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A Comparative Framework For Competitive Power Markets Under Green Energy Integration

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ABSTRACT

The rapid growth in industry, urbanization, and population expansion results in an increase in world energy demand. This relies heavily on the main grid, which needs a large amount of natural resources that are depleting day by day. The use of natural resources for power generation leads to environmental pollution and poses significant long-term sustainability challenges. In response, renewable energy sources have emerged as viable alternatives due to their clean, sustainable, and environmentally friendly characteristics. The global transition toward green energy is therefore very much required for achieving sustainable development and meeting future energy needs. In this context, green energy management and forecasting have become critical components of modern power systems. This approach uses renewable sources to share the load with the main grid; ultimately, it reduces the burden on conventional generations. Furthermore, it provides a platform for every utility to buy and sell energy based on their deficiency and excess availability. This paper presents a comprehensive comparison of conventional and renewable energy trading markets using Machine Learning. This study mainly considers the impact of renewable energy on price variation and overall power market stability. Key parameters such as Market Clearing Price, Market Clearing Volume, purchase bids, and sell bids are utilized to evaluate the performance of the Day-Ahead Market, Green Day-Ahead Market, and Real-Time Market. Results indicate that the Green Day-Ahead Market offers improved stability and decarburization compared to the Day-Ahead Market and Real-Time Market. Also, the study suggests the use of AI-driven predictive methodology to improve market efficiency and enhance renewable energy involvement. These findings contribute to building resilient, low-carbon, and economically efficient electricity markets.

Keywords: Smart Grid, Electricity Market, Market Clearing Price (MCP), Market Clearing Volume (MCV), Day-Ahead Market (DAM), Green Day-Ahead Market (GDAM), and Real-Time Market (RTM)., Market Clearing Price, Renewable Energy, Power Trading.

I. INTRODUCTION

In the smart grid, greater efficiency, dependability and the smooth integration of renewable energy sources like solar and wind are made possible. The smart grid also monitors and controls electricity flow in real time via two way communication digitally and provide automate control. Increased efficiency, better asset management, sustainable energy integration, consumer empowerment and reduced environmental impact are some of the benefits of the smart grid. Digital technology sensors and software are used in smart grids, which are electrical networks that better balance economic factors of electricity in real time while lowering prices and preserving grid security and dependability [1].

Smart grid and smart meters: Smart meters are digital meters taking readings in real time. It can transfer data wirelessly to utilities [2].

Two-way communication: The smart grid offers two way communication between buyers and sellers for better management of supply and demand [3].

HEMS and IEMS: These systems help to monitor, analyze, and optimize energy use in real time across equipment. The smart grid can integrate consumers by making them active in managing their energy usage and consumption.

Fault detection and self-healing: Smart grids can automatically detect faults and reroute power, reducing

outage duration and improving system reliability.
Key benefits of Smart Grid: To increase efficiency, improved reliability, integration of renewables, better management

Power trading
Energy that is generated by the power grid is either utilized immediately or has to be transferred from one form to another. So, when the power grid generates excess power more than demand, it has to be available for sale to other consumers. Buying and selling power amongst players in the energy sector is known as power trading. Power trading can take many different forms, from short- term trading to long term trading based on the market structure [4] [5]. Since electricity must be produced and consumed at the same time, it is a special kind of commodity [6]. Power trading facilitates supply and demand matching in real time [7]

II.PROBLEM STATEMENT
The over-reliance on fossil fuels and inefficient energy utilization has led to:
- Resource depletion
- Environmental degradation
- Increased energy costs
- Grid instability

Additionally, traditional electricity markets face:
- High price volatility
- Demand-supply mismatch
- Limited renewable integration

Therefore, there is a need for:
- Smart grid-based solutions
- Efficient market mechanisms
- Sustainable energy trading frameworks

