Digital Tokenization of Demand Response Capacity Right in Blockchain-Based Energy Market

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The increasing penetration of renewable energy resources and the digitalization of modern power systems have intensified the need for flexible, transparent, and market-oriented demand response mechanisms. However, existing DR frameworks remain largely centralized and lack robust infrastructures for secure, traceable, and tradeable flexibility exchange among distributed energy participants. In this paper, a blockchain-based peer-to-peer platform is proposed to enable the digital tokenization of DR capacity rights. Within the proposed framework, DR capacity is represented as a fungible token, allowing flexibility assets to be fractionalized, transferred, and exchanged within decentralized energy markets. To operationalize this concept, a four-stage token lifecycle model—comprising creation, bidding, transfer, and redemption— is developed and encoded through smart contract logic, facilitating automated transaction management and lifecycle traceability. The proposed Digital Tokenized Demand Response Exchange establishes a decentralized architectural layer designed to enhance transparency, auditability, and procedural automation in flexibility trading environments. By transforming DR capacity into a standardized digital asset, the framework supports broader prosumers participation and contributes a conceptual foundation for the evolution of decentralized flexibility markets within future digital energy ecosystems.

Keywords: *Demand Response, Blockchain, Tokenization, Peer-to-Peer Energy Trading, Smart Contracts, Flexibility Markets, Digital Energy Assets.*

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Nomenclature

Symbols and Variables

Id	Unique identifier of a fungible token (FT) instance in the DRX ledger
DRXclient	Identifier of the invoking client in the DRX platform (token creator/owner)
buyer / DRbuyer	Identifier of the buyer participating in bidding/transfer
holder / Holder	Current holder (owner) of the token in the ledger
DRFTtype	Type/category of the DR fungible token (e.g., service class or program type)
for_transfer	Boolean flag indicating whether the token is created for transfer to a buyer
FT	Fungible token object read from the ledger (includes fields such as value, holder, bid map, etc.)
FT_Updated	Updated token structure to be written to the ledger after creation/modification
DRValues	Demand response capacity value associated with a token (capacity units as defined in the platform)
DRvalue	Incremental DR capacity value to be added/updated during creation or update steps
ForSale	Boolean field indicating whether the token is available for exchange/trading
DRbidvalue	DR capacity value requested by the bidder for purchase (bid quantity)
DRbidder	Identifier of the bidder placing an offer on the token
Bidmap	Mapping structure storing bidders and their requested bid quantities/values
DRexistingval	Previously recorded bid value of a bidder (used when updating an existing bid)
counter	Redemption counter/quantity parameter used in the redemption function (as defined in pseudo-code)

Acronyms

DR	Demand Response
DRX	Demand Response Exchange
DRFT	Demand Response Fungible Token
P2P	Peer-to-Peer
DSO	Distribution System Operator

RES	Renewable Energy Sources
FT	Fungible Token
NFT	Non-Fungible Token

1. Introduction

The high penetration of renewable energy sources (RES) and the increasing demand for electrical energy have imposed a significant level of uncertainty on the distribution systems. In order to maintain the level of reliability and resilience, the digitalization of energy systems is proposed, which requires the monitoring, control, and automation infrastructures of smart grids. One of the resources that could be integrated into the system to cope with the corresponding uncertainties is the optimal employment of Demand Response (DR) programs [1]. However, adequate smart grid infrastructure is required for the proper employment of DR programs. In addition, due to different customer sectors and sizes, DR providers could participate in different electricity markets such as day-ahead, intra-day, and spot markets. Therefore, it would be desirable for the distribution system operator (DSO) point of view if all DR providers could participate in a uniform, secure and decentralized marketplace by various uncertainty and forecast models, which is the paper's primary objective. With the emergence of smart grids, DR has evolved from manual load curtailment to fully automated, data-driven systems utilizing IoT sensors, cloud computing, and machine learning for forecasting and control [2]. However, despite technological progress, most DR programs are still centrally managed, which limits transparency, trust, and active consumer participation [3]. Centralized architectures suffer from single points of failure, settlement delays in centralized processes, and lack of verifiable audit trails, motivating the exploration of decentralized solutions such as blockchain. Blockchain technology has emerged as a promising infrastructure for decentralized energy markets, enabling secure peer-to-peer transactions, automated settlement, and transparent data exchange across distributed grid ecosystems [4].

