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Utilization of a blockchainized reputation management service for performance enhancement of Smart Grid 2.0 applications

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ABSTRACT

Blockchain has become the technology enabler in delivering modern Smart Grid 2.0 functionalities. Many services including Peer-to-Peer energy trading, distribution network management, financial settlements, and energy data management are catered through blockchain-enabled platforms. However, areas such as service quality-based pricing strategies, supply–demand balancing in distribution system to attain enhanced reliability and consumption-oriented rewarding mechanisms need improving in order to achieve the full benefits of the envisaged grid architecture. In response, this study proposes a novel Blockchain-as-a-Service for Energy Trading (BaaSET) platform, which offers reputation-based services, executed through smart contracts for smart grid applications. Reputation-based grid operations are automatically executed through smart contracts deployed onto a blockchain. The reputation is estimated using power quality and reliability indices, obtained through grid measurements. Further, tests have been conducted to evaluate the associated latency and the implementation cost of the proposed blockchainized service architecture. Test results signify the performance to be comparatively better considering the state-of-the-art. The results further suggest alternatives to improve the scalability of the architecture, to cater the increasing number of stakeholders in the SG 2.0 environment.

1. Introduction

Smart grids are identified as the solution for meeting rising electricity demands by bringing together diverse energy sources closer to where power is needed. They offer various advantages such as integrating Renewable Energy Sources (RES) more smoothly, establishing dynamic energy markets, and enabling automated grid operations [1]. Unlike traditional grids that only allow one-way power flow, smart grids use bidirectional communication with numerous measurement and control devices, leveraging the capabilities of the Internet of Things (IoT).

Smart grids are the driving force towards a future in electricity distribution, which involves less reliance on intermediaries such as the Distribution System Operator (DSO) while encouraging increased consumer involvement [2,3]. This shift has given rise to the concept of the Internet of Energy (IoE), often referred to as Smart Grid 2.0 (SG 2.0). SG 2.0 aims to execute decentralized grid operations with minimal intermediary interference. It offers services independent of intermediaries, such as Peer-to-Peer (P2P) energy trading for proactive prosumers, advanced distribution network management integrating grid automation, and Demand-Side Management that allows consumers to actively balance supply and demand. The architecture of SG 2.0 is outlined Fig. 1. The glossary of terms used in the article is given in Table 1.

The advancement of SG 2.0 faces various challenges, which require attention for its practical application. To ensure integrity and privacy, it is important to control the access privileges given to stakeholders. Further, a platform supporting the automated execution of distributed operations is necessary to realize the goals of future energy grids. This includes supply–demand balancing to sustain grid stability, enhance the reliability of the power supply, and maintain the power quality within desirable limits. Transparent and tamper-proof data management is essential to enable such operations with minimal third-party involvement. Blockchain technology has emerged as a promising solution due to its inherent characteristics such as being distributed, immutable, secure, and pseudonymous. Smart contracts, executed on blockchain, facilitate autonomous operations, eliminating the need for intermediaries.

Blockchain technology has significantly impacted various sectors such as finance, healthcare, and supply chain management [4,5],

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Table 1
Glossary.

Acronym	Definition
Blockchain-as-a-Service for Energy Trading (BaaSET)	Proposed blockchain-based service architecture for energy trading in Smart Grid 2.0
Decentralized Application (DApp)	Web application developed to provide input data for Smart Contract execution
Distributed Generation (DG)	Generation located close to the consumer loads
Distributed Energy Resources (DER)	Energy resources including renewable generation and storage facilities, located close to the consumer
Demand Response (DR)	An initiative where consumers adjust their electricity consumption during peak hours in response to the available generation
Demand Side Integration (DSI)	Voluntary participation of the consumers in facilitating to maintain the supply–demand balance, by either selling the excess generation or adjusting the consumption patterns
Distribution System Operator (DSO)	A central authority responsible for co-ordinating the operations of the distribution network
Demand Side Management (DSM)	Adjusting the consumer demand to match the available generation,
Energy Storage System (ESS)	Battery storage and alternative energy storage such as pumped hydro plants, hydrogen storage
Internet of Energy (IoE)/Smart Grid 2.0	Future electricity grids with bi-directional energy flow and communication deployed over the Internet
Renewable Energy Sources (RES)	Energy resources including solar Photovoltaic and wind generation

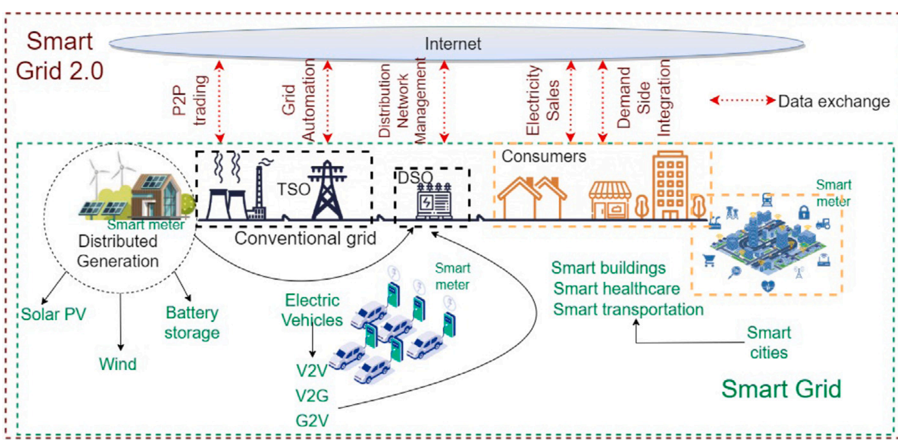


Fig. 1. Smart Grid 2.0 architecture.

healthcare [6,7], and supply chain management [8–10]. In the context of smart grids, attempts have been made to leverage commercial blockchain platforms for the transformation of traditional grids to the next generation, as highlighted in previous studies [2,11]. However, these efforts have not provided an adaptable solution for the diverse applications of smart grids. Existing solutions tend to focus on specific use cases, whereas there is a recognized need for a more universal approach [2,12,13]. This study emphasizes areas that have not been adequately addressed, such as implementing dynamic pricing strategies that consider prosumer selling patterns and consumer behaviour, assessing the surplus generation capacity of DSOs to ensure reliable power supply, and offering attractive incentives to participants in demand-side management. These aspects remain insufficiently covered by existing research in the field.

In response to the identified SG 2.0 goals and opportunities available to achieve them in the current context, this work proposes a novel Blockchain-as-a-Service for Energy Trading (BaaSET) platform. The services offered through BaaSET cater user verification, P2P marketplace operations, selection service for network management, reputation management, and immutable data management. Further, this offers the benefit of implementing transparent pricing mechanisms and dynamic incentive schemes, with the maintenance of continuously updating reputation scores.

This is the very first implementation related to blockchainized service delivery for the envisaged SG 2.0 architecture, to the best of the knowledge of the authors. The proposed Blockchain-as-a-Service aims to evaluate the associated latency and cost of implementation thereby, propose improvements to elevate the performance of the SG 2.0 network. The services are implemented on a blockchain platform, to be delivered at an affordable cost.

Contributions of this paper can be summarized as follows:

- Propose a novel, Blockchain-as-a-Service for Energy Trading architecture for SG 2.0, which offers electricity network-related services to connected stakeholders. This is the first of such platform, presented for smart grids to the best of the knowledge of the authors.
- Implement a comprehensive set of blockchainized services, to facilitate operations of SG 2.0, including user management service,

marketplace service, selection service, reputation management service, payment settlement service, and energy data management service .
- Evaluation of the cost, latency, and scalability of BaaSET platform in a simulation environment and validate the integration of blockchain to facilitate the SG 2.0 services delivered by the proposed architecture.
- Assess alternative techniques that can be integrated to improve the scalability of the blockchainized service platform, by reducing the associated latency.

The remaining sections of the paper are organized as follows: Section 2 discusses the background and existing challenges identified in the operations of SG 2.0 with a summary of the related work. Section 3 elaborates the proposed BaaSET platform for SG 2.0, highlighting the associated stakeholders and services that are offered. Section 4 presents a detailed overview of the services offered with their implementation. Sections 5 and 6 summarize the results obtained from the simulation setup and the deployment of the BaaSET platform on an existing test network, respectively.

2. Background

2.1. Smart Grid 2.0

Smart grids have been identified as a reliable solution to the rising demand for electricity, which integrates advanced metering facilities for monitoring with communication networks handling the information exchange. However, decentralization has not been fully implemented with the involvement of an intermediary such as the DSO [1]. DSO is responsible for the operations within the distribution system, including generation coordination to balance the demand with the available supply, infrastructure planning, management, and fault clearance. The second generation of smart grids (Smart Grid 2.0) has evolved through the timely requirement, offering better connectivity at a distributed level of operations. SG 2.0 embodies microgrids containing distributed RES, which are monitored using IoT devices and controlled through Artificial Intelligence (AI) technologies [14]. Further, distributed computing utilizing edge devices and big data handle the energy data management system, to delegate operations of SG 2.0 [15]. This envisions optimization of the existing infrastructure to facilitate decentralized, autonomous grids. Applications of SG 2.0 can be identified as P2P energy markets, microgrids establishing local energy operations with grids integrated RES, Demand Side Integration (DSI) to facilitate Demand Side Management (DSM), co-coordinated distribution network management, and energy data utilization to improve the accuracy in decision making [11,16].

2.2. Existing challenges in Smart Grid 2.0

Several challenges have been identified in reaching the goals outlined by the envisaged SG 2.0 architecture. This section outlines such challenges identified during practical applications and highlights the viability of utilizing blockchain and smart contracts to resolve them.

- Access control and identity management
  Automating authorization of access for verified parties while denying transactions from fraudulent entities is a challenge to overcome in the envisaged smart grids. Under the current context, such functionalities are handled through the DSO. In the light of achieving autonomy, it is important to ensure SG 2.0 security and privacy of the stakeholder data. Threats including identity spoofing to gain access to unauthorized access, injection of fraudulent data, modification of data and malicious node injection need to be eliminated in the envisaged SG 2.0 architecture [17].
- Dynamic price signalling in P2P energy trading
  Real-time electricity pricing schemes, which reflect how clean the received energy is, add value to the selection decision of the consumer and gain a competitive advantage for the prosumer. The current system does not adapt a criterion-based pricing mechanism [18] while a study presented in [19] incorporates the reputation of the prosumer in determining the market-clearing price for P2P trading. However, it should be noted that consumer engagement in sustainable energy consumption patterns would also play a key role in the future smart grids. Thus, integrating electricity consumption patterns of the consumer into the price equation, through a reputation score will give a better representation of the actual marketplace operation. A similar approach has been adapted for P2P energy trading and an emission trading system in [20,21] respectively, where the seller and buyer reputations are considered in formulating a priority value for the selection process.
- Impacts of connecting RES to the distribution network
  The connection of heterogeneous sources of energy, predominantly renewable generation, to fulfil the growing energy demand would be the driving trend of future smart grids. Electric Vehicles (EVs) dispersed in a wide area along with battery storage charging to store the excess energy and discharging to balance the demand deficiencies would create a dynamic power system. Integration of massive-scale converter-based technologies and expansion in an uncoordinated manner will lead to deterioration of power quality. Most importantly, a significant rise in voltage can be observed with high penetration of solar PhotoVoltaic (PV) [22]. Lack of standards to regulate power quality of heterogeneous connections will affect the consumer expectations related to the received electricity supply.
- Performance reflective incentive mechanism for Demand Side Integration
  Currently, incentives/penalties schemes incorporate fixed values, which does not reflect the level of compliance/non-compliance of the consumer to the contractual electricity consumption. Compliance is rewarded through a constant discounted electricity price, irrespective of the level of compliance, while deviations are penalized through a fixed price escalation, which is less transparent [23,24].
- Data management security
  Maintaining the integrity of the accumulated energy data has been identified as a scalability challenge, with the increasing number of nodes connecting to the grid. Massive IoT deployments have integrated billions of devices including smart sensors, smart meters, and intelligent controllable consumer loads, which efficiently transmit large data sets [25]. Transmitted data comprises electrical measurements, power consumption patterns, and identity credentials, where management of such sensitive information by a single point of authority creates trust issues, integrity breaches, vulnerabilities of unauthorized data access, and sharing [17].

