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Conceptualization of blockchain enabled interconnected smart microgrids

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A B S T R A C T

Power systems are undergoing rapid transitions to incorporate renewable sources of generation and to combat climate change. The next stage of transitions will lead to a shift from large-scale, centralized systems to networks of small-sized, distributed electricity systems, which require distributed or decentralized ledgers for database management for efficient transactions. Distributed Ledger Technology (DLT) are a form of decentralized ledgers where the transactions (energy, information, and money) among various entities are maintained. One such DLT is blockchain technology which offers several advantages. Data recorded in blockchains are difficult to tamper with; have privacy protection; facilitate fast, accurate, and real-time settlement of financial transactions. Contemporary research has started focusing on their possible applications in energy systems. State-of-the-art suggests that while business and market aspects have been extensively discussed, the electrical constraints and implementation methodologies have not been adequately addressed. Furthermore, all the reviewed projects have implemented only peer-to-peer transactions that are not scalable. To incorporate the new entities like prosumers, inter-microgrid transactions, and interactions with the legacy power grid, new structural and operational frameworks are necessary. The proposed research explores the possibility of developing blockchain enabled smart microgrids (BSMG) with the above frameworks. It aims to build a conceptual framework of BSMG, including the transaction protocols and process flows. It proposes the inclusion of network constraints in a three-level transaction setup executed over a four-layered architecture. Another practical challenge is that BSMGs may be set up on different blockchain platforms. Hence, this paper also proposes implementing Inter-Blockchain Protocol for the first time to include interoperability and communication between different platforms. Finally, the performance metrics that will be used to validate the BSMGs are outlined.

1. Introduction

Globally, national electricity systems are undergoing significant transitions in alignment with meeting climate change mitigation targets and utilizing opportunities provided by economical renewable energy systems. One of the preferred transitions is from large-scale, centralized fossil fuel systems with unidirectional energy flows to small-scale renewable energy-based distributed systems with bidirectional energy flows. There are proposals to add features such as unified payments interface (UPI) and distributed ledger technologies (DLT) to enable real-time electricity transactions by prosumers (producer plus consumer of electricity). This has been enabled by advancements in smart grids, microgrids, scalable and modular renewable energy systems, information and communication technologies, UPIs, and DLTs [1,2]. With these advancements coupled with the proposed structural and operational changes, the future electricity systems are expected to transform into interconnected smart microgrids that can allow real-time bidirectional flow of electricity, money, and information. Such networked or interconnected smart microgrids also provide higher reliability and energy security in the events of power disruptions, shortages, and cyber-physical attacks since they act as reserves for each other and collaborate to restore services [3,4]. They act as virtual storages, ensure supply-demand matching, and manage both the energy surplus and deficit in different areas. Collectively, they are able to manage the variability, uncertainty, and intermittency in such renewable energy-based small systems. Such microgrids offer faster response and flexible operation as compared to the traditional, large grid [4].

As stated above, the interconnected smart microgrid requires advanced communication and data management systems for effective functioning. With the decentralized energy generation and operations, even the database management system must be decentralized and distributed. Such decentralized systems are more flexible, active, and faster than the centralized database systems [3]. Distributed Ledger

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Nomenclature

ABCI	Application Blockchain Interface
ADMM	Alternating Direction Method of Multipliers
BCT	Blockchain Technology
BED	Burlington Electric Department
BESS	Battery Energy Storage Systems
BFT	Byzantine Fault Tolerance
BMP	Brooklyn Microgrid Project
BSMG	Blockchain Enabled Smart Microgrid
CHP	Combined Heat and Power
DENA	Deutsche Energie-Agentur GmbH
DER	Distributed Energy Resource
DLT	Distributed Ledger Technology
DR	Demand Response
DSCOPF	Distributed Security Constrained Optimal Flow
DSO	Distribution System Operator
ECC	Elliptical Curve Cryptography
ESMT	European School of Management and Technology
EV	Electric Vehicle
EVM	Ethereum Virtual Machine
EWT	Energy Web Token
FISTA	Fast Iterative Shrinkage/Thresholding Algorithm
FNCS	Framework for Network Co-Simulation
FRO	First Rejected Offer
HEMS	Home Energy Management System
HTLC	Hashed Timelock Contract
HTTP	Hypertext Transfer Protocol
IBC	InterBlockchain Communication Protocol
ICT	Information and Communications Technology
ILP	Interledger Protocol
IoT	Internet of Things
LAO	Last Accepted Offer
LEM	Local Energy Market
LMP	Locational Marginal Price
MUV	Multiple Unit Vickrey
P2P	Peer to Peer
PoA	Proof of Authority
PoS	Proof of Stake
PV	Photovoltaic System
R–OPF	Reactive Optimal Power Flow
REC	Renewable Energy Certificates
SDK	Software Development Kit
SoS	System of Systems
ST	Smart Thermostat
TESP	Transactive Energy Simulation Platform
TMSP	Tendermint Socket Protocol
UPI	Unified Payments Interface
VCG	Vickrey-Clark-Groves
VPP	Virtual Power Plant

Technology (DLT) is a decentralized digital database which is widely used in a distributed environment, such as the one mentioned above, with trustless participants [5] where the database can be shared and appended simultaneously by many users. Blockchain, directed acyclic graph, hashgraph, holochain, and cerberus are some of the most popular types of DLTs [5,6]. Out of these, blockchain technology (BCT) has garnered interest in many industries like finance, supply chain, energy, and internet of things (IoT). It was initially designed to handle completely decentralized, peer-to-peer trustless financial transactions [7]. It consists of both shared and distributed digital ledgers which securely store the information on transactions without the presence of a central authority [7]. BCT facilitates the real-time execution of smart contracts and ensures quick settlement of payments [8]. Due to these advantages, the application of BCT in energy industry is being investigated rigorously.

Globally, there are about 140 projects and start-ups that are either planning to or already have applied blockchain in smart microgrids [9]. Of these, the Brooklyn Microgrid Project (BMP), which promotes peer-to-peer (P2P) energy transactions, is one of the first projects to be set up adopting BCT. The first transaction occurred in 2016 when five prosumers were connected to five consumers in the pilot stage. Presently, more than 300 prosumers have signed up for the next stage of the project [10]. These smart microgrids include control, information, and communication infrastructure along with the physical infrastructure used for power distribution. Control, communication, and computing devices are used for data, power, and financial exchanges while maintaining grid stability [3]. The emergence of distributed and decentralized power systems with DLT-based interconnected smart microgrids has given rise to change in the existing protocols, process flows, and frameworks. This concept of power grid has been called by different names - TransActive Grid [11] and Energy Internet [12,13] are some of the popular names. Henceforth, we shall refer to blockchain enabled smart microgrids as BSMGs in this paper.

For transactions in BSMG, firstly, auction mechanisms must ideally satisfy the four distinct market properties: individual rationality, budget balance, incentive compatibility, and economic efficiency [14]. So, just P2P trading algorithms are not sufficient. Secondly, from the literature reviewed, many of the active projects around the world advocate for P2P transactions, which also need to be checked for maintaining the electrical constraints of the system before clearing the market for the actual energy exchange [15]. Many of the models developed use optimal power flow analysis which may not be adopted by the distributed prosumers [16]. It has been further shown in Ref. [17] that scaling P2P models allow for more sustainable network. However, this is overshadowed by the significant rise in the number of violations along with the rise in the number of users, which lowers the validity of transactions and, thereby, the credibility of the network. Thus, such models are not scalable - especially to the tune of millions of users. Hence, a semi-decentralized system might help in overcoming this drawback [18].