Although blockchain technology has been widely investigated for demand response coordination and flexibility trading, existing frameworks exhibit several structural limitations. blockchain-enabled peer-to-peer energy trading and flexibility coordination frameworks such as [5–6]. While these contributions improve data immutability and trust among participants, they largely treat demand response as an operational service rather than a tradable digital asset. In such architectures, flexibility activation is executed through predefined contractual agreements, without enabling asset divisibility, ownership transfer, or secondary market exchange. Consequently, demand response capacity remains locked within bilateral or aggregator-mediated structures, limiting market liquidity and participation of smaller actors. Furthermore, prior works lack standardized lifecycle modeling for flexibility assets. Processes such as token issuance, bidding mechanisms, fractional transfer, and post-event redemption are either absent or only partially addressed. This restricts the automation depth and economic scalability of decentralized flexibility markets. These limitations highlight the need for a structured tokenization framework capable of transforming demand response capacity into a divisible, transferable, and lifecycle-governed digital asset—an objective addressed by the proposed DRX model. Recent studies have explored blockchain-based frameworks for flexibility trading, extending beyond traditional energy exchanges. Kouhestani et al. [7] proposed a blockchain-enabled flexibility market architecture integrating consumers, aggregators, and system operators, ensuring transparency in settlement. Pop et al. [8] presented a blockchain-based decentralized management framework for DR programs, enabling secure and transparent energy flexibility trading among participants. Similarly, Ahl et al. [9] reviewed blockchain applications in distributed energy markets, emphasizing the potential to empower prosumers and reduce dependence on intermediaries. A review of real-world P2P energy trading initiatives highlights the growing interest in decentralized market structures [10]. In practical implementations, Mengelkamp et al. [11] demonstrated the Brooklyn Microgrid project, where blockchain was used to facilitate peer-to-peer (P2P) energy trading in a local community. Decentralized peer-to-peer energy trading frameworks have been widely investigated to facilitate localized flexibility exchange under network constraints [12]. In the DR domain, blockchain can automate the verification, pricing, and settlement of DR events through smart contracts, thereby reducing administrative overhead and enhancing trust [13]. However, most existing blockchain-based DR frameworks handle DR as a service transaction, not as a digitalized and tradeable asset, leaving a significant research gap that this paper aims to address. Hasankhani et al. [14] implemented a smart contract-based dynamic pricing mechanism for DR, which enhanced automation and auditability of DR transactions. Wang et al. [15] utilized blockchain to coordinate multi-agent flexibility trading in smart distribution networks, reducing latency and improving scalability. Tokenization refers to the digital representation of physical or virtual assets on a blockchain. It enables fractional ownership, traceability, and liquidity of otherwise illiquid assets [16]. Tokens are generally categorized into Fungible Tokens (FTs) divisible and interchangeable and Non-Fungible Tokens (NFTs) unique and indivisible [17]. In the energy domain, tokenization has been applied to renewable energy certificates, carbon credits, and electricity trading. Tian et al. [18] proposed blockchain-based infrastructure tokenization to improve transparency in energy financing. Mezquita et al. [19] developed a multi-agent architecture for blockchain-based P2P energy trading, demonstrating that tokenized assets could enhance prosumer participation. More recently, Zhao et al. [20] introduced carbon-neutral energy tokens for traceable renewable generation within blockchain-enabled markets. Additionally, Choi and Kim [21] proposed hybrid tokenization using NFTs for individualized energy assets, indicating the potential of combining fungible and non-fungible tokens in decentralized energy ecosystems. Despite these advancements, very few studies have focused on tokenizing DR capacity the right to provide load flexibility as a digital, divisible, and transferable asset. Unlike conventional energy tokens, DR capacity tokens encapsulate both the potential flexibility and operational reliability of a participant, representing a novel form of digital asset within decentralized flexibility markets. There are many notable efforts in the area of the smart grid trading problem by suggesting a blockchain-based energy market that would allow energy to be traded between prosumers in a peer to peer manner [22]. However, there is no study to address the DR transaction modeling via digital tokenization. Therefore, the main contribution of this paper is to model the capacity right of DR providers in a local energy system through digital tokenization (FT) in a blockchain-based energy market, which provides advantages such as energy provenance, transactions privacy, and immutability. The framework presented in this paper fills this gap by developing a four-stage DR fungible token (DRFT) model, implementing the complete process via smart contracts to ensure transparency, divisibility, and traceability of DR capacity rights. In this paper, a blockchain-based transaction platform is explained to trade DR capacities that include different types of prosumers, the grid operator, and third-party entities such as aggregators, which are identified as stakeholders. The trading forms and DR capacities that are transacted are described. The DR capacity is encapsulated in an FT structure that includes the token level and identities. Then, the methods and algorithms are developed to carry the token through the 4-step life cycle. The proposed framework has the potential to enhance transaction automation and transparency through decentralized smart contract execution. To strengthen the academic positioning of the proposed framework, Table 1 presents a comparative analysis of recent blockchain-based demand response and flexibility trading studies.

Table 1. Comparative analysis of recent blockchain-based demand response and flexibility trading frameworks.

Ref.	Platform Focus	Tokenization	Lifecycle Modeling	Fractional Trading	Smart Contract Automation	Market Liquidity
[5]	DR coordination	No	Partial	No	Medium	Limited
[6]	DR settlement	No	Partial	No	Medium	Limited
[13]	Flexibility trading	Limited	Partial	Limited	Medium	Limited
[14]	Dynamic pricing DR	No	No	No	Medium	Low
[15]	Multi-agent flexibility	No	No	No	Medium	Low
This Work	Tokenized DR market	Yes	Full (4-stage)	Yes	Advanced	High

Table 2. Comparative Feature Analysis

Capability	Existing DR Platforms	Proposed DRX
DR as digital asset	No	Yes
Fungible token model	No	Yes
Fractional trading	Limited	Full
Lifecycle modeling	Partial	Complete
Secondary market	No	Yes
Smart contract automation	Medium	Advanced

As observed, existing frameworks primarily focus on transaction automation and DR event coordination. However, structured token lifecycle modeling, fractional asset ownership, and secondary market liquidity remain largely unaddressed. The proposed DRX framework advances the state of the art by introducing a fungible token structure governing the complete lifecycle of demand response capacity rights. Unlike existing blockchain-based DR frameworks that primarily focus on transaction automation, the proposed DRX model redefines DR capacity as a tradable digital asset with a complete lifecycle structure. It should be noted that this study focuses on the conceptual design and architectural modeling of the DR tokenization framework. Full-scale experimental validation, including blockchain deployment, smart contract execution benchmarking, and performance measurement, remains part of future work. Nevertheless, the presented lifecycle model and contract logic provide the foundational infrastructure required for such implementations. Despite its conceptual contributions, the proposed framework faces several limitations. These include scalability challenges under large transaction volumes, regulatory uncertainties surrounding tokenized energy assets, and infrastructure deployment costs. Furthermore, real-world validation through blockchain testbeds remains part of future work. The abstraction adopted in this study is intentional to facilitate architectural modeling of tokenized DR markets. Operational and economic complexities will be incorporated in subsequent implementation studies. The advantage of the proposed DRX framework should not be interpreted solely through conventional performance metrics. While computational efficiency is relevant, the primary innovation lies in enabling tokenized flexibility markets through lifecycle-based asset modeling. Existing blockchain DR platforms focus on event verification and settlement, whereas the proposed framework introduces tradable DR capacity rights, fractional ownership, and secondary market liquidity. This functional expansion represents a structural advancement in flexibility market design rather than a purely operational optimization. To further clarify the functional distinction between existing platforms and the proposed DRX framework, Table 2 summarizes a high-level feature comparison.

