Contribution to the Operation of Deregulated Electricity Markets under High Penetration of Energy Storage and Renewable Energy Sources

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the Technical University of Crete or other institute, except where due acknowledgement has been made in the text.

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Abstract

In this study, we delve into the modeling of electricity market end-users and the design and implementation of a hierarchical blockchain-powered electricity market for peer-to-peer trading. This work harnesses the potential of decentralized energy trading by creating a structured framework where end-users can participate actively in electricity trading across multiple market levels. The entire process was anchored in a three-tiered market structure: the Community level, the District level, and the overarching Smart Grid level.

To achieve this, we first modelled residential prosumers, renewable energy sources, Electric Vehicle aggregators, and medium-to-large consumers and producers that would participate in a peer-to-peer market to identify their characteristics and behaviors before generating their value-price pairs for market participation. With that knowledge we then designed and implemented a hierarchical blockchain-powered electricity market framework to facilitate p2p energy trading between end-users. The proposed market was built using the Hyperledger Fabric framework featuring a multi-blockchain design with a sophisticated per-hierarchical-level smart contracts implementation. The design and implementation of the proposed market scheme focused on scalability, and privacy by implementing aggregation of orders at each market level.

Our framework was then put to the test in a comprehensive case study that consisted of 50 simulations, and showcased a scenario of 1056 prosumers of various sizes. The results highlighted the system's proficiency in facilitating trading across multiple market tiers. By leveraging aggregated pricing, the system was able to achieve a commendable clearance of quantities for all participating prosumers.

A performance analysis was also conducted to gauge the system's operational capabilities. The results from this examination were quite promising, with our implementation showcasing exceptional throughput rates and impressive latency numbers, especially when compared to similar Hyperledger Fabric architectures. These findings, combined with the positive outcomes of our case study, underline the potential and readiness of our design for real-world adoption.

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Lastly, to my dearest family and friends, words cannot express how thankful I am for your endless love and support. Thank you for believing in me. Your faith and love pushed me to complete this journey with perseverance and determination.

This thesis is not just a reflection of my efforts, but a testament to the collective efforts, love, and support of everyone mentioned above. Thank you.

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Chapter 1

Introduction

As the global energy landscape undergoes a paradigm shift, with a growing emphasis on decentralized systems and technological integration, the conventional frameworks governing electricity markets are being reevaluated. Emerging technologies, including blockchain and smart grids, present new avenues to address the complex challenges posed by distributed energy resources, rising electricity demand, and sustainability imperatives. This thesis delves into the potential of these technologies to revamp the design and operation of electricity markets, aiming to establish systems that are efficient, scalable, and tailored for the 21st-century energy needs.

The transition from a centralized to a more decentralized energy landscape is not merely a shift in infrastructure; it also calls for a rethinking of policy, economic models, and the technical methodologies underpinning energy systems. As distributed generation becomes more prevalent, driven by the surge in renewable energy sources, the dynamics of how energy is produced, distributed, and consumed are fundamentally changing. This decentralization introduces both challenges and opportunities. While it promises greater resilience, reduced transmission losses, and enhanced adaptability to local energy needs, it also necessitates more sophisticated coordination mechanisms, real-time data analytics, and innovative market structures. Additionally, with the rise of prosumers—entities that both produce and consume energy—the traditional distinctions between consumers, producers, and distributors are blurring, calling for a more holistic and integrated approach.

1.1 Background and Motivation

The genesis of the electrical power system revolution is deeply rooted in the rise of distributed energy resources (DERs), especially renewable energy sources such as solar and wind. Alongside these, the incorporation of energy storage systems has played a pivotal role, offering solutions to intermittency issues and ensuring a steady power supply. However, while these DERs and storage solutions promised sustainability, resilience, and self-sufficiency, they also ushered in a plethora of challenges in grid management, energy trading, and system stability. Additionally, as the digital age advanced, consumer behavior evolved, gradually transforming passive consumers into active prosumers, who not only consume but also produce and potentially trade electricity. The duality of these changes emphasized the inadequacy of traditional electricity markets and magnified the need for more adaptive and forward-looking solutions.

1.2 Objectives and Scope

The primary objective of this thesis is to explore the synergies between blockchain technology and smart grid functionalities, laying the groundwork for a contemporary electricity market framework. Central to this exploration is the evaluation of decentralized peer-to-peer energy trading systems. As end-users play a pivotal role in the evolving energy landscape, this thesis also delves into the optimal scheduling of their activities, ensuring that consumption, storage, and generation patterns align with the broader system's objectives. Such scheduling not only optimizes energy usage for individual households but also maintains grid stability, even during peak demand periods. Beyond these specific components, this research ambitiously integrates these individual technological solutions into a holistic framework. The aspiration is to deliver a system that not only meets the challenges of growing electricity demands and evolving grid infrastructures but also champions scalability, efficiency, and robustness.

1.3 Contributions

This thesis offers significant contributions to the blooming field of decentralized electricity markets, as detailed below:

- We introduce a cutting-edge multichain hierarchical model that tackles fundamental challenges in scalability, modularity, and privacy. The architecture is enriched with multiple blockchains at each tier, optimizing scalability and lightening the load on individual chains. Additionally, mechanisms to bolster privacy are embedded, guaranteeing data confidentiality.

- A hierarchical electricity market mechanism is put forward. This clearance procedure simplifies energy market transactions, bolstering scalability, privacy, and impartiality, all the while ensuring the electricity market operates within grid constraints.

- The implementation of a deployable prototype. Our work uses Hyperledger Fabric, Node.js, a JavaScript runtime environment and Linux Bash scripting for automating tasks. The scalability and configurability of the prototype makes it suitable for real-world applications. By constructing a concrete and functional prototype, the thesis showcases the potential for practical implementation of the proposed model.

- A realistic case study, encompassing 50 simulations, is conducted to effectively demonstrate the system's capabilities and characteristics. Through the evaluation of system performance, including remarkable throughput and minimal latency, the effectiveness of the proposed model is highlighted.

1.4 Thesis Structure

The subsequent chapters of this thesis are methodically structured to provide readers with a coherent progression through the research. Chapter 2 offers a comprehensive literature review, laying the foundation for the concepts explored in the thesis as well as showcase our work's publications. Chapter 3 delves into the modelling and representation of the end-users that are considered to participate in a contemporary electricity market. Chapter 4 provides an overview of the proposed electricity market architecture, presents the electricity market implementation, including the design of smart contracts, and describes the complete electricity market procedure. In Chapter 5, a comprehensive case study is presented, demonstrating the practical application of the proposed electricity market architecture as well as a performance analysis highlighting the capabilities, efficiency and limitations of the system. Finally, Chapter 6 concludes this work by summarizing the key findings, discussing the results of the research, and suggesting potential avenues for future work.

Chapter 2

Literature Review

2.1 Evolution of Electrical Power Systems

The evolution of electrical power systems traces back to the late 19th century with the advent of centralized power generation and transmission systems. The last few decades have seen a monumental shift, marked by the transition from centralized to decentralized systems. In this section, we will journey through the transformative history of electrical power systems. By delving into its intricate developments, we aim to foster a deeper understanding of the complexities and nuances that have shaped what many regard as the most expansive and influential system ever constructed by humanity.

2.1.1 The Dawn of Centralized Systems

In the late 19th century, the genesis of electrical power systems was predominantly characterized by centralized power generation and transmission. This era, often referred to as the age of electrification, saw an upsurge in the development and use of electricity, transforming how society functioned. The technological constraints and efficiencies of the time warranted a centralized approach. Large-scale power plants, often coal-fired, emerged as the dominant sources of electricity generation. These behemoths of energy production were not only a testament to the engineering marvels of the time but also embodied the socio-economic progress societies were undergoing.

The infrastructure to support this centralized generation model was vast. Expansive networks of high-voltage power lines stretched across regions, connecting power plants with urban centers and facilitating the movement of electricity over long distances. The cities, in turn, became hubs of energy consumption, drawing their power primarily from these centralized sources. Such a structure ensured a unidirectional flow of electricity, moving from large generators, through transmission systems, and eventually reaching the consumers. This paradigm was not just a technological necessity but also reflected the economic and regulatory environment of the period, where centralized control and distribution were deemed efficient and practical [1].

2.1.2 Rise of Decentralization and DERs

The journey from centralized power systems to the modern decentralized model is a narrative of innovation, environmental awareness, and the pursuit of energy resilience. As the 20th century approached its twilight years, a series of technological, economic, and socio-political forces began to converge, setting the stage for the rise of Distributed Energy Resources (DERs).

One of the most impactful technological drivers of this era was the rapid development and maturation of solar photovoltaic (PV) technology [2]. Initially, solar panels were costly and had limited efficiency, making them a niche, often experimental, energy source. However, sustained research and development efforts, combined with economies of scale in manufacturing, dramatically reduced costs and enhanced efficiency levels. By the dawn of the 21st century, solar PV not only became a feasible option for large-scale utility projects but also for individual households and businesses, effectively turning consumers into prosumers - entities that both consume and produce electricity.

Parallel to solar energy's ascendancy, wind power underwent its own renaissance. Wind turbines, once a quaint reminder of pre-industrial times, were re-engineered into towering structures capable of harnessing vast amounts of energy. Their deployment, especially in regions with consistent wind patterns, provided a clean and renewable alternative to fossil fuels. When integrated with modern grid management systems, these turbines could contribute significantly to a region's energy mix [3].

Energy storage systems, particularly advancements in battery technology, further catalyzed the DER movement. The rise of lithium-ion batteries, known for their high energy density and longevity, facilitated the storage of energy generated by intermittent renewable sources. This storage capability was a game-changer, allowing for the harnessing of solar energy during sunny days and its use during nighttime or cloudy periods. Similarly, wind energy could be stored during gusty periods and deployed during calms [4].

Another driving force behind the shift to DERs was the growing environmental consciousness and the desire to combat climate change. As the detrimental impacts of fossil fuels became undeniable, there was a global push towards sustainability. Policymakers, cognizant of the environmental benefits of renewable energy sources, implemented incentives, subsidies, and regulatory frameworks that favored the adoption of DERs.

Finally, from an economic standpoint, the decentralization of energy production had profound implications. By empowering consumers to generate their own electricity, the traditional utility business model was challenged. This democratization meant reduced transmission losses, increased grid resilience, and the potential for novel peer-to-peer energy trading mechanisms.

2.1.3 The Prosumer Revolution

The dawn of the 21st century saw not just technological evolution but also a transformation in the perception and participation of electricity consumers. Historically, the relationship between consumers and the electrical power system had been largely unidirectional: utilities generated electricity, transmitted it across vast distances, and delivered it to end-users. These users, in turn, consumed this electricity with little to no interaction with its generation or distribution processes.

However, as distributed energy resources began to proliferate, thanks in part to technological advancements and decreasing costs, a new breed of consumer started to emerge. These individuals were not simply passive recipients of electricity but active participants in its generation, storage, and even its distribution. Termed "prosumers", a portmanteau of 'producer' and 'consumer', these individuals, businesses, or entities began producing their electricity, typically from renewable sources like solar photovoltaic panels, small-scale wind turbines, or biomass. Rooftop solar installations, in particular, became symbolic of this movement, allowing homeowners to transform previously passive rooftops into active electricity generation assets.

This paradigm shift in energy production and consumption had profound implications for the traditional utility model. As more and more consumers began generating their electricity, demand from centralized utilities reduced. Furthermore, with the capability to feed excess electricity back to the grid, utilities had to evolve to accommodate and manage this bidirectional flow of electricity [5],[6].

2.1.4 Embracing Sustainability

The latter part of the 20th century and the onset of the 21st bore witness to a pronounced global awakening concerning the environmental repercussions of prolonged fossil fuel dependency. Rampant industrialization, urbanization, and increasing energy demands had precipitated significant greenhouse gas emissions, contributing to global warming and exacerbating climate change. The stark reality of melting ice caps, rising sea levels, and the increase in frequency and intensity of extreme weather events underscored the necessity for a more sustainable energy trajectory.

Governments worldwide began to grasp the magnitude of the challenge. Policy makers, prompted by both scientific findings and public outcry, began crafting strategies to reduce carbon footprints, aiming for a more resilient and sustainable energy future. Central to these strategies was the shift from coal, oil, and natural gas to more renewable sources of energy, such as wind, solar, and hydroelectric power.

The Paris Agreement of 2015 stood as a testament to this global commitment. Almost 200 countries pledged to work collectively to limit global warming to well below 2 degrees Celsius above pre-industrial levels, aiming for 1.5 degrees. Such a target, while ambitious, underscored the magnitude of the challenge and the collective will to address it.

In tandem with policy efforts, the renewable energy sector experienced exponential technological advancements. The efficiency of solar panels and wind turbines dramatically improved, while costs plummeted, making these technologies increasingly competitive with conventional fossil fuels. Solar and wind power, once viewed as supplementary, began to challenge the dominance of traditional energy sources [7], [8], [9].

2.2 Smart Grids and Distributed Generation

Building on the momentum from the previous chapter, which highlighted the transition towards renewable energy sources and decentralized power systems, this section delves into the birth and development of the smart grid concept. Such a shift in the energy landscape, reminiscent of the telecommunications transformation, necessitates an advanced and intelligent grid system. It is within this backdrop of changing energy dynamics that the Smart Grid emerges. Coupled with distributed generation, it holds the promise to significantly reshape the future outlook of electrical power systems.

2.2.1 Introduction to Smart Grids

The concept of the Smart Grid can be likened to the evolution of the telecommunications industry. Just as the old telephone systems—entirely manual and operator-dependent—evolved into today's sophisticated internet and cellular networks, the electricity grid is undergoing a similar metamorphosis.

At a high level, Smart Grids can be viewed as the next-generation electrical system, designed to accommodate bidirectional energy flows, integrate decentralized energy resources, and enable advanced communication and control capabilities. Through the use of sensors, advanced meters (often referred to as "smart meters"), and communication networks, Smart Grids provide real-time information to both utilities and consumers. This enables better decision-making about energy use, enhances the ability to integrate renewable sources like solar and wind, and improves the overall reliability and efficiency of the power system.

The evolution towards Smart Grids is also closely linked to the increasing penetration of renewable energy sources, the desire for enhanced energy efficiency, and the need for grid reliability in the face of uncertain supply and demand conditions. By embracing digital technology and advanced analytics, Smart Grids allow for more dynamic and flexible grid management, addressing challenges posed by intermittent renewable generation and evolving consumption patterns.

Several foundational texts and scientific articles have expounded on the principles, challenges, and potentials of Smart Grids. One such seminal work is [10] by Momoh et al. Momoh delves into the intricate components of the Smart Grid, highlighting its significance in addressing 21st-century energy challenges. Similarly, the work in [11] provides a comprehensive overview of the integration of communication technologies with traditional grid infrastructure, emphasizing the importance of consumer participation in energy management.

2.2.2 Key Features of Smart Grids

Real-Time Monitoring and Control

Smart Grids leverage a combination of sensors, advanced metering infrastructure (AMI), and communication networks to achieve real-time monitoring and control over various grid components. This ability to continually gather and analyze data is fundamental to the proactive management of modern electrical systems.

The deployment of AMI goes beyond just smart meters that measure consumption in households. It encompasses a wider array of devices that can measure and report on different aspects of the grid, from voltage levels to current flows and even the health status of equipment. These devices, often referred to collectively as phasor measurement units (PMUs) and distribution automation devices, provide granular data with high temporal resolution, enabling grid operators to understand the system's dynamics like never before [12].

Moreover, with the integration of communication technologies, these real-time measurements can be conveyed almost instantly to central control rooms or local substations. This allows operators to adjust to variations in supply, such as the intermittent nature of renewable sources, and demand, like sudden surges due to events or temperature changes. Furthermore, predictive analytics, when applied to this real-time data, can also forecast potential grid instabilities or failures, leading to preventive measures rather than reactive ones [13].

The importance of real-time monitoring becomes even more pronounced when considering distributed energy resources (DERs). As consumers and businesses increasingly adopt solar panels, wind turbines, and energy storage systems, ensuring their harmonious integration with the traditional grid requires in-depth, real-time insights. This facilitates grid balancing, reduces the strain on centralized energy generation, and aids in optimizing the flow of energy [14].

Integration of Renewable Energy

The integration of renewable energy sources into the electrical grid is pivotal for the transition to a sustainable energy system. Smart Grids, by their very design, cater to this transition, offering dynamic solutions to assimilate renewable outputs seamlessly into the conventional grid.

Renewable energy sources, notably solar and wind, are inherently variable. Their energy generation is contingent upon natural factors, making them intermittent and somewhat unpredictable. For example, solar energy generation peaks during the day and drops to zero during the night, while wind energy is contingent upon wind speeds which can be erratic [15]. This variability, if not addressed, can cause grid instability and reduce the efficiency of energy distribution.

Smart Grids, equipped with state-of-the-art monitoring, control, and communication capabilities, provide the necessary infrastructure to manage this variability. Advanced metering infrastructure and predictive analytics tools within Smart Grids can forecast renewable output based on real-time data and historical trends. This allows for better grid management and preparation for anticipated energy fluctuations [16].

Furthermore, the integration of energy storage solutions, like batteries and pumped storage, in Smart Grids facilitates the storage of excess renewable energy generated during peak times. This stored energy can later be dispatched during periods of low renewable output or high demand, ensuring a constant, reliable power supply [17]. Additionally, demand response mechanisms within Smart Grids can adjust consumption patterns in response to available renewable supply, further optimizing energy usage [18].

Demand Response

Demand Response (DR) stands as one of the cornerstones of Smart Grid technology, aiming to cultivate a more interactive and responsive relationship between electricity suppliers and consumers. The primary objective behind DR is to ensure that electricity consumption aligns efficiently with grid capabilities, especially during peak demand periods or in situations where renewable energy supply might be limited.

Traditionally, the approach to high demand periods was to increase supply, often by activating auxiliary, often less efficient, power plants. However, with DR, the emphasis is on modulating demand to match supply. For instance, during times when electricity generation from renewables is high and consumption is low, DR can incentivize consumers to increase their consumption by offering lower prices. Similarly, during peak demand or low renewable generation, prices might increase, prompting consumers to defer non-essential tasks or reduce their overall consumption [19].

Furthermore, with the integration of advanced metering infrastructure (AMI) and real-time pricing models, consumers can receive real-time feedback about their energy usage and associated costs. Such insights empower consumers to adjust their consumption patterns, leading to potential cost savings and a reduction in peak demand pressures on the grid [20].

Another fascinating offshoot of DR is the concept of "negawatts", where consumers are effectively "paid" for not using electricity during peak times. This not only helps in alleviating grid pressure but also fosters an energy-conscious mindset among consumers, further supporting energy sustainability goals [21].

In essence, through DR, Smart Grids foster a symbiotic relationship between consumers and providers, ensuring grid stability, efficiency, and sustainability while also offering economic benefits to the end-users.

2.2.3 Distributed Generation

Distributed Generation (DG) pertains to a set of energy generation technologies primarily characterized by their decentralized nature. Instead of relying on a few large-scale centralized power generation facilities, DG focuses on deploying numerous smaller-scale generation units situated closer to the end-users. These technologies encompass solar photovoltaic panels, wind turbines, combined heat and power (CHP) systems, micro-hydro systems, and even some forms of energy storage.

Advantages of Distributed Generation

Distributed Generation (DG) introduces an array of benefits, from increased energy efficiency due to proximity to consumers, to enhanced grid resilience through diversified power sources. As DG technologies continue to evolve, these advantages underscore a transformative shift in energy production and distribution.

- Efficiency Improvements: Since DG systems are closer to consumers, transmission distances are shorter, leading to significant reductions in energy loss. This proximity also enhances the overall efficiency of the energy supply chain.

- Enhanced Resilience: A distributed network of generation sources makes the entire system less vulnerable to large-scale outages. In the event of a failure or malfunction at one generation site, others can compensate, ensuring uninterrupted power supply.

- Reduction in Transmission Infrastructure: Localized generation diminishes the dependence on long transmission networks, leading to cost savings in infrastructure development and maintenance.

- Environmental Benefits: Many DG systems, especially those based on renewable sources like wind or solar, have a smaller carbon footprint. Their deployment can substantially decrease greenhouse gas emissions and other pollutants.
- Economic Empowerment: Local communities can benefit economically from owning and operating small-scale generation units, retaining more energy dollars within the community.

Challenges of Distributed Generation

While Distributed Generation offers promising advantages, it also presents distinct challenges, from the unpredictability of certain renewable sources to complexities in grid integration. Addressing these hurdles is paramount for the seamless adoption and maximized potential of DG technologies.

- Intermittency: Renewable sources, especially solar and wind, are subject to natural variations. This unpredictability necessitates the need for backup systems and advanced grid management technologies to maintain stability.
- Grid Integration: The legacy power grids, designed predominantly for unidirectional power flow, can find it challenging to accommodate the bidirectional flows intrinsic to DG systems.
- Economic Challenges: Despite the decreasing costs of technologies like solar panels and wind turbines, the initial capital requirement for DG systems can be substantial. Moreover, the return on investment can be prolonged, especially without supportive policies or subsidies.
- Standardization and Regulation: There is a need for standardization in technology and operational protocols for DG systems. Inconsistent regulatory frameworks across regions can hinder the widespread adoption of DG.