In [19], a DC microgrid is simulated using Modelica, which is interfaced with Hyperledger Fabric. Additionally [20], incorporated a blockchain-in-the-loop framework using Hyperledger Fabric and Transactive Energy Simulation Platform (TESP). However, only P2P transactions are simulated, and inter-microgrid energy exchanges are not explored in these works. Also, BSMGs are set up on different blockchain platforms by different service providers. They use different protocols which provide inconsistent experience and may hinder data exchange. Thus, for the first time in energy, InterBlockchain Communication Protocol (IBC) is proposed to ensure interoperability between BSMGs. Lastly, different pricing structures, auction and incentive mechanisms, and protocols may need to be adapted for different BSMGs. The conceptual model proposed in this paper tries to address these gaps. Thus, the contributions of this paper are –

1. A literature review discussing the existing projects on Ethereum, Tendermint, Hyperledger, and open-source platforms, and about the significance and applications of blockchain in the energy industry.
2. A semi-decentralized system with three levels of transactions has been proposed: intra-microgrid, inter-microgrid, and microgrid to large grid transactions.
3. Many layers have been developed previously while evolving the architecture of BSMGs. The paper has re- organized some of these layers and a concise four layered architecture has been proposed.

4. A modified process flow which accounts for electrical constraints (like the nodal and transmission line constraints) of the distribution network has been proposed.
5. Discussion on proposed BSMG setup on Ethereum, Hyperledger Fabric, and Tendermint along with Inter Blockchain Communication Protocol and its evaluation using qualitative and quantitative measures.

This paper explores the potential applications of blockchain technology in energy and discusses some of the important projects designed or implemented. Together, a general overview of application of blockchain in energy markets has been provided. Literature on existing architecture and its layers, constituents, and types of BSMGs, protocols, and the process flows have been systematically reviewed and discussed too. It also discusses various existing BCT frameworks, their shortcomings, and attempts to address these gaps by proposing a new structural and operational framework for such blockchain enabled smart microgrids (BSMGs).

2. Literature review

2.1. Significance of blockchain in smart microgrids

With the advent of Blockchain 2.0 and 3.0, implementation of blockchain in energy sector looks lucrative, which is corroborated by many independent studies around the world. In this section, we explore the potential application of Blockchain in the field of energy and its disruptive capabilities as perceived by the experts. An IEEE future directions white paper on blockchain claims that it will change the way electricity is bought, delivered, and sold [21]. About 70 German executives in the energy sector (members of Deutsche Energie-Agentur GmbH (DENA) network and the alumni of European School of Management and Technology (ESMT)) were surveyed to ascertain the potential of blockchain [22]. Around 13% were in the process of implementing blockchain in a project whereas 39% had plans for in the future. Nearly 21% thought that blockchain would be a game changer to the energy industry. Similarly, senior executives across 15 companies were interviewed to elicit their responses with respect to importance of blockchain in energy industries [23]. Around 87% of the respondents thought that blockchain will significantly impact the energy industry and around half had already deployed blockchain applications. A report by Accenture Consulting states that 78% of the respondents prefer digital channels for customized experience in energy trading [24].

A PwC report in 2016 [25] claims that overall, BCT will simplify the traditional multi-tiered system of energy producers, T&D system operators and aggregators by directly connecting the suppliers to the demand. It also predicts the emergence of new business models due to incorporation of blockchain as users can transact according to their terms. Seeing this market potential, Burlington Electric Department (BED) used the Omega Grid system (an indigenously developed public blockchain which offers rewards to incentivize peak shaving amongst consumers) and projected $10 million annual reductions on peak generation charges and 70% of this saving will be offered as rebates to the users [26]. Thus, it can be concluded that BCT is viewed as a disruptive technology and experts worldwide consider it to have great potential in the energy sector.

2.2. Applications of blockchain in energy industry

Potential applications of BCT in energy industry can be classified into that focusing on documenting ownership, reliable automated transactions, and maintaining distributed ledgers for transaction records [25]. A 2018 report by McKinsey & Co [27] lists six main applications of BCT in the energy industry. It lists issuing green energy certificates, peer-to-peer generation and distribution of energy, electrifying undeveloped markets, conducting real-time transactions, managing infrastructure, and connecting EVs to the grid. Firstly, it discusses issuing and trading of green certificates or renewable energy certificates (RECs). Coupling of energy and carbon trading markets in a blockchain-based peer-to-peer trading setup has been proposed in Ref. [28]. Such secure storage of ownership can facilitate tamper-proof data transaction in emission trading [25]. CarbonX in Canada, Energy-Blockchain Lab and IBM’s venture in China, Grid Singularity in Austria, Poseidon in Switzerland, Veridium Labs in Hong Kong [9] and Volt Markets in collaboration with Ideo CoLab, Nasdaq’s Link and Filament in USA [27] are some of the popular projects in this field.

The next rapidly emerging application is to enable peer-to-peer (P2P) energy trading [27,29]. It is a completely decentralized energy market where the prosumers bid and interact with one another for the sake of energy exchange without the involvement of a third party. The earliest such project was the Brooklyn Microgrid (BMG) project established by LO3 Energy [11] and is currently a partnership between LO3 Energy, Consensus, Siemens, and Centrica [9]. It is a network of prosumers and consumers who want to purchase local solar energy within Brooklyn area. Consumers can choose to buy local solar, renewable energy or the Con Edison (independent system operator) grid energy from the energy trading platform developed by BMG [30]. BCT combined with microgrids can be utilized to electrify undeveloped regions and explore their markets [27]. For example, Bankymoon is a peer-to-peer energy trading project started in South Africa which has now adopted BCT and is linked with the crowdfunding platform, Usizo [31].

Blockchains can also be used to monitor the energy infrastructure, like grid management and congestion management [9]. They can optimize the flexible resources and decrease the tariffs. Blockchains can also be used for bidirectional communication between smart devices. BCT can be combined with internet of things (IoT) to form energyIoT or eIoT [32]. A blockchain-based decentralized registry can be used to record the ownership and regulate asset management. This would include controlling the operation of smart meters, home management systems, networks and generation systems [25]. BCT can be further enhanced by using cryptocurrencies, which can be developed to encourage prosumers to trade via blockchain-based markets. These cryptocurrencies can be later traded for fiat money like Jouliette [33], SolarCoin and NRGCoin [34]. Additionally, smart contracts can be incorporated for instantaneous real-time settlement of payment. It contains codes within a software (here, blockchain platforms) which carry out contractual or non-contractual agreements. The logic is embedded within every block of the blockchain. Smart contracts can be used along with smart meters, it can generate automatic billing for consumers and load aggregators, even with real-time pricing schemes. This can also be used in wholesale purchase of energy. Completing the energy value chain, BCT coupled with electric mobility for charging station handling, payment, and ride sharing like Share & Charge [23].

