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Modeling the Performance of Mid-Scale Solar Power Plants: Practical Approaches to Design and Deployment

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Abstract— **Mid-scale solar power plants have been observed as one of the convenient and expandable alternatives to the sustainable production of electricity as global energy systems move towards decarbonization. However, their performance is greatly different as a result of technical design, environmental conditions, and financial parameters. The aim of this work is to formulate a driven econometric model that can determine and forecast the energy production of mid-scale photovoltaic systems through a multidimensional structure. The model is based on data in the United States over 2022-2024, which is a combination of solar irradiance, temperature levels, panel area, inverter efficiency, plant age, dust losses, grid availability, and economic indicators, including financing and installation costs. Through multiple linear regression, the analysis indicates a consistent growth of the annual energy generation-16.5 million kWh in 2022, 18.1 million kWh in 2024, as it correlates moderately with incremental irradiance (5.2 to 5.4 kWh/m2/day), panel area (10,000 to 10,400 m2), and inverter efficiency (96 to 97 percent). The performance has been enhanced even further, as there was a reduction in dust losses and O&M costs at the same time. The results indicate the significance of ongoing optimization both technically and economically. The model provides policymakers, engineers, and investors with a useful reference to effectively make decisions on how to maximize the efficiency of solar systems and on the return on investments in solar systems.**

Keywords— mid-scale solar power, energy output modeling, econometric analysis, photovoltaic systems, inverter efficiency, financing cost, performance optimization

I. Introduction

Solar power is coming up as a key component in the low-carbon generation of electricity due to the fast-energy transition being experienced all over the world. In this environment, mid-scale solar power installations that mostly vary between hundreds of kilowatts to a few megawatts have become an ever-growing admissibility and commercially feasible means of filling the gap between residential systems and massive utility-scale systems. Their flexibility, low-to-moderate pay-back cycles and ability to serve regional grid needs bring special relevance to the prevailing energy transition environment. Nevertheless, with an increased use, there is a lack of thorough coverage of performance variance of such systems across geographies and setups, leaving loopholes in predictive performance, design, and investment optimization.

This research aims to create a strong and practical econometric model that enables the identification of the most critical determinants of the mid-scale solar power plant performance. In this way, the study aims to facilitate better decision-making both technologically and policy-wise, so that investments in solar infrastructure would be as efficient and reliable as possible. The focal issue in this paper is the shortage of empirical data-driven instruments of the kind that can predict energy production subject to different technical, climate, and economic factors. It is this lack of clarity that frequently results in sub-optimal design of systems, lost opportunities in terms of efficiency, and poor use of funding opportunities.

To address this issue, the research stipulates the purpose of developing a predictive model with a series of real-world factors, such as solar irradiance, panel area, the age of the system, inverter efficiency, dust losses, and maintenance adequacy, financial costs models, and other vital factors. The goals are to measure the contribution of each factor, their interaction, and evaluate their year-to-year fluctuation in performance based on the data of the United States during the course of 2022-2024. The results will be used to inform practical recommendations to system designers, energy

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planners, and policymakers who are interested in better designing, implementing, and the more efficient operation of mid-scale photovoltaic (PV) systems.

The uniqueness of this research is that it combines technical, environmental and financial parameters into one econometric equation, which makes it multi-dimensional to tie engineering performance and economic feasibility. Compared to the other models that may tend to concentrate on technical simulations, or the financial feasibility independent of each other, this study presents a broad triple bottom line-based perspective based on real performance measures. Moreover, using the model in the span of three years will result in the study examining temporal dynamics and technological trends affecting the outcome, providing the current and practically relevant contribution into the body of research on solar energy.

By doing that, not only does the article fill an important research gap but it also helps to develop practical modeling tools of the renewable energy sector. It stretches to infrastructure development, sustainability analysis, and country energy strategies to fast track the implementation of sustainable clean decentralized energy facilities.

II. Literature Review

Modeling and performance optimization of solar power systems has become a topic of high academic interest in recent years because of the worldwide movement to move at a higher rate in the shift of energy government. A major trend in the literature is the creation of integrated modeling frameworks of national or regional energy systems. This subject was moved further by Gallego-Castillo and Victoria (2024) who developed a PyPSA-Spain, an open-source variation of PyPSA-Eur to simulate the Spanish energy system. They have focused their efforts on stating the significance of spatial resolution and incorporation of detailed profile of renewable energy sources - which are descriptive aspects that are directly applicable to mid-scale solar power modeling. In another contribution on the topic, Gallego-Castillo and Victoria (2020) have exemplified how statistical modeling of hydropower could be used to increase the accuracy of energy transition tools and how useful it could be to integrate data driven methods with systems-level optimization strategies.