III.LITERATURE SURVEY
A power market is a system in which electricity is bought and sold among generators, utilities, retailers, traders and consumers. It is a market-based mechanism that enables efficient generation, transmission, distribution and consumption of electrical energy. There are some types of power markets.
1. Wholesale Power Market- This is where large-scale electricity generators sell power to retailers or large consumers. There are three subtypes of power markets [8].
Day-Ahead Market (DAM): Electricity is traded a day before it is delivered. Prices are set hourly for the next day.
Real- Time Market (RTM): Electricity is bought and sold in near real-time (usually every 5-15 minutes). Balances differences between forecasted and actual demand.
Bilateral Contracts: Long-term agreements directly between a generator and buyer (utility, large consumer). Not traded on an exchange
2. Retail Power Market: It is a type of electricity industry where power is sold directly to end consumers like industries, residential, and commercial.
3 .Spot Market: It is a segment of the power market where electricity is bought and sold for immediate delivery (Same day or next day).
4. Green Power Market: It is a sector of the power market where electricity generated from renewable and environmentally friendly sources is bought and sold. The goal is to promote clean energy and reduce greenhouse gas emissions. [10].
Exclusive trading of green energy sources like solar, wind, and hydro is made possible by the Green Day Ahead Market, which provides a cleaner, more sustainable substitute for the traditional wholesale power market. In contrast to the standard Day-Ahead Market, which incorporates fossil fuel-based power, the Green Day Ahead Market helps states, utilities, and businesses fulfil their sustainability objectives and Renewable Purchase Obligations (RPOs) by offering transparent price discovery for green energy [11]. It ensures continuous, dedicated scheduling of renewable energy sources, promotes grid decarburization, and reduces dependency on volatile fossil fuel prices. Green Day Ahead Market is emerging as a key instrument in India's transition to a reliable, low-carbon, and market-driven energy system thanks to strong legislative support and growing participation. [12] [13].

Green Power Trading
Buyers may support renewable development by purchasing renewable energy or securities like RECs through specialist markets or trading platforms. India's Ministry of Power introduced real-time trading in response to

the instability caused by the integration of renewable energy sources.
This system is based on a bidding approach and is separated into Indian zones. The Energy Exchange of India and the Power Exchange of India Ltd. are the platforms used for energy trading. To make sure that transmission corridor availability is taken into account, these exchanges collaborate closely with load dispatch centers [14]. These activities are supervised by Power Grid and the central electrical regulatory body. Auctions open every 15 minutes; real-time power trading takes place in 30-minute increments. Green power exchanges work similarly to commodities exchanges, allowing consumers and utilities of renewable energy to interact through spot contracts for a range of durations [15].
Media of communication are Renewable Energy Certificates (RECs) and Day-Ahead and Term-Ahead Contracts for the selling and buying of power. Power Exchange India Ltd. (PXIL) and Indian Energy Exchange (IEX) play the main role in this market in India. The Power Exchange in India, Hindustan Power Exchange Ltd. (HPX), was launched by PTC India Ltd. and the Bombay Stock Exchange (BSE). Renewable Energy Certificates (RECs): It makes renewable energy accessible to distribution firms, open access users, and other organizations without requiring an initial financial outlay. A national market for renewable energy is created via the REC framework [16].
Green Term-Ahead Market (GTAM): Green power trading, also known as renewable energy trading, is made possible by GTAM, which gives producers the option to sell power on the spot market. In the exchange market, producers and consumers both gain from this flexibility.
Intra-day contracts: The cut-off time for these 15- minute national contracts is 3.5 hours prior to delivery, and they are open for trade 24/7.
Day-ahead contingency contracts: These are nationwide contracts for 15-minute periods that are traded every day for the delivery of power the next day between 0000 and 2400 hours. Every day between 1500 and 2300 hours, the trading session takes place [17] [18].

IV.ANALOGY IN MARKETS

In this paper, the main focus is on a comparison of the Wholesale Power market and the Green Energy market. Although they are both marketplaces for the selling and buying of electricity, the wholesale market and the green market differ in their target markets, goals, and traits. The following statements show an analogy in markets.