Following the extent of potential changes that blockchain can bring to energy domain as discussed in the previous section, there are several successful cases of energy markets incorporating blockchain platforms across the world. While some of them are in the prototype stage, others are planning to shift to advanced stages of their projects. Piclo is an early project, like BMG, established in the UK in 2013 and developed by Open Utility. It is a flexible energy trading platform where business consumers can directly purchase from the local renewable generators, while keeping the network constraints in mind [35]. Piclo’s energy trading platform uses the meter data for determining the electric load, generators’ prices and the consumers’ preferences (which are pre-fed into the platform) to match the supply and demand for every 30 min block of time. The trading algorithm has been combined with blockchain along with charging methods including price-based incentive methods [36].

We can say that blockchain will not only maintain a distributed ledger (the intention with which DLT was being considered) but will also be combined with IoT for managing the assets. Also, it can implement smart contracts and provide escrow (protection from defaulting on payments) which will help implement real-time payment settlement for the energy transactions. It has the potential to launch new crypto-currencies or digital wallets as an alternative payment technique. It can also be combined with demand response (DR) methods like incentive or price-based techniques to positively influence consumer behaviour.

2.3. Selected existing projects: a review

Around 140 projects/companies along with their field of activity, BCT platform used, consensus mechanism and country of operation are listed in Ref. [9]. About 60% of the projects surveyed used Ethereum as the blockchain platform as it is open-source and flexible. Although Energy Web was used in 10% of the projects, it is Ethereum-derived, hence it is not considered separately. Hyperledger and Tendermint were the next two popular platforms with 11% and 7% share, respectively. Since these three platforms make up a majority of the market share, projects deployed on them have been reviewed subsequently.

2.3.1. Ethereum

A local energy market (LEM) including prosumers and P2P trading is implemented on Ethereum using Proof-of- Concept mechanism in Ref. [37]. ERC20 tokens are used for transactions between the entities, as per the recently modified Portuguese energy regulations. An ADMM (Alternating Direction Method of Multipliers) and FISTA (Fast Iterative Shrinkage/Thresholding Algorithm) based decentralized market clearing mechanism is proposed on Ethereum's private blockchain platform [38]. There are four smart contracts deployed on Remix IDE - the first contract updates the data like generation, cost and blockchain addresses before the transaction begins; the second contract provides the preferred bidding strategies and prices; the third contract is a negotiation contract which is invoked during the transaction period and a fourth contract to calculate and transfer the required tokens after the transaction period. Layer 2 or off-chain transactions are expected to be introduced in the next stage of work. The smart contracts will later be deployed on sub chains like Plasma sub chain or Polkadot parachains to reduce the computation burden on the main chain. SynergyChain is yet another Ethereum-based model which employs reinforcement learning (RL) to create self-adaptive virtual prosumer groups [39]. The smart contracts are written on Remix IDE in Solidity language and deployed on Ethereum test networks like Ropsten and Rinkeby. Since Solidity does not support complex algorithms yet, Python web3 is used to interface the smart contracts with the RL algorithm.

In [40], a private Ethereum-based, fully distributed optimization model using ADMM is implemented on the Lille Catholic university grid. The test system consists of four buildings, two PV generators, a storage system, several EV charging stations, and connection to the distribution grid. The smart contracts are built on Remix IDE in Solidity, on Ethereum blockchain with Proof-of-Authority (PoA) consensus mechanism. The various users interact with the blockchain layer using Python scripts. The user nodes are simulated in Ganache software in Truffle. A P2P trading mechanism for virtual power plants (VPP) is set on Ethereum Virtual Machine (EVM) using Ropsten test network. The smart contracts include bidding, withdrawal and control modules. Thus, the agent checks its smart meter and deploys the contracts through Ethereum Client APIs like web3. js and web3. py via Hypertext Transfer Protocol (HTTP) [41]. Non-cooperative game theoretical models are used to minimize the individual cost of electricity, overall consumption, and manage energy storage [42]. The smart contracts are coded in Remix IDE, along with Metamask as the user interface, and deployed on Ropsten Test Network.

2.3.2. HyperLedger

Single feeder radial distribution topology with bidirectional power flow in a DC microgrid is simulated in Modelica [19]. This is interfaced via HTTP to Hyperledger Fabric which monitors the operational variables. The API is implemented as RESTful web service. Hyperledger Composer Rest Server is used to demonstrate P2P energy trading in Ref. [43]. The implementations of backend and frontend processes have been shown and discussed too. Hyperledger Fabric has been used to store the energy bids of battery energy storage systems (BESS), electric vehicles (EVs), photovoltaic systems (PV), and smart thermostats (ST) [44,45]. Smart contracts deploy the double auction mechanism and interact with the home energy management system (HEMS). The model is tested on the Kortright Centre Microgrid with 8 homes. The literature comparison of different open-source blockchain platforms like Ethereum, Hyperledger, and Corda is carried out, using which the authors have proposed a conceptual architecture [46–48]. The work is extended to involve a blockchain-in-the-loop framework to execute P2P energy trading of prosumers with solar rooftop PV on Hyperledger Fabric along with a lab setup [47]. Two auction-less and one auction schemes are simulated in a microgrid with 30 homes. In Ref. [48], Hyperledger Fabric is interfaced with Transactive Energy Simulation Platform (TESP) and uses Framework for Network Co-Simulation (FNCS) for time synchronized message exchanges. Locational Marginal Price (LMP) is obtained from PyPower while incentivization and penalization occurs in the blockchain layer. An implementation of blockchain-based renewable energy transaction and storage management system is discussed in Refs. [49,50] with Hyperledger Fabric and is called RenewLedger. It has also incorporated demand response incentives and gamification. The findings have been benchmarked using Hyperledger Caliper.

2.3.3. Tendermint

Brooklyn Microgrid Project (BMG) operates on a permissioned, private, indigenous platform called Exergy which promotes peer-to-peer energy transactions [30]. It uses the Tendermint protocol, which is a modification of the Byzantine Fault Tolerance (BFT), for consensus. The TransActive Grid blockchain architecture and smart meter have been implemented [11]. It follows a closed book order, double auction market mechanism which is conducted every 15 min. In Ref. [20], reactive optimal power flow (R–OPF) has been used to determine the reactive power at each bus (for ancillary services), using which remuneration is also calculated accordingly. The financial transactions between the buses is implemented on Tendermint through an Application Blockchain Interface (ABCI) written in Java. The P2P energy transactions have been demonstrated by the same group in Ref. [51]. Tendermint Core is the consent engine used as it provides the flexibility of using any programming language. The interactions are managed using ABCI [52].

2.4. Open-source projects

Over the years, several open-source projects have been implemented on various blockchain platforms. Microgrid Transactive Energy Smart Contract is one such project developed in the Brazilian microgrid sector. It interacts with NEO blockchain and can be deployed on NeoCompiler Eco [53]. A blockchain-based P2P trading in LEMs is simulated in Ref. [54] using Python on Ganache blockchain. The smart contract is created on Truffle. The Energy Web Chain is a well-known open-source project started on Ethereum which features Energy Web Token (EWT) [55]. It is derived from the Ethereum code base but has different stack and chain and is created exclusively for the energy sector.

