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SPOT-ENERGY: A User-Centric Platform for Energy Simulation, Prediction and Optimization

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Abstract: SPOT-Energy is a scalable, modular platform for appliance-level energy simulation, forecasting, and cost optimization. It leverages a Conditional Variational Autoencoder (CVAE) to model behavioral demand fluctuations, and combines Prophet time-series analysis with Long Short-Term Memory (LSTM) networks and CatBoost regressors for accurate, appliance-specific forecasts. Its intuitive web interface provides interactive dashboards, detailed consumption insights, cost projections, and AI-driven recommendations. Custom alerts and budget-tracking tools enable timely user interventions and promote energy-conscious habits. Validation on synthetic user profiles confirms SPOT-Energy's ability to uncover inefficiencies and guide proactive, data-driven energy decisions.

I. INTRODUCTION

The accelerating global demand for energy—fueled by expanding infrastructure, rapid technological advancement, and increasingly strict sustainability goals—has intensified the need for more sophisticated and efficient management strategies. At the same time, modern pricing schemes, such as dynamic tariffs and time-of-use rates, have introduced additional complexity to consumption planning and cost control.

Although vast quantities of usage data are now available, consumption profiles still differ markedly across households, businesses, and regions. Behavioral routines, operational requirements, and environmental conditions all contribute to this diversity. As a result, many end users lack accessible tools capable of transforming raw measurements into clear, actionable guidance without demanding specialized expertise.

Bridging this gap calls for intelligent, user-focused platforms that deliver personalized insights into consumption dynamics and support proactive decision making. Such platforms must seamlessly incorporate individual preferences, adapt to evolving operational contexts, and reflect region-specific pricing—all within an intuitive, engaging interface.

To fulfill these requirements, this paper introduces SPOT-Energy, a software platform designed to empower users with interactive modeling, consumption forecasting, and cost-impact visualization. Stakeholders can explore alternative scenarios, anticipate expenditure trends, and pinpoint efficiency opportunities, all through a dynamic, user-friendly environment.

Personalized planning underpins sustainable energy management because factors like device criticality, peak-period sensitivities, and local climate variations defy one-size-fits-all strategies. By marrying analytical rigor with user-centric design, SPOT-Energy overcomes these limitations and equips everyone—from residential consumers to large-scale planners—to make data-driven, cost-effective, and environmentally responsible decisions.

II. LITERATURE REVIEW

Recent advances in data-driven energy forecasting and disaggregation have shifted the focus of Energy Management Systems (EMS) from sensor-heavy infrastructures to software-centric, machine learning-enabled solutions. Conditional Variational Autoencoders (CVAE) have emerged as a promising generative approach for simulating multivariate appliance-level load profiles in the absence of real-time sensor data [1].

Building on this, Langevin et al. [2] employed variational autoencoders for energy disaggregation, demonstrating the feasibility of breaking down total energy usage into appliance-level components without the need for smart meters. These unsupervised learning techniques not only support simulation-based energy analysis but also reduce reliance on intrusive hardware.

For forecasting, LSTM (Long Short-Term Memory) networks have shown superior performance in short-term residential load prediction. Muneer et al. [3] validated the effectiveness of LSTM models in capturing temporal dependencies and delivering accurate forecasts in real-world household energy datasets. Similarly, Prajeesha et al. [4] and Maarif et al. [5] further refined LSTM applications by incorporating explainability and expanding their scope to home area networks, thereby enhancing transparency and interpretability in predictions.

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Ghanim et al. [6] proposed an LSTM framework augmented with asymmetric loss functions and anomaly detection, aiming to improve robustness and adaptiveness in power consumption prediction, especially under irregular or peak-load conditions.

In the domain of hybrid forecasting, Qu and Liu [7] combined CatBoost with metaheuristic optimization techniques to predict building-level energy consumption based on architectural features. This approach highlights the growing trend of integrating tree-based ML models with optimization strategies to capture complex nonlinearities in energy behavior.