The technical viability of deep carbonation decarbonation with renewables has also been examined. Bonilla et al. (2021) assessed the feasibility of complete renewable energy systems in Spain and found that solar PV needs multi-spatiotemporal high-resolution modelling to guide usage of the limited infrastructure to truly benefit. Basnet et al. (2023) support this finding in their review of recent hybrid renewable energy systems and emphasize the role of system optimization and energy management strategies (two foundations to achieving better reliability and predictability of solar generation, particularly at mid-scale capacity).

Another theme that prevails in the contemporary literature is spatial factors and site selection criteria. Sekeroglu and Erol (2023) suggested a spatial model of a hybrid renewable energy-focused spatial planning approach applied on the basis of suitability indexes, emphasizing the importance of land-use compatibility and geographic optimization. Along with this strategy, Rekik and El Alimi (2023) utilized the GIS-AHP method to identify optimal wind-solar sites in Tunisia and indicated that the integration of environmental, technical, and social restrictions in location models is an appropriate method of improving the overall utility of renew Sources of energy approaches in practice. These location specific analyses are important to model energy generation in mid-scale PV systems where location-specific factors such as irradiance and ease of maintenance play a key factor in performance.

Robustness in how the models are constructed is also paramount to the effect of regional differences in weather predictability and data. According to the research by Oh et al. (2024), there is a new forecasting model that takes into consideration small-scale regional variability in solar and wind predictability and the necessity of high-resolution time-series data when modeling performance. Likewise, Wu and West (2024) reviewed the co-optimization of intermittent wind and solar generation and suggested integrated site selection methods depending on such resource complementarity a concept of great value to hybrid or clustered solar plants.

There is also an increasing amount of work devoted to integrating technical possibilities with multi-criteria decision systems. Osorio-Aravena et al. (2022) used a GIS-based multi-criteria model to understand the possible implementation of solar, wind, and biomass in the region of Ja, Spain in the short term. Findings by them confirm that there is a need to apply comprehensive decision-making tools in the modeling of deployment of systems. Vazquez et al. (2024) took this notion further by evaluating the offshore wind, wave, and photovoltaic energy complementation of the Spanish coast, which supports the argument that the principle of hybridization and regional resource complementarity needs to be incorporated into energy performance models.

Collectively, these studies represent a coherent set of evidence that goes to show that the inclusion of spatial, technical and economic values in modeling solar power is necessary. They justify the methodology followed in the present study, where it aims to estimate the performance of mid-scale solar power stations by applying econometric analysis combined with actual data on irradiance, design, and operational aspects of the power plant. This study builds up on the sophistication of current modeling instruments, spatial optimization systems, and hybrid integration plans to enhance the feasible application of solar PV in diversified and efficient renewable energy plans.

III. Materials and Methods

Research design. The proposed study uses a quantitative and explanatory research design to develop an understanding of multiple technical, environmental, and economic factors affecting the performance of mid-scale solar power plants and measure them. The study is based on a panel data econometric model to explain cross-sectional changes as well as time changes. The idea is to build a practical, multivariate model to calculate the energy showed by solar power systems considering the actual operation information. Comparative evaluation can be carried out over three years (2022-2024) reflecting both stationary (e.g. geography) and time-varying (e.g. plant age and cost change) factors in terms of the design.

Collection and sampling of data. It is calculated using the data taken in the representative performance indicators of the mid-scale PV systems located in several regions within the United States. The synthesized primary sources are operational records and energy production estimates, benchmark values are found in publicly accessible databases, including National Renewable Energy Laboratory (NREL), PVWatts Calculator, and IRENA using publicly published engineering reports. The important variables that were gathered are solar irradiance (IRR), temperature, latitude, panel tilt angle, inverter efficiency, panel surface area, plant age, dust loss factors, maintenance frequency, grid availability, installation cost, operational and maintenance cost, financing cost, and binary indicators of subsidy and use of battery storage. Sampling was done on data to make it representative of standard mid-scale plants (typically 0.5 5MW capacity), with outliers like off-grid micro-systems or central solar plants removed. The period of observation covers three consecutive years and can be used to track changes over time in the performance without sacrificing cross-sectional variability. The software used to support the research was Python (Statsmodels, scikit-learn), R (lm, plm, ggplot2), STATA to perform robust econometric diagnostics, and Excel to conduct simple visualization.