The main contributions of this work can be summarized as follows:

1. Proposing a blockchain-based framework for tokenizing demand response capacity rights as fungible digital assets.
2. Designing a four-stage lifecycle model encompassing creation, bidding, transfer, and redemption of DR tokens.
3. Developing smart contract algorithms to automate DR capacity trading and settlement processes.
4. Enabling fractional ownership and secondary market exchange of flexibility resources.
5. Establishing a decentralized architecture that enhances transparency, traceability, and transaction automation in demand response markets.

2. P2P transactions in energy systems

Blockchain technology could play an essential role in solving the emerging smart grid problems. Blockchains are used as secure ledgers to store all digital transactions of smart peer-to-peer (P2P) contracts in a distributed authority concept [23]. They share databases enabling users to change in ledgers simultaneously and provide solutions for challenges faced by the energy sector. Decarbonization, decentralization and digitalization, democratization, and deregulation can be stated as 5 Giga trends in future power systems [24]. Market principles and incentives restrict the participation of small consumers in electricity markets. Blockchain supports P2P energy trading under digital transactional platforms. Blockchain developers play a crucial role in the smart grid environment by providing local marketplaces and Internet of Things (IoT) applications [25].

P2P trading in local and customer-oriented markets in blockchain technology could cause cost savings for consumers. Energy balancing in trading platforms makes it possible to consider each prosumer's heterogeneous preferences with minimum uncertainties [26]. Hence, P2P market platforms can be introduced as community-level stakeholders that present business models considering privacy, autonomy, trust, control, and coordination for energy trading [27]. P2P trading markets in blockchain distributed ledger provide transparency, transaction traceability, and transaction verification, sharing the same biding information between all stakeholders simultaneously [28]. A smart P2P contract is run on blockchain platforms composed of transactions between aggregators, prosumers, and system operator. Electricity tokenization and smart P2P contracts consisting of financial and billing transactions information lead to lower transaction costs.

Smart contract-enabled energy transaction platforms have demonstrated the feasibility of automated decentralized market execution [5]. However, the potential of tokenization is not fully exploited due to limited technical infrastructures, regulatory uncertainties, volatility in the token market, and a lack of public sector. Tokens are used as a tangible representation of qualities, values, and facts divided into FTs and NFTs and stored in a digital ledger, a so-called blockchain. FT is identical, divisible, and completely exchangeable with each other, while NFT provides a unique and not interchangeable digital asset, so it cannot be broken down into smaller units [29]. Blockchain platforms, e.g., Bitcoin and Ethereum, facilitate the management of broad digital assets and enable different participants to conduct transactions in the same marketplace. Tokens represent assets to facilitate these transactions. In an energy transaction system, energy systems can be modeled either as FT or NFT [5]: NFT if they have a unique identifier and are not indivisible, and FT if tokens can be broken down and traded in parts.

Assets in power system are usually considered non-fungible tokens however, electrical energy could be considered as fungible tokens. The fungibility of an element refers to its interchangeable behavior compared to others so that it is indistinguishable from another without any significant or detectable difference. There are several reasons for the distinguishability of a given value of energy from another: Energy resources such as renewables and fossil fuels as well as geographical location and time period of power grid operation significantly differentiate future energy tokens. Local energy markets built on peer-to-peer trading principles enable direct prosumer participation and decentralized price discovery [30]. The authors of [22] introduced a P2P energy market based on blockchain technology and non-fungible tokens so that prosumers' access control and automatic matching between bids and offers are considered in the energy trading process. According to [5], one of the most critical issues in designing and applying fungible and non-fungible tokens-based transaction systems is the lifecycle of the tokens. Four common steps of FT or NFT transactions are considered in this paper to model the life cycle of the token issuance to redemption [5]:

Creation of the token by a seller or DR provider: Firstly, the client organization identity and the client identity are checked. It should be checked that the client organization or DR provider is permitted to create this token type. The token ID and owner are then determined based on its buyer and invoker. Bidding on this token by a buyer: In this step, the bids of the tokens are checked. Each token is checked whether it is for sale or there is no bid on it. If there is no bid on a token, the bid stream should be updated. Assign the value of the token to the buyer: Each token is read and checked that the invoker client is its owner and there is a bid on this token. If there is a bid on a token and the token owner requests its transfer, the token's value is assigned to the buyer. Redemption of its value for the token owner: The token owner cannot redeem it if there is a bid on this token. Hence, it is checked that there is no bid on redeemed tokens.

3. Blockchain-based transaction platform

The future power distribution systems are subject to decentralization, digitalization, decarburization, energy diversification, and advanced metering infrastructure (AMI). Which consists of new technologies for their real-time monitoring, control and protection. All system components should collaborate via a secure, high-speed and reliable two-way communication facility in order to improve its efficiency, resiliency and robust performance of the system under uncertain operating conditions. Digitalization of energy systems is known as a key enabler to achieve a sustainable and energy efficient smart community with lower carbon footprints. Hence, investment in digital technologies by various companies is rapidly growing, which leads to their rapid deployment across smarter energy landscapes.