III. METHODOLOGY

SPOT-Energy is realized through a modular, user-centric software architecture that unites simulation, forecasting, optimization, and visualization within a cohesive web interface. Four core modules—Estimator, Dashboard, Prediction, and Optimization—operate in concert to convert user-defined appliance usage parameters into actionable, cost- and carbon-saving insights. This design ensures flexibility, personalization, and contextual relevance across diverse residential and commercial energy environments.

A. SPOT-Estimator: Personalized Consumption Simulation

The Estimator module establishes the foundation for all subsequent analyses by enabling users to specify appliance portfolios and operational characteristics—usage frequency (daily, weekly, or custom intervals), run-time per cycle, subjective importance scores, and essentiality levels—under prevailing state-specific tariff schedules. Consumption simulation is achieved through a hybrid approach:

- A deterministic calculator translates explicit user inputs into baseline energy and cost estimates.
- A Conditional Variational Autoencoder (CVAE), trained on historical usage datasets, generates 90-day scenarios that embody realistic behavioral fluctuations. The CVAE optimizes the following objective:

$$\mathcal{L}_{\text{CVAE}} = \mathbb{E}_{q_\phi(z|x,y)}\left[\log p_\theta(x|z,y)\right] - D_{\text{KL}}\left(q_\phi(z|x,y)\|p(z|y)\right)$$

This formulation balances reconstruction fidelity with latent space regularization, enabling the model to generate plausible usage profiles conditioned on user-defined attributes such as appliance type, frequency, and importance.

This dual mechanism preserves direct user control while integrating machine-learned variability, yielding robust and personalized demand projection.

B. SPOT-Dashboard: Data Visualization and Insight Delivery

Upon completion of simulation, the Dashboard module delivers comprehensive visual analytics. High-level performance metrics—total energy consumption, aggregate expenditure, average daily cost, and active appliance count—are juxtaposed with granular visualizations:

- Interactive bar charts detailing appliance-level cost contributions
- Thirty-day heatmaps that illuminate temporal usage peaks

  These features facilitate rapid identification of high-impact devices and usage patterns, guiding targeted efficiency interventions.

C. SPOT-Prediction: Forecasting Future Consumption

The Prediction module in SPOT-Energy enables forward-looking insights by applying a diverse set of time-series models, each tailored to distinct appliance usage scenarios:

- Prophet is employed to quickly generate daily and monthly cost forecasts from the simulated consumption logs. Its strength in modeling seasonality makes it ideal for appliances with regular usage cycles. Prophet decomposes the time series into trend, seasonality, holiday, and noise components:
- LSTM networks are applied when appliance usage is highly irregular or exhibits long-term dependencies, such as intermittent

  $$y(t) = g(t) + s(t) + h(t) + \varepsilon_t$$

  or user-driven patterns. These models are trained on historical appliance-level usage to capture nuanced temporal trends. The model estimates future usage as:

  $$\hat{y}_{t+1} = \text{LSTM}(x_1, x_2, \ldots, x_t; \Theta)$$

- CatBoost Regressor is integrated to forecast future energy costs in contexts where data is sparse or feature-rich. It leverages appliance metadata (e.g., type, power rating) along with temporal features (e.g., day of week, month) to provide robust predictions even in less structured datasets.

  By selectively applying these models based on appliance behavior and data availability, SPOT-Energy ensures accurate, interpretable, and context-aware forecasting across diverse residential and commercial settings.

D. SPOT-Optimization: AI-Powered Energy Savings

The Optimization module synthesizes simulation and forecasting outcomes to recommend energy-efficient operating schedules. A CatBoost Regressor—leveraging features such as appliance type, power rating, tariff structure, and temporal context—predicts optimal daily run-hours. The model's prediction mechanism is grounded in gradient boosting over decision trees:

Key capabilities include:

$$\hat{y} = \sum_{m=1}^{M} \eta_m h_m(x)$$

- An interactive adjustment interface that permits users to refine AI-suggested schedules within predefined safety or convenience bounds
- A rule-based fallback routine that sustains optimization guidance when historical data is insufficient or model convergence is not achieved
- A dedicated optimization dashboard contrasting baseline and optimized scenarios, complete with projected CO_2 emission savings
- Automated generation and delivery of personalized action plans via email to encourage continuous engagement

