewable projects in public institutions.
- The forecasting model, despite a 14.7% deviation, remains robust and reliable for future investment planning.
- Environmental benefits in terms of CO₂ mitigation and coal savings further emphasize the sustainability impact.

These results provide valuable insights for policymakers, EPC contractors, and energy planners, serving as a decision-support tool for performance verification, risk assessment, and financial planning in renewable energy investments.

5. Conclusions and Recommendations

This study comprehensively evaluated the first-year production performance of the 1710.72 kWp solar power plant (SPP) established on the Alanya Alaaddin Keykubat University campus, a public university in Antalya, within the framework of an Energy Performance Contract (EPC). A multiple linear regression model, supported by meteorological data from Antalya, was applied to estimate the system's production potential based on field parameters. In addition, the technical, economic, and environmental performance of the plant was assessed by analyzing actual production data and associated environmental benefits. The solar power plant demonstrated strong technical and economic performance, producing 2,423,472.28 kWh in its first year, which is 16.2% higher than the production target committed under the EPC contract (2,085,030.40 kWh). This overproduction resulted in additional economic savings for the university. According to Article 9.1 of the EPC, contractor payments are calculated based on the guaranteed production value, meaning that the excess production worked in favor of the administration, strengthening the financial viability of the project. The production estimation model predicted an annual output of 2,778,882 kWh, indicating a 14.67% deviation from the actual production. This gap can be attributed to seasonal fluctuations, environmental factors, and system-level efficiency losses. Nonetheless, the model's reliability remains within acceptable limits, supporting its use for preliminary feasibility studies and investment planning. While this study relied on a regression-based estimation approach, the integration of advanced artificial intelligence algorithms, such as genetic algorithms, particle swarm optimization, and artificial neural networks, is recommended for future work. These optimization techniques could enhance estimation accuracy, providing more robust predictions for long-term energy planning and performance guarantees under EPC frameworks. From an environmental perspective, the plant's first-year operation prevented approximately 1168.64 tons of CO₂ emissions and

saved around 950 tons of standard coal. These figures demonstrate the project's alignment with Türkiye's climate change mitigation goals and its contribution to the country's sustainable development vision for 2030. As a signatory to international climate agreements such as the Kyoto Protocol and the Paris Agreement, Türkiye has committed to promoting low-carbon energy production while maintaining economic growth. EPC applications offer a financial mechanism fully aligned with these commitments, enabling renewable energy deployment in public buildings at scale. In conclusion, this case study shows that EPCs can serve as not only a financial tool but also a technical and environmental strategy for advancing renewable energy initiatives in public institutions. For future projects, it is recommended that integrated forecasting models supported by multi-dimensional analyses of meteorological data and optimization algorithms be adopted. Additionally, national energy policies could benefit from incorporating data-driven decision-support tools to ensure sustainability and efficiency. However, this study is not free from limitations. The use of a multiple linear regression model may not fully capture complex, nonlinear interactions between environmental and technical variables influencing solar energy production. Moreover, the analysis was limited to a single case study, a solar power plant on one university campus, which constrains the generalizability of findings to other geographic locations or institutional contexts. Future studies could address these limitations by verifying the applied approach in multiple public institutions across diverse regions, expanding the model to include dynamic variables such as electricity price fluctuations, investment cost changes, and inflation trends, and conducting sensitivity analyses to better understand the influence of key parameters on model outcomes. Incorporating advanced AI-based methods could improve predictive precision and adaptability, which is crucial for developing robust performance guarantees, reducing financial risks, and scaling EPC-based renewable energy solutions in the public sector.

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