In recent years, a distributed ledger technology or blockchain concept has been developed in different fields of energy sector studies such as wholesale and retail energy trading, environmental pollutants reduction, and demand-side management strategies to facilitate the distributed transactions by removing the central management. In a blockchain environment, data structure such as digital transactions can be securely stored and shared through a central authority point. It allows for automated execution of smart contracts in P2P energy markets. A smart contract is similar to conventional ones but it is stored and shared with all users, is automatically executed and cannot be changed or marked as inactive, while its ledger record remains immutable. Moreover, blockchains are known as alternative databases, which enables multi-users to simultaneously make changes in each ledger.

Integration of conventional end-users and prosumers with digitalized energy grids will be based on smart contract and blockchains. A consumer is usually an individual with a crypto-contract that collects information about other participants to manage its demand. Prosumers are those electricity customers that procure a part of their energy requirement and can vary from small (for example, smart home and electric vehicles) to large (such as industrial communities and high-rise buildings) scales. Financial transactions of participation of prosumers and consumers in smart P2P energy markets can be modeled using blockchain to save energy as high as possible.

As illustrated in Fig. 1, there is a list of user's encrypted and timestamped data/transactions in each block. Each block header is encrypted by a hash function to prevent any data manipulation. Some advantages of blockchains can be described as stated as follows:

Data integrity: In a P2P energy trading framework, all transactions/data are shared with all energy users. Hence, any data manipulation in one block is detected in others and data integrity is guaranteed. ˝ For adding a new transaction, data passes through numerous verification steps and cannot be marked as inactive, while its ledger record remains immutable or edited after approval.

Tamper proofing and manipulation detection: Blocking, removing, and manipulating in transactions/data is not allowed.

Cost-effectiveness and robustness: Since there is no need for third parties and blockchain is a distributed and not-centralized model. Hence, a significant cost saving is achieved and no single failure point is detected.

Transparency: The transactions/data is stored and shared across the entire network. Hence, all energy users access these ledgers using simple authentication procedures.

Supports automated settlement and timely information sharing: Direct communication between different energy users has caused the efficient data sharing. Using blockchain technology or distributed ledger, it is possible to securely track near real-time automated DR services assuring data integrity and fast sharing and registry in low and medium voltage smart grids. Moreover, implementation of trackable and tamper-proof flexible energy transactions can be carried out ensuring the reliability and decentralized operation of the smart grids, especially in the presence of distributed energy prosumers. It should be noted that successful application of demand-side management programs depends on flexible generation/market segments, DR participants and mechanisms, communication system, energy tariffs, and revenue model. Tokenization of energy: In blockchain-enabled systems, consumers can directly connect to prosumers or wholesale energy markets. This may lead to higher energy efficiency and lower costs for generation companies and retailers. In a blockchain-based energy trading platform, for a specific value of electrical power produced by RES or non-sustainable ones, a token is generated and then sold to consumers or wholesale markets. Hence, energy exchanges between providers and consumers will be enhanced. The block chain-based energy market, is a P2P market in which there is a FT for each DR capacity during a predetermined time horizon. The local energy system operator determines the forecasted demand for the next 24 hours. The data should be sent to the P2P market through blockchain oracles. The oracles enter the data via the external transactions. Hence, all information required to verify blockchain, are available within it.

Moreover, each player proposes its bid and offer in the DRX market. The DRX operator notifies the DR event and activates the information of the smart contracts. The availability and baseline of each smart contract is distributed on the blockchain. During the DR event, consumers and prosumers read the demanded load reduction from the blockchain platform and submitted its DR capacity to the DRX operator. In addition, the consumers' demands are stored in the blockchain environment. In the next day, the DRX operator activates the smart contracts to assess the compatibility of their consumption with its requested load reduction capacity. If the consumers' demand is compliant with the DRX demand reduction request, the rewards are assigned to the participating consumers using the FTs.

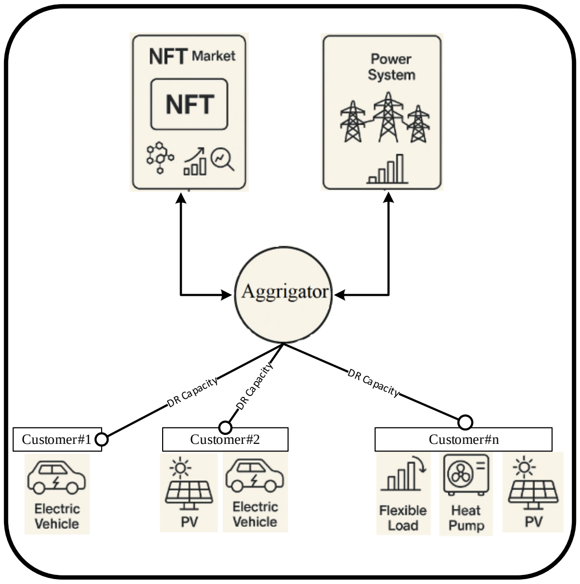

Fig. 1. A schematic presentation of a blockchain-based P2P energy trading platform

4. Digital Tokenization Model of Demand Response

4.1. Process Flow Description

The DR token transaction process begins with the registration of demand response providers within the DRX platform. Following identity authentication, tokenized capacity is issued through smart contract execution. Market participants then submit bids on available token fractions. The smart contract verifies bid validity and records transactions on the blockchain ledger. Upon bid acceptance, token ownership is transferred to the buyer through automated contract triggers. The distributed ledger is updated accordingly. Finally, redeemed tokens are settled following successful DR event participation, completing the lifecycle transaction loop. Fig. 2 Process Flow of Tokenized Demand Response Transactions in the DRX Platform. This figure illustrates the operational workflow of tokenized demand response transactions within the proposed DRX framework. The process begins with DR provider registration and token issuance, followed by market bidding, smart contract validation, ownership transfer, and final redemption upon successful DR event participation.

