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A DECENTRALIZED ENERGY TRADING PLATFORM FOR DISTRIBUTION SYSTEM OPERATORS

Vu Nguyen Huynh Anh[1]

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A B S T R A C T

The transitioning electricity market is characterized by increased use of renewable energy sources in the power system. However, there is a need to accommodate a decentralized energy transaction and supply system (DER) that comprises the energy produced from DERs. This paper presents the solutions to identify issues in the current energy market. It takes place to present a detailed description of the methodologies, technologies, and functioning of the decentralized energy trading platform. We demonstrate a distribution system operator (DSO)-to-consumer flexibility market platform deploying blockchain-based smart contracts for local grid congestion and voltage management. The use case aims to illustrate the concept of a disruptive approach to energy trading that takes advantage of blockchain's inherent strengths in decentralization, transparency, and security.

1. INTRODUCTION

Blockchain technology has emerged as a promising solution to evolving energy landscapes, and distribution system operators (DSOs) are facing increasingly challenging challenges from integrating and widespread electrifying renewable energy sources (RES). The technology's inherent characteristics (decentralized trust architecture, distributed validation mechanisms, and the invariability of transaction records) offer critical advantages for managing flexible resources in distribution networks without centralized intermediaries (Musleh et al., 2018). These characteristics align with the path toward decentralization of the energy sector and address key concerns relating to data security, transaction transparency, and operational resistance to potential system failures and cyber threats. In flexibility markets, blockchain provides a robust framework for secure, transparent, and efficient coordination between DSOs, flexibility service providers (FSPs), and prosumers (Gazioğlu et al., 2023). The technology's ability to preserve transaction privacy while maintaining validation capability creates new opportunities for market participation and value exchange in distributed energy systems (Kirli et al., 2022). Furthermore, blockchain's immutable ledger ensures regulatory compliance and auditability - critical factors for establishing trust among participants with potentially competing interests in emerging flexibility markets (Andoni et al., 2019; Brilliantova & Thurner, 2019).

The decentralized energy trading platform for Distribution System Operators (DSOs) that is presented in this paper allows prosumers and DSOs to exchange

[1] Corresponding author: Vu Nguyen Huynh Anh
Email: vunha@hub.edu.vn

flexibility services. The goal is to find strategies to support DSOs in managing energy flows on the network with greater flexibility and direct involvement. On the same platform, it simplifies the requirements of DSOs and prosumers. Blockchain-based distributed ledger technology (DLT) (Adhami et al, 2018; Ali et al, 2022; Bambara et al, 2018; Berntzen et al, 2021; Vemuri, 2018) will be used to create efficient signaling systems and proper coordination. We want to increase efficiency in several areas of the trading process, such as asset registration, metering data validation, and settling related financial procedures that might be handled with DLT and smart contracts.

The paper uses a strategic modeling framework (Yu, 1997; Yu et al., 2011) to model the trading platform. To do this, we suggest an organization setting for creating a blockchain-based energy trading platform. In this approach, the organizational setting and management structures are represented using strategic modeling tools. This approach is implemented inside certain stages to align the processes in the blockchain-based energy trading platform development.

The structure of this paper is as follows. Section 2 introduces the research approach and methodology. Section 3 illustrates the development model for the blockchain-based energy trading systems named DeEnTP. A use case is shown in Section 4 while Section 5 discusses the use of the platform. Section 6 draws the paper's conclusion.

2. RESEARCH APPROACH AND METHODOLOGY

2.1 Research Question

This section provides sufficient detail about the study question to maintain focus on our investigation. After the preliminary investigation, we will conduct the following research inquiry based on the research context and purpose:

How can organizational modelling for a blockchain-based energy trading platform be represented?

By offering organizational modelling, project managers can guide development processes that meet stakeholder requirements and expectations for IT/Business alignment. The next section illustrates the steps involved in conducting research.