2.2.4 Smart Grids and Distributed Generation: A symbiotic Relationship

The integration of Smart Grids and Distributed Generation can be likened to two pieces of a jigsaw puzzle that fit perfectly. Individually, each presents its advantages: DG democratizes energy production, making it local and often more sustainable, while Smart Grids enhance the flexibility and responsiveness of the power system. When combined, they amplify each other's strengths.

The union of these two offers more than just the sum of their benefits. For instance, as DG introduces intermittent renewable energy sources to the power mix, Smart Grids provide the necessary tools to manage this intermittency, ensuring reliability. Moreover, Smart Grids, with their advanced monitoring and control capabilities, can maximize the use of local energy resources, reducing transmission losses and promoting energy efficiency.

The decentralized nature of DG also means a shift in the traditional top-down power flow model. Power can now flow in multiple directions, from consumers back to the grid and vice versa. Smart Grids facilitate this bidirectional flow, ensuring seamless integration and distribution.

Furthermore, with the rise of prosumers—consumers who also produce energy—there is a growing need for sophisticated energy management systems, real-time pricing mechanisms, and advanced metering. Smart Grids cater to these needs, allowing for dynamic pricing that can incentivize or discourage energy consumption based on real-time demand and supply.

From an innovation standpoint, the symbiotic relationship between Smart Grids and DG also opens doors for new business models, services, and technologies. Microgrids, community energy storage solutions, and peer-to-peer energy trading are just a few examples of the transformative innovations emerging from this synergy.

As the world strives for a sustainable energy future, the integration of Smart Grids and Distributed Generation represents a beacon of hope and a roadmap for achieving it. Their mutual reinforcement promises a power system that is not only green and efficient but also resilient and adaptable to the ever-evolving energy landscape.

2.3 Peer-to-Peer Energy Trading

2.3.1 Introduction in Electricity Markets and Peer-to-Peer Energy Trading.

Electricity markets are dynamic ecosystems where electricity is traded as a commodity between producers, retailers, and, in some cases, consumers. These markets traditionally operate on a central clearinghouse mechanism, where prices are determined based on supply and demand equilibria. Over the years, as power systems evolved, these markets underwent profound changes, adapting to the complexities introduced by renewable energy sources, distributed generation, and the increasing role of prosumers—entities that both consume and produce electricity.

The concept of peer-to-peer (P2P) trading in electricity markets introduces a paradigm shift. Instead of solely relying on centralized markets or large utility companies for electricity procurement or sale, P2P trading empowers individual prosumers and consumers to trade electricity directly amongst themselves. This decentralization not only democratizes the energy sector but also makes the grid more resilient and adaptive to fluctuations in supply and demand.

P2P trading capitalizes on the advancements in digital technologies, especially blockchain, to ensure secure, transparent, and auditable transactions. By eliminating intermediaries, P2P trading can potentially lead to reduced transaction costs, better price discovery, and a more efficient allocation of energy resources. Moreover, it incentivizes the adoption of renewable energy sources, as individuals and small-scale producers can monetize their surplus generation by selling it directly to their peers.

Tying this to the broader electricity market landscape, P2P trading can be visualized as an evolution in response to the changing dynamics of power systems. As the world increasingly veers towards decentralized and green energy solutions, the integration of P2P trading mechanisms into electricity markets signifies a step forward in aligning market structures with contemporary energy realities. This integration not only fosters greater market participation but also imbues the system with flexibility, fostering a more sustainable and resilient energy future.

2.3.2 Applications of Peer-to-Peer Energy Trading in Modern Electricity Markets

As environmental concerns intensify and technological evolution accelerates, modern energy landscapes are increasingly leaning towards decentralization and green solutions. A notable aspect of this transformative journey is the emergence of distributed generation, characterized by electricity production closer to its consumption point rather than from large centralized plants. Driven predominantly by renewable assets like solar and wind installations, this approach is introducing profound transformations in contemporary electricity markets, underscoring the urgency for more participatory and adaptive market designs [22].

Peer-to-Peer (P2P) electricity markets exemplify this new direction. They serve as platforms enabling individuals to exchange surplus electricity, primarily harvested from renewable sources, directly with each other. These platforms are celebrated for their potential to balance power efficiently, harness distributed renewable energy, and empower consumers by fostering local energy economies and ensuring equitable market participation [23].

In this evolving energy scenario, P2P trading is a beacon of democratization. Propelled by the rapid adoption of distributed energy resources (DERs) such as solar and wind, households and commercial entities are transitioning from being passive consumers to proactive 'prosumers', contributing to the energy grid. This shift doesn't only contribute to environmental sustainability but also facilitates grassroots participation in energy trade dynamics [24]. Recent strategies to integrate multiple renewable sources in a harmonized manner, aiming for diversification, are further enhancing the resilience and reliability of these systems [25].

Yet, the road to P2P market optimization is strewn with challenges. Legacy electricity infrastructures and their associated market constructs were not architected with numerous decentralized producers in mind. Moreover, the inherently unpredictable nature of renewable energy generation demands sophisticated forecasting and strategy for seamless grid integration. The community is calling for innovative market frameworks capable of navigating the intricacies of P2P transactions, ensuring equitable pricing, managing inconsistent renewable outputs, and preserving grid integrity [26]. Research, such as that presented in [27], delves into the potentialities of P2P trading in the wake of blockchain proliferation and widespread deployment of rooftop PV systems. The study sheds light on the dichotomy between market strategies and energy exchange paradigms. Another comprehensive review by Tushar et al. illuminates the anticipated grid benefits and delineates challenges, proposing technical strategies to overcome them while offering a roadmap for future investigations [28].

In [29] the authors present a decentralized blockchain-driven P2P energy marketplace, designed to mitigate prevalent challenges inherent in renewable energy trading realms. This marketplace, built atop the Hyperledger Fabric infrastructure, is meticulously engineered to uphold pivotal attributes such as privacy, trustworthiness, and regulatory compliance. Enlisting the oversight of a regulatory body, the framework adeptly navigates the terrain of governance, while simultaneously safeguarding user privacy and facilitating automated trading operations.

Furthermore, in [30] the authors chart a novel course with their Block Alliance Consensus (BAC) mechanism, tailored explicitly to surmount challenges germane to P2P energy trading landscapes. This innovative consensus mechanism, implemented within the Hyperledger Fabric ecosystem, circumvents the constraints posed by the traditional blockchain trilemma by striking a delicate balance between decentralization and scalability. Through the adoption of sharding techniques, coupled with the integration of Hashgraph within individual shards, the proposed mechanism exhibits commendable throughput and transaction speeds. Notably, a cross-shard facilitation protocol further enriches transactional fluidity across disparate shards, thereby underscoring the promise of the BAC paradigm in fortifying security and scalability metrics in P2P energy trading scenarios.

In [31] the authors introduce a blockchain-oriented framework tailored explicitly for distributed photovoltaic power trading. Embracing decentralized model training methodologies alongside a graph-based algorithm for producer-consumer matching, this framework, tested on the Hyperledger Fabric platform, showcases tangible advancements in prediction accuracy and transactional efficiency. These findings collectively underscore the auspicious prospects of leveraging blockchain technology in fostering sustainable and efficient green electricity trading ecosystems.

Hierarchical Structures in P2P Electricity Markets

The idea of a hierarchical structure in P2P electricity markets has garnered attention in academic research. In [32], the authors introduce a hierarchical model for local electricity markets (LEMs) aiming to seamlessly incorporate distributed energy resources (DERs) into the distribution system. When tested on an adapted IEEE-123 bus system with significant DER presence, the hierarchical LEM showcased enhanced market efficiency and cost reductions, as evidenced by simulation results. Esfahani's research [33] presents a multi-tiered Blockchain-based electricity market system tailored for secure energy trades within and across Microgrids. The proposed model enhances the energy transaction methodology, market clearing procedure, and overall power market safety. The system prioritizes power reliability checks before greenlighting transactions, integrates blockchain ledger summaries, and proves its efficacy, especially in transmission paths experiencing congestion.

In [34], the authors advocate for a hierarchically structured electricity market aligned with the cellular approach (CA) in envisioned energy frameworks. This innovative design fuses the technical strengths of localized energy management and decentralized operations with the fiscal advantages of markets overseen by independent system operators (ISOs). The paper further elaborates on the key market players and delves into the governance dynamics of the ISOs. Another research [35] underscores the potential of blockchain technology in ensuring the safety of both energy trades and distributed control mechanisms in a microgrid setting that caters to six prosumers. The tiered blockchain infrastructure, fortified with smart contracts and a Proof-of-Authority consensus method, guarantees control system robustness and transactional ease. Through various case studies, the multi-tiered blockchain model is validated, highlighting its practicality and efficiency in safeguarding control frameworks while enhancing the gains for prosumers.

In their work [36], the authors introduce a sophisticated three-layer architecture tailored for Peer-to-Peer (P2P) electricity trading, underpinned by blockchain technology, with a primary focus on bolstering privacy safeguards. The proposed framework integrates cutting-edge methodologies such as homomorphic encryption and secure multi-party computing to ensure the confidentiality of transactions during order processing and settlement phases. Empirical investigations, conducted utilizing the IBM Hyperledger Fabric platform, corroborate the efficacy of the proposed paradigm.

2.4 Blockchain Technology

2.4.1 Introduction to Blockchain

At its core, blockchain is a digital ledger technology that records transactions in a secure, transparent, and immutable manner. Imagine a growing chain of blocks, where each block contains a list of transactions. Every time a new transaction occurs, it is verified by a network of computers and, once approved, added to a block. This block is then sealed using cryptographic principles and linked to the preceding block, thus forming a chain. What distinguishes blockchain from traditional databases is its decentralized architecture: instead of being stored on a single server or controlled by a single entity, copies of the blockchain are distributed across multiple computers worldwide. This decentralized nature ensures that the data is resistant to tampering, as altering any piece of information would require the consensus of the majority of the network. Moreover, every transaction on the ledger is transparent to all participants and, once recorded, becomes virtually unalterable, providing an unparalleled level of trust and security in the digital realm.

2.4.2 How Blockchain Works

At its core, blockchain is a digital ledger that records and verifies transactions in a secure, transparent, and immutable manner. Each piece of information or transaction added to this ledger is termed a "block."

When a transaction occurs, it's bundled with other transactions into a proposed block. Before this block is added to the chain, however, it must be verified. This verification process involves network participants, often referred to as "nodes." Depending on the blockchain type, different consensus mechanisms, like Proof of Work (PoW) or Proof of Stake (PoS), might be employed. These mechanisms ensure that all participating nodes agree on the validity of the transactions within the block.

Once verified, the block receives a unique identifier called a hash. This hash is cryptographically generated and is influenced by the contents of the block and the hash of the previous block in the chain. This interdependency ensures that once a block is added to the blockchain, its information becomes immutable; changing any information within it would require the consensus of the majority of the network, making unauthorized alterations practically impossible.

Unlike traditional databases, where data is stored on a central server, blockchain information is stored across a network of computers. This decentralization means there's no single point of failure. If one node is compromised, the integrity of the entire blockchain remains intact, as other nodes in the network retain unchanged, verified copies of the ledger. This distributed nature also provides inherent protection against malicious attacks and fraud.

Every node in the network has access to the entire blockchain, promoting transparency. This transparency, combined with the immutable nature of blockchain records, fosters trust among participants. While details of the transaction are visible, the identities of the parties involved can be pseudonymous, maintaining privacy.

Beyond just recording transactions, blockchain can also automate and enforce agreements through smart contracts. These are self-executing contracts with the terms of the agreement directly written into lines of code. They automatically enact and verify the terms of a contract when certain conditions are met, reducing the need for intermediaries and potential points of dispute.

2.4.3 Blockchain in the Energy Sector

Peer-to-Peer Energy Trading and Blockchain

With the challenges posed by decentralization and the need for trust in P2P electricity markets, blockchain technology emerges as a promising remedy. The intrinsic attributes of blockchain—decentralization, immutability, and transparency—position it as a potential cornerstone for P2P electricity transactions [37]. Not only does it promise to enhance trust and ensure transparency in transactions, but it also stands to substantially reduce transactional overheads and streamline the incorporation of multiple decentralized energy entities. Nevertheless, embracing blockchain is not devoid of challenges, a fact acknowledged and addressed by contemporary research. These studies have been instrumental in navigating the technological intricacies and potential bottlenecks associated with blockchain deployment [38]. An exhaustive investigation by [39] spotlighted the pivotal role blockchain is assuming in the energy sector's transformation. In another insightful research by Afzal et al., the synergy between the Internet of Things and blockchain in sculpting a new-age distributed electricity market system is explored [40].

In recent times, empirical studies have underlined the pragmatic advantages of infusing blockchain into P2P electricity markets. A study by Esmat et al. [41] introduced a groundbreaking decentralized P2P energy trading platform, balancing economic efficiency, privacy concerns, and other challenges through a singular blockchain framework. Another research [42] delineated a resilient architecture for P2P energy trading, emphasizing decentralized operations and cybersecurity. This model adeptly integrated microgrids and smart grids, displaying a remarkable resilience to cyber threats. Yang et al. [43] ventured into a more public blockchain realm for P2P energy trading. Their system minimized the conventional blockchain's energy overhead by incorporating a Proof-of-Stake (PoS) consensus mechanism, resulting in a more sustainable and economically viable model. Further, a pioneering architecture called the Unified Permissioned Blockchain-based P2P Energy Trading Architecture

(UBETA) was proposed by [44]. UBETA's performance surpassed extant models with enhanced throughput, scalability, and overall efficacy.

Another noteworthy study [57] devised an optimal P2P energy trading model suitable for residential systems with diverse energy resources. This model, emphasizing both supply-demand alignment and geographical efficiency, was subsequently realized on a permissioned blockchain platform, underscoring its real-world applicability. In Table 2.1, we provide a summary of related works in the field of P2P electricity markets. The table presents a comparative analysis of various scientific works, highlighting whether specific aspects, such as market design, trading mechanisms, scalability, decentralization, privacy, and implementation, have been considered, partially considered, or not considered in each work.

2.4.4 Scalability of Energy Trading Platforms

The energy sector, with its vast and intricate networks, is often characterized by an immense number of transactions. This magnitude becomes even more pronounced in a decentralized system, where each node or participant can potentially initiate or be a part of multiple transactions simultaneously. Blockchain, as a nascent technology, is grappling with scalability challenges to cater to such high transactional demands, especially in its public implementations.

In traditional public blockchains like Bitcoin or Ethereum, the scalability issue is evident. For instance, Ethereum, with its smart contract capability, can process roughly 30 transactions per second (tps), while Bitcoin's limit stands around 7 tps [58]. This constraint is minuscule compared to the transactional needs of the energy sector in a decentralized setting.

Furthermore, as blockchain networks grow, the need for consensus amongst increasing numbers of nodes exacerbates the scalability problem. Larger networks require more time to reach consensus due to the increased number of participants [59]. This delay can hinder real-time operations, which are crucial in the energy sector for operations like load balancing and demand response.

Emerging solutions, such as off-chain transactions, sharding, and layer 2 proto-

Table 2.1 – Comparison between related scientific work.
✓ - considered, ❍ - partially considered, ✗ - not considered

Scientific Work	Market Design	Trading Mechanism	Scalability	Decentralization	Privacy	Implementation
[33]	✓	❍	✓	❍	✓	✗
[45]	✓	✓	✗	❍	✗	✓
[46]	✓	✓	✗	✗	✓	❍
[47]	❍	❍	✗	❍	✓	❍
[48]	✓	✓	❍	❍	✗	❍
[49]	❍	❍	✗	✗	✗	✓
[50]	✓	✓	✗	✗	❍	❍
[51]	✓	❍	✗	❍	✗	✓
[31]	✓	✓	❍	✗	❍	✓
[30]	✓	✗	✓	❍	✓	✓
[52]	✓	✓	✗	❍	✗	✗
[29]	✓	✓	✗	❍	✓	✓
[53]	✓	✓	✗	❍	❍	✓
[54]	❍	❍	✗	❍	✓	✓
[55]	✓	✓	✗	❍	❍	❍
[56]	✓	✓	✗	❍	✗	✓
Our work	✓	✓	✓	✓	✓	✓

cols, are being explored to enhance blockchain's scalability [60]. However, these are still under rigorous scrutiny and evaluation for their efficacy, security, and adaptability to diverse sectors, including energy.

Integration with Existing Systems

Incorporating blockchain technology into the prevailing energy infrastructure introduces both technical and operational obstacles. A large part of the existing energy infrastructure is founded upon legacy systems, conceptualized and executed well before blockchain technology came into prominence. These archaic systems often rely on unique protocols, standards, and communication frameworks, which might not be instantly congruent with blockchain's decentralized ethos.

1. *Complexity of Legacy Systems*: Numerous existing energy infrastructures function on proprietary platforms with closed architectures. Such platforms typically lack the adaptability and compatibility required for a straightforward blockchain integration. This might mean that blending blockchain might necessitate extensive tailor-made solutions or alternative approaches, thereby driving up costs and lengthening deployment durations.

2. *Data Consistency and Migration*: The incorporation of blockchain into the energy landscape mandates the migration of vast amounts of data from traditional databases to the blockchain. Maintaining the integrity and precision of this data migration is pivotal. Furthermore, ensuring that data remains consistent across both blockchain and old systems during this transitional phase poses its own set of challenges.

3. *Security Concerns*: Despite blockchain's acclaim for its enhanced security, merging it with age-old systems could unveil certain vulnerabilities. These legacy systems were not originally designed keeping in mind the security protocols of blockchain, potentially leading to unforeseen risks.

Regulatory and Legal Concerns

Blockchain's decentralization brings forth a spectrum of regulatory and legal concerns. Its very essence challenges traditional energy governance structures and mechanisms.

1. *Standardization and Protocols*: Unlike traditional centralized systems, decentralized blockchain networks lack a singular point of governance. This means that there is no universally accepted standard or protocol. Developing, agreeing upon, and enforcing such standards in a decentralized environment can be a formidable task, especially when dealing with cross-border energy transactions where multiple regulatory jurisdictions are involved.

2. *Liability and Dispute Resolution*: In a decentralized blockchain network, pinpointing responsibility in the event of failures, breaches, or disputes becomes complex. Traditional legal systems rely on well-defined entities or intermediaries to resolve disputes, but blockchain's peer-to-peer nature might blur these lines of responsibility.

3. *Cross-Border Regulations*: Each country or region has its own set of regulations governing energy transactions. When energy trades occur across borders using a decentralized blockchain system, it's imperative to consider whose regulatory and legal framework will dominate. This presents challenges in compliance, auditing, and ensuring transparency.

4. *Data Privacy and Protection*: With energy transactions recorded on a public ledger, concerns regarding data privacy come to the fore. Blockchain might record transactional data, but specifics about parties involved, especially in private or consortium chains, could raise data protection concerns, especially under regulations like the General Data Protection Regulation (GDPR) in Europe.

5. *Environmental Regulations*: Blockchain, especially platforms like Bitcoin, can be resource-intensive and have been scrutinized for their environmental impact.

As energy sectors move towards more sustainable solutions, blockchain's environmental footprint could become a regulatory concern.

2.5 Research Gap and Our Contributions

In our research, we harness the capabilities of Hyperledger Fabric [61], a renowned open-source blockchain framework widely known for its adaptability, robust performance, scalability, and top-tier security features.

While the latest literature showcases the integration of Hyperledger Fabric and similar technologies into hierarchical designs for electricity markets, notable gaps persist. Existing studies predominantly center on singular blockchain models, neglecting the exploration of multiple blockchains per hierarchical tier. This limitation stifles scalability and adaptability. Even among the scant few papers investigating multi-chain designs spanning hierarchical levels, detailed implementations are lacking. Moreover, segmentation of each level into independent subsystems and the mechanisms supporting a fully extendable market remain underexplored. In Table 2.1, we offer a synopsis of pertinent works in the P2P electricity markets domain. The table conducts a comparative analysis, discerning the treatment of market design, trading mechanisms, clearing mechanisms, scalability, decentralization, privacy, and implementation in each study.

In this research, we operate on two fronts. Firstly, we model the end users of a smart grid to better understand the dynamics of distributed energy trading platforms. Secondly, we introduce ScaleNex, a hierarchical multi-chain P2P electricity market model powered by Hyperledger Fabric, aimed at bridging these research gaps. ScaleNex adeptly manages P2P electricity trading across multiple market levels through interconnected blockchains per market level. Our contributions are as follows:

- Modeling a distributed system's end users, including residential users, EV aggregators, renewable energy sources (RESs), and large producers.
- Presentation of a novel multi-chain hierarchical model addressing key chal-

lenges in scalability, modularity, and privacy. This design incorporates multiple blockchains per level, facilitating efficient scaling and reducing strain on individual chains. Privacy-enhancing mechanisms ensure data confidentiality.

- Introduction of a novel hierarchical electricity market procedure enhancing transactional efficiency, scalability, privacy, and fairness, while accommodating constrained electricity market operations under grid constraints.
- Deployment of a functional prototype leveraging Hyperledger Fabric. The prototype's scalability and configurability render it suitable for real-world deployment, showcasing the practical viability of the proposed model.
- Conducting a comprehensive case study encompassing 50 simulations, elucidating system characteristics and capabilities.
- Performance evaluation highlighting exceptional throughput and minimal latency, affirming the efficacy of the proposed system.

