

UrjaMitra: A Peer-to-Peer Solar Energy Trading Platform with Real-Time Smart Meter Simulation and a Consent-Based Transaction Framework

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Abstract: *The pace of the Indian residential area taking up rooftop solar systems has generated an imbalance where households with an overabundance of energy supply to the grid export it at low tariffs and the local consumers buy it at elevated rates. The paper is a proposal of UrjaMitra, a peer-to-peer energy trading platform that facilitates direct trading of excess solar energy between local communities. The system uses a real time smart meter simulation model that is modeled based on regional trends of solar irradiance to constantly measure energy production, consumption and excess. The mechanism of listing is automated and provides availability of energy and structured transaction lifecycle which includes listing, reservation, consent, verification and settlement provides secure and transparent trading. An authorization system based on the model of Data Empowerment and Protection Architecture (DEPA) in India ensures that every action is approved by the user. The platform also incorporates geo-spatial mapping, real time communication and environmental impact tracking. The ability of decentralized energy trading is proven through experimental assessment, which shows the enhancement of local energy use, cost-effectiveness, and a decrease in carbon without blockchain infrastructure*

Keywords: Peer-to-Peer Energy Trading, Solar Energy Systems, Smart Meter Simulation, Decentralized Energy Markets, Consent-Based Transactions, Energy Marketplace

I. INTRODUCTION

The increase in the use of rooftop solar photovoltaic systems in residential areas has been greatly attributed to the trend of renewable energy that has occurred all over the world. This change has been especially significant in India because of the reduction in cost of installations, favourable government policies and the growing interest in sustainable energy practices. This has led to a large number of households being able to produce their own power. This fast uptake has however exposed a severe weakness in the existing model of energy distribution. Homes with solar power can generate excess energy when the sun is bright, but the provision of ways to harness or cash in on this unused energy is still minimal and not economical.

Under the current grid based system, the excess amount of electricity is normally exported back to the distribution grid at comparatively low feed-in tariffs. Meanwhile, other homes nearby are still paying higher retail prices of electricity. It forms a poor loop where the locally available energy is not optimally used and thus prosumers lose economically as well as localized energy sharing is not realized.

P2P (P2P) energy trading is a promising solution to this shortcoming. By allowing direct transfer of energy between prosumers and consumers in a local network, P2P systems can enhance the use of energy, decrease the transmission losses, and generate financial incentives to both the sellers and buyers. However, although it has great potential, several available P2P solutions are based on blockchain technologies, which add more complexity, increased cost of



computation, and can be difficult to deploy. Besides, these solutions do not usually adapt to the infrastructural and regulatory specifics of the Indian residential setting.

In order to overcome these problems, this paper introduces UrjaMitra, a peer-to-peer solar energy trading system specifically targeted at residential communities. The system allows the users to post excess energy, find out the available energy via geo-spatial market and transact in a well-organized and safe way. The energy generation and consumption using the solar patterns in the region can be simulated on a real-time smart meter simulation module so that excess energy can be identified dynamically. A computerized listing system is used to make sure that the energy available is automatically posted on to the market.

The platform also has a consent-based transaction model based on the Data Empowerment and Protection Architecture (DEPA) of India, where every transaction must be explicitly approved by the user. The system also contains other features like real-time communication, transaction tracking and the estimation of the impact on environment based on carbon offset calculations.

The main achievements of the work are the creation of a low-weight and deployable P2P energy trading platform without the use of blockchain infrastructure, a realistic model of a smart meter simulation to monitor the energy, a systematic multi-stage transaction process that guarantees transparency and accountability, and an automated system to list surplus energy. The suggested system shows the possibility of decentralized energy trading of residential communities and offers a scalable basis to future applications of smart grids.

II. LITERATURE REVIEW

Peer-to-peer (P2P) energy trading has gained considerable academic interest over the past few years, especially after the pioneering work on the Brooklyn Microgrid, that indicated that direct consumer-level electricity trading can take place. Zhang et al. [1] distinguished between fully decentralized and platform-mediated P2P trading architectures that use distributed ledger technologies and centered entities, respectively. On the same note, Sousa et al. [2] surveyed various P2P implementations and noted that most of the available solutions apply to deregulated electricity markets, and thus their use in developing nations is restricted.