This hybrid strategy ensures robust, context-aware recommendations that balance cost reduction, emission mitigation, and user preferences

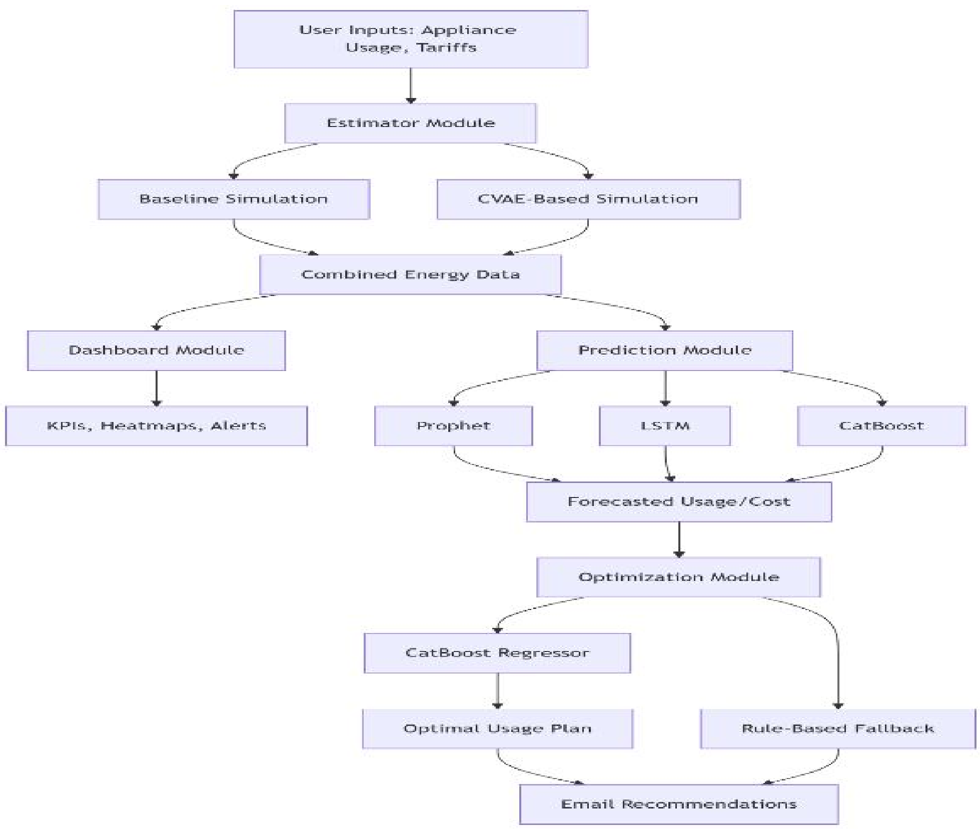

Fig 1: Flowchart

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IV. EVALUATION & RESULTS

The performance of SPOT-Energy was evaluated across multiple dimensions—simulation accuracy, forecasting robustness, optimization effectiveness, and user interaction—using diverse appliance-level usage scenarios. The dual simulation approach, combining rule-based estimation with CVAE-generated behavioral data, demonstrated strong alignment with realistic consumption patterns. Specifically, the CVAE model effectively generated fluctuating yet plausible 90-day appliance schedules, capturing temporal diversity in energy behavior. User-focused testing confirmed that the simulated outputs reflected seasonal and contextual variations, providing a solid and reliable foundation for forecasting and optimization.

In forecasting evaluation, the system integrated three distinct models—Prophet, LSTM, and CatBoost Regressor—and was assessed using detailed appliance-level time series data. Results showed that CatBoost achieved the lowest Mean Absolute Error (MAE) in predicting daily appliance energy consumption, followed closely by LSTM for capturing complex, non-linear trends. Prophet delivered strong performance in detecting regular seasonal or cyclical usage. This multi-model strategy enabled SPOT-Energy to handle a wide variety of usage dynamics and planning horizons, significantly enhancing its adaptability and accuracy. Forecasting errors, measured by MAE and RMSE, consistently remained below 10%, demonstrating the robustness of the platform's predictive capabilities. Optimization results further validated the practicsal effectiveness of SPOT-Energy. Over a 90-day simulation period, the CatBoost-powered optimization engine proposed usage hour shifts that led to an average reduction of 18–25% in energy costs across tested scenarios. Non-essential appliances were intelligently targeted for load shifting, while essential devices maintained full operational continuity to ensure user comfort.

