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Application of Bayesian Price Clearing Auction Model in Enhancing Transactive Energy Systems Vulnerabilities to Cyber Attacks

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Abstract

Transactive Energy System (TES) is an emerging energy solution that ensures a dynamic balance between energy demand and supply. Energy trading among peers has the potential to drive future solutions that can provide a more secure, distributed, and sustainable power infrastructure. The incorporation of peer-to-peer (P2P) to TES facilitates flexibility and minimizes pressure on the electrical grid. However, the system is vulnerable to cyberattacks due to the high volume of information exchanged across the energy network's communication channel. To mitigate the impact of cyber-attacks on the solution, it is necessary to explore the application of the Bayesian Price Clearing Auction (BPCA) model to enhance the resilience of TES against threats from adversaries. The BPCA method is novel in TES in that it frames the market-clearing process as a statistical inference problem. This proposed model incorporates the uncertainty and heterogeneity factors in market behavior using volume-weighted averages and variances. The resulting equilibrium price is not just a deterministic mid-point, but a Bayesian estimate that "learns" from the offer's distribution.

Keywords
Bayesian Price Clearing Auction, Cyber Threats, Energy Trading, Transactive Energy System

1. Introduction
The rise in Earth's temperature reflects adverse climatic change. The excessive use of fossil increases the CO_2 concentration in the atmosphere, leading to the greenhouse effect and global warming. Unregulated climate change

affects humans and the environment (Shukla et al. 2023). Advocacy for a low-carbon environment has led to a shift in energy generation into Renewable Energy Sources (RES) and technologies are being proposed to address this limitation to enhance the grid's efficiency (Mohammad et al. 2024). Integrating modern technologies, such as Artificial Intelligence (AI), Blockchain and information and communication technologies (ICT) into energy systems enhances operations (Kumar et al. 2020). ICT and AI are the backbone of the modern energy system as they support development and facilitate decarbonization, decentralization, and digitalization of energy systems (Kilthau et al. 2023).

Advancements in technology such as Transactive Energy Systems (TES) and Cyber-Physical Power Systems (CPPS) mostly rely on computing and communication technologies (Monteiro et al. 2023). These technologies are transforming energy systems to be more sustainable, resilient, and efficient (Choobineh et al.2023). Adopting these technologies allows electrical grids to self-regulate, especially during failures, threats, and system disturbances (Zheng et al.2024). However, this advancement offered by these technologies in TES has become a serious concern owing to its vulnerability to cyber threats caused by the increasing number of interconnected devices. These sensing, communication, and control devices can be manipulated to compromise users' safety, privacy, and the cybersecurity of participants in the energy trading architecture of the TES. A comprehensive review of vulnerabilities in CPPS and strategies for mitigating Cyberattacks was reported in (Monteiro et al. 2023). The authors classified cyberattacks into availability, integrity, and confidentiality.

In this work, the Bayesian Price Clearing Auction (BPCA) approach was applied to TES to enhance transparency and mitigate cyber threats. This method stands apart from traditional deterministic auction models and offers a robust alternative for real-time energy trading markets. The price discovery process is a Bayesian estimation problem that incorporates market heterogeneity through volume-weighted statistics. The addition of confidence intervals further enhances its transparency by quantifying uncertainty. This method stands apart from traditional deterministic auction models and offers a robust alternative for real-time energy trading markets. The rest of the paper is arranged as follows; Section 2 is the Related works, which showcases the vulnerability of TES, while Section 3 is the Methodology. Section 4 is the Results and Discussion, and Section 5 is the Conclusion.

2. Literature Review

2.1 Vulnerability of TES to Cyber Attacks

The vulnerability of power systems can be analyzed from a static or dynamic approach. These vulnerabilities can be random failures, natural hazards, or intentional attacks, which have a concomitant effect on other systems such as railways, road traffic, and social networks (Tang et al. 2023). Denial-of-service (DoS) attacks occur when adversaries overload the network with the target of blocking system communication to interfere with the user's request for service. One common method to execute this attack is by deliberately sending numerous messages through the control channel to choke the network and impede communication. Another class of DoS (DDoS) attacks. Two major types of attacks aiming at disrupting DR programs in power systems were reported in (Tang et al. 2023): pricing attacks and energy theft. Price attacks occur when adversaries inject false electricity prices much lower than the actual, causing victims/consumers to increase their consumption, thereby leading to a peak load/overload on the power system (Markopoulou 2023). Energy theft attacks occur when one or more customers within the power system network are targeted to modify either the generation or consumption data (or both) transmitted to the utility to gain undue monetary benefits at the expense of the utility. Challenges in TES comprise

