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AUTOMATED ENERGY PERFORMANCE MONITORING AND OCCUPANT ENGAGEMENT IN BUILDINGS THROUGH BLOCKCHAIN-ENABLED NON-FUNGIBLE TOKENS

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SUMMARY: *Building energy efficiency programs face significant challenges in performance monitoring and occupant engagement, which hinder the achievement of sustainability goals in the built environment. Traditional systems often suffer from intermediary-dependent workflows, insufficient transparency, and reliability issues, leading to conflicts among stakeholders and reduced occupant participation. This study proposes a blockchain-enabled solution that leverages Non-Fungible Tokens (NFTs) to improve the transparency, reliability, and traceability of performance monitoring systems. By integrating Digital Twin (DT) technology, blockchain, and a token marketplace, the platform not only enhances monitoring capabilities but also incentivizes occupants to adopt energy-efficient behaviors through Fungible Token (FT) rewards. A proof-of-concept prototype was developed using a synthetic case study, demonstrating the feasibility, cost efficiency, and scalability of the framework. The findings emphasize the importance of network selection for wider blockchain adoption. This transparent and immutable framework addresses key challenges in energy performance monitoring, offering a foundation for advancing sustainability in the built environment.*

KEYWORDS: *Blockchain, Digital Twins, Fungible Tokens, Non-Fungible Tokens, Building Energy Performance, Building Sustainability.*

REFERENCE: *Hossein Naderi, Alireza Shojaei, Mohammad Hossein Heydari (2025). Automated Energy Performance Monitoring and Occupant Engagement in Buildings through Blockchain-Enabled Non-Fungible Tokens. Journal of Information Technology in Construction (ITcon), Vol. 30, pg. 133-158, DOI: 10.36680/j.itcon.2025.007*

1. INTRODUCTION

Around 40% of the world's energy usage and greenhouse gas emissions are attributed to the built environment. The operational phase of buildings accounts for 80-90% of energy consumption and carbon emissions (Hamilton & Rapf, 2020). Energy efficiency measures is widely mentioned as one of the main ways for minimizing the energy consumption of sector by 2050 (Santamouris & Vasilakopoulou, 2021). Despite energy conservation efforts, the building sector's energy demand grew by more than 20% from 2000 to 2017. This substantial increase can be attributed to the limited improvement in energy efficiency projects (IEA, 2019), including inadequate performance monitoring systems, and ineffective occupant engagements.

Performance monitoring plays a crucial role in managing building energy performance and implementing energy efficiency initiatives (Messenger et al., 2010). However, existing systems rely heavily on intermediary-based workflow, which rely on centralized servers to process and store energy performance data. For example, in traditional systems, energy data collected from sensors is transmitted to a centralized server managed by an external organization or service provider. This setup creates bottlenecks, as the intermediary has full control over the data, which can lead to delayed reporting, limited accessibility, and increased costs. Furthermore, reliance on these centralized systems makes it challenging to ensure continuous uptime and resilience, as a single server failure could disrupt the entire monitoring process. This intermediary-based workflow lays the foundation for lack a secure, transparent, and accurate performance monitoring mechanism (Z. Wang et al., 2019; Yang & Chou, 2017). This deficiency leads to the building energy performance gap, where actual building energy performance fails to match predictions and claims (Menezes et al., 2012).

Furthermore, the lack of trust between Energy Service Companies (ESCO) and clients in current systems have discussed as one of the main barriers in the successful implementation of Energy Performance Contracting (EPC) projects (Garbuzova-Schlifter & Madlener, 2016). In existing centralized setups, energy performance data stays on centralized servers or client systems, where it is vulnerable to tampering or manipulation. For example, an ESCO might manipulate reported performance data to meet contractual targets, or a building owner might overstate efficiency improvements to gain financial incentives. Such manipulations erode trust between stakeholders, including ESCOs, building owners, and regulatory bodies, and compromise the credibility of energy performance claims. This lack of transparency discourages stakeholders from actively participating in energy efficiency programs and reduces confidence in Energy Performance Contracting (EPC) projects, which rely heavily on accurate and verifiable performance metrics. Therefore, the building energy performance monitoring is in need to address challenges associated with existing centralized systems.

Another major challenge in achieving building energy efficiency goals is occupant engagement (U.S. Green Building Council, 2015). The behavior of occupants directly impacts the energy consumption of a building and potentially lead to substantial disparities between the actual energy demand and the predicted values (De Wilde, 2014). Current systems often overlook the complexities of occupant behavior for the sake of simplicity. Furthermore, these systems fail to engage occupants, which contribute to a 50% increase in energy demand in energy retrofitted buildings, effectively nullifying the energy and economic benefits of these projects (Ascione et al., 2020). This study seeks an innovative solution to take one step closer to address centralized energy performance monitoring systems and occupant engagement challenges within building energy efficiency programs.

Recently, the decentralized structure inherent in blockchain technology has been utilized by different studies as a solution to address limitation of existing centralized systems (Lee et al., 2021; Shojaei et al., 2019). Blockchain's decentralized nature eliminates the need for intermediaries, ensuring that data is securely stored and accessed in a distributed manner, making it tamper-resistant, transparent, and readily verifiable. This characteristic makes blockchain an appropriate choice for addressing the data integrity and trust challenges associated with centralized systems. Building on blockchain's capability, non-fungible tokens (NFTs) introduce a powerful feature to tokenize data, enabling the visualization of energy performance metrics in an accessible and user-friendly format (Naderi et al., 2023; Q. Wang et al., 2021). NFTs allow immutable representation of historical performance data, while dynamic NFTs (dNFTs) (Howell, 2022) extend this functionality by dynamically updating to reflect current energy performance. This adaptability makes dNFTs a tool for providing real-time feedback and engaging stakeholders in building energy management.

On the other hand, Digital twin (DT) technology has recently been utilized to improve energy monitoring by offering real-time performance insights into the built environment (Arsecularatne et al., 2024). By adding NFTs on top of this technology, we can expect to take one step toward addressing the challenges associated with centralized systems in building energy performance. This integration enables not only the visualization of energy data but also the dynamic updating of performance metrics in a secure and decentralized manner, further enhancing the transparency and reliability of monitoring systems.

Building on these characteristics, this study aims to (1) investigate how a solution based on blockchain, and specifically tokens, can map open issues stemming from existing practices; (2) propose a comprehensive and industry-wide framework, which represent building energy performance in the dNFT and reward users for their participation; (3) develop a decentralized application (dApp) to validate the feasibility and applicability of framework (proof of concept). Overall, this study contributes to the field by introducing dNFTs as a reliable and accurate reflection of building energy performance. In addition, incentivizes user participation in energy efficiency programs by rewarding exemplary performance with FTs, enhancing occupant engagement. Moreover, we have incorporated a decentralized oracle network (DON) to serve as a safe bridge between off-chain and on-chain worlds, which addresses one of main limitations in blockchain-based solutions in the Architecture, Engineering, and Construction (AEC) (Hamledari & Fischer, 2021; Hunhevicz et al., 2022). This platform also serves as a gateway to the complete historical data of a building's energy performance, facilitating transparent tracking, monitoring, and evaluation by all stakeholders involved. By leveraging the proposed framework and utilizing dNFTs, this study is a step away toward facilitating the inclusion of buildings in carbon credit market, thereby enabling the industry to actively participate in reducing carbon emissions and mitigating climate change.

Section 2 provides an overview of blockchain-enabled tokens and explores the distinctive attributes of tokens, specifically dynamic non-fungible tokens (dNFTs), in addressing the unresolved challenges within existing practices and occupant engagement mechanisms. In section 3, a conceptual framework is proposed to address these issues. The framework is then implemented as a proof of concept in section 4. Section 5 discusses the results obtained in the preceding section, examining them from various perspectives, while section 6 provides research limitations. Finally, in section 7, we present the conclusions drawn from this study.

2. BACKGROUND

2.1 Technologies for Building Energy Management

To address building energy performance challenges, innovative technologies are increasingly being utilized (Cao et al., 2016). Among these, Building Information Modeling (BIM) has emerged as a transformative tool for energy management in construction and operation phases. BIM serves as a digital representation of a building's physical and functional characteristics, allowing stakeholders to visualize, simulate, and analyze energy performance throughout the lifecycle of a building. It supports energy modeling by integrating data on materials, design geometry, and environmental factors to predict and optimize energy consumption (Sanhudo et al., 2018a). Studies have shown that BIM can enhance energy efficiency by enabling better-informed decisions during the design and operational phases of buildings (Hodorog et al., 2021).

Another technology is Internet of Things (IoT) devices, including smart sensors and meters, are increasingly integrated into buildings to monitor and manage energy usage in real-time. These systems collect granular data on parameters such as temperature, occupancy, and lighting, which can be analyzed to optimize energy consumption dynamically (Hannan et al., 2018). Volkov and et al. (Volkov et al., 2013) discussed that IoT-enabled systems can help for predictive maintenance and adaptive control, reducing energy waste and operational costs (Sanhudo et al., 2018b). One another technology is Artificial Intelligence (AI) and machine learning algorithms, mostly applied in energy management systems including buildings to predict energy demand, optimize HVAC systems (Khan et al., 2023). This can help to identify inefficiencies by training the models on the historical data and test them on real-time data (Amani & Soroush, 2020). Recently, a lot of attention has paid to Digital Twins, as a technology that focuses on creating a real-time digital replica of physical building, enabling continuous monitoring and simulation of energy performance (Naderi & Shojaei, 2022). This technology benefits from the capabilities of other mentioned technologies, such as BIM, IoT, and AI, to predict and maintain the building energy performance in an acceptable level. By comparing real-world data with simulated scenarios, digital twins identify inefficiencies and potential improvements, making them valuable for long-term energy optimization strategies (Bortolini et al., 2022).

While these technologies have significantly advanced the field of building energy management, they are predominantly developed within intermediary workflows. This centralized approach introduces a single point of failure, making systems vulnerable to disruptions such as cyberattacks, hardware malfunctions, or data corruption (Abdallah et al., 2019; Sanhudo et al., 2018b). For example, IoT-based energy management platforms often depend on centralized cloud servers to collect and process data. If these servers are compromised, either through a cyberattack or an outage, the entire system can fail, leaving buildings unable to monitor or optimize their energy consumption. Additionally, interoperability issues, high implementation costs, and data silos remain significant barriers to their widespread adoption (Lockl et al., 2020).

Recently, studies (Alhammad et al., 2024; Porsani et al., 2021) discussed that building energy modeling (BEM) systems provide greater visibility and transparency in monitoring various energy performance criteria, leading to significant achievements in the field. However, it is important to note that these systems typically rely on centralized servers, which inherently pose transparency and security challenges. For instance, data transmitted to centralized servers may be prone to manipulation or loss, undermining trust in the system's outputs. On the other hand, blockchain-based systems offer decentralized and immutable data storage, ensuring greater transparency and trustworthiness. Moreover, reliance on centralized servers creates a single point of failure, whereas blockchain's decentralized nature enhances resilience and reliability, making it a more robust solution for sustainable building energy performance monitoring.

2.2 Blockchain Overview

Distributed Ledger Technology (DLT), commonly known as Blockchain, is a peer-to-peer network that organizes cryptographically signed transactions into blocks. These blocks are then linked together through cryptographic hashes, creating an immutable chain. As new blocks are added, older blocks become increasingly resistant to modification. The blockchain's immutability is a key characteristic, ensuring that once data is added, it remains unalterable. Each block contains a timestamp, transaction information, and a hash of the previous block, creating a robust structure that would require altering subsequent blocks to tamper with data (Atlam et al., 2018). The consensus mechanism plays a vital role in maintaining the reliability of the blockchain network. Through a consensus algorithm, all transaction data is consistently and identically replicated across blocks (Euromoney, 2023). Blockchain technology also offers data traceability and integrity. Validated and recorded transactions can be easily traced by accessing any node in the distributed network. Furthermore, the integrity of the blockchain is preserved as all blocks are linked back to the genesis block, the initial block in the chain (Nofer et al., 2017).

2.3 From Blockchain to Tokens

Blockchain, like many other advanced technologies, continues to evolve and develop new features as it progresses. Its journey began with the introduction of Bitcoin in 2008 by the pseudonymous figure, Satoshi Nakamoto (Nakamoto, 2008). Bitcoin, launched in 2009, brought decentralized digital currency to the forefront, eliminating the need for intermediaries. Ethereum, introduced later, revolutionized the blockchain landscape by introducing smart contracts (Buterin, n.d.). These contracts allowed peers to execute code and enforce rules on blockchain networks without relying on trusted third parties (Han et al., 2020). This breakthrough opened doors for blockchain to disrupt industries beyond finance.

Tokenization, a key development, enabled the conversion of real-world assets, rights, and values into blockchain-backed digital representations (Freni et al., 2020). Tokens can now represent various forms of value or access rights, such as company shares, property ownership, project bonds, or even energy production. Essentially, any value or right can be tokenized and managed as digital assets or virtual tokens on the blockchain network. Users can mint tokens by defining a set of governing rules, giving them the flexibility to create and manage their own digital assets.

2.4 Features Associated with Token-Based Solution

A token-based solution harnesses the advantages of blockchain technology, inheriting its key features. Transactions involving tokens are transparent and traceable since they are recorded on public ledgers. The immutability of blockchain ensures that the information, value, and rights associated with tokenization remain secure and unchangeable. By eliminating intermediaries and central authorities, a token-based solution facilitates reliable workflows, integrating blockchain security into tokens and encouraging greater participation. Moreover, tokens are generated through smart contracts, automating and enforcing the tokenization process.

One of the significant benefits of tokenization is the enhanced liquidity it offers. By tokenizing assets, tokens can be traded on secondary markets chosen by the issuer, without restrictions on time or geographic location. This expanded access to a wide range of potential traders boosts liquidity (Yongfang et al., 2022). Furthermore, token-based solution brings about an ease-of-use for many proposed blockchain applications by representing tokens as tangible digital units that embody the advantages of blockchain technology (Naderi, Heydari, et al., 2024).

2.5 Token-based solution

This section demonstrates how a token-based solution can help address the challenges associated with existing monitoring practices and occupant engagement. While there may be other solutions to address these challenges, a token-based solution offers several unique features that make it a potential solution. To this end, Figure 1 depicts the identified challenges in existing building energy performance management, especially in monitoring and occupant engagement, paired with the explored token-based decentralized application (dApp). The left block represents features of the token-based dApps, while the right block indicates the challenges and consequences associated with existing practices. Arrows, directed from features to issues, indicate which feature has the potential to address the corresponding issue.

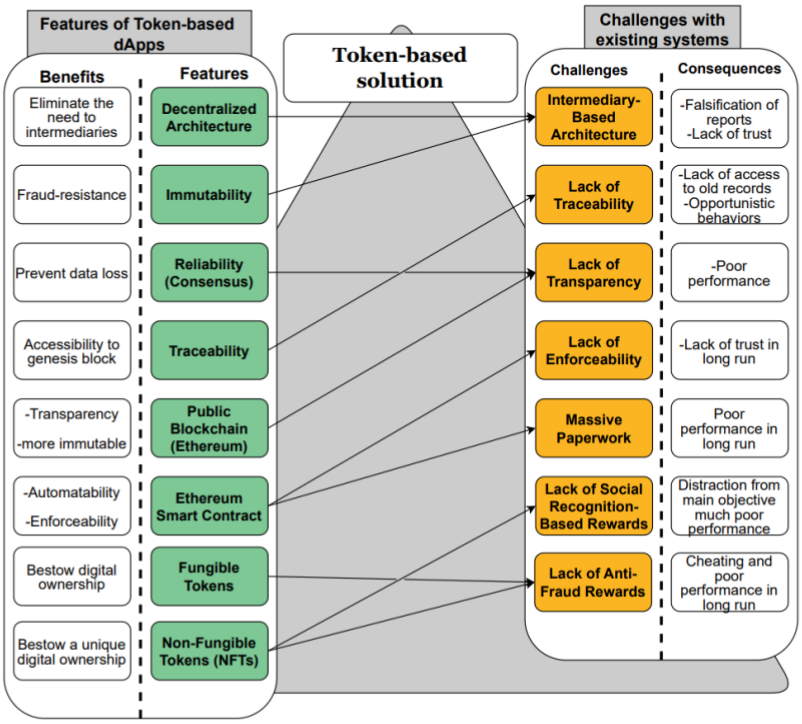

Figure 1: Aligning token-based solution with identified challenges in building energy performance monitoring.

These features and their potential for addressing the challenges outlined in Figure 1 serve as hypotheses guiding this study. For example, the decentralized architecture is hypothesized to eliminate intermediary inefficiencies, while immutability and traceability can enhance transparency and accountability by reducing falsified reports and improving access to records. These hypotheses aim to lay the foundation for addressing this study objectives.

2.6 Related Study and Point of Departure

Blockchain-based solutions are frequently being applied to address energy management challenges in the pursuit of a sustainable future (Figueiredo et al., 2022; Upadhyay et al., 2021). One study proposed a platform that leverages blockchain and Internet of Things (IoT) technologies to enable automated personalized temperature control (Jeoung et al., 2022). This platform significantly improved thermal comfort and energy efficiency compared to manual indoor temperature control methods. Additionally, blockchain technology has been utilized to enhance sustainability in prefabricated housing construction (Li et al., 2018) and the supply chain management of the built environment (Shojaei et al., 2021).

In the domain of building energy performance, only a few studies have explored the potential of blockchain-based solutions. One study proposed a solution for digitizing energy performance contracts by integrating DTs and blockchain-enabled smart contracts (Hunhevicz et al., 2022). The study also validated this concept through a proof-of-concept implementation. When it comes to monitoring, to best of the authors' knowledge, one study has demonstrated the potential application of blockchain for monitoring building energy performance (Woo et al., 2021). However, this study limited its scope to a theoretical review of potential applications without delving into practical implementation or presenting a proof-of-concept. Our research distinguishes itself by advancing the discourse through the development of a comprehensive framework and a decentralized prototype specifically designed to tackle the prevailing challenges in building energy monitoring. This study proposes the creation of a dApp that not only offers a transparent, token-based solution for precise energy performance monitoring but also introduces an innovative, incentivized mechanism. This mechanism is strategically designed to actively engage building occupants in energy performance programs, thereby enhancing participation and efficiency in energy conservation efforts.

3. FRAMEWORK

This section outlines the framework for developing our platform or dApp that provides users with a dNFT representing real-time building performance. The dApp will automatically distribute token-based rewards to buildings based on their performance. An overview of the framework is provided to give a comprehensive understanding of the system architecture and its included modules. The following sections will delve into the details of these modules to present the features and functions of the proposed dApp.

3.1 Scope

The study focuses on presenting buildings' energy performance within a reliable market-based platform and incentivizing user behavior towards energy-conscious practices. To accomplish this, it is necessary to define the scope of each task before delving into designing the framework. Firstly, the dApp primarily focuses on representing energy performance, while leaving room for the incorporation of other Key Performance Indicators (KPIs) in future research. The design process is developed in such a way that these additional KPIs can be seamlessly integrated into the dApp after its initial successful implementation. Secondly, the dApp is focused on presenting the energy performance of a built environment instead of involving design and construction stages of constructing buildings or infrastructures.

3.2 Overview

Figure 2 presents an overview of our framework, highlighting its main modules and components. This visual representation demonstrates how the framework, along with its included modules, enables us to achieve the goals of our dApp: representing the performance of the built environment in a reliable market and rewarding buildings with good performance. It provides a comprehensive understanding of the dApp and its workings. As depicted in Figure 2, the framework is built upon four main modules: (a) Physical world, (b) Off-chain components, (c) On-chain components, and (d) NFT marketplace. While the application of smart contracts and blockchain technology alone cannot support automated mechanisms for representing building energy performance as they lack connection to the physical space of actual buildings, our dApp requires a link to physical buildings by monitoring their energy performance. Module A, which relates to the physical world, serves as the data source for the entire platform. It showcases a sample building, "Building A," along with its associated manager in different time states.

Module B is focused on virtual environment operations. In this module, the DT of "Building A" is continually updated with energy data obtained from module A. Module C is related to operations on blockchain network. Module C is responsible for generating dNFT and distributing rewards to users. It is connected to Module B in a reliable and secure manner through a Decentralized Oracle (DON). The presence of an oracle component is necessary to bridge the off-chain module with smart contracts and blockchain nodes in the on-chain environment. Oracles act as middleware agents that link real-world off-chain data to blockchain on-chain networks (Al-Breiki et al., 2020). Therefore, the oracle component in Figure 2 is proposed to transfer the output of the DT component to smart contracts and, consequently, blockchain nodes. Smart contracts, in module C, play a central role in our proposed system, enabling us to define functions for interacting with the blockchain nodes. They serve as the dApp back-end for representing building performance and distributing rewards.

Module D depicts generated dNFTs that uniquely represent the energy performance of buildings. They are accessible to public through a NFT marketplace, where users have access to public data of M&V in a reliable manner. This module also brings social recognition and reputation for buildings with better energy performance. Good energy performance of buildings are also compensated by FT rewards that encourage energy-conscious behavior among users. In the following sections, the core modules of the dApp will be discussed in more detail, exploring associated challenges, main features, and functions.

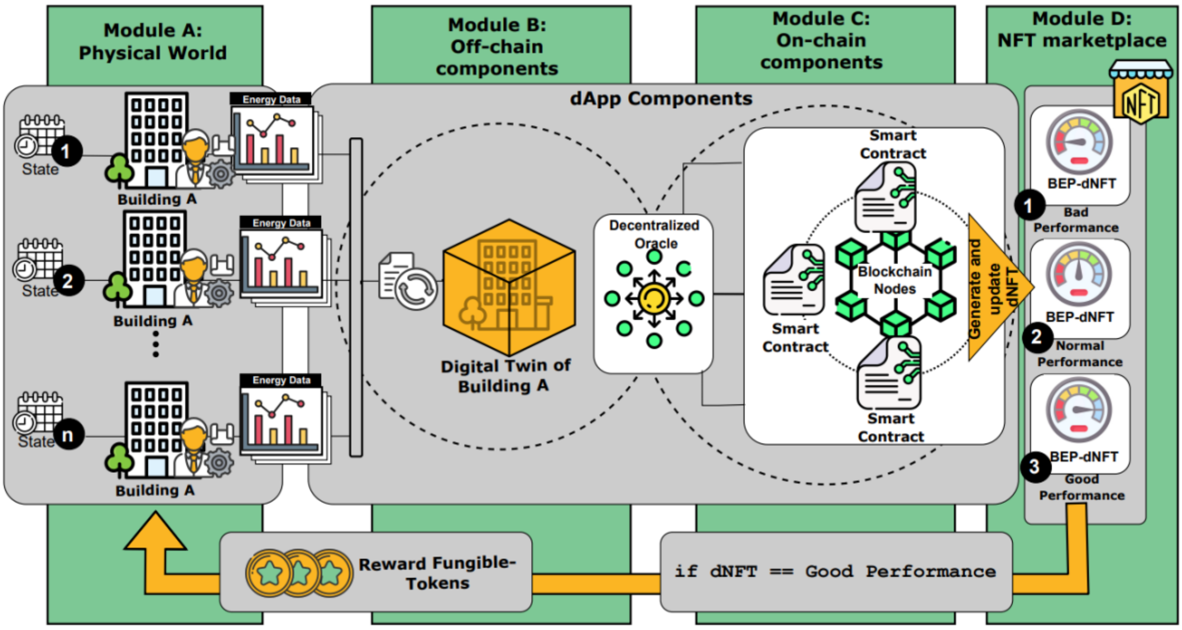

Figure 2: Overall structure of framework.

3.3 Module A: Physical Built Environment

This module represents the actual buildings and their behavior, serving as the primary data source for other modules. Various KPIs are crucial in assessing the quality of the built environment throughout its lifecycle. However, this study specifically focuses on energy-related KPIs during the Operation and Maintenance (O&M) phase of the built environment. To extract energy data, IoT devices are deployed and used to transmit the gathered information to the subsequent module. Additionally, each building is associated with an individual or a team responsible for facility management. In existing systems, these managers were entrusted with overseeing the overall energy performance of the buildings. However, in the proposed platform, they are not only responsible for overseeing energy performance but are also rewarded based on the overall energy performance achieved. This incentivizes them to actively engage and encourage occupants to contribute towards enhancing the overall performance of the buildings.

3.4 Module B: Digital Twins

DT is a virtual replica of a physical asset (Grieves & Vickers, 2017), which should be connected to the physical entity in real-time to reflect one or multiple behaviors of the physical entity (Kritzinger et al., 2018). Building energy data from Module A is transmitted into digital twins using essential elements (Naderi & Shojaei, 2023): a bi-directional communication channel and twinning technologies (information models, data acquisition tools, and data processing techniques). Figure 3 depicts these technologies and details the workflow of DT in the off-chain module, where green blocks represent its external relationships. The data acquisition technologies, continuously receive data, while the information models update the DT state based on this incoming data. Data processing techniques are utilized to compare buildings' energy data with energy performance baselines defined by clients or regulatory agencies. This comparison allows for the assessment of the overall building energy performance.

To address the costs of storing data on the blockchain, our framework utilizes the Interplanetary File System (IPFS). One such solution is Interplanetary File System (IPFS) (Benet, 2014), a peer-to-peer distributed file system that provides users with a content-addressable file sharing solution. Content addressability is defined as a mechanism to retrieve data based on its content rather than the file location. In IPFS, each file published is assigned a tamper-resistant content identifier (CID), which serves as a hash for retrieving the data. Our framework stores project data on IPFS, enhancing its integrity. To further enhance security, we store both input and output data on IPFS, associating their CIDs in the minting process of NFTs. This approach enables users to verify the validity of the output by referencing the associated input data, ensuring transparency and validating the integrity of NFT-associated data.

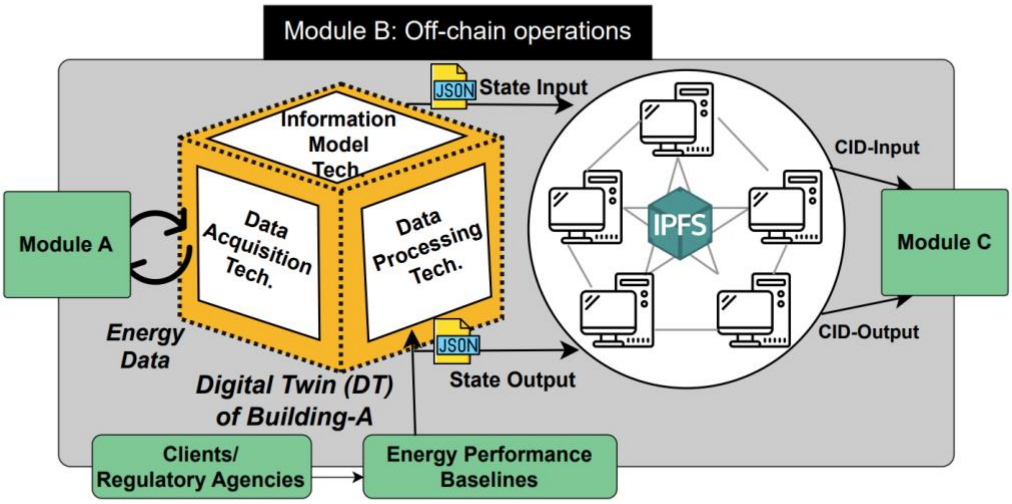

Figure 3: Mechanism of Digital Twin Module.

3.5 Bridging Module B and Module C: Decentralized Oracle (DON)

This module aims to integrate the content of CIDs, created in the previous module, into smart contracts and blockchains. However, smart contracts developed on blockchain networks lack the inherent capability to interact with external sources and retrieve data. To overcome this challenge, oracles are commonly employed to establish connections between blockchains and the outside world. Nevertheless, a significant limitation of conventional oracles is their centralized nature, which renders them susceptible to issues associated with traditional centralized systems, such as single points of failure and the potential for altering past reports. This critical challenge has been frequently acknowledged in numerous studies within the AEC domain (Hamledari & Fischer, 2021; Hunhevicz et al., 2022).

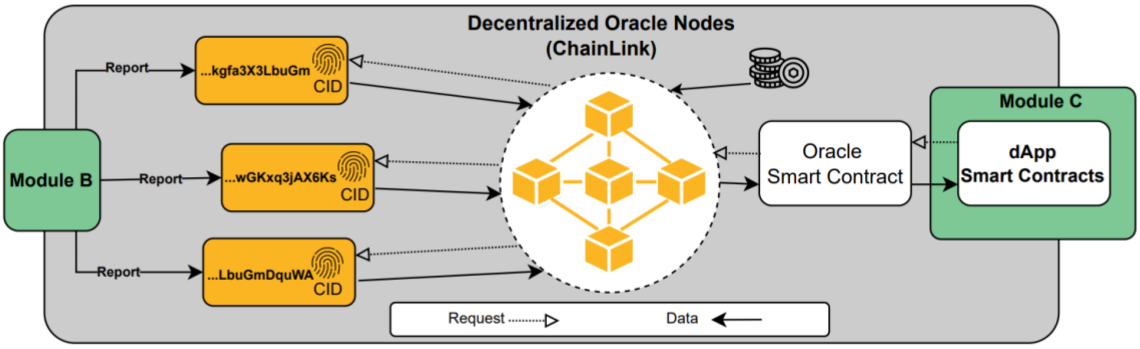

Figure 4: Mechanism of Decentralized Oracle module.

Recently, DONs have emerged as a solution to address the challenge (Ellis et al., 2017). In this module, we leverage ChainLink (Breidenbach et al., 2021), a popular DON that provides interfaces for smart contracts. Figure 4 illustrates how ChainLink interacts with other modules. Requests for data in smart contracts are first sent to an on-chain oracle contract and then forwarded to decentralized oracle nodes, which require funding with FTs as compensation for their services. These decentralized nodes interact with IPFS servers and retrieve data using the generated CIDs from the previous module. As a result, data can be securely transferred into on-chain smart contracts in a trustless and immutable manner.

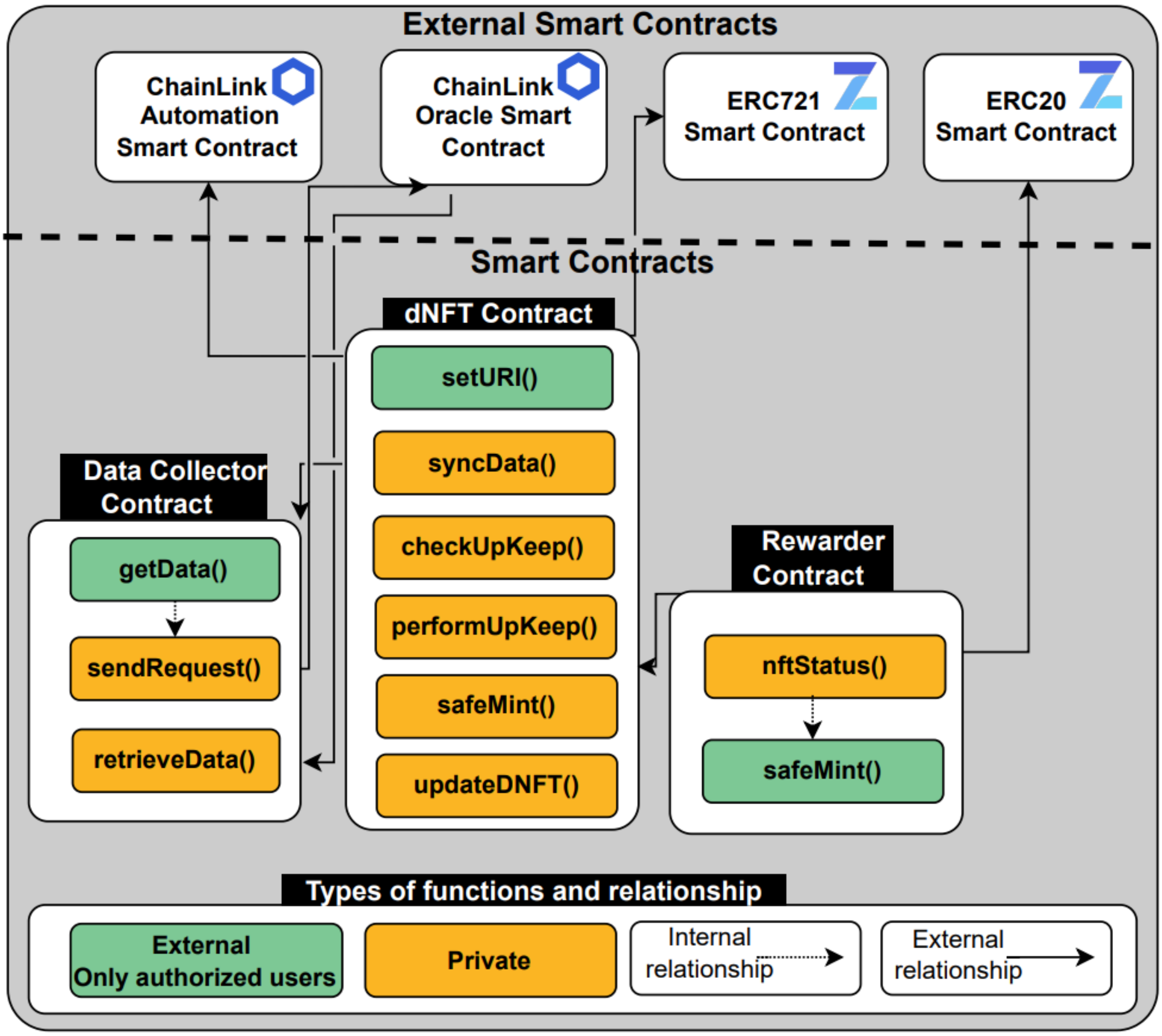

Figure 5: Interaction map of smart contacts and its functions.

3.6 Module C: Smart Contracts Design

The focus of this module was on designing and developing the smart contracts that serve as the backend of the dApp, enabling the M&V of buildings with dNFTs and rewarding them with FTs based on data retrieved from the previous modules. To accomplish this goal, ERC-20 (Vogelsteller & Buterin, 2015) and ERC-721 (Entriken et al., 2018) standards were utilized to create FTs and NFTs , respectively. However, a challenge with these standards is that they merely provide guidelines and functions for developers and do not offer verified implementations. Consequently, it is not uncommon for self-developed smart contracts to have security issues and incur unnecessary implementation costs due to the inclusion of unnecessary functions. To tackle this problem, this module employs OpenZeppelin (OpenZeppelin, 2022) as an open-source framework that enables developers to customize their smart contracts based on verified implementations of ERC-20 and ERC-721 smart contracts.

Three primary smart contracts are required to implement the core functionalities of the dApp. These smart contracts are interconnected with each other as well as with external smart contracts. Figure 5 provides an overview of these three main smart contracts: (a) Data Collector, (b) dNFT, and (c) Rewarder. The Data Collector contract serves as the initial point for retrieving energy performance data from Module B. Authorized users can execute the "getData()" function, which subsequently calls the "sendRequest()" function. This function sends a request to the DON smart contracts. The "retrieveData()" function is then triggered, enabling the retrieval of building energy performance data from the reports in Module B.

The dNFT contract plays a vital role in our dApp as it is responsible for generating and updating dNFTs according to building energy performance data. However, a significant challenge arises as NFTs cannot be modified once they are created. To overcome this limitation, our study incorporates the Chainlink Automation smart contract. The smart contract uses the "checkUpKeep()" function to evaluate whether certain conditions are met. If the conditions are satisfied, the "performUpKeep()" function is triggered. After a dNFT is generated using the "safeMint()" function, the "performUpKeep()" function updates the dNFT's status based on the time condition defined in the "checkUpKeep()" function. Another important smart contract is the "Rewarder," which handles the creation of FTs based on the latest dNFT status and their distribution to the building and its occupants. To accomplish this, the "nftStatus()" function retrieves the most recent state of the dNFT from the dNFT contract and then calls the "safeMint()" function to generate FTs, which are subsequently sent to the users.

3.7 Module D: NFT marketplace

This module functions as a front-end interface for generated dNFTs, providing users with an interactive platform to access the latest M&V reports in a reliable manner. Additionally, building owners can leverage this marketplace to differentiate their buildings from other assets by showcasing the energy efficiency of their properties. This fosters healthy competition among buildings, encouraging them to adopt more energy-efficient practices. To establish such a marketplace, various approaches can be employed. OpenSea, the pioneering and largest web3 marketplace for NFTs, presents a viable option for showcasing buildings' dNFTs alongside other NFTs. Alternatively, communities can develop their own customized marketplace to cater to their specific requirements, utilizing tools such as Web.js and React.

4. PROOF OF CONCEPT: DAPP IMPLEMENTATION

In this section, a synthetic case study approach is selected to test the proposed framework's feasibility and better illustrate its application. A synthetic case study stimulated a scenario for exemplary energy data consumption by a sample university building and verifying the correct function of dNFT and FT rewards. All codes and files used for dApp implementation are available under open-source license[1].

4.1 Digital Twinning

This section implements Module B of the proposed framework using a synthetic case study approach. For this purpose, we selected Bishop-Favrao Hall (BFH), which is located at the Myers-Lawson School of Construction in Virginia Tech, as a sample building for our implementation. As shown in Figure 6, the BIM of BFH was created using Revit software. To transform the model into a digital twin (DT), energy data is required. Due to data confidentiality concerns regarding BFH and the synthetic nature of this study, a publicly available dataset was utilized as the primary source for energy consumption data (NREL, 2021) Since the building is in Virginia, we used typical commercial building data from the state for our analysis.

To assess the energy performance of BFH, we compare its average daily energy consumption, based on our dataset, with the average daily energy consumption of universities (EIA, 2016). A three-week scenario is designed to evaluate the system's performance and feasibility. Equation 1 is used to establish a performance baseline. The BFH has a total square footage of 26,238, and the average annual kWh consumption for universities is 18.9 (EIA, 2016). Using the equation, the baseline for daily energy consumption is set at 13,547. Figure 6-b illustrates the BFH energy performance. According to the diagram, if the actual energy consumption is within a ten percent range

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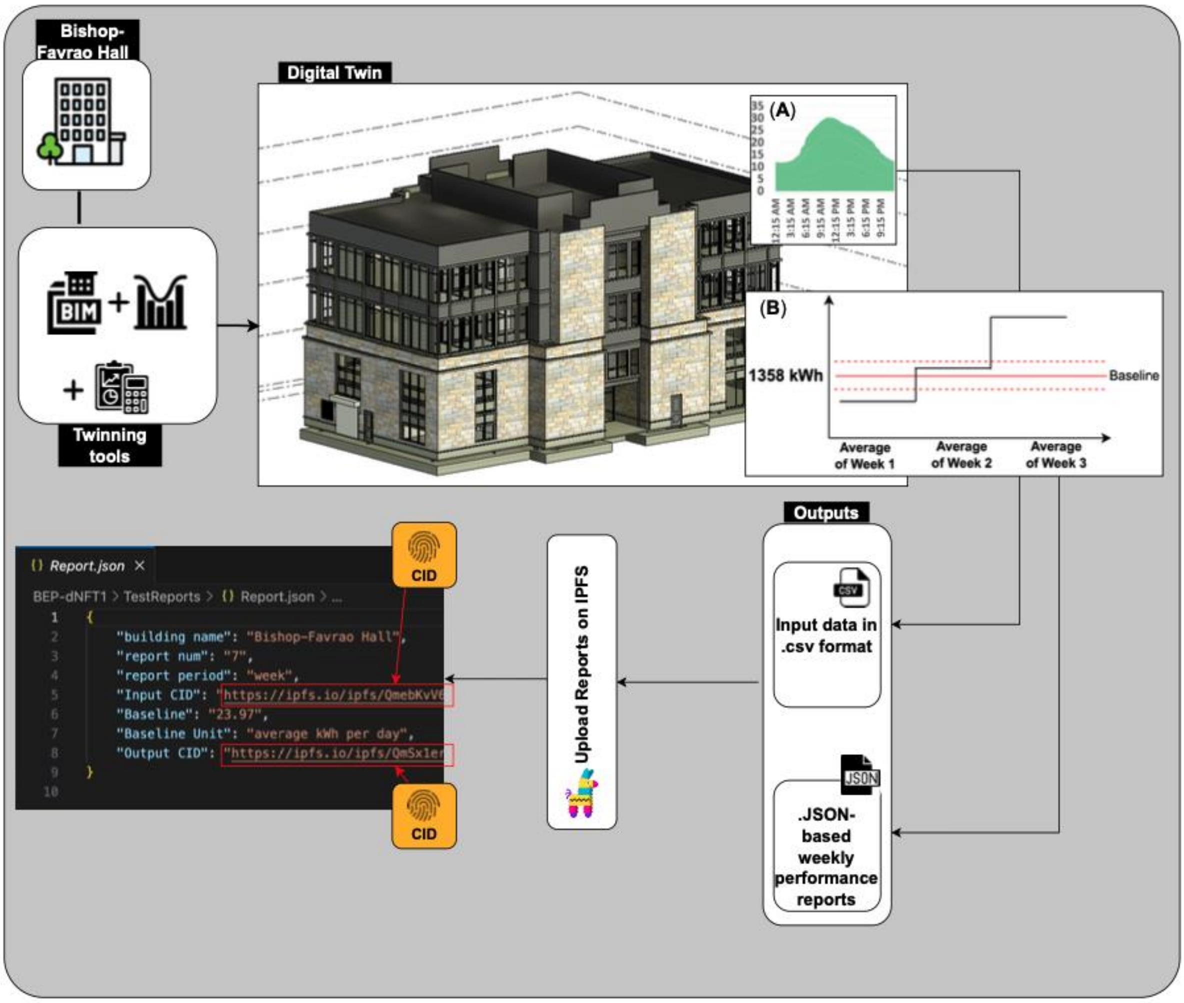
[1] https://github.com/h-naderi/BEP-dNFT1

above or below the average consumption, the performance report indicates normal performance. However, if the daily energy performance exceeds or falls below the average consumption by more than 10 percent, the report indicates good or bad performance, respectively. Based on this explanation, the BFH demonstrates good performance in the first week, normal performance in the second week, and bad performance in the third week of the scenario.

$$\boldsymbol{Average\ kWh\ per\ day} = \frac{(\boldsymbol{Total\ square\ footage}) \times\ (\boldsymbol{Average\ kWh\ per\ year})}{\mathbf{365}} \qquad (1)$$

In accordance with our proposed framework explained in section 3.4, the daily input energy data is prepared in comma-separated values (CSV) format and promptly uploaded to the IPFS. Likewise, the processed energy performance report is prepared in JavaScript Object Notation (JSON) format and uploaded to IPFS. The received CIDs will be used for the subsequent steps of the implementation. Although this study chose BFH as its case study, it should be noted that this approach can be extended to other types of buildings, including residential and industrial, as it primarily relies on two fundamental requirements: access to the building's energy meters and its BIM. As long as energy consumption data and a BIM are available, the proposed framework can be adapted to evaluate energy performance, regardless of the building's function or type. By normalizing energy consumption metrics based on square footage and typical performance benchmarks for specific building categories, the system ensures scalability and applicability across diverse building types. This flexibility underscores the broader potential of the framework to support energy performance evaluation beyond tertiary buildings like BFH.



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    "Baseline": "23.97",
    "Baseline Unit": "average kWh per day",
    "Output CID": "https://ipfs.io/ipfs/QmSx1er
}
```

Figure 6: Workflow of Digital Twin module.

```
import "@chainlink/contracts/src/v0.8/ChainlinkClient.sol";
import "@chainlink/contracts/src/v0.8/ConfirmedOwner.sol";

/**
 * Request testnet LINK and ETH here: https://faucets.chain.link/
 * Find information on LINK Token Contracts and get the latest ET
 */

/**
 * THIS IS AN EXAMPLE CONTRACT WHICH USES HARDCODED VALUES FOR CL
 * THIS EXAMPLE USES UN-AUDITED CODE.
 * DO NOT USE THIS CODE IN PRODUCTION.
 */

contract DataCollector is ChainlinkClient, ConfirmedOwner {
    using Chainlink for Chainlink.Request;

    uint256 public data;
    bytes32 private jobId;
    uint256 private fee;

    event RequestData(bytes32 indexed requestId, uint256 data);

    function getData() external view returns (uint256){
        return data;
    }
    /**
     * @notice Initialize the link token and target oracle
     *
     * Sepolia Testnet details:
     * Link Token: 0x779877A7B0D9E8603169DdbD7836e478b4624789
     * Oracle: 0x6090149792dAAeE9D1D568c9f9a6F6B46AA29eFD (Chainl
     * jobId: ca98366cc7314957b8c012c72f05aeeb
     * setChainlinkToken(0x326C977E6efc84E512bB9C30f76E30c160eD06
     * setChainlinkOracle(0xCC79157eb46F5624204f47AB42b3906cAA40e
     */
```

```
import "@openzeppelin/contracts@4.6.0/token/ERC721/ERC721.sol";
import "@openzeppelin/contracts@4.6.0/token/ERC721/extensions/ERC
import "@openzeppelin/contracts@4.6.0/access/Ownable.sol";
import "@openzeppelin/contracts@4.6.0/utils/Counters.sol";
import "./Data Collector.sol";

contract dynNFT is ERC721, ERC721URIStorage, Ownable {
    using Counters for Counters.Counter;

    DataCollector dc= DataCollector(0xbB23bDFC95F7E6CfC08c6E12A19
    uint256 actPerformance=dc.getData();

    Counters.Counter private _tokenIdCounter;
    string[] IpfsUri=["https://gateway.pinata.cloud/ipfs/QmXrmG7P
    "https://gateway.pinata.cloud/ipfs/QmUnJKYAzzRqo3nGBWWahRucBK
    "https://gateway.pinata.cloud/ipfs/QmQYkNqU3bjTUP3dv3BsuCM6qC
    // Metadata information for each stage of the NFT on IPFS.


    function setURI(string memory _ipfs) external onlyOwner(){
        IpfsUri.push(_ipfs);
    }

    function getURI() public view returns (string[] memory){
    return IpfsUri;
}



    uint interval;
    uint lastTimeStamp;

    constructor(uint _interval) ERC721("dNFTs", "dNFT") {
        interval=_interval;
        lastTimeStamp=block.timestamp;
    }

```

```
pragma solidity ^0.8.0;

import "@openzeppelin/contracts/token/ERC20/ERC20.sol";
import {dynNFT as DNFT} from "./dynamicNFT.sol";

contract TokenMinter is ERC20{

    DNFT dNFT = DNFT(0xe469a61972d426eaaE30c0Db0FDAc378106e8Ee
    uint256 reward=dNFT.BEPStage(0);

    //Initialization of ERC20 contract and definition of toker
    constructor() ERC20("Building Energy Performance Tokens",

    //definition of decimals for tokens.
    function decimals() override public pure returns (uint8) {
    return 0;
    }

    function mint() external{
        if (reward==2){
            _mint(msg.sender, 2);
        }
        else if (reward==1){
            _mint(msg.sender, 1);
        }
    }

}
```

Figure 7: Smart contract codes: (a) Smart contract for collecting data; (b) Smart contract for generating and updating dNFTs; (c) smart contract for rewarding FTs.

4.2 Smart Contracts Development

In this section, three main smart contracts were implemented using the Solidity language and compiled using Remix, an open-source Integrated Development Environment (IDE) for Solidity. The first contract developed is the DataCollector smart contract, which plays a fundamental role in retrieving data and performance reports. In

Solidity, the inheritance feature was utilized to derive DataCollector from the "ChainlinkClient" and "ConfirmedOwner" smart contracts in the Chainlink library. These parent contracts allow secure data retrieval from the DON since only the contract owner can trigger and receive the data. This contract was encoded based on the required functions defined in the proposed framework (refer to Figure 7-a).

The next smart contract is dynamicNFT, responsible for representing BFH's energy performance as a unique and immutable Non-Fungible Token (NFT). This contract inherits the features of the ERC-721 standard smart contract from OpenZeppelin, which provides secure standard functions without the need for rewriting them. The smart contract is also connected to the DataCollector contract to check performance reports using the "CheckUpkeep" function and update the NFT status using the "growBEP" function (see Figure 7-b). The third smart contract is TokenMinter, which rewards users based on their current dynamicNFT status. To accomplish this, the dynamicNFT smart contract is imported to check whether a user is eligible for rewards or not. TokenMinter also inherits the features of the ERC-20 standard smart contract from OpenZeppelin. The "decimals" field of the TokenMinter contract is set to zero, preventing arbitrary amounts from being exchanged in the FTs (see Figure 7-c). After developing all the smart contracts, they were compiled and deployed on the Goerli Testnet, and the contract addresses were saved for further processing. This testnet helps us to test functionality of our smart contracts and dApp without sacrificing users' financial sources.

4.3 Implementation process

This section presents the implementation process of the proposed dApp. The process involves eight components, including users, the dApp owner, DT, three smart contracts (explained in section 4.2), and the blockchain network, as shown in Figure 8. The implementation follows ten steps, listed alphabetically from (a) to (j). Before executing the steps, some preparation is required. First, the dApp owner's wallet is funded with Goerli ETH to cover transaction costs. Then, the smart contracts are funded with LINK tokens to facilitate interactions with the DON and automate smart contract operations. The dApp owner, who deployed the contracts, initiates the data transfer process between the DT and the DataCollector contract by executing the requestVolumeData() function (step a). This function sends a transaction to the blockchain network. In step b, the DataCollector contract retrieves performance data from the DON and IPFS, following the approach explained in section 3.5.

Furthermore, the dynamicNFT contract obtains the performance data from the DataCollector contract (step c) and mints the associated dNFT using the safeMint() function (step d). The transaction is sent to the blockchain network. The timestamp of the block containing the transaction is used to track the time and update the dNFT. Once the defined time threshold is reached, the performUpKeep() function updates the dNFT based on the building's energy performance (step e). Step f demonstrates that users can securely view the latest version of the building's energy performance on the Opensea website, which is a popular NFT marketplace. In step h, the TokenMinter contract is linked to the dynamicNFT contract to store the latest performance data in a variable. This variable is then used to determine if users are eligible for receiving rewards. When the performance score exceeds 110, the FT token is minted and sent to the users' wallets.

4.4 Results

This section demonstrates the outcomes of the dApp implementation, underscoring the feasibility and applicability of the proposed framework over a three-week test run. Throughout the test period, six groups of operations were executed, following the steps outlined in the implementation map (refer to Figure 8) that substantiates the dApp's functionality. Table 1 lists these operation groups, with the first two rows representing preparation processes and the remaining rows corresponding to the main functionality of the dApp. The table also displays the number of transactions in each operation group, along with the primary smart contract associated with it. A critical aspect of showed results is the computational expense incurred by these operations, quantified through Gas Usage displayed in the table's final column. Gas, in this context, signifies the computational efforts needed for blockchain operations (Ethereum, 2022).

At the conclusion of the testing period, the dNFT representing the energy performance of BFH was successfully displayed on the OpenSea NFT marketplace. This integration served as the frontend for our developed dApp, allowing users to interact with our platform and securely access the latest energy performance data of BFH. Furthermore, the functionality of the TokenMinter contract was validated as a FT-based reward was successfully distributed to the user. These outcomes confirm the effectiveness of our proposed framework in engaging users to actively participate in building energy performance programs. Figure 9 showcases some of these final results, including the BFH's energy performance displayed as a dNFT on the OpenSea website (Figure 9-a), the successful update of the dNFT using the performUpKeep() function in our smart contract (Figure 9-b), and the reward received in the user's Metamask wallet (Figure 9-c).