2.3. Related works

Existing studies have evaluated the applicability of blockchain-based solutions in developing the SG 2.0 solutions and several of them have implemented a prototype of the proposed architecture. An EV charging pile management system based on a blockchain ecosystem is proposed in [26], where a security model is developed on a lightning network for user registration and identity verification. Further, [27] proposes a user authorization scheme, where the Key Management Centre (KMC) utilizes a Bloom filter along with Zero-Knowledge Proof (ZKP) for fast authentication. A review conducted in [28] highlights the applications of several present-day blockchain platforms in the domains of smart infrastructure, EV, and RES. Further, it analyses the blockchain integration with SG in different aspects including identity management, network management, automation management and consensus management and extends the discussion in the direction of challenges identified in each domain, hindering the implementation of SG applications. A study conducted in [6] has identified requirements of the smart grids while providing a guidelines to select an appropriate blockchain platform to cater them. Further, the study presents an extensive analysis on the technology gaps of blockchain platforms, to fulfil the requirements of the envisaged advancements in smart grids, which will be map for the future developments in blockchain. The applicability of blockchain platforms for energy network services can be justified through a similar review carried out for supply-chain management scenario [29]. Here the authors highlight how blockchain can integrate transparency, traceability, efficiency, and information security to the application and also emphasizes the lack of implemented cases as opposed to many of the conceptual studies evaluated.

P2P energy trading has been acknowledged as an effective method for reducing peak demand and benefiting proactive consumers to share their excess energy generation. The review presented in [30] discusses the physical and virtual layer elements, which are required for facilitating the P2P trading mechanism and the existing challenges in each of these layers including supply–demand balancing, dealing with uncertainty and asynchronicity, pricing mechanism, security and maintaining the power quality within the desirable limits. Further, technologies that could facilitate overcoming the challenges have been identified among which, blockchain is a promising candidate. An insightful discussion on the challenges that need to be addressed regarding P2P energy trading and advancements to overcome the constraints is presented in [31]. The study conducted in [32] emphasizes the importance of considering resilience in the context of supply-chain management, which can be adapted to energy grids as it is a dynamic system, prone to faults if the balance between supply and demand is not maintained. Brooklyn Micro Grid (BMG) is considered to be the first prototype implementation of a blockchain-based P2P energy trading platform [12]. BMG is implemented to share the excess solar energy generated by the prosumers with their neighbours, in exchange for cryptocurrency tokens. With the evolution of similar initiatives, seller selection and price scheduling in P2P trading, based on the past performance of the seller has been in discussion, in the recent era of smart grids. The lessons learnt from the studies conducted in [33,34] could be integrated in seller selection process of the P2P energy trading, where fuzzy-based and Stackelberg game approaches respectively, have been proposed for supplier selection in supply-chain management applications.Authors of [20] have elaborated on blockchainized matchmaking between seller and buyer offers. In this study, a priority value is formulated for decision-making based on seller and buyer reputation scores, which indicates their commitment towards P2P trading. The study presented in [18] has discussed how game theoretic approaches such as the Stackelberg game can be applied to determine a competitive electricity selling price, while [35] has analysed the impact of the reputation factor of the prosumer reflecting the past performance in delivering the committed energy in selecting a suitable seller, and implemented on a lightweight blockchain platform.

Consumers participating in DSI initiatives are rewarded or penalized with fixed rates in [23], which requires modification in order to maximize benefits received by the participants. Further, a blockchain-based, diagnostic service provider selection procedure is proposed in [11]. This study focuses on integrating blockchain platforms to provide efficient fault recovery services and coordinated distribution network maintenance, which lead to a reliable power supply with minimal interruptions. This approach can be further modified through a reputation-based selection scheme fro improved efficiency.

The existing studies have not implemented the identified requirements of future smart grid operations such as grid performance-based scoring for stakeholders, reputation-based pricing and selection mechanisms, and strategies to encourage stakeholders to enhance the power quality and reliability. The proposed service architecture caters the above requirements by offering reputation-based pricing and selection mechanisms for SG 2.0 operations. The reputation score is derived based on the historical performance/ contribution to enhance power quality and reliability. Further, it is suggested that the service architecture be deployed onto the blockchain and executed automatically through smart contracts, eliminating the requirement of a centralized entity.

3. Proposed BaaSET architecture

This paper proposes a Blockchain-as-a-Service for Energy Trading (BaaSET) platform, which delivers services to facilitate user and energy information management and reputation-based, P2P marketplace operations, supply–demand balancing of the main grid and consumer load regulation through demand side management alternatives. These further enable realization of the envisaged autonomous SG 2.0, and maximize the benefits through the integration of Distributed Energy Resources (DERs). BaaSET platform will be deployed as a modularized architecture, overlaying across the entire grid, which facilitates secure, privacy-preserving operations while eliminating the adversaries of single-point failure related to conventional centralized smart grid infrastructure. Smart contracts are utilized to provide the blockchain-based services.

BaaSET operates as an overlay entity, which is spread across the SG 2.0 ecosystem. An overlay blockchain enables utilizing the smart grid as well as non-smart grid nodes in the mining process hence, either a public or a consortium blockchain is suitable for the implementation of the proposed architecture. It is possible to utilize existing platforms such as Ethereum to implement the proposed services of BaaSET. Blockchain nodes assigned to each stakeholder are capable of performing customized services in the electricity grid. This offers the benefit of increased scalability to handle high volumes of transactions with low latency associated with data transmission.

The blockchain deployment model can be customized according to the capabilities of each connected stakeholder. TSOs, DSOs and diagnostic service providers who possess sufficient resources to handle computation burden will be operable as full nodes as well as miner nodes. Further, any external non-smart grid entity with sufficient computational capabilities will be operating as miner nodes in the overlay blockchain. Prosumers, microgrid operators and EVs, which possess comparatively less computational capabilities with their modularized data processing equipment will be serving as light nodes. These light nodes possess sufficient information from the blockchain to validate the SG 2.0 transactions and at the same time, they can request additional data from the DSOs, who will be maintaining a copy of the distributed ledger.

The stakeholders of the BaaSET architecture are required to provide information as inputs to the system, which in turn will execute the smart contracts, given that sufficient conditions are fulfilled. The input information can either be stored on-chain or use off-chain solutions such as Inter-Planetary File System (IPFS) and store the corresponding hash value in the blockchain in order to reduce the storage requirement. Data stored off-chain will be retrieved upon request for transaction verification and smart contract execution. Upon successful execution of the smart contracts to deliver the services of the BaaSET architecture, the results and measurements will be updated to the blockchain, which will be utilized for reputation score calculations in future transactions. The interaction between the on-chain (blockchain) and off-chain (IPFS) related to a transaction is illustrated in Fig. 3.

The BaaSET architecture is illustrated in Fig. 2. Stakeholders connected to the SG 2.0 gain the capability to obtain services that are offered by the BaaSET platform. Deployment of these services will be achieved through the smart contract execution on the blockchain platform.

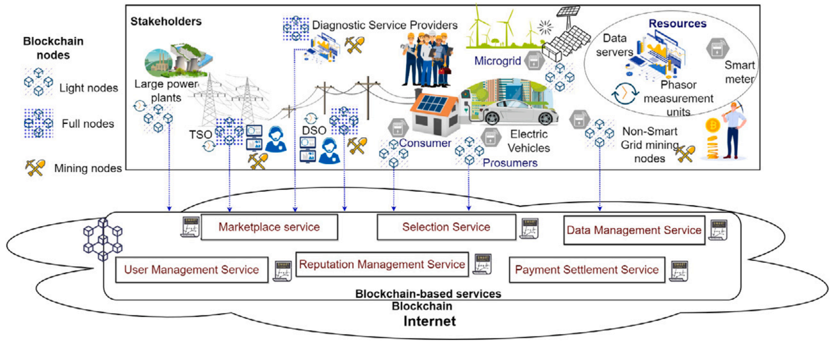


Fig. 2. Deployment of blockchain for BaaSET architecture.

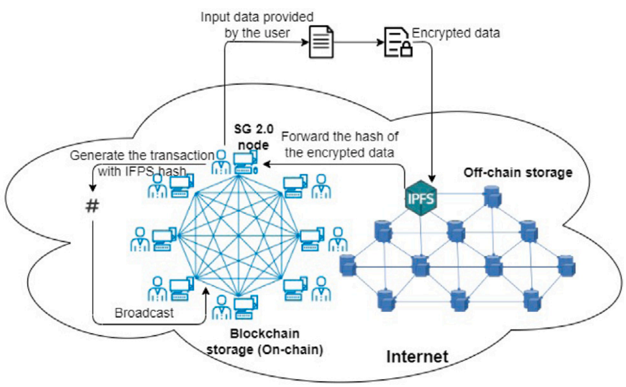


Fig. 3. Interactions between on-chain and off-chain for SG 2.0 transactions.

3.1. Key components of the architecture

The BaaSET architecture facilitates the delivery of services including, user registration and authentication, marketplace operations, electricity grid management, performance tracking for reputation calculation and information handling, to the stakeholders of the smart grid environment. These services are implemented through smart contracts, which are deployed onto the blockchain and the process is similar to carrying out online transactions through the internet. BaaSET services enable autonomous grid operations and facilitate the transition from traditional smart grids to next-generation realizations. The stakeholders involved with the BaaSET architecture and services delivered are listed below.

3.1.1. Stakeholders

BaaSET caters many parties involved in electricity generation, transmission, distribution, and the consumption. The list of stakeholders related to SG 2.0 is listed below.