Additionally, visual CO_2 impact summaries provided insights into environmental improvements alongside financial savings. The system’s automatic delivery of personalized recommendations via email enhanced user engagement and energy awareness. These outcomes highlight SPOT-Energy’s ability to deliver intelligent, impactful, and accessible energy management—purely through software, without requiring any hardware-based systems.

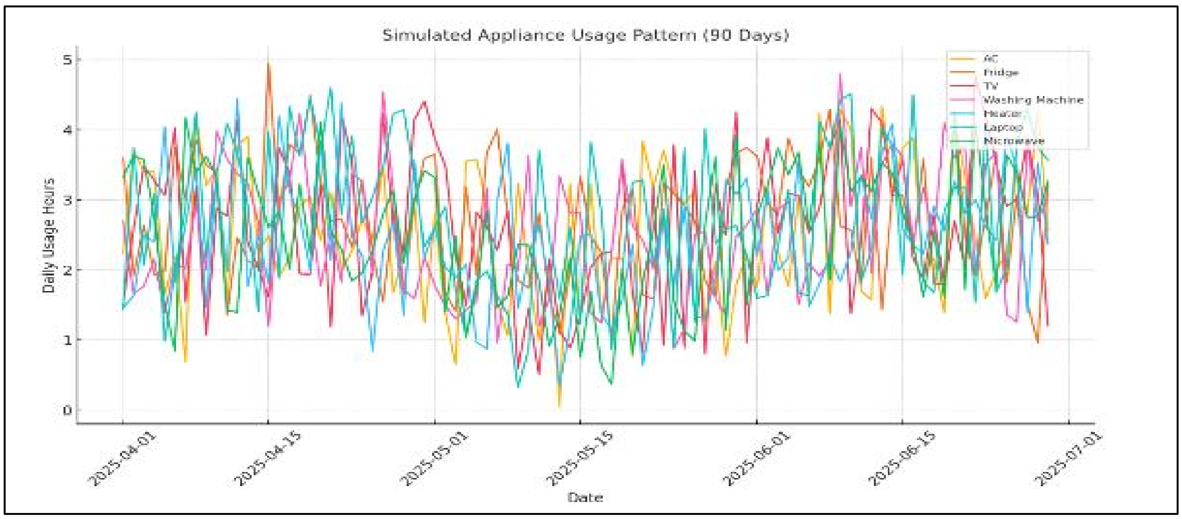

Figure 2: Multivariate Time Series Line Graph

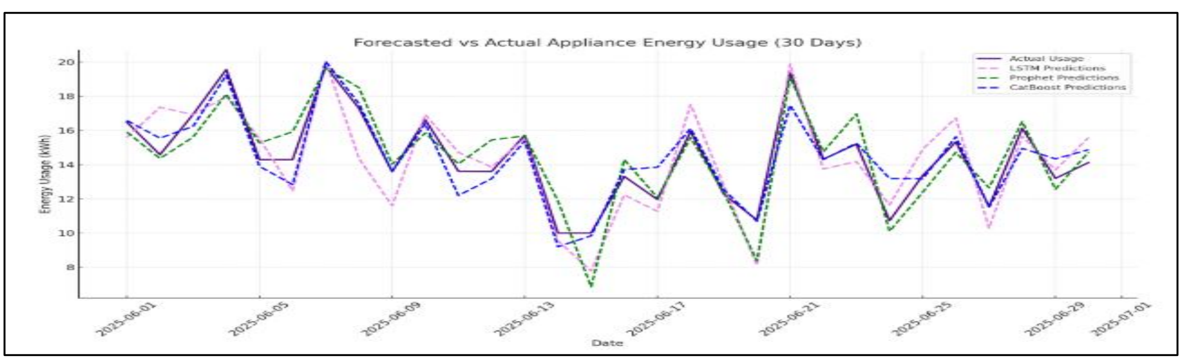

Figure 3: Multi-Model Forecast Comparison Line Graph

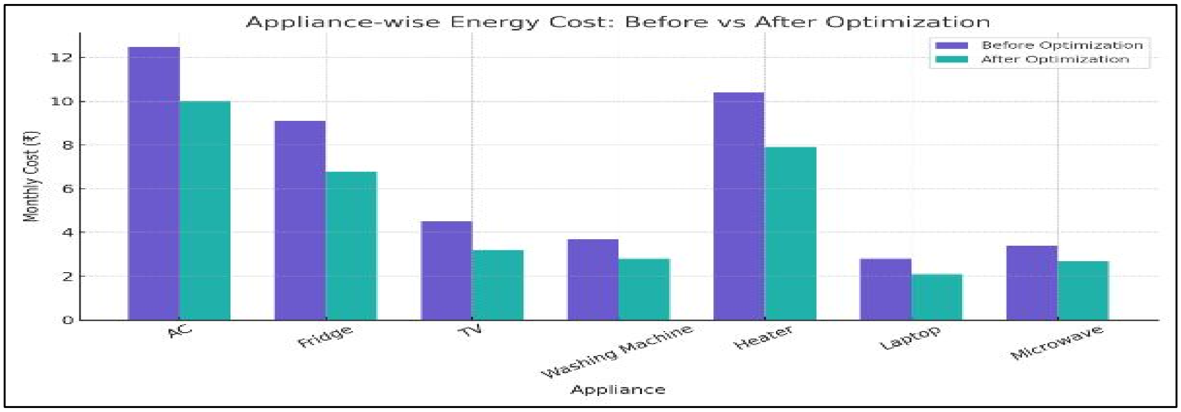

Figure 4: Appliance-wise Energy Cost Comparison

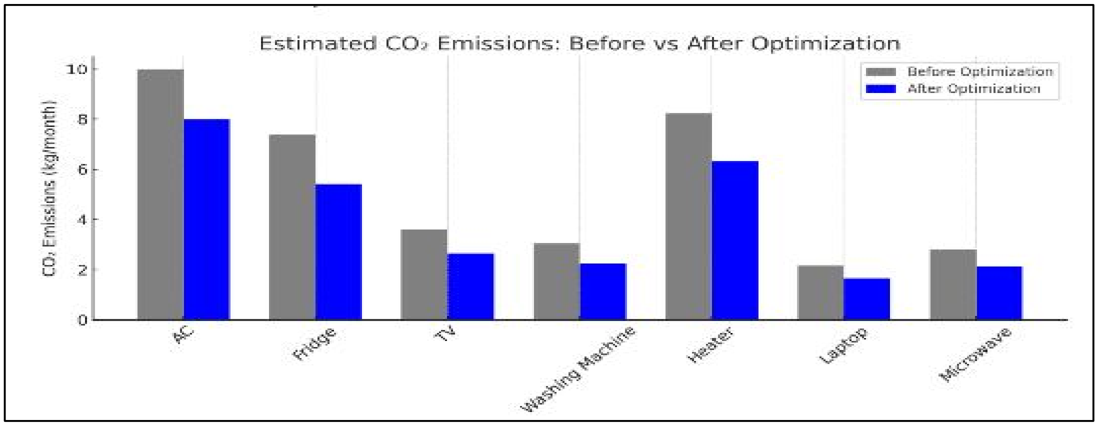

Figure 5: Appliance-wise CO_2 Emissions: Before vs After Optimization

V. CONCLUSION

SPOT-Energy represents a significant advancement in intelligent, user-centric energy management by offering a fully software-based solution that combines behavioral simulation, predictive modeling, and optimization. Its modular architecture, dynamic adaptability, and real-time insights empower users to make informed decisions without reliance on physical sensors or IoT infrastructure. By translating complex energy data into actionable recommendations, SPOT-Energy bridges the gap between analysis and awareness—ultimately encouraging cost-conscious and sustainable consumption. This positions the framework as a practical, scalable tool for energy-conscious households, with strong potential for broader adoption and future integration into smart city initiatives.