An Ethereum-based energy trading platform is designed and implemented in Ref. [56]. Two types of energy market mechanisms - bilateral energy trading and merit order-based energy trading - have been simulated and tested on 20 participants. Microgrid-Blockchain-Project is a P2P energy market setup which is based along the lines of BMG and deployed on Ethereum [57]. Two architectures have been proposed. While one architecture is completely decentralized with a continuous double auction mechanism, the other is partially so and requires a component to be off-chain in order to reduce the computational burden of clearing uniform price auction mechanism on the blockchain [58]. A P2P Ethereum DApp using data from SunDance has been created in Ref. [59]. It is created with the vision of enabling prosumers to sell electricity back to the grid.

In the project titled "Decentralized Energy Trading in Microgrids through Blockchain and Smart Contracts", game theoretical models are used to predict market participation [60]. The energy allocation is solved as an optimization problem and deployed on Hyperledger Fabric. Hyperledger for microgrids and intra-community real-time energy marketplace is explored further in Ref. [61].

However, all of the projects reviewed so far have adopted P2P transactions without interactions with the current main power grid. Clustering of prosumers into functional smart microgrids has not been explored too. Apart from Ref. [19] which modeled the DC microgrid using Modelica [48], which employed TESP co-simulated with Hyper-Ledger Fabric in the loop and [20] which accounted for reactive optimal power flow solved using glow worm swarm optimizer, electrical constraints of the physical infrastructure have not been modeled in any of the works so far. Further more, none of the papers so far have included inter-microgrid and microgrid-main grid markets. As the size of the participants increase, Game Theoretical based market models alone may not be sufficient to satisfy the network requirements. Thus, further research in BCT based energy trading between interconnected smart microgrids is required. Based on the extensive literature review conducted, a theoretical structural and operational framework for BSMGs has been proposed in the subsequent section.

3. Proposed structural and operational framework of BSMG

This section details the formulation and design of BSMGs in order to aid the transformation of the power system from a large, centralized grid with unidirectional power flow to smaller, distributed grids with bidirectional power flows. This section will deal with the classification of the microgrids, layers in the BSMG setup and the various processes involved.

Fig. 1 pictorially shows the intended transformed power systems. It shows different types of loads connected to the main grid via a utility cell (which will be discussed later). These loads are said to have access to DERs which makes them prosumers. They interact with each other via the main grid (existing infrastructure) if the local generation is unable to meet the demand.

3.1. Proposed structural framework of BSMG

This section discusses the different structures adopted by smart microgrid projects. As the user base grows, the system needs to demonstrate security, scalability, and efficiency. A good system architecture will ensure this. System of systems (SoS) architecture with bi-level optimization has been proposed in Ref. [18]. It involves connecting and coordinating autonomous systems to behave as a larger system. It is claimed to have advantages in modeling, analyzing, and optimizing the operations within the system over other approaches like multi-agent system and certain scenarios of decentralized control. Interconnected or networked microgrids have been discussed and proposed in Refs. [3,62,63]. Their advantages over stand-alone microgrids have been elaborated in these papers and have been mentioned previously too. In Ref. [64], three types of energy trading models have been discussed. They are infrastructure-based P2P energy trading (like the Brooklyn Microgrid Project); ad hoc P2P energy trading (where local microgrids are integrated with large-scale energy producers); and large-scale energy storage-based trading (where large-scale energy storage entities can sell directly to the grid) [64].

3.1.1. Constituents of a BSMG

In [65], the setting up of peer-to-peer trading was discussed. The peers were classified based on their sizes into premises, microgrids, cells and regions in the ascending order. A premise is a single house or a building. A group of such premises connected to the electrical network along with DERs is called a microgrid. A group of microgrids is called a cell whereas multiple cells constitute a region. These four entities can trade with each other. Consequently [66], lists the five major components of microgrid - consumers, producers, spinning reserves (to ensure stabilization of voltage and frequency), the coupling point (where the microgrid is connected to the larger grid) and the controller (the brain of the microgrid which matches demand and supply optimally).

According to Ref. [12], BSMGs consist of energy cells (energy producing entities) which can be classified into four types - prosumers with dominant consumption, producers with minor consumption, pure consumers, pure producers. BSMG also contains utility cell (service provider) and clearance house (information house and price clearance).

Fig. 1. Representative diagram of different loads and energy cells connected to the main grid.

Prosumers can also consist of residential places, businesses with rooftop solar, farmers with solar panels or windmills on their agricultural land and companies that used to discharge heat previously but is now used to generate electricity, as mentioned in Ref. [67].

In the proposed structure, a blockchain enabled smart microgrid consists of two parts – energy cells and utility cell.

- Energy Cell: The energy cell consists of the prosumers and consumers that participate in the energy trade in BSMG. Each prosumer unit is considered as an individual energy cell. The energy cell can be a home, building, commercial place like a mall or office workspace.
- Utility Cell: Utility cells are required to maintain the physical infrastructure that supports energy, data and financial transfers. It will act as the present day Power System Operator (PSO) which maintains the operations of the power grid. Similarly, a utility cell will ensure that the power balance within the BSMG is maintained. It will also help in market clearance for all types of transactions. The utility cell in a BSMG will also approve the registration of participating nodes in that microgrid.

Fig. 2 depicts the direction of flow of energy, communication between devices and financial transactions within the BSMG and outside. An energy cell of a residential BSMG (BSMG 2) is taken as an example. Each house acts as an energy cell equipped with a smart energy meter and blockchain node. The smart meter derives the information on the net energy requirement (whether energy is in deficit or excess). The excess energy available for selling or the deficit energy required to be bought will then be communicated to the blockchain node. The blockchain node participates in the mining process to finalize the block. It also communicates with the utility cell to facilitate communication and financial transfers. Finally, the utility cell communicates with the other utility cells of the neighbouring BSMGs.

According to Ref. [68], the loads can be mainly classified into the following categories: critical loads (loads which operate at fixed power ratings and frequency, like the ventilators in hospitals which can't be switched off once they are in use), time shiftable loads (loads which can be deferred or advanced to another time slot) and power shiftable loads (loads which have a fixed time of operation but variable rated power like air conditioners and refrigerators). The BSMGs are classified into other categories based on their purpose and the types of loads they cater to. This is done so, because the energy consumption patterns of agricultural loads (as an example) will differ from the requirements of commercial loads. Also, the generation capacity through DERs will also be significantly different. For example, prosumers in bungalows or independent houses may have sufficient space to install rooftop solar panels, whereas the consumers living in high rise apartments may not. Also, with the advent of cloud computing services, cloud service providers have been and will build large data centres. Their energy consumption will be significant and may require demand response measures [69]. Thus, data centres need to be considered as a type of BSMG, if not now, then at the least in the future. A BSMG maybe treated as a homogeneous or heterogeneous microgrid. Thus, different structures of pricing, incentive mechanisms, and protocols may need to be adapted for different