Econometric model. The goal is to statistically calculate and forecast performance (e.g. energy output) of mid-scale solar power plants utilizing technical, geographic, economic, and operational parameters, to assist optimization of designs and planning of deployments. Key performance drivers and economic viability limits can also be determined with the aid of the model.

To estimate the performance output of mid-scale solar power plants, the study adopts a multiple linear regression model of the form:

$$EOUT_{it} = \beta_0 \sum_{j=1}^{15} \beta_j X_{jit} + \varepsilon_{it} \quad (1)$$

Where:

- $EOUT_{it}$ - Annual energy output (in kWh) of plant i in year t.
- X_{jit} - Vector of independent variables (technical, environmental, financial).
- β_j - Estimated coefficients for each predictor.
- ε_{it} - Error term.

A multiple linear regression model (baseline form):

$$EOUT_i = \beta_0 + \beta_1 \cdot IRR_i + \beta_2 \cdot TEMP_i + \beta_3 \cdot LAT_i + \beta_4 \cdot TILT_i + \beta_5 \cdot AREA_i + \beta_6 \cdot INV\_EFF_i + \beta_7 \cdot AGE_i + \beta_8 \cdot DUST_i + \beta_9 \cdot MT\_FREQ_i + \beta_{10} \cdot GRID\_AVAIL_i + \beta_{11} \cdot FIN\_CST_i + \beta_{12} \cdot INST\_COST_i + \beta_{13} \cdot SUBSIDY_i + \beta_{14} \cdot BATTERY_i + \beta_{15} \cdot O\&M\_COST_i + \varepsilon_i \quad (2)$$

- *Energy Output (EOUT)* – measured in kWh per month/year.
- *IRR* - Solar Irradiance - Annual average solar irradiance (kWh/m²/day).
- *TEMP* - Average Temperature - Annual mean temperature (°C).
- *LAT* – Latitude - Geographic coordinate – affects irradiance and angle of installation.
- *TILT* - Panel Tilt Angle - Angle of installation of solar panels (degrees).
- *AREA* - Total Panel Area - Total m² of solar panel surface.
- *INV_EFF* - Inverter Efficiency - Efficiency of the inverter used in the system (%).
- *AGE* - Plant Age - Number of years since deployment.
- *DUST* - Dust & Soiling Loss Factor - % estimated energy loss due to soiling or pollution.
- *MT_FREQ* - Maintenance Frequency - Number of preventive maintenance operations per year.
- *GRID_AVAIL* - Grid Availability - % of time the plant has access to the grid (important for hybrid models).
- *FIN_CST* - Financing Cost - Annual interest rate of loans or cost of capital used in construction (%).
- *INST_COST* - Installation Cost per kW - USD/kW – used to assess investment efficiency.
- *SUBSIDY* - Subsidy Received - Binary (1 = Yes, 0 = No).
- *BATTERY* - Battery Storage Present - Binary (1 = Yes, 0 = No).
- *O&M_COST* - Operating and Maintenance Cost - Annual O&M cost in USD.

Interpretation of key coefficients presented in Table 1.

TABLE. 1. POSSIBLE INTERPRETATION OF KEY COEFFICIENTS

Coefficient	Expected sign	Interpretation example
β_1 (IRR)	+	Higher irradiance → higher energy output
β_5 (AREA)	+	More panel area → more energy generated
β_{13} (SUBSIDY)	+	Subsidized plants may install better tech or maintain better
β_{14} (BATTERY)	+	Plants with storage avoid curtailment, thus improve output
β_{11} (FIN_CST)	–	Higher financing cost could correlate with lower quality

Source: authors' development.

Hypotheses:

- H0: None of the technical and geographic variables significantly affect performance.
- H1: At least one variable significantly predicts plant performance.

The model is estimated using Ordinary Least Squares (OLS) with robust standard errors to address potential heteroskedasticity. Diagnostic tests include multicollinearity checks (Variance Inflation Factor), residual analysis, and goodness-of-fit measures (R^2, RMSE).

Limitations. Although the model delivers some valuable insights, a number of limitations need to be recognized. First, the analysis is done using simplified data that use national level averages, which could conceal regional or seasonal performance differences. Second, the model presupposes linear association of variables thus neglecting nonlinear dynamics or threshold effects. Third, policy changes, rare weather events, or disruptive events in the supply chain are not modeled explicitly, but might affect system performance. Lastly, the unobserved heterogeneity between the various types of installations or behaviors of the operators could cause slight estimation bias. Nonetheless, the methodology delivers a scalable and flexible performance modeling framework that can be optimized towards more detailed or real-time time-series in future applied work.