2.5.1 Publications

Published

- Symiakakis M.S, Kanellos F.D., "ScaleNex: A Scalable Blockchain-Powered Electricity Market Implementation for Smart Grid Environment.", Smart Grids and Sustainable Energy, 2024 [62]

Published

- Symiakakis M.S, Kanellos F.D., "Towards the detailed modeling of deregulated electricity markets comprising Smart prosumers and peer to peer energy trading." Electric Power Systems Research, 2023 [63]

  Note: Results and models of this work were used to develop the blockchain-based-P2P electricity market method proposed in this work.

Chapter 3

Modeling and Representation of Prosumers in the Smart Grid

In this chapter, we present comprehensive models for the prosumers that would interact with the proposed electricity market scheme, capturing their unique generation and consumption patterns, storage capabilities, and interaction with the wider grid. These models not only underscore the growing significance of prosumers in today's energy landscape but also provide a foundation for optimizing grid operations, enhancing system resilience, and facilitating peer-to-peer energy trading.

In the ensuing sections, for the express purpose of this research, we delve into the modeling and optimization of certain consumption profiles. This modeling is rooted in the premise of projected forecasts for electricity prices, a vital piece of information that each end-user can readily access. We symbolically represent these prices as $p(t)$, where the function denotes the price at any given time instance t within a day.

3.1 Residential End-Users

3.1.1 Profiling Residential Consumers

We consider each household to consist of 1-6 inhabitants, spanning various age groups and occupational backgrounds, which influence their energy consumption pat-

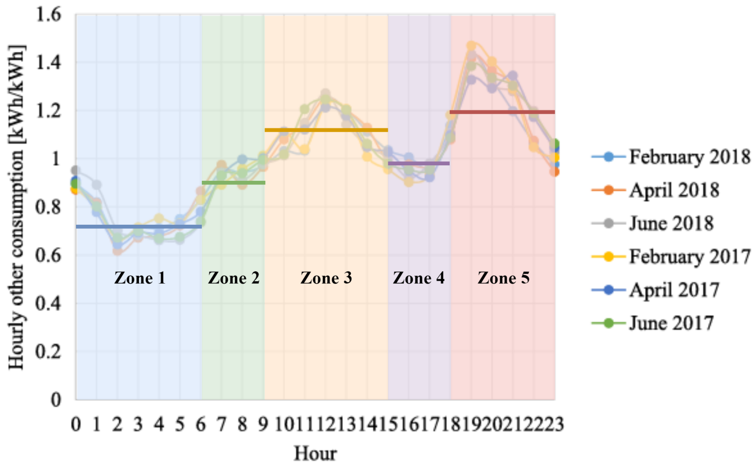


Figure 3.1 – Archetypal daily time zones for electricity consumption.

terns. Each of these residences is set up for two-way data communication, with certain homes boasting energy storage solutions and solar panel installations. Integral to these homes are various appliances, each with distinct operating hours and power demands, dividing the household's energy consumption into inelastic and flexible components.

Inelastic energy demand outlines the routine energy usage patterns based on the residents' daily activities. This demand varies during the day, drawing from archetypal models and statistical data relating to age-specific consumption patterns [41]. In this context, we segment residents into three primary age groups: 1) children (0-17 years), 2) adults (18-64 years) – further divided by their work patterns into day-shift, night-shift, or remote work – and 3) seniors (over 65 years).

Through meticulous analysis of data presented by Csoknyai et al., which studied the daily energy usage habits of a plethora of households via statistical techniques and smart meter readings [64], we demarcated five distinct energy consumption time zones, as depicted in Fig. 3.1. Each of these zones was characterized by its mean energy consumption that can be seen by the colored horizontal lines. Factoring in these time zones, we modified the energy usage profiles for each resident type, ensuring they aligned with these established archetypes.

3.1.2 Household Energy Profiling

The daily energy signature of a household is constituted by the aggregation of three pivotal profiles: its inherent load, battery usage, and photovoltaic (PV) generation. This segment delves into each of these facets, inaugurating with the intrinsic household load.

The foundational load profile for a household h is structured as:

$$P_{\min}^{h}(t) = \sum_{m=1}^{M} P_{\min}^{mh}(t) + \sum_{a=1}^{A} P_{\min}^{ah}(t) \tag{3.1}$$

Herein, $P_{\min}^{m}$ symbolizes the fundamental load for the m^{th} household member, whereas $P_{\min}^{a}$ denotes the inherent load of the a^{th} shared household appliance (e.g. oven, laundry machine, refrigerator).

Every household possesses a predetermined limit for power exchange, defined by its electrical line capacity, C_{line}^{h}, formulated as:

$$P_{\max}^{h} \leq C_{\text{line}}^{h} \tag{3.2}$$

Given the latitude in power consumption, every household has a designated flexible energy consumption allocation, E_{h}^{flex}, coupled with the combined energy expenditure for all appliances, E_{h}^{a}. Furthermore, an implicit energy expenditure, E_{h}^{m}, is attributed to each household member. The collective household energy consumption, E_{h}^{total}, is then computed as:

$$E_{h}^{m} = \sum_{m=1}^{M} \sum_{t=1}^{T} P_{\min}^{m}(t) \cdot dt \tag{3.3}$$

$$E_{h}^{a} = \sum_{a=1}^{A} \sum_{t=1}^{T} P_{\min}^{a}(t) \cdot dt \tag{3.4}$$

$$E_{h}^{\text{total}} = E_{h}^{\text{flex}} + E_{h}^{m} + E_{h}^{a} \tag{3.5}$$

Given the anticipated daily electricity prices p, the total household power consumption $x_h(t)$ at time t, and the overall energy usage E_{h}^{total}, we define an objective function to minimize the daily electricity cost:

$$\min_{x_h} \sum_{t=1}^{T} p(t) \cdot x_h(t) \cdot dt \tag{3.6}$$

Subject to:

$$P^h_{\min}(t) \leq x_h(t) \leq P^h_{\max} \quad \forall t \in T \tag{3.7}$$

$$\sum_{t=1}^{T} (x_h(t) - P^h_{\min}(t)) \cdot dt = E^{\text{flex}}_h \tag{3.8}$$

$$P^{\text{flex}}_{\min} \leq x_h(t) - P^h_{\min}(t) \leq P^{\text{flex}}_{\max} \tag{3.9}$$

The ideal household load profile is ascertained by solving constraints 3.7–3.9 and is later merged with the battery and PV profiles to form the collective household daily energy outline.

Every household battery has upper and lower energy limits $E_{\max}$ and $E_{\min}$. It starts the day at E_0 and ends at E_f. Moreover, there are power limits for charging and discharging, $P^b_{\max}$ and $P^b_{\min}$.

To account for both purchasing and selling electricity at different prices, we define:

$$x_b^+(t) = \max\{0,\, x_b(t)\}, \qquad x_b^-(t) = \max\{0,\, -x_b(t)\}.$$

Hence $x_b^+(t)$ is the power drawn from the grid (if $x_b(t) > 0$) and $x_b^-(t)$ is the power fed to the grid (if $x_b(t) < 0$).

We then formulate the following cost minimization:

$$\min_{x_b} \sum_{t=1}^{T} \Big[p_{\text{buy}}(t)\, x_b^+(t) \;-\; p_{\text{sell}}(t)\, x_b^-(t) \Big]\, dt, \tag{3.10}$$

subject to per-time-step constraints. For instance, if we use a binary $ch(t) \in \{0, 1\}$ (1 = charging, 0 = discharging), we might enforce

$$P^b_{\min}(t) \;\leq\; n_{\text{ch}} \cdot x_b(t) \;\leq\; P^b_{\max}(t) \quad \text{if } ch(t) = 1, \tag{3.11}$$

$$P^b_{\min}(t) \;\leq\; \frac{x_b(t)}{n_{\text{dis}}} \;\leq\; P^b_{\max}(t) \quad \text{if } ch(t) = 0, \tag{3.12}$$

where n_{ch} and n_{dis} (charging and discharging efficiencies) are both 0.95. To track the battery energy more accurately, one updates the state of charge $E(t)$ at each time step:

$$E(t+1) = E(t) + \left[ch(t)\, n_{\text{ch}}\,(-x_b(t)) + \Big(1 - ch(t)\Big)\, \frac{x_b(t)}{n_{\text{dis}}}\right] \Delta t, \tag{3.13}$$

subject to

$$E_{\min} \leq E(t) \leq E_{\max}, \quad \forall\, t, \qquad E(1) = E_0, \quad E(T+1) = E_f.$$

Here, $p_{\text{buy}}(t)$ is the electricity purchase price, $p_{\text{sell}}(t)$ is the selling price, and $x_b(t)$ is the battery's power (positive for drawing from the grid, negative for feeding in).

By solving the above objective and constraints, we derive an optimal battery-charging and discharging pattern. These results are then combined with the household's PV generation to form the complete energy profile. Consequently, the instantaneous net power consumption of the household at time t is simply

$$P_h(t) = x_h(t) + x_b(t) - x_{\text{PV}}(t), \tag{3.14}$$

3.2 EV Aggregators

We assume that each EV Aggregator can gather forecasting data for its fleet's daily activity and the prevailing electricity prices, denoted by p. Each aggregator can methodically deduce its fleet's energy boundaries for a day, demarcated as $E^{\text{EVF}}_{\max}$ and $E^{\text{EVF}}_{\min}$, along with the accumulated charging and discharging power values, $P^{\text{EVF}}_{\max}$ and $P^{\text{EVF}}_{\min}$, respectively. With these data in hand, the subsequent optimization problem is postulated:

$$\min_{x_{\text{EVF}}} \int_1^T p(t) \cdot x_{\text{EVF}}(t)\, dt \tag{3.15}$$

Under the constraints:

$$P^{\text{EVF}}_{\min}(t) \leq n_{\text{ch}} \cdot x_{\text{EVF}}(t) \leq P^{\text{EVF}}_{\max}(t) \quad \text{, if } ch(t) = 1 \tag{3.16}$$

$$P_{\min}^{\text{EVF}}(t) \leq -\frac{x_{\text{EVF}}(t)}{n_{\text{dis}}} \leq P_{\max}^{\text{EVF}}(t) \quad , \text{if } ch(t) = 0 \tag{3.17}$$

$$E_f = \frac{E_{\max}^{\text{EVF}}(t) + E_{\min}^{\text{EVF}}(t)}{2} \quad , t = T \tag{3.18}$$

$$E_0 = \frac{E_{\max}^{\text{EVF}}(t) + E_{\min}^{\text{EVF}}(t)}{2} \quad , t = 1 \tag{3.19}$$

$$E_f - E_0 = \sum_{t=1}^{T} \left(ch(t) \cdot n_{\text{ch}} \cdot x_{\text{EVF}}(t) + (1 - ch(t)) \cdot \frac{x_{\text{EVF}}(t)}{n_{\text{dis}}} \right) dt \tag{3.20}$$

$$\sum_{1}^{T} \left(ch(t) \cdot n_{\text{ch}} \cdot x_{\text{EVF}}(t) + (1 - ch(t)) \cdot \frac{x_{\text{EVF}}(t)}{n_{\text{dis}}} \right) dt \leq E_{\max}^{\text{EVF}}(t) - E_0 \tag{3.21}$$

$$\sum_{1}^{T} \left(ch(t) \cdot n_{\text{ch}} \cdot x_{\text{EVF}}(t) + (1 - ch(t)) \cdot \frac{x_{\text{EVF}}(t)}{n_{\text{dis}}} \right) dt \geq E_{\min}^{\text{EVF}}(t) - E_0 \tag{3.22}$$

The term $x_{\text{EVF}}(t)$ stands as a representation of the net power consumption attributed to a specific aggregator at the time instance t.

3.3 Renewable Energy Sources (RES)

3.3.1 Modeling of a Solar RES

Solar energy production primarily depends on irradiance and temperature. A comprehensive model would consider factors such as the position of the sun, cloud cover, panel angle, efficiency degradation due to temperature, and more. We will be now attempt to model a solar renewable energy source that would participate in the electricity market.

Solar Irradiance and Panel Orientation

To calculate the solar irradiance $I_s(t)$ impinging on the panel at time t, we consider three components: (1) the direct (beam) irradiance, (2) the diffuse irradiance from the sky, and (3) the irradiance reflected from the ground. This leads to the following equation for a panel tilted by an angle β:

$$I_s(t) = I_b(t)\,\cos\Big(\theta(t)\Big) \;+\; I_d(t)\,\frac{1+\cos(\beta)}{2} \;+\; \rho\left[I_b(t) + I_d(t)\right]\frac{1-\cos(\beta)}{2}, \quad (3.23)$$

where

- $I_b(t)$ is the direct (beam) irradiance normal to the sun's rays,
- $I_d(t)$ is the diffuse sky irradiance,
- ρ is the ground reflectance (albedo),
- β is the tilt angle of the panel relative to the horizontal,
- $\theta(t)$ is the angle of incidence between the sun's rays and the panel normal.

Temperature Effects

The efficiency $\eta(t)$ of the panel can be approximated by assuming that the panel (cell) temperature is equal to the ambient temperature $T_{\text{ambient}}(t)$. A common linear approximation is:

$$\eta(t) = \eta_0 - \beta\Big(T_{\text{ambient}}(t) - T_{\text{STC}}\Big), \quad (3.24)$$

where:

- η_0 is the panel efficiency under standard test conditions (STC),
- β is the temperature coefficient of the panel,
- $T_{\text{ambient}}(t)$ is the ambient temperature at time t,
- T_{STC} is the temperature under STC (usually 25°C).

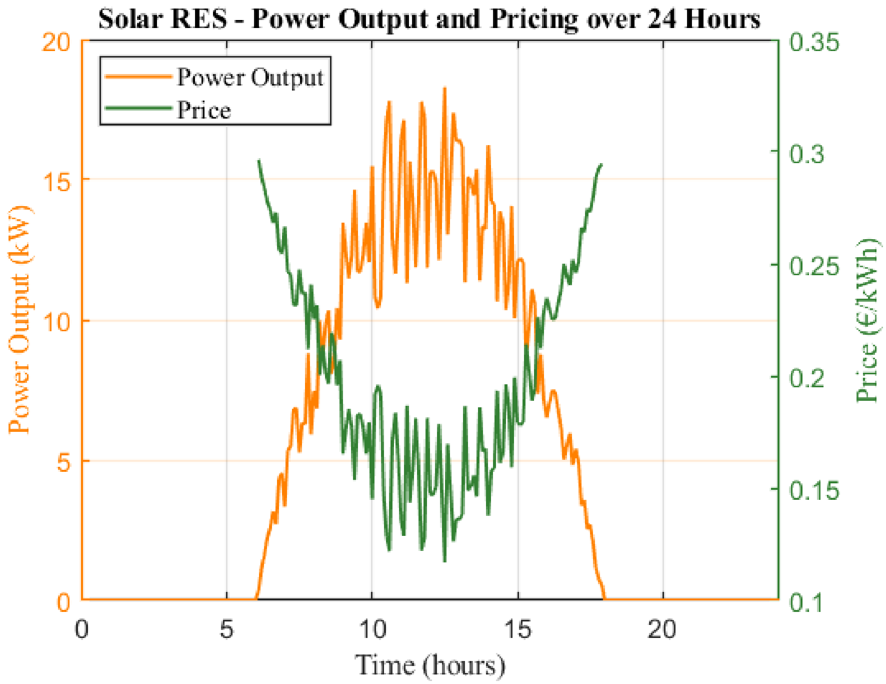


Figure 3.2 – Solar Power Output and Pricing for a 24-hour window.

Power Output

The instantaneous power output is then:

$$P_{\text{solar}}(t) = \eta(t) \times A \times I_s(t), \tag{3.25}$$

where:

- A is the area of the solar panel,
- $\eta(t)$ is the (temperature-adjusted) efficiency,
- $I_s(t)$ is the total solar irradiance (direct + diffuse + reflected) impinging on the panel.

Constraints

- $P_{solar}(t)$ must be between 0 and P_{max}, where P_{max} is the panel's maximum power rating.
- $0 \leq I_s(t) \leq I_{max}$, where I_{max} is typically around $1000\,\text{W/m}^2$.

In Figure 3.2, we present the diurnal solar power output of a PV park characterized as small to medium-sized. This output graphically illustrates its participation within a 24-hour timeframe in the electricity market. It's noteworthy to mention that such representations are indicative of the typical activity of solar RES (Renewable Energy Sources) end-users within the system. While there exist more intricate and granular modeling techniques to capture the nuances of solar energy production and market behavior, for the objectives of our study, this level of modeling provides a comprehensive and sufficient understanding.

3.3.2 Modeling of a Wind RES

Wind power production is influenced by wind speed, air density, and turbine characteristics.

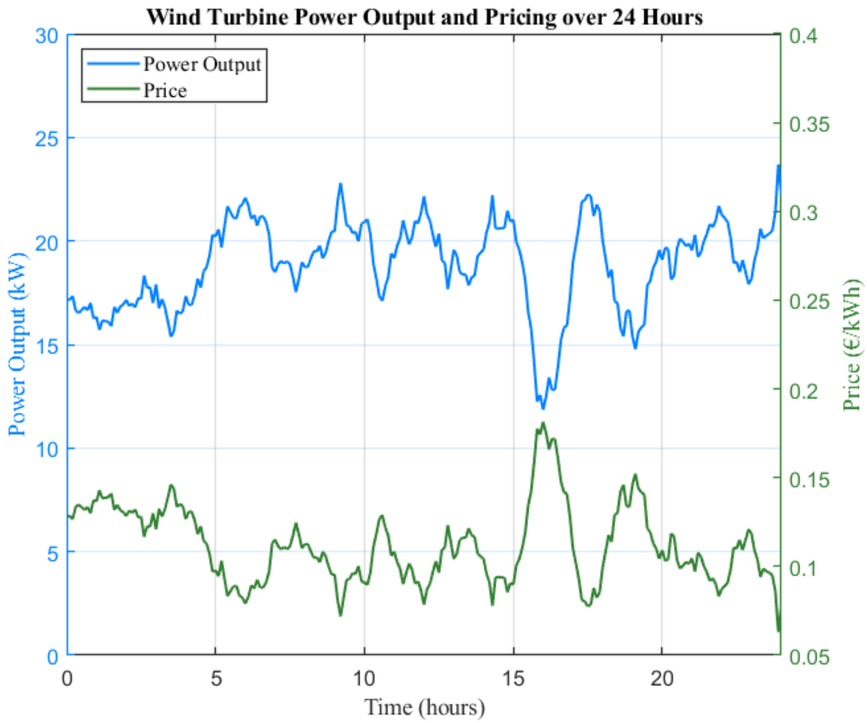


Figure 3.3 – Wind Power Output and Pricing for a 24-hour window.

Wind Power Curve

A power curve $P(w)$ is associated with most wind turbines, describing power output as a function of wind speed w. A common relationship is:

$$P_{wind}(t) = \frac{1}{2} \times \rho \times A \times C_p(w(t)) \times w(t)^3 \tag{3.26}$$

where:

- ρ = Air density
- A = Area swept by the turbine blades
- $C_p(w(t))$ = Power coefficient as a function of wind speed

Constraints

- $P_{wind}(t)$ should be within $[0, P_{rated}]$, where P_{rated} denotes the rated power of the turbine.
- $w(t)$ should fall between w_{cut-in} and $w_{cut-out}$, indicating the operational wind speed range.

In Figure 3.3, we showcase the daily wind turbine power output for a representative small-sized wind turbine and its associated pricing over a 24-hour period within the electricity market. This graphical depiction provides a snapshot into the operational rhythm of wind RES (Renewable Energy Sources) participants in the power grid. While there are more advanced and intricate modeling techniques available to delineate every nuance of wind energy generation and its market dynamics, for the purposes of our research, this level of detail offers an apt and comprehensive overview.

3.4 Medium-Scale and Large-Scale Consumers and Producers

As we delve deeper into the intricacies of our proposed electricity market, it becomes imperative to elucidate the roles and behaviors of two pivotal entities: the medium-scale and large-scale consumers and producers. These participants, distinct from their smaller counterparts, bring about unique dynamics and challenges to the market landscape due to their significant energy demands or contributions. In the forthcoming sections, we will systematically model and present the characteristics of these larger entities. Their integration and active participation will undeniably shape the overall functionality of the proposed electricity marketplace.

3.4.1 Medium and Large Scale Consumers

Given a predetermined inelastic base load $P^{\text{lc}}_{\text{min}}$, the price forecast $p(t)$, and a total daily energy expenditure $E^{\text{lc}}_{\text{total}}$ we consider medium and large consumers to calculate their optimal load schedule through the following optimization problem:

$$\min_{x_{\text{lc}}} \sum_{t=1}^{T} p(t)x_{\text{lc}}(t)dt \tag{3.27}$$

subject to

$$P_{\min}^{\text{lc}}(t) \leq x_{\text{lc}}(t) \leq P_{\max}^{\text{lc}}(t) \quad \forall t \in T \tag{3.28}$$

$$\sum_{t=1}^{T} x_{\text{lc}}(t)dt = E_{\text{total}}^{\text{lc}} \tag{3.29}$$

Where $P_{\max}^{\text{lc}}$ is the maximum amount of power that can be transferred to each commercial or industrial end-user. $x_{\text{lc}}(t)$ is the power consumption of large consumer lc at time t.