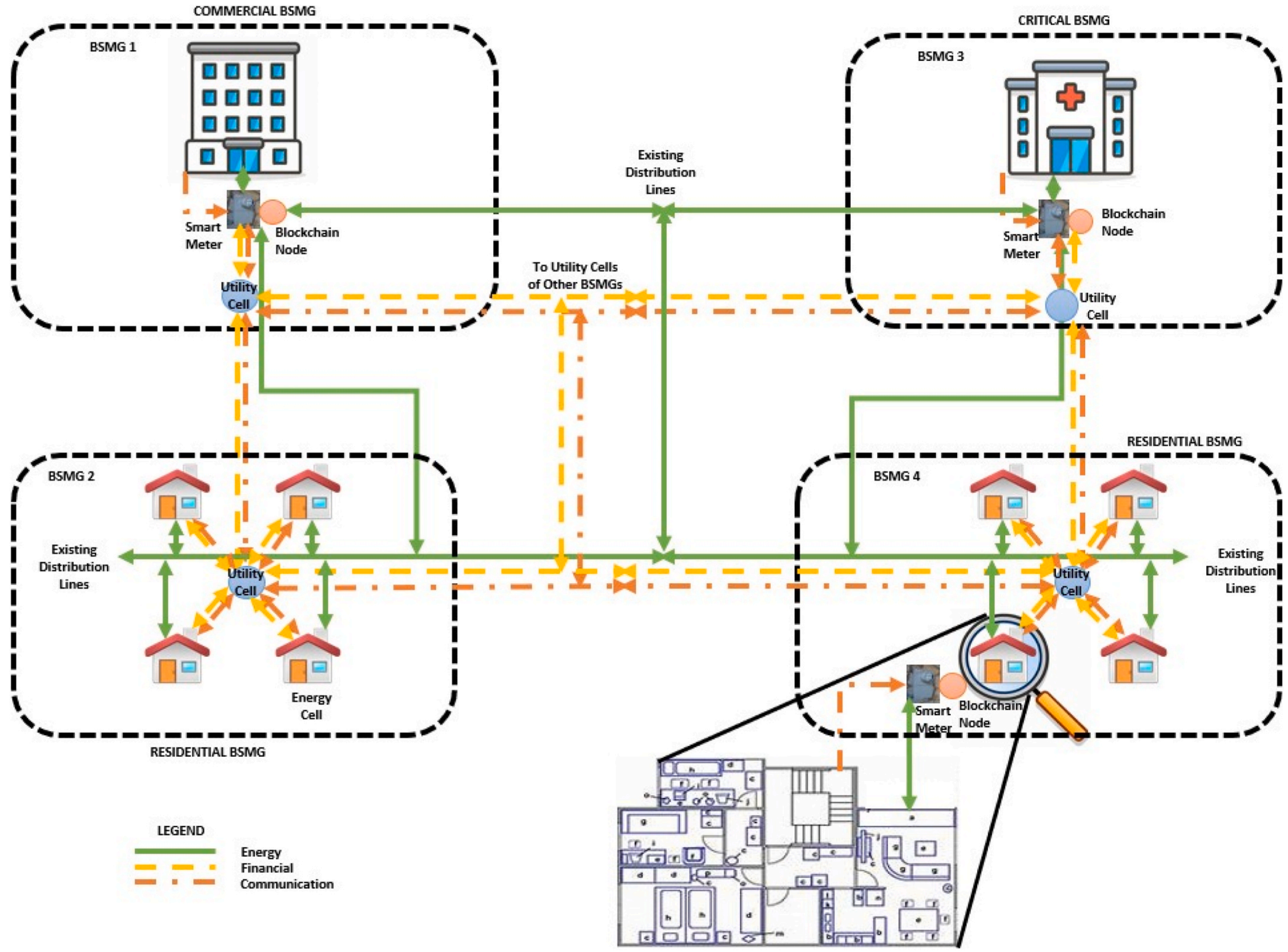

Fig. 2. Flow of energy, communication and financial channels in the BSMG.

microgrids. Different auctioning and pricing systems can be proposed based on the type of microgrid.

3.1.2. Layers in BSMG

The literature suggests possibility of different layers in a smart microgrid. For example [65], proposes a three dimensional system architecture. The first dimension which consists of important operations of the setup, is made up of four-layers for peer-to-peer trading. It consists of the power grid layer (for all the physical components), ICT layer (for the communication devices and protocols), control layer (for the control operations in the system) and the business layer (for energy transaction among the peers). The second dimension consists of the size of the peers discussed in Section 3.1.1 and the third contains the trading processes which will be discussed in Section 3.2. In Ref. [3], the authors describe the blockchain-based transactive energy system to consist of three layers - the power network (physical layer), blockchain network (cyber layer) and the financial network (market layer). A 3-layered architecture consisting of user layer, communication layer and aggregator layer has been proposed in Ref. [70]. A 3-layer blockchain-based transactive energy grid framework has been proposed in Ref. [48]. The coordination layer in Ref. [48] can contain auction-based schemes, auction less schemes or market schemes. It consists of the physical layer, coordination layer, and blockchain layer. Zia et al. discusses a 5-layered architecture comprising of users layer, microgrid operator/energy management layer, market layer, communication layer and regulation layer [71]. A review paper has discussed different types of architecture in Ref. [6]. The authors have also proposed a seven layered architecture - user layer, network layer, system operator layer, market layer, distributed ledger layer, communication layer and regulation layer. This has been adopted by Brooklyn Microgrid Project too [11]. Finally [12], proposes a seven layered architecture of energy internet, along the lines of the Open Systems Interconnection model. It contains the physical layer, energy link, network layer, transmission layer, consumption, communication and business layers.

In the presented research, four layers have been proposed as depicted in Fig. 3. The functions of these layers can be expanded as follows:

- Infrastructure Layer: This layer consists of the physical devices, connections, meters and control systems that are already present. This layer represents the channel through which the electricity flows and energy transactions take place physically.
- Cyber Layer: This layer carries out the checks to ensure that the system operates in safe mode. For the system to operate in the normal state, one set of equality conditions (balancing between generation and demand) and the set of inequality constraints (which express the limitations of the physical equipment like current and voltage limits) must be satisfied [72]. It ensures that the system operates in normal state in spite of the peer-to-peer energy exchanges. It also directs the control systems in the infrastructure layer to maintain the normal state if any of the constraints are violated.
- Financial Layer: This layer involves the auction mechanism in the system. Bids from the buyers and offers from the sellers are collected and auctioned. The market clearance happens according to the protocols set in this layer. The final calculation of the prices (depending on the meter recordings from the infrastructure layer) are also determined here.
- Blockchain Layer: This layer consists of the blockchain setup that will facilitate the operation of smart contracts, sealing of the agreements at the end of auctions, and accurate database management of the transactions. While the previous layer pertains to maintaining the health of the system, this layer pertains to the transactions and distributed database management.

Regulations are crucial for the implementation of BSMGs. They determine the market mechanism and process flow. They also define taxes and surcharge policies which can have bearing on customer acceptance and participation [6]. While the bids, taxes, market mechanism, and surcharges are included in the financial layer, energy security and cybersecurity are encapsulated in the cyber layer. Requirements from the participants at various levels like individual, microgrid, utilities, and energy market regulators are coded in the smart contracts in the blockchain layer. To summarize, the power exchanges take place in the infrastructure layer. The cyber layer ensures that the system operates in a reliable mode. The blockchain layer facilitates the recording of the transaction. It, along with the financial layer, are responsible for the final payment settlement among the participants.