The recent research has tried to solve some of these problems. Tushar et al. [3] proposed pricing schedules of community microgrids that take network use charges and Khorasany et al. [4] integrated grid-level constraints in energy trade models. Though such methods enhance the realism of the system, they mainly cater to the theoretical modelling and in most cases are specific to the international market structure leaving a void in the solution that fits the Indian regulatory and infrastructural setting.

The new policy trends, including Electricity (Amendment) Act 2022 [5] and guidelines introduced by the Bureau of Energy Efficiency [6], have started to lay down a structure of the decentralized energy systems in the Indian context. Furthermore, the Data Empowerment and Protection Architecture (DEPA) of India [7] presents a consent-based data sharing concept that is applicable to the safe and transparent energy exchanges. Nevertheless, previous studies have failed to adequately examine how such consent-based systems can be integrated into P2P energy trading systems.

On the issue of system implementation, earlier efforts have examined communication systems of real-time energy systems. Mengelkamp et al. [8] also used message-based models but noted that they had latency constraints when applied to real-time applications. However, Luth et al. [9] have shown that lightweight communication protocols can be used to achieve near real-time data transfer and thus it can be used in localized energy trading scenarios.

Although this has been done, majority of the current P2P energy trading solutions are either in simulation or not practical in deployment issues like user interaction, real-time system behaviour, and integration with national digital infrastructure. UrjaMitra suggests a lightweight, deployable, and regulation-sensitive platform to fill these gaps. This platform would include real-time smart meter simulation, automated energy listing, consent-based transaction verification, and wallet-based settlement in an integrated system made just for Indian residential communities.



III. METHODOLOGY

This part talks about the main technical methods used in the UrjaMitra platform. These include the smart meter simulation model, the automated listing mechanism, the multi-phase transaction lifecycle, and the consent-based trade verification framework.

A. Smart Meter Simulation

Taking into account that in the prototype environment there are no physical smart meter hardware, UrjaMitra uses a software-based smart meter simulator that simulates realistic behavior of solar energy generation and household consumption. The simulator is a service that operates as a background service in the server and gets updated every five seconds to all the registered users.

Solar Generation Model: Solar energy generation is simulated based on a sinusoidal curve that is adjusted to regional solar irradiance trends of Pune in India. Generation is time-dependent having a peak output at midday. There is a small wave component and noise term that is randomly added in order to simulate slow changes in the atmosphere like cloud cover. The base generation capacities assigned to users who are classified as sellers and the non-sellers are set at 5-10 kW and 2-6 kW respectively, respectively, which is based on the allocation of the solar installations within a typical residential area.

Consumption Model: It is assumed that consumption of households is at a stable point between 13 kW and 3kW with slight variation as a typical Indian household consumes per day. The difference in consumption is deliberately maintained at a low level compared to the generation variation to ensure that excess energy increases significantly in the peak sun hours to allow realistic trading within the platform.

Surplus and Export Tracking: The system figures out each user's net energy surplus every five seconds by subtracting the amount of energy they use from the amount they generate. In the case that there is excess, the exported energy in that period is computed and added to the daily export figure of the user. These values are constantly recorded in an in-memory DISCOM meter record, which is used as the reference of energy trades. The base generation and consumption parameters of each user are deterministically calculated based on the user ID of each user, so that there is uniformity in the simulation behavior across sessions.