3.4.2 Medium and Large Scale Producers

Given the unit cost of the fuel consumed by the nth generator p_{fuel}^{n} and its fuel consumption function parameters (a_n, b_n, c_n), the medium or large producer calculates the respective cost of power production as follows:

$$F_n(P_{n,t}) = (a_n P_n(t)^2 + b_n P_n(t) + c_n)p_{\text{fuel}}^{n} \tag{3.30}$$

Given the electricity price forecast $p(t)$, the economic profit Ω_n of the nth generator is given by:

$$\Omega_n(t) = p(t)P_n(t) - F_n(P_n(t)) \tag{3.31}$$

Each producer, whether large or medium, is seen as a market participant. They aim to maximize their profit while trying to minimize their bid price to the maximum extent. This ensures their continued participation in the market and strikes a balance between maximizing revenue and maintaining market share.

The first step in this process is to calculate the optimal power production given the forecasted electricity price $p(t)$:

$$\frac{d\Omega_n}{dP_n} = 0 \Rightarrow \frac{dF_n}{dP_n} = p \tag{3.32}$$

After calculations, the above equation can be transformed to determine the optimal power production of the nth generator:

$$P_n(t) = \frac{p(t)}{p^n_{\text{fuel}}} - \frac{b_n}{2a_n} \tag{3.33}$$

Subsequently, we define an optimization problem to estimate the minimum possible asking price, $\hat{p}_n(t)$. This price should not diminish the economic profit below a predetermined value. This value is given by the parameter r_n, which is multiplied by the maximum economic profit specified by the nth generator owner. At this point, it is worth noting that this constant is determined by each end user and should be derived from a thorough economic analysis, which we will not discuss here, as it falls outside the scope of our work. For our proposed implementation, we consider a constant r_n value of 0.8.

$$\max_{\hat{p}_n(t)} \{p(t) - \hat{p}_n(t)\} \tag{3.34}$$

Subject to:

$$\Omega_n(\hat{p}_n(t), P_n(t)) > r_n(t)\Omega_n(p(t), P_n(t)) \tag{3.35}$$

$$0 < \hat{p}_n(t) < p(t) \tag{3.36}$$

$$0 < r_n(t) < 1 \tag{3.37}$$

3.5 Summary

Throughout this chapter, we have presented the models characterizing some notable prosumers, consumers, and producers in a contemporary electrical power system. Through rigorous analyses, we captured the nuanced generation and consumption behaviors and storage proficiencies.

With our prosumer models now aptly delineated and scheduled, a consequential imperative emerges: the need for these entities to engage in transactions predicated on their respective quantity-value pairs. These transactions, quintessential to the effective functioning and dynamic adaptability of a smart grid system, require an innovative, secure, and scalable platform for peer-to-peer energy trading.

Anticipating this necessity, the upcoming chapter unveils our proposition: a hierarchical, blockchain-powered electricity market for peer-to-peer energy trading. In this framework, end-users are empowered to transact seamlessly, and trustworthily. Central to this model is the utilization of Hyperledger Fabric—a cutting-edge framework that serves as the bedrock for our proposed blockchain architecture. Through its state-of-the-art capabilities, we present a novel implementation where energy transactions are not just facilitated, but also fortified with privacy and scalability.

Chapter 4

Hierarchical Blockchain-Powered Electricity Market

Having established a comprehensive model and scheduling framework for electricity market end-users, it becomes imperative to transition from theoretical constructs to actionable platforms. In order to truly harness the potential of the modeled end-users, we require a robust trading platform that doesn't just accommodate them, but also efficiently facilitates their electricity trading activities. This platform should not only be scalable, effortlessly supporting thousands of concurrent transactions, but also should be founded on enterprise-class software to ensure reliability, security, and seamless integration with existing infrastructures. By translating our end-user modeling into a tangible, high-performance trading environment, we can fully realize the envisioned benefits of decentralized energy trading, bridging the gap between theoretical groundwork and real-world implementation.

4.1 Hyperledger Fabric: An Overview

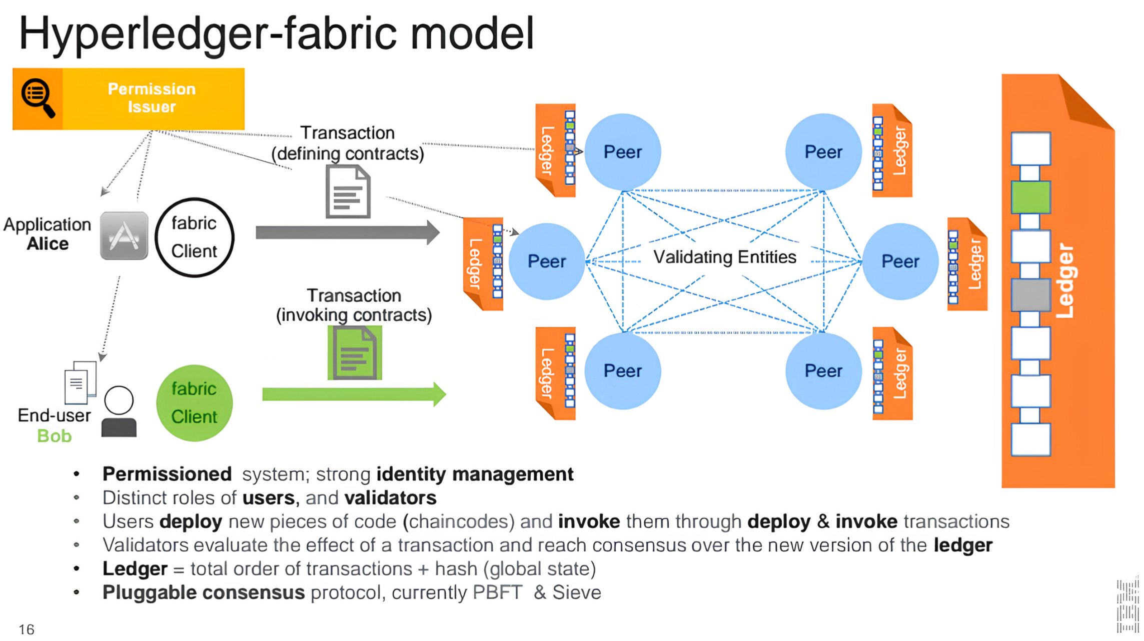


Figure 4.1 – Overview of Hyperledger Fabric.

4.1.1 Introduction

Hyperledger Fabric, a leading contender in the realm of blockchain technology, emerges as the preferred choice for the intricate dynamics of electricity markets. Its innate capability to cultivate permissioned, private networks sets it apart, allowing participants to engage in secure, confidential transactions. Beyond mere confidentiality, Hyperledger Fabric's modularity and extensibility are its significant strengths, allowing organizations to craft solutions befitting their unique requirements.

The platform's design ethos emphasizes flexibility and scalability, ensuring it can handle the varied demands of electricity markets, from small-scale local trades to extensive grid interactions. Fabric's architecture is built upon a pluggable consensus mechanism, which means it can integrate with the specific governance and operational norms of electricity markets across the globe. This flexibility transcends to its smart contracts, termed 'chaincode,' allowing bespoke logic to drive market-specific functionalities.

Moreover, the decentralized nature of Hyperledger Fabric empowers all participants — power producers, consumers, or intermediaries — to have transparent access to transactions, ensuring trust and credibility in the market. Its robust security framework, underpinned by comprehensive identity management and authentication processes, fortifies the integrity of the entire system.

In a domain where real-time decisions, trustworthiness, and transactional clarity are paramount, Hyperledger Fabric emerges not just as a technology choice but as a strategic enabler, reshaping the future contours of electricity trading.

Having introduced the transformative capabilities of Hyperledger Fabric in reshaping the landscape of decentralized systems, it is pivotal to delve deeper into its intricate workings. To truly appreciate its potential and comprehend its role in our proposed framework, we need to dissect its architecture, components, and underlying principles. In the following sections, we will look at an overview of Hyperledger Fabric, shedding light on its core components, consensus mechanisms, and the nuances that set it apart in the world of blockchain technologies.

4.1.2 Membership Structure

Hyperledger Fabric's membership model is a critical component, providing both security and structure to its decentralized network. The architecture begins with the Root Certificate Authority (CA), a centralized figure that stands as the primary trust source. The Root CA's main role is to issue certificates to subordinate CAs, thereby establishing a hierarchical chain of trust. This structure is beneficial for:

- Efficient distribution of authentication and verification tasks, promoting faster network operations.
- Enhancing security by reducing the Root CA's exposure to direct network interactions, thus lowering potential risk points.
- Associating blockchain identities with their real-world counterparts, which reinforces network accountability and transparency.

In Hyperledger Fabric's framework, entities such as communities, districts, and infrastructures like the Smart Grid are categorized as "organizations." These organizations are key participants in the blockchain network. Every member within an organization is provided a digital identity, validated and certified by a CA.

The Membership Service Provider (MSP) is responsible for managing these identities. It handles the authentication of members and defines their roles and permissions within the network. By ensuring proper identity verification and role definition, the MSP plays a vital role in maintaining transaction integrity and order in the Hyperledger Fabric network.

4.1.3 Channels and Nodes

In the Hyperledger Fabric ecosystem, channels are an essential mechanism that facilitates private communication between specific network members. Each channel operates with its own unique ledger, allowing for transactional data to remain confidential and accessible only to authorized parties. Given the importance of data segregation and privacy, in our implementation as well will later also see, we have chosen to associate each organization with its individual channel, allowing for enhanced data protection and autonomy.

Nodes, which are integral components of the network's operation and management, can be categorized as peer nodes and orderer nodes:

- **Peer Nodes:** Responsible for the maintenance and synchronization of the ledger data, peer nodes ensure that all network participants possess a consistent view of the ledger. Peer nodes can be further classified into:
  - **Committing Peers:** As the name suggests, these peers are mainly involved in committing or adding verified transactions to the ledger.
  - **Endorsing Peers:** These peers have an added responsibility. Before any transaction is committed, it must be verified and endorsed. Endorsing peers take charge of this verification process, ensuring the transactions abide by network policies.

- **Orderer Nodes:** These nodes play a pivotal role in maintaining the order of transactions. They collect proposed transaction data, sequence them into blocks, and subsequently distribute these blocks to peer nodes for validation and commitment. The orderer nodes essentially act as a central mechanism ensuring that transactions across the network are consistently ordered.

Through this combination of channels and different node types, Hyperledger Fabric attains a balance between privacy and transparency, ensuring that each organization can operate securely while still being a part of a larger, interconnected network.

4.1.4 Transactions

Transactions in Hyperledger Fabric are the core actions that reflect changes or updates to the blockchain state. Before they are permanently written or "committed" to the ledger, transactions undergo a validation process to ensure their legitimacy and compliance with established network rules. Once validated and added to the ledger, these records are immutable, meaning they cannot be altered or deleted, ensuring the integrity of the historical record.

4.1.5 Ordering Service and Consensus Algorithms

At the core of Hyperledger Fabric's operation is the ordering service, a centralized system responsible for managing the sequence and broadcast of transactions. It uses consensus algorithms, like Raft, to ensure:

- Proper sequencing of transactions, ensuring they're processed in the order they were received.
- Agreement or consensus across all nodes regarding the order and validity of transactions.
- Mitigation of common threats in decentralized systems, including the risk of double-spending or recording conflicting transactions.

The Raft consensus algorithm is particularly well-suited for Hyperledger Fabric because:

- It provides efficient log replication, ensuring all nodes have consistent and up-to-date transaction records.
- It maintains data consistency across nodes, even if some nodes fail or are temporarily disconnected. This fault tolerance ensures the network remains operational and secure under various conditions.

The ordering service, with its nodes, is diligent in recording every action on the network. Moreover, it maintains a distinct log for each channel, allowing for detailed and organized record-keeping tailored to each organization's activities within the network.

4.1.6 Chaincode

Chaincode in Hyperledger Fabric is essentially the programmatic logic that drives the behavior of applications on the blockchain. It plays a pivotal role in defining the operations that can be performed on the ledger and under what conditions. Key aspects of Chaincode include:

- **Business Logic Implementation:** Chaincode encodes the agreed-upon rules and protocols of operations for the network participants. This ensures that every transaction aligns with the established guidelines, thereby upholding the trustworthiness of the system.
- **Smart Contract Foundations:** Beyond the basic transactional operations, Chaincode enables the development and deployment of smart contracts. These are self-executing contracts where the agreement between parties is directly written into code. Through Chaincode, smart contracts automate and streamline complex business processes, enhancing efficiency and transparency.
- **Endorsement Mechanisms:** Before any transaction is added to the ledger, it needs to be endorsed based on the Chaincode's criteria. The Chaincode ensures

that transactions get the necessary endorsements from the right nodes, and only then is a transaction deemed valid for commitment.

Given its integral role, Chaincode is paramount in maintaining the consistency, transparency, and security of the Hyperledger Fabric network.

4.2 Proposed Hierarchical Blockchain-Powered Market Framework (ScaleNex)

After an in-depth exploration of Hyperledger Fabric's intricacies, from its consensus algorithms to the pivotal role of Chaincode, it becomes evident that this platform serves as an ideal foundation for advanced decentralized systems. Hyperledger Fabric not only offers a robust framework for maintaining transaction integrity, consistency, and security but also provides a modular and customizable infrastructure that can be tailored to diverse applications. Building upon this profound understanding of Hyperledger Fabric's capabilities, we now pivot to a visionary application: ScaleNex, our proposed scalable hierarchical blockchain-powered market framework. This innovative framework harnesses the strengths of Hyperledger Fabric and augments it with specific adaptations and extensions, tailored to meet the unique demands of a decentralized electricity market.

4.2.1 Electricity Market Architecture

In our endeavor to outline the architecture of our blockchain-enabled utility grid system, we identify three core components as essential. These components are pivotal in forming the structural backbone of our innovative electricity market scheme.

1. **Physical Layer:** Anchored in the tangible realm, this layer presides over energy generation, consumption, and transfer. It encompasses vital assets including power plants, photovoltaic panels, wind turbines, smart meters, and a plethora of infrastructural components. The imperative of this layer is twofold:

realize energy processes and maintain an accurate data landscape of the energy paradigm.

2. **Data Layer:** This layer assimilates energy metrics from the Physical Layer, establishing a ledger characterized by transparency, resilience, and security. Moreover, it doubles as a repository, cataloging utility grid assets and infrastructure data.

3. **Application Layer:** Herein lies the operational bedrock of the utility grid. Facilitating peer-to-peer (P2P) energy transactions, it serves as the nexus for market participants. Integral to this layer are digital instruments like smart contracts, which are harnessed to streamline intricate transactions and market mechanisms. Furthermore, its design offers flexibility, adapting to grid dynamics while catering to myriad operational facets.

While the spotlight of our exploration predominantly illuminates the Data and Application Layers, it's pivotal to note that our groundwork establishes interfaces for the holistic operation of the electricity market under grid constraints.

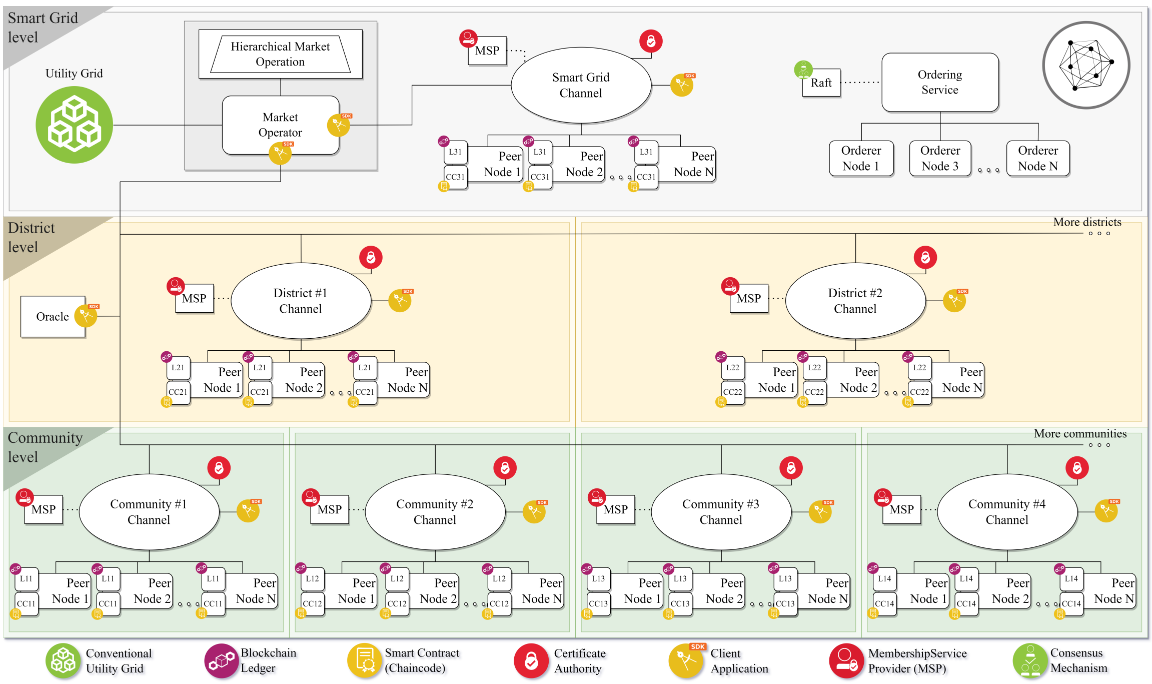


Figure 4.2 – Overview of the proposed electricity market architecture.

Our proposition sets forth a hierarchical blueprint for electricity markets in smart environments. By definition, every power system end-user integrated into a Smart-Grid qualifies as a prosumer. This is premised on their bidirectional power interaction and their connectivity within the grid. The architecture is trifurcated into Community, District, and Smart Grid levels, each resonating with a distinct scale of prosumer and geographic relevance. The ensuing hierarchical layout, visually encapsulated in Fig. 4.2, presents these levels:

- **Community Level:** Tailored for small-scale prosumers of defined geographic communities. Unsettled transactions are aggregated and subsequently directed to their respective District level for market participation.
- **District Level:** Caters to medium-scale prosumers within a geographic districts. It assimilates both direct district end-users and aggregated outputs from communities. Unresolved transactions are elevated to the Smart Grid level.
- **Smart Grid Level:** Encompasses large-scale prosumers across an expansive grid region including same level prosumer and District level aggregated orders. Residual, uncleared transactions subsequently interface with the conventional grid for final clearance.

The transactional flow initiates at the Community level, progressing upwards. Each community's residual transactions are processed at the District level, which then cascades its aggregated transactions to the Smart Grid level. This systematic procedure culminates in a single electricity market timestep, ensuring efficiency and coherence.

4.2.2 Data Layer - Blockchain System Design

In our architectural blueprint, organizations represent various hierarchical structures: communities, districts, and the overarching Smart Grid. Here's a detailed breakdown of ScaleNex's structure and configuration:

Certificate Authority and Cryptography

Our design postulates a single Root Certificate Authority (CA) embodied by the Smart Grid CA. Communities and districts, in turn, possess intermediary CAs, all generated by the Root CA. This hierarchical CA structure is entrusted with the duty of producing and managing the cryptographic materials essential for peers and users within their respective organizations.

Channels and Ledger Design

Each organization operates within an exclusive channel, thereby granting each community, district, and the Smart Grid its individual blockchain via a channel-specific ledger. The inaugural block, known as the genesis block, retains vital data about its associated peer nodes, orderer nodes, channel operations' governing policies, and the Member Service Provider (MSP) configuration for every organization member.

To promote decentralization, fault tolerance, load balancing, and consensus, multiple endorsing peers are integrated. Multiple peers enhance network security, resilience, and scalability, catering to high-transaction scenarios.

Orderer Configuration

Addressing the unique demands of each channel, 3 additional orderer nodes are designated for every channel as a cluster. For each organization, the ordering service comprises a cluster of three orderers, within which the selection of a leader, and consequently, the assignment of followers, takes place. This ensures redundancy, prevents disruptions during unforeseen down times, and equitably divides the ordering workload. In our model we chose three orderer nodes, so that the system can tolerate the failure of one node while still maintaining consensus and operational integrity.

