Energy Reports 7 (2021) 5269–5288

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Blockchain based decentralized local energy flexibility market

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ARTICLE INFO

Article history:
Received 1 February 2021
Received in revised form 16 April 2021
Accepted 12 August 2021
Available online xxxx

Keywords:
Local flexibility market
Peer-to-peer flexibility trading
Blockchain
Bids and offers matching
Oracles

ABSTRACT

Large-scale deployment of renewable energy sources brings new challenges for smart grid management requiring the development of decentralized solutions and active participation of prosumer and non-grid-owned assets. Local energy flexibility markets can help in monitoring energy flows, motivate changes in prosumers' energy supply and demand, achieving local energy balance, and optimization of electricity flows. In this paper, we propose a blockchain-based decentralized energy flexibility market enabling small-scale prosumers to trade in a peer-to-peer fashion their flexibility in terms of load modulation concerning the baseline energy profiles. We have defined an energy flexibility token for digitizing the flexibility of prosumers allowing to be traded on the market as an asset and self-enforcing smart contracts for decentralized market operation including functions such as the placement of flexibility bids/offers, trading session management, or energy and financial settlement of energy flexibility transactions. For matching the flexibility bids and offers, a solution based on a greedy heuristic and a bipartite graph is proposed for minimizing the number of flexibility transactions and reducing the blockchain-associated costs, while Oracles are used to assure its secure integration with the blockchain. The blockchain-based flexibility market was validated with the help of the Terni city Distribution System Operator, showing promising results in enabling the self-consumption of renewable energy generated in a small scale urban micro-grid considering live energy monitoring data, and in assuring the local balancing of the demand side in a simulated environment considering many market participants and historical energy data.

1. Introduction

In Europe, the defined policies and incentives have led to the installation of a massive number of small-scale Renewable Energy Sources (RES) that are now connected to the energy grid. This brings new challenges for the Distribution System Operators (DSO), to balance these variable energy sources while ensuring the safe distribution and power quality for consumers (Prettico et al., 2019). Nowadays, feed-in management for balancing energy generation (disconnecting the renewable energy source for the grid and redisposing the load to a power plant) comes with high economic costs and negative economic impact (Lago et al., 2021). Moreover, in centralized management of the energy system case, it is often difficult and costly to achieve such balance due to the local variations of renewable energy generation paving the way towards decentralized energy systems with bidirectional energy flow among smaller assets and multiple prosumers (producers and consumers) (Junker et al., 2018) and towards new local markets design. The energy systems are transitioning to cooperative decentralized scenarios, in which peer-to-peer (P2P) coordination among prosumers is requested to adjust the demand according to the available generation while exploiting the local non-grid-owned flexible loads (Cioara et al., 2020). The prosumers may bring added value in the management of the electric grids using their energy flexibility, however, the socio-technological framework for engaging and motivating their participation as well as for economic trading of energy flexibility is still in the early development.

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https://doi.org/10.1016/j.egyr.2021.08.118

In this context, local energy flexibility markets can help in monitoring energy flows, motivating changes in prosumers' energy supply and demand, achieving local energy balance, and contributing to the EU goal of becoming a climate-neutral continent by 2050 (Raveduto et al., 2020). In such energy flexibility markets, the participants can trade their energy flexibility in advance, adjust their energy profiles by leveraging on their flexibility, negotiate better energy prices empowering local communities to take control of their energy system, and contribute to its resilience. As a result, more energy will be used locally thus reducing the amount of energy to be transported on longer distances enabling local optimization of electricity flows (Jansen et al., 2021). Several attempts have been made to stimulate individual prosumers' engagement in flexibility-driven Demand Response (DR), by modulating their energy profiles and matching supply and demand at the local level (Park et al., 2020; Jindal et al., 2020). Individual households have been integrated, thanks to the recent advent of Information and Communication Technology (ICT) and Internet of Things (IoT) energy metering devices, as flexible assets able to provide energy flexibility services. However, the potential of the flexibility of energy consumers has not been fully exploited, due to several reasons, including the lack of appropriate consideration of intra-community P2P flexibility trading. Another load flexibility that could be used is the control of energy profiles by smart scheduling of flexibility actions such as controlling the charging of electric vehicles (EVs). The high peak consumption requested by EVs is pushing the adoption of new decentralized strategies to increase the local energy system's resilience and efficiency. However, to enable increased levels of flexibility it is required to improve the management of energy systems by engaging and coordinating a larger variety of small-scale flexible prosumers. Planning of energy balance with lower refresh rates and linking flexibility services in local micro-grids which are characterized by low inertia and fast dynamic transient states may even expose the system to the risk of collapse (Anwar et al., 2019; Stawska et al., 2021).

The distributed ledger technology has known a rapid increase in the last years in terms of research development and applicability in different technological domains (Pop et al., 2020c; Chowdhury et al., 2019). The main reason is related to the benefits that this technology brings, as opposed to the traditional centralized management systems. Among these advantages, the following are also applying to the management energy flexibility markets such as provenance, immutability, peers' consensus, and integration self-enforcing smart contracts. Provenance is the property of the blockchain that allows for tracking the traded asset through tokenization until the moment of creation in the blockchain Sigwart et al. (2020) and Batista et al. (2021). This property is ensured by the data structure used to compose the distributed ledger, a linked list, which ensures that all the transactional data can be accessed at any time by simply iterating through the blocks of the chain. Furthermore, each transaction that occurs in the blockchain must spend tokens that were previously received through another transaction, whose hash pointer needs to be specified. Consequently, it becomes very easy to track back the tokens to their origin in the chain. The immutability of blockchain technology ensures that any transaction or prosumer monitored energy data registered in the chain will remain unchanged and cannot be tampered by a third party (Casino et al., 2020; Pop et al., 2019). The probability of changing a value in a block by an attacker decreases with the number of blocks following which need to be re-hashed, requiring an immense amount of computational power, not being feasible with the current processors. This ensures the security of data because it makes it impossible for an attacker to change the information contained in transactions such as receiver of the tokens, amount of sent tokens, registered energy data, etc. Furthermore, the asymmetric algorithm used for encryption ensures that a piece of data can be signed only by the person holding the private key (Wang et al., 2019b). This means that the only way to forge the signature is if the private key is obtained from the holder himself. The block replication and consensus mechanisms implemented in the blockchain system allow for tracking all peers' actions and validating at each point the transactional state (Wang et al., 2019c; Pop et al., 2020b). This means that each peer node is responsible to validate the integrity of the registered actions such as tokens issued, bids and offers, monitored values, etc. Finally, the self-enforcing smart contracts may encode different business rules both at the levels of peer node level but also at the level of the decentralized application operation (Wang et al., 2019a; Han et al., 2020). The smart contracts are stored in the blockchain and are enforced upon new transactions registration on the chain, determining a state update.

To benefit from the above advantages, we propose a public blockchain-based implementation of energy flexibility markets for managing and balancing the local energy flexibility of non-grid-owned energy assets by allowing individual small-scale prosumers to trade their flexibility in a P2P fashion. Starting from the existing state of the art reviewed in Section 2 several challenges have been addressed in developing such a decentralized energy flexibility market. The first challenge is represented by the definition of a token representing the asset to be traded, in this case, the prosumers energy flexibility, and of a pipeline of instructions for registering an order of the token (sell or buy energy flexibility) in a market session. We propose a non-fungible flexibility token based on the ERC721 standard (ERC721, 2021) which stores specific information on available flexibility and allows for the quantification of prosumers-owned flexibility tokens in smart contracts. The pipeline of activities for registering flexibility trades is managed in a decentralized manner using smart contracts associated with each market participant, while the session configuration and order book management is done using session-level smart contracts replicated in all network peer nodes for improved auditability features. The second issue is the complexity of decentralized flexibility matching and clearing price computation. The flexibility order matching algorithms are based on heuristics that require computational complex operations such as sorting, searching, making them costly and unfeasible to be executed on the chain. In our approach, we have leveraged on the concept of Oracle for allowing the integration of chain flexibility matching solutions and we have defined matching algorithms that allow the minimization of the number of flexibility transactions among peers while still meeting the flexibility amounts, energy profiles, and delivery interval requirements. The third issue is the flexibility delivery tracking and financial settlement of participants' wallets. The tamper-proof energy monitoring and atomicity of the settlement are mandatory to ensure the consistency of the transfer between the participants involved. In our approach market participants, smart contracts are integrated with smart energy meters allowing the tracking of energy profiles against the flexibility agreed in energy flexibility transactions and implementing decentralized delivery versus payment model. An additional issue to be addressed is market scalability. High transactional throughput and low response time for flexibility bid and offers matching are requested to ensure that the flexibility orders are efficiently registered, matched, and settled. The results in both operational micro-grid and simulation environments are promising.

The paper brings the following contribution:

- Definition of an energy flexibility token for digitizing the flexibility of various prosumers allowing to be traded on the market as an asset.

Table 1
Abbreviations and letter symbols.

Abbreviation	Unit or term
API	Application Programming Interface
BRP	Balancing Responsible Party
DR	Demand Response
DSO	Distribution System Operators
EV	Electric vehicles
HVAC	Heating, ventilation, and air conditioning
ICT	Information and Communication Technology
IoT	Internet of Things
LV	Low Voltage
P2P	Peer to peer
RES	Renewable Energy Sources
TSO	Transmission System Operator
$E_{baseline}^{prosumer,[t_s,t_e]}$	Baseline energy profile of prosumer for an interval $T = [t_s, t_e]$
X_{days}	Number of days
$E_{Flex-above}^{prosumer,[t_s,t_e]}$	Energy flexibility above
$E_{Flex-below}^{prosumer,[t_s,t_e]}$	Energy flexibility below
$P_{forecasted}^{prosumer}$	Prosumer predicted power profile
$P_{baseline}^{prosumer}$	Prosumer baseline power profile
$FlexibilityType$	Flexibility type (i.e. above or below the baseline)
$[startDTime, enDTime]$	Delivery time interval
kWh	Kilowatt-hour
$bids[B]$	Flexibility active Bids
$offers[S]$	Flexibility sell Offers
$Price\_clearing$	Clearing price
bid_{price}	Flexibility bid price
$offer_{price}$	Flexibility offer price
$flex_{request}$	Bid flexibility amount
$flex_{offer}$	Offer flexibility amount
$offers_{matched}$	Subset of matching flexibility offers
M	Number of bids
N	Number of offers
$C_{source}^{offer_i}$, $C_{bid_j}^{sink}$	Graph edges specific capacities
$cost_{ij}$	Cost of sending an energy flexibility flow
$N_{transaction}$	Number of transactions

- Development of self-enforcing smart contracts for decentralizing market operation functions such as the placement of flexibility bids and offers, trading session management, and energy and financial settlement of energy flexibility transactions.
- Definition of algorithms for flexibility bids and offers matching based on greedy heuristic and on bipartite graphs for minimizing the number of flexibility transactions. Oracles are used to assure their secure integration with the blockchain-based market.
- Validation of the proposed public blockchain-based flexibility market for managing the flexibility of a micro-grid in Terni and feasibility for many trading participants using a simulation that considers monitored energy data of prosumers in the same region.

Table 1 describes the terms and technical abbreviations used throughout the paper.

The rest of the paper is structured as follows: Section 2 presents the state of the art approaches concerning energy flexibility and decentralized energy markets; Section 3 defines the energy flexibility and the associated token, market operation leveraging on smart contracts and algorithms for flexibility bids and offers matching and Section 4 presents market validation results for the Terni micro-grid together with simulation results for the integration of many participants. Finally, Section 5 presents the paper's conclusions and planned future work.

2. Related work

The distributed ledger is a fast-emerging technology that can be used for implementing decentralized, transparent, and democratic solutions for smart energy grid management (Cioara et al., 2020; Kumari et al., 2020). It offers several benefits for grid decentralization following ones the following ones appearing often in state-of-the-art literature: tampered registration of energy data (Pop et al., 2019), P2P energy loads management (Esmat et al., 2021), secure energy transactions (Wang et al., 2021), or near real-time settlement of DR (Ellis and Hubbard, 2018), etc. Several authors are addressing decentralized management of the energy grid by proposing blockchain-enabled P2P energy trading solutions (Son et al., 2020; Monroe et al., 2020). The developed platforms allow consumers and producers to directly trade energy in a P2P network, while others are relying on a mediator to match the trading parties (Zhou et al., 2020). In the latter case, the matching is done by the DSO, which is a node in the network, while the energy price is determined using generation and consumption rates in the region (Andoni et al., 2019). DR management using blockchain was proposed in Pop et al. (2020b), Ellis and Hubbard (2018) and Saxena et al. (2021). Monitored energy data is tamper-proof stored in by the distributed ledger, while the actual management of expected energy profiles, program established incentives and penalties, or the grid balancing rules are defined using smart contracts. IoT technologies are used for smart home management and delivery of additional ambient assistive living services while a blockchain-based platform is proposed to integrate with the energy system and to transact energy using self-enforcing smart contracts (Alam et al., 2019; Lombardi et al., 2018). It has been shown (Morstyn et al., 2019; Pop et al., 2020a) that the blockchain could be considered as a solution to distribute the flexibility and control in a distributed fashion in every node of the network. New distributed ledger technology-enabled business models that could fit the decentralized cross sectors operations are proposed (Teufel et al., 2019). Blockchain has other applications, such as authentication of carbon emission rights (Kim and Huh, 2020), management of IoT systems (Lee et al., 2019; Milne et al., 2020), construction of virtual power plants (Raveduto et al., 2020; Seven et al., 2020), and local energy systems (Yu et al., 2018; Zepter et al., 2019). Novel applications are addressing the integration of EV with blockchain in an energy price-aware manner (Lasla et al., 2020) while considering their privacy (Danish et al., 2020). Blockchain may as well play an important role in improving the coordination between prosumers in community-based settings for improving locally the balance of energy supply and demand (Zepter et al., 2019; van Leeuwen et al., 2020). This way energy networks will be more stable and integrated with virtual community development targets (Raveduto et al., 2020; Schlund and German, 2019).