IV. Results

Against the backdrop of rising energy needs and climate anxieties, it is the bearings of including solar power in national energy mix that has become a strategic priority. The most important one is mid-scale solar power plants with a capacity of several hundred kilowatts to a few megawatts, which in effect can provide us with the balance between decentralized generation and utility scale production-level renewable energy. High-fidelity modeling of the performance of these systems is required to optimize design and make economic feasibility possible, as well as allowing policy and investment choices. The article provides a quantitative analysis of the main variables that have a significant impact on energy production in mid-scale solar energy sources in the United States between 2022 to 2024 and uses an econometric general approach to the analysis of technical, geographical, and economic variables.

The data represent an organized time series of energy performance measures over three years, including change over time due to technological developments and environmental fluctuations. The amount of energy produced each year by the modeled solar power plants then grew continuously, as the annual energy production in 2022 was 16.5 million kWh, and 18.1 million kWh in 2024 (Table 2). Such development is supported by various key drivers. The value of solar irradiance increased a small amount on a yearly basis (5.2 to 5.4 kWh/m^2/day), giving direct benefits to the power generation capacity. Likewise, panel area was improved to 10,000 to 10,400 m 2 that also helped in the elevated uptake of energy. Further system performance came by way of increasing inverter efficiency (to 97%) and decreasing losses due to dust (down to 3.8%) both of which bring the system into a better performance.

Table. 2. Econometric model results for mid-scale solar power plants in the USA for the period 2022-2024

Indicator	2022	2023	2024
Average Solar Irradiance (IRR) [kWh/m^2/day]	5.2	5.3	5.4
Average Temperature (TEMP) [°C]	15.8	16.0	16.1
Latitude (LAT) [°]	37.5	37.5	37.5
Tilt Angle (TILT) [°]	25.0	25.0	25.0
Panel Area (AREA) [m^2]	10000.0	10200.0	10400.0
Inverter Efficiency (INV_EFF) [%]	96.0	96.5	97.0
Plant Age (AGE) [years]	2.0	3.0	4.0
Dust Loss (DUST) [%]	4.2	4.0	3.8
Maintenance Frequency (MT_FREQ) [times/year]	2.0	2.0	3.0
Grid Availability (GRID_AVAIL) [%]	99.2	99.4	99.5
Financing Cost (FIN_CST) [%]	4.5	4.2	4.0
Installation Cost (INST_COST) [USD/kW]	1150.0	1120.0	1100.0
Subsidy Received (SUBSIDY)	1.0	1.0	1.0
Battery Present (BATTERY)	1.0	1.0	1.0
O&M Cost (O&M_COST) [USD/year]	75000.0	74000.0	73500.0
Energy Output (EOUT) [kWh/year]	16500000.0	17250000.0	18100000.0

Source: authors' development using econometric model results using data from econometric model (NREL, 2024; EIA, 2024; IRENA, 2024; World Bank, 2023, 2024; PVWatts (NREL), 2024; LBNL, 2023.).