- **Prosumers & Consumers:** These are the major stakeholders related to energy trading, which is the key transaction that takes place in SG 2.0 operations. Consumer liberalization has transformed their passive role into an active prosumer. This has diversified the alternatives in the electricity trading marketplace, ranging from large power plants to microgeneration, and EV charging piles. Consumers may voluntarily contribute to minimizing the load imbalance through smart homes.
- **Transmission System Operator (TSO):** This is the entity, which has the authority over the transmission network infrastructure and its management.
- **Distribution System Operator (DSO):** This is the entity, which has the authority over the distribution network infrastructure and management. DERs are typically integrated at the distribution level of the hierarchy of the electricity grid and are currently coordinated through the DSO.
- **Diagnostic service providers:** This includes device manufacturers and third-party entities that offer services malfunctioning and system outages.
- **Data analysts:** Smart grid 2.0 is predominantly driven through predictive analysis and intelligent decision making deployed using AI, Machine Learning (ML) techniques. Entities who offer services in big data management would play a significant role in the envisaged smart grids.

3.1.2. Services

BaaSET architecture delivers services that are listed below, to facilitate operations of the envisaged SG 2.0.

- **User Management Service:** Enables registration and authentication of participating stakeholders and their resources.
- **Reputation Management Service:** Calculates and stores reputation scores of different participating stakeholders, which reflect their historical performance related to smart grid operations.
- **Marketplace Service:** Facilitates retail electricity trading in a P2P manner.
- **Selection Service:** Executes a selection process to achieve proper coordination between the TSO and DSOs. This enhances the grid management capabilities with better fault recovery and efficient data analysis, which leads to accurate prediction of energy usage.
- **Payment Settlement Service:** Enables negotiations in dynamic agreements, which offer incentives/penalties and allow secure monetary transfers.
- **Energy Data Management Service:** Facilitates stakeholders and resources to store energy data and share them with authorized parties, securely and transparently.

Each of these services creates a value addition to the BaaSET-based SG 2.0 operations and an in-depth analysis is presented for the services mentioned above, in the following section.

4. Services in BaaSET

This section elaborates the implementation of the BaaSET service, identified in Section 3.1.2 in a step-wise manner and the acronyms relevant to the algorithms are summarized in Table 2. These services can be deployed individually or in conjunction with one another to facilitate the operations of SG 2.0.

4.1. User management service

This service is two-folds and offers the capability of registering stakeholders/resources and authenticating them before initiating the connection with the electricity grid. The overlay of this service on a blockchain platform enables trust establishment through the use of

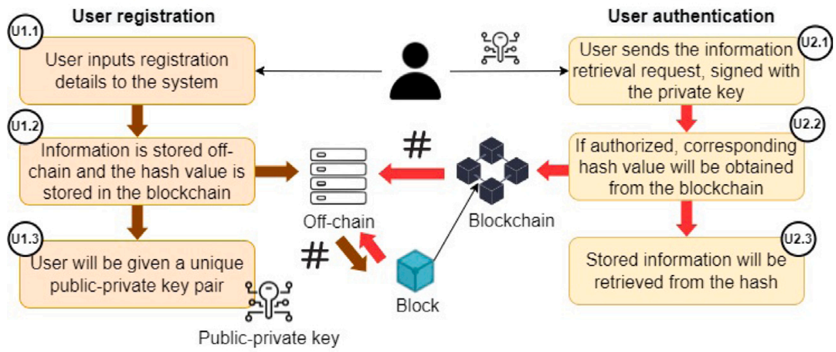


Fig. 4. Deployment of user management service.

Table 2
Summary of Notations.

Acronym	Definition
d	Distance from the LV transformer to the PV connected node
EP_{DSO}	Electricity price in TSO–DSO coordination operations
$EP_{DSO,max}$	Maximum electricity price in TSO–DSO coordination operations
EP_{MP}	Electricity price P2P marketplace
E_{PV}	Excess PV generation
J_{tot}	Total momentum of PV capacities
M_{new}	Proposed markup for electricity price
M_{pros}	Prosumer centric markup for electricity price
M_{trad}	Traditional markup for electricity price
MRT	Minimum Rating Threshold
R_C, R_{DSO}, R_P	Consumer, DSO and prosumer reputation score
S_{PV}	PV capacity
S_{res}	Reserve capacity of the DSO
SC_{DSO}	DSO Selection Score
W_{EP}	Weight of electricity price
W_R	Weight of reputation score

asymmetric encryption to authenticate user credentials, with minimal third-party participation. The steps that are followed in the process are summarized in Fig. 4 and elaborated below.

4.1.1. User registration

Registration of the user details is achieved through the following procedure.

U1.1 The stakeholder/resource anticipated to interconnect with the grid would require to provide the relevant credentials to the registration system. Table 3 elaborates the list of parameters requested by each stakeholder/resource upon a registration request made.

U1.2 The user details will be recorded in an off-chain platform such as IPFS to minimize the on-chain storage requirement and the respective hash will be stored in the blockchain.

U1.3 A unique public–private key pair will be assigned to each user. The public key preserves the pseudo-anonymity of the user among the blockchain peer nodes while the private key is utilized as the digital signature.

4.1.2. User authentication

User authentication upon receiving a grid interconnection request is performed in the following manner.

U2.1 Stakeholder/resource will send the interconnection request, encrypted with the private key. This request will be decrypted using the shared public key of the user for verification.

U2.2 Corresponding hash value will be obtained from the blockchain.

U2.3 Data will be retrieved by the authorized person.

4.2. Reputation management service

This service offers the capability of performing blockchain-based reputation management. This further facilitates tamper-proof record-keeping of data reflecting the past performance of the stakeholders and independent, transparent calculation of the reputation scores at the end of each transaction.

BaaSET proposes incorporating reputation scores in calculating real-time electricity prices for P2P electricity trading, integrating reputation score with selection process of suitable DSO, and associating consumer reputation with the rewarding mechanism for DSI participation. Thus, it is required to calculate the prosumer, consumer and DSO reputation scores for the implementation of the proposed marketplace, DSO selection and demand side management algorithms, respectively. The following sections elaborate on the calculation of each of these reputation scores.

4.2.1. Prosumer reputation score

Prosumer reputation score proposed by the BaaSET reflects the contribution of each prosumer engaged in energy trading, to the voltage rise identified in the electricity grid. Considering the context, which connects solar PV installations to the main grid, a voltage rise is observed in the Point of Common Coupling (PCC), which is a negative impact on the distribution feeder. Studies have revealed that the capacity and the location of the connected solar plant have an impact on the voltage distribution of the Low Voltage (LV) grid. A comprehensive study carried out in [22] investigates the relationship of these two factors on the observed voltage rise and defines a quantity, namely the momentum. It has further identified that the total momentum of the installed PV capacities shows a linear relationship with the voltage rise. The total momentum of the PV installations is calculated in [22] as given by Eq. (1).

$$J_{tot} = \Sigma(S_{i,PV}.d_i) \tag{1}$$

The total momentum of the PV installations is incorporated for the calculation of prosumer reputation score, in the BaaSET architecture. The percentage contribution of each PV installation to the cumulative momentum of the installed capacities is incorporated in calculating the prosumer reputation score, which is further described in Eq. (2).

$$R_p = (1 - (\frac{E_{PV}.d}{J_{tot}})) \tag{2}$$

Prosumers who contribute less to the total calculated momentum, hence creating a minor impact on the voltage profile would receive a

Table 3
Input parameters associated with the user registration service.

Type		Registration Details
Stakeholders	Electricity user	Name and address, Electricity account number, Connected DSO No., Ethereum address
	TSO and DSO	Owner name and address, ID, Ethereum address
	Ancillary services	Name and address, Ethereum address
Resources	DG	Electricity account no., Capacity, Price, Connected DSO no.
	EV and ESS	Electricity account no.. GPS location, State of Charge (SoC) of the battery, Price
	Charging pile	Electricity account no., GPS location, Price
	Large power plants	Owner's electricity account no., Capacity, Price
	Distribution network assets	ID, DSO no., GPS location
	Smart meters, smart sensors	Owner's name and address, Electricity account no.
	Smart appliances	Owner's name and address, Electricity account no. Expected electricity units consumption,

higher reputation score, in the proposed system. This further indicates that the consumers residing closer to the feeder have greater viability to connect solar PV installations to the main grid, whereas the distance becomes a limiting factor in increasing the capacity of generation for energy producers located at the far end of the feeder. This encourages the users to engage in energy trading within their close proximity markets, which benefits the main grid to maintain a better voltage profile with large-scale integration of RES.

4.2.2. Consumer reputation score

The consumer reputation score is considered to be proportional to electricity consumption patterns, where energy-efficient consumers will have a higher reputation. This will be incorporated in calculating the market-clearing price in P2P trading and determining the incentive/penalty received by the consumer who is participating in DSI initiatives.

4.2.3. DSO reputation score

To define the reputation of a DSO, we could incorporate its capability to follow the dispatch order from the TSO. TSO will formulate a dispatch order for the DSOs, based on the speculated demand for the next planning time horizon. A DSO's ability to follow this dispatch request is determined through the availability of excess generation with sufficient energy storage capacity and DSI facilities. Calculation of the DSO reputation score is given by Eq. (3)

$$R_{DSO} \propto S_{res} \tag{3}$$

Thus, DSOs, which possess higher percentages of excess generation/storage capacity and have better opportunities to integrate DSI options are given a higher reputation score in the BaaSET architecture.

Blockchain platform serves the best for the practical implementation of a real-time updated reputation management system, by offering tamper-proof data aggregation solutions, operating in a distributed and privacy-preserving manner.

The steps followed in the reputation management service are summarized below.

Step 1: Average reputation score is assigned as the initial value upon the registration of a new stakeholder.

Step 2: Upon completion of each transaction, reputation scores of the stakeholders engaged are updated to the blockchain according to the measured parameters given in Table 4.

Table 4
Input parameters associated with the reputation management service.

Type	Parameter
Prosumer	Capacity of PV installations traded during the transaction period, distance from LV transformer to each node
Consumer	Energy meter reading during the transaction period
DSO	Excess storage capacity available for trading during the transaction period

4.3. Marketplace service

Marketplace service facilitates the prosumers to trade surplus energy with the main grid in order to fulfilling the demand requirement of connected consumers. In the proposed BaaSET platform, DSOs select the prosumers who deliver energy with the highest power quality, facilitating consumers to receive a better service, in contrast to the traditional grid hierarchy. BaaSET achieves this through a parameter defined as the "Seller rating", which is calculated as a weighted ratio between the prosumer reputation R_P and electricity selling price EP_{MP}, as given in Eq. (4).

$$Seller\ Rating = \frac{(W_R * R_P)}{(W_{EP} * EP_{MP})} \tag{4}$$

A higher seller rating reflects a prosumer delivering energy with a higher power quality at the most economical price. DSO will select the prosumer, whose rating exceeds a Minimum Rating Threshold (MRT) (Eq. (5)), which is determined considering the requirements of the consumer who makes the energy purchase request.

$$Seller\ Rating > MRT \tag{5}$$

For instance, consumers with sensitive equipment demand for a power supply with higher quality thus, the weights and the MRT are determined based on these user requirements. Consumers thereby, get the opportunity of receiving an energy supply with a desired power quality for the price paid, which is not possible with the existing grid architecture.

