Utilization of a Blockchain-based Reputation Management System for Energy Trading in Smart Grid 2.0

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***Abstract*—The futuristic energy grids comprise of predominantly renewable generation, to align with the sustainable development goals. This would require integration of renewable energy sources at different levels of the power system out of which, consumers turning into power producers, often referred to as prosumers is an important aspect. Prosumers who generate excess power beyond self-consumption are keen on selling it to the neighbourhood in a peer-to-peer manner, expecting a profit. On the other hand, consumers expect concessions for using more of the green energy. Further, with the high intermittency of these generation, Distribution System Operators (DSO) face the challenge of securing a reliable power supply. In the envisaged grid context, deciding the price for energy trading between prosumers and consumers as well as estimating the reliability of each DSO is considered to be crucial. Hence, this study proposes utilizing an end-to-end reputation management system to maintain the past record related to the performance of each stakeholder, which can be integrated in the price determination and selection decisions. To further ensure decentralized and secure operations of such reputation management systems, a blockchain-based service architecture and smart contracts have been incorporated. The impact of this to the performance of the proposed energy trading system is analysed through cost and latency indices.**

***Index Terms*—Blockchain, Peer-to-Peer Trading, Reputation Management, Smart Contracts, Smart Grid 2.0, Supply-Demand Balancing**

I. Introduction

Internet-based services are identified as a prospective solution to overcome the challenges observed in the traditional electricity grids and the first generation of smart grids. These integrated services facilitate meeting the demand for electricity within the locality with minimal involvement of a central authority. The envisaged era of electricity grids, "Smart Grid 2.0 (SG 2.0)" is the next generation of electricity generation and distribution. SG 2.0 caters to stakeholders related to electricity generation, transmission, distribution, and consumption by enabling connectivity among one another through the internet [1], hence also known as Internet of Energy (IoE). This has come to exist [2] to achieve an automated grid architecture that has a minimum influence of a centralized authority.

Two prominent SG 2.0 applications have been identified for this study, and their blockchain-integrated operations are elaborated. The first application is Peer-to-Peer (P2P) energy trading, which enables electricity producers (prosumers) to interact directly with buyers (consumers) without the involvement of an intermediary [3]. Prosumers are capable of trading their excess renewable energy generation with the neighboring consumers who are willing to buy electricity from clean energy sources [4]. Consumers expect to receive a reliable electricity supply harvested from renewable energy sources, delivered at an acceptable power quality. Meanwhile, prosumers are concerned about the excessive consumption of electricity by the consumers. Second application involves the interactions between the Transmission System Operator (TSO) and the Distribution System Operators (DSOs) to select prospective generation options and maintain supply-demand balance for stable grid frequency. This decision is made based on the energy storage capacity of each DSO [5], where DSOs with excess capacity will contribute towards better frequency regulation by facilitating a reliable supply-demand balance.

Electricity price plays a key role in increasing both prosumer and consumer participation in P2P trading and at the same time restrains the excessive consumption of electricity. Proper coordination of trading patterns is required to maintain the power quality within desirable limits. Moreover, criteria to select prospective prosumers, consumers and DSOs to participate in energy trading transactions should be based on a fair process that evaluates the contribution of each individual to the desirable operations of the smart grid, in the context of reliability and power quality. Estimating the reputation score of each stakeholder, which reflects their past performance has been identified as a suitable approach in literature to improve the operations of smart grids. However, these solutions have restricted their scope to optimizing the reputation of an individual stakeholder, while the effect of others have not been considered.

To address the identified research gap, this study proposes a cohesive reputation management system for SG 2.0 architecture and evaluates its utilization in P2P energy trading and TSO-DSO transactions. The reputation management scheme incorporates historical data into the decision-making process to improve its performance. A decentralized, transparent, and secure mechanism, which has the capabilities of automated execution of the P2P energy trading and facilitating DSO-TSO interactions, is seen as a timely requirement. Blockchain, a Distributed Ledger Technology (DLT) [6], creates a conducive environment for the realization of the applications of SG 2.0 [5], [7], [8] along with smart contracts, which are automated scripts of the process deployed onto the blockchain. Hence, the proposed reputation management system is integrated with the blockchain architecture and automated using smart contracts.

The rest of the paper is organized as follows: Section II provides a concise survey of existing works. Section III introduces the proposed architecture, whereas prototypical implementation is discussed in Section IV. Section V elaborates on the experimental results. Section VII presents the concluding remarks and summarizes the future work followed by this study.

II. Related Works

Previous studies have evaluated the feasibility of using reputation scores for generation dispatching and seller selection operations [9]. Matchmaking of seller and buyer offers in P2P trading based on the respective reputation scores is elaborated in [10]. The reputation scores of this blockchain-based solution indicate prosumer commitment towards P2P trading. However, the effect of consumption patterns has not been considered in this analysis.

Studies presented in [11] and [12] have analyzed the impact of integrating the sellers' reputation factors in the selection process, reflecting the prosumer's past performance in delivering the committed energy. However, the calculated reputation score is not integrated in the determination of the electricity price, which would further offer a competitive advantage for both consumers and consumers with high reputation scores.

Previous studies have further emphasized the importance of considering supply-demand balance along with P2P energy sharing to increase the monetary benefits [13], [14]. However, co-existance of stakeholders including DSOs is often neglected and further, the impact of P2P trading patterns on the power quality of the network is not considered. Implementing a comprehensive solution, integrating all major stakeholders such as prosumers/consumers and DSOs was identified as a timely requirement. Therefore, this study aims to address these identified research gaps as follows: proposing a marketplace service to select a seller-buyer pair for P2P trading with the highest reputation while determining the electricity price based on their historical records, and an automated selection service for the TSOs to effectively utilize the available excess generation and storage capacity of the DSOs, to achieve the balance between electricity supply and demand. Together these eliminate the risk of,

- Single-point failure arising due to the dependence on a central authority
- Privacy violation of data with a large number of grid integration
- Less reliable electricity supply with low power quality
- High electricity prices are being paid by consumers for renewable energy generation despite poor power quality.

Further, previous studies have not evaluated the impact of incorporating blockchain architecture with smart contracts to automatically execute reputation management and other relevant processes of energy trading within the smart grid. Thus, the blockchain-based service architecture proposed in this study provides an end-to-end solution to the envisaged SG 2.0.

III. Blockchain-based Service Architecture for Smart Grid 2.0

This study presents a novel architecture to facilitate P2P energy trading and TSO-DSO interactions in SG 2.0. The main stakeholders are electricity users (prosumers and consumers), DSOs, and TSOs. Blockchain is proposed to offer services to P2P energy trading and supply-demand balancing, and the basic functions of the proposed platform are elaborated with the rationale. The high-level overview of the proposed platform is depicted in Fig. 1.

A. User Registration

A new user has to register with the proposed platform through the registration service, prior to receiving/participating in any service offered. Further, this enables managing user information for future reference and identification.

An account is created whenever a new user (prosumer/consumer/DSO/TSO) accesses the platform. Upon verifying whether an account already exists, user enters details including name, address, location, and generation/storage capacity information, which are subsequently stored in an off-chain database such as InterPlanetary File System (IPFS). The hash corresponding to stored data is included in the blockchain. Each user is given a unique ID, which can be used for referencing and performing transactions, without revealing the true identity. Smart contracts guarantee that only one account is created per user.

Upon successful registration, a universal wallet is created in the blockchain for each stakeholder. Usage charges are deducted from the available balance while electricity sales revenue is credited directly to this wallet, through the deployment of smart contracts. Each wallet represents a user registered with the system through a unique pseudo-identity, which allows the user to participate in a decentralized network without revealing the true identity. This preserves the security and privacy of the user, which is not an available feature in the current system, where each electricity user is required to reveal details, including electricity account number, name, address, and connected DSO details, in a public domain, which raises security and privacy concerns including identity spoofing.