2.2 Research Approach and Method

This section describes the research approach and builds up and validates the entire systems development process in terms of blockchain technology and software engineering disciplines. By offering a management layer for the blockchain-based energy trading system that is integrated with the current software engineering layers, the proposed model essentially expands the agile paradigm (Beck et al., 2001). Following the generic agile development process (Ambler, 2007; Dingsøyr, T. et al., 2012) and the generic DevOps (Ebert, 2016; Senapathi et al., 2018), practitioners in this management layer are guided by the organizational setting and management structures, which are expressed through strategic modelling methodologies.

2.3 Design Science

Based on the Design Science Research (DSR) methodology for information systems (Hevner et al., 2004; Peffers et al., 2008) the research process outlined in this paper begins with an explanation of the solution's goals: a suitable method for creating a decentralized energy trading platform for DSOs that are in line with stakeholders' long-term strategy. Table 1 displayed the steps of the acquisition architecture that we applied in our study.

Table 1. DSR Methodology for Information Systems: Acquisition architecture’s steps.

Steps	Description
1. *Problem identification and motivation*	The core problem is to enable DSOs to manage energy flows on the network with greater flexibility and direct involvement from pursuing a trading contract for several reasons, including control, trust, and cost (Section 1);
2. *Definition of the objectives for a solution*	The objectives are to explore how a blockchain-based energy trading systems fits with an organization's long-term plan and to provide the organizational setting for its development;
3. *Design and development*	We primarily focus on the organizational context of energy trading systems based on blockchain technology. In this method, we characterize the blockchain-based trading system as an organization composed of multiple dependent stakeholders using i* diagrams (Dalpiaz et al., 2016) at various stages. Section 3 provides a thorough discussion of this endeavor.
4. *Demonstration*	This step illustrates how effectively operational energy trading processes may be aided by the blockchain-based system. A thorough use case is provided in Section 4;
5. *Evaluation*	The organizational structure for the blockchain-based energy trading system will be evaluated in light of the long-term organizational strategy. The evaluation is found in Section 4;
6. *Communication*	In this paper, it is fulfilled the task.

3. MODEL

The generic model called DeEnTP for describing the blockchain-based energy trading platform is illustrated in this section. We depict the organizational setting for the creation of the systems within the framework of agile modelling methodologies in this model. Additionally, it provides an overview of the platform from both an organizational modelling and a systems architecture perspective.

The DeEnTP integrated paradigm for the development of blockchain-based energy trading platforms with Agile principles is explained in this section. This paradigm extends the Agile model. This extension aims to make it feasible to design an agile blockchain-based energy trading system that can satisfy stakeholders' demands and expectations. Figure 1 displays the DeEnTP development model. The model has three organizational decision levels (the strategic level, the tactical level, and the operational level). DeEnTP is mostly structured in the same way as a generic Agile approach, with a vertically presented discipline for developing blockchain-based energy trading platform and a horizontally depicted phase sequence.

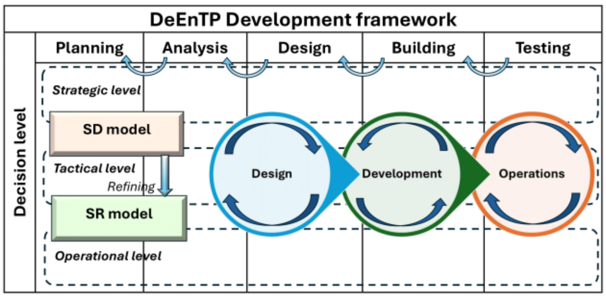

Figure 1. The DeEnTP model.

Figure 2 illustrates the main i* elements and their graphical representation used in the diagrams of the paper.

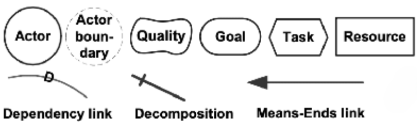

Figure 2. i* Elements and their Graphical Representation.