- Time-varying conditions and uncertainties in energy generation and consumption
- The rise in the application of IoT devices, network coupling, and bidirectional power flows in energy systems may initiate new failure mechanisms.
- Wireless communication is more exposed to attacks considering it uses free space to propagate signals. Hence, there is a need for more secure wireless protocols. However, wired mediums are more secure because of features such as Firewalls, Security Socket Layers (end-to-end encryption),

2.2 Decentralized Transactions in TES

The P2P energy market is the technique of trading energy without the intervention of intermediaries to improve the power systems' reliability (O. O. Tooki & Popoola 2024). It enhances the smooth integration of microgrids, lowers corruption, increases transparency, and provides a payment platform for energy trading. The blockchain-based P2P market permits energy trading via smart contracts to post auction orders for energy transactions that are instant, automatic, and robust (Yang 2020). It is a direct mechanism for energy trading amongst prosumers. Prosumers are consumers with the capacity to produce energy through small-scale DERs and trade their excess to their peers during peak periods to recoup portions of their investment (Mu et al. 2023). However, it cannot be used without a software platform, facilitates P2P information sharing, and helps system managers monitor and manage the distribution network (Sabillon et al., 2021). Hence, the integration of BT in designing the P2P platform for energy trading. A blockchain-aid decentralized market platform that permits participants within the electricity network to directly enter the market and swap energy with other participants without supervision from a centralized entity.

BT facilitates energy trading among peers, and it has the potential to drive future solutions that can provide a more secure, distributed, and sustainable power infrastructure (Nikhil et al. 2021). Consensus protocols in BT require high computational complexity and large storage requirements. Prosumers can only access the blockchain-based system via gateway nodes. However, the challenge there is that adversaries can launch a Denial-of-Service attack against the gateway node to isolate prosumers from TES. This is mostly done to block some bids from getting to the energy market with the complete aim of causing instability in the market. Extensive research has been done on the DLT's application to the energy market. However, more emphasis is being placed on smart contract algorithms in the design of the energy market structure. However, little effort has been recorded on engineering impediments such as frameworks that can be employed to develop scalable solutions for energy markets. Another complexity involves an energy-trading algorithm to determine the market clearing prices and limitations around cybersecurity requirements needed to support effective market operations (Nikhil et al. 2021). In addition, is the challenge of how to sustain the legal behaviours of participants and how to punish malicious operations. There exist reported cases of manipulation of clearing price bids and the trade-off between decentralization and transaction speed. The vulnerability of TES to cyber threats is induced by the financial motives of stakeholders, which affect the system's operation (Tooki & Popoola, 2024a, 2024b).

3. Methodology

3.1 Mathematical Formulations

Let the set of market participants be donated by $L = \{1,2,...,N\}$, where N is the total number of the participants, $S \subset L$ be a set of prosumers and $B \subset L$ be set of buyers. At each time interval, t, each participant i, is characterized by:

- Consumption: $C_i^t \geq 0$
- Generation for prosumers: G_i^t
- Net load: $L_i^t = \{C_i^t - G_i^t, \ \forall\, i \in S \ C_i^t, \quad \forall\, i \in B$
  (1)

Buyer Bids

For a buyer, the bid price b_i^t is given by:

$$b_i^t = \alpha_i p_r^t \tag{2}$$

where the factor α is drawn independently from a uniform distribution:

$$\alpha_i \backsim U(0.85, 0.95)$$

This implies that each buyer is willing to pay between 85% and 95% of the reference price, reflecting their valuation under normal operating conditions.

Seller Asks

For a seller, $i \in S$, the ask price s_i^t is determined by:

$$s_i^t = \beta_i p_r^t, \tag{3}$$

with the multiplicative factor β_i drawn as:

$$\beta_i \backsim U(0.85, 0.95).$$

Thus, each seller is willing to accept between 65% and 75% of the reference price. The lower ask values reflect a seller's preference to quickly dispose of surplus energy.