- **Core Function and Power Type**

The Wholesale Power Market acts as a high-volume hub where large-scale electricity is traded between generators and suppliers. It is technology-agnostic, encompassing all energy forms including fossil fuels, nuclear, hydro, and renewables. On the other hand, the Green Energy Market focuses on the production and use of green energy sources, such as solar, wind, hydro, and biomass.

- **Market Focus and Objectives**

Wholesale Market: Focuses on economic and technical efficiency, which includes finding prices, balancing supply and demand, and guaranteeing grid stability. Whereas t h e Green Market is motivated by ecological objectives, emphasizing carbon footprint reduction and environmental sustainability

- **Participants and Stakeholders**

Green Market Participants: Includes renewable energy producers like NGOs, governments, and corporations looking to meet sustainability targets. Industrial- scale companies, including grid operators, utilities, big-box stores, and conventional generators, dominate the wholesale market. Participants in the green market include producers of renewable energy as well as mission-driven organizations, governments, and businesses aiming to achieve sustainability goals.

- **Trading Instruments**

Wholesale markets rely on energy-delivery contracts (spot, day-ahead, or bilateral). Green markets often trade in "attributes" via Renewable Energy Certificates (RECs), Guarantees of Origin (GoO), and specific green tariffs.

- **Time Horizons**

Wholesale trading is highly dynamic, ranging from real-time and day-ahead transactions to long-term bilateral agreements. Green energy markets lean more toward long-term contracts and certificate-based trading systems.

- **Market Examples**

Wholesale markets: PJM (USA), Nord Pool (Europe), IEX (India); Green energy markets: REC markets (USA, India), GoO (EU), Green-e (USA).

V.METHODOLOGY

The objective of this study is to evaluate and compare the operational characteristics of three major electricity trading platforms: the Day-Ahead Market (DAM), Green Day-Ahead Market (GDAM), and Real-Time Market (RTM). The analysis focuses on understanding market behavior, demand–supply dynamics, price formation mechanisms, and market efficiency using historical market data and data-driven analytical techniques

1) Data Collection and Preprocessing

Power market dataset for the Day Ahead Market, Green Day-Ahead Market and Real-Time Market is collected from respective electricity market databases. The information shows hourly and daily trading records containing:

- Purchase Bid Volume (Demand) in MW
- Sell Bid Volume (Supply) in MW
- Market Clearing Volume (MCV) in MW
- Market Clearing Price (MCP) in ₹/MWh In preprocessing, the following steps are included:

1. Deleting the missing and partial records.
2. All market dataset bring to the same time equilibrium.
3. Data normalization and number formatting are done.
4. Arrange the collected data into a time-series model for comparison.

2) Data -Driven Analytical Framework

Analysis of the power market will become easy by using a data-driven approach. This is adopted to extract required insights from market operations. AI-ML and statistical analysis tools were used primarily for observation, trend learning, and performance checking. The analysis framework consists of the following stages

Step 1: Market Data Acquisition
Step 2: Data Cleaning and Processing
Step 3: Time-Series Visualization
Step 4: Demand–Supply Trend Analysis
Step 5: Price Ups and Downs Assessment
Step 6: Market Performance Evaluation

3) Statistical Performance Metrics

The following analysis is used to compare DAM, GDAM, and RTM

$$\text{Mean} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

Where:
xi = observed market parameter
N = total observations Standard Deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$

μ = mean value Coefficient of Variation

$$CV = \frac{\sigma}{\mu} \times 100$$

4) Software Tools Used

These are some of the data analytics and visualization tools used for analysis:

- Python
- Pandas
- NumPy
- Matplotlib
- Seaborn
- Microsoft Excel

Using these tools, processing becomes more efficient for large datasets. Also, graphical representation of market parameters and statistical evaluation of market behavior will be more systematic.
Approach:

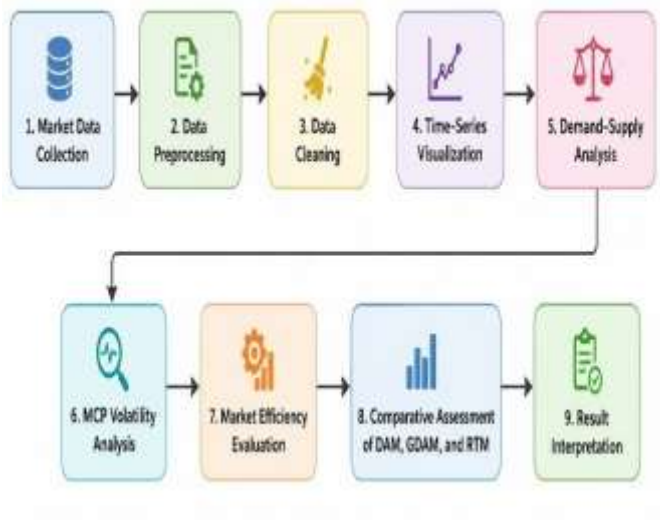

Figure 1: Flowchart of Methodology

VI. RESULT

A. Day Ahead Market

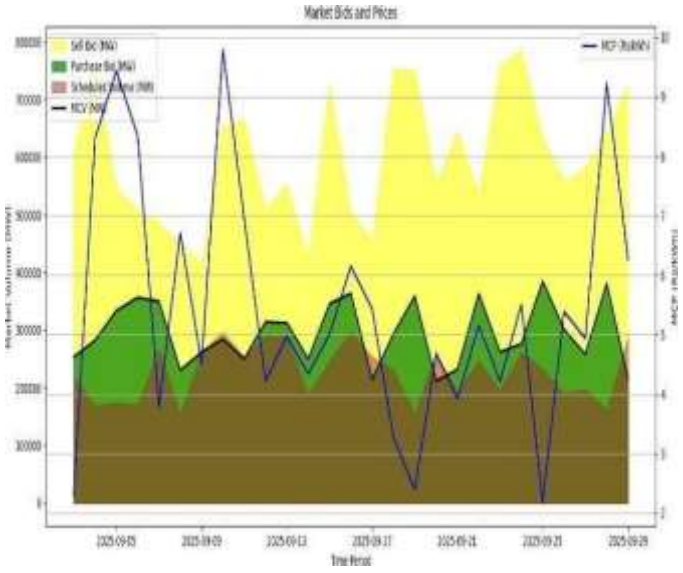

Figure 2: Day ahead market graphical analysis

Graph is of variations in scheduled volume, Market clearing volume, Market clearing price, purchase bid, and sell bid during the period from 03-09-2025 to 30-09-2025.

Green Area – It shows Purchase Bid (MW), which is the demand for electricity given by buyers. It varies between approximately 15,000 MW and 28,000 MW.

Yellow Area - It shows Sell Bid (MW): This is electricity provided by generators. Its volume is always greater than the purchase bid volume; it indicates sufficient supply available in the market.

Brown Area- It shows Scheduled Volume (MW): This is electricity volume which is successfully scheduled for delivery after market clearing. It is less than the total sell bids. Black Line – It shows Market Clearing Volume (MCV) (MW): that is the actual traded electricity quantity in the market. It is relatively stable.

Blue Line – It shows Market Clearing Price (MCP) (₹/kWh) that is the market clearing price which is decided by the bidding process. MCP shows changes consistently within the study period, approximately ranging from ₹2.5/kWh to ₹10/kWh.

Market Behavior: The graph shows that the market works under supply-surplus conditions during the study period, September 2025. Here, it shows demand and cleared volumes are stable, but the Market Clearing Price shows considerable volatility; it ultimately reflects changes in market conditions and bidding

strategies. The market is able to maintain stable cleared volumes during fluctuating bids, demonstrating efficient market operation and effective balancing of electricity demand and supply.