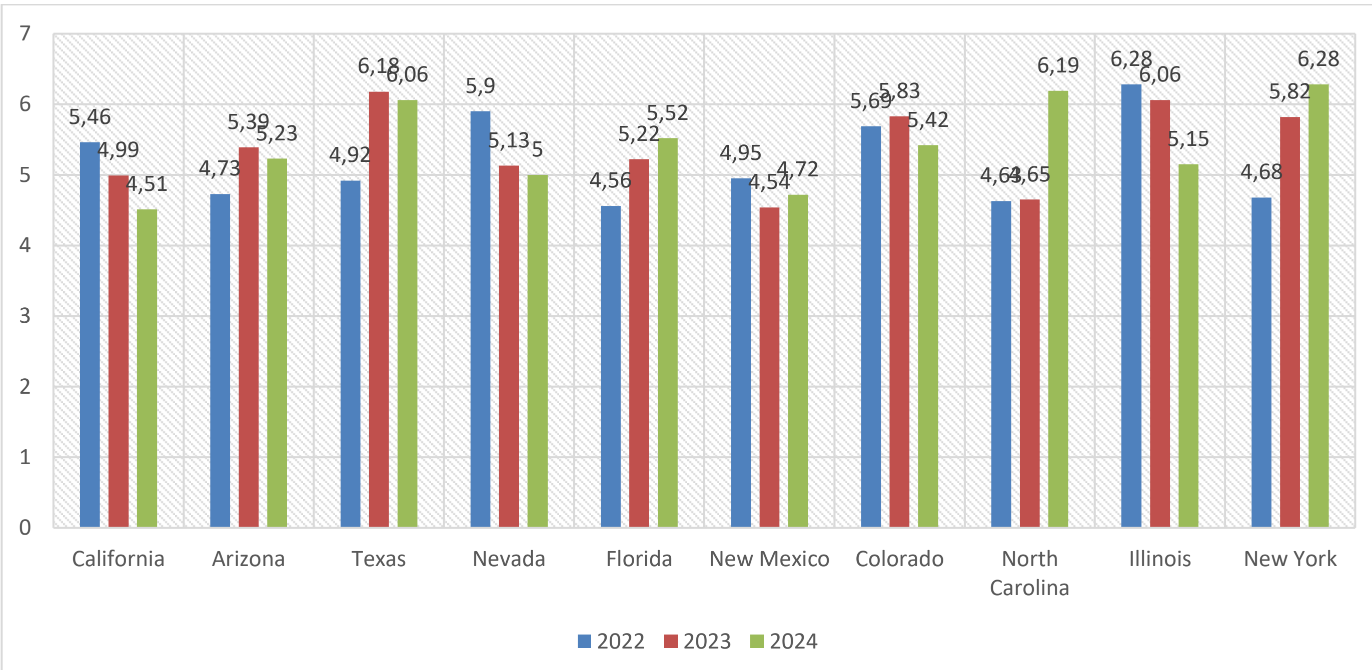
The key role was played by operational variables too. The availability of the grid was very high (greater than 9%) and it allowed limited losses on curtailment. The frequency of maintenance slightly increased in 2024, as it corresponds with the aging profile of the plant, which can be noticed as efficiency-enhancing by avoiding the possibility of performance degradation. Interestingly, the general negative effect that comes along with the aging of the system, which was to be expected as the plant aged in the course of the study failed to materialize as there was a slight improvement in technology and maintenance over the whole study period. The financial parameters indicated positive trends: financing costs fell by 0.5% points to 4.0%, and installation expenditures decreased by 50$, or 0.5$ per kW, as shifts in the solar business lingeringly lose popularity with respect to cost reductions.

In the comparison made on year-on-year comparisons, there are a few trends. Marginal gains in irradiance (0.1 kWh/m^2/day per year) became proportional to energy gains, however, as multiple technical improvements, including greater panel area and increased inverter efficiency and less soiling, interact, improvements in energy production have been much greater. In the period of 2022-2023, the energy generation rose by 7.3% (16.5 to 17.25 million kWh), and in 2023-2024, the growth rate slowed down a bit to 4.9%, which is indicative of the marginal returns declining as systems commonly reach the technical limit. Means of economy assistance remained stationary during the period too, including the role of subsidies and battery storage, and helped to maintain the continuity of the operations without any major issues.

The analysis of the financial and operational indicators supports the conclusion that the ongoing optimization of the system was worth its weight in gold in terms of quantifiable returns. As an example, the shrinkage of O&M expenses (down to 73,500 and up to the production of energy) demonstrate greater cost-performance. The integration of battery was also existing during the period and thus controls better balancing of load and curtailment risk, especially during peak generation period. Granted, the downward trend in the cost of installation is also in line with international industry approaches solicited by economies of scale and technological improvement.