3.2. Proposed operational framework of BSMG

3.2.1. Process flow

Li et al. (2019) proposes a framework, which is divided into ex-ante, real-time and ex-post phases, for the market operation and clearance [3]. Smart contracts embedded in the blockchain carry out the market initialisation at the Distribution System Operator (DSO) stage. They execute energy trading and state estimation for all participants for that particular time block. Finally, smart contracts also settle the markets for the participants depending on the actual energy transfers in the real-time phase [62]. A three-stage process is discussed in Ref. [65]. The first stage is the bidding stage (which occurs for a duration of 30 min) where different entities lay out trading agreements, followed by the actual energy exchange an hour later for a duration of 30 min and ending with the settlement stage when financial transactions occur and

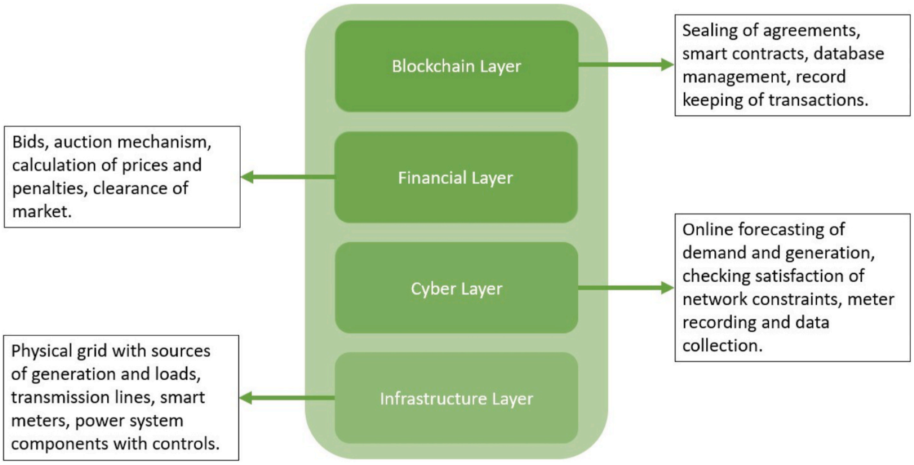

Fig. 3. Block diagram of different loads and energy cells connected to the main grid.

can take 1–31 days to settle.

The proposed process flow in the BSMG is depicted in Fig. 4. The different stages of the process along with the er in which it takes place have been provided. Previous literature has also provided various frameworks and process ws [3,12,65]. The proposed process flow occurs in the real-time market in the retail and wholesale markets. After he BSMGs are clustered according to the types of loads and requirements, the utility cell forecasts the generation and demand of its respective BSMG. This helps schedule the energy exchanges over the next 15 min, which is the time slot adopted. As per these forecasts, the prosumers then call for bids. Here too, the prosumers and consumers may decide to choose between allocating their preferred prices or automatic calculation of prices.

The next process involves the energy transfer. The meter readings are then taken along with the decentralized state estimation process to find the actual energy transaction (end demand with loss of transmission). The final prices are then recalculated and the financial transaction between the participants occur via blockchain technology, using smart contracts. Based on the error in forecast and actual transaction, the buyers and sellers are scored and ranked based on the reliability and trust. These are further used to either penalize or incentivize the participants for future transactions. Except for the energy transfer, meter reading, and sending bids which involve the energy cells, the other parts of the process occur in the utility cell.

3.2.2. Pricing mechanisms. When the market settlement involves only the participants submitting bids, the participants mention the price range for which they are willing to sell or buy energy units. In case the market settlement accounts for the end energy transactions and meter readings, prices are calculated based on several methods, as discussed further. Locational Marginal Price (LMP) is the marginal increase in cost to the system to supply one additional MW of load at a particular bus/node [3,73]. This method is used for uniform pricing. In Ref. [74], three auction mechanisms - last accepted offer (LAO), first rejected offer (FRO) and multiple unit Vickrey (MUV) - have been mentioned. The different auction mechanisms have been compared on the basis of pricing and market mechanism. Auction mechanisms such as discriminatory k-double auction, uniform k-double auction, Vickrey-Clark-Groves (VCG) and trade reduction have been reviewed in Ref. [75]. Three schemes are explored in Ref. [48] where the market operation is coded in smart contract on Hyperledger Fabric. The first scheme is simple without auctions where the tariff structure has been pre-decided. The second scheme involves sorting the producers in ascending order and consumers in descending order. The market still functions without auctions. The third scheme includes a simple auction mechanism to determine the rate structure along with penalties for deviating from the promised bids. To summarize, there are two types of approaches - the first is to clear the market in a non-cooperative game setup and use market bidding strategies to achieve equilibrium. The second is to optimize the energy block allocations and then clear the market using a cooperative game setup.

In the proposed work, there are three types of market transactions - intra-microgrid transactions, inter-microgrid transactions and microgrid to large grid transactions. The utility cell processes the bids and determines the first set of clearance. Distributed Security Constrained Optimal Flow analysis (DSCOPF) is carried out for the first two types of transactions [76]. Thus, through this process, each microgrid determines the upper and lower bounds of its selling price. Also, with varying energy transactions, the system needs to check if the equality and inequality constraints are satisfied. Thus, the voltage control strategy will be decentralized using alternating direction method of multipliers (ADMM) in Ref. [15]. If the constraints are violated, the auction occurs again until the security constraints are satisfied. The market is cleared at the last iteration and the agreement between the participants is sealed.

3.2.3. Interoperability between heterogeneous blockchain platforms. Interactions between two BSMGs are simple if they are based on homogeneous blockchain platforms. This is so because they will be technologically similar as consensus mechanism, block formation, and security mechanism will be consistent, making data and asset transfers straightforward. However, with the increasing adoption of BSMGs, there will be an emergence of heterogeneous chains which may be public, private or consortium types of blockchain. Since the chains are inherently different, there may be lack of trust, communication issues, and difficulty in exchanging data and assets [77]. However, in order to prevent the monopoly of one type of blockchain, enhance scalability, and ensure equitable participation of all users, BSMGs must be interoperable. There are mainly three methods of cross-chain interaction as reviewed in Refs. [77,78] - hash lock, notary mechanism, and relay chain.

Hashed timelock contract (HTLC) is a channel contract which ensures a global state across the different nodes through hashes [79]. Bitcoin Lightning Network first implemented it to make high volume, low latency digital payments which are scalable, secure, off-chain and bidirectional [78,79]. Interledger Protocol (ILP) extends this concept to execute financial swaps between Bitcoin and other payment networks like Ethereum and Venmo [80]. However, ILP and HTLC - in general, according to Ref. [77] - are currently limited to asset transfer. Notary mechanism is a simple cross-chain which consists of a trusted federation of notaries which acts as an intermediary between the two heterogeneous chains to be linked. It listens for events on one chain and verifies them for the other chain. This concept is implemented in the Liquid Network which is a Bitcoin layer-2 which executes trustless swaps [81]. The major drawback of this mechanism is that if the notary is attacked, it becomes untrustworthy, exposing a huge risk of single point failure [77].