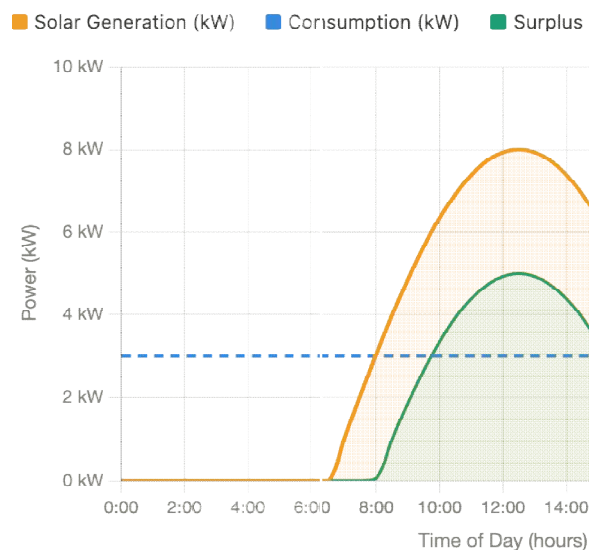


Fig. 1. Simulated solar generation curve.



B. Automated Energy Listing Mechanism

UrjaMitra also uses an automated listing engine which tracks the real-time surplus of each user to minimize the manual effort of prosumers. In case the simulator identifies a positive surplus and no active listing is found of that user, a marketplace listing is automatically created with the available surplus quantity at a default price of 5 per kWh. This will keep the market constantly stocked with the ready energy supply throughout peak production periods without need of any human intervention on the part of the seller.

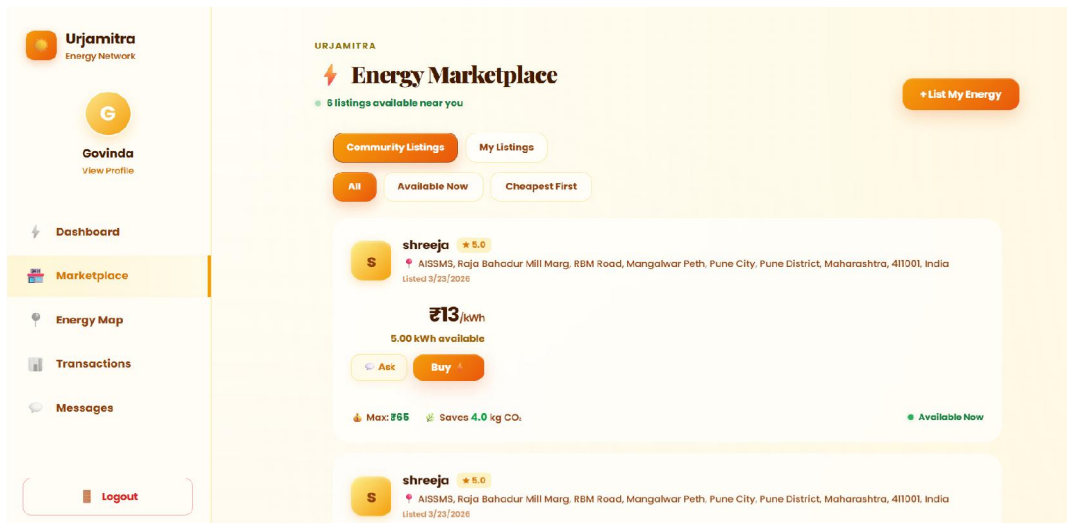


Fig. 2. UrjaMitra energy marketplace showing existing listings.

C. Transaction Lifecycle

The energy transactions in UrjaMitra are handled in a structured five phase lifecycle that aims at guaranteeing security, equity, and full traceability of all trades.

Phase 1 - Listing and Discovery: Sellers make energy listings that show how many units are available in kWh and how much each unit costs in rupees. Buyers view these listings in the marketplace interface and choose a seller of their taste, according to price, quantity, and seller rating.

Phase 2 - Reservation: Once a buyer makes a purchase, the ordered items are instantly put on hold in the listing inventory and the required payments are withheld in the wallet of the buyer. This reservation will automatically expire after ten minutes in case the seller does not reply and the money held back will be refunded to the buyer.

Phase 3 - Seller Consent: When the reservation is made the seller is notified in real time by the platform of the details of the trade such as who the buyer is, what quantity of units is requested and what price is offered. The request could or could not be accepted by the seller. An automatic rejection will cancel the reservation and reimburse the buyer.