Concerning the development of energy flexibility markets various mechanisms have been proposed which can be classified into two main categories: centralized and decentralized (Zhou et al., 2020; Guerrero et al., 2017).

Centralized markets are organized using a typical server-side architecture and N to 1 trading models, where the DSO or the TSO submit bids and receive flexibility offers various trading parties in intraday or day-ahead timeframe. They are based on a quotation model to assure flexibility trading and usually, only the system operators can buy flexibility (Olivella-Rosell et al., 2018; Faia et al., 2019). Such markets may be used by third parties such as aggregators to gather either the demand side flexibility or the supply side flexibility and provide it to the system operator (Jin et al., 2020). In Olivella-Rosell et al. (2018) local flexibility market is designed where the aggregator as controlling agent manages the flexible loads of individual assets to provide aggregate flexibility to DSO and BRPs for congestion management, day-ahead portfolio optimization, or controlled islanding. The trades matching process uses a multi-period minimization cost objective function allocating the least expensive flexibility offers in the auction processes. An energy sharing coordinator to manage the assets flexibility via a market model is proposed in Long et al. (2018). It uses a constrained non-linear programming optimization algorithm to minimize the energy costs and rule-based control for synchronizing real-time measurements with the control setpoints. Near-optimal energy cost optimization algorithms have been proposed for coordinating the energy trading between small producers in centralized markets while at the same time solving the fair cost distribution problem by enforcing Pareto optimality (Alam et al., 2019). Other approaches propose the usage of game theory such as the Stackelberg game for adding a distributed nature to the centralized markets pricing mechanism to assure sellers price and buyers seller selection competition (Paudel et al., 2019). In Tushar et al. (2020) game theory is used to define an energy trading scheme for flexible markets to reduce the total electricity demand of the customers, especially around peak hours. A framework to integrate prosumers into the existing centralized flexibility markets is described in Zepter et al. (2019) and used on a stochastic programming approach for taking decisions under uncertainty of renewables and prices. A local electricity market for flexibility negotiation to assist the DSO in congestion management is proposed in Faia et al. (2019). The authors propose an asymmetric action model coordinated by an aggregator.

Most state-of-the-art literature approaches about decentralized energy markets are focused on peer-to-peer energy trading and only a few approaches are addressing the flexibility as a traded asset (Ellis and Hubbard, 2018; Morstyn et al., 2019). Decentralized energy markets should operate closer to real-time, have no central authority, and are organized based on a market model where DSO/TSO become also trading parties together with the flexibility providers. In Morstyn et al. (2019) such a market is proposed allowing a DSO to obtain flexibility from competing entities also facilitating bilateral energy transactions to reach Pareto efficiency. Blockchain technology seems promising for developing such flexible markets and in the last years, it gained growing interest for researchers aiming to construct efficient, secure, and automated P2P trading models. Blockchain-based decentralized P2P energy trading models are analyzed and classified in Ali et al. (2020) into (i) infrastructure-based trading where prosumers have a direct connection and can directly trade energy, (ii) ad-hoc trading, where micro-grids are integrated with energy producers/consumers through blockchain and (iii) large scale energy storage based trading when energy storage facilities add to the prosumers and the smart grid in the list of market actors. Open issues for decentralized trading identified in the research are related to the integration of energy sources that do not use smart meters, the creation of coalitions of prosumers, and optimization of demand response schemes through ML techniques. The authors of Wang et al. (2021) propose a decentralized energy market that uses blockchain smart contracts and transparent on-chain market clearing. They define a blockchain-based electricity transaction scheme for prosumers where the market participants can construct or adhere to sub-chains to enhance the trading efficiency. The approach is validated and tested on the Ethereum private blockchain. A decentralized P2P energy trading platform is presented in Esmat et al. (2021). A market layer is designed for short-term auction using as a clearing mechanism an Ant-Colony Optimization technique. The blockchain layer is used for real-time settlements through smart contracts while assuring the privacy and security of the participants. Electron startup proposed a trading platform for demand-side flexibility offering for grid balancing (Ellis and Hubbard, 2018). It uses blockchain to create incentives for all market participants and to assure bilateral trading. In Hamouda et al. (2021) a framework for energy flexibility trading based on blockchain is described. The end-user marginal price is the core element of the market model and blockchain is used to manage equitably the rates for customers. A permissioned blockchain-based energy trading approach is proposed in Saxena et al. (2021). It is implemented on the Hyperledger Fabric platform, in which a decentralized ledger is used to store the energy bids, and smart contracts are used for executing double auction mechanisms. Since prosumer privacy is fundamental, in Son et al. (2020) the authors propose a P2P energy trading system that uses a private Ethereum blockchain and bids encryption for privacy preservation. Smart contracts are used for peer matching and for performing transactions in the nodes in a publicly verifiable manner through smart contracts. TRANSAX, a blockchain-based decentralized energy market that uses smart contracts implemented in the VeriSolid framework is proposed in Eisele et al. (2020). It also tackles aspects such as market safety and privacy. The proposed solution uses external solvers to reduce the computational load of smart contracts logic and a lightweight consensus algorithm to deal with the verification of trade processes. Other approaches propose combining agent-based modeling with blockchain for simulating and validating P2P electricity trading in decentralized flexibility markets (Monroe et al., 2020). The Power Ledger blockchain platform is used to gather consumption data from households and fed as input for an agenda-based energy trading system that can generate schedules for the prosumers to automatically offer flexibility in the grid considering different constraints such as renewable availability.

3. Decentralized flexibility market

The proposed blockchain-based energy flexibility market allows the participants to trade their flexibility in a P2P fashion. It facilitates the interaction of two types of market participants: flexibility buyers and flexibility sellers (see Fig. 1). The flexibility buyers are entities such as the aggregators, DSOs (Distribution System Operators), or even the TSOs (Transmission System Operators), while the flexibility sellers are energy prosumers that can adjust their energy profile to deliver flexibility. The aggregators can act either as flexibility buyers (i.e. buy and aggregate flexibility from individual prosumers) or flexibility sellers (i.e. sell aggregated flexibility on their enrolled to interested players such as the DSO) in a specific market session. The energy flexibility to trade is digitized using non-fungible flexibility tokens which allows for the quantification of prosumers-owned flexibility tokens in smart contracts.

The decentralized flexibility market operation is assured by using five types of smart contracts. The interaction flow among them is presented in Fig. 2. The market session contract creates a new session for the buyers and sellers to register and publish flexibility bids and offers (step 1). The buyers using their associated smart contracts publish bids specifying a flexibility request profile, amount of flexibility for the interval, and the price (step 2a). Upon successful validation of the registered flexibility bids (step 2b), the flexibility buyer contract will forward (step 2c) the bid to the corresponding market session, while the contract will continue to act as a custodian for the buyer's deposit until the end of the market session. The sellers will publish their flexibility offers which are bound by their flexibility potential using their smart contracts (step 3a). The sellers are required to generate flexibility tokens proportional to the flexibility offer, create an associated delivery insurance deposit (steps 3b, 3c), and only then the sell orders are published in the market session (step 3d).

The market session smart contract at the end of the session will trigger the matching service using the Oracle to return a list

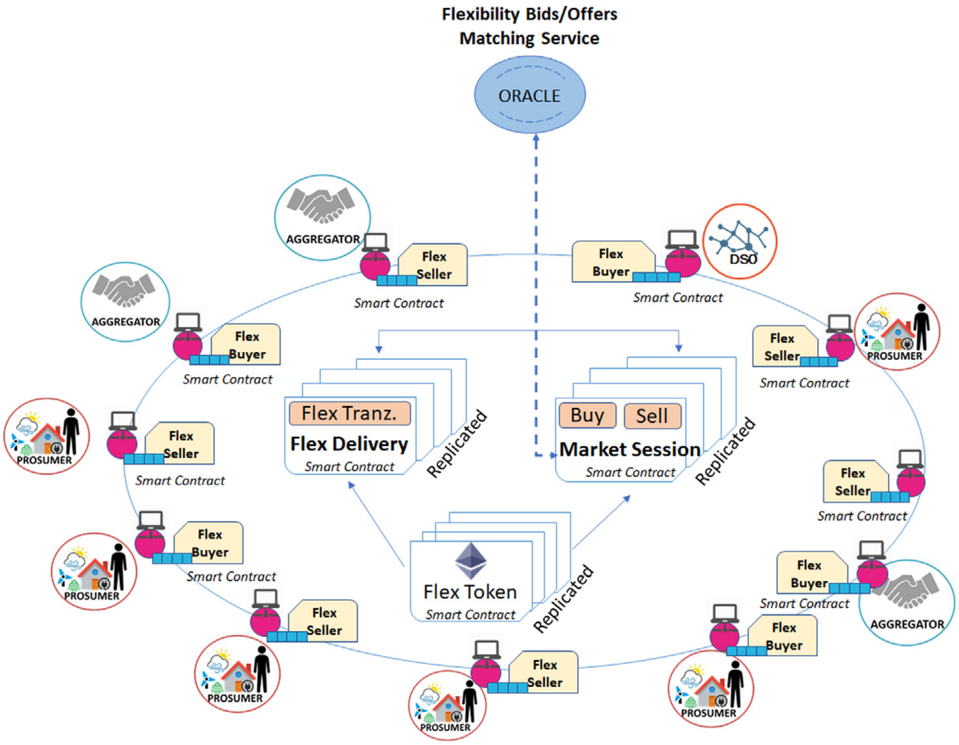


Fig. 1. High-level view on flexibility market participants and the defined smart contracts.

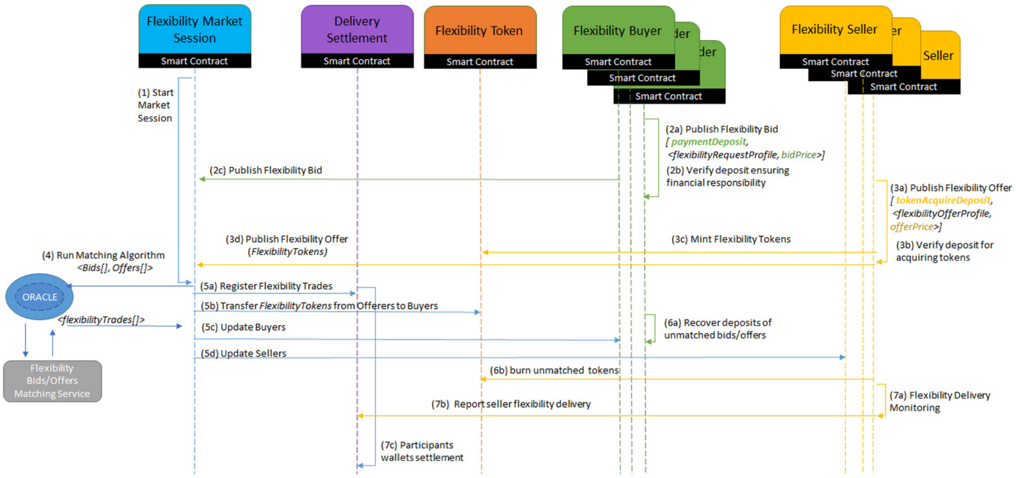


Fig. 2. Smart contracts interaction flow for decentralized flexibility market operation.

of flexibility trades (step 4). The flexibility trades are forwarded to the delivery settlement contract (step 5a). Following the flexibility transactions, the tokens are transferred from the flexibility sellers to the flexibility buyers (step 5b). The flexibility buyers and sellers are updated about the matched profiles that are then evaluated in near-real-time. The unmatched orders are returned to the smart contracts that had generated them (step 6a) to burn the tokens (step 6b) and return the deposits made.

During flexibility delivery time, the monitored energy is sent to flexibility seller smart contract, where the deviation is computed between the flexibility order matched and the flexibility delivered (i.e. computed as the increased/decreased energy monitored towards the baseline value). The flexibility delivered will be further reported to the delivery settlement contract. According to the registered flexibility, if a significant deviation (i.e. over 10%) is registered, the flexibility seller is held accountable and will be required to pay a penalty (7b), otherwise, the seller will be rewarded and the funds locked by the smart contract will be unlocked for future use.

In the next sub-sections, we present the design of the blockchain-based flexibility market detailing the definition of energy flexibility tokens, the smart contracts implementation for market operation, as well as the flexibility matching solution and its integration with the chain using Oracles.

3.1. Energy flexibility token

We define the energy flexibility of a prosumer as a measure of its energy profile adaptation in relation to its baseline (Vesa et al., 2020). The baseline energy expresses the normal electricity generated or consumed by a prosumer without participation to DR programs. There are several state-of-the-art methods for calculating the baseline energy profile most of them being based on averaging relevant past energy profiles. To determine the baseline energy profile of a prosumer for an interval $[t_s, t_e]$ we have selected and averaged similar intervals from X previous days, not including the highest and lowest profiles

$$E_{baseline}^{prosumer,[t_s,t_e]} = \frac{1}{X_{days}-2} \sum_{[t_s,t_e]\in MID(X_{days})}^{X_{days}-2} E_{monitored}^{prosumer,[t_s,t_e]}(t),\ t \in [t_s, t_e] \tag{1}$$

where X_{days} represent the number of days in the past considered. To estimate the amount of energy with which the prosumer can increase or decrease its energy profile during interval $[t_s, t_e]$ into the future, we define the flexibility as:

$$E_{Flex-upward}^{prosumer,[t_s,t_e]} = \int_{t_s}^{t_e} P_{forecasted}^{prosumer}(t)\,dt - \int_{t_s}^{t_e} P_{baseline}^{prosumer}(t)\,dt, \quad if\ P_{forecasted}^{prosumer}(t) > P_{baseline}^{prosumer}(t)\ \forall t \in [t_s, t_e] \tag{2}$$

$$E_{Flex-downward}^{prosumer,[t_s,t_e]} = \int_{t_s}^{t_e} P_{baseline}^{prosumer}(t)\,t - \int_{t_s}^{t_e} P_{forecasted}^{prosumer}(t)\,dt, \quad if\ P_{forecasted}^{prosumer}(t) < P_{baseline}^{prosumer}(t)\ \forall t \in [t_s, t_e] \tag{3}$$

where the upward energy flexibility is determined using the prosumer energy profiles bigger than the baseline, while the downward energy flexibility using the prosumer profiles that are under the baseline.