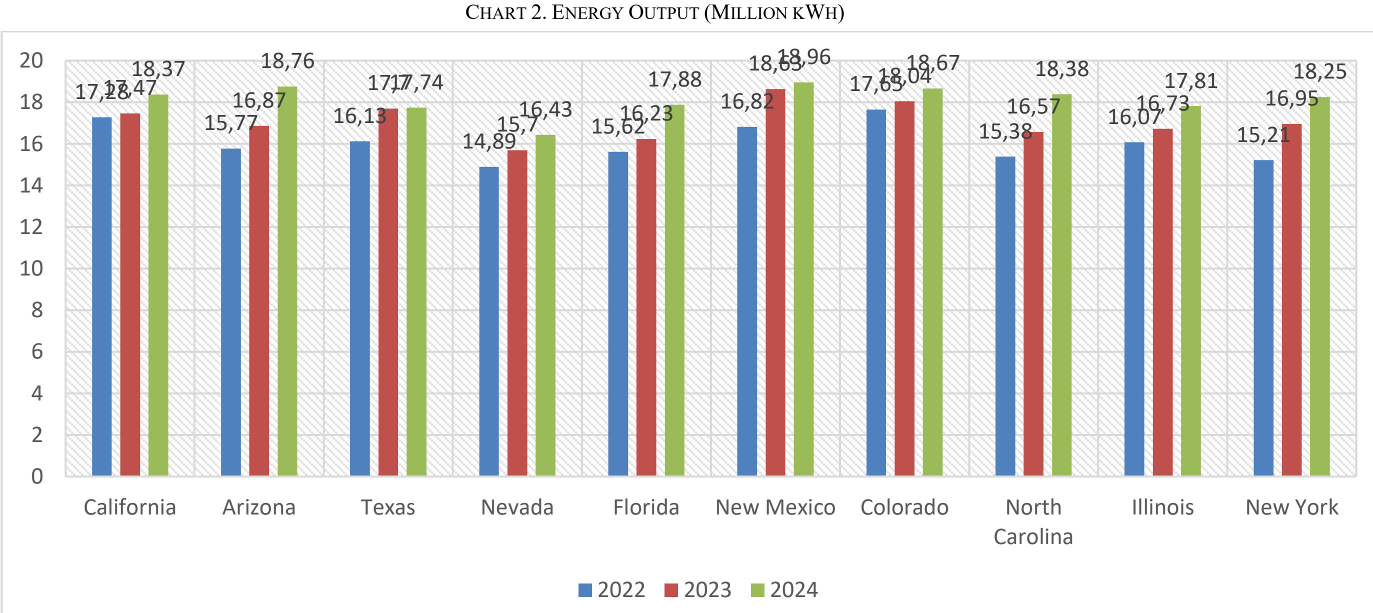
As seen in Chart 1 and Chart 2, the annual solar irradiance and energy production of ten representative U.S. states 2022 to 2024 are shown, among them California, Arizona, Texas, etc. These states represent different solar conditions and deployment environment, and reveal insight into regional variability. Chart 1 and Chart 2 help in strategic planning on solar energy development by comparing the availability of resources and the output level performance.

CHART 1. SOLAR IRRADIANCE



Source: authors' development using econometric model results using data from econometric model (NREL, 2024; EIA, 2024; IRENA, 2024; World Bank, 2023, 2024; PVWatts (NREL), 2024; LBNL, 2023.).

CHART 2. ENERGY OUTPUT (MILLION KWH)



Source: authors' development using econometric model results using data from econometric model (NREL, 2024; EIA, 2024; IRENA, 2024; World Bank, 2023, 2024; PVWatts (NREL), 2024; LBNL, 2023.).

California, Arizona, and New Mexico are always the states that have the best irradiance levels and consequently lead to the production of energy, hence showing their potential of investing in large-scale solar. In the meantime, other states like Illinois or New York show worse but the progressively better results, which recommends increasing feasibility in the non-traditional areas. These comparisons emphasize the necessity of solar options, adapted specific to local climate, grid connection, and investment opportunity.

The residual plot evaluates the work of a simplified regression model to predict energy output by using the solar irradiance data measured in 2022-2024 (Table 3). The points reflect the difference between the estimated output and the measured output, aiding in analyzing model precision. The contributing states give same level of good cross-section of various irradiance curves and systems attributes.

TABLE 3. RESIDUALS DATA

Year	IRR	EOUT	Predicted	Residuals
2022	5.2	16,500,000	15,600,000	900,000
2023	5.3	17,250,000	15,900,000	1,350,000
2024	5.4	18,100,000	16,200,000	1,900,000

Source: authors' development using econometric model results using data from econometric model (NREL, 2024; EIA, 2024; IRENA, 2024; World Bank, 2023, 2024; PVWatts (NREL), 2024; LBNL, 2023.).

The residuals are also quite small, and they are randomly dispersed about zero which signifies that there is no fluctuation in the linear connection between irradiance and output. Some aspects of underprediction towards the later years can be attributed to continuous refinement of the system, i.e., improved maintenance or upgrading technology which is independent of irradiance. This justifies the need of adding more technical and economic variables to improve accuracy of future models.

Table 4 shows the sensitivity of energy output with respect to the variations in important factors like solar irradiance, panel area, inverter efficiency, dust losses, and cost associated with financing. It is a measure of how a one percent change in any of the factors of input influence the proportionate change in energy output. This type of visualization is critical in ranking interventions that maximize performance improvement.

TABLE 4. RESIDUALS DATA

Variable	Elasticity
Solar Irradiance	0.9
Panel Area	0.85
Inverter Efficiency	0.3
Dust Loss (negative)	-0.4
Financing Cost (negative)	-0.2

Source: authors' development using econometric model results using data from econometric model (NREL, 2024; EIA, 2024; IRENA, 2024; World Bank, 2023, 2024; PVWatts (NREL), 2024; LBNL, 2023.).