The long-term development strategy is acknowledged as the DeEnTP's strategic-level goal at the strategic decision level. This level is beneficial to top managers. It examines the Environment for managing blockchain-based agile development processes. It enables the parties concerned to reach an agreement on a comprehensive understanding of the dependencies that development methods should support before, during, and after development. The Strategic Dependency (SD) model of the i* modelling framework (Yu et al., 2011; Dalpiaz et al., 2016) for acceptable representations of the tactical-level functional demands of systems development is made up of actors and connections that connect them. Middle managers who monitor attaining the strategic level's goals can benefit from using sophisticated organizational concepts such as tasks, goals, qualities, resources, and the actors who rely on them.

The SD diagram has six main actors (*Buyer*, *Seller*, *Matching Engine*, *Smart Contract*, *Network Exchange*, and *Network Ledger*), resources (*Requests*, *Offers*, *Tokens*, *Transaction*, and *Regulations*), quality (*Ensure continuous transactions*) and task (*Perform contracts*). This also illustrates the dependencies between actors.

In the SD diagram, the *Matching Engine* depends on the *Buyer* and the *Seller* to ensure the offers data, and the requests data are secured. The *Smart Contract* depends on the *Matching Engine* to ensure the regulations are secured and continuous transactions quality is achieved based on performing contracts. The *Smart Contract* depends on the *Network Exchange* to ensure the tokens is validated. The *Smart Contract* depends on the *Network Ledger* to ensure the transactions data is recorded. Figure 3 depicts an SD diagram applied at the strategic level as well as at the tactical level of the DeEnTP.

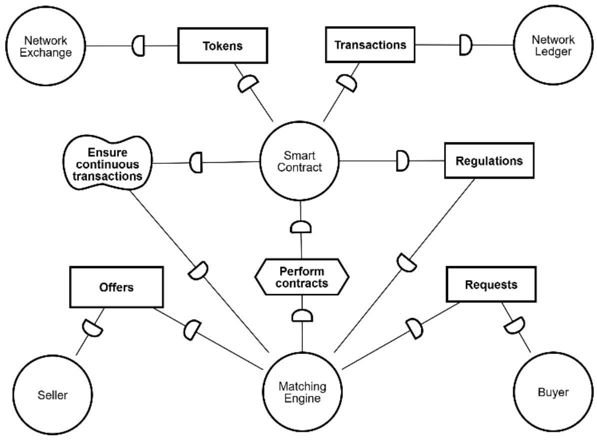

Figure 3. DeEnTP as a strategic dependency diagram.

Figure 4 presents the SR diagram applied at the operational level of the DeEnTP. It is refined from the SD model.

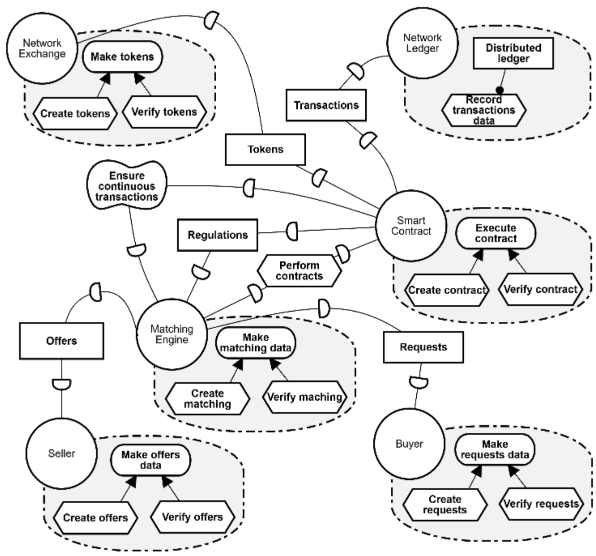

Figure 4. DeEnTP as a strategic rationale diagram.

Each component required for the operational fulfilment of the systems is carried out by atomic tasks that supervise the completion of the strategically selected sub-processes. This level can benefit front-line managers and operators. The tactical-level models are then converted into several design models, which are then displayed at this level from different perspectives. For sufficient descriptions of the functional and non-functional requirements of the systems, we propose using the i* modelling framework's Strategic Rationale (SR) model (Yu et al., 2011; Dalpiaz et al., 2016).