To digitize the prosumers' energy flexibility which can be eventually traded, we have adapted the ERC721 (ERC721, 2021) standard, which allows the creation of non-fungible tokens in the blockchain system (see Algorithm 1).

In the ERC721 metadata we have changed the original mapping of the *_tokenURIs* with the *_tokenDetails* mapping (see line 4) which has instead of a metadata Uniform Resource Identifier (URI), a data structure *FlexibilityMetadata*:

$$\begin{aligned} &struct\ FlexibilityMetadata\{enum\ FlexibilityType \\ &\quad type;\ uint\ startDTime; \\ &\quad uint\ endDTime;\ uint\ timestep;\ string\ measureUnit; \\ &\quad address\ prosumer\} \end{aligned} \tag{4}$$

The defined data structure holds flexibility offer specific information about the traded flexibility token, such as the flexibility type (i.e. upward or downward in relation with the baseline), delivery time interval and timestep inside the interval, the measurement unit, and prosumer address which are relevant to the flexibility market management processes. These details are verified by the flexibility delivery smart contract. It validates the sold flexibility token matches the request of the buyer and that the actual flexibility delivered by a seller is consistent with the characteristics of flexibility tokens.

The amount of flexibility tokens in a smart contract associated with a contract owner is tracked using the ERC721 standard (see lines 2–3) metadata allowing to distinguish tokens. A mapping is defined keeping the association between the contract address and amount of flexibility token. This allows us to distinguish the flexibility assets traded regarding the delivery time and amount of flexibility and allows flexibility delivery tracking process based on the energy meters data. Also, after registration on the market as a sell flexibility offer, the total amount of energy can be distributed to fit one or more flexibility bids. The defined flexibility token is also mintable thus the defined adaptations are improving this feature. In our case, a new flexibility token can be created considering the seller flexibility delivery estimation (see lines 10–15) while in ERC721 only one token may be generated during minting.

3.2. Market operation and smart contracts

The participant interaction with the decentralized flexibility market is managed using self-enforcing smart contracts conforming to interface contracts specific for flexibility buyers and sellers (see Table 2).

To be able to submit a flexibility offer on the proposed blockchain-based flexibility marketplace the flexibility seller smart contract will leverage on its estimated energy flexibility over an interval of delivery $[t_s..t_e]$, as shown in Table 3. The flexibility seller contract state variables (see Table 3) reflect the amount with which they are willing to alter their energy profile either by increasing or decreasing it in relation to the baseline. To submit the offer, the flexibility seller will associate a price to its energy flexibility for each time instance of the delivery interval.

The flexibility seller can register his flexibility offer by signing a transaction that contains the flexibility profile, prices, and a deposit that acts as assurance during the real-time operation, in case that the flexibility seller misbehaves. The pseudocode of the proposed functionality is depicted in Algorithm 2. Once the transaction reaches the chain, the execution of the contract will be triggered. Firstly, the authenticity and authorization of the signing prosumer are verified (line 9), through the custom-defined modifier *onlyOwner*. Then the references to the market and token registry contracts are obtained (lines 11, 12) to create the corresponding offer for each flexibility amount and price association (lines 16, 17) and publish (line 18) it into the market session. The total flexibility is computed (line 19) to verify that the seller has indeed deposited the required amount necessary as assurance for the real-time operation (lines 22–24).

The flexibility buyer bids are either for increasing or reducing the energy profiles. In the first case, the matched flexibility sellers will have to increase their energy profiles by shifting flexible energy in the interval of the delivery, while in the second case they will have to decrease the energy profiles by shifting energy flexibility away from the flexibility request time interval. The state variables modeled for the flexibility buyer contract can be seen in Table 4.

Through their associated smart contract, each flexibility buyer or seller can register its estimated energy flexibility and corresponding bids and offers in the flexibility energy marketplace (see Table 5).

At the end of the market session, an energy flexibility transaction is generated considering the matching of submitted bids and offers and the clearing price calculated. Table 5 shows the smart contracts state variables used for tracking the flexibility delivery. Using the prosumer's metered energy values, the amount of flexibility delivered is assessed against promised values registered by the blockchain transactions. In case of the delivered amount does not meet the traded value, the prosumer will be penalized based on the deviation registered.

The market operation functionality is implemented using two types of smart contracts: Market Session Contract and Delivery Settlement Contract.

The Market Session Contract creates the market session for a predefined interval and stores the submitted flexibility bids and offers (see Table 6).

The Market Session Contract enforces rules for the bids and offers submission, the owner being able to update, suspend or re-activate them. Thus, whenever a market participant submits a new bid or offer (see Algorithm 3), the contract will validate that the targeted session is open (line 28), verify the identity of the publisher (line 29) and the correctness of the traded token amount (line 30) and will store the order in the order book (line 31).

When the market session closes the smart contract generates an end of the market session event triggering the matching of bids

Algorithm 1: Smart Contract for Flexibility Token Definition based on ERC721 Mintable

```
State:
  MAP (tokeinId => address owner) private _tokenOwner;
  MAP (address owner=> MAP (tokenId => balance) private _ ownedTokensBalances;
  MAP (tokeinId => FlexibilityMetadata) internal _tokensDetails;

 Function mintWithTokenMetadata
    Input: address to, uint256 tokenId, string tokenMetadata, uint quantity
    Output: -
    Modifiers: onlyMinter
    Begin:
      Requires tokenId ! exists
      _tokenOwner[tokenId] = to
      _ownedTokensBalances[to][tokenId] = quantity
      _setTokenMetadata( tokenId, tokenMetadata)
    End
```

Table 2
Self-enforcing smart contracts methods for managing flexibility buyer and seller interaction.

Smart contract interface		Description
IFlexibilitySeller	*publishSellFlexOffer*	The flexibility seller can make an offer by registering the profile of flexibility and the corresponding price for the delivery interval. For each hour of the interval, the smart contract will register a sell flexibility offer in the flexibility market. **State update**: Flexibility Offers
	registerDeposit	Upon registering a sell offer, it will also make a tokens deposit representing an assurance for the case it fails to deliver the promised flexibility. **State update**: Contract Balance
	setMatchedFlexibility	Once the market session closes and the flexibility bids and offers are matched and the matched values are updated in the flexibility seller contract to be tracked and validated during real-time. **State update**: Flexibility Trades
	trackFlexDelivery	During near-real-time hourly aggregated monitored values are registered by the smart metering device as payload to the delivery transactions. The smart contract will verify the delivered flexibility against the sell offer that was previously committed. The financial settlement will be automatically computed, and the flexibility seller will be rewarded if the delivery is correct. **State update**: Actual Delivered Flexibility, Contract Balance
IFlexibilityBuyer	*publishBuyFlexBid*	The flexibility buyer can place a flexibility bid by registering the profile of flexibility and the corresponding prices requested for the delivery interval. For each hour of the interval, the smart contract will register a bid order in the flexibility market. **State update**: Flexibility Bids

Table 3
Flexibility seller smart contract state variables.

State variable			Description
Prosumer baseline			Calculated energy baseline profile of the flexibility seller over the delivery interval
Sell flexibility offer	Energy Flexibility	Amount	Total energy flexibility which may be delivered during an interval
		Profile	Energy flexibility profile representing the estimated increase or decrease over the regular energy baseline.
	Flexibility type		Defined in relation to the prosumer baseline: upward if there is an increase in comparison to the baseline energy profile or downward if there is a decrease in relation to the baseline energy profile.
	Sell price		The price for the estimated flexibility (e.g. Euro/kWh for a timestep of 1 h)

Table 4
Flexibility buyer smart contract state variables.

State variable			Description
Buy flexibility bid	Energy flexibility	Amount	Total energy flexibility request for the delivery interval
		Profile	Requested energy flexibility profile over the delivery interval
	Price		The price to be paid for estimated flexibility

and offers process using a second-tier service. The flexibility bids and offers are fetched and the algorithms described in Section 3.3 are executed. Energy flexibility transactions are created and replicated in the network. They will be inserted in a new block and will be confirmed and validated before the block is added to the blockchain. The flexibility sellers and buyers' contracts will be injected with the obtained matched traded values, which will act as promised values and evaluated in real-time against the

Algorithm 2: Smart Contract of Flexibility Seller

```
State:
  address _owner, _marketAddress, _tokenRegistryAddress
  int[] _baseline,_downwardFlexibility, _upwardFlexibility
  int[] _promisedValues, _actualValues

Function PublishSellFlexOffer
   Input: tx.origin, msg.value, $E_{Flex}$, $Flex_{Price}$, startDTime, endDTime, timestep, flexibilityType
   Output: -
   Modifiers: onlyOwner, payable
   Begin:
      MarketContract m ← MarketContract(_marketAddress)
      FlexibilityTokenRegistry tokenReg ← FlexibilityTokenRegistry (tokenRegistryAddress)
      totalFlexibility ← 0
      For each $f_{value}$ , $f_{price}$in $E_{Flex}$, $Flex_{Price}$ do
        FlexibilityMetadata metadata ← FlexibilityMetadata (flexibilityType, KWh, startDTime, endDTime tx.origin);
        tokenId ← tokenReg.mintWithTokenMetadata (tx.origin,  metadata, $f_{value}$)
        Order order ← Order (OrderSide.SELL, now (), tokenId, metadata, $f_{value}$, $f_{price}$)
        m.publishOrder(order)
        totalFlexibility ← totalFlexibility + $f_{value}$
        startTime ← startTime +1 hour
      End For
      marketDepositPerUnit  ← m.getDepositPerUnit()
      depositRequired ← totalFlexibility * marketDepositPerUnit
      Deposit(depositRequired)
   End
```

Algorithm 3: Smart Contract for Market Session

```
State:
  address _tokenRegistryAddress
  struct MarketSessionConfiguration sessionConfiguration
  MAP (orderId => Order) _activeBids;
  MAP (orderId => Order) _activeSells;

Function publishSellOrder
   Input: order, tx.origin
   Output: -
   Modifiers: onlyFlexParticipantContract
   Begin:
     FlexibilityTokenRegistry tokenReg ← FlexibilityTokenRegistry (tokenRegistryAddress)
     Requires sessionConfiguration.startTime < now() && sessionConfiguration,.endTime> now()
     Requires order.prosumer == tx.origin
     Requires tokenReg.balanceOf(tx.origin, order.tokenId) >= order.quantity
      _activeSells[order.id] ← order
   End
```

monitored values. Furthermore, the contracts will also act as an escrow for the flexibility trades, locking the funds according to the clearing prices until the end of the delivery phase. During the delivery, the funds locked will be managed by the contract, such that if the delivery is correct, the funds will remain in the contract and will be withdrawn by the prosumer by the end of the delivery phase. Otherwise, the funds will be used to pay for the imbalances created by forwarding the necessary funds to the delivery settlement contract.

The Delivery Settlement smart contracts evaluate and track the delivery of flexibility according to the flexibility transactions (see Table 7 for contract state variables).

The market's energy and financial settlement is achieved by using the consensus validation implemented in the blockchain that keeps track of all transactional changes and validates the state updates. Each transaction is validated by the prosumers smart contracts for the integrity of the flexibility tokens, energy values, etc. The results of each prosumer are used to establish the validity of the transactions and the block before adding it to the main chain. When energy flexibility values are monitored and registered in the participant contract, the Delivery Settlement contract will be invoked and the monitored quantity will be evaluated considering the registered energy transactions (Algorithm 4, line 10). In case of violation of the initial transactions promised values, the prosumer will be penalized according to the deviation amount and penalization prices (Algorithm 4, line 12). As a result, the decision on the actual energy flexibility delivered by each peer, tokens distribution, or penalties will be agreed upon by all peers.

Algorithm 4: Smart Contract for Delivery Settlement

```
1. State:
2.   MAP (prosumer => TradedFlexibility[] ) _settledTrades;
3.   _penalizationPrice[] ;
4.
5. Function settleDelivery
6.   Input: monitoredValue, timeslot,  tx.origin, msg.value
7.   Output: -
8.   Modifiers: onlyFlexParticipantContract
9.   Begin:
10.    diff ← _ settledTrades[tx.origin][timeslot] – monitoredValue
11.    If (diff> threshold) then
12.       Require msg.value >= diff * _penalizationPrice[timeslot]
13. End
```

Table 5
Flexibility Seller/Buyer smart contract state variables for flexibility trading.

State variable		Description
Flexibility trades	Energy flexibility amount	Energy flexibility transactions specifying the amounts of flexibility to be delivered and the price.
	Clearing price	
Actual flexibility profile		Monitored energy values

Table 6
Market session smart contract state variables.

State variable	Notation	Description
Market session configuration		The information about the rules for bids and offers submission and time interval.
Flexibility bids (*bids*[B])		An array that holds the active bids for buying flexibility registered in the current market session.
Flexibility offers (*offers*[S])		The array which holds the active sell offers registered in the current market session.

Table 7
Delivery settlement contract state variables.

State variable	Description
Flexibility transactions	Specifies the amount of flexibility to be delivered by a seller to a buyer and the price.
Penalization	The penalization applied by the contract in case of unsuccessful delivery of flexibility amount.