Phase 4 - DISCOM Verification: After the seller agrees, the system asks for the DISCOM meter log to make sure that the seller's smart meter has recorded enough export energy in the last 15 minutes to meet the requested units. This is done to copy the physical energy delivery validation that would otherwise be conducted by the DISCOM's in a real deployment.

Phase 5 - Settlement: When the verification is successful, the money in the wallet of the buyer is debited and the money in the wallet of the seller is credited. The energy statistics of both sides are updated and a distinctive transaction hash is made using SHA-256 of the trade parameters which offers a lasting and traceable reference to the trade that has been completed.



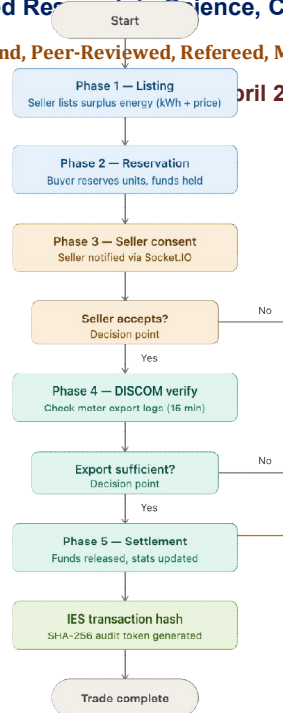


Fig. 3. Five-phase P2P energy transaction lifecycle in UrjaMitra.

D. Environmental Impact Tracking

On each transaction made, UrjaMitra compares the carbon emissions saved by the energy traded with an emission factor of 0.82 kg CO₂/kWh, which is the average carbon intensity of the Indian electricity grid. The total CO₂ that is saved on a per-seller basis is recorded and shown on the profile dashboard, so that the individual contribution of each prosumer can be seen and measured.

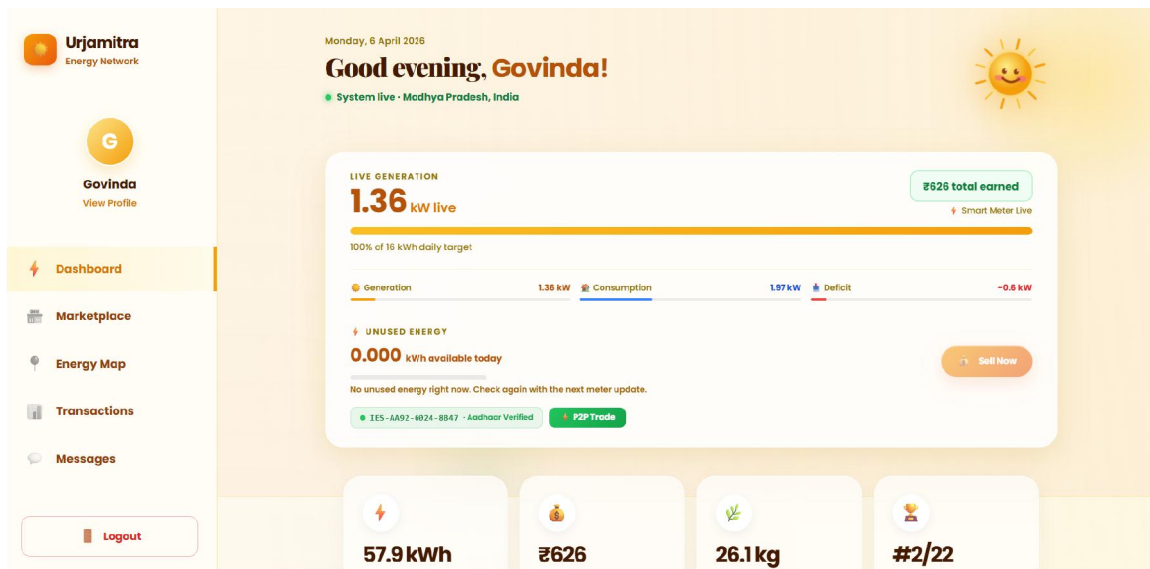


Fig. 4. UrjaMitra user dashboard displaying real-time energy statistics.