To further enhance the benefits received by the consumer and prosumer, BaaSET market place service modifies the profit margin determining the electricity price, based on the prosumer and consumer reputation scores, as given in Eq. (6). Electricity price in the current context is calculated using the generation cost and network utilization fee (accounting for the transmission losses), to which a fixed profit margin M_{trad} is added [19].

$$M_{proposed} = M_{trad} * \frac{1 + R_P}{\alpha - R_C} \tag{6}$$

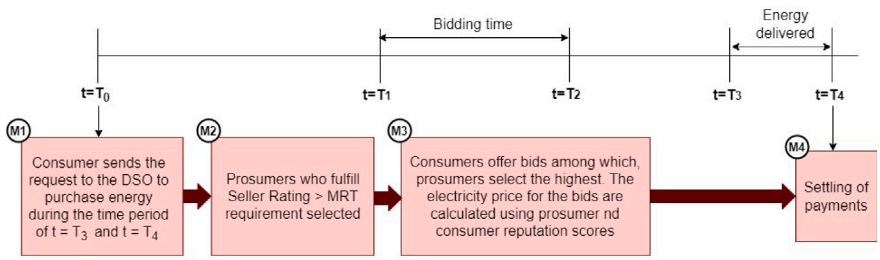


Fig. 5. Deployment of marketplace service.

Table 5
Input parameters associated with the marketplace service.

Type	Parameter
Prosumer	Electricity price offered, excess PV capacity traded during the previous transaction period, distance to the PV installation from the LV transformer
Consumer	Energy meter reading during the previous transaction period

Table 6
Input parameters associated with the selection service.

Type	Parameter
DSO	Electricity price offered and the excess storage capacity available during the transaction period

where, α is used to adjust the maximum benefit received by the prosumer and consumer, compared to the current marketplace context. The impact of incorporating prosumer and consumer reputation for the determination of the profit margin is further analysed in Section 5.1.

$M_{proposed}$ expects to reflect the impact of large-scale grid integration of RES (predominantly solar PV) to the voltage profile of the main grid as well as the buyer's electricity consumption patterns. These factors are captured by the BaaSET architecture, through the prosumer and consumer reputation scores, respectively. Prosumer reputation accounts for how clean the green energy is while consumer reputation score signifies the individual's sustainable consumption patterns. Blockchain facilitates record keeping by offering secure and tamper-proof data storage and sharing, for the accountability of the pricing strategy.

Fig. 5 summarizes the implementation of the marketplace service and the step-wise procedure is elaborated below.

M1 At $t = T_0$ consumers sends a request to the DSO for purchasing energy for $t = T_3$ - T_4 duration, from the close proximity.

M2 Seller Rating is calculated as in Eq. (4) for all prospective prosumers. Prosumers with their ratings exceeding the MRT will be screened for the bidding process.

M3 From $t = T_1$ to T_2, bidding takes place where each prosumer selects the consumer who offers the highest bid. The electricity price is calculated based on Eq. (6), with input parameters given in Table 5.

M4 During $t = T_3$ and $T = T_4$, energy transfer takes place and at $T = T_4$ the universal wallets of the prosumer and the consumer will be credited and debited respectively, with the corresponding electricity charge. Further, the reputation scores of the prosumer and consumer are updated upon completion of the transaction.

4.4. Selection service

The selection service offered by the BaaSET architecture is capable of facilitating DSO energy trading with the TSO, to ensure a reliable power supply. TSOs are responsible for the supply–demand management of the electricity grid, which is achieved through coordinated dispatching of the generation (non-renewable and renewable) connected to different DSOs. Proper coordination among the DSOs is required to attain frequency control of the grid. This will overcome the challenge of providing a reliable supply to the consumer with inception of an era of distributed generation. To enhance the reliability of the envisaged smart grids, a reputation-based selection process will be incorporated to deploy the TSO dispatch order.

Selection services are deployed through blockchain-based smart contracts and facilitate prioritizing the prospective DSO candidates by incorporating a "DSO selection score". The DSO selection score considers two parameters, namely the electricity price quoted by the DSO and reputation score calculated for the DSO, which reflects the surplus energy capacity available for trading. The weighted quantities of the selected parameters are incorporated for the calculation of the DSO selection score, as given in Eq. (7)

$$SC_{DSO} = W_{EP}(EP_{DSO,max} - EP_{DSO}) + W_R * R_{DSO} \quad (7)$$

The weights are determined based on the price and power quality requirements of the TSO, which eventually benefit the connected consumer with a quality power supply at an affordable price. A detailed explanation on this analysis is presented in Section 5.2.

The selection process is illustrated in Fig. 6.

Implementation of TSO/DSO coordination using the BaaSET platform and the associated steps are given below.

S1 TSO sends a generation dispatch request to the prospective DSOs.

S2 DSO selection score will be calculated for all prospective DSOs using Eq. (7) with the input parameters given in Table 6.

S3 Generation dispatch order of the DSOs will be determined by arranging the DSO selection scores in the descending order.

4.5. Agreement establishment and payment settlement service

The payment settlement service is proposed to handle the financial transactions related to the SG 2.0 operations. Applications of envisaged smart grids, including electricity sales (P2P trading and energy transactions between TSO and DSOs) and the rewarding DSI initiatives require the establishment of a dynamic contract between the two parties engaged in the transaction. The former establishes an agreement between the seller and buyer while the latter offers the consumer rewards for compliance and penalties for non-compliance. The BaaSET platform, offers this through the following steps.

Step 1: Smart contract will initiate a dynamic contract between the service provider and the beneficiary.

Step 2: Upon completion of the energy transaction, the corresponding value will be deducted from the beneficiary's wallet and transferred to the service provider.

4.6. Energy data management service

This service offers the benefit of maintaining energy consumption data, measurement data and control information, which are incorporated in decision making, price/incentive calculation, bill preparation

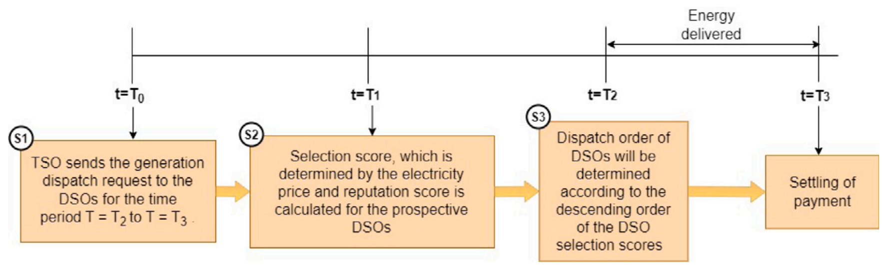


Fig. 6. DSO selection process.

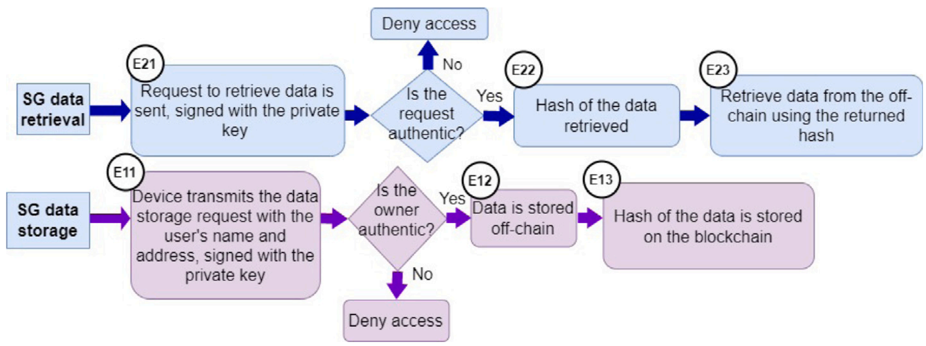


Fig. 7. Deployment of energy data management service.

and grid operation management. The number of stakeholders connected to the novel SG 2.0 increases with the diversity of applications envisaged with the distributed grid architecture. This leads to the aggregation of data in large volumes, which will be impossible to manage with a context of a centralized hierarchy. Centralized data management systems lead to many security and privacy breaches, mainly single-point failure. Blockchain-based platforms are capable of offering decentralized, distributed solutions for data aggregation and secure storage, eliminating the risk of modification, deletion, and unauthorized access.

Fig. 7 illustrates the procedure to be followed for blockchain-based data storage and retrieval.

4.6.1. Smart grid data storage

E1.1 Data storage request is made by the user, which is signed with the private key and transmitted to the blockchain.

E1.2 Smart contract checks the authenticity of the data origin and stores the data off-chain to minimize the space requirement on the blockchain.

E1.3 Corresponding hash value will be stored on the blockchain.

4.6.2. Smart grid data retrieval

E2.1 User sends data retrieval request, signed with his private key.

E2.2 Smart contract verifies the access privileges authorized to the receiver and if verified as an authentic request, the hash of the data is retrieved.

E2.3 Receiver retrieves data from the off-chain.

5. Simulation analysis

BaaSET facilitates SG 2.0 operations through the application of services individually or combining them, to achieve objectives such as decentralization, autonomy, and transparency. The reputation management service offers benefits to many stakeholders of the BaaSET architecture with the incorporation of measurement-based SG 2.0 operations. This service contributes to continuously calculate and update the reputation score of each stakeholder, based on the measurement obtained from their previous transaction. This study identifies three aspects of the envisaged SG 2.0 architecture, which can be enhanced through the application of the reputation management service, namely price determination in P2P energy trading, selection of a DSO to deliver the deficit in generation and consumer rewarding for participation in DSI initiatives. A simulation analysis is used to evaluate the impacts of incorporating the reputation score to enhance the benefits obtained from the identified aspects of SG 2.0.

The simulation model comprises of 100 users (prosumers/consumers) who are grouped into ten DSOs, namely, (DSO_1, $DSO_2, \ldots.., DSO_{10}$). Each of the ten DSOs will be coordinated through a TSO, with connected consumers voluntarily participating in DSI initiatives. A schematic diagram of the simulation setup is illustrated in Fig. 8. The simulation setup in MATLAB emulates three cases namely, (1) electricity price models for P2P energy trading, (2) DSO selection process carried out by the TSO to determine the dispatch order, and (3) a dynamic incentive scheme for rewarding DSI participants, and results are compared with that of the existing grid architecture.

The following sections explicitly discuss the methodology, results, and analysis of the observations made.

5.1. Case 1: Reputation-based electricity price models for P2P energy trading

This case analyses the impacts of incorporating a reputation-based pricing scheme for P2P energy trading.

5.1.1. Methodology

As discussed in Section 4.3 the marketplace service offered by the BaaSET, calculates the profit margin $M_{proposed}$ as in Eq. (6) and restated in Eq. (8)

$$M_{proposed} = M_{trad} * \frac{1 + R_P}{\alpha - R_C} \tag{8}$$

The range for α is selected as $(2 \leq \alpha < 3)$ to model a realistic market-clearing price, which is pre-calculated and stored, for decision making with minimal latency.