3.3. Oracles based flexibility matching

In the designed decentralized flexibility market during an open market session bids and offers from S flexibility sellers and B flexibility buyers are registered. At the end of the session they need to be matched and then flexibility transactions are created. Blockchain smart contracts have limited resources for on-chain logic computation. At the same time, the matching on flexibility bids and offers and clearing price calculation is a heavy computational problem that needs to be addressed using heuristics not feasible to be run on the chain. Thus, we have implemented an off-chain solution that also assures secure integration with the public blockchain implementation of the energy flexibility market (see Fig. 3). The solution is based on the concept of Oracles for supporting the call of the complex logic or other Application Programming Interfaces (APIs) from outside the blockchain (i.e. Flexibility Bids-Offers Matching Service) and to provide in response the results necessary in the execution of the smart contract. In the proposed Oracle-based solution the end market session event is intercepted and forwarded as a request to an external service implementing the flexibility matching process.

The Oracle and the service should be maintained by an entity that is independent of any of the energy domain stakeholders which have an interest in the flexibility market: flexibility buyers, sellers, DSO, aggregators, etc. A fee should be paid by the flexibility market session participants for each call made. No market participant should have any influence on the operation and outcome of the flexibility bids and offers matching provided. This third-party entity will have a similar role to the role of the market operator in the case of an energy market. In this way, there will be a higher degree of trust that the Oracle and the associated service are operated fairly and impartially, and the flexibility will be used most efficiently. On the other hand, guarantying independence and auditing the fairness of the Oracle is an open research problem. A couple of solutions are being proposed such as reputation systems in which the performance of the Oracle is recorded and evaluated or the use of multiple oracles into a decentralized network (Egberts, 2017; Ellis et al., 2017).

The Flexibility Bids-Offers Matching Service has an associated pair of public–private keys, where the public key is stored on-chain. The Oracle module continuously listens for end of the market session events to intercept them and trigger the Flexibility Bids-Offers Matching Service execution by sending the bids and offers submitted into the current market session (steps 2, 3). Once the list of matched energy flexibility transactions is obtained the service will sign them using the private key and return them to the Oracle (step 5). The signature is necessary since the Oracle or any other entity that intercepts the request can be a malicious entity aiming to tamper the matching results. Through this signature, the Flexibility Bids-Offers Matching Service must prove itself as the entity authorized to make this computation. The results together with the signature are injected on-chain using a call-back function and the Market Session contract will validate that the data has not been tampered with (steps 6, 7).

The Flexibility Bids-Offers Matching Service will find the subset of flexibility offers that, grouped, can match a subset of the registered flexibility bids for each time instance of the delivery interval, where the price of the last matched offer is less than the price of the last matched bid. It works as a pipeline of two algorithms, as shown in the example from Fig. 4 for a market session of one hour.

The first algorithm (i.e. flexibility matching) selects the subset of the bids and offers that can be matched only considering the total amount of flexibility and the associated price. Based on the matching the clearing price and the settled flexibility amount for the market session to be traded (see Fig. 4). Not looking at the specificity of the flexibility profiles of the bids and offers may result in a high number of very small transactions. Thus, the second algorithm (i.e. transactions minimization) aims to minimize the number of energy flexibility transactions between matched participants considering the actual flexibility profiles of bids and offers during the delivery interval. The minimization is done under the constraint the total amount of flexibility and price remain unchanged thus the profits of trading flexibility is preserved while the total cost with the number of transactions is reduced. The main reason for minimizing the number of transactions is the high costs and relatively low throughput associated with transactions processing on the public blockchain. Moreover, whenever the matching algorithm is executed, the number of trades generated between the flexibility sellers and buyers will also influence the cost of executing the smart contract functions. When registering flexibility transactions on-chain, which are triggering functions from the smart contracts, the buyers and the sellers must commit coins for rewarding the miner for verifying the transactions and registration them securely to the chain. In the case of peer-to-peer energy trading, the number of potential transactions can be high if only the total amount of flexibility and price is considered per session.

The *flexibility matching algorithm* (see Algorithm 5) has as inputs the set of flexibility bids and flexibility offers and will

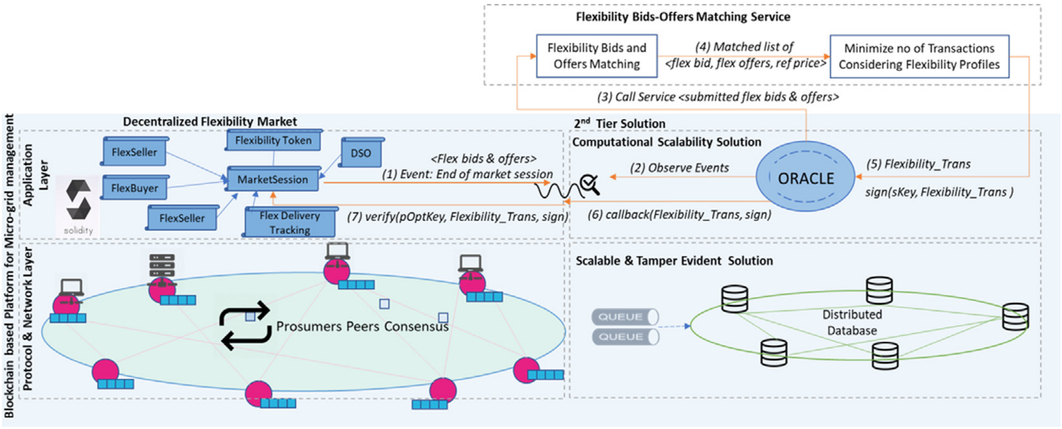
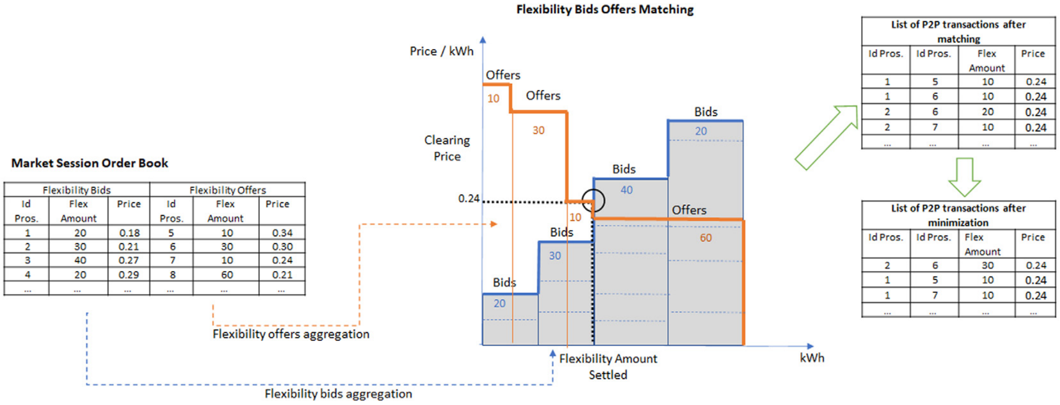


Fig. 3. Blockchain integration of Flexibility Bids-Offers Matching Service using an Oracle.



Market Session Order Book

Flexibility Bids			Flexibility Offers		
Id Pros.	Flex Amount	Price	Id Pros.	Flex Amount	Price
1	20	0.18	5	10	0.34
2	30	0.21	6	30	0.30
3	40	0.27	7	10	0.24
4	20	0.29	8	60	0.21
...	...	...	...	...	...

List of P2P transactions after matching

Id Pros.	Id Pros.	Flex Amount	Price
1	5	10	0.24
1	6	10	0.24
2	6	20	0.24
2	7	10	0.24
...	...	...	...

List of P2P transactions after minimization

Id Pros.	Id Pros.	Flex Amount	Price
2	6	30	0.24
1	5	10	0.24
1	7	10	0.24
...	...	...	...

Fig. 4. Flexibility matching and transactions minimization example for 1 h.

determine a subset of M bids and N offers that fulfill the following rules:

- Rule 1: The total amount of flexibility sold should equal to the total amount of flexibility bought no fractions of bids and offers being accepted:

$$\sum_{k=1}^{N} offers[k] = \sum_{k=1}^{M} bids[k] \tag{5}$$

- Rule 2: The flexibility offers and bids price constraints are met. In other words, it ensures that the price of the flexibility bid is greater than the highest price of the matched flexibility offers:

$$Bid_{price} > Max(offers_{matched_{price}}) \tag{6}$$

The problem of finding the two subsets of flexibility bids and offers that meet the defined rules is an NP-hard problem. Thus, we propose a solution that uses a greedy heuristic derived from the best-fit approximation algorithm used for multidimensional bin-packing problems (Karp, 1972). The proposed algorithm is based on the Next Fit Decreasing Height algorithm (Xia and Tan, 2010) and is used to determine an approximate solution for multidimensional packing problems.

The matching algorithm starts by computing each flexibility bid and offer total price according to the flexibility profiles (lines 4–5 and 7–8). The information is then used for sorting descending all the flexibility bids submitted in the market session giving priority to the flexibility bids of the flexibility buyers that have associated the largest sum of money (see line 6). The flexibility offers are sorted ascending giving priority to the flexibility offers with the smallest price associated (see line 9). The algorithm iterates through the flexibility bids (see lines 13–16), and for each bid, it determines the subset of matching flexibility offers (line 13), grouped as $offers_{matched}$, that is *not greater than* the *bid* to be matched. The *greater than* operator is constructed according to the following formula and is true only if all the elements of the first array are greater than the elements of the second array given as an argument. The algorithm increments an index that iterates the set of flexibility offers and insert in a map structure the bid the matched offers and the calculated clearing price (lines 18–19).

Next, the transactions minimization algorithm (see Algorithm 6) determines the minimum number of P2P flexibility transactions that can be generated among the determined flexibility bids and offers matchings considering their energy flexibility profiles over the delivery interval $T = [t_s..t_e]$. The problem to be solved aims to determine the minimum number of mappings between the flexibility profiles of the matched sets of M bids and N offers. We construct a matrix $P \in R^{M*N*T}$ (M - number of bids, T - length of the delivery interval, N - number of matched offers), where each element $P(i, j, t)$ defines the percentage of the bid_i energy flexibility profile that is matched at timestep $t \in T$ by the flexibility offer $offer_j$ energy profile:

$$\sum_{j=1}^{N} P(i, j, t) = 1, \forall i \in \{1..M\} \ and \ t \in T \tag{7}$$

Thus, the matrix decomposes the energy profile of the flexibility bid with index i at every timestep t of the delivery interval

Algorithm 5: Greedy heuristic for flexibility bids offers matching

```
Inputs: $offers[S]$, $bids[B]$ the sets of flexibility offers and bids submitted in a market session
Outputs: $mapMatched < bids, offers, Price\_clearing >$ subset of flexibility bids, matched flexibility offers
        and clearing price
Begin
  Foreach $bid$ in $bids[B]$ do
      Compute flexibility bid total price $bid_{price} = \sum_{t=1}^{T} flex_{request}[t] * flex_{Price}[t]$
  Sort ($bids[B], DESC, bid_{price}$)
  Foreach $offer$ in $offer[S]$ do
      Compute flexibility offer total price as $offer_{price} = \sum_{t=1}^{T} flex_{offer}[t] * price[t]$
  Sort ($offers[S], ASC, offer_{price}$)
  $index_{offer} = 0$; $bids_{matched} = \emptyset$
  Foreach $bid$ in $bids[B]$ do
      $offers_{matched} = \emptyset$
      While ! $greaterThan(offers_{matched}, bid)$ do
          $index_{offer} ++$;
          addTo ($offers[index_{offer}], offers_{matched}$)
      End while
      $addTo\ (bid, bids_{matched})$
      $Price_{clearing} = MIN\ (Bid_{price}, MAX(offers_{matched_{price}}))$
      $mapMatched.put(bid, offers_{matched}, Price_{clearing})$
  End Foreach
  Return $mapTrades$
End
```

T to each of the matched offers at that timestep:

$$bid_i(t) = \sum_{j=1}^{N} P(i,j,t) * offers_{\text{matched}}[i](t), \forall i \in \{1..M\}, t \in T \quad (8)$$

The goal is to minimize the number of elements of the matrix that are not zero, thus the objective can be defined as:

$$MIN(\sum_{t=t_s}^{t_e}\sum_{i=1}^{N}\sum_{j=1}^{M} f(P(i,j,t))) \quad (9)$$

where the function f is defined as a step function:

$$f: [0,1] \to \{0,1\}, f(x) = \begin{cases} 0, & if\ x = 0 \\ 1, & if\ x > 0 \end{cases} \quad (10)$$

The above-defined optimization problem is classified as Non-linear Programming because the unknown variable in the optimization function is the matrix P containing real values in the interval [0, 1], and the objective function is not linear (i.e. the step function f). The optimization problem can be decomposed in T NP-complete problems, one for each timestep within interval T, similar to the partition problem in computer science which is aiming to partition a set of positive integers S into two subsets S_1 and S_2 such that the sum of the numbers in S_1 equals the sum of the numbers in S_2.

$$MIN(\sum_{t=t_s}^{t_e}\sum_{i=1}^{N}\sum_{j=1}^{M} f(P(i,j,t))) = \sum_{t=t_s}^{t_e} MIN(\sum_{i=1}^{N}\sum_{j=1}^{M} f(P(i,j,t))) \quad (11)$$

We aim to compute the minimum number of transactions for each time interval $t \in T$, corresponding to $MIN(\sum_{i=1}^{N}\sum_{j=1}^{M} f(P(i,j,t)))$ using a *Graph-based approach.* A bipartite graph $G = \{V_1, V_2, E\}$ is constructed, where the vertices are formed by the M bids and N offers to have their energy flexibility profiles matched to each timestep of the delivery interval.

$$V_1 = \{bid[j](t) | j \in \{1..M\}, t \in T\} \quad (12)$$

$$V_2 = \{offer_{matched}[i](t) | i \in \{1..N\}, t \in T\} \quad (13)$$

An edge $e_{it} \in E$ represents a flexibility transaction from $offer_{matched}[i](t)$ to $bid[j](t)$. We define the function $f: \{V_1 \cup V_2\} \to R$ as an energy flow function between the vertices, with the following constraint:

$$f_{ij} = f(e_{ij}) \leq offer_{matched}[i](t) \quad (14)$$

We use concepts from the Minimum-cost flow problem to compute an approximate solution to the problem. We add a source connected to all the nodes from V_1 and a sink to all the nodes from V_2. We connect all the nodes from V_1 to all the nodes from V_2, by creating a complete bipartite graph (see Fig. 5).