B. Real Time Market

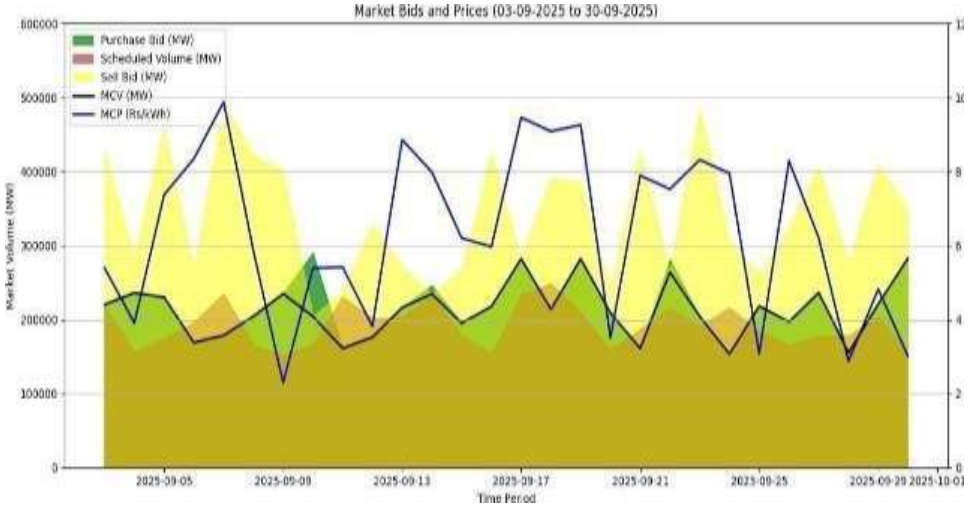

Figure 3: Real Time market graphical analysis

Graph is of variations in Market Volumes (MW) and Market Clearing Price (MCP) in the Real-Time Market (RTM) during the period from 03-09-2025 to 30-09-2025.

Yellow Area – It shows Sell Bid (MW): That is electricity provided by generators for sale. Its volume is always greater than the purchase bid volume; it indicates sufficient supply available in the market.

Light Green Area – It shows total cleared volume (MW) that denotes the electricity quantity traded in the aftermarket clearing. It is less than the total sell bids.

Dark Green Area – It shows Purchase Bid Volume (MW) the total electricity demand submitted by buyers. The purchase bids moderately fluctuate, showing changes in real-time electricity demand.

Black Line – It shows total MCV (MW) which shows the Market Clearing Volume, which is the actual electricity quantity transacted in the market. The MCV is generally stable as compared to the sell bid.

Blue Line - It shows Market Clearing Price (MCP) (₹/kWh) it is the market clearing price. The MCP has significant variations; it shows sharp spikes and dips during the study period.

Market Behavior: The RTM graph results show that the market worked under predominantly surplus supply conditions where sell bids consistently exceed purchase bids. Here, the Market Clearing Volume remains relatively stable, but Market Clearing Price exhibits significant volatility, reflecting the dynamic nature of real-time electricity trading. The results demonstrate that the RTM is able to balance short-term demand–supply variations efficiently while ensuring reliable market operation.

C. Green Day Ahead Market

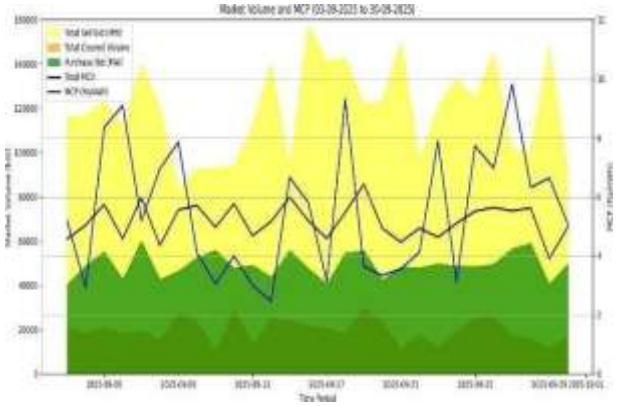

Figure 4: Green day-ahead market graphical analysis

Graph is of variations in Sell Bid Volume, Purchase Bid Volume, Scheduled Volume, Market Clearing Volume (MCV), and Market Clearing Price (MCP) during the period of 03-09-2025 to 30-09-2025.