In the SR diagram, the *Buyer* performs two specific tasks (*Create requests*, and *Verify requests*) to make requests data. The **Seller** performs two specific tasks (*Create offers*, and *Verify offer*) to make offer data. The *Matching Engine* performs two specific tasks *(Create matching*, and *Verify matching*) to make matching data. The *Network Exchange* performs two specific tasks (*Create tokens*, and *Verify tokens*) to make tokens. The *Smart Contract* performs two specific tasks (*Define contract*, and *Verify contract*) to execute contracts. The *Network Ledger* performs one task (*Record transaction data*) on the distributed ledger.

4. USE CASE

In this section, we illustrate the DeEnTP flexibility services for long-term congestion management, which allows more renewable connections without unreasonable DSO network investments. Flexibility services for operational congestion management reduce the impact of outage events or forecast deviations. Flexibility can be used to balance the energy of a balanced group. Energy suppliers generate forecasts each day for the next day (day-ahead forecast). In intraday, a prediction is computed again each hour for the next hours. Flexibility can be used to equilibrate the difference between forecasted and consumed energy and thus to reduce the penalties paid by the energy suppliers. DeEnTP transactions involve two key parties: buyers (DSOs) and sellers (FSPs and/or prosumers). Figure 5 illustrates the DeEnTP in use.

The transaction begins with the purchase of the token, and the participant enters the platform by purchasing a specific trading token. These tokens serve as the main mechanism of energy exchange and create standardized value units for different regions and service providers. Once a token is acquired, the participant can submit purchase requests and offers through the matching engine of the platform using advanced algorithms to optimize energy trading based on supply, demand, and regional characteristics.

The main components of the system are its robust verification and validation mechanisms. When the transaction is initiated, the platform conducts comprehensive fund validation to ensure the financial integrity of the exchange. The matching algorithm then accurately coordinates between sellers (represented by flexible service providers (FSPs), prosumers (PSMs), and buyers (such as distribution system operators (DSOs)) in different regions. This process allows granular energy trade that can consider local energy production, consumption patterns, and regional changes.

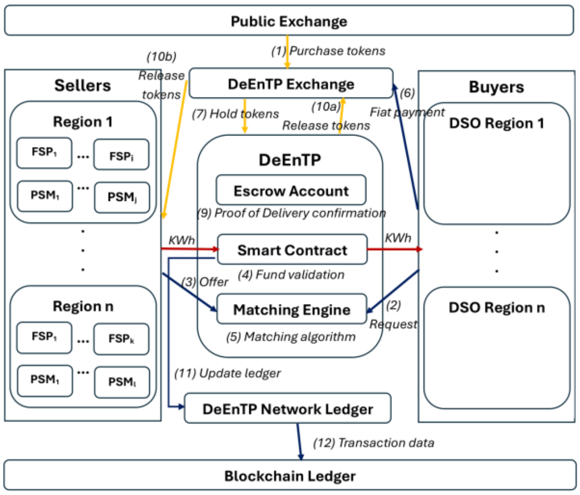

Figure 5. The DeEnTP in use.

The platform includes escrow accounts and smart contract infrastructures that provide additional security and trust. The technology components ensure that tokens are securely held during the transaction process and released only after successful delivery verification. The delivery confirmation proof mechanism adds another important checkpoint, ensuring that the energy is actually transferred as agreed before the transaction is completed. The entire system is based on blockchain technology, with two interconnected ledgers, the DeEnTP network ledger and the blockchain ledger, which maintain transparent and invariable records of all transactions. Every transaction is precisely documented, from the initial token purchase to the final energy supply, establishing a verification trace that enhances accountability and trust. By allowing many players to participate in a secure, decentralized market, this public exchange mechanism significantly opened up the energy trading process.

The platform's design is particularly scalable and flexible, accommodating several regions with different energy production and consumption characteristics. Each region has multiple FSPs and PSMs, allowing a complex and dynamic energy trading environment. The system supports fiat payments in addition to token exchanges and combines traditional financial systems with innovative blockchain technologies.