We augment the graph by defining the energy flexibility capacity of the edges. All edges connecting the source and the vertices from V_1 have the capacities $C_{source}^{offer_i}$, while all the edges connecting the nodes from V_2 with the sink have capacities $C_{bid_j}^{sink}$. They are defined as:

$$C_{source}^{offer_i} = offer_{matched}[i](t), C_{bid}^{sink} = bid[j](t) \quad (15)$$

All the edges connecting nodes from V_1 to V_2 have an energy flexibility capacity of:

$$MIN(offer_{matched}[i](t), bid[j](t)) \quad (16)$$

and a positive cost a_{ij}, considered as weights:

$$a_{ij} = |bid[j](t) - offer_{matched}[i](t)| \quad (17)$$

The cost of sending an energy flexibility flow along the edge e_{ij} is computed as:

$$cost_{ij} = f_{ij} * a_{ij} \quad (18)$$

In this case the bids and offers flexibility profiles mapping problem is represented in the graph as an amount of energy to be sent from source to sink to minimize the cost of the energy flow over the edges:

$$\sum_{i=1}^{N} offer_{matched}[i](t) = bid[j](t), \forall t \in T \quad (19)$$

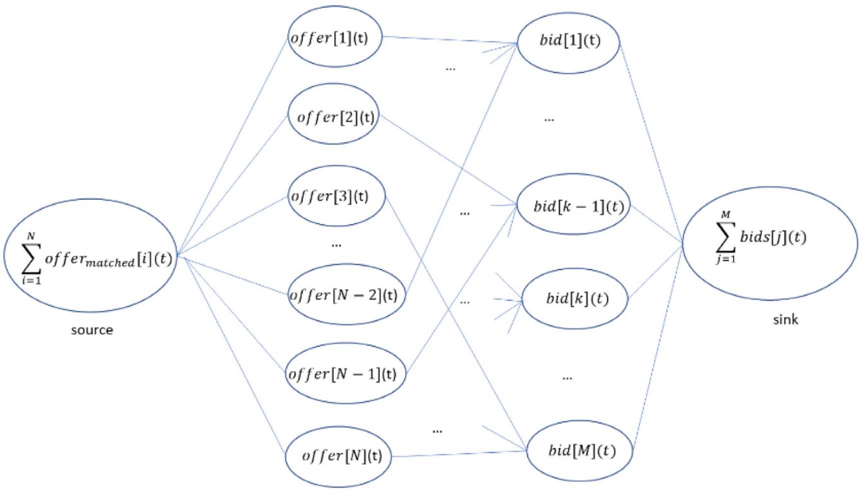


Fig. 5. Augmented graph for modeling the energy flow among flexibility bid and matched offers.

$$MIN(\sum_{i=1}^{N}\sum_{j=1}^{M} cost_{ij}) \tag{20}$$

The optimization problem needs to be solved under the following constraints:

- Capacity constraints: $f_{ij} \leq c_{ij}$
- Flow conservation: $\sum_{w\in V_1\cup V_2} f_{uw} = 0, \forall u \in V_1 \cup V_2$
- Required flow: $\sum_{w\in V_1\cup V_2} f_{source-w} = s = \sum_{w\in V_1\cup V_2} f_{w-sink}$

The graph-based solution starts by applying the Bellman–Ford algorithm that has a complexity of $O(|N+M|*|E|)$ to increase the edge weights to positive values, so that the Dijkstra algorithm can be applied (see Algorithm 6). According to the graph construction, the number of edges is $E = N + N*M + 1$ and the number of vertices is $V = N+M+2$. Dijkstra is applied in the main loop of the algorithm due to its lower complexity of $O(|E|+|V|\log(|V|))$ when using a Fibonacci heap. It computes, the shortest path from the source to the sink (see lines 6–7), with the weights represented by the augmented costs a_{it}, while the flow is computed as the minimum of the capacities (see lines 8–9). The graph-based algorithm ends when no paths are found from the source to the sink having an overall complexity of $O(N*M^2*log\ N)$.

The mappings between the flexibility profiles of the bid and the matched offers are computed by the number of energy flows between the sources and the sinks the solution being contained in the energy flow values of the edges connecting nodes of the bipartite graph. To generate the list of flexibility transactions the graph data structure is iterated and in case flow $f_{uw} > 0$ a trade is generated to mark a transaction between the offer with identifier u and the bid with the identifier w. Then, a list of such trades is generated and published to the blockchain by Oracle as a single transaction.

4. Experiments and results

The pilot site used for demonstration and validation of the decentralized flexibility market is in Terni, a city in the center of Italy, and it was set up with the help of ASM Terni S.p.A. multi-utility company, that owns and operates the local power distribution network, covering a surface of 211 km^2 and delivering about 400 GWh to 65 500 customers annually. First, we have validated our solution on a small-scale urban micro-grid with few prosumers considering live energy monitoring data and the self-consumption of renewable energy generated. Second, we have evaluated the flexibility market on a simulated environment considering many market participants and historical monitored energy data targeting the local balancing of the demand side. Finally, the proposed flexibility market scalability is assessed.

4.1. Small scale pilot validation

Concerning decentralized flexibility trading demonstration, we have considered an urban Low Voltage (LV) microgrid equipped with IoT devices enabling the implementation of flexibility-driven demand response programs (see Fig. 6).

The main prosumers connected to the energy network are:

- Two PV arrays (180 kWp and 60 kWp), able to produce yearly 200 MWh and 75 MWh respectively.
- A Storage system equipped with 72 kWh 2nd life Li-ion battery energy storage.
- A building (6800 m^2) with offices usually having an energy demand between 50 kWh and 90 kWh depending on seasonal factors. The building is equipped with a Building Management Energy System enacting the actuation of flexibility shifting actions in relation to the control of the heating, ventilation, and air conditioning (HVAC).
- Three smart charging stations (see Fig. 7): two 22 kW charging stations (SpotLink EVO) and one 50 kW charging station (Efacec QC45). The pilot also includes six electric vehicles: two Renault ZOE 22 kWh, two Renault ZOE 41 kWh, and two Nissan Leaf 24 kWh.

To get real-time measurements and support flexibility trading the prosumers are equipped with advanced smart meters which exploit the unbundled smart meter concept for systematization: a three-phase smart meter leveraging DLMS protocol and a PQ Analyzer which exploits HTTP protocol for data transfer. The smart energy metering functionalities are addressing metrological and hard-driven real-time functions. It has been deployed on a low-power open-source single-board computer, BeagleBone Black, and it is connected to smart meters for enabling real-time data gathering. Two models are used, namely, a three-phase smart meter leveraging DLMS protocol and a PQ Analyzer which exploits HTTP protocol for data transfer.

To manage the access to the different modules and IoT smart energy metering devices a common infrastructure and data model was developed (see Fig. 8). The communication with the smart meters and the electric vehicle supply equipment is built using the MQTT standard (Schmitt et al., 2018). The devices transmit new data every five seconds. Two different types of readings can

Algorithm 6: Minimizing the number of transactions based on flexibility profiles

```
Input: The augmented bipartite graph constructed for flexibility bid and matched offers
Output: Energy flows on the edges of the graph
Begin
  Apply the Bellman-Ford algorithm to increase the costs of the edges and make them positive
    While ($\exists$ $path\ from\ source\ to\ sink$)
      Path (source, sink) = Dijkstra (with edge $e_{ij}$ and weights as a $a_{ij}$)
      flow = $Min_{capacity}$ (path (sink, source))
      For $e_{ij} \in$ $path(sink, source)$ do
        $e_{ij}.capacity = e_{ij}.capacity - flow$
    End while
End
```

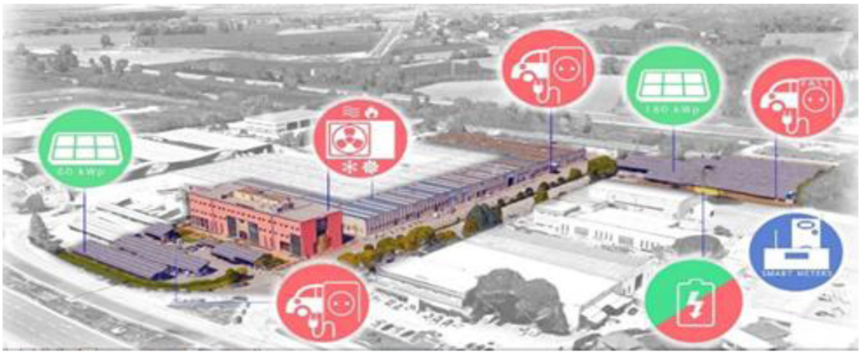


Fig. 6. The pilot site infrastructure used for decentralized flexibility market validation.

Fig. 7. SpotLink EVO charging stations and electrical vehicles used in tests.

be sent depending on the smart meter type: power values as instantaneous values or energy values as an incremental counter which increases after each reading. In this case, the instantaneous value was computed as the difference between two consecutive readings.

The charging stations provide instantaneous power readings following the same convention and format used by the smart meters. The monitored energy data is forward to device-specific MQTT message queues to be aggregated and digitally fingerprinted using our proposed solution for high scalability described in Pop et al. (2019) and then are registered on-chain in the corresponding prosumer smart contract for flexibility delivery tracking.

The control of the prosumers energy demand levels for delivering the expected amount of flexibility is done either manually in case of the EVs which need to be plugged in or automated in case of controllable assets (e.g. building management system or the energy storage). The potential flexibility control actions and associated control variables are determined based on the prosumer's available assets and a flexibility audit. The optimal combination of control variables for altering the prosumer energy demand and shifting energy flexibility in time is determined using algorithms like the ones proposed by us in Cioara et al. (2018) and Antal et al. (2020). An automated system can be used to link the planned flexibility actions with the prosumer's smart contract which can act as an actuator for the controllable devices. By incorporating smart controllable devices, these can be programmed to listen for blockchain events that signal the activation of a particular flexibility action whenever the corresponding market order is matched, thus the equivalent energy flexibility is required to be delivered.

The prosumers' energy consumption profiles have been monitored for a longer period and the data have been used to calculate the baseline demand and predicted energy flexibility upward or downward concerning the baseline (see Fig. 9). For flexibility prediction, we have used the energy prediction model described by us in Vesa et al. (2020) where an ensemble of neural network models to minimize uncertainty related to the flexibility market participation. The information on available flexibility is then injected into the smart contract associated with the individual

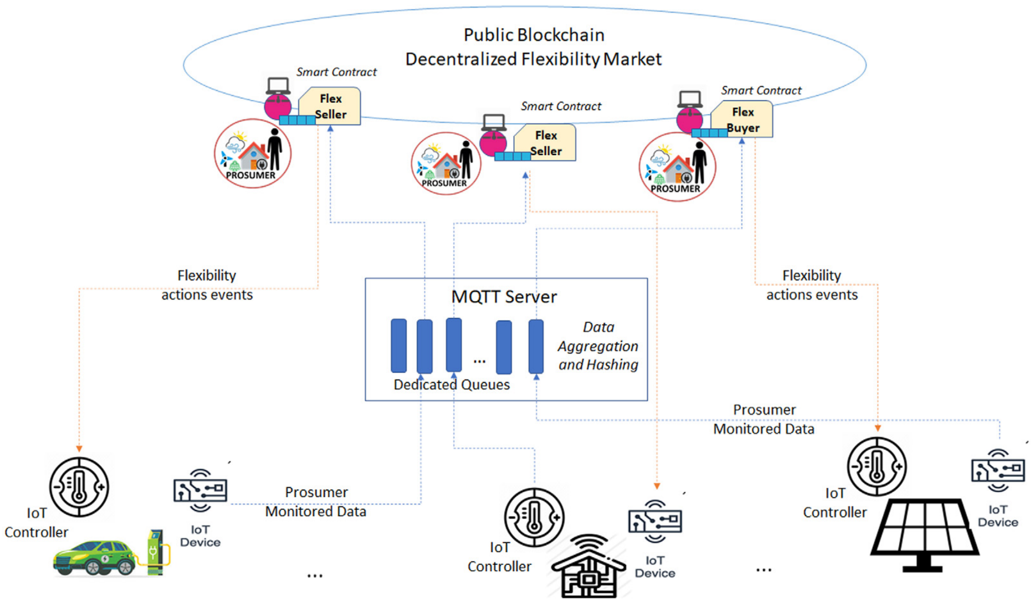


Fig. 8. Energy data-gathering infrastructure and blockchain integration.

prosumer. The difference between the calculated baseline demand and forecasted flexibility determines the amount of energy flexibility published by the prosumer as an offer into the open session of the decentralized flexibility market.

The prosumers with renewable energy profiles will act as a flexibility buyer on the flexibility market. In this case, the difference between the forecasted renewable energy generation and the baseline energy generation profiles is used to determine the amount of flexibility to be bought from the market by publishing bids (see Fig. 10).

The prices associated by the prosumers to bids and offers are determined using the settlement price of the previous market session as a reference.

Once the market session closes, and the matching algorithm is run, the flexibility transactions are generated (see Fig. 11).