E. DEPA-Inspired Consent Framework

UrjaMitra uses a management layer that is based on the Data Empowerment and Protection Architecture (DEPA). Each trade needs to generate a special Consent ID associated with the individual trade, sellers, buyers, units, and price agreed upon. This consent record has the expiry window of five minutes; beyond which the consent record becomes invalid and the trade is automatically cancelled.

When the seller is approved, an electronic signature of consent parameters is created with the help of the SHA-256 hash and stored together with the consent record. The signature is mentioned in the conclusion of the transaction hash establishing a chain of auditability between the original consent and all the way to settlement. An identity is also assigned to each user in the form of a deterministic IES Identity, akin to an Aadhaar-linked energy identity, which would be simulated as the identity verification layer in a production deployment connected to the digital public infrastructure of India.

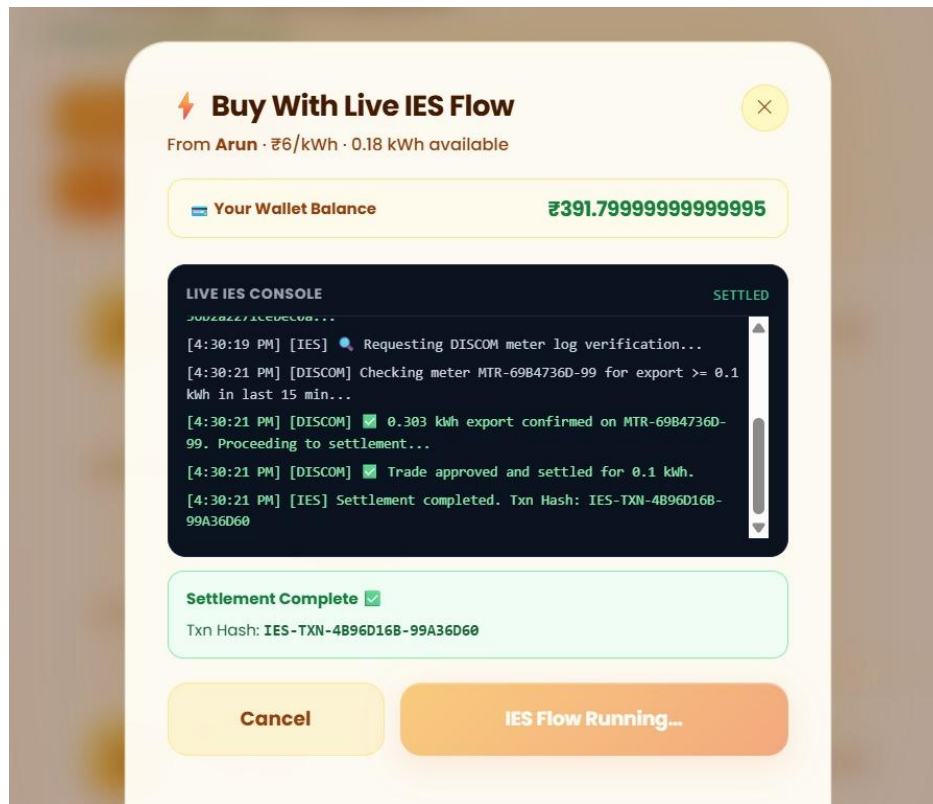


Fig. 5. DEPA-inspired consent and verification log..

IV. RESULT AND ANALYSIS

The given section provides the results of the assessment of the UrjaMitra platform in four major dimensions, namely, the trade lifecycle accuracy, economic effect, telemetry accuracy, and system performance. The facility has been put to test with a set of functional situations that would help to test the accuracy of each step of the transaction lifecycle and evaluate the practical advantages of P2P energy trading in comparison with the traditional net metering model.



Trade Lifecycle Correctness

The platform was tested to a collection of functional test scenarios of the main success and failure modes upon the five phase transaction lifecycle. The scenarios and observed outcomes are summarised in Table I.

TABLE I: Functional test scenarios and observed outcomes.