Ledger Composition

Our blockchain ledger is tailor-made to manage a diverse set of assets efficiently. While it preserves an unalterable transaction history, its world state functions as a

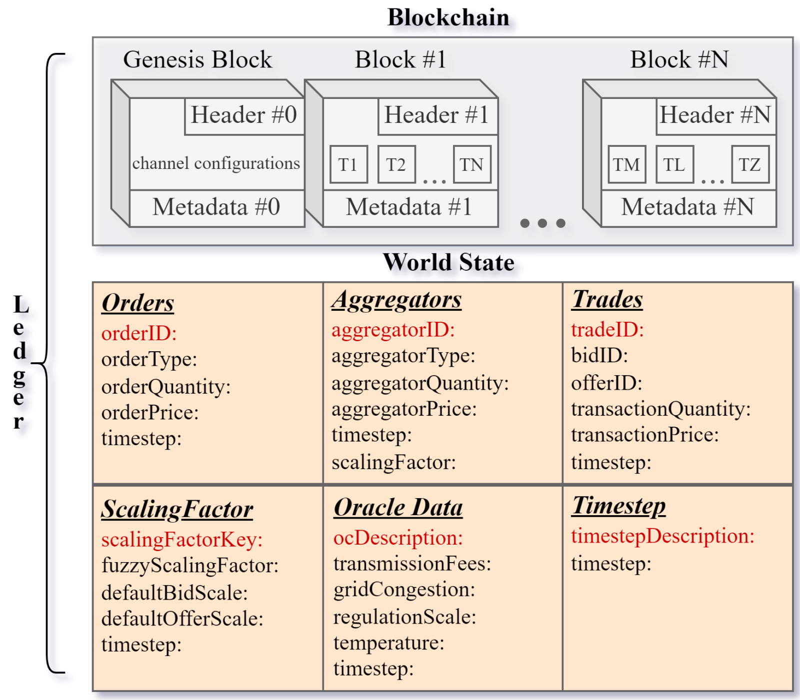


Figure 4.3 – Illustration of the proposed ledger structure.

cache depicting the current status of all ledger assets. Our world state, primarily a NoSQL database driven by CouchDB, employs a key-value pair storage mechanism. This state not only records every transaction in the ledger but predominantly interacts with applications and Chaincodes, furnishing the present state snapshot of all network assets. The assets we catalogue in the world state are:

1. **Orders**: They represent the market participating orders. Each bid and offer is recorded as a unique order in the world state, and contains the order's ID, the type of the order, being bid or offer, the quantity of electricity for trade, the desired trading price, and the current market timestep.

2. **Aggregators**: They represent the aggregated orders of a given organization. Each bid and offer contains the aggregator's ID, the type of the aggregator, being bid or offer, the quantity of electricity for trade, the desired trading price, the timestep of the aggregated order, and the scaling factor for adjusting the aggregated transmitted price for participation in higher market levels.

3. **Trades**: When a bid and an offer match, a trade occurs. Each trade is stored as a separate entry in the world state. It includes the tradeID, the buyer ID, the seller ID, the traded quantity of electricity, the price at which the trade occurred, and the timestep of the electricity market at which the trade occured.

4. **Scaling Factor**: The scaling factor is a variable that would enable aggregators to participate at higher-level markets by adjusting their order prices to account for the different market conditions. Each organization defines a set of defaultBidScale and defaultOfferScale variables that would be multiplied with the calculated fuzzy order scale, as we will later see, and that would ultimately give the scaling factor that would be influencing aggregated bid and offer prices separately. The ultimate goal of the Scaling Factor is to escalate the aggregated order prices of each organization to enable them to effectively participate to higher level electricity markets. This asset is uniquely identified through its key and stored at the world state.

5. **Oracle Data**: For the calculation of the fuzzy order scale variable and ultimately the scaling factor property of the aggregators the chaincode needs specific off-chain data. These data are submitted at every timestep by the Oracle service and are stored in the world state. These data describe parameters of the market the aggregators would participate in and include the transmission fees, grid congestion, regulation price scaling, and the current temperature. It is important to note that if another scaling mechanism is applied, the off-chain data might be subject to change.

6. **Timestep**: Each time all market levels complete their electricity market operations and a new cycle begins, the current timestep is recorded and updated. Each entry in the world state is submitted for a specific timestep in which it should be considered for participation to the electricity market. This is crucial for administering the electricity market with the current timestep's participants as well as maintaining the chronological order of transactions and for tracking the evolution of the market over time.

Figure 4.3 visualizes the world state's structure, enabling swift access to the current state of electricity market assets. It offers a trustworthy audit trail, integrating trades specific to each timestep. Red indicators signify key components within the key-value pair assets database.

4.2.3 Application Layer - Smart-Contract Implementation

Smart contracts, fundamental to blockchain paradigms, are code-driven protocols that autonomously initiate tasks when set conditions are satisfied. These digitally encoded pacts ensure contract stipulations using cryptographic means, making every transaction transparent, indelible, and auditable.

1) Smart-Contract Design: The pivotal aim of the smart contracts is to digitalize and automate operations within the delineated electricity trade model. The contracts should accommodate various transaction categories in the market, including bid and offer placements, bid-offer matching, and the computation of unsettled aggregated orders. It's imperative to note the instantaneous nature of trade finalization upon bid and offer pairing. The settlement and delivery of the physical counterparts to the submitted quantities fall outside the scope of our work.

ScaleNex incorporates three adaptable chaincode types, each tailored for a specific market tier. Community, district, and Smart Grid entities deploy the respective chaincodes befitting their market echelons. These chaincodes embed logic for order placement and retrieval of orders and transactions for each member within the given organization. Additionally, they are imbued with functionalities that drive the local electricity market and interfaces that enable these organizations to enter higher-tier markets through their pending aggregated orders. Fig. 4.4 offers a conceptual dissection of the function palette within each chaincode type.

A pivotal intermediary is essential for the seamless functioning of our model and for channel communication of the accumulated uncleared orders. An actor that consolidates these orders and routes them to the correct channels. This entity also supervises the electricity market, invoking functions that distribute settled aggre-

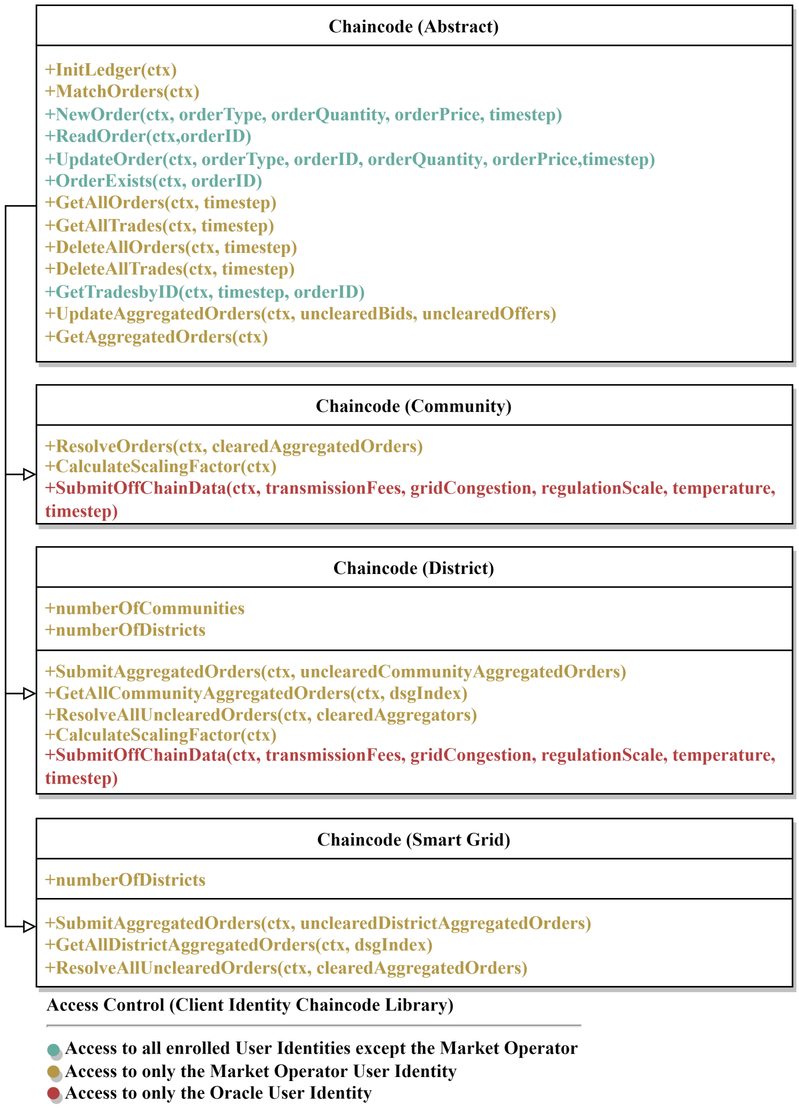


Figure 4.4 – UML Schema presenting the contractual extension of Chaincodes for Community, District, and Smart Grid contracts.

gated quantities post-market operations. The "market operator" assumes this role. Assigned distinct identity profiles for each network channel it accesses, as observed in Fig. 4.4, the market operator orchestrates the cyclic electricity market at designated timesteps. The rhythm of these timesteps is dictated by the market type—real-time, intra-day, or day-ahead—mirroring the unique operational nuances of each variant.

2) Electricity Market Operation: The orchestrated operations of the electricity market form the cornerstone of our model, enabling multi-tiered trading. We now traverse the electricity market's procedure, encompassing all stakeholders, and spotlighting the interplay between the market operator and the blockchain framework via the sequence layout in Fig. 4.5.

Subsequent to the initialization of the Hyperledger Fabric network, registered end-users, via a client application, liaise with their respective organizations (Community, District, or Smart Grid) to post their bids and offers using the NewOrder function. Concurrently, the market operator orchestrates a procedure that anticipates a defined time window before commencing electricity markets on various levels. Through connections with each community, the market operator invokes MatchOrders, CalculateScalingFactor, UpdateAggregatedOrders, and GetAggregatedOrders functions, orchestrating the current timestep order matching, scaling factor computation, uncleared aggregated order adjustments based on recent matching outcomes, and eventual retrieval of these to the market operator. Following this, the market operator interacts with districts, transmitting each community's aggregated uncleared orders through the SubmitAggregatedOrders function.

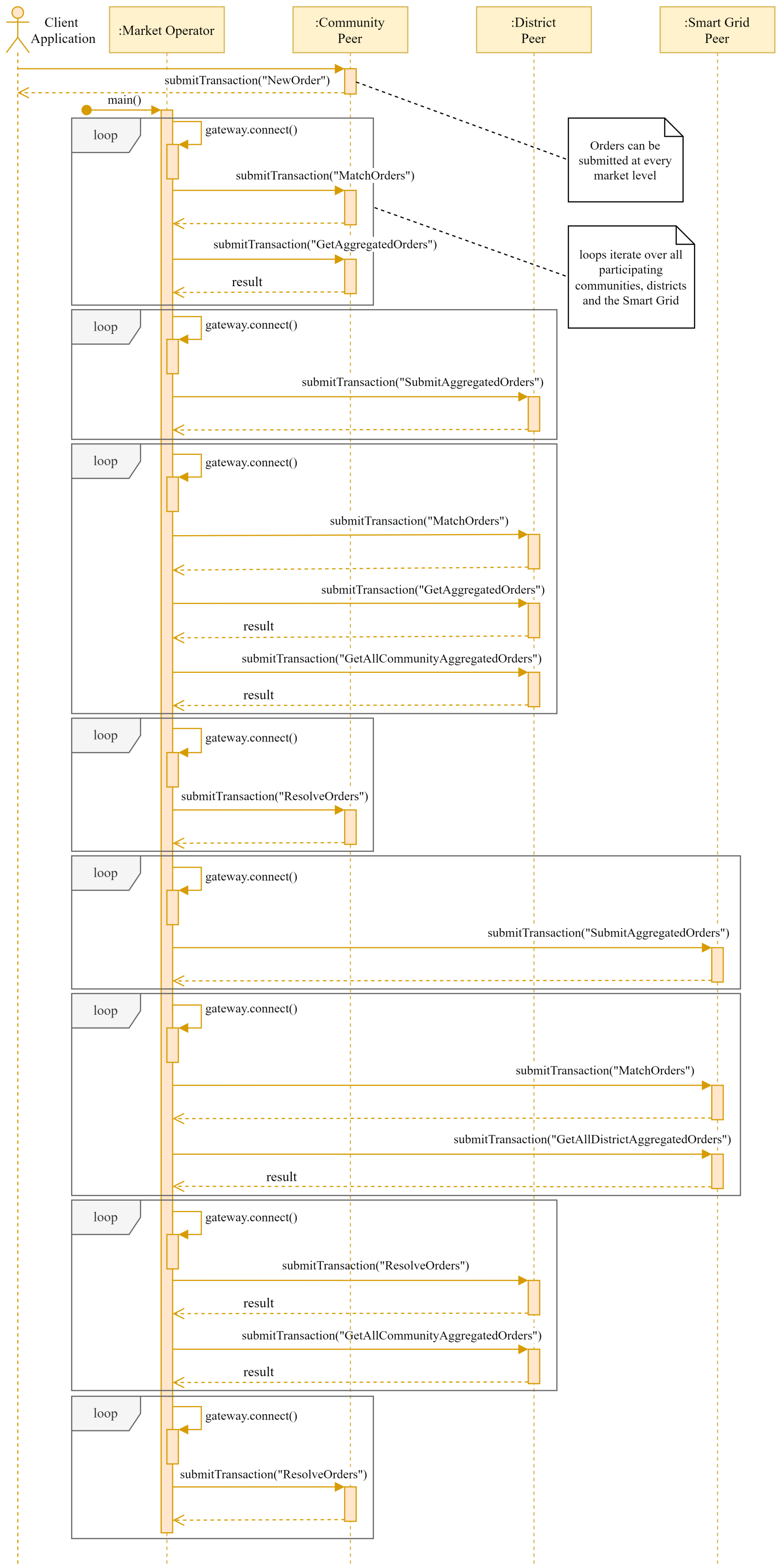


Figure 4.5 – Operational sequence diagram of the electricity market.

With the orders dispatched to districts, the electricity market operator engages with districts sequentially, triggering MatchOrders, CalculateScalingFactor, UpdateAggregatedOrders, GetAggregatedOrders, and GetAllCommunityAggregatedOrders functions to process district order matches, derive scaling factors, retrieve district-specific uncleared aggregated orders, and gather the settled community aggregated orders post the district market clearing, along with their transaction rates. The next step sees the market operator reaching out to communities, deploying the ResolveOrders function to disburse cleared quantities to the constituent bids and offers. The subsequent stage involves the market operator interfacing with the Smart Grid, initiating SubmitAggregatedOrders, MatchOrders, GetAggregatedOrders, and GetAllDistrictAggregatedOrders functions to dispatch previously accumulated district uncleared aggregated orders, pair Smart Grid market participants, and collect cleared district aggregated orders post-clearance. Thereafter, the market operator connects with districts, triggering ResolveOrders and GetAllCommunityAggregatedOrders functions to distribute cleared district aggregated quantities to their source orders and gather cleared community aggregated orders post Smart Grid level clearance. The finale witnesses the market operator syncing with each Community, using the ResolveOrders function to apportion cleared quantities to the root orders of the community aggregated quantities. Any residual uncleared quantities are aggregated at the Smart Grid tier are relayed to another Smart Grid or the traditional grid for additional clearance.

In the ensuing segment, we will explore the practical facets of this operation, elucidating its intrinsic operational mechanism.

4.3 Electricity Market Implementation

In earlier sections, we discussed in depth the design paradigms and the technological foundation underpinning our decentralized electricity market blueprint. That said, the true essence of this model is the underlying algorithmic procedures that dictate its operation. This ensures transactions within the electricity market are conducted effectively and impartially. Here, we'll delve deep into these notions, highlighting the algorithms steering our chosen techniques, and elaborate on some significant smart contract functions, thus providing a comprehensive understanding of the market's implementation.

4.3.1 Market Matching Algorithm

Central to our peer-to-peer electricity trading paradigm is the discriminatory K-double auction (KDA). The strength of the KDA design for our application stems from its innate ability to manage multi-unit trades among buyers and sellers. This makes it an optimal mechanism to couple bid-ask pairs.

Consider a bid represented by the pair $b = (q_b, p_b)$, wherein q_b is the quantity the buyer aims to procure and p_b outlines the apex price the buyer is amenable to shell out. Conversely, an offer can be depicted as $a = (q_a, p_a)$, with q_a indicating the quantity the seller is set to vend, and p_a highlighting the least price the seller anticipates. The bid collection can be characterized as $B = \{(q_b^i, p_b^i)|i = 1, ..., m\}$, where m represents the entire bid count, and the offer collection is symbolized as $A = \{(q_a^j, p_a^j)|j = 1, ..., n\}$, with n standing for the total offer count. In the KDA framework, bid-ask pairs are ranked to optimize matching.

- Bids undergo arrangement in a descending order based on prices: $p_b^1 \geq p_b^2 \geq ... \geq p_b^m$.
- Conversely, offers are ordered in an ascending sequence, dictated by their prices: $p_a^1 \leq p_a^2 \leq ... \leq p_a^n$.

Upon organization, the market operator commences the matching process by pairing the topmost bid with the least priced offer. A successful trade transpires if the bid's valuation surpasses or matches the offer's value, signified by $p_b^i \geq p_a^j$. The pairing persists until a mismatch arises where the bid value is undercut by the offer, captured by $p_b^k < p_a^l$. At this juncture, market proceedings are deemed finalized, and the price at which trades are executed (the clearing price) is influenced by the particular KDA iteration being employed.

For our model, we've embraced the median pricing or the "split-the-difference" pricing strategy to ascertain the transactional price in our decentralized electricity platform. Given a coupled bid $b = (q_b, p_b)$ and offer $a = (q_a, p_a)$, where q_b and q_a symbolize the respective volumes and p_b and p_a represent the concomitant valuations, the transaction's price, p_t, is deduced as:

$$p_t = \frac{p_b + p_a}{2} \tag{4.1}$$

With this method, the transactional rate is the average of the bid and ask rates. This mechanism ensures a harmonized and fair trading landscape. Notably, the market operator does not charge any fees for transactions. The intricacies of the bid-ask pairing mechanism, along with its algorithmic representation, are elucidated in Algorithm 4.1.

Algorithm 4.1: MatchOrders

```
Get all current-timestep orders from the world state
Sort Bids in decreasing order of price
Sort Offers in increasing order of price
Let i = 0, j = 0
while i < Bids.length and j < Offers.length do
  if Bids[i].price >= Offers[j].price then
    quantityToTrade = min(Bids[i].quantity, Offers[j].quantity)
    remainingBidQuantity = Bids[i].quantity - quantityToTrade
    remainingOfferQuantity = Offers[j].quantity - quantityToTrade
    tradingPrice = (Bids[i].price + Offers[j].price) / 2
    Update Bids[i] and Offers[j] with remaining quantities in the world state
    Create and store the trade in the world state
    if remainingBidQuantity = 0 then
      i++
    end if
    if remainingOfferQuantity = 0 then
      j++
    end if
  else
    Break (Market clears)
  end if
end while
Call CalculateScalingFactor()
Call UpdateAggregatedOrders(Bids, Offers)
Update the timestep to the world state
```

4.3.2 Aggregated Orders Pricing through Fuzzy Logic and Off-Chain Data

The trading tendency within any given market layer is primarily steered by a couple of key determinants: the pricing structure set by participants operating at that identical layer, and the magnification of aggregated orders stemming from the inferior market tiers. Together, these factors choreograph the trading landscape's vitality; their alignment to trading activities generally correlates with the rate of clearance for participants at that level.

In our delineated electricity market model, the privilege to determine the initial order pricing rests downright with the market participants. This characteristic resonates with the principles of laissez-faire market dynamics, where individuals independently calibrate their actions hinging on personal insights, evaluations, and tactical game plans. In our implementation each end-user at the first bidding phase, as well as in the later stages through the collective efforts of a community or district independently calibrate and determine their orders.

Algorithm 4.2: CalculateScalingFactor

Get the Fuzzy Logic System (FLS) inputs regulationFees, transmissionFees, gridCongestion, and temperature from the world state.
Initialize an FLS
for each input **do**
  Define the membership functions (low, medium, high) and add them to the FLS
end for
Define the membership functions (low, medium, high) for the output (fuzzyOrderScale) and add them to the FLS
Create a rule for each combination of input membership functions, as specified, and add them to the FLS
Call the FLS
Store the crisp output fuzzyOrderScale of the FLS to the world state with the current timestep.

Yet, there exists a dimension where market mechanisms wield potential sway — specifically, the amplitude adjustment of aggregated order prices. To elucidate, it's about the vigor or restraint with which aggregated orders are upscaled when transitioning from a subordinate market tier to a superior one. This amplitude, known as the scaling factor, bestows a level of indirect governance over market flux. It's pertinent to underscore that this scaling factor is shapeablel and can be unilaterally modified by each participating entity. Such modulation enables entities to finetune their market footprint, acclimatize to evolving scenarios, or chase distinct strategic horizons within the overarching electricity market framework.

The derivation of the scaling factor is pivotal. It fine-tunes the non-cleared aggregated order prices to resonate with the attributes of the imminent market. A fuzzy logic system facilitates this calculation, assimilating essential variables like transmission fees, grid congestion, regulatory fees, and current temperature. This results in a discrete value we coin as fuzzyOrderScale. Additionally, we integrate a default-OfferScale and a defaultBidScale. In conjunction with the fuzzyOrderScale, these determinants sculpt the scaling factor, which subsequently escalates the aggregated order prices when navigating to higher level markets. The default values that we mentioned are unique to every organization, are determined based on local-specific criteria, and are stored in the world state. The reason why we chose this format is because the fuzzy logic system's output is inherently bounded and as such it would not be flexible by itself to drive prices unless another variable was determined to be multiplied with so that the significance of the fuzzyOrderScale's impact would be manageable and configurable.