The flexibility actions associated with the matched flexibility offer will become active and different assets/devices owned by the prosumer will be scheduled, to ensure the correct delivery of promised flexibility. The flexibility delivery smart contract will track the delivery of flexibility according to the monitored energy data of each prosumer involved in the established energy flexibility transaction (see Table 8 for a blockchain flexibility transaction example).

As it can be seen in Fig. 12 during the flexibility delivery the prosumers can increase their energy demand based on the traded flexibility agreement being able to consume as all the renewable generated avoiding a potential local unbalance to be exported in the main grid.

4.2. Simulation results for many market participants

To evaluate the decentralized flexibility market operation considering many participants we have leveraged on a dataset of historical energy monitored data created by ASM Terni on various of its prosumer sites. The dataset corresponds to the energy consumption and production measured every 15 min from 2015 to 2018 of more than 1000 prosumers connected to the distribution grid. The data have been collected utilizing smart meters and monitoring software infrastructure like the one described in the previous section. The energy data is temporarily stored in an electric energy meter concentrator (one concentrator for about 400 m), extracted, aggregated, and transmitted via a GPRS network.

From this data set, we have selected 300 consumers based on their energy demand values (less than 30 kWh) and geographic location (located in the same microgrid). Fig. 13 shows the distribution of the considered prosumers in clusters based on their baseline energy demand. In this case, Principal Component Analysis was used for dimensionality reduction. Fig. 14 shows their energy flexibility distribution in flexibility bands upward and downward in comparison to the baseline.

Considering the baseline and flexibility information of each prosumer self-enforcing smart contracts have been used to submit bid and offers into the flexibility market session. We have randomly split the set of prosumers into 2 subsets one corresponding to flexibility sellers and one to flexibility buyers. For the flexibility buyers, we have considered that their upward energy flexibility is the actual demand and we have used the difference with the baseline (i.e. increase of energy demand) to submit buy flexibility offers to compensate for the increase. The flexibility sellers are leveraging on their energy baseline and potential decrease on energy demand to submit sell flexibility offers to balance the energy demand in the micro-grid. Algorithm 5 was used for matching the flexibility bids to offers submitted in the market session by looking only at the total amount of flexibility and the results being presented in Fig. 15.

In this case, 80 flexibility sellers have been mapped to 80 flexibility buyers considering a flexibility delivery interval of 24 h. The number of transactions generated is determined using the relation below:

$$N_{transaction} = \sum_{i=1}^{bid_{matched}} map_{matched}.get\left(bid\left(i\right)\right).length \qquad (21)$$

Algorithm 6 is then used to minimize the number of energy flexibility transactions by also looking at the profiles of the flexibility bids and offers, reducing the number of transactions. This is important considering the cost associated with transactions on the blockchain. Each smart contract operation has a cost in terms of consumed gas multiplied by the gas price. Having transactions on-chain enabling the execution of smart contracts functions enough coins are needed to reward the miner.

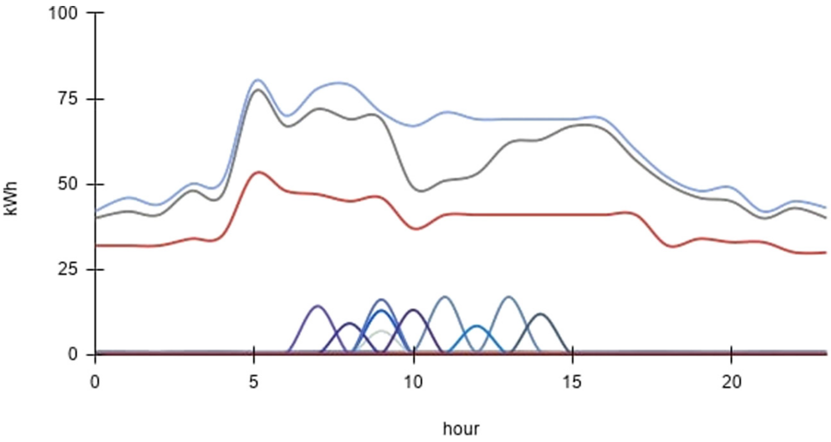


Fig. 9. Prosumers demand baseline (with gray), upward energy flexibility (with blue), and downward energy flexibility (with red); EV charging station values are market with the dotted rectangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

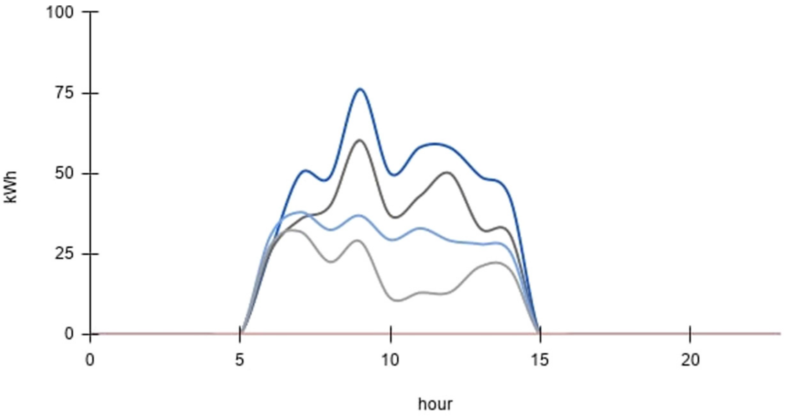


Fig. 10. Prosumers (PV panels) generation baseline (with gray) and upward energy flexibility (with blue).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

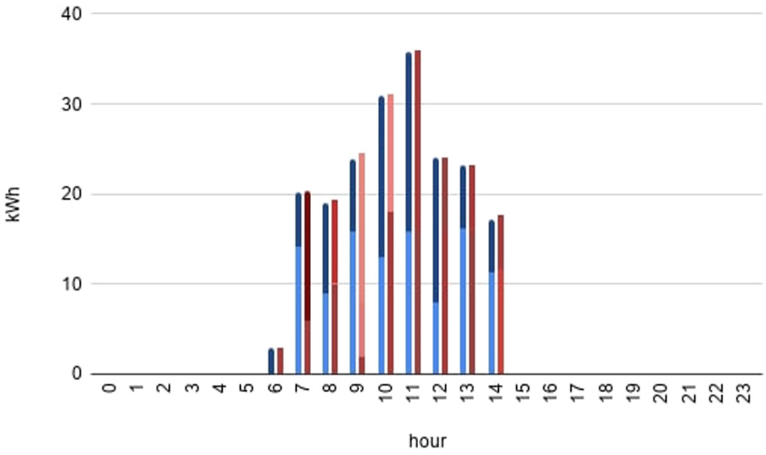


Fig. 11. Flexibility bids and offers matching and transactions generation on an hourly basis. The columns on the left represent the total offers while the column on the right the total bids. Different colors intensities are used to represent offers and bids of different flexibility buyers or sellers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

By using the decentralized flexibility market, we managed to assure a balance of the energy demand in the microgrid the entire flexibility delivery interval even in the case of high increase of the energy consumption of many prosumers only relying upon P2P trading of flexibility with other prosumers (see Fig. 16). In this case, the absolute energy exchange between the microgrid and the utility grid is minimum during the entire flexibility delivery interval.

Finally, we have conducted experiments to determine the scalability of the proposed blockchain-based energy flexibility market with the number of flexibility bids and offers submitted into a market session. The first evaluation was of the time needed to execute both the flexibility matching algorithm and transactions

Table 8
Blockchain flexibility transaction.

Tx Hash	0 × 5e1df553ac35ed791d152842af6d6d19d7a02c0a87e00a92d53a0d310c933e41	
Bid details	ID	0 × 5b253c13ffa98bce40db53de347d685c06fd443d64150e0b160e7a7f631c1d36
	Producer	0xf8291CEaE8347194aDAcb19752Ba6233E3e9aF10
	Price	600 Gwei
	Metadata	Energy Type - Renewable
Offer details	ID	0 × 16903e6a4090c67bfca6512260282a12e69840af293c2e5d0c3a436c073a1792
	Consumer	0xc9f711F29512123360046fdE9f982CA085A093F9
	Price	640 Gwei
	Metadata	Energy type - Renewable
Price	586	

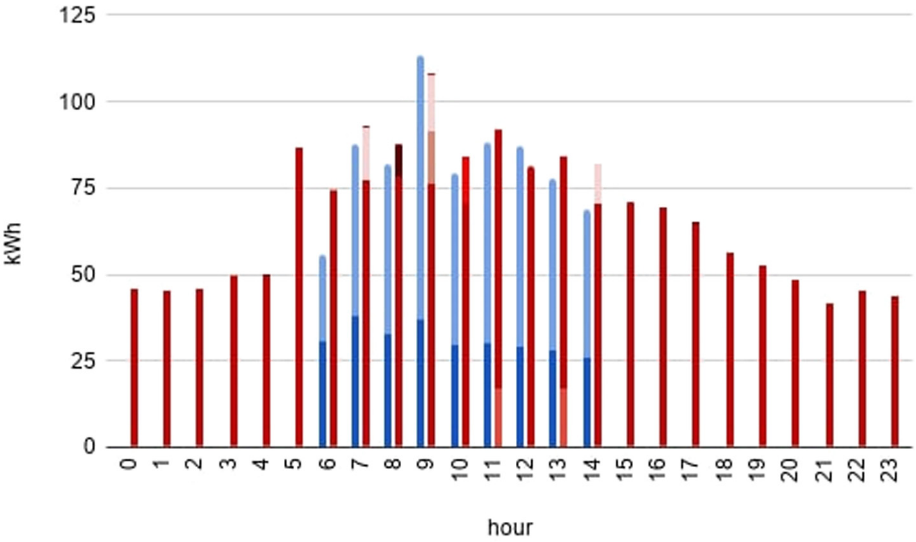


Fig. 12. Tracking the delivery of energy flexibility based on the transactions generated. The energy consumption is marked with red while the energy production is marked with blue. The lighter colors show the traded flexibility. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

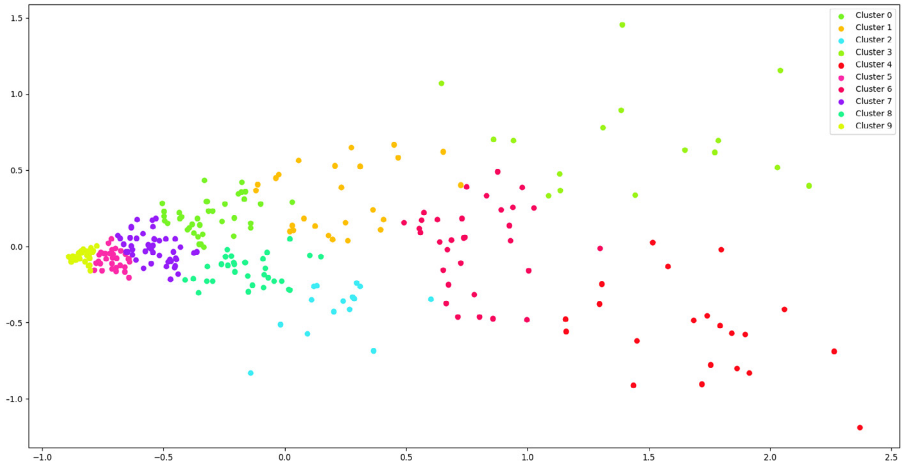


Fig. 13. Prosumers clustering based on their baseline energy demand.

minimization one (Algorithms 5 & 6) considering an incremental number of flexibility bids and offers. Fig. 17 shows that the prosed algorithms execution time scale linearly with the number of submitted flexibility bids and offers. It returns the list of matched bids and offers in a reasonable time even for a high number of flexibility trades (90 ms for 300 flexibility members).

The second evaluation is aiming to assess the improvement brought by the graph-based solution for flexibility transactions minimization (Algorithm 6) compared to the greedy heuristic for flexibility matching (Algorithm 5). Because the complexity of the flexibility matching algorithms depends on both the number of offers N and bids M, we consider two experiments (see Fig. 18): (a) one of N or M increases much faster than the other; (b) N and M are approximately the same. For each experiment, test cases were run multiple times and the number of energy transactions obtained was averaged.

The number of energy flexibility transactions generated by the greedy heuristic (Algorithm 3) is larger than the number of transactions generated by our graph-based solution. But in the

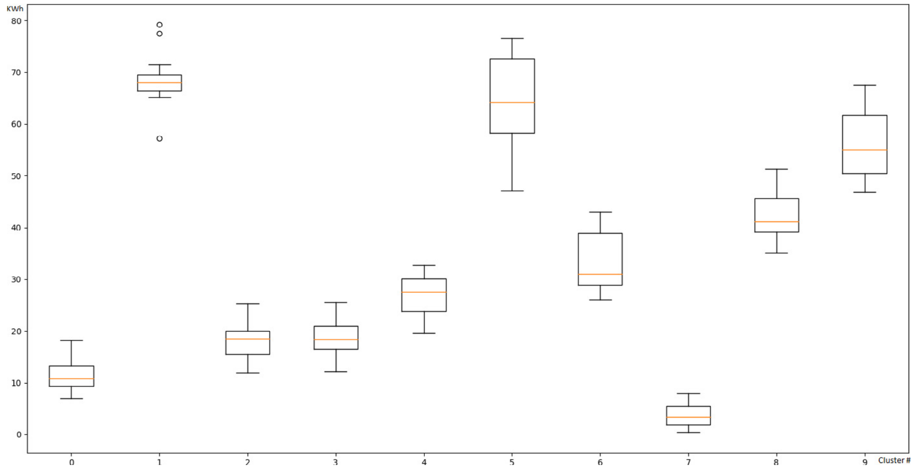


Fig. 14. Prosumers flexibility distribution upward and downward the baseline.