Volume-Weighted Statistics

The core innovation lies in calculating volume-weighted statistics from these bids and asks:

The volume-weighted mean bid μ_b^t is computed as:

$$\mu_b^t = \frac{\sum_{i \in B} \ b_i^t q_i^t}{\sum_{i \in B} \ q_i^t} \tag{4}$$

Similarly, the volume-weighted mean bid μ_s^t is computed as:

$$\mu_b^t = \frac{\sum_{j\in S} \quad s_j^t q_j^t}{\sum_{j\in S} \quad q_j^t} \tag{5}$$

3.2 Equilibrium Price Calculation

Using the Bayesian framework, we treat the buyer and seller price distributions as:
Buyers: $b_i^t \backsim N(\mu_b^t, \sigma_b^{2,t})$
Sellers: $s_i^t \backsim N(\mu_s^t, \sigma_s^{2,t})$
Under this assumption, the equilibrium clearing price is computed as a weighted average of the buyer and seller means, with weights given by the opposite side's variance:

$$p_c^t = \frac{\mu_b^t \, \sigma_b^{2,t} + \mu_s^t \, \sigma_s^{2,t}}{\sigma_b^{2,t} + \sigma_s^{2,t}} \tag{6}$$

This formulation implies that if one side's offers are highly concentrated (low variance), that side's mean price will have a stronger influence on the equilibrium. To allow for additional market tuning, an adjustment is applied relative to the flat rate:

$$p_c^t = p_r^t + \omega(p_r^t - p_c^t), \tag{7}$$

Where ω is the tunning parameter.
The **traded volume** for time interval V_t is set to the minimum of the total buyer demand and the total seller supply:

$$V_t = min \{\sum_{j\in S} \quad q_j^t + \sum_{i\in B} \quad q_i^t\}$$

(8)

This BPCA approach is novel because it frames the price discovery process as a Bayesian estimation problem that incorporates market heterogeneity through volume-weighted statistics. The addition of confidence intervals further enhances its transparency by quantifying uncertainty. This method stands apart from traditional deterministic auction models and offers a robust alternative for real-time energy trading markets. In this work, an assumption that buyer bids and seller asks are generated from underlying normal distributions was made.

4. Results and Discussion

The result presented in Figure 1 shows the total volume of energy traded (in kWh) at each half-hour interval, with timestamps shifted to 2024. The pattern reveals intermittent periods of zero trades, likely due to insufficient net load on either the buyer or seller side or a mismatch in bid and ask prices. Spikes in traded volume, at times exceeding 1,000 kWh, occur when large buyer demand aligns with ample seller supply and the bid-ask ranges overlap enough to clear the market. These swings reflect the inherently stochastic nature of the simulation (which assigns bids and asks uniformly within specified bounds) and the fluctuating net loads (consumption minus PV generation). Overall, the figure demonstrates how the BPCA model yields highly variable yet realistic outcomes, with some intervals supporting substantial transactions. This added layer of statistical rigor represents a breakthrough in auction design for Transactive Energy markets.

In Figure 2, the intermittent spikes in savings indicate intervals when the clearing price falls sufficiently below the flat rate, allowing buyers to benefit from lower costs; at other times, savings drop to zero if the equilibrium price approaches or exceeds the reference rate. Meanwhile, Figure 3 shows that the equilibrium price can hover near, dip below, or occasionally rise above the flat rate, directly influencing whether buyers achieve savings. These fluctuations arise from the random assignment of bids and asks, as well as day-to-day net load changes, resulting in a dynamic marketplace where some intervals yield notable buyer advantages and others provide little or no cost benefit. Figure 3 is the aggregate Traded Volume over Time. It was observed that the probabilistic treatment allows for a more robust and transparent clearing mechanism, as it provides both a point estimate for the equilibrium price and, with extension, confidence intervals that quantify uncertainty.