To provide a clearer technical understanding of the proposed framework, the operational methodology of the DRX platform is structured around a four-stage token lifecycle model. Each stage represents a distinct functional layer governing the creation, exchange, transfer, and settlement of tokenized demand response capacity rights. The lifecycle begins with the token creation stage, in which demand response providers are issued fungible tokens representing their verified flexibility capacity. This process is executed through identity authentication, capacity validation, and smart contract initialization mechanisms embedded within the blockchain network. Following issuance, the bidding stage enables market participants—including aggregators, operators, and prosumers—to submit bids on fractional portions of available DR tokens. The bidding logic supports divisible asset allocation and records all bid transactions through cryptographically secured smart contract entries. Upon successful bid acceptance, the transfer stage governs the ownership reassignment of token fractions. Smart contracts automatically generate new token instances reflecting updated ownership structures while preserving transaction traceability across the distributed ledger. Finally, the redemption stage facilitates the settlement of fulfilled demand response obligations. Token holders may redeem their tokenized capacity value upon successful DR event participation, completing the lifecycle loop. This structured lifecycle architecture ensures secure, transparent, and automated management of flexibility assets within the decentralized DRX marketplace.

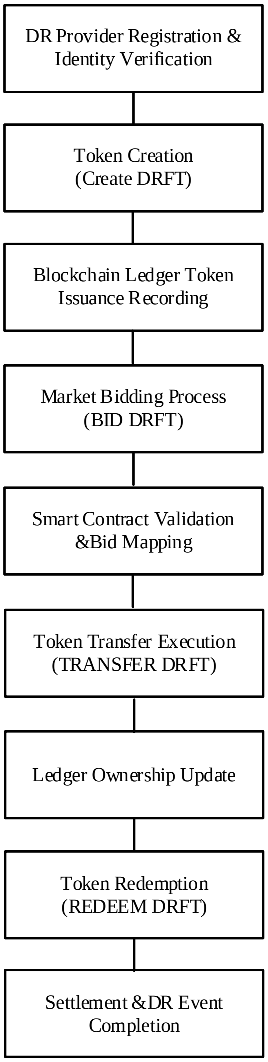

Fig. 2. Process flow diagram

Each lifecycle stage is implemented through dedicated smart contract functions that govern state transitions of DR tokens within the blockchain ledger. These functions enforce access control, transaction validation, bid mapping, and ownership immutability, ensuring that token operations remain tamper-proof and auditable across all network nodes. To response the increased demand in the smart grids, various information and communication technologies are used to implement demand response exchanging process in P2P energy markets. There is a bidirectional data flow in the blockchain based energy market, which enables the active participation of consumers/prosumers in the DR Exchange (DRX) platform. As discussed in introduction section, the fungible tokens are interchangeable and partible. In the DRX process, DR capacities are interchangeable and divisible, so can be exchanged using the fungible tokens. The token ID which consists of the client identifier and the token type is one of the issues considered in the smart contracts of the blockchain based P2P energy markets. For the buyers, it is possible to bid upon any fungible token in a way that the buyer's identity as well as the value of bided energy are recorded in the blockchain environment. After bidding upon each fungible token, the token value is then updated. It is possible to bid on a FT several times while there is a fraction of this token without any bid upon it.

In a DRX platform, DR providers are considered as the FTs owners. The value of each FT represents the DR provider capacity. In other words, each DR provider can exchange a fraction of its FT either in one transaction or multiple ones. During each FT based DR trading process, the original token is redeemed and the new one will be created to update the DR capacity of this provider. The players of the blockchain based DRX platform consist of DR capacity sellers and buyers. DR sellers refer to consumers and prosumers, while DR buyers composed are DRX operator and prosumers. The DR capacity can be exchanged either via the DRX operator or directly between the sellers and buyers. It should be mentioned that all DR transactions are encoded using smart contracts.

Despite the conceptual advantages of the proposed DRX framework, several practical considerations must be addressed for real-world deployment. Interoperability with existing demand response infrastructures remains a key requirement. The integration of blockchain platforms with legacy DSO management systems can be enabled through secure APIs and blockchain oracles that facilitate trusted data exchange. Cybersecurity is another critical concern. While blockchain ensures immutability, smart contract vulnerabilities and oracle attacks may introduce risks. Permissioned blockchain networks, identity verification layers, and encrypted transaction channels can mitigate such threats. From an economic perspective, blockchain deployment introduces computational and infrastructure costs. However, consortium-based or private blockchain models can significantly reduce transaction fees and operational overhead. Scalability must also be considered, particularly in scenarios involving large populations of prosumers. Techniques such as off-chain transaction aggregation, sidechain processing, and hierarchical validation structures may enhance system throughput. Finally, regulatory and market constraints remain key adoption barriers. The legal recognition of tokenized demand response assets, compliance with electricity market settlement rules, and alignment with grid operator policies are essential for practical implementation. Each token, in this paper contains of a key value pair where the key is the ID of the token and the value consists of fields with information about the token as shown in Table 3. The fields in the token are:

- ID uniquely identifies the token in the network.
- DRValue illustrates the amount of DR in this token
- ForSale is a Boolean flag that is set to TRUE if the token is for sale.
- Holder stores the identity of how have the token.
- Bid field accepts a bid on the token. This field is implemented as a hashmap to accept multiple bids. A bid in this system registers a binding interest in a token.
- Notes field is a placeholder to store other details of the token such as price or terms and conditions that may be needed in the exact use case but are not general enough for our work.