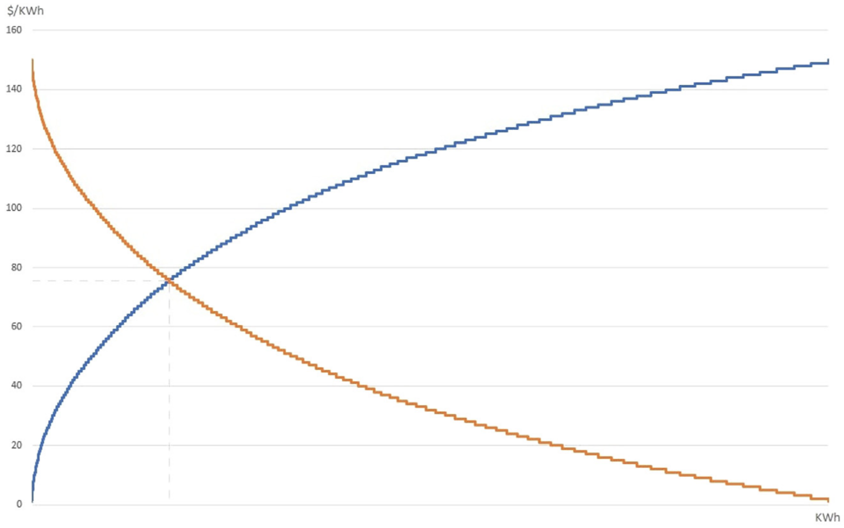


Fig. 15. Flexibility bids and offers matching at the end of the market session: submitted flexibility offers (with blue), submitted flexibility bids (with red), matched ones (marked with dotted line).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

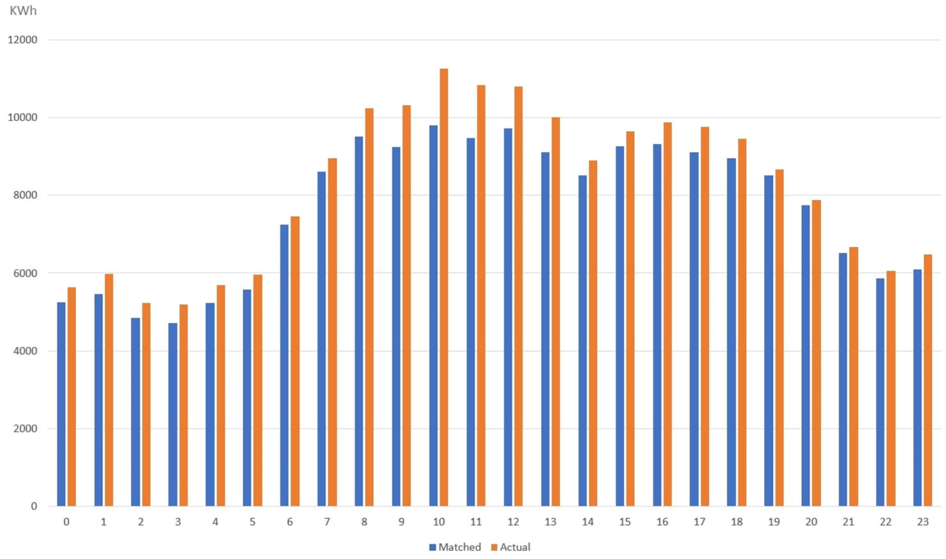


Fig. 16. Energy demand (with blue) adaptation using flexibility delivery to match the generated renewable in the micro-grid. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

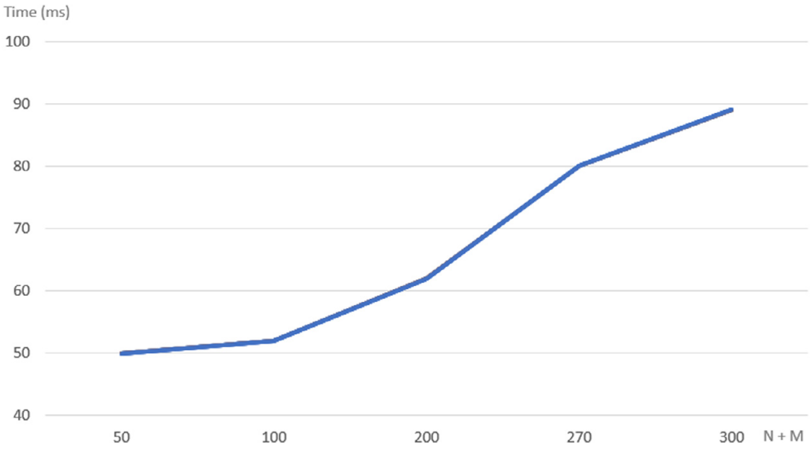


Fig. 17. The response time of flexibility matching algorithms with an increasing number of bids (M) and offers (N).

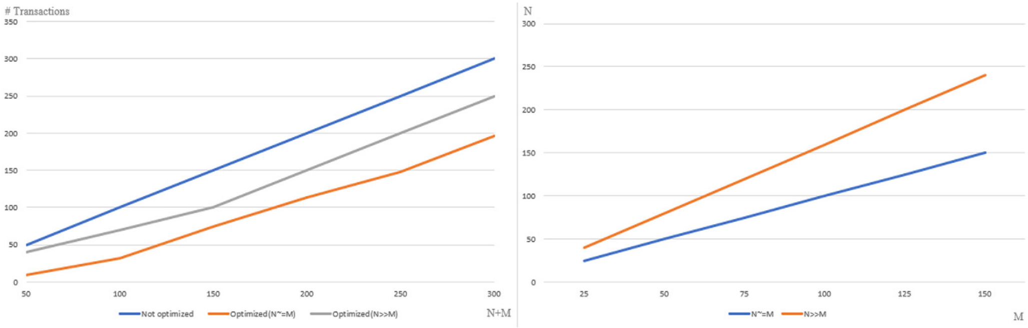


Fig. 18. Number of energy flexibility transactions reduction. The left chart shows the results in case the number of offers is much higher than the offers (N≫M) while the right chart for the case of an equal number of bids and offers (N∼ = M).

case of a much higher number of offers than bids, the improvement brought by the graph-based algorithm is only around 15%, while in the case of a similar number of flexibility bids and offers the graph-based algorithm being able to reduce the number of flexibility transactions with more than 30%. This is also due to the similar value ranges between bids and offers in the dataset.

5. Conclusion and discussion

In this paper, we have described the implementation of a decentralized energy flexibility local market using blockchain technology which allows small-scale prosumers to trade their flexibility in a peer-to-peer fashion. We have defined energy flexibility tokens for representing the asset to be traded, and smart contracts allowing prosumer to register flexibility bids and offers as orders of the token in a market session. Session-level smart contracts replicated in all network peer nodes are used to manage the market session flexibility orders book, while for decentralized flexibility matching a greedy heuristic and bipartite graph approach has been defined for energy flexibility transactions minimization among peers while still meeting the flexibility amounts, energy profiles, and delivery interval requirements. Finally, smart contracts are integrated with smart energy meters allowing the tracking of energy profiles against the energy flexibility transactions and decentralized settlement of participant wallets.

The evaluation of the decentralized energy flexibility in both operational micro-grid and simulation environments shows promising results. They validate some of the benefits of the proposed decentralized energy flexibility market in the local microgrid such as:

- Up to 100% ratio of self-consumption of renewable energy in the local micro-grid in which it was produced facilitating the demand-side management via peer to peer trading of flexibility among prosumers.
- Minimizing up to Net Zero Energy the exchange between the microgrid and utility grid even in case of high variance of the energy demand of prosumers thus maximizing the degree of autarchy of the micro-grid.
- Better monitoring of energy flows, energy generation, and demand at micro-grid level achieving local energy balance by mobilizing higher amounts of energy flexibility.
- Reduction of electricity costs if enough liquidity and flexibility are mobilized in the market.

The decentralized flexibility market provides opportunities for citizens to potentially save energy and gain money by trading their flexibility. Smart grid blockchain-driven decentralization and flexibility digitalization (smart metering, flexibility tokens, etc.) are enabling consumers and local energy communities with options to produce and self-consume their electricity, to manage their loads using peer to peer trading of flexibility, and to reduce the energy exchange with the utility grid up to islanding operational mode. This enables new roles for the prosumers in the energy system such as producing and trading electricity, but also as sellers or buyers of energy flexibility. Prosumers could shift their flexibility or reduce demand during peak periods in response to price signals or other incentives and exploiting flexibility in such a local market. The coupling of renewable energy production with decentralized management of flexibility and exploitation of synergies with other utility infrastructures (e.g. water, waste) is possible only with local community engagement in local flexibility markets and/or in participating in shared investments. The local peer-to-peer energy flexibility trading may improve community social cohesion, improve local air quality, and turn on smart districts/villages as examples of future green energy systems.

However, these opportunities are not commercially exploited, and the potential of energy flexibility is far to be been unlocked. Several barriers to the full exploitation of the flexibility potential from small prosumers, which include:

- Technological barriers such as the lack of solutions to enable flexibility assets retrofitting and to support the shift from traditional DR to decentralized market-based models.
- Economic and regulatory barriers are given by the actual business models which are unable to capture and convey an appropriate value small scale prosumer flexibility so the potential reward from exploiting their flexibility remaining unclear or unattractive. At the same time, series of changes on the current energy policy, laws, and energy trading systems are still required before it becomes a reality.
- Organizational barriers concerning insufficient prosumers or community engagement. To involve at the largest possible extent the communities of local energy consumers as a social environment where individual consumers may find motivation beyond the economic aspects to be enrolled in decentralized flexibility markets. Also, with the proliferation of IoT devices, end users are mostly reluctant to give control of their actions for exploiting available, yet latent, flexibility exploitation in order not to compromise their privacy (and in this aspect consumers are supported by GDPRs).

As future work, we plan to investigate the applicability of the proposed decentralized flexibility market and peer-to-peer trading for supporting the implementation of local self-sustainable energy communities. In this sense, smart contracts enablers will be developed for capturing intra-community interaction dynamics, prosumers social features, and local energy network constraints (e.g. voltage limitations of the nodes, available community shared assets, etc.). Several market mechanisms should be defined for allowing community flexibility aggregation on top of the market using cooperative models including other market drivers besides the prosumers profit such as local sustainability, decarbonization, or handling incentives for investing in new green energy assets at the community level. Finally, the decentralized flexibility market can be extended to support the management of cross-commodity value stacking flexibility by integrating other energy flavors or utilities besides electricity such as heat, gas, water, and non-energy services such as mobility, comfort, smart home, personal safety, etc.

CRediT authorship contribution statement

Claudia Antal: Formal analysis, Writing – original draft, Project administration. **Tudor Cioara:** Conceptualization, Methodology, Writing – original draft, Supervision. **Marcel Antal:** Formal analysis, Data curation, Project administration. **Vlad Mihailescu:** Investigation, Software, Writing – original draft. **Dan Mitrea:** Investigation, Software, Writing – original draft. **Ionut Anghel:** Writing – review & editing, Visualization, Writing – original draft. **Ioan Salomie:** Writing – review & editing, Formal analysis, Supervision. **Giuseppe Raveduto:** Visualization, Formal analysis, Writing – review & editing. **Massimo Bertoncini:** Writing – review & editing, Funding acquisition. **Vincenzo Croce:** Visualization, Formal analysis, Writing – review & editing. **Tommaso Bragatto:** Validation, Resources, Writing – review & editing. **Federico Carere:** Validation, Resources, Writing – review & editing. **Francesco Bellesini:** Validation, Resources, Writing – review & editing.

Declaration of competing interest

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

Acknowledgments

This research was funded by the European Union's Horizon 2020 research and innovation programme grant number 957816 (BRIGHT) and grant number 774478 (eDREAM).

References

Alam, M.R., St-Hilaire, M., Kunz, T., 2019. Peer-to-peer energy trading among smart homes. Appl. Energy 238, 1434–1443.

Ali, F., Aloqaily, M., Alfandi, O., Ozkasap, O., 2020. Cyberphysical blockchain-enabled peer-to-peer energy trading. Computer 53 (09), 56–65.

Andoni, Merlinda, Robu, Valentin, Flynn, David, Abram, Simone, Geach, Dale, Jenkins, David, McCallum, Peter, Peacock, Andrew, 2019. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renew. Sustain. Energy Rev. 100, 143–174.

Antal, Marcel, Pop, Claudia, Cioara, Tudor, Anghel, Ionut, Salomie, Ioan, Pop, Florin, 2020. A system of systems approach for data centers optimization and integration into smart energy grids. Future Gener. Comput. Syst. (ISSN: 0167-739X) 105, 948–963. http://dx.doi.org/10.1016/j.future.2017.05.021.

Anwar, M.B., Qazi, H.W., Burke, D.J., O'Malley, M.J., 2019. Harnessing the flexibility of demand-side resources. IEEE Trans. Smart Grid 10 (4), 4151–4163. http://dx.doi.org/10.1109/TSG.2018.2850439.

Batista, D., Kim, H., Lemieux, V.L., Stancic, H., Unnithan, C., 2021. Blockchains and provenance: How a technical system for tracing origins, ownership and authenticity can transform social trust. In: Lemieux, V.L., Feng, C. (Eds.), Building Decentralized Trust. Springer, Cham.

Casino, F., Politou, E., Alepis, E., Patsakis, C., 2020. Immutability and decentralized storage: An analysis of emerging threats. IEEE Access 8, 4737–4744. http://dx.doi.org/10.1109/ACCESS.2019.2962017.

Chowdhury, M.J.M., et al., 2019. A comparative analysis of distributed ledger technology platforms. IEEE Access 7, 167930-167943. http://dx.doi.org/10.1109/ACCESS.2019.2953729.