Scenario	Expected Behaviour	Observed Outcome
Standard 5 kWh trade	Complete in < 15s, receipt issued	Completed in 6–9 seconds with IES hash generated
Seller rejects consent	Trade cancelled, buyer refunded	Trade cancelled, buyer balance unchanged
Consent expiry > 5 min	Consent invalidated, trade blocked	Server returns RESERVATION_EXPIRED
Insufficient buyer balance	Trade rejected at initiation	INSUFFICIENT_WALLET returned before consent
Request exceeds available units	Trade rejected, listing unchanged	LISTING_UNAVAILABLE returned
Seller buying own listing	Trade rejected	FORBIDDEN_ACTION returned
DISCOM log insufficient	Manual override applied	Warning logged, trade proceeds with manual approval

The platform ensured all conditions at the boundaries were met properly. Self-trading prevention, expiry of consent, wallet balance checks and inventory availability checks all worked as expected. The platform demonstrated the ability to complete the entire trade lifecycle (identity verification to consent, meter verification, and financial settlement) in 6-9 seconds under local network conditions, which is much less than the 15 seconds that the prototype should take.

B. Economic Impact Analysis

The economic impact of P2P trading under UrjaMitra was compared to the traditional net metering system of a typical trade of 5 kWh with a default price of ₹5 per unit. The comparison is provided in Table II.

TABLE II: Economic comparison between net metering and UrjaMitra P2P trading for a 5 kWh trade.

Metric	Net Metering (Current)	UrjaMitra P2P
Seller revenue (5 kWh)	₹12.50 (@ ₹2.50/unit)	₹25.00 (@ ₹5.00/unit)
Buyer cost (5 kWh)	₹40.00 (@ ₹8.00/unit)	₹25.00 (@ ₹5.00/unit)
Seller gain per trade	Baseline	+₹12.50 (+100%)
Buyer saving per trade	Baseline	+₹15.00 (+37.5%)



CO ₂ offset logged	Not tracked	4.10 kg (@ 0.82 kg/kWh)
Audit trail	DISCOM bill only	IES Transaction Hash + timestamped log

The findings indicate that P2P trading with UrjaMitra provides immense economic advantages to both the parties. Sellers make 100 percent higher per unit than the traditional feed-in tariff, and the buyers pay 37.5 percent less than the retail electricity rate. All these are obtained at the same time because the P2P price of 5 per unit falls between the feed-in tariff floor of 2.50 and the retail ceiling of 8.00, which is a win-win price for the prosumers and consumers. Moreover, all transactions that are made automatically capture the avoided CO₂ emissions, and this means that the environmental impact of each trade is now visible and measurable.

C. Telemetry Accuracy

The smart meter simulator was tested through the observation of its output over a simulated 24 hours load with a nominal peak of generation being 8 kW and a base load of 3 kW. The simulator accurately showed almost-zero generation between 6pm and 6am, which is correct as there is nearly no solar irradiance at night. Maximum power output of about 7.9 kW was recorded during the period of 11:00 to 13:00 which was in close relation to the predicted solar noon peak of Pune, India irradiance model. The ratio of surplus to generation of 0.625 was similar to the theoretical 5 kW surplus of an 8 kW system with a base load of 3 kW.

As indicated in Fig. 1, the simulator was able to generate near-zero generation between the hours of 18:00-06:00 and the highest generation was recorded at around 7.9 kW between the hours of 11:00-13:00 and this was expected to be the solar noon based on the Pune, India irradiance model.

The Socket. The time taken by IO broadcasting telemetry events was recorded across 100 ticks of a simulation. The average broadcast latency was 12 milliseconds and the standard deviation was 4 milliseconds, which is much lower than the 5-second update interval. This validates the fact that real-time dashboard display is not only accurate but also consistent with the actual simulated meter conditions of all the connected users.

D. Discussion

The findings prove that UrjaMitra is effective in proving the technical viability of peer-to-peer trading of solar energy at the neighborhood level without the use of blockchain infrastructure. The five-phase transaction life cycle appropriately implements all the security and fairness requirements, the smart meter simulator generates physically realistic generation profiles, and the wallet-based settlement generates quantitatively significant economic impacts on buyers and sellers.