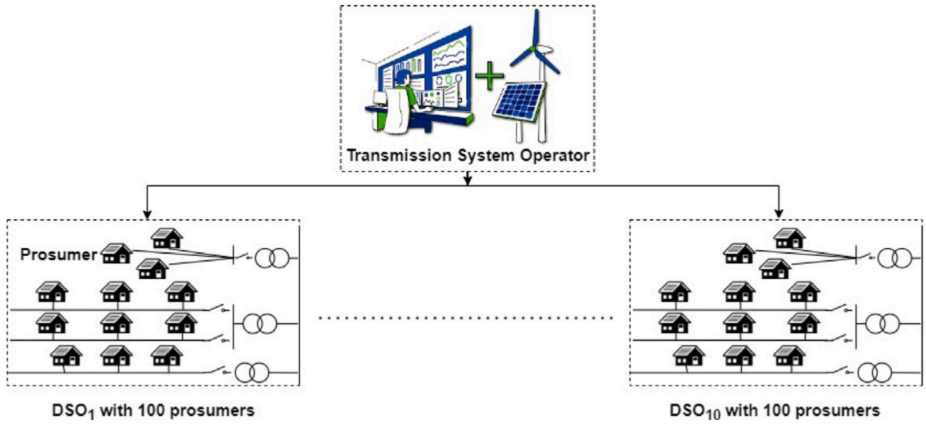


Fig. 8. Schematic of the simulation setup.

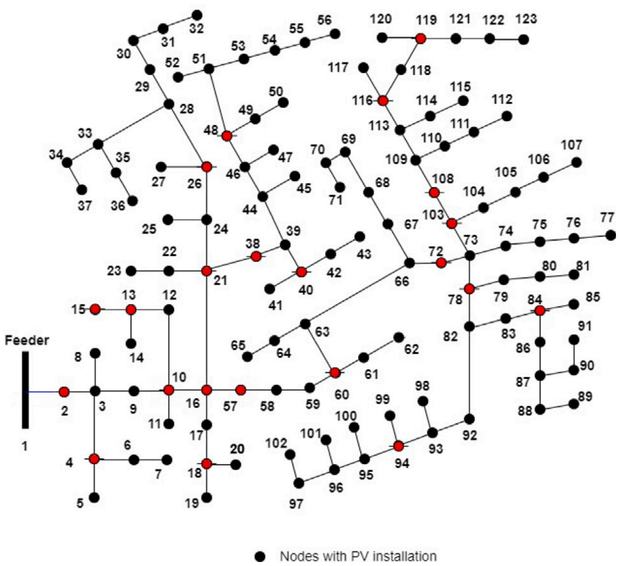


Fig. 9. Modified IEEE 123 node distribution network.

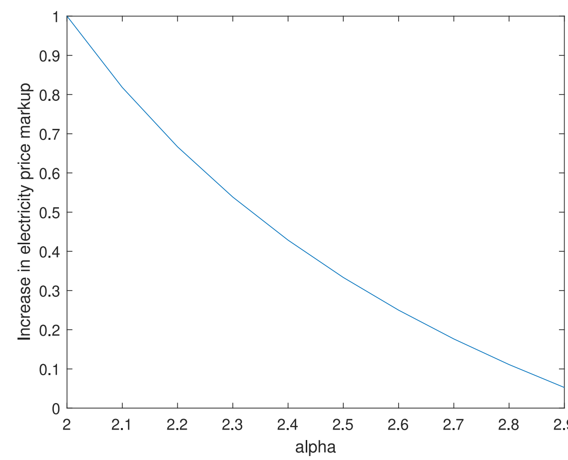


Fig. 10. Variation of the increase in electricity profit margin with α.

The proposed pricing scheme is compared against a study conducted in [19], which calculates the electricity price using only the prosumer reputation score. This in our study will be referred to as the prosumer model and the profit margin is calculated by Eq. (9).

$$M_{prosumer} = M_{trad} * R_P \tag{9}$$

Prosumer and consumer reputation scores are varied in the range of 1–100 following a discrete uniform distribution to compare $M_{proposed}$ with $M_{prosumer}$.

To further analyse benefits obtained from the reputation-based marketplace service of BaaSET, $M_{proposed}$ is applied to the modified IEEE 123 node distribution test network, shown in Fig. 9 [36]. Hundred prosumers with PV installations have been modelled on the test network and distance from the LV transformer to each node is obtained from the standard line data for the benchmark system [36]. Installed PV capacities are randomly varied from 0–1.2 MW [36].

5.1.2. Results

Variation of the increase in the profit margin with α is plotted in Fig. 10.

A comparison of the profit margins, $M_{proposed}$ and $M_{prosumer}$ is illustrated in Fig. 11. Further, M_{trad}, which will not depend on either the prosumer or consumer reputation score, is also plotted on the same graph for comparison purposes. The profit margin (for $\alpha = 2.5$) received by the prosumers of this test network, is illustrated in the enlarged section of Fig. 11.

Electricity price in the proposed architecture is used to reflect the prosumer contribution towards maintaining a desirable grid voltage profile. Further, it indicates the prosumer about the consumption patterns of individual consumers, leading towards a better selection decision in the bidding process. Consumers receive the opportunity to purchase power from a prosumer who contributes less towards voltage distortions due to large-scale integration of RES. The reputation-based marketplace operations for P2P energy trading thus, enhances the grid quality with RES integration in the envisaged SG 2.0 and promote energy-efficient electricity consumption patterns.

5.2. Case 2: Reputation-based DSO selection process for dispatch order

This case aims at evaluating the impact of utilizing reputation scores of the DSOs in the selection process performed by the TSO to implement the dispatch order.

5.2.1. Methodology

The DSO selection score is calculated as in Eq. (7) and restated in Eq. (10).

$$SC_{DSO} = W_{EP}(EP_{DSO,max} - EP_{DSO}) + W_R * R_{DSO} \tag{10}$$

To obtain a better correlation among the electricity price and the reputation score of the DSO, three systems are proposed in the analysis.

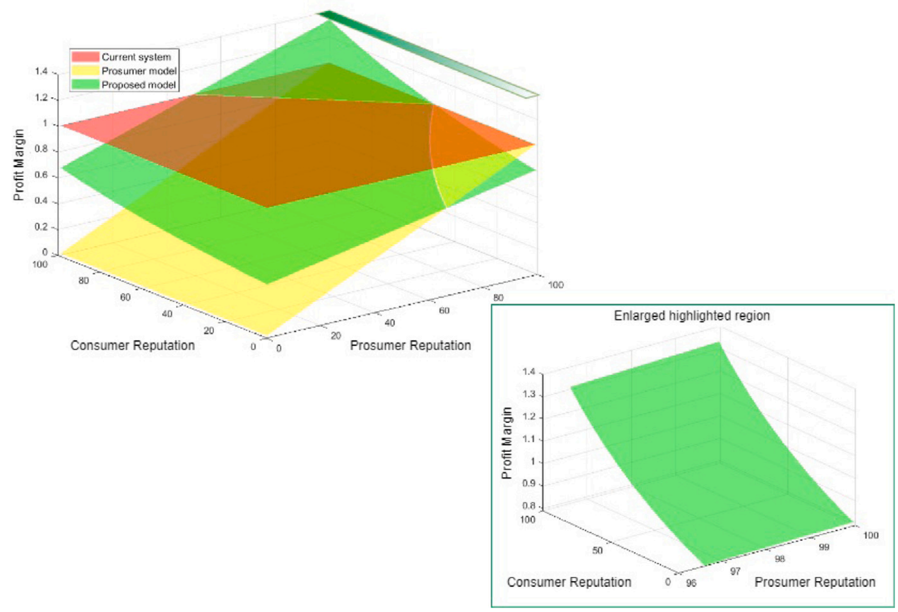


Fig. 11. Comparison of profit margin.

DSO reputation score in all these systems is varied in the interval 75–100 percent, following a discrete uniform distribution.

- *Proposed System 1 (PS1):* This assumes there is no correlation between the electricity price and the reputation score. Electricity price EP_{DSO} is equal to a random value EP_{rand} selected from the range of USD 0.08–0.1, following a uniform distribution, as given in Eq. (11). The specified range represents the average electricity prices of renewable energy generation based on the study in [20]. PS1 resembles DSOs defining their competitive electricity price independently, based on the market operations.

$$EP_{DSO} = EP_{rand} \tag{11}$$

- *Proposed System 2 (PS2):* This assumes a correlation among the electricity price and the reputation score by multiplying a constant value, (EP_{const}) in the range of USD 0.08–0.1 according to the DSO reputation. This is shown in Eq. (12), which reflects a scenario where a regulated electricity price is modified according to their reputation score.

$$EP_{DSO} = EP_{const}.R_{DSO} \tag{12}$$

- *Proposed System 3 (PS3):* This assumes a correlation between the electricity price and the reputation score by multiplying a random value EP_{rand} selected from the range of USD 0.08–0.1, following a uniform distribution, with the reputation score. This is explained in Eq. (13), which resembles the competitive electricity price offered by each DSO being modified according to their respective reputation score.

$$EP_{DSO} = EP_{rand}.R_{DSO} \tag{13}$$

DSO selection scores to emulate 100 dispatch scenarios are calculated for each proposed system and the price and reputation score of the selected DSO are obtained. The traditional system (TS) is represented by setting W_R=0, which implies that the reputation score of the DSO is not considered in the selection process.

5.2.2. Results

The qualifying DSO is determined following the proposed selection process and the variation of the obtained electricity price and reputation score are plotted in Fig. 12 for different combinations of W_{EP} and W_R. Further, the electricity price and the reputation score of the DSO selected through the TS are plotted on the same graphs for comparison.

Since reputation score of the DSO reflects its capability to follow the TSO dispatch order, the proposed selection process ensures a reliable power supply to the consumer. Determining the reputation score involves measurements obtained from the DSO operations, which associates an additional cost. This explains the difference in electricity prices of the proposed systems and the traditional approach, with the latter being unable to guarantee a reliable power supply. However, based on the consumer requirements, TSO has the discretion to determine the weights assigned for the electricity price and DSO reputation. Consumer will receive the opportunity to receive the desired power supply at an affordable cost.

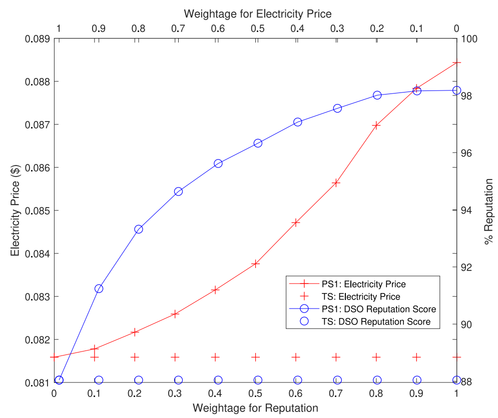
5.3. Case 3: Reputation-based dynamic incentive scheme for rewarding DSI participants

This case study reflects the impact of integrating consumer reputation score in determining rewards for voluntary participation in DSI. Consumers who have registered for DSI would respond to a Demand Response (DR) signal, generated by the DSO, taking into account the total available generation and the total demand. The DR signal would be the expected consumption pattern of a consumer, during considered the DSI instance.