Within our framework, the fuzzy logic machinery ingests four input vectors:

- regulationFees: Low, Medium, High
- transmissionFees: Low, Medium, High
- gridCongestion: Low, Medium, High
- temperature: Low, Medium, High

Fuzzy guidelines have been established to correlate these input fuzzy categories with output classes representing the *fuzzyOrderScale*: low, medium, high. A typical

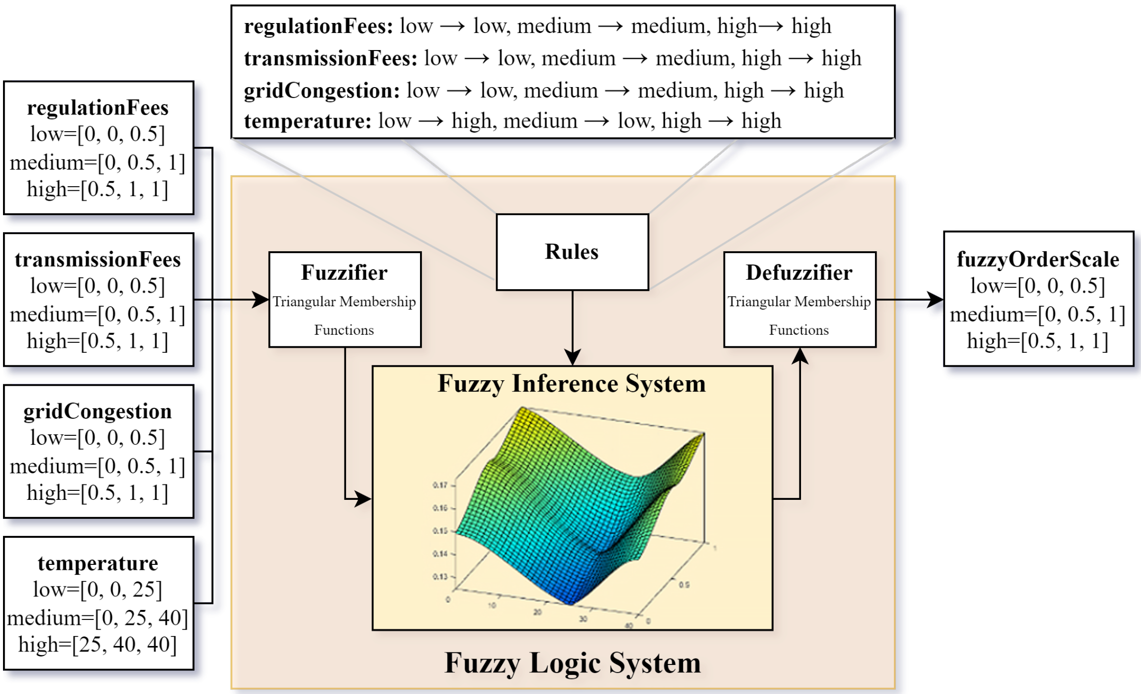


Figure 4.6 – Schematic representation of the Fuzzy Logic Mechanism employed for deriving the fuzzyOrderScale of aggregated order valuations.

guideline can be expressed as, "When transmission fees are low, then the *fuzzyOrderScale* is classified as low."

The resultant metric from the fuzzy logic system is a tangible value symbolizing the *fuzzyOrderScale*. This value undergoes a "defuzzification" process, converting it from a vague set to a definitive numerical figure. The algorithmic blueprint of the affiliated function integrated within the smart contracts is demonstrated in Algorithm 4.2.

The coefficients for the scaling of aggregated order values are computed by multiplying the *defaultBidScale* or *defaultOfferScale* of each consolidated order by the *fuzzyOrderScale* derived from the fuzzy logic system:

$$f_{\text{bids}} = \mathit{defaultBidScale} \times \mathit{fuzzyOrderScale} \tag{4.2}$$

$$f_{\text{offers}} = \mathit{defaultOfferScale} \times \mathit{fuzzyOrderScale} \tag{4.3}$$

Let $p_{\text{bids}}^{\text{avg}}$ denote the mean bid price calculated for the aggregated bids, and similarly, $p_{\text{offers}}^{\text{avg}}$ be the mean offer price ascertained for the aggregated offers. Using the above expressions and equations (4.2), (4.3), the scaled aggregated prices of the orders can be evaluated as:

$$p_{\text{bids}}^{\text{scaled}} = p_{\text{bids}}^{\text{avg}} \times (1 + f_{\text{bids}}) \tag{4.4}$$

$$p_{\text{offers}}^{\text{scaled}} = p_{\text{offers}}^{\text{avg}} \times (1 + f_{\text{offers}}) \tag{4.5}$$

4.3.3 Distribution of cleared aggregated order quantities

Consider A_{orders}^{init} to denote the initial aggregated orders prior to market involvement. Similarly, let A_{orders}^{clr} stand for the aggregated orders that have been cleared at more advanced market stages. The task at hand is to evenly allocate these cleared quantities among the prosumers who made up the initial aggregate.

The expression for A_{orders}^{init} can be given as:

$$A_{\text{orders}}^{init} = \sum_{i=1}^{n} q_i^{\text{order}} \tag{4.6}$$

Where, n represents the total number of prosumers whose orders are aggregated, and q_i^{order} denotes the quantity associated with prosumer i.

With s_i^{order} representing the fraction of prosumer i in the aggregated orders, it can be expressed as:

$$s_i^{\text{order}} = \frac{q_i^{\text{order}}}{A_{\text{orders}}^{init}} \tag{4.7}$$

Using these proportions, we can ascertain the quantity each prosumer trades, denoted by q_i^{traded}:

$$q_i^{\text{traded}} = s_i^{\text{order}} \times A_{\text{orders}}^{clr} \tag{4.8}$$

Further, the pricing for dispatched quantities is determined based on the premium associated with the aggregated orders' prices. For this, let d_{bid} symbolize the price premium for aggregated bids, and d_{offer} for aggregated offers.

Algorithm 4.3: ResolveOrders

```
Require: clearedAggregatedBids, clearedAggregatedOffers, dsgIndex
dsgIndex is the name of the assigned district or smart grid from which the
cleared aggregated bids and offers are returned
Get initialAggregatedBids and initialAggregatedOffers from the world state.
Calculate clearedBidsQuantity = initialAggregatedBids.quantity -
clearedAggregatedBids.quantity
Calculate clearedOffersQuantity = initialAggregatedOffers.quantity -
clearedAggregatedOffers.quantity
Update initialAggregatedBids with clearedAggregatedBids by storing
clearedAggregatedBids with initialAggregatedBids.price in the world state.
Update initialAggregatedOffers with clearedAggregatedOffers by storing
clearedAggregatedOffers with initialAggregatedOffers.price in the world state.
Calculate tradedBidsPricePremium = 1 + (clearedAggregatedBids.price -
scaledAggregatedBids.price)/scaledAggregatedBids.price
Calculate tradedOffersPricePremium = 1 + (clearedAggregatedOffers.price -
scaledAggregatedOffers.price)/scaledAggregatedOffers.price
Get timestep from the world state.
Get all orders from the world state.
for each order do
  if order.timestep == timestep-1 then
    if order.type == "Bid" AND order.quantity > 0 then
      Calculate bidValueShare = order.quantity /
      initialAggregatedBids.quantity
      Calculate bidSoldQuantity = bidValueShare *
      clearedAggregatedBids.quantity
      Calculate order.quantity = order.quantity - bidSoldQuantity
      Calculate tradedBidPrice = tradedBidsPricePremium * order.price
      Store trade between order and dsgIndex at price tradedBidPrice in the
      world state
      Store the updated order to the world state
    else if order.type == "Offer" AND order.quantity > 0 then
      Calculate offerValueShare = order.quantity /
      initialAggregatedBids.quantity
      Calculate offerSoldQuantity = offerValueShare *
      clearedAggregatedBids.quantity
      Calculate order.quantity = order.quantity - offerSoldQuantity
      Calculate tradedOfferPrice = tradedOffersPricePremium * order.price
      Store trade between order and dsgIndex at price tradedOfferPrice in the
      world state
      Store the updated order to the world state
    end if
  end if
end for
```

These premiums, d_{bid} and d_{offer}, are derived by juxtaposing the trading price of cleared aggregated values p^{clr}_{bids} and p^{clr}_{offers} against the scaled prices proposed by their corresponding aggregated orders before their market participation in higher level markets:

$$d_{\text{bid}} = 1 + \frac{p^{\text{clr}}_{\text{bids}} - p^{\text{scaled}}_{\text{bids}}}{p^{\text{scaled}}_{\text{bids}}} \tag{4.9}$$

$$d_{\text{offer}} = 1 + \frac{p^{\text{clr}}_{\text{offers}} - p^{\text{scaled}}_{\text{offers}}}{p^{\text{scaled}}_{\text{offers}}} \tag{4.10}$$

By calculating these traded price premiums, the market mechanism assesses the divergence between the finalized traded prices and the original proposed prices, giving a clearer picture of the deviation of cleared prices from the aggregate orders' average prices. Importantly, these premiums are integral for determining the ultimate traded prices for the dispatched quantities, thus ensuring both fairness and operational efficiency in the cleared quantities distribution among participating prosumers.

The ultimate traded prices for dispatched quantities are:

$$\text{tradedPrice}^{\text{bid}}_{i} = d_{\text{bid}} \times \text{p}^{\text{bid}}_{i} \tag{4.11}$$

$$\text{tradedPrice}^{\text{offer}}_{j} = d_{\text{offer}} \times \text{p}^{\text{offer}}_{j} \tag{4.12}$$

By invoking the *ResolveOrders* function encompassing the above computations, the market guarantees an equitable distribution of cleared quantities among prosumers. Each participant thus acquires their corresponding quantity sold, with trading prices being adjusted based on the associated price premiums of the aggregated orders. The aformentioned function implementation can be seen in Algorithm 4.3.

To better illustrate the operational workflow of our proposed electricity market scheme, we present a detailed flowchart depicting the sequential steps involved in the market process Fig. 4.7.

In the foregoing sections, we've elucidated the core mechanisms of our suggested electricity market framework. We will now shift our focus to a case study, aiming to illustrate the practical implementation of our model in a real-world context.

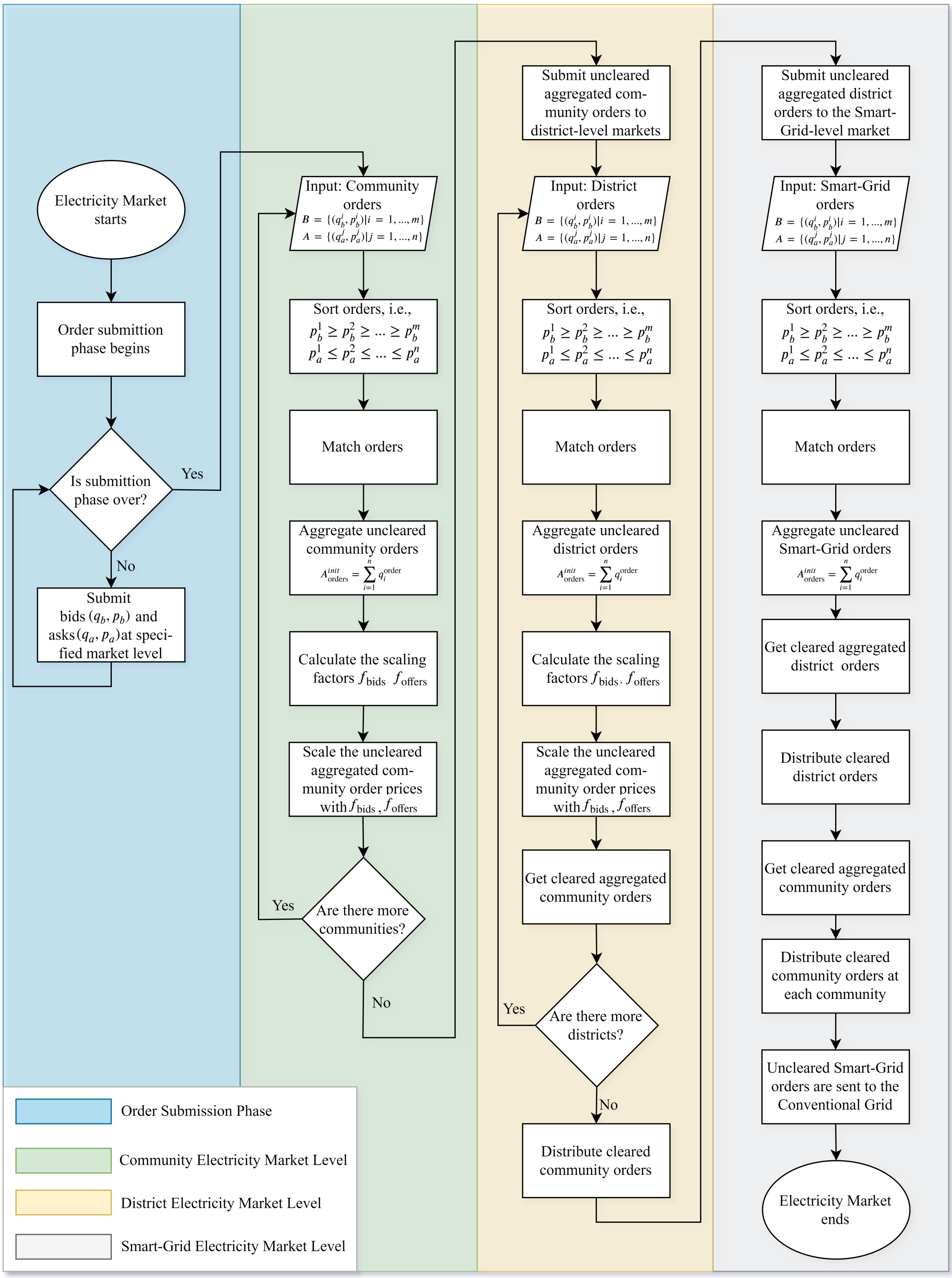


Figure 4.7 – Flowchart of the proposed electricity market methodology.

Chapter 5

Results and Analysis

This chapter delves into the empirical results derived from our proposed electricity market framework. Through a rigorous examination of various scenarios and performance metrics, we endeavor to present a comprehensive understanding of the system's efficiency, robustness, and reliability. The insights gleaned from these analyses will serve to validate the theoretical foundations laid out in the preceding chapters.

Firstly, in the case study section, we provide a detailed account of the system in action, focusing on select scenarios to elucidate its real-world applicability and benefits. This is achieved by offering a snapshot of the system under 50 different scenarios, encompassing various market conditions, participant behaviors, and external factors.

Subsequently, the performance analysis section delves deeper into the system's operational metrics. By evaluating factors such as latency, throughput, and execution time, we furnish an in-depth understanding of the system's capability to handle high-demand situations, its responsiveness, and its overall efficiency.

5.1 Case Study

In this study, a realistic scenario is showcased through the Hyperledger Fabric (HF) platform. This scenario incorporates four distinct communities, two districts, and an overarching smart grid, with a collective total of 1056 prosumers distributed across different market levels. The primary aim is to vividly exhibit the multifaceted opportunities and versatile applications that the platform facilitates. The results derived are intended to be both lucid and systematically verifiable.

Our prototype system was instantiated on Ubuntu 22.04.2 LTS WSL2. The hardware specifications utilized encompassed an 8-core CPU, a memory of 16 GB RAM, and a disk storage of 50 GB.

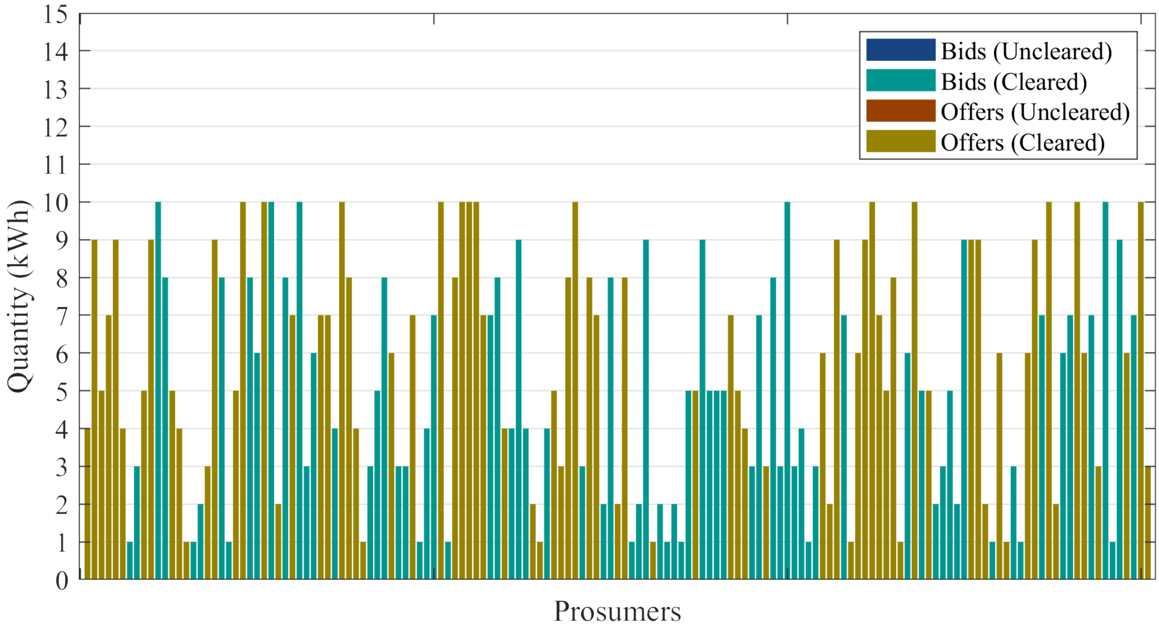


Figure 5.1 – Distribution of prosumer quantities within Community #1's electricity market.

The market configuration was executed on a Hyperledger Fabric network (version 2.5.0). Each component, such as the peer node, orderer, and certificate authority (CA), were instantiated as distinct containers on the hosting machine, utilizing Docker's products. The databases for each peer node, specifically CouchDB databases, were also initiated as standalone containers. Both the market operator and the oracle functioned as dedicated services on the host machine. Rather than fetching real-time external data, our simulations operated the oracle service using pre-configured artificial datasets to emulate its responses, ensuring a controlled environment for consistent analysis. The architecture comprised of three peer node containers for each organization, a corresponding database container, and one certificate authority container. Additionally, 21 orderer node containers were used, distribut-

Level	Parameters									
	Prosumers			Aggregators		Fuzzy Logic System				
	Bid Price (€)	**Offer Price (€)**	**Quantity (kWh)**	**DBS**	**DOS**	**RF**	**TF**	**GC**	**T (C°)**	**FOS**
Community	0.09-0.14	0.07-0.13	1-10	1.53	0.64	0-1	0-1	0-1	0-40	0-1
District	0.12-0.17	0.10-0.15	10-100	1.11	0.46	0-1	0-1	0-1	0-40	0-1
Smart Grid	0.17-0.22	0.14-0.18	100-1000	-	-	-	-	-	-	-

Table 5.1 – Parameter value ranges for each market level.
DBS = DefaultBidScale, DOS = DefaultOfferScale, RF = Regulation Fees, TF = Transmission Fees, GC = Grid Congestion, T = Temperature, FOS = FuzzyOrderScale

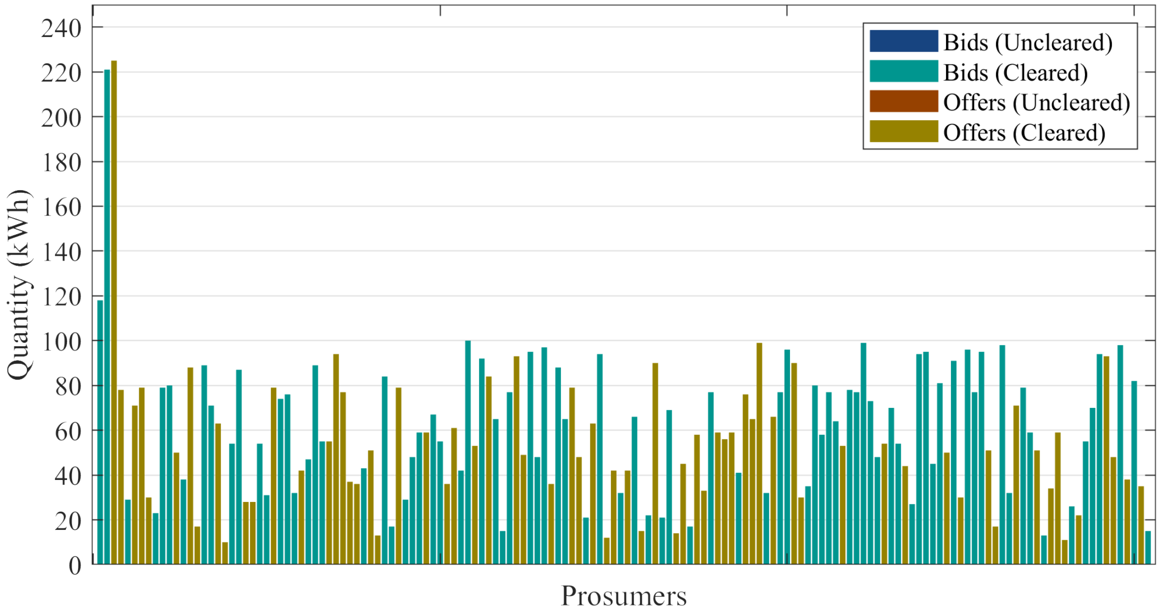


Figure 5.2 – Distribution of prosumer quantities within District #1's electricity market.

ing 3 to each channel. It's pertinent to note that in a live production scenario, all the nodes, alongside the market operator and the oracle service, would operate from distinct machines.