Yellow Area – It shows Sell Bid (MW) which represents the total renewable energy offered by generators in the Green Day-Ahead Market. Here, the sell bid volume remains considerably higher than the purchase bid volume throughout most of the study period, indicating enough green energy availability.

Green Area – It shows Purchase Bid (MW): which represents the renewable electricity demand submitted by buyers. The purchase bids vary moderately, reflecting fluctuations in green energy demand.

Brown Area – It shows Scheduled Volume (MW) which indicates the renewable energy volume successfully scheduled for delivery after market clearing. It closely follows the demand trend.

Black Line – It shows Market Clearing Volume (MCV) (MW) which indicates the traded actual quantity of electricity in the market. Most of the time, MCV matches the scheduled volume. Blue Line – It shows Market Clearing Price (MCP) (₹/kWh) where the market-clearing price is calculated by the bidding process. MCP changes between approximately ₹2/kWh and

₹10/kWh, indicating fluctuating market conditions.

Market Behavior: The Green Day-Ahead Market (GDAM) shows a fundamentally buyer-favorable structure due to an oversupply of sell bids from renewable generators who need zero fuel costs so that they can bid at minimum rates to avoid the extra burden of fossil fuel prices on buyers. Green energy supply is dependent on weather as well as time of day. During daytime, GDAM shows massive supply, but during evening time it shows sharp scarcity and high price spikes. Considering all this, it needs intelligent bidding strategies against the conventional market. Consequently, the GDAM is highly reliable and recommended for buyers, getting moderate price volatility with zero marginal cost of renewable energy, highly sustainable, helping in decarburization as zero fossil fuel involvement, less risk factor due to flexibility; unclear bids carry over to DAM.

Summary Comparison

The comparison table summarizes the advantages of Green Day-Ahead Market (GDAM) over conventional energy markets

Table 1: Summary comparison markets

Metric	Day-Ahead Market (DAM)	Real-Time Market (RTM)	Green Day-Ahead Market (GDAM)
Price Volatility	High (frequent spikes up to 10 Rs/kWh)	Extreme (unpredictable intraday spikes)	Moderated by zero-marginal-cost RE
Risk Management	Standard day-ahead matching	High stress due to hour-ahead balancing	Flexible; unclear bids carry over to DAM
Sustainability Value	Nil (Conventional mix)	Nil (Conventional mix)	100% Green (Earns RPO credits)
Carbonization	Huge involvement (Fossil Fuel)	Huge involvement (Fossil Fuel)	Zero involvement (Green Energy)

VII.CONCLUSION

Overall study of comparison of power markets such as conventional markets and green power markets highlights mainly on strategic pathway for modern power grid which are aiming to provide sustainable power supply with minimum cost, and most importantly it promotes zero carbonization. The conventional Day-Ahead Market (DAM) and Real-Time Market (RTM) are dependent on fossil fuel; this causes high price spikes from

₹2/kWh to₹10/kWh, which is unpredictable, creating high stress on intraday, while the Green Day-Ahead Market (GDAM) provides a very good alternative. The green energy market is superior to DAM and RTM due to three important advantages:

Economic Protection: As GDAM is totally dependent on renewable sources, it provides zero marginal cost, but at the same time conventional markets show expensive price peaks due to volatile fossil fuel or gas prices.

Efficiency and Flexibility: Order Carry Forward (OCF) features ensure that there will not be any waste in clean energy bids. If it remains unclear in the green segment, it will be rolled over to the conventional pool to adjust supply to fulfil demand in DAM and RTM.

Dual-Value Procurement: In the conventional pool, you can only buy physical electricity, but in the green market every purchase of a megawatt-hour gives you clean electricity and satisfies statutory Renewable Purchase Obligations (RPOs). Ultimately, the green energy market is an economically superior strategy that motivates decarburization, sustainable power supply with zero risk, and it improves the financial health of the country.

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