Table 3. The FT structure

Key: ID
ID (string) DRValue (float) ForSale (Boolean) Holder (string) Bid (hashmap)

4.2. Token Valuation Design Variables

The valuation and operational behavior of demand response tokens within the DRX platform are governed by a set of design variables reflecting the technical and performance characteristics of participating providers. These variables ensure that tokenized flexibility assets accurately represent the real operational capabilities and reliability of demand response participants within the blockchain marketplace.

Key design variables incorporated into the token valuation model include reliability, response latency, participation factor, and network location significance. Reliability represents the historical performance consistency of a DR provider in fulfilling committed load reduction obligations. Response latency measures the time delay between DR event notification and actual load adjustment, directly influencing operational responsiveness. Participation factor reflects the engagement frequency of providers in prior DR events and serves as an indicator of market commitment. Network location captures the electrical significance of the participant within the grid topology, particularly in congested or critical nodes where flexibility holds higher system value.

These design variables dynamically influence token valuation within the DRX platform. Providers demonstrating higher reliability, faster response times, and consistent participation are assigned higher token value coefficients. Similarly, flexibility assets located in network-constrained regions may carry increased market significance. This valuation mechanism ensures that tokenized DR capacity reflects not only quantitative load reduction potential but also qualitative operational performance attributes. The defined variables also affect lifecycle operations, including bidding attractiveness, transfer priority, and redemption eligibility. By embedding performance-sensitive parameters into token logic, the DRX framework enables a market-driven valuation ecosystem for flexibility assets. These valuation parameters are embedded within the token creation and lifecycle management algorithms described in the following subsections.

4.3. Creating a DR Fungible Token

As depicted in Fig.3, firstly FTs are created by checking the client's identity. The identity of the DRX of which the client is a part. It then conducts a check to make sure that the invoker DRX is permitted to create the requested token type. At that moment sets the value of the additional DRX apart from the invoker that must be added to the endorsement policy. The ID and Owner of the token will depend on whether the token is being created as part of a transfer to a buyer or is being created for the invoker. DRX operator assigns an FT to each DR provider, which changes into different values over the time based on their performance and DRX indices. All generated FTs have the same initial value according to their DR capacities.

The DRX indices includes:

- Latency
- Participation factor (0/1)
- Reliability
- Location in the network

Changes in any above-mentioned parameters have an effect on the FT value. If the participation factor of a consumer in a previous DRX transaction goes zero, its FT value would be decreased. Higher reliability increases the FT value, and if the location of a consumer is congested (for example), its FT value will increase. The CREATEDRFT algorithm initializes and issues a new fungible token (FT) that digitally represents a demand response (DR) provider's available capacity within the blockchain-based DR Exchange (DRX) platform. Each token acts as a transferable and divisible asset that can be traded in the peer-to-peer (P2P) market.

1. The DR provider (client) identity and its affiliation with a registered DRX entity are first authenticated through the blockchain identity verification layer.
2. The algorithm checks whether the client has permission to create a specific token type.
3. If validated, it generates a unique token ID by concatenating the DRX client ID and the FT type.
4. The token holder field is assigned either to the DR provider (issuer) or, in the case of transfer creation, to the buyer.
5. The system then reads the blockchain ledger to check for any pre-existing tokens with the same ID.
6. If a token already exists, its DRValue (the DR capacity associated with the token) is updated; otherwise, a new token object is created and stored in the distributed ledger.

Each generated token contains a set of fields that define its operational parameters:ID, DRValue, ForSale, Holder and, Bidmap. Notes: Metadata such as price, contractual terms, or DR event details

The FT value dynamically changes according to several operational indicators defined by the DRX system:

- Latency: The time delay in the provider's response to DR events (higher latency → lower FT value).
- Participation Factor (0/1): Binary index indicating whether the provider participated in prior DR events.
- Reliability: The provider's performance consistency in previous DR activations.
- Location: The geographical or electrical network location—capacity in congested or critical nodes may be assigned higher value.

The CREATEDRFT function is the foundational step of the tokenization process. It formalizes the DR capacity as a digital, traceable, and tradeable asset, ensuring that every participant in the DRX marketplace holds a verified digital certificate of flexibility rights. The detailed pseudo-code implementation of each lifecycle stage is presented in the following subsections. To enhance the technical clarity of the proposed tokenization framework, each stage of the DR token lifecycle is supported by dedicated pseudo-code representations. These algorithmic descriptions formalize the logical execution sequence of token operations within the blockchain environment. The pseudo-code structures are designed to illustrate identity verification procedures, token state transitions, bid registration logic, and ownership transfer mechanisms. By translating smart contract functions into structured algorithmic steps, the proposed framework enables clearer reproducibility and conceptual understanding of lifecycle processes. The development of a dedicated token lifecycle algorithm is motivated by the limitations of conventional demand response transaction models. Existing systems primarily facilitate event activation and settlement without enabling divisible ownership, secondary exchange, or lifecycle traceability of flexibility assets. The proposed algorithmic structure addresses these limitations by embedding token creation, bidding, transfer, and redemption within a unified smart contract execution framework. Each lifecycle algorithm governs a specific operational state transition of DR tokens within the blockchain environment. The creation algorithm validates provider eligibility and issues tokenized capacity assets. The bidding algorithm manages market allocation of token fractions. The transfer algorithm controls ownership reassignment, while the redemption algorithm finalizes settlement upon DR event fulfillment.

Together, these algorithms establish a closed-loop transactional infrastructure for tokenized flexibility exchange.