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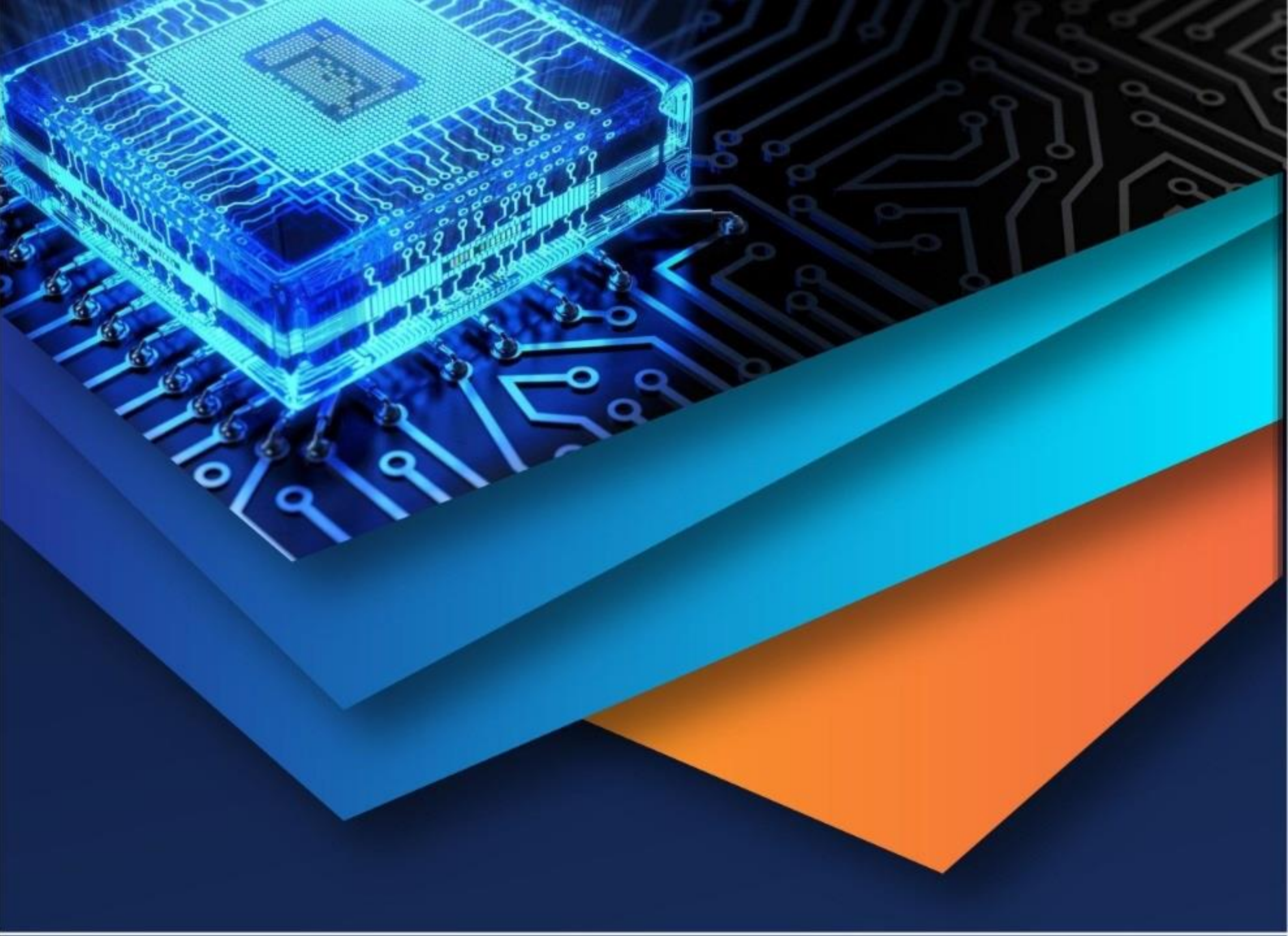

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