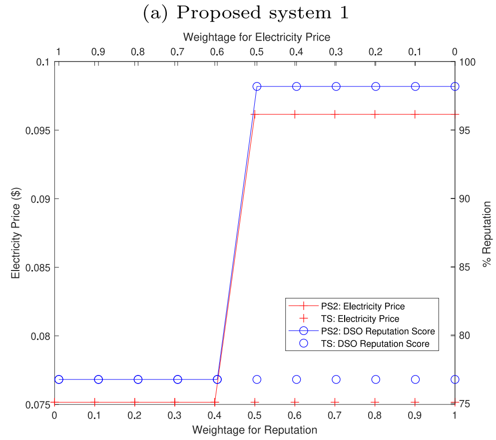
5.3.1. Methodology

BaaSET proposes to determine the rewards and penalties for DSI participants according to their level of compliance with the expected energy consumption patterns. The desirable range for deviations from the DR signal is defined as 0–10% [23]. A discount proportional to the level of compliance, and subjected to a maximum of 10% is offered as an incentive. Similarly, deviations beyond the prescribed range is penalized with a proportional price hike, subjected to a maximum of 120% of the nominal electricity price. To evaluate the performance of the reputation-based rewarding mechanism, the simulation emulates 100 DSI instances of a consumer. The reputation score of the consumer is updated at the end of each DSI instance, in proportion to the measured deviation from the expected consumption pattern.

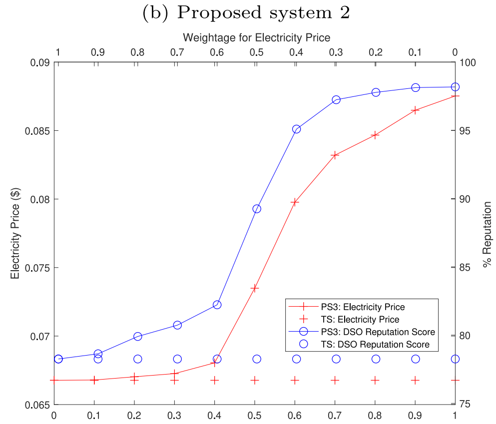
These results are compared against that of a study conducted in [23], which proposes a rewarding mechanism with a flat discount of 10% for deviation within the permitted range and a constant price increase by 20% of the nominal electricity price for non-compliance.



(a) Proposed system 1



(b) Proposed system 2



(c) Proposed system 3

Fig. 12. DSO selection mechanism.

5.3.2. Results

Curves representing the discounted electricity price received by a consumer for 100 DSI instances, while exhibiting 0%, 0.01%, 0.1%, 1% and 5% deviations from the DR signal are plotted in Fig. 13(a).

Curves corresponding to the penalties received by a consumer in 100 DSI instances, for 11%, 15% and 20% deviations from the expected consumption pattern are illustrated in Fig. 13(b).

Based on Figs. 13(a) and 13(b), maximum reputation is achieved when there is no deviation from the expected DR signal. However, the reputation reduces greatly with the increase in the deviation from the prescribed demand, which significantly reduces the discount in the electricity price the DSI participant receives from the DSO. Similarly, the price escalation is proportionate to the reduction in the reputation based on the historical performance. This because reputation is inversely proportional to the deviation rate.

5.4. Importance of using blockchain for reputation-based services of Smart Grid 2.0

Benefits obtained from the reputation-based services delivered for the SG 2.0 architecture can be maximized by the utilization of blockchain platforms. This provides the advantage of enhanced security and integrates privacy-preserving features into the process. The following tests validate the significance of incorporating blockchain technology to deliver services of the proposed BaaSET architecture.

5.4.1. Blockchain to eliminate the risk of insider attacks in the implementation of a reputation-based electricity pricing scheme for P2P energy trading

The inception of the smart meter era has raised concerns related to cyber–physical attacks among which, hardware tampering leads to energy theft. Malicious stakeholders of the system will damage physical equipment disrupting the real-time measurement process, deliberately inject false data to the obtained measurements, masquerade attacks and modification of energy data are the common vulnerabilities observed in the smart grid architecture and further considered to be insider attacks.

The services of the proposed BaaSET architecture are based upon reputation scores relevant to the performance of each stakeholder. This requires preserving the data integrity of the obtained measurements, which are the input parameters of the proposed reputation management service. However, past studies have revealed the inability of the existing smart grid architecture to prevent cyber–physical attacks in instances such as outage management [37]. Hence, the pre-requisite of preventing data modification is fulfilled by the utilization of a blockchain platform, which is inherently decentralized and distributed, prevents vulnerabilities related to data falsification.

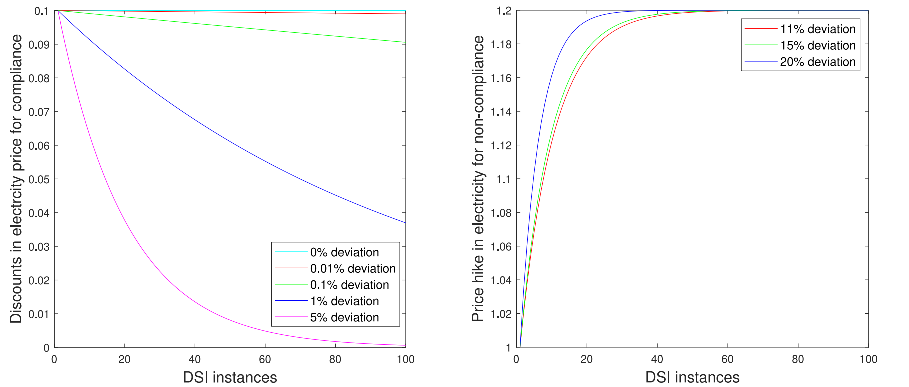
To compare the performance of the proposed reputation-based electricity pricing scheme implemented for the P2P energy trading of BaaSET under a data modification attack against the centralized counterpart, a node in the modified IEEE 123 node distribution system is considered to be malicious and fabricates voltage measurement. This attack is present during the transaction period of 2 h - 8 h, as given in Fig. 14.

The malicious prosumer modifies voltage measurement data intending to increase the reputation score, thereby gaining higher profit margins during the period, in which the system is under attack. Modification of measurement data is not possible with the distributed ledger architecture of blockchain, where changes made to a single copy will be reflected through the contradicting transaction hash values stored on-chain. Therefore, it is evident that blockchain facilitates to achieve a transparent, reputation-based pricing mechanism in P2P marketplace operations.

5.4.2. Blockchain to improve the fairness of the selection process of the proposed architecture

Reputation-based pricing mechanisms, as well as selection algorithms, are gaining attention in recent years in many sectors including finance, energy, healthcare, smart cities and transportation [19]. However, only a few of them have analysed the fairness of these reputation-based algorithms. Current algorithms tend to favour the high reputation stakeholders with a high probability to participate in transactions, which in turn will result in them increasing their reputation even further and not contributing towards an equal level playing field.

In order to address the research gap, a fairness algorithm is proposed in this study. A group of nodes having an equal reputation score is assumed and an algorithm is implemented to prioritize the node that has the longest waiting time among them. This is achieved by



(a) Adjustment to the discount in electricity price with deviation from DR signal (b) Adjustment to the penalty received with deviation from DR signal

Fig. 13. DSI participation.

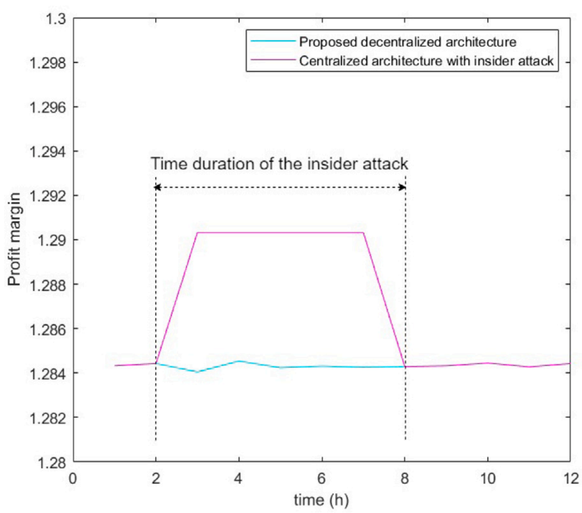


Fig. 14. Performance of the reputation-based electricity pricing scheme under an insider attack.

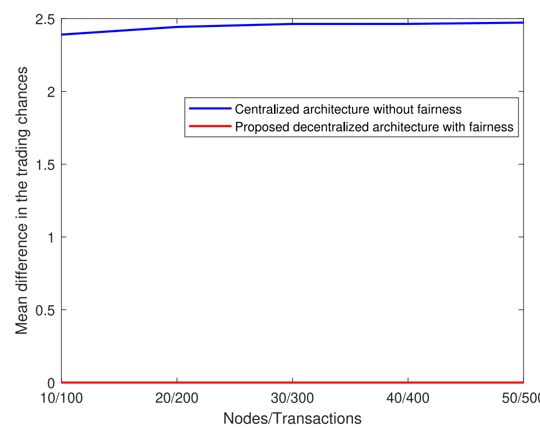


Fig. 15. Comparison of the proposed fairness algorithm with the existing approach.

modifying the weights for reputation score and electricity price of Eqs. (4) and (7).

Fig. 15 illustrates the mean difference of the chances received by a node for participating in energy trading against getting an equal opportunity, which is fair for all participating nodes. The proposed algorithm succeeds in allocating equal opportunities for all participants irrespective of the number of transactions compared to the scenario without a proper fairness mechanism implemented, which allows high reputation participants to receive more chances than the others, hence an offset is observed. The ratio $\frac{Nodes\ with\ equal\ reputation}{No.\ of\ transactions}$ is maintained constant through out the test to ensure consistency in the chances received for energy trading over scaling up the transactions.

It is evident from the figure that the fairness algorithm proposed in this study benefits all stakeholders with equal opportunities to engage in energy trading. This further, requires a tamper-proof data management system to record the waiting time of each node from the last transaction it has engaged. Blockchain has the inherent feature of hash-based distributed storage of data, which will be favourable for the implementation of the proposed fairness algorithm while the existing centralized approach is vulnerable to data modification and falsification.