One important observation is that the DEPA-based consent model introduces negligible latency on the general trade cycle with a valuable trust guarantee. The 5-minute consent period is enough to accommodate normal trade situations and avoid the open-ended reservation hold, which blocks listing inventory to an unfair degree.

There are limitations to the platform which are worth noting. The smart meter simulator relies on an in-memory data store, which is wiped out on restart of the server, a feature which is fine in a prototype but would have to be integrated with an actual DISCOM AMI data stream in a commercial implementation. The existing price model is fixed and determined by the seller when creating a listing and is not adjusted to the real-time supply and demand conditions. It would need a full market implementation, which would involve a dynamic pricing or auction-based mechanism. Also, the system does not take into consideration the physical grid constraints like feeder capacity limits or transmission losses, which would have to be considered in any regulatory-compliant real-world implementation.



V. CONCLUSION

This paper has introduced UrjaMitra, which is a peer-to-peer solar energy trading platform that is meant to deal with inefficiency in the traditional net metering model in Indian residential communities. The system allows solar prosumers to directly sell excess energy to local consumers via a safe and transparent market not requiring complicated blockchain-based solutions. An intelligent meter simulator, a software-driven simulation of a smart meter based on the regional solar irradiance profile, offers realistic real-time energy telemetry, and an automated listing system to maintain the availability of the marketplace at all times during peak generation periods.

The suggested five-stage transaction lifecycle provides a good enforcement of security and fairness strains, and the implementation of reliable trade execution under a few seconds. It is integrated with a DEPA-inspired consent framework that will guarantee that every operation must be explicitly approved by the user to increase the level of transparency and trust. Economic analysis proves that the platform has a considerable positive economic impact on the financial performance of both parties, as well as allows to measure the reduction in the carbon emission by local use of renewable energy. Even though the present implementation is a prototype with limitations (simulated data and fixed prices) it creates a usable and regulation-conscious basis of decentralized energy trading. The future work will be aimed at the integration of the actual smart meter infrastructure, the dynamic pricing mechanism, and the extension of the system to large-scale implementation.

Finally, UrjaMitra shows that peer-to-peer energy trading at the neighborhood level is technically, economically and scalable and is a promising solution to sustainable and decentralized energy management in India.

ACKNOWLEDGMENT

The authors would like to acknowledge the Department of Information Technology, the Institute of Information Technology, AISSMS, Pune, as it was in this academic setting that enabled them to carry out this work. The faculty members are given special credit and their advice and comments are credited to the creation and solution of this study.

REFERENCES

- [1] Zhang, C., Wu, J., Zhou, Y., Cheng, M., and Long, C. (2018). Peer-to-Peer Energy Trading in a Microgrid. *Applied Energy*, 220, 1–12.
- [2] Sousa, T., et al. (2019). Peer-to-Peer and Community-Based Markets: A Comprehensive Review. *Renewable and Sustainable Energy Reviews*, 104, 367–378.
- [3] Tushar, W., et al. (2020). Peer-to-Peer Trading in Electricity Networks: An Overview. *IEEE Transactions on Smart Grid*, 11(4), 3185–3200.
- [4] Khorasany, M., Mishra, Y., and Ledwich, G. (2021). A Decentralised Bilateral Energy Trading System. *IEEE Transactions on Industrial Electronics*, 68(4), 3403–3414.
- [5] Ministry of Power, Government of India. (2022). Electricity (Amendment) Act 2022.
- [6] Bureau of Energy Efficiency (BEE). (2019). Technical Specification for Advanced Metering Infrastructure. New Delhi: Ministry of Power.
- [7] NITI Aayog. (2020). Data Empowerment and Protection Architecture. New Delhi: Government of India.
- [8] Mengelkamp, E., et al. (2018). A Blockchain-Based Smart Grid: Towards Sustainable Local Energy Markets. *Computer Science Research and Development*, 33(1), 207–214.
- [9] Lüth, A., et al. (2020). Local Electricity Market Designs for Peer-to-Peer Trading. *Applied Energy*, 229, 1233–1243