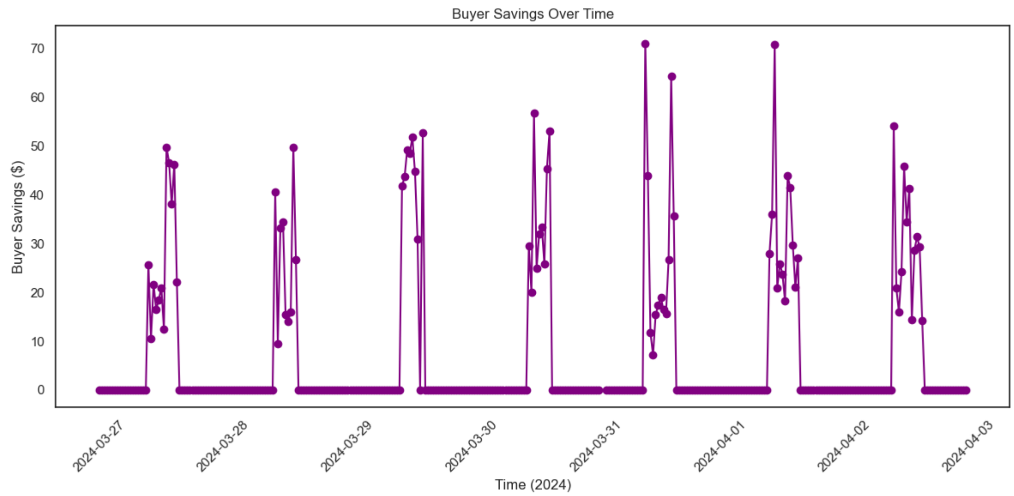

Figure 1. Buyers' Savings Over Time

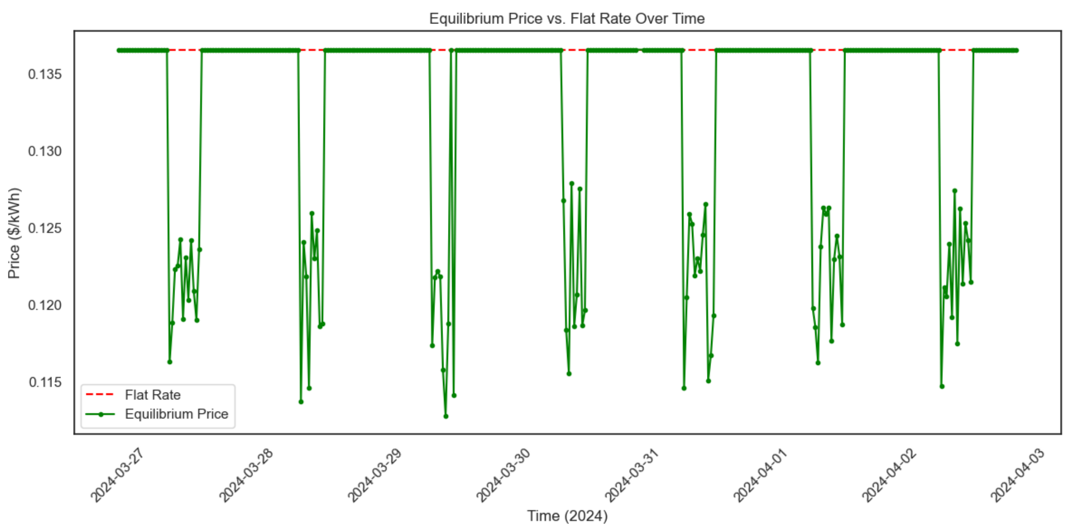

Figure 2. Equilibrium Price Vs. Flat Rate

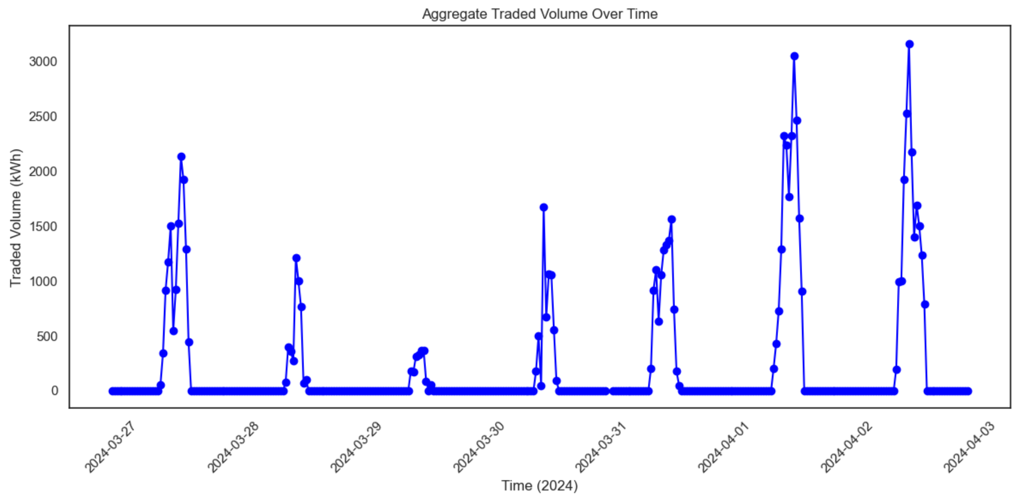

Figure 3. Aggregate Traded Volume over Time

6. Conclusion

The Bayesian Price Clearing Auction (BPCA) simulation demonstrates that randomly assigned bids and asks, combined with fluctuating net load, can yield highly variable yet realistic market outcomes. The clearing price often dips below or hovers around the flat rate, directly driving buyer savings, which appear in spikes whenever the equilibrium price is low enough to offer a cost advantage. Conversely, periods of zero savings arise when the market-clearing price matches or exceeds the reference rate or when supply and demand do not align sufficiently to produce trades. Overall, the results confirm that this approach captures the inherent dynamism of transactive energy systems, where real-time conditions and participant behaviors heavily influence price formation and cost benefits.

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