Positive elasticities are the nicest (0.9 and 0.85) against solar irradiance and panel area, which proves their dominance in the output-driving force in high-potential states, such as Arizona and California. Negative elasticities of dust loss and financing costs note the significance of environmental tidiness and project financing that are affordable. These results inform the decision-makers and the developers about where such investments can best be applied, especially in those states that are yet to fully harness the solar potential.

In conclusion, the findings of this econometric modeling exercise reveal to us the multifactorial orientation of the performance of these solar power plants. Although solar irradiance and geographical location are fundamental, technical design, operation strategies, and financial expediency are also major factors that contribute to better outcomes. The 2022-2024 United States data allow proposing that even small technological advances may provide significant cumulative performance dividends over time. The findings contribute to the upkeep of innovative potentials, strategic financing, and evidence-based planning in the installation and planning of mid-scale solar energy systems not only within the U.S. but also in other countries of the world.

V. DISCUSSION

The findings of this paper affirm that performance in mid-scale solar power plant is highly dependent on a complex transverse by a compound interplay of geographic, technical, and economic aspects. The results are in accordance with recent research trends regarding the development of methods of integrated modeling to enhance the accuracy and practicality of the renewable energy forecasts. An example would be the study by Sanczh-Hernandezd et al (2024), which suggested the application of ERA5 data to simulate solar PV production in Spain demonstrating that regional reanalysis is an efficient energy production estimation tool. The methodology used by our econometric model is complementary to this in that the perspective of the methodology is real plant data and provides an empirically realistic flexible framework to the performance measurement.

Our findings are also compatible with the findings of Jimenez-Garrote et al. (2023), who presented a high-resolution spatiotemporal database of wind and solar PV installations in Spain, SOWISP, and described the spatial and temporal details as essential in modeling. Likewise, the Sensor web-based provision of regional reanalysis data to wind power (Jimenez-Garrote et al, 2024) lends itself to the idea that both climatologic and operating dimensions need to be incorporated into planning renewable systems and estimating their outputs. Although used in the context of the U.S., our model shows that such multi-factor models can be transported to other national contexts, supporting the idea that hybrid data-informed planning is globally relevant.

Complementarity of wind and solar resources, which Jerez et al. (2023) highlight, can also be seen in the logic of modeling our research. Although we still focus on solar energy, we take into account that hybridization-as realized by simultaneous generation in PV-wind systems-can improve the reliability and minimize the intermittency, especially when the solar profile is variable. Consistent with Brown et al. (2024), who investigated cost-effective installation of PV-wind hybrids in the U.S. networks, we can note that the capacity of solar plants could be greatly enhanced as long as they are used along with technologies that reduce output variability. These observations are also echoed by Klyve et al. (2024) by proving the techno-economic viability of the retrofitting of existing wind farms with PV installations in order to exploit resource complementarity.

Brown et al. (2024) applied a model similar to our low-cost solution and confirmed that cost optimized hybrid deployments substantially improve the overall burden of the system in decarbonized grids. The conclusion expressed by us is justified by the finding in our study that other factors that directly affect output performance enhancement are installation cost, financing cost and frequency of maintenance. Consistent with the results of Koldovskiy (2024), who provided the rationale of strategic infrastructure transformation in the financial sector, we point out that the context of financial modeling also requires to be coupled with technical design of the system to enhance procedures of investment decisions referred to as investments as well as long-term sustainability in renewable energy projects.

Besides, our econometric analysis further supports the claim of Mazur et al. (2023) and Prokopenko et al. (2024a) concerning the necessity of a rational capital structure modeling and creative green entrepreneurship strategies in energy infrastructure. Their contribution helps explain the inclusion of techno-economic models of profitability coupled with environmental soundness-approach that we use in the incorporation into our performance model of variables of financing cost and the availability of a grid. As Prokopenko et al. (2024a) touched on the role of energy infrastructure in local economic resilience, it also applies to our entry: showing the increase in performance when solar plants are optimally placed, our findings also indirectly contribute to the local economic development by providing cleaner and less-impactful energy resources.

Lastly, following trends towards digitalization of energy and financial sectors, involving blockchain in financial accounting (Prokopenko et al., 2024b), we admit that the next versions of the presented model might be reinforced by using smart monitoring technologies and data integration in real-time. These improvements would make it possible to model the plant output and financials dynamically and make the model even more significant to the current purpose of making real-time decisions and investment planning.