Cioara, Tudor, Anghel, Ionut, Bertoncini, Massimo, Salomie, Ioan, Arnone, Diego, Mammina, Marzia, Velivassaki, Terpsichori-Helen, Antal, Marcel, 2018. Optimized flexibility management enacting data centres participation in smart demand response programs. Future Gener. Comput. Syst. (ISSN: 0167-739X) 78 (Part 1), 330–342. http://dx.doi.org/10.1016/j.future.2016.05.010.

Cioara, Tudor, (Antal), Claudia Pop, Zanc, Razvan, Anghel, Ionut, Antal, Marcel, Salomie, Ioan, 2020. Smart grid management using blockchain: Future scenarios and challenges. In: 19th RoEduNet Conference: Networking in Education and Research.

Danish, S.M., Zhang, K., Jacobsen, H.-A., 2020. A blockchain-based privacy-preserving intelligent charging station selection for electric vehicles. In: 2020 IEEE International Conference on Blockchain and Cryptocurrency (ICBC). Toronto, ON, Canada, pp. 1–3.

Egberts, Alexander, 2017. The oracle problem - An analysis of how blockchain oracles undermine the advantages of decentralized ledger systems. Available at SSRN: https://ssrn.com/abstract=3382343 or http://dx.doi.org/10.2139/ssrn.3382343.

Eisele, S., et al., 2020. Blockchains for transactive energy systems: Opportunities, challenges, and approaches. Computer 53 (09), 66–76.

Ellis, Paul, Hubbard, Joanna, 2018. Chapter 8 - Flexibility trading platform—Using blockchain to create the most efficient demand-side response trading market. In: Marke, Alastair (Ed.), Transforming Climate Finance and Green Investment with Blockchains. Academic Press, ISBN: 9780128144473, pp. 99–109.

Ellis, S., Jules, A., Nazarov, S., 2017. ChainLink - A decentralized oracle network. Retrieved from smartcontract.com: https://link.smartcontract.com/whitepaper.

ERC721 non-fungible token standard, 2021. https://ethereum.org/en/developers/docs/standards/tokens/erc-721/.

Esmat, Ayman, de Vos, Martijn, Ghiassi-Farrokhfal, Yashar, Palensky, Peter, Epema, Dick, 2021. A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. Appl. Energy (ISSN: 0306-2619) 282 (Part A), 116123.

Faia, R., Pinto, T., Vale, Z., Corchado, J.M., 2019. A local electricity market model for DSO flexibility trading. In: 2019 16th International Conference on the European Energy Market (EEM). Ljubljana, Slovenia, pp. 1–5. http://dx.doi.org/10.1109/EEM.2019.8916563.

Guerrero, J., Chapman, A., Verbic, G., 2017. A study of energy trading in a low-voltage network: Centralised and distributed approaches. In: 2017 Australasian Universities Power Engineering Conference (AUPEC). Melbourne, VIC, pp. 1–6. http://dx.doi.org/10.1109/AUPEC.2017.8282502.

Hamouda, M.R., Nassar, M.E., Salama, M.M.A., 2021. A novel energy trading framework using adapted blockchain technology. IEEE Trans. Smart Grid 12 (3), 2165–2175. http://dx.doi.org/10.1109/TSG.2020.3045662.

Han, Dong, Zhang, Chengzhenghao, Ping, Jian, Yan, Zheng, 2020. Smart contract architecture for decentralized energy trading and management based on blockchains. Energy 199, 117417.

Jansen, Sabine, Mohammadi, Saleh, Bokel, Regina, 2021. Developing a locally balanced energy system for an existing neighbourhood, using the 'Smart Urban Isle' approach. Sustainable Cities Soc. 64, 102496.

Jin, Xiaolong, Wu, Qiuwei, Jia, Hongjie, 2020. Local flexibility markets: Literature review on concepts, models and clearing methods. Appl. Energy 261.

Jindal, Anish, Kumar, Neeraj, Singh, Mukesh, 2020. Internet of energy-based demand response management scheme for smart homes and PHEVs using SVM. Future Gener. Comput. Syst. (ISSN: 0167-739X) 108, 1058–1068.

Junker, Rune Grønborg, Azar, Armin Ghasem, Lopes, Rui Amaral, Lindberg, Karen Byskov, Reynders, Glenn, Relan, Rishi, Madsen, Henrik, 2018. Characterizing the energy flexibility of buildings and districts. Appl. Energy (ISSN: 0306-2619) 225, 175–182. http://dx.doi.org/10.1016/j.apenergy.2018.05.037.

Karp, Richard M., 1972. Reducibility among combinatorial problems (PDF). In: Miller, R.E., Thatcher, J.W., Bohlinger, J.D. (Eds.), Complexity of Computer Computations. Plenum, New York, ISBN: 978-1-4684-2003-6, pp. 85–103. http://dx.doi.org/10.1007/978-1-4684-2001-2_9.

Kim, S.-K., Huh, J.-H., 2020. Blockchain of carbon trading for UN sustainable development goals. Sustainability 12, 4021.

Kumari, A., Gupta, R., Tanwar, S., Tyagi, S., Kumar, N., 2020. When blockchain meets smart grid: Secure energy trading in demand response management. IEEE Netw. 34 (5), 299–305. http://dx.doi.org/10.1109/MNET.001.1900660.

Lago, Jesus, Poplavskaya, Ksenia, Suryanarayana, Gowri, De Schutter, Bart, 2021. A market framework for grid balancing support through imbalances trading. Renew. Sustain. Energy Rev. 137, 110467.

Lasla, N., Al-Ammari, M., Abdallah, M., Younis, M., 2020. Blockchain based trading platform for electric vehicle charging in smart cities. IEEE Open J. Intell. Transp. Syst. 1, 80–92. http://dx.doi.org/10.1109/OJITS.2020.3004870.

Lee, Jay, Azamfar, Moslem, Singh, Jaskaran, 2019. A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems. Manuf. Lett. (ISSN: 2213-8463) 20, 34–39.

Lombardi, F., Aniello, L., De Angelis, S., Margheri, A., Sassone, V., 2018. A blockchain-based infrastructure for reliable and cost-effective IoT-aided smart grids. In: Living in the Internet of Things: Cybersecurity of the IoT - 2018. London, pp. 1–6. http://dx.doi.org/10.1049/cp.2018.0042.

Long, C., Wu, J., Zhou, Y., Jenkins, N., 2018. Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid. Appl. Energy 226, 261–276.

Milne, A.J.M., Beckmann, A., Kumar, P., 2020. Cyber-physical trust systems driven by blockchain. IEEE Access 8, 66423–66437. http://dx.doi.org/10.1109/ACCESS.2020.2984675.

Monroe, J.G., Hansen, P., Sorell, M., Berglund, E.Z., 2020. Agent-based model of a blockchain enabled peer-to-peer energy market: Application for a neighborhood trial in Perth, Australia. Smart Cities 3, 1072–1099.

Morstyn, T., Teytelboym, A., McCulloch, M.D., 2019. Designing decentralized markets for distribution system flexibility. IEEE Trans. Power Syst. 34, 1–12.

Olivella-Rosell, P., Lloret-Gallego, P., Munné-Collado, Í., Villafafila-Robles, R., Sumper, A., Ottessen, S.Ø., Rajasekharan, J., Bremdal, B.A., 2018. Local flexibility market design for aggregators providing multiple flexibility services at distribution network level. Energies 11, 822.

Park, M., Lee, J., Won, D.-J., 2020. Demand response strategy of energy prosumer based on robust optimization through aggregator. IEEE Access 8, 202969-202979. http://dx.doi.org/10.1109/ACCESS.2020.3034870.

Paudel, A., Chaudhari, K., Long, C., Gooi, H.B., 2019. Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model. IEEE Trans. Ind. Electron. 66 (8), 6087–6097. http://dx.doi.org/10.1109/TIE.2018.2874578.

Pop, C., Antal, M., Cioara, T., Anghel, Ionut, 2020a. In: Gulshan, Shrivastava, Dac-Nhuong, Le, Kavita, Sharma (Eds.), Trading Energy as a Digital Asset: A Blockchain Based Energy Market, Cryptocurrencies and Blockchain Technologies and Applications: Decentralization and Smart Contracts. Wiley-Scrivener, ISBN: 978-1-119-62116-4.

Pop, C.D., Antal, M., Cioara, T., Anghel, I., Salomie, I., 2020b. Blockchain and demand response: Zero-knowledge proofs for energy transactions privacy. Sensors 20, 5678.

Pop, C., Antal, M., Cioara, T., Anghel, I., Sera, D., Salomie, I., Raveduto, G., Ziu, D., Croce, V., Bertoncini, M., 2019. Blockchain-based scalable and tamper-evident solution for registering energy data. Sensors 19, 3033.

Pop, Claudia, Cioara, Tudor, Anghel, Ionut, Antal, Marcel, Salomie, Ioan, 2020c. Blockchain based decentralized applications: Technology review and development guidelines. arxiv.

Prettico, G., Flammini, M.G., Andreadou, N., Vitiello, S., Fulli, G., Masera, M., 2019. Distribution System Operators Observatory 2018-Overview of the Electricity Distribution System in Europe. Technical Report EUR 29615EN, Publications Office of the European Union, Luxembourg, http://dx.doi.org/10.2760/104777.

Raveduto, G., Croce, V., Antal, M., Pop, C., Anghel, I., Cioara, T., Dynamic coalitions of prosumers in virtual power plants for energy trading and profit optimization. In: 2020 IEEE 20th Mediterranean Electrotechnical Conference (MELECON). Palermo, Italy, 16-18 2020.

Saxena, S., Farag, H.E.Z., Brookson, A., Turesson, H., Kim, H., 2021. A permissioned blockchain system to reduce peak demand in residential communities via energy trading: a real-world case study. IEEE Access 9, 5517–5530. http://dx.doi.org/10.1109/ACCESS.2020.3047885.

Schlund, J., German, R., 2019. A distributed ledger based platform for community-driven flexibility provision. Energy Inf. 2, 5.

Schmitt, Alexandre, Carlier, Florent, Renault, Valérie, 2018. Dynamic bridge generation for IoT data exchange via the MQTT protocol. Procedia Comput. Sci. 130, 90–97.

Seven, S., Yao, G., Soran, A., Onen, A., Muyeen, S.M., 2020. Peer-to-peer energy trading in virtual power plant based on blockchain smart contracts. IEEE Access 8, 175713-175726. http://dx.doi.org/10.1109/ACCESS.2020.3026180.

Sigwart, M., Borkowski, M., Peise, M., et al., 2020. A secure and extensible blockchain-based data provenance framework for the Internet of Things. Pers. Ubiquit Comput..

Son, Y.-B., Im, J.-H., Kwon, H.-Y., Jeon, S.-Y., Lee, M.-K., 2020. Privacy-preserving peer-to-peer energy trading in blockchain-enabled smart grids using functional encryption. Energies 13, 1321.

Stawska, Anna, Romero, Natalia, de Weerdt, Mathijs, Verzijlbergh, Remco, 2021. Demand response: For congestion management or for grid balancing? Energy Policy (ISSN: 0301-4215) 148 (Part A), 111920.

Teufel, Bernd, Sentic, Anton, Barmet, Mathias, 2019. Blockchain energy: Blockchain in future energy systems. J. Electron. Sci. Technol. 17 (4), 100011.

Tushar, W., et al., 2020. Grid influenced peer-to-peer energy trading. IEEE Trans. Smart Grid 11 (2), 1407–1418. http://dx.doi.org/10.1109/TSG.2019.2937981.

van Leeuwen, Gijs, AlSkaif, Tarek, Gibescu, Madeleine, van Sark, Wilfried, 2020. An integrated blockchain-based energy management platform with bilateral trading for microgrid communities. Appl. Energy 263.

Vesa, A.V., Cioara, T., Anghel, I., Antal, M., Pop, C., Iancu, B., Salomie, I., Dadarlat, V.T., 2020. Energy flexibility prediction for data center engagement in demand response programs. Sustainability 12, 1417.

Wang, S., Ouyang, L., Yuan, Y., Ni, X., Han, X., Wang, F., 2019a. Blockchain-enabled smart contracts: Architecture, applications, and future trends. IEEE Trans. Syst. Man Cybern.: Syst. 49 (11), 2266–2277. http://dx.doi.org/10.1109/TSMC.2019.2895123.

Wang, Licheng, Shen, Xiaoying, Li, Jing, Shao, Jun, Yang, Yixian, 2019b. Cryptographic primitives in blockchains. J. Netw. Comput. Appl. (ISSN: 1084-8045) 127, 43–58.

Wang, Beibei, Zhao, Shengnan, Li, Yachao, Wu, Chen, Tan, Jian, Li, Hu, Yukita, Kazuto, 2021. Design of a privacy-preserving decentralized energy trading scheme in blockchain network environment. Int. J. Electr. Power Energy Syst. (ISSN: 0142-0615) 125, 106465.

Wang, W., et al., 2019c. A survey on consensus mechanisms and mining strategy management in blockchain networks. IEEE Access 7, 22328–22370. http://dx.doi.org/10.1109/ACCESS.2019.2896108.

Xia, Binzhou, Tan, Zhiyi, 2010. Tighter bounds of the First Fit algorithm for the bin-packing problem. Discrete Appl. Math. (ISSN: 0166-218X) 158 (15), 1668–1675.

Yu, Q., Meeuw, A., Wortmann, F., 2018. Design and implementation of a blockchain multi-energy system. Energy Inf. 1, 17. http://dx.doi.org/10.1186/s42162-018-0040-4.

Zepter, J.M., Lüth, A., del Granado, P.C., Egging, R., 2019. Prosumer integration in wholesale electricity markets: synergies of peer-to-peer trade and residential storage. Energy Build. 184, 163–176.

Zhou, Yue, Wu, Jianzhong, Long, Chao, Ming, Wenlong, 2020. State-of-the-art analysis and perspectives for peer-to-peer energy trading. Engineering 6 (7), 739–753.