Prior to initializing each network channel, three standard users and one administrative user profile were configured for every organization. The "User1" profile in each organization was designated for the market operator, while "User2" was assigned to the oracle service. The "User3" profile in each entity was kept reserved for streamlining the submission process of bids and offers across all channels. Meanwhile, the admin user profile was employed for chaincode management and maintenance tasks. Fig. 4.4 elucidates the chaincode architecture, detailing specific access privileges associated with each user.

Within the scope of our case study, we opted for arbitrary selection in terms of quantities, prices, and input variables tailored for the fuzzy logic system. Such a strategy facilitated the exploration of the system's resilience and adaptability across a multitude of scenarios, ensuring a comprehensive assessment of its versatility in diverse circumstances. The varied parameter ranges, encompassing factors such as order price and quantity for each market participant, grid congestion, regulation and

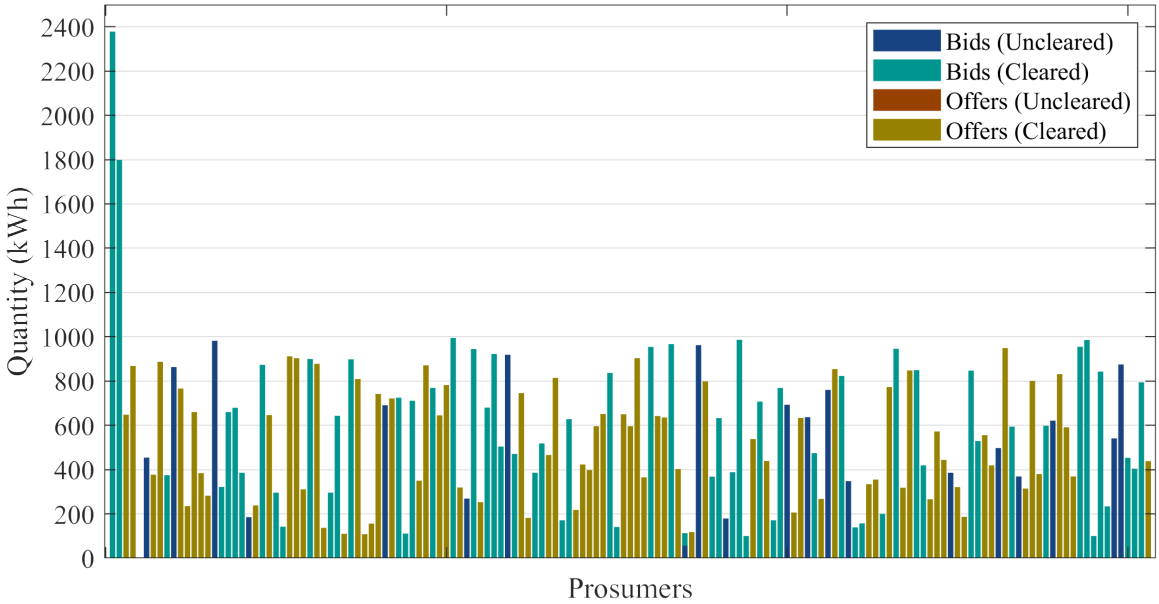


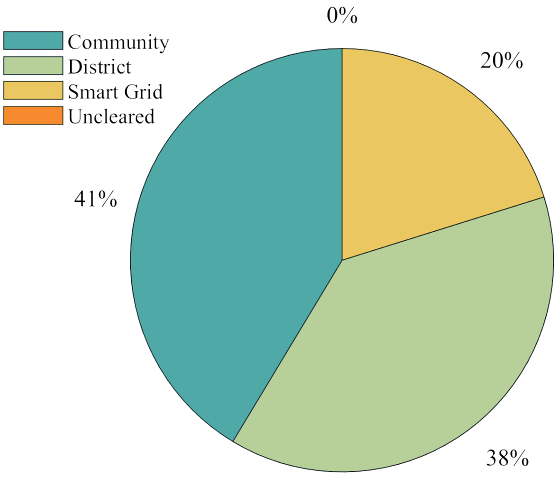
Figure 5.3 – Distribution of prosumer quantities within the overarching Smart Grid's electricity market.

Level	**Fuzzy Logic System Parameters**				
	RF	**TF**	**GC**	**T (C°)**	**FOS**
Community	0.15	0.08	0.14	25	0.359
District	0.38	0.45	0.3	25	0.413

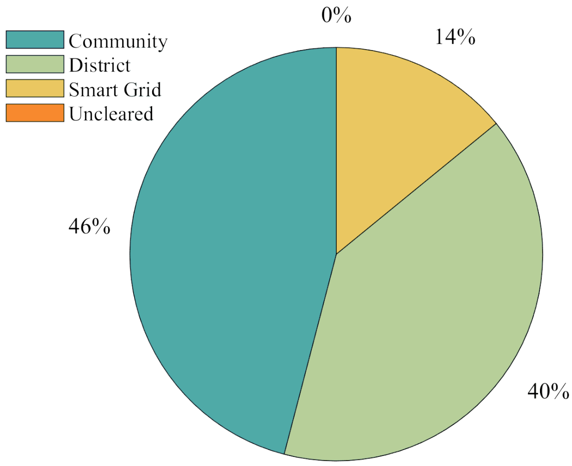
Table 5.2 – Fuzzy Logic System parameters for each market level.

transmission fees, temperature, fuzzyOrderScale, and the predetermined bid and offer scales for every market tier, are systematically tabulated in Table 5.1. At this point, it is worth noting that while we could have conducted a more in-depth investigation for the selection of these parameters, it falls outside the scope of this work. It's crucial to underline that our study was grounded in 50 distinct simulations, each pivoted on different parameter values. For a granular insight into the conceptual architecture, we illustrate a specific scenario which incorporates the parameters of prosumers detailed in Table 5.1 and those of the Fuzzy Logic System in Table 5.2.

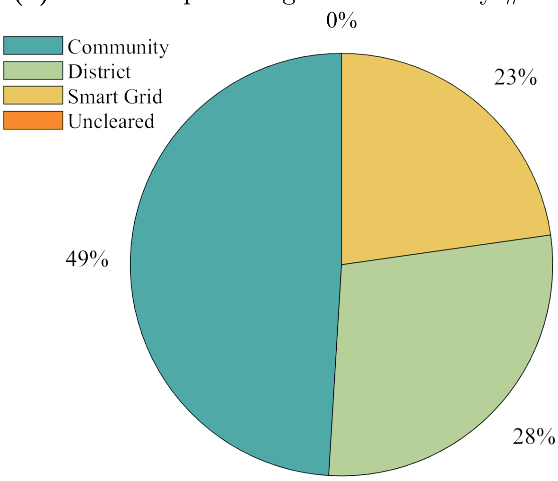
Figures 5.1 through 5.3 visually detail the prosumer quantities across different market levels. In Fig. 5.1, observing Community #1, bids are represented in blue while offers are in green. The absence of darker shades of blue and green indicates that all the bids and offers were successfully cleared, either at that level or a higher



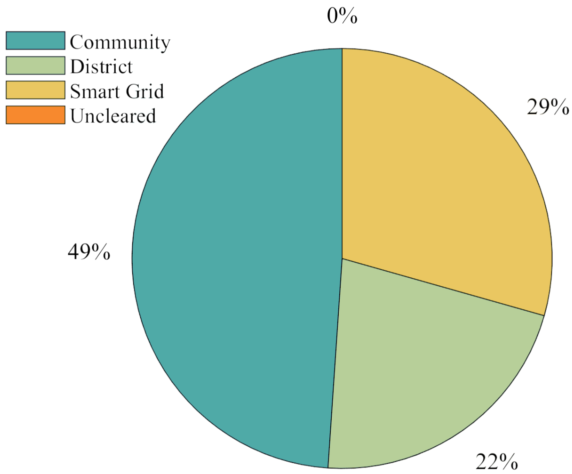
(a) Clearance percentages of Community #1.



(b) Clearance percentages of Community #2.

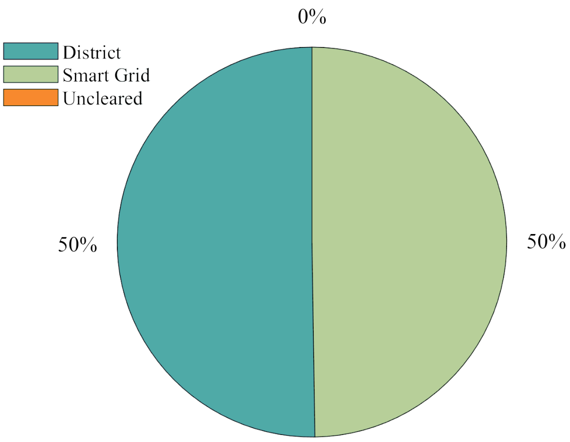


(c) Clearance percentages of Community #3.

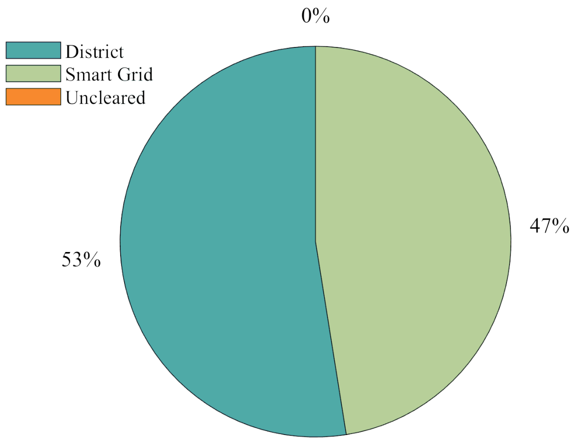


(d) Clearance percentages of Community #4.

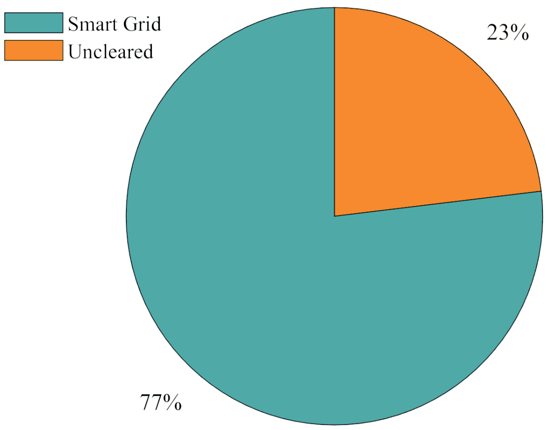
Figure 5.4 – Clearance percentages of community-level prosumers for all market levels.



(a) Clearance percentages of District #1.



(b) Clearance percentages of District #2.



(c) Clearance percentages of Smart Grid.

Figure 5.5 – Clearance percentages of district-level and smart-grid-level prosumers.

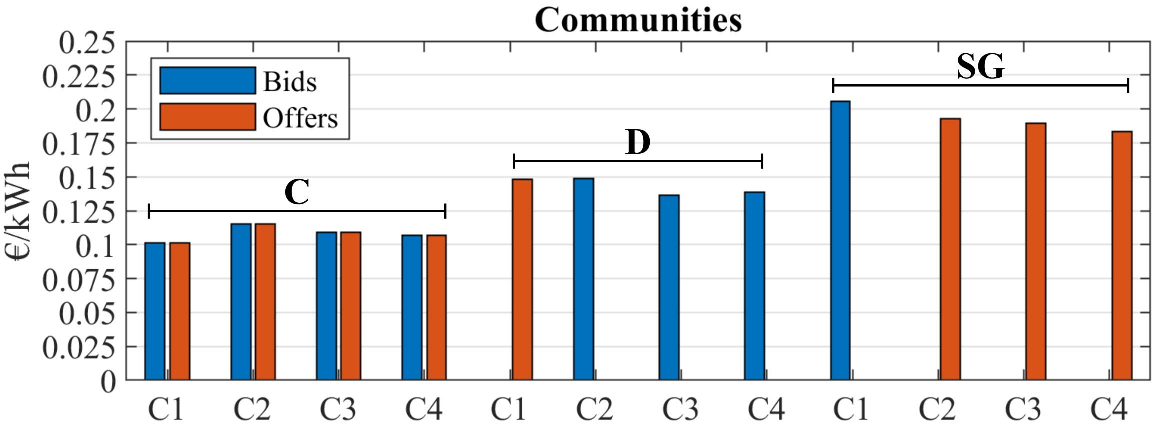
one. These quantities were derived randomly using the range values from Table 5.1. Turning to Fig. 5.2, we note a full clearance of quantities for District #1, similar to the observations in Fig. 5.1. The initial four quantities represent community consolidated orders, which were entered along with district-level prosumer quantities in the District #1 electricity market. These aggregated order prices were adjusted based on the fuzzyOrderScale, as discussed in Algorithm 2.

Fig. 5.3 displays the quantities presented in the Smart Grid electricity market. The initial four bars highlight the district's combined orders. While the light blue and green bars represent the cleared bids and offers, some dark blue bars indicate bids that weren't cleared in the Smart Grid electricity market. In this context, while all offers in the Smart Grid level were cleared, some bids remained uncleared. Such uncleared bids can then be routed to a traditional utility grid or another smart grid for potential processing or fulfillment.

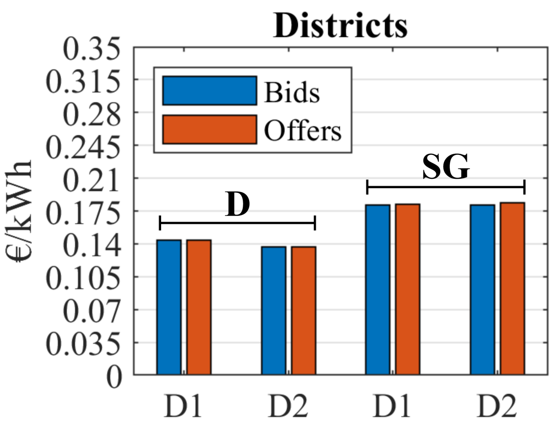
Our study utilized an aggresive scaling strategy for both aggregated bids and offers, as depicted by the chosen DBS, DOS, and FOS values in Tables 5.1 and 5.2. By aggressive, we mean that the defaultBidScale for bidders of the system was set to a very low value, while the defaultOfferScale was set to a very high value. As such, when bid and offer prices from communities are introduced to district markets, their prices are intensified by factors of x1.55 and x1.23, respectively. As these aggregated bids and offers transition from district to Smart Grid markets, their prices experience further scaling: x1.49 for bids and x1.19 for offers. This strategy emphasizes our aim to enhance the significance of activities from lower-market levels as they progress within the hierarchical market framework, compensating for the emerging market dynamics at elevated tiers.

Figures 5.4 and 5.5 illustrate the clearance ratios for prosumers at all market levels they engaged in. Fig.5.4 offers an expansive view of clearance ratios for community prosumers across all market levels. Each pie in Fig.5.4 illustrates the clearance distribution for a distinct community. It's immediately apparent that community prosumers have a varied array of clearance pathways spanning the three market levels: community, district, and smart grid. This accentuates the system's intrinsic adaptability and underlines the expansive range of opportunities for community prosumers.

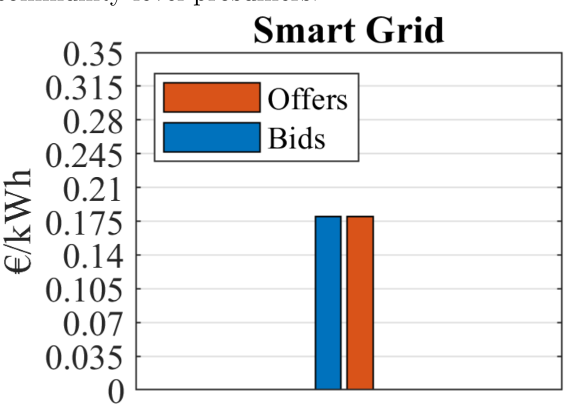
They can engage in local community trades, district trades via aggregators, or broader smart grid trades, ensuring a multifaceted suite of clearance options.



(a) Average traded prices of community-level prosumers.



(b) Average traded prices of district-level prosumers.



(c) Average traded prices of smart-grid-level prosumers.

Figure 5.6 – Average traded prices of bids and offers for each community, district and the smart grid at different market levels.
C = Community level, D = District level, SG = Smart Grid level

Fig.5.5 shifts our focus to prosumers operating within the district and smart grid levels. This figure presents a triad of pie charts elucidating the clearance rates at these two levels. Charts 5.5a and 5.5b depict the clearance percentages for District #1 and District #2 prosumers, spanning both their intrinsic districts and the overarching smart grid. In contrast, 5.5c sheds light on clearance metrics at the smart grid level, with 77% being cleared and the remaining 23% indicating unfulfilled quantities. The system's commendable efficiency can be attributed to the aggressive pricing models employed by aggregators and the adeptly set prices by prosumers, as highlighted earlier.

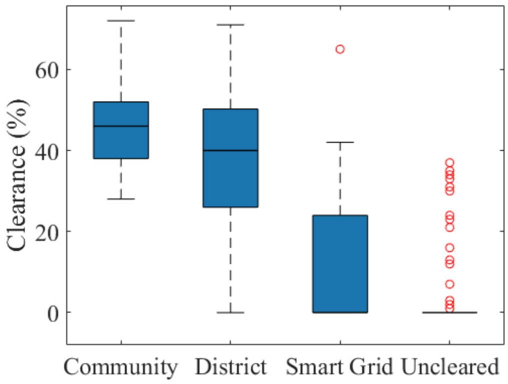
In Fig.5.6a, we observe the mean traded prices for bids and offers across distinct communities and their respective market tiers. At the grassroots community level, every community negotiates both bids and offers at the indicated rates. Transitioning to the district stratum, there's a pronounced shift in trading dynamics. Notably, Community #1 exclusively conducts offer trades, while Communities #2, #3, and #4 restrict themselves to bid trades. Advancing to the smart grid layer, Community #1 is engaged in bid trading, while its counterparts primarily deal with offer trades. A discernable surge in prices can be witnessed as communities traverse to loftier market tiers. This price inflation across ascending market echelons is expected, given the heightened complexities and stakes of upper-level markets.

Fig.5.6b showcases the average cleared prices for districts at both their inherent level and the overarching smart grid level. As observed, there's a trend of increasing prices when transitioning from the district to the smart grid level. This price augmentation aligns with the trend noted for communities, highlighting the complex interplays and increased stakes inherent to the smart grid environment.

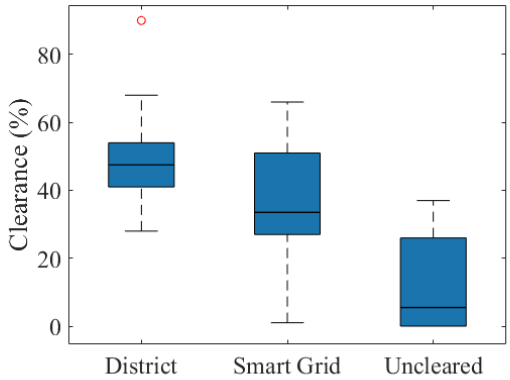
Fig.5.6c, on the other hand, zooms in on the smart grid domain, revealing the average cleared prices exclusive to this apex market stratum. The depicted data reinforces the overarching narrative of escalating prices with the rise in market levels, emphasizing the value proposition and significance of the expansive smart grid environment.

Across the varying market strata, a consistent trajectory of price augmentation emerges, underscoring the intricate interactions and amplified commitments synonymous with more advanced market stages. This recurrent pattern accentuates the imperative for judicious strategy formulation and discerning decision-making for stakeholders active across diverse market landscapes.

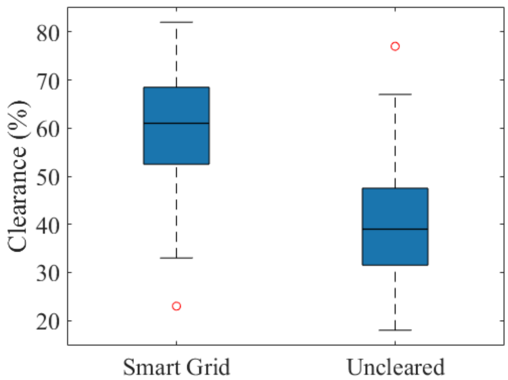
Compiling data from 50 unique simulations, each characterized by distinct parameters, we present three illustrative box-and-whiskers plots in Fig.5.7. These diagrams offer an exhaustive visual delineation of the clearance percentage spectrum for community, district, and smart grid participants throughout all the market tiers considered in our study.



(a) Clearance percentages of community quantities at different market levels.



(b) Clearance percentages of district quantities at different market levels.



(c) Clearance percentages of the Smart Grid quantities.

Figure 5.7 – Distribution of clearance percentages for community-level, district-level, and smart-grid-level prosumer quantities.

In Fig.5.7a, we discern the clearance percentage bandwidth for communities across the different markets they engage in. At the community level, clearance oscillates between 38-52%. In contrast, at the district and smart grid levels, the rates span between 26-50% and 0-24%, respectively. Remarkably, only a few instances of uncleared quantities emerge from communities, symbolized by the red circles in the terminal bar.

Fig.5.7b immerses us into the clearance percentages pertinent to districts at their active market stages. Within the district arena, the clearance percentages vary between 41-54%, while at the smart grid echelon, they range from 27-51%. It's noteworthy that uncleared quantities at the district stage witness a surge compared to the community level, with clearance percentages resting between 0-26%.