5.4.3. Scalability of the proposed BaaSET architecture

The scalability of the blockchain platform plays a critical role in the implementation of the proposed BaaSET architecture for SG 2.0. This will decide the number of users the system can cater, which defines the throughput. Having greater scalability for the SG 2.0 applications is required with the dynamic nature of the operations and the rapid growth of users connected with the diverse possibilities. The following Table 7 elaborates the number of users that the services of the proposed BaaSET architecture will cater. This is calculated considering the maximum number of transactions that can be incorporated in a block in Ethereum, which is defined by the block gas limit. Currently, the block gas limit is set at 30000000. Thus, the number of transactions included in a block for each service in the BaaSET architecture is determined by Eq. (14).

$$Max\ no.\ of\ transactions\ included\ in\ a\ block = \frac{Block\ gas\ limit}{Transaction\ gas\ cost} \tag{14}$$

Considering an average block creation time of the Ethereum network as 12.5 s, the experiment evaluates the number of users catered per second, while revoking the specified number of smart contracts in order to fulfil each individual transaction.

The scalability can be improved by utilizing an efficient consensus algorithm, which facilitates integrating more number of transactions in a block, thus enabling catering more users within a block creation time. For instance, Hyperledger Fabric blockchain platform enables the user

Table 7
Number of users catered by the services of BaaSET.

Service	No. of SCs	Users/block time	Users/s
P2P marketplace user management service	1	48	3
P2P marketplace selection service	3	40	3
P2P marketplace reputation management service	1	277	22
P2P marketplace payment settlement service	4	38	3
DSO trading user management service	1	38	3
DSO trading reputation management service	1	331	26
DSO trading selection service	2	28	2

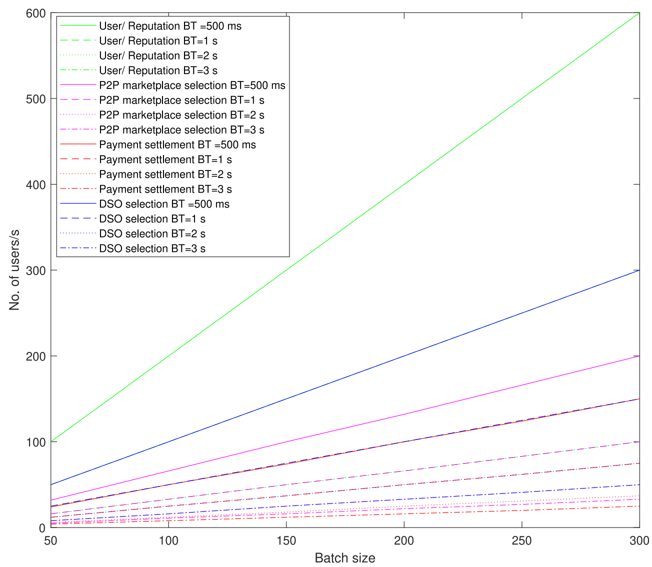


Fig. 16. Improving the scalability of the BaaSET services using hyperledger fabric blockchain.

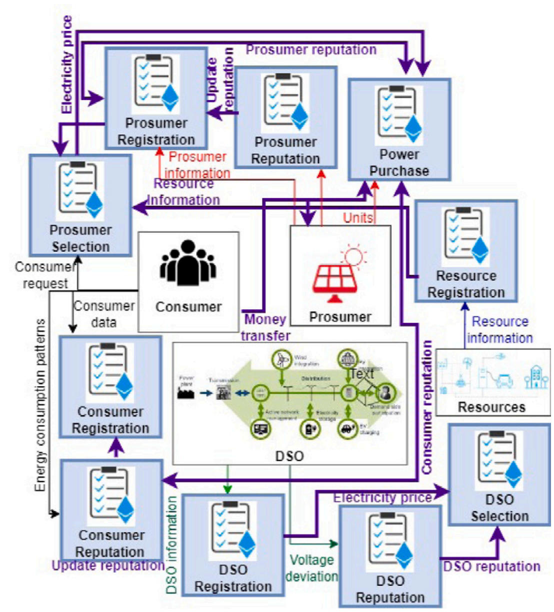


Fig. 17. Interactions between smart contracts.

to specify the maximum transaction count (batch size) within the specified batch time out (BT), to cater the requirement of the application. This is further illustrated in Fig. 16, where the number of users catered by a service of the proposed BaaSET architecture can be improved by utilizing the Hyperledger Fabric blockchain platform. A transaction rate similar to that of the instance with Ethereum blockchain implemented has been considered and further, it is assumed that there are sufficient number of Hyperledger Fabric nodes to cater for the speculated number of users per second. However, Ethereum facilitates testing purposes through the available test networks, hence this study has utilized one such test network for the convenience of simulating the real world scenarios.

6. Implementation of BaaSET architecture

This section discusses the results of the implementation of the BaaSET services defined in Section 3, on an existing blockchain platform. Smart contracts are executed to deploy each of the services and a cost-latency analysis is conducted to evaluate the performance of the proposed BaaSET architecture.

6.1. Prototype

The practical viability of the services offered by BaaSET is tested through the deployment of smart contracts. The elements of the test platform include a front-end client application, which runs as HTTP servers, and a decentralized back-end server using an Ethereum blockchain. The former has been deployed in the localhost using the Node Package Management (NPM) tool while the latter is implemented using the Ropston test network and hosted in the cloud. Metamask plugin installed to the web browser acts as a link between the front-end client application and the blockchain while communications are made possible through the Web3.js package. Smart contracts are deployed on the blockchain, which facilitates services related to P2P marketplace, DSO coordination, and DSI deployment. The front-end application accepts user inputs and relevant smart contracts will be initiated if the pre-requisites have been fulfilled.

This Decentralized Application (DApp) represents different stakeholders of the SG 2.0 architecture and interacts with the user by accepting inputs.

Ropston test network is capable of mimicking the Ethereum mainnet, since both use Proof-of-Work (PoW) consensus algorithm. The average block creation time is 30 s in this test network. However, the Ropston test net is not immune to spam attacks. Further, when comparing the consistent and timely manner of block creation, Rinkby and Koven test networks could be considered as better alternatives.

6.2. Smart contracts

Smart contracts are deployed to achieve the functionalities of the proposed architecture and the interactions between these contracts are depicted in Fig. 17

Codes are written in Solidity language, using Remix IDE, which is a browser-based smart contract deployment environment. A detailed explanation, containing the variables and the associated functions of these smart contracts is given in Appendix A.

The functionalities of each smart contract is explained in Table 8

Table 8
Functionalities of smart contracts in proposed BaaSET.

Smart contract	Functionality
Consumer registration	Register consumers having a valid electricity account number. Duplicates are eliminated and the user input details are stored in the distributed ledger, to be shared among the peers.
DSO registration	Register DSOs, and record the available RSE generation and battery storage capacities along with electricity price.
Prosumer registration	Records details of the consumers having renewable energy generation (solar PV), and capable of trading their surplus. Duplicate are eliminated.
Resource registration	Registers and stores data related to resources owned by registered prosumers/DSOs.
Prosumer selection	Initiated once a consumer sends a request to buy electricity from the close proximity. A selection score is calculated based on the offered electricity price and the prosumer contribution towards the voltage rise profile.
DSO selection	Facilitates the selection process of a DSO for supply–demand balancing. A DSO selection score is formulated based on the electricity selling price and reputation.
Power purchase	Tasks scheduled include calculating the electricity charge, which is to be paid by the consumer, authorizing the payment, and settling the amount related to the transaction by debiting and crediting the consumer and prosumer wallets respectively. The modified electricity price is calculated based on the prosumer and consumer reputation records.
Reputation management	Updates the records related to the indices, which are used for the calculation of the prosumer, consumer, and DSO reputation scores. These will be utilized in price/reward calculations in a consumer-centric market and determining the relevant selection scores.

6.3. Experimental results

The performance BaaSET for SG 2.0 is analysed in the aspects of the cost of smart contract execution and transaction latency. Execution cost incurred at smart contract deployment, for each functionality of the BaaSET is obtained from the Remix IDE. The end-to-end latency defined by the difference between the transaction initiation and transaction completion is calculated. The below sections elaborate on the experimental results obtained for the tests carried out for P2P marketplace operations and the DSO selection procedure.

6.3.1. P2P marketplace operations

The proposed P2P marketplace service is modelled using the DApp and executed via Ethereum-based smart contracts. Evaluation of the developed platform involved tests conducted on the Ropston testnet. Execution of the P2P marketplace operations involves the deployment of smart contracts including consumer registration, prosumer registration, resource registration, prosumer selection, power purchase, and reputation management, in the Remix IDE.

Cost Analysis: Execution costs have been obtained as given in Table 9.

The total cost associated with execution of all functions related to the P2P marketplace operations is $ 17.2.

Latency: The latency associated with the proposed P2P trading platform is evaluated by considering three scenarios, which include (1) selecting a prosumer to purchase electricity, (2) calculation of the electricity charge to be paid by the consumer, (3) settling the outstanding payments and updating the reputation scores. The P2P energy trading operation is repeated for hundred iterations while testing for different inputs to mimic users accessing the system through the DApp, which invoke smart contracts corresponding to them.

The results obtained for the latency associated with prosumer querying, calculating the electricity charge, and settling of the electricity bill are plotted in Figs. 18(a), 18(b), and 18(c) respectively, with a 95% confidence interval.

Based on the Figs. 18(a), 18(b), and 18(c), it can observed that the execution of the prosumer search, electricity bill calculation and the payment settlement functions associate delays of 39.59s, 41.99s and 38.61s, respectively. These include an average block verification time of 30 s for the Ropston testnet. This can be further reduced by selecting an optimal consensus algorithm. The total execution time of the P2P marketplace service is approximately 120 s.

6.3.2. DSO selection

DSO selection procedure requires the deployment of smart contracts related to DSO registration, selection, and reputation management. The proposed DSO selection service is modelled using the DApp and executed via Ethereum-based smart contracts and the evaluation involved 100 tests conducted on the Ropston testnet.

Cost Analysis: The execution costs related to DSO registration, selection, and reputation management, obtained from Remix IDE is given in Table 10.

Latency: DSO selection process is repeated for 100 iterations by providing different user inputs to the DApp to mimic independent operation instances. Latency corresponding to the execution of the DSO selection contract is evaluated. The results obtained from the testing scenario are plotted in Fig. 19, along with the 95% confidence interval.

The total execution cost is around USD 6.5, with the latency associated with the process execution observed as 39.8s. However, the cost incurred and the latency associated with the process completion can be minimized through the selection of the blockchain platform.

7. Discussion

7.1. Comparison with related work

A comparison of features offered by the proposed BaaSET architecture with the existing literature has been elaborated in the section followed and summarized in Table 11. This includes a comparison with the functionalities offered through the proposed user management, marketplace service, selection service, reputation management and energy data management services.