The pseudo code of the DRFT is presented as follows:

Algorithm 1. CREATE DRFT

```
DRXclient ← GetClientId().GetFTID()
if for_transfer == true then
    id ← buyer + "_" + FTtype
    holder ← buyer
else
    id ← DRXclient + "_" + DRFTtype
    holder ← DRXclient
end if
    FT ← ReadToken(id)
if FT! = nil then
    FT.DRValues ← FT.DRValues + DRvalue
else
    FT_Updated ← Updated_FT(ID ← id, DRFTType ← FTtype, DRValues ← DRvalue, Holder ← holder)
end if
```

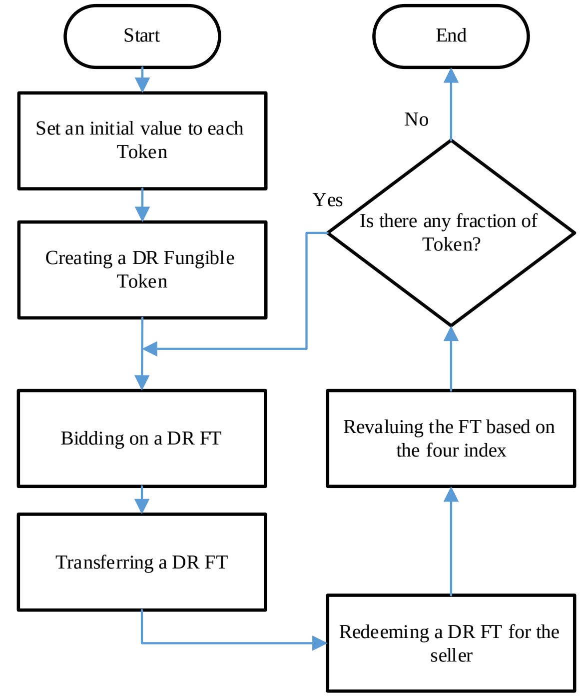

Fig. 3. The flowchart of the proposed FT based DRX strategy

4.4. Bidding on a DR FT

A buyer can bid upon each fraction of a fungible token. If there is any fraction of a token and there is no request or bid on it, the DRX algorithm is updated using the buyer identity.

The BIDDRFT algorithm governs the bidding mechanism through which buyers (such as system operators, aggregators, or prosumers) submit offers to purchase portions of a DR provider's tokenized capacity.

1. The algorithm reads the selected FT from the blockchain ledger.
2. It verifies that the token is marked as for sale (ForSale = TRUE).
3. It ensures that the bid amount (DRbidvalue) does not exceed the available DRValue of the token.
4. The buyer's identity (DRbidder) is authenticated and retrieved from the blockchain's identity layer.

5. If a bid from the same buyer already exists in the token's Bidmap, the bid value is incremented; otherwise, a new bid entry is created.
6. The token's remaining DRValue is reduced accordingly to reflect the pending bid.

The Bidmap structure (implemented as a hashmap) allows for multiple concurrent bids on the same token, each associated with a buyer ID and bid value. This mechanism supports fractional bidding, meaning that a single token can be divided and partially sold to several buyers simultaneously. All bids are cryptographically hashed and timestamped, ensuring immutability and transparency. The BIDDRFT function forms the competitive layer of the DRX platform. It enables market-driven pricing of DR capacity, introduces liquidity, and ensures open participation among all network players while maintaining full data integrity and security.

The pseudo code of the bidding on a DRFT is as follows:

Algorithm 2. BID DRFT

```
FT ← ReadFT(id)
if FT.ForSale != true then
    return "The FTID token is not for exchange."
end if
if FT.DRValues < DRbidvalue then
    Return "DR value FT.DRValues is lower than bid DRbidvalue"
end if
DRbidder ← GetClientId ().GetFTID()
if FT.Bidmap[DRbidder]! = nil then
    FT.Bidmap[DRbidder] ← DRexistingval + DRbidvalue
else
    FT.Bidmap[DRbidder] = DRbidvalue
end if
FT.DRValues = FT.DRValues - DRbidvalue
```

4.5. Transferring a DR FT

According to the following code, the FT owner can transfer the requested fraction of the token to the buyer bidding on this value. If the transfer of the token fraction is requested by the token owner, it will be done. Then, the list of FTs of the owner is updated according to the transferred fractions. It is not possible to update the token ID. Hence, a new token will be created by the buyer who received this fraction. Hence, the primary token owned by the seller will be removed from the algorithm.

The TRANSFERDRFT algorithm executes the transfer of token ownership from the seller (DR provider) to the buyer after successful bidding and acceptance. It represents the digital equivalent of an energy transaction settlement.

1. The algorithm authenticates the invoking client and verifies that it matches the current token holder (Holder). Unauthorized users are denied transfer rights.
2. The function iterates through the Bidmap, processing each buyer's accepted bid sequentially.
3. For every valid bid, a new token is generated and assigned to the corresponding buyer. The new token inherits the original token type and value equal to the purchased DR portion. Each transfer triggers a blockchain event, recording all transactional details immutably.
4. The original token is then updated or marked as inactive, while its ledger record remains immutable depending on whether any residual DR capacity remains.
5. The Bidmap is cleared, finalizing the transaction cycle.

The creation of a new token for each partial transfer avoids mutating existing tokens, ensuring the immutability of blockchain records. Each transaction triggers ledger synchronization across all blockchain nodes, guaranteeing that the new ownership status is simultaneously visible to all market participants. TRANSFERDRFT represents the settlement phase of the tokenized DR market. It ensures full traceability of asset transfers, enforces non-repudiation, and guarantees that no duplicated or counterfeit DR rights exist in the system.