HTLC and notary mechanisms allow for only asset transfers. It is imperative to have data transfer also in order to achieve true interoperability amongst BSMGs. Relay mechanism consists of a sidechain with a smart contract which functions as a light client of another chain. BTC Relay is one such unidirectional bridge between Bitcoin and Ethereum smart contracts [82]. Polkadot and Cosmos are bidirectional bridges created to connect those blockchains which are built using the same SDKs [78]. Polkadot is a relay chain that facilitates information and asset transactions between different types of networks and chains in a

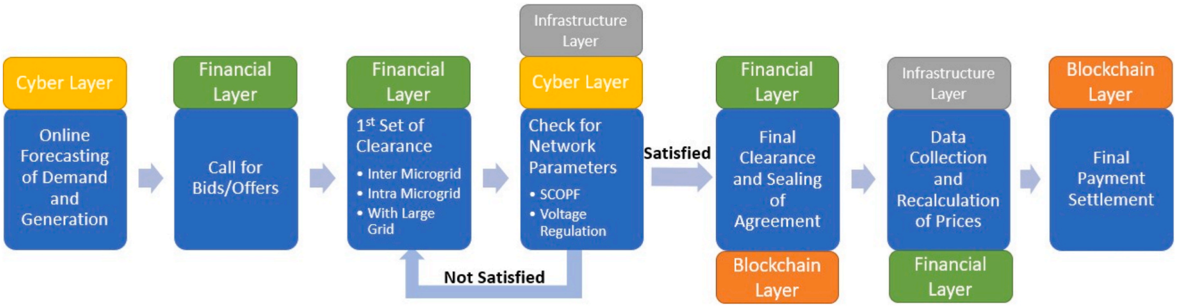

Fig. 4. Process flow diagram of different loads and energy cells connected to the main grid.

trustless manner [83]. Here, the validators are responsible for the validation of member chain blocks [78]. On the other hand, Cosmos validators leave the security to the member chains and have a simpler relay chain. Cosmos apps and services connect using Inter-Blockchain Protocol (IBC) which allows exchange of data and assets across multiple decentralized blockchains [84]. However, it is difficult to connect the blockchains that do not have compatible characteristics (like the consensus mechanism).

A cross-chain payment scheme using hash locking mechanism with data privacy preservation is implemented in Ref. [85]. Cryptographic algorithms like elliptical curve cryptography (ECC), non-interactive zero-knowledge (NIZK), and hash locking contracts are used to preserve data privacy of the traders. However, the simulation is executed over Ethereum test network Rinkeby and blockchain Ganache. Transactions across heterogeneous chains are yet to be done. Relay chain mechanism is implemented in Ref. [86] for a heterogeneous energy blockchain transaction model based on energy internet (EI-HEB). There are different chains for wind generation, demand side, thermal power generation, energy storage, PV, and PHEV that are interconnected via the main chain which also acts as the relay chain. The model uses Boneh-Lynn-Shacham signature scheme consensus algorithm based on PoS and BFT [86]. The authors note that the performance of the relay chain, and thereby, the trading efficiency needs to be improved. However, there is no research in the energy domain which addresses the issue of interoperability between different blockchain platforms.

In the proposed work, a relay chain called Inter-Blockchain Communication Protocol (IBC) will be used to facilitate interactions and transfers between heterogeneous blockchains. It consists of two layers - the transport layer (TAO) and the application layer. The former ensures data and transfer security between the chains while the latter determines the packaging and interpretation of data [87]. Due to this separation, process of sending data is defined but the structure of data is not standardised, making IBC very flexible and different from the other interoperability solutions [88]. The practical implementation will be discussed in the future research paper.

3.2.4. *Proposed setup of BSMG*

According to Ref. [9], Ethereum, HyperLedger and Tendermint are the most popularly used blockchain platforms. Hence, they have been discussed in this paper. Fig. 5 shows the proposed setup for BSMG. The energy cell consists of the user or the client. A virtual node is created for every user along with a digital wallet for financial transactions. The node interacts with the blockchain via an interface medium. The blockchain setup consists of the blockchain platform, consensus mechanism through which the blocks are validated and linked to the existing blockchain and smart contracts which execute the market agreement. The smart contracts are then interfaced with microgrid simulators at the utility cell.

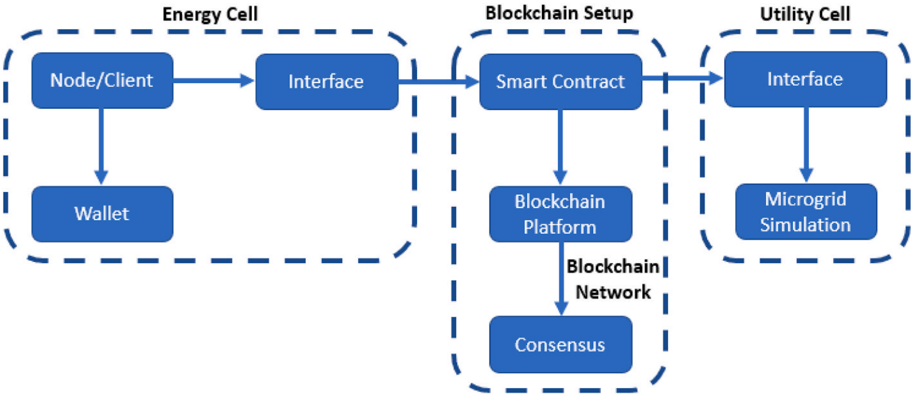

Fig. 5. Proposed setup of BSMG

As mentioned earlier, according to Ref. [9], Ethereum, Hyperledger, and Tendermint are the most commonly used to blockchain platforms for energy projects. Thus, we have proposed a BSMG setup involving these platforms in this paper. In Fig. 6, a hypothetical Microgrid setup is depicted where Microgrids 1, 2, and 3 are set up on Ethereum, Tendermint and HyperLedger Fabric platforms, respectively.

- Ethereum: Ethereum is a popular public blockchain platform which supports permissionless blockchain. It can be programmed in C++, Python, GoLang and Solidity [89,90]. In Microgrid 1, the user of an energy cell can create a virtual node in Infura and a corresponding wallet in Metamask. It is interfaced with the Ethereum blockchain setup with Web3. py where Remix IDE in Solidity language is used to build smart contracts on the EVM. Infura uses Proof-of-Stake consensus mechanism and the setup is deployed on Kovan Test Network.
- Tendermint: Similarly, Tendermint is a modular open-source protocol which consists of a blockchain consensus engine and an interface application [91,92]. Microgrid 2 is built on the Cosmos platform with Tendermint Core network and consensus mechanism. Tendermint Socket Protocol (TMSP) is used to write smart contracts. The node is connected to a digital wallet in Lunie or Ledger Nano. It is interfaced with Tendermint through ABCI.
- Hyperledger: Hyperledger is an over-arching project which contains many open-source blockchain projects [93]. In Hyperledger Fabric, private and permissioned networks can be created. It is also flexible as it contains modular architecture and allows plug-and-play consensus mechanism [94]. Microgrid 3 is built on HyperLedger Fabric which allows for pluggable consensus mechanism. The smart contract is built on Chaincode and interfacing with the energy and utility cells takes place via REST-API. HyperLedger supports three types of wallets - file system, memory and CacheDB.

While intra-microgrid transactions occur on the same blockchain platform, inter-microgrid transactions and microgrid to large grid transactions may involve different platforms. This practical difficulty has been considered in this paper for the first time. The microgrids can be connected through the utility cells via the InterBlockchain Communication Protocol (IBC), as shown in Fig. 6.