Concluding with Fig.5.7c, the diagram illuminates the clearance percentage variances intrinsic to the smart grid layer, fluctuating between 52-68%. The uncleared percentages sit between 31-47%, symbolizing the aggregated trading propensities of all encompassed communities and districts.

At this point it is worth mentioning that the clearance shown in the aforementioned figures depict the clearance percentages of only the local end-users to each market-level and not the aggregated end-users that participate from lower market levels. Through these visual depictions, our objective is to underscore the robustness and potential of our proposed framework. The variance in clearance percentages across distinct market levels imparts invaluable insights into the operational dynamics of decentralized energy trading mechanisms.

5.2 Performance Analysis

Building on the multifaceted evaluations outlined in the case study, it's imperative to delve deeper into the individual performance metrics of the framework. Undertaking such an in-depth review offers a comprehensive perspective on the system's adaptability across varied scenarios and workload demands. Through this lens, we can identify potential areas of improvement, and highlight the intricate facets of the proposed design. By examining specific system traits like throughput and latency, our aim is to elucidate the benefits or hurdles brought about by diverse system configurations.

5.2.1 Throughput and Latency

To gauge the system's throughput, we honed in on its query and invoke functions, as these metrics aptly reflect the system's capacity to cater to its users and its scalability potential. After a stringent series of invoke tests, we discerned an approximate throughput rate of 160 TPS for invoke operations, and a spectrum of 300 to 380 TPS for query operations across each channel. Such a performance pattern is consistent with and anticipated for single-channel designs.

Given our system's multi-chain architecture, the cumulative throughput is computed as:

$$T_{\text{cumulative}} = N_{\text{channels}} \times T_{\text{per channel}} \quad (5.1)$$

Where:

- $T_{\text{cumulative}}$ denotes the aggregate transaction speed in transactions per second (TPS).
- N_{channels} signifies the overall count of channels or chains within the network.
- $T_{\text{per channel}}$ represents the transaction velocity for each individual channel, quantified in TPS.

In alignment with our case study, incorporating 7 channels, this results in an aggregate throughput nearing 1120 TPS for invoke operations and spanning between 2100 and 2660 TPS for query operations. The resilience of the system's performance, even with a surging user count, stands testament to its robust horizontal scalability attributes. An expansive visualization of the cumulative TPS is portrayed in Fig.5.8.

Transaction latency, another cornerstone metric, has been meticulously evaluated for both invoke and query operations. As transaction submissions amplify, we witness a proportional growth in latency, as encapsulated in Fig.5.9. Our framework's exceptional latency metrics, when juxtaposed with peer studies, can be attributed to its distinct multi-chain design, fostering lateral scalability across a multitude of chains and ordering clusters. As the consortium of organizations within the network broadens, orderers grapple with an escalated log volume. Yet, the granularity of these logs remains compact, mitigating the system's overall latency during transaction sequencing.

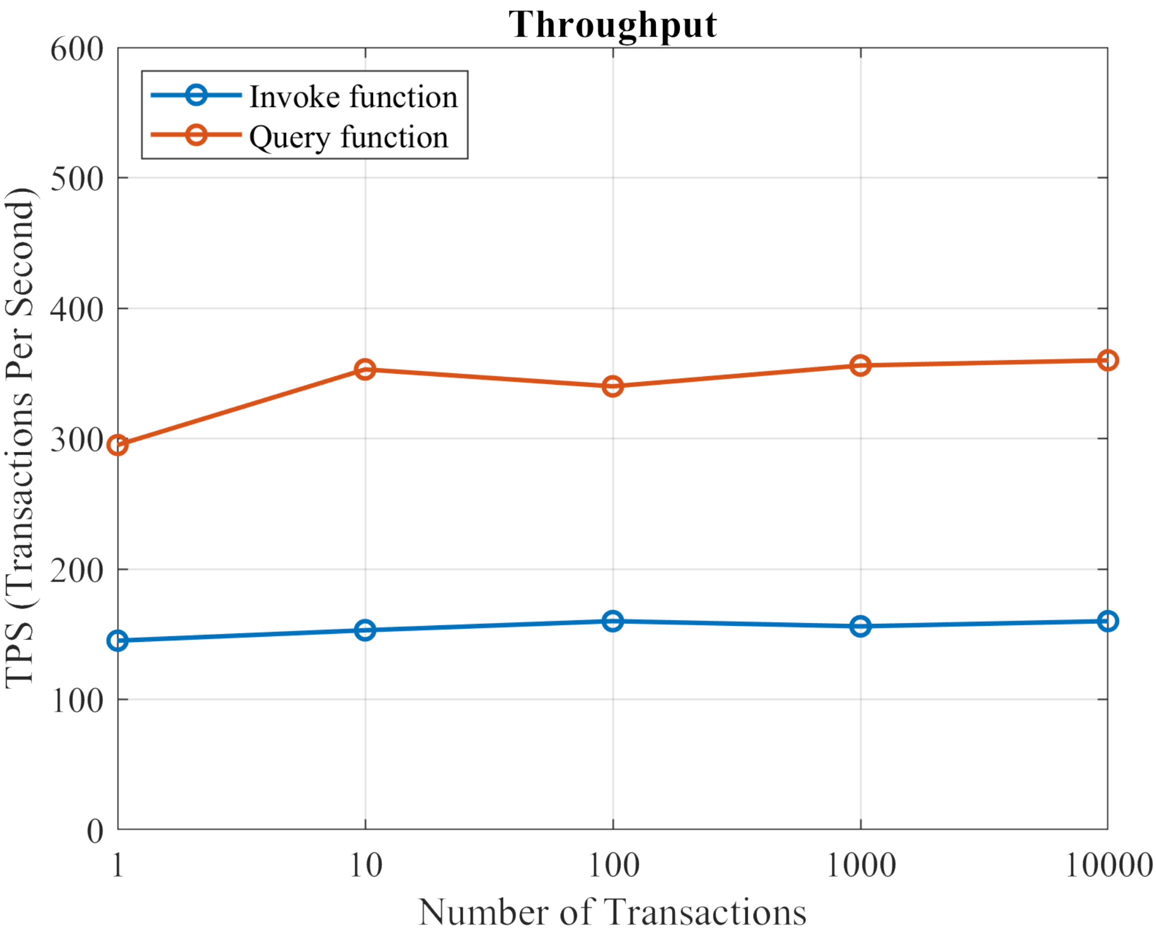


Figure 5.8 – Throughput of the invoke and query functions.

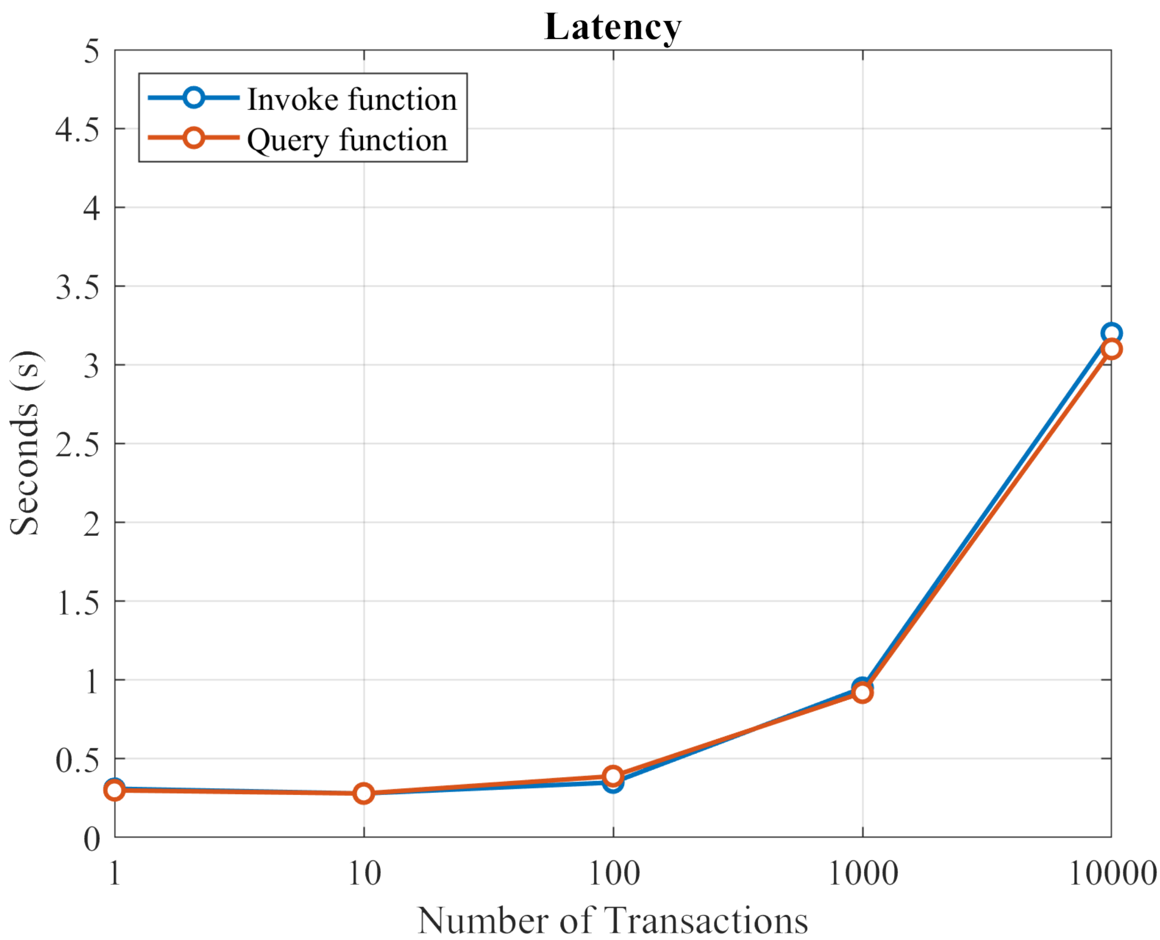


Figure 5.9 – Latency of the invoke and query functions.

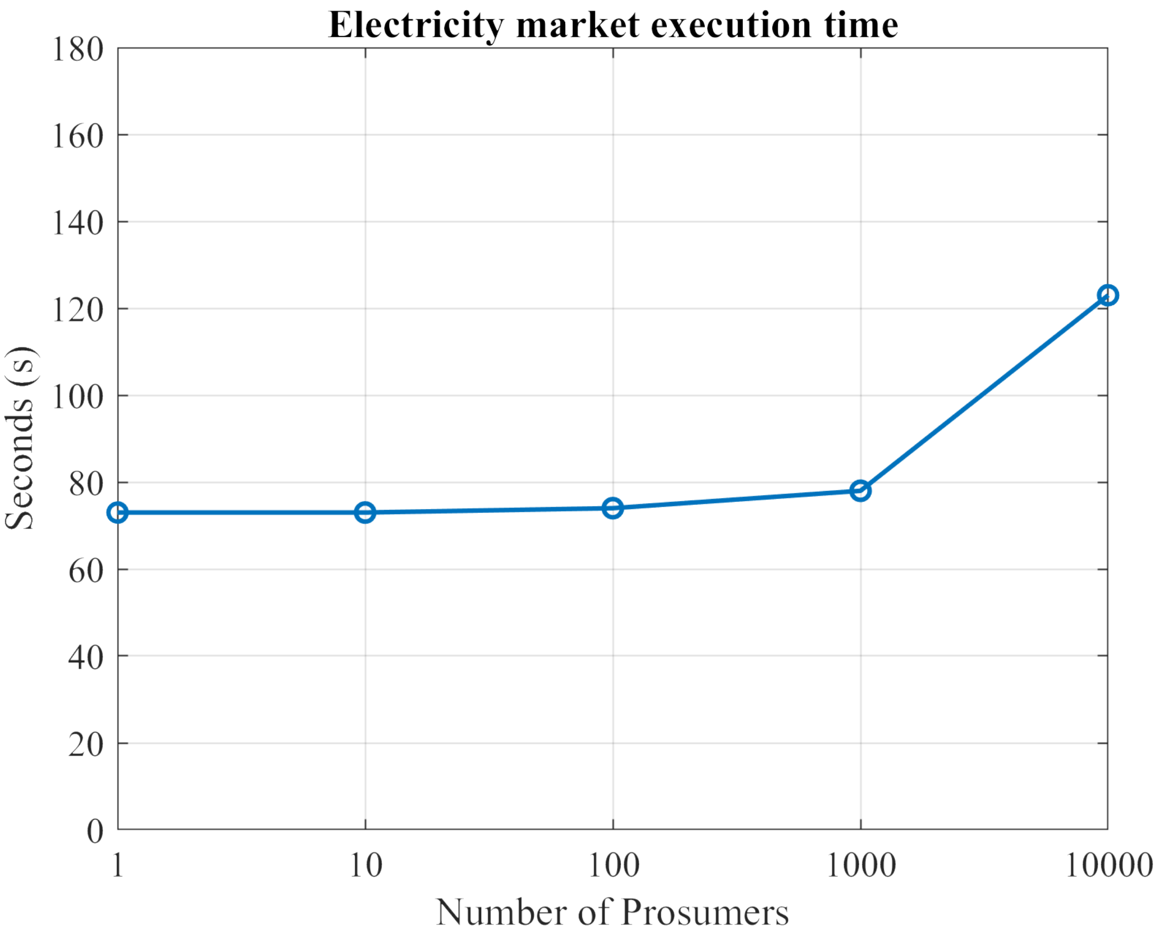


Figure 5.10 – Electricity market execution time considering different number of participating prosumers.

5.2.2 Scalability

Scalability is a measure of how well a system can adapt to an increased load without compromising its performance. In our evaluations, we expanded the number of prosumers incrementally to observe its impact. The outcomes were encouraging. As depicted in Fig. 5.10, even with prosumer counts spanning from 1 to 10,000, the execution duration remained relatively consistent for the first several hundred participants. However, as the numbers scaled from 1,000 to 10,000, we observed a linear growth in execution time. Coupled with the previously demonstrated throughput and latency results, these findings affirm that the blockchain foundation can efficiently accommodate an expanding electricity market. One way to potentially reduce the execution duration in future iterations might be the integration of parallel computing techniques, an avenue not explored in this study.

5.2.3 Resource Utilization

Optimal resource allocation is crucial for the system's smooth operation, ensuring that the underlying infrastructure isn't overwhelmed. Our investigations revealed:

- CPU Utilization: Even during periods of high transactional activity, the CPU's operational load was consistent. Specifically, during invocation processes, the CPU's activity settled around 25-30%. The peak value we noted was a modest 35%, highlighting the system's adeptness at processing without undue stress.

- Memory Utilization: The system demonstrated a steady memory footprint, with an aggregate memory use of approximately 6600 MB across the network. Such uniform memory engagement, devoid of abrupt surges, suggests a robust system design free of potential memory inefficiencies or constraints.

5.2.4 Comparative Analysis

Table 2.1 provides an overview of the comparison between our framework and existing approaches in the field. To provide a more quantitative perspective on

ScaleNex's performance compared to similar frameworks, we will delve deeper into specific comparisons in this section.

Our analysis focuses on scalability, privacy, and decentralization as pivotal metrics for evaluating the effectiveness and robustness of electricity market frameworks. Through a detailed assessment of these metrics, we aim to demonstrate the unique contributions of ScaleNex and its potential to address current limitations in the field.

It's important to note that our analysis will utilize the implementation of our case study, following the three-level multi-blockchain architecture discussed earlier. While the forthcoming results are impressive, there remains potential for further performance improvements through the use of additional computing power and horizontal scaling.

Based on the performance evaluations conducted in the respective studies, we can compare the throughput and latency characteristics of ScaleNex with those of [56], [31] and [30]. In [56] the authors focused on testing the maximum write transactions per second (TPS) using different consensus mechanisms, achieving a sustained throughput of approximately 200 TPS across all mechanisms, with QBFT (Quorum Byzantine Fault Tolerance) exhibiting the best latency. However, the scalability of their framework was limited by the number of validator nodes, resulting in a throughput reduction of up to 42% with 24 validators.

In [31] the authors evaluated the performance of their Blockchain Framework for Large-Scale Energy Systems (BFLSC) framework under varying batch sizes. They conducted experiments with batch sizes set to 100, 200, and 300, while increasing the sending rate of transaction requests. Their results showed that as the sending rate exceeded certain thresholds, the throughput of the system started to decline. For instance, when the batch size was set to 100, the system maintained a relatively stable throughput until the sending rate reached 200 transactions per second (TPS). However, beyond this point, the throughput began to decrease, indicating limitations in the system's capacity to handle higher transaction volumes efficiently.

In [30] the authors assessed their energy trading blockchain (ETB) system's throughput under different workloads, achieving peak read throughput of 1056 TPS and write throughput of 936 TPS. However, they noted a significant increase in latency after reaching peak throughput, highlighting the importance of managing transaction queues to maintain service quality. All three of the referenced works overlook the importance of addressing privacy concerns inherent in the transparency of transactions within the Hyperledger Fabric framework. None of them have implemented solutions such as private data collections or separate channel implementations to safeguard the privacy of transaction data. This deficiency underscores a significant privacy issue present in their market implementations. Moreover, while these frameworks demonstrate strong decentralization characteristics by leveraging the Hyperledger Fabric architecture, they remain vulnerable to total system outages if a sufficient number of validation or orderer nodes are compromised.

ScaleNex demonstrates a highly scalable architecture, leveraging a multi-blockchain model to achieve remarkable throughput. In a 7-channel configuration, ScaleNex achieves exceptional throughput ranging from 1120 to 2660 transactions per second (TPS) for both invoke and query functions, adhering to the default batch size of the Hyperledger Fabric Network. Notably, the system maintains low latency, with maximum latency peaking at just 3.2 seconds across a total of 10,000 recorded transactions. However, it's important to acknowledge that the electricity market procedure time for 10,000 users stands at 120 seconds, indicating potential for improvement through the utilization of parallel computing techniques. Regarding privacy, ScaleNex's architecture significantly enhances end-user privacy by ensuring that data sharing between blockchains is limited to aggregated quantities only. Furthermore, in terms of decentralization, the proposed model allows for the operation of the hierarchical electricity market even if some nodes or blockchains are compromised, as long as they are not essential such as the Market Operator node, the orderer nodes, and the smart grid blockchain. This ensures robustness and resilience in the face of potential network disruptions.

In our investigation, we observed substantial performance enhancements across key metrics compared to alternative frameworks. Throughput improvements ranged impressively from 5.7% to a remarkable 82% in ScaleNex when compared to the showcased alternatives. Additionally, latency in our system exhibited significant improvements, with some cases showcasing reductions of up to 50% compared to other frameworks. These findings underscore the effectiveness of ScaleNex in addressing critical performance challenges within electricity market frameworks, positioning it as a promising solution for the smart grid environment.

Chapter 6

Conclusion and Future Work

This research presented a hierarchical blockchain-powered electricity market platform using the Hyperledger Fabric framework. The architecture delineates three successive electricity market stages: the Community, District, and Smart Grid levels. Depending on the number of communities and districts present, multiple electricity markets can emerge at both the Community and District levels. Within this structure, communities are nested within districts, and all districts are encompassed by a singular Smart Grid. Prosumers are mapped to designated markets based on their magnitude and geographic positioning, allowing them to engage both in their local markets and ascend to superior market tiers via aggregators. These aggregators consolidate the unprocessed quantities from various markets, utilize a fuzzy logic system for price determination, and then place their orders in higher-ranking electricity markets. Overseeing this complex chain of operations is the market operator, who orchestrates the market procedure, propelling aggregated quantities up the hierarchy, culminating in the Smart Grid level. Following this, any quantities that remain unresolved post the Smart Grid's operations are transitioned either to other Smart Grids or the traditional grid for further processing.

The designed framework was put to the test across varied scenarios with diverse parameters. A specific case involving 1056 prosumers of differing scales was spotlighted to gauge both performance metrics and qualitative outcomes. The findings underscored the system's proficiency in fostering transactions across its multi-layered structure, harnessing aggregated price adjustments to optimize the clearance rates for prosumers. With a peak clearance rate of 82% and a median rate of 61% recorded over 50 test simulations, the efficiency of the system is evident. The empirical analysis provided insights into the system's operational characteristics and potential constraints. Remarkably, the throughput, measured between 1120-2660 TPS for both invoke and query functions, surpassed performance benchmarks set by comparable Hyperledger Fabric endeavors. The low latency values, enabled by the system's horizontal expansion across multiple chains and orderer clusters, further emphasized the robustness of the design.

Future Work. We now briefly outline some potential directions for future work, which could refine and expand the proposed approach:

- First, attention could be given to designing a more advanced price-scaling mechanism for aggregated bids and their participation in higher-level markets, potentially employing machine learning methods.
- There is also ample scope for experimenting with different input configurations and system parameters in order to optimize overall performance. The outcomes of such an analysis would, in our view, be particularly useful for drawing more comprehensive conclusions regarding the approach's effectiveness.
- Another avenue worth exploring within the current system is the incorporation of smart equipment (e.g. smart meters), allowing for an integrated and fully automated electricity market operation.
- Finally, a far more in-depth performance assessment across various scenarios of the proposed system could yield a clearer picture of its capabilities and limitations.

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