This process replaces conventional market intermediaries with automated, smart contract-based settlements, by replacing manual intermediaries with automated smart contracts.

Algorithm 3. TRANSFER DRFT

```
FT ← ReadFT(id)
DRXclient ← GetClientId ().GetFTID()
if DRXclient != FT.Holder then
    return "The client holderclient is not legal to transfer token holed by FT.Holder"
end if
for num, FTvalue ← range(FT.Bidmap) do
    CreateToken(FT.TokenType, TRUE, num, FTvalue)
    delete(FT.Bidmap, num)
end for
```

4.6. Redeeming a DR FT

It should be noted that when any fraction of a FT is transferred to the buyer bidding upon it, the transferred fraction of the token causes a new token to be created and the original token will be no longer active for trading, while its transaction record remains immutable on the ledger, as coded in the following. But the transaction report will be updated and recorded. Moreover, the token owner cannot redeem any FT which has a bid on it.

The REDEEM_DRFT algorithm manages the redemption process of a token after a DR event has been completed. It enables the token holder to "cash in" or retire part or all of their token value once obligations have been fulfilled.

1. The invoking client's identity is validated to ensure that only the legitimate token owner can execute redemption.
2. The algorithm checks that there are no pending bids on the token; if any bid is active, redemption is blocked to prevent market inconsistencies.
3. The requested redemption value (counter) is verified against the token's current DRValue.
4. The token's remaining DRValue is decreased by the redeemed amount, and the blockchain ledger is updated accordingly.
5. The redeemed transaction is recorded as an immutable entry, forming part of the DR provider's performance record.

The redemption process is equivalent to financial or operational settlement in traditional markets.

The DR provider can now receive monetary compensation, carbon credits, or energy tokens equivalent to the redeemed DR capacity.

The blockchain ensures that:

- Tokens cannot be redeemed multiple times.
- The redemption records serve as verified historical data for auditing and reputation scoring of participants.

REDEEM_DRFT finalizes the life cycle of the tokenized DR asset.

It provides accountability, closes financial settlements, and feeds back validated performance metrics into the DRX ecosystem, enabling future forecasting and adaptive market participation. Table 4 shows the summary of the Token Life Cycle.

Algorithm 4. REDEEM DRFT

```
FT ← ReadFT(id)
DRXclient ← GetClientId ().GetFTID()
if DRXclient! = FT.Holder then
        return "The DRXclient is not authorized to redeem token token.FTID holded by another"
end if
if counter > FT.DRValues then
        return "The token FT.FTID has FT.DRValues values, is lower than demanded redeem value counter"
end if
FT.DRValues ← FT.DRValues – counter
```

Together, these four algorithms define a closed-loop digital ecosystem for demand response trading.

They provide:

- Automation through smart contracts
- Transparency through immutable blockchain records
- Flexibility through divisible and transferable digital assets
- Trust and security without reliance on a centralized authority

This algorithmic framework supports timely monitoring within decentralized infrastructures, settlement, and valuation of distributed flexibility resources, serving as a blueprint for future decentralized energy markets.

The integration of pseudo-code and process flow modeling bridges the gap between conceptual system architecture and practical smart contract implementation. While the pseudo-code captures algorithmic logic, the flow representations illustrate operational sequencing, stakeholder interactions, and data propagation across the blockchain infrastructure. Despite its architectural advantages, the proposed algorithmic framework presents certain limitations. The execution efficiency of lifecycle transactions may be influenced by blockchain processing latency and network congestion. In large-scale deployments involving thousands of prosumers, transaction throughput constraints may emerge. Additionally, the algorithm relies on accurate off-chain data feeds for DR event verification. Any compromise in data integrity or oracle reliability may impact settlement accuracy. Regulatory constraints surrounding tokenized flexibility assets may also affect practical implementation in existing electricity markets.

Table 4. Summary of the Token Life Cycle

Algorithm	Main Role	Key Functionality	Contribution to the DRX Ecosystem
CREATEDRFT	Token Initialization	Authenticates identity and issues DR capacity tokens	Establishes digital ownership and valuation of DR assets
BidDRFT	Market Bidding	Records multiple simultaneous bids with bid–value mapping	Enables price discovery and liquidity in P2P trading
TRANSFERDRFT	Ownership Transfer	Transfers fractional DR capacities and generates new tokens	Ensures traceable, immutable, and reduced procedural overhead
REDEEMDRFT	Token Redemption	Redeems or retires DR tokens post-event	Completes financial and operational settlement of DR capacities

5. Conclusions

This paper introduced a blockchain-based framework for the digital tokenization of demand response capacity rights within peer-to-peer energy markets. By modeling DR capacity as fungible tokens, the proposed DRX platform enables divisible, transferable, and traceable flexibility transactions. The defined token lifecycle—creation, bidding, transfer, and redemption—establishes an automated mechanism for managing DR exchanges through smart contracts. The conceptual architecture enhances transparency, reduces reliance on centralized intermediaries, and supports broader participation of consumers and prosumers in flexibility markets. While the present study focuses on architectural and lifecycle modeling, future work will involve real-world blockchain deployment, performance benchmarking, and economic feasibility assessment. The proposed framework lays the groundwork for scalable and decentralized demand response ecosystems in next-generation smart grids. By positioning demand response capacity as a first-class digital asset, this work opens new pathways for scalable, market-driven flexibility management in future smart grids.

It should be noted that the present study focuses on the conceptual and architectural modeling of tokenized demand response markets. Full-scale implementation, including blockchain deployment, smart contract execution benchmarking, and performance measurement, remains part of future research. Future validation efforts will involve testing the DRX framework within blockchain testbeds to evaluate throughput, latency, transaction cost, and scalability under real operational conditions.

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