3.3. *Evaluation and benchmarking*

The proposed model needs to be evaluated using both qualitative and quantitative criteria. The qualitative metrics derived from the characteristics of BSMG as mentioned in literature as follows. The concept of Energy Internet its architecture is discussed in Ref. [13]. The authors have mentioned the main characteristics for the power grid to be considered as Energy Internet. They are: renewable energy should be the primary generation source (R_1), the set up should have the provision to

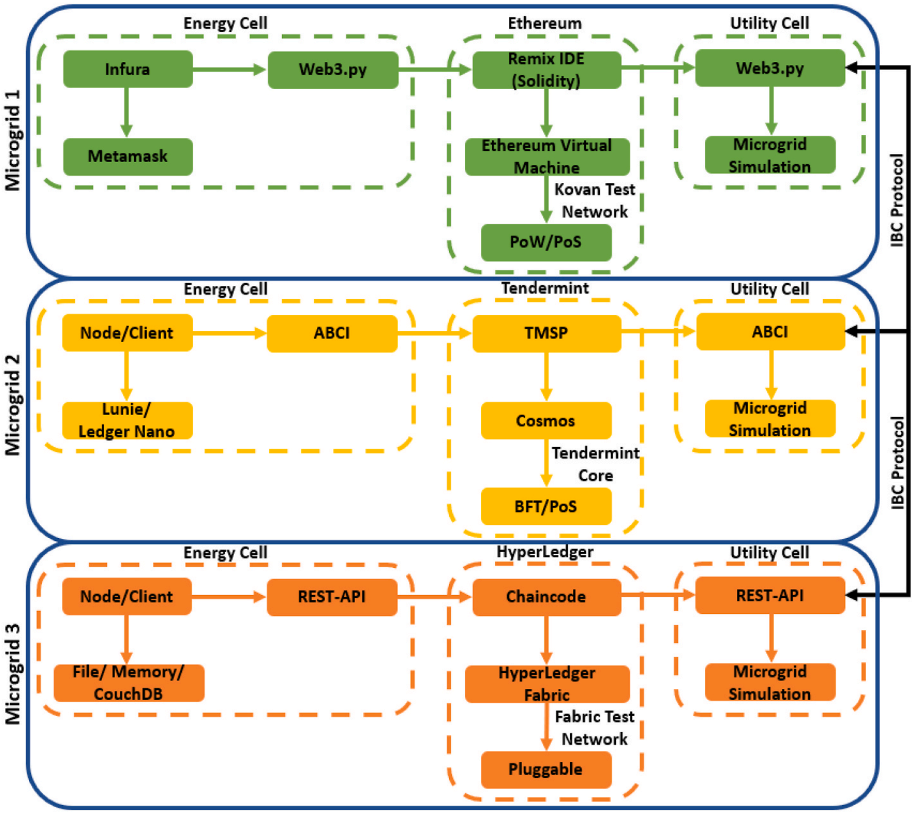

Fig. 6. Proposed inter-microgrid setup.

connect large-scale distributed generations and energy storage systems to the said system (R_2), internet should be used for information sharing between entities (R_3), and finally, it should support EVs (R_4). This concept has been adopted from Ref. [96]. SoS or multi microgrid architecture has the following characteristics: the system should be autonomous (S_1), belonging to the said system (S_2), connectivity to other participants (S_3), diversity within the system (S_4) and emergence (S_5) [18,97].

Similarly [66], discusses seven fundamental components that must be fulfilled within a microgrid with combined heat and power (CHP). The authors mention that there should be online mechanism for real-time demand-supply matching, bundled allocation for heat and electricity along with upper and lower limiting constraints, price signals, stable operation, opportunity to include large-scale power grid, and lastly, forecasts for both, demand and supply. This concept is modified using [98] and adapted by Ref. [11] into seven primary components of any BSMG. There should be a clear microgrid setup (C_1), it should be connected to the grid (C_2), the market participants must be well connected for which information system should be present (C_3), bidding rules must be encompassed in market mechanism (C_4) along with pricing mechanism (C_5). Additionally, an energy management trading system should be prevalent (C_6) and the entire microgrid market must be regulated (C_7). The BMG project satisfies the first six of the requirements while the authors accept that the regulation component, while important, is usually overlooked [11]. Table 1 provides the benchmarking and testing of compliance of the proposed BSMG framework with the established characteristics mentioned in the literature. As can be seen, proposed BSMG complies with all the characteristics/components (i.e., R_1-R_4, S_1–S_5, and C_1–C_7).

HyperLedger Caliper is used to quantitatively measure the performance of the blockchain setup. It can be used to benchmark and measure models built on Ethereum (through the web3 RPC interface) and HyperLedger Fabric [99]. Several metrics are defined in Ref. [100] like the Read Latency, Read Throughput, Transaction Latency, and Transaction Throughput. The proposed model will be tested on these parameters in the subsequent research papers.

Table 1
Qualitative validation of BSMG.

Characteristic	Compliance
R_1	✓
R_2	✓
R_3	✓
R_4	✓
S_1	✓(Each prosumer is autonomous in its actions. Similarly, each microgrid is autonomous in its operations and decision making)
S_2	✓(Each prosumer can act as a part of the system whereas each microgrid acts as a system. When the microgrids are interconnected, they belong to an overall system too)
S_3	✓
S_4	✓(Since different types of loads, BSMGs and interactions are included, this system can be said to be diverse)
S_5	✓(The good and bad behaviour is foreseen and used to rank the participants [95] in order to make the system more reliable)
C_1	✓
C_2	✓
C_3	✓
C_4	✓
C_5	✓
C_6	✓(This process takes place in the Utility Cell component of BSMG)
C_7	✓(The regulations can be incorporated into the smart contracts as and when they are rolled out. The regulation layer has been incorporated within the blockchain layer itself)

4. Conclusion

Power systems are undergoing significant structural changes in recent times. There is a push towards inclusion of renewable sources of energy at the distribution level, thereby transforming the pure consumers of electricity into prosumers. As seen in this paper, blockchain technology has an eclectic variety of applications in the energy industry and outside of it. Blockchain is a tamper-proof and privacy-protected distributed ledger technology which can be combined with smart contracts and IoT to enhance performance. Thus, blockchain enabled smart microgrids (BSMGs) will play a critical role in providing quick, innovative, and flexible solutions to control, operate, and manage the new and modern power systems. The concept of peer-to-peer energy transactions in small to medium-scaled energy system setups has been demonstrated across the world through various active projects.

The contribution of this paper is to review such works and conceptualize a suitable architecture and process flow for BSMGs. This paper discusses existing projects undertaken on Ethereum, Tendermint, Hyperledger, and open-source platforms. It recognizes the need for including electrical constraints and executing inter-microgrid energy markets. Keeping this in mind, three types of transactions have been proposed, which will operate and be managed across a four-layered architecture. In order to facilitate transactions between BSMGs set up on different blockchain platforms, use of an inter-blockchain protocol has been proposed too. Finally, qualitative and quantitative metrics to gauge the performance of BSMGs have been discussed, which will be used as performance metrics in the subsequent research works. Further research is necessary to prove blockchain technology's merits and realize its full potential in the energy domain. This requires studying the feasibility of actual field implementation of BSMGs and is scope for future research.

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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