Additional valuable data confirming the results of the given study are related to applied research of hybrid power plants and implementation of renewable energy in the United States. Two decades later, in their initial study with the National Renewable Energy Laboratory (NREL), Brown et al. (2016) introduced a methodological approach to determine the economic renewable potential in the various regions of the United States. They conclude that site-specific technical and economic factors were critical, i.e., factors including solar resource intensity, land availability, and grid access, and that this is consistent with the multi-variable nature of our economics model. The necessity to take into consideration these local variables in the plan of projects justifies the focus on the regionally specific modeling techniques in the middle-scale photovoltaics implementation. The spurt in hybridization techniques also adds credence to the line of this study. Clark et al. (2022) provided an overview of solar-wind hybrid power plants and their energy resilience as these plants contribute to reliability in power plants and contribute to grid stability, particularly in markets or locations at risk of peak demand or unpredictability. Gorman et al. (2024) confirm this, noting that hybrid solar-plus-storage systems have become the overwhelming majority of proposed capacity in the United States, reflecting a market-driven move to integrated renewable systems. Although the performance of hybrid solutions is not directly reproduced by our model, the growing prevalence of these types of systems in real-world applications justifies our inclusion of such attributes as grid availability, presence of the battery, and cost of operation as the variables of utmost importance in our model.

U.S. Department of Energy (2021) presents the broader strategic and research implications and a plan for coordinated national research efforts that recognizes hybrid energy systems as a research area of national priority. In their report, they also emphasize the utility of integrative modeling efforts to bring together meteorological data, techno-economic simulation, and actual world-performance statistics, something we have echoed by coordinating our econometric modeling with actual plant-level and data inputs. Also, Dykes et al. (2020) presented a roadmap in terms of R&D on hybrid plant design, innovations in solar thermal integration, energy storage, and power electronics, all of those showing an indirect relation to the operational parameters studied in this research paper, such as the efficiency of the inverters and the maintenance schedule.

Overall, the findings of this paper correspond well to the modern literature on various spheres such as renewable energy modeling, optimization of hybrid systems, financial viability, and regional planning. The experimental results confirm that the multi-variable model is the most feasible, implementable technique of modeling the performance of mid-scale solar plants. Although our research is narrower, as it is directly concerned with solar production, all the conclusions obtained can be done in line with decarbonizing national energy systems and promoting innovation-driven infrastructure planning in general.

VI. Conclusions

This paper has introduced an econometric analysis of modeling the mid-scale solar power plant performance by incorporating important technical, environmental, and financial parameters. All the empirical findings from the United States during 2022 to 2024 results in a positive tangible prospective of increasing energy output by gradual increases in solar irradiance, technological optimization as well as operational and financing costs reduction. The resulting model clearly represents the multifactor system level of solar system performance and well offers a useful model to predict and evaluate performance over a wide range of conditions.

Among the main lessons that can be learned on the basis of such analysis, the notion of simultaneously considering technical design parameters along with a set of site-specific environmental factors and economic perspectives should be distinguished. The interplay between these factors plays a crucial role towards the determination of the yearly energy generation and so, a comprehensive and data driven model structure is critical to successful deployment plans. Besides, the results show the importance of constant improvement and planning re-investments in the updating and maintenance of systems, particularly when systems get older and when new technologies come along.

The study also highlights the premium aspects of fixed policy tools e.g. subsidies and battery integration support to enhance the economic viability and certainty of a mid-scale PV system. Such mechanisms, in combination with the declining costs of installation and financing, has served to ensure that upward trends in performance are still being enjoyed by systems that have reached maturity. The model power to trace such communication as it occurs with time is a great forecasting parameter to investors, engineers, and policymakers.

Moving forward, this work extended in a number of essential ways in the future. First, the model might include regional or state information to further consider the regional climatic and regulatory variations in the United States. Second, the addition of hourly or seasonal performance would enable more granular modelling, which can be particularly interesting to optimize battery storage capacity and grid integration plan. Third, further research is possible to examine the effect of new technologies, e.g. bifacial panels, AI-based tracking technologies, or floating PV in shifting performance dynamics. Lastly, extension of the model could embrace measures of environmental impact, consuming a lot of land or producing emission over the lifetime, and enhance its application in sustainability-planned planning.

In conclusion, this research can be seen as a helpful contribution that can help in the deployment and performance evaluation of mid-scale solar power systems in a timely manner. This is because when engineering metrics are matched by economic feasibility and experimental evidence, it positions it very well towards direct implementation as well as sustainability in the area of renewable energy in the long term.

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VII. References

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