The use of the platform for flexibility services in congestion management proves its practical utility in allowing additional renewable connections while avoiding excessive DSO network investments. The token-based transaction system, along with rigorous verification and validation processes, enables a dependable marketplace for energy flexibility that is consistent with the sector's evolving philosophy of decentralization and democratization. DeEnTP promotes more efficient energy distribution and the transition to sustainable energy ecosystems by optimizing the matching of energy supply and demand across diverse locations.

5. DISCUSSION

The decentralized energy trading platform (DeEnTP) presented in this paper offers a transformative approach to managing energy distribution and trading within distribution system operators (DSOs). By leveraging blockchain technology, the platform addresses several critical challenges in the current energy market, including the integration of renewable energy sources, congestion management, and transaction transparency.

One of the key advantages of the DeEnTP platform is its ability to facilitate secure and transparent transactions without the need for centralized intermediaries. This is achieved through the use of blockchain's decentralized trust architecture and distributed validation mechanisms, which ensure that all transactions are immutable and verifiable (Musleh et al., 2018). This characteristic is particularly important in the energy sector, where trust and transparency are paramount for effective market participation and regulatory compliance (Andoni et al., 2019).

The platform's strategic modelling framework, which integrates agile and DevOps methodologies, provides a robust foundation for the development and deployment of the DeEnTP system. By aligning the organizational setting and management structures with the strategic, tactical, and operational decision levels, the platform ensures that all stakeholders' requirements and expectations are met (Yu et al., 2011; Dalpiaz et al., 2016). This approach not only enhances the efficiency of the development process but also ensures that the platform can adapt to the evolving needs of the energy market.

The use case presented in the paper demonstrates the practical utility of the DeEnTP platform in managing long-term congestion and balancing energy supply and demand. By using tokens for transactions and incorporating rigorous verification and validation mechanisms, the platform provides a dependable marketplace for energy flexibility. This is particularly beneficial for DSOs, as it allows them to manage energy flows on the network with greater flexibility and direct involvement, thereby reducing the need for costly network investments (Gazioğlu et al., 2023). The implementation of smart contracts within the platform not only enhances the efficiency of energy trading processes but also ensures that all transactions are compliant with regulatory requirements and auditability standards (Brilliantova & Thurner, 2019).

Flexibility marketplaces like the DeEnTP platform can make the procurement process to make it easier for aggregators and flexibility providers to view the local opportunities and to participate in the procurement process. P2P (peer-to-peer) trading is expected to give multiple benefits to the grid in minimizing the peak load demand and energy consumption costs and eliminating network losses. However, installing P2P energy trading on a broader level in electrical-based networks presents a number of modelling problems in physical and virtual network layers. On a larger scale, when there are more users and thousands of transactions happen, the platform should be capable of handling a significant amount of grid users with sufficient efficiency and security levels. For a P2P platform to be successful, it is crucial that people be educated and given awareness about new technologies and provided incentives to accommodate devices such as smart meters.

6. CONCLUSION

The DeEnTP is an innovative blockchain-based platform designed to facilitate complex energy trading across several regions. At the core, this platform creates a decentralized ecosystem and provides seamless interaction between energy suppliers and buyers through a complex technology framework. The system, which uses blockchain technology, ensures transparency, security, and efficiency in energy transactions and goes beyond traditional centralized energy trading models.

DeEnTP ultimately represents a transformative approach to energy trading, leveraging the inherent strengths of blockchain decentralization, transparency, and security. The system can optimize energy distribution, reduce inefficiency, and support the transition to a more flexible and sustainable energy ecosystem by creating a platform that efficiently synchronizes energy supply and demand in various regions.

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Vu Nguyen Huynh Anh
Ho Chi Minh University of Banking,
Ho Chi Minh City,
Vietnam
vunha@hub.edu.vn
ORCID 0000-0002-4359-5943