B. Reputation Management

The reputation management function of the proposed system is responsible for maintaining the reputation score for each registered stakeholder to capture the historical performance in the current transactions. This will discourage undesirable behaviour in the electricity grid. Citeria selected

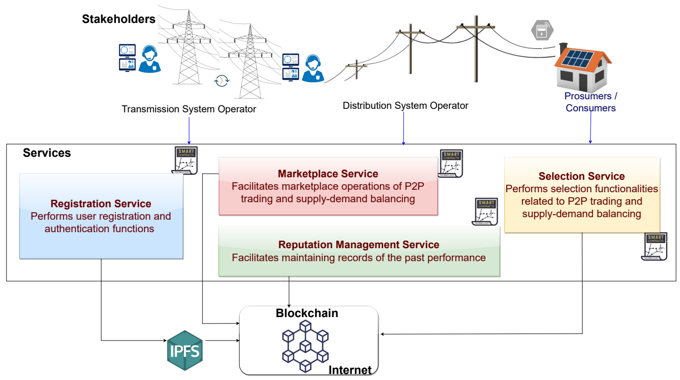

Fig. 1: High-level view of the proposed architecture

to calculate the reputation value reflects the stakeholder's behaviour, on the smart grid's normal operations. Incentives will be given to those who adhere to the prescribed standards, while penalizing the deviations, which create negative consequences on the grid. At the instance of registration, the system sets the reputation score of each user to the average value, to maintain equality among the users. This will be later updated upon the successful completion of each transaction, using the relevant data.

1) Prosumer reputation: Integrating large volumes of solar Photo Voltaic (PV) installations in an uncoordinated manner negatively impacts the voltage profile and the power quality of the electricity grid. Even though several initiatives focus on trading excess power generation from the consumer, within the neighborhood, the majority of them do not consider the consequences of random trading patterns in this transactive energy market. Undesirable voltage fluctuations and harmonic components have been observed as factors that degrade the power quality. Hence, this study incorporates the contribution of each prosumer towards maintaining the voltage profile within the desirable limits, with many solar PV installations. Prosumer reputation score R_P reflects the contribution of their generation to the voltage rise identified in the electricity grid. The percentage contribution of each PV installation to the cumulative voltage rise is proposed as the prosumer reputation score in this study, as given in Eq. 1.

$$R_{Pi} = \frac{Voltage\ rise\ due\ to\ i\ th\ prosumer}{Total\ feeder\ voltage\ rise} \tag{1}$$

2) Consumer reputation: The consumer reputation score R_C is determined by their energy consumption patterns, as in Eq. 2. Individuals exhibiting an electricity consumption close to the average value determined for the consumer category are allocated a higher score. Such an initiative will encourage consumers to reduce excessive consumption while gaining more visibility during the bidding process.

$$R_C \propto \frac{1}{Excess\ over\ average\ consumption} \tag{2}$$

3) DSO reputation: A reliable energy supply is key to a satisfied consumer, which is catered through balancing the supply with the demand. This is mainly affected by the capability of a DSO to follow the dispatch request sent by a TSO. This is determined by its availability of excess generation with sufficient energy storage capacity. This study selects this criterion as the reputation score for the DSO R_{DSO} as in Eq. 3, which further emulates a reliable energy supply.

$$R_{DSO} = \%\ of\ storage\ capacity \tag{3}$$

The prosumer and consumer reputation scores are incorporated in calculating real-time electricity prices for P2P electricity trading. In the meantime, the selection process of viable DSOs for supply-demand balancing incorporates the DSO reputation score. The reputation scores are updated at the end of each transaction, with the measurements obtained from the current phase.

The functionalities proposed in the novel architecture to facilitate P2P energy trading and supply-demand balancing in SG 2.0 are illustrated in Fig. 2.

C. Marketplace Service

Registered prosumers and consumers will participate in energy trading in a P2P manner by following the below procedure.

The process is executed in an intra-day electricity market in which a consumer requests to purchase energy from a nearby seller during the next hour. The bidding starts, and the sellers offer bids corresponding to the electricity selling price. Consumers place their bids for their energy requirements. The market clearing price for the transaction is calculated by incorporating the reputation scores of both the prosumer and the consumer. Thereafter, the seller will select the highest bid and the transaction is initialized.

The proposed pricing strategy calculates the profit margin $M_{proposed}$ based on the prosumer and consumer reputation scores, which is added to the regular electricity cost comprising the cost of generation and transmission overhead. The proposed pricing mechanism's objective is to incentivize prosumers who engage in P2P energy trading by offering a higher price than the existing market price. As a holistic approach, the profit margin should be proportional to the pro-

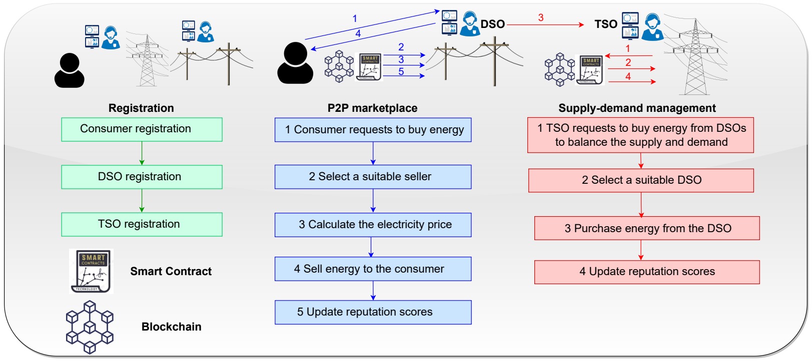

Fig. 2: Functions of the proposed architecture for blockchain integrated SG 2.0

sumer's reputation score while being inversely proportional to the consumer's, as given in Eq. 4.

$$M_{proposed} \propto \frac{R_P}{R_C} \tag{4}$$

D. Selection Service

Registered DSOs will contribute to the supply-demand management process through their excess storage. The proposed DSO selection service is triggered upon determining the dispatch order for the next time slot. The reputation score of the DSO is incorporated as a selection criterion, which reflects the excess generation and storage capacity of the DSO.

IV. Implementation

This section elaborates on the deployment of smart contracts to incorporate the proposed reputation management system in P2P energy trading and supply-demand balancing. The proposed approach is implemented as a prototype using an Ethereum-based Decentralized Application (DApp), where its performance is evaluated using the Ropston test network, to emulate the Ethereum main net.

Smart contracts automate the process execution, which will be triggered upon fulfilling the favorable conditions. Upon reaching consensus, verified transactions are added to the next proposed block, and the blockchain miners mine this block to be added to the sequence. Thus, transactions become immutable and minimize the issues related to double-spending. Smart contracts associated with the proposed architecture are explained below.

1) User registration contract: Users with a valid electricity account number can register with the network, allowing them to engage in P2P trading. User verification is performed to ensure that a particular consumer is registered and prevent unauthorized access to the network to guarantee the security of transactions. Prosumers among the users will be further registered as a seller and the energy source as a resource through prosumer and resource registration contracts, respectively.

2) Reputation management contract: Updates the reputation scores of prosumers, consumers, and DSOs. These will be utilized in price calculations in P2P trading and in determining the DSO dispatch order.

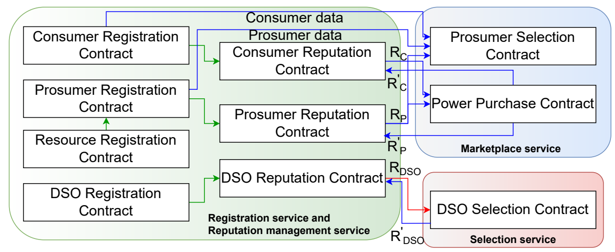

Fig. 3: Interactions between smart contracts

3) Prosumer selection contract: The contract is initiated once a consumer sends a request to buy electricity from the proximity.

4) Power Purchase contract: The tasks scheduled for this contract include calculating the electricity charge, authorizing payments, and settling the consumer and prosumer wallets. The modified electricity price is calculated based on Eq 4.

5) DSO selection contract: This contract facilitates the selection process of a DSO for supply-demand balancing.

Fig 3 represents the interaction between these smart contracts.

V. Numerical Analysis

Tests were conducted to compare the proposed service architecture with the current electricity market operations. Further, the impact on the system's performance by the blockchain integration and deployment of smart contracts is analyzed through the cost of smart contract execution and transaction latency. The execution costs corresponding to the deployment of smart contracts are obtained from the Remix IDE, where the smart contracts were coded in Solidity language. Latency measurements are observed from the time elapsed between transaction initiation and transaction completion.

A. Comparison with the conventional electricity grid operation

A comparison of the electricity price between the current scheme, which does not incorporate a reputation score, and the proposed reputation-based approach is illustrated in Fig. 4. It is considered that the current electricity market offers a constant profit margin, added to the electricity cost. The proposed scheme integrates a reputation-based profit margin, and it is designed to attract more prosumers and consumers to gain maximum benefits by delivering a reliable power supply with enhanced quality.

The expected profit margin of the proposed pricing structure can be determined according to the market requirements. This further indicates the expected prosumer and consumer reputation scores for the market operations. Such initiation will inevitably sustain the power quality, even with a significant amount of renewable grid integration.

B. Latency

Smart contracts associated with the services were deployed by using dummy data as inputs, and the time taken from the initiation of the request to get the transaction recorded in a block was measured through the Ropston test net. To improve the accuracy, 100 simulations were performed, and the average value is recorded with a 95% confidence interval in Table I. The user registration function was simulated by deploying the respective contract while providing dummy user data as inputs to the DApp. The time taken for the registration request to be approved by the blockchain and added in the next block, after authentication of the input data and verifying that the user doesn't already exist, is considered as the latency in Table I. Selection functions measure the time taken to determine the seller/DSO, which fulfills the criteria and validates the transaction by the blockchain miners. P2P marketplace contract handles the electricity price calculation and payment settlement functions. Hence the corresponding time is recorded from the test network, upon verifying the transaction by the blockchain. Finally, the reputation management function updates the scores after every verified transaction and records the updated values in an immutable manner, for future purposes.

All the above measure times include an average block creation time on the Ropston test network, which lies in the range of $15 - 30s$.

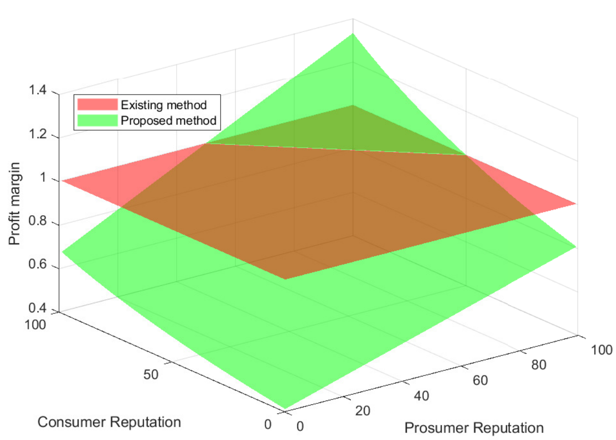

Fig. 4: Comparison of profit margin for existing and proposed systems

C. Cost analysis

A transaction cost is incurred to send the smart contract code to the blockchain along with the relevant data for validation. This depends on the size of the contract. The complexity of execution of each transaction on the Ethereum network is quantified by a scalar value known as gas. Gas price defines the amount a user pays for the gas used for the computation, which is a dynamic quantity determined by the market competition. The miners will be paid the value of $gas \times gas\ price$. Hence they tend to select transactions that offer the highest gas price, into the next block that is mined. Gas limit is the parameter, which is the maximum amount of gas the transactor is willing to spend. Any unspent gas will be refunded to the user.

To avoid unnecessary competition, the priority fee (gas price) is defined as 2 Gwei in the experiments carried out. Further, the gas limit of each contract is set to 2000000 Gwei. The transaction cost of each smart contract associated with the P2P marketplace and supply-demand balancing operations is obtained from the Remix IDE, as given in Table II.

VI. Discussion

The profit margin obtained from the proposed system is higher than the current scheme, in cases where high prosumer and reputation scores are observed. This is considered an incentive for prosumers, who contribute to power generation while strictly adhering to the power quality regulations. In the meantime, consumers are guaranteed a clean and reliable power supply, to compensate for the additional cost they incur while purchasing electricity from the P2P market, compared to the utility supply. Moreover, the profit margins obtained for lower prosumer and consumer reputation scores are justifiable as this provides a clear warning to each stakeholder to fulfill their responsibility by delivering power with better quality and purchasing electricity generated from renewable sources, to increase their ratings. Maintaining higher reputation scores, thus, provides an incentive for both sellers and buyers, in terms of a market-dependent electricity price.

It is evident from the results that the block creation time of the utilized consensus algorithm affects significantly the latency observed between transaction initiation and completion. This will create limitations on the number of transactions the system will be capable of processing during the market

TABLE I: Latency measurements for smart grid operations

Contract	Latency (s)
User Registration	25.8400 ± 2.2955
Resource Registration	25.7600 ± 2.3660
Seller Selection	39.5900 ± 4.2579
DSO Selection	39.8000 ± 4.2326
P2P marketplace	80.6000 ± 6.6675
Reputation Management	23.8600 ± 1.6766

time frame of one hour. To overcome such difficulties, it is suggested to adopt an efficient consensus algorithm, which will significantly reduce the block creation time.

The total cost incurred in the execution of the smart contracts related to the P2P trading application is approximately $5.19, which is a relatively economical solution. Furthermore, the execution of smart contracts related to supply-demand balancing utilizing the storage capacity available in DSOs associates a cost of approximately $4.35. Thus, the costs incurred in smart contract execution are significantly less and could be conveniently attributed to the overall energy cost.

VII. Conclusion and Future Works

This paper proposes a novel blockchain-based architecture to facilitate applications of the envisaged SG 2.0. The proposed platform introduces a universal account to the users, which enables authorized access to the system. In addition, smart contracts are deployed for decision-making without the intervention of a third party, in different functions of SG 2.0, such as P2P energy trading and supply-demand balancing. Furthermore, a blockchain-based reputation management system facilitates enhancing the services offered by the proposed architecture. The proposed architecture is evaluated on the Ethereum blockchain platform and analyzed performance factors, including transaction cost and latency associated with the procedure.

The results reflect that the proposed approach is cost-effective, offering the benefits of a secure, privacy-preserving yet decentralized and transparent platform to conduct SG 2.0 operations. This standout among existing blockchain-based solutions, since it delivers several functionalities to address challenges revealed in previous work related to SG 2.0. The analysis presented in the paper focuses on evaluating the impact of blockchain integration on reputation management systems catering SG 2.0 architecture. However, in a macro scale, the performance of the proposed system has to be evaluated considering different DSO configurations comprising of the heterogeneous energy mix and the social welfare of the prosumers/consumers needs to be accounted for. These factors are expected to be incorporated as an extension to this study as future prospects.

TABLE II: Transaction costs for smart contracts

Smart contract	Execution Cost	
	Gwei [a]	USD
Consumer registration	620635	1.14
Prosumer registration	224317	0.41
Resource registration	354311	0.65
Prosumer selection	745263	1.36
Power purchase	782472	1.43
Reputation management	108291	0.20
DSO registration	174677	0.32
DSO selection	2284270	4.18
DSO Reputation management	90371	0.17

[a] 1 Ether (ETH) = 10^9 Gwei, 1 ETH = USD 1829.23 on 05.08.2023

This study will be further extended to optimize the delay incurred with the services executed through blockchain-based smart contracts. This will lead to improvements in the scalability of the system through an increased number of users the service can deliver at a given instance. An efficient consensus mechanism will facilitate this objective by reducing the latency incorporated into solving a complex cryptographic puzzle. Current consensus mechanisms include an additional computational burden, which can be eliminated by the introduction of a smart grid-specific algorithm.

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