- Universal identity and wallet to achieve access control
  The proposed user management service (See Section 4.1) executes smart contracts to grant access to the system upon verification. Off-chain solutions can be incorporated to store the data of the registered users and the corresponding hash value is copied to the blockchain. This ensures data integrity, eliminating the risk of unauthorized access and tampering with user data privacy, while optimizing the storage space for record keeping.
- Reputation-based electricity pricing approach for dynamic price signalling in P2P energy transfer
  The study has evaluated the viability of incorporating reputation-based electricity pricing strategies for P2P marketplace operations (See Section 4.2). Reputation scores can be continuously updated transparently, through immutable blockchain storage. Smart contracts are deployed onto the blockchain to execute autonomous, real-time electricity price calculations and update the reputation scores upon completion of a transaction.
- Reputation score-based selection process to enhance the reliability of achieving the balance in supply and demand
  Large-scale grid integration of distributed generation should be coordinated in a manner such that the impact on the distribution network is minimized. This would ensure better voltage profiles and higher power quality management in the electricity grid. Further, better coordination among these energy resources can

Table 9
Execution costs for smart contracts of P2P marketplace.

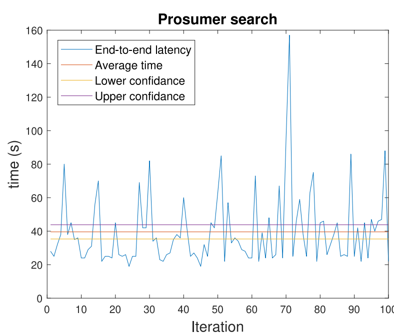
Smart contract	Execution Cost			
	SC deployment		SC transaction	
	Gwei[a]	USD	Gwei	USD
Consumer registration	1551588	4.57	301525	2.22
Prosumer registration	560793	1.65	45769	0.33
Resource registration	885748	2.61	256633	1.89
Prosumer selection	1863128	5.49	490812	3.61
Power purchase	1956150	5.77	234504	1.72
Reputation management	270728	0.80	42986	0.31

[a] 1 Ether (ETH) = 10^9 Gwei, 1 ETH = USD 2949.29 on 24.04.2022.

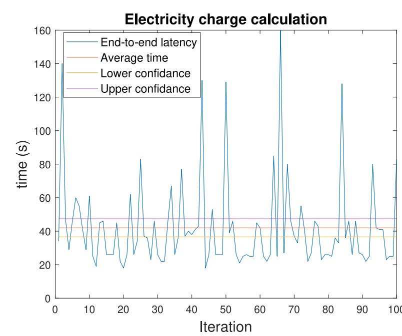
Table 10
Execution costs for smart contracts of DSO coordination.

Smart contract	Execution Cost			
	SC deployment		SC transaction	
	Gwei[a]	USD	Gwei	USD
DSO registration	1966469	5.8	60933	1.78
DSO selection	2633337	7.7	53705	0.16
Reputation management	90371	0.66	826938	2.44

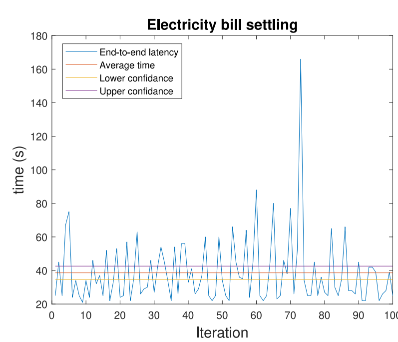
[a] 1 Ether (ETH) = 10^9 Gwei, 1 ETH = USD 2949.29 on 24.04.2022.



(a) End-to-end latency of prosumer selection



(b) End-to-end latency of electricity charge calculation



(c) End-to-end latency of electricity bill payment

Fig. 18. P2P Marketplace operations.

ensure a reliable power supply, facilitated with supply–demand management with surplus generation. The reputation management service of BaaSET (See Section 4.2) architecture is capable of maintaining immutable records related to measured voltages at the PCC of a renewable installation, energy-intensive electricity consumption patterns of the user, percentage compliance with the DR signal issued by the DSO for DSM and surplus energy capacity of the DSO; on the blockchain. This offers a transparent mechanism to incorporate data relevant to the past performance of the stakeholders in arriving at future decisions, thereby, resulting in an implementable autonomous smart grid.

- Reputation scores, which are updated proportional to the performance, to offer incentives for the participation in DSM initiatives The contribution of the consumer towards achieving reliability goals of the electricity supply is identified as facilitating the

Table 11
Comparison of important related work.

	[2]	[12]	[13]	[20]	[23]	[26]	[35]	[38]	[39]	[40]	[41]	[42]	Our
Access control	×	×	×	×	o	×	×	o	✓	✓	✓	×	✓
Universal wallet	×	×	×	×	×	×	×	o	×	×	o	×	✓
Dynamic price signalling	×	×	×	o	×	×	o	×	×	×	×	×	✓
Reliability of maintaining the balance in supply–demand	×	×	×	×	×	×	×	×	×	×	×	×	✓
Performance related incentive mechanism	×	×	×	×	×	×	×	×	×	×	o	×	✓
Energy information management	✓	×	o	×	×	×	×	×	o	✓	o	×	✓

✓ Sufficiently covered o Partially covered × Not covered

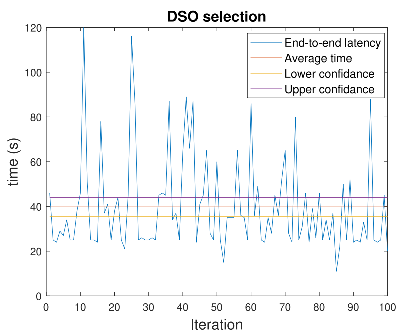


Fig. 19. End-to-end latency of DSO selection.

intended demand profile. This study proposes a mechanism (See Section 4.2) to encourage active participation in complying with the DR signal is rewarded through a proportional rewarding scheme. Maintenance of the related records is achieved through the distributed ledger storage, which is tamper-proof hence, ensures transparency of the pricing strategy. Smart contracts are executed to initiate payment settlement and update the reputation scores of the DSi participants.

- Blockchain empowered information management approach for enhanced data security
Blockchain incorporation to maintain records related to transaction information, measured data related to reputation criterion, and performance monitoring eliminates the risk of data tampering, modification, fraudulent data implanting, and unauthorized data sharing leading towards privacy violation. This further, makes the proposed system less vulnerable to single-point failure with heterogeneous sources accumulating data in a distributed manner (See Section 4.6).

It is worthwhile to note that the BaaSET aims at providing low cost and low-latency solutions to address the limitations identified in Section 2.2, which hinder the operations of the envisaged SG 2.0 architecture. In summary, it was identified that the BaaSET architecture proposed in this paper is capable of addressing the key requirements of envisaged SG 2.0 elaborated below, which to the knowledge of the authors have not been sufficiently addressed in the existing work.

- Reputation-based market clearing pricing strategy, which incorporates both the prosumer and consumer reputation scores: Such initiative would incorporate the impact of large-scale RES integration on the distribution network as an indicator of clean energy supply to the consumer while alerting prosumer on inefficient energy consumption patterns of individual users.
- Facilitate reliable power supply through well-coordinated TSO–DSO interactions: This would be implemented by a reputation-based DSO selection process.
- Performance-based DSI rewarding scheme: This study has explored the possibilities of utilizing a dynamic rewarding mechanism to encourage DSI participants, which offers discounts and penalties proportional to their level of contribution.

7.2. Limitations of the BaaSET architecture

BaaSET caters to heterogeneous applications of the envisaged smart grids. This can be identified as a solitary solution to integrate autonomous intelligence with smart grids and related applications, as speculated by the beyond 5G networks. This section further summarizes the limitations of the proposal, which have room for improvement, resulting in greater adaptability.

As the number of nodes integrating with BaaSET platform increases, it will not be viable to attain the latency observed with the prototype implementation. Scalability with affordability should be ensured in order to attract more stakeholders to connect to the system thereby, maximizing benefits as a whole. Permissioned or consortium blockchain platforms can be extended to achieve the economic goals of the envisaged smart grids.

Latency is a constituent of any blockchain platform utilized to provide services to SG 2.0. High-latency would affect the accuracy of the decisions obtained through the application of AI and ML techniques, which is a challenge to be overcome when aiming at autonomous smart grids.

A significant percentage of the latency is impacted by the block creation time relevant to the applied consensus algorithm of the blockchain platform. Thus, reduced latency can be achieved through the appropriate selection of the blockchain solution. Further, it can be improved by customized consensus algorithms, which are capable of catering to the requirements of smart grid operations.

7.3. Future works

As future work, this study proposes a dedicated consensus mechanism developed for energy blockchain applications. This would minimize the latency associated with a complex puzzle-solving-based block verification process. This would further increase the throughput of the blockchain platform, thereby improving the efficiency of the envisaged electricity grid operations.

A dedicated consensus mechanism is proposed to eliminate the additional computational power required and the associated latency of the legacy algorithms, where a complex mathematical problem is solved to claim victory. This could be replaced by useful work performed in the grid operations to get the benefit over performing some additional computation tasks. Regular grid monitoring is a prospective candidate for this, which will not require external hardware.

Furthermore, the proposed reputation management scheme is proposed to be extended to ensure both consumer and prosumer receive the benefits of retaining a higher score, through the desired energy consumption/ generation patterns. An extensive evaluation is proposed to identify the implications of the proposed power quality-based reputation scoring mechanism towards elevating the operation standards of the Smart Grid 2.0 architecture. Further, a validation of the proposed reputation management scheme is to be conducted using real-world data and implemented using a practical blockchain platform, to measure the associated latency.

8. Conclusion

Smart Grid 2.0 is a powerful architecture with distinguishing potential in heterogeneous application context. This paper identifies blockchain-enabled smart contracts as the game changing technology of envisaged electricity grids. The autonomous execution of smart contracts and tamper-proof, cryptographic encryption enabled blockchain technology fulfil the requirements of the distributed grid operations. Potential applications of the SG 2.0 architecture have been identified while the limitations in the existing grid context have been highlighted. A BaaS architecture, BaaSET is proposed as a solution to overcome the identified challenges. The proposed approach is evaluated on a Matlab simulation tool. Through the simulation results it is evident that the proposed method is cost effective and improves the power delivery process and grid condition of electricity networks. Further, it was observed that the reputation management service adapted in the marketplace and distribution network operations shows a positive impact on the electricity pricing strategy, DSO selection process and DSI incentive mechanism, which proves the significance of our contribution. Further, tests have been performed to validate the importance of integrating blockchain to implement the service architecture, which will thereby ensure security, privacy of the data and transparency of the process. The functional performance of the proposed method is evaluated through DApp built using web3.js library and smart contracts deployed to the Ropston Ethereum testnet. Upon comparison of the obtained latency and cost measurements with the state of the art, the study identified that the consensus mechanism of the blockchain creates a bottleneck in improving the scalability of the proposed solution. Hence, it is proposed to integrate a consensus algorithm, which will result in a lower latency thereby, increase the throughput and scalability to cater the increasing number of stakeholders.

CRediT authorship contribution statement

Charithri Yapa: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Chamitha De Alwis:** Funding acquisition, Methodology, Supervision, Writing – review & editing. **Madhusanka Liyanage:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Janaka Ekanayake:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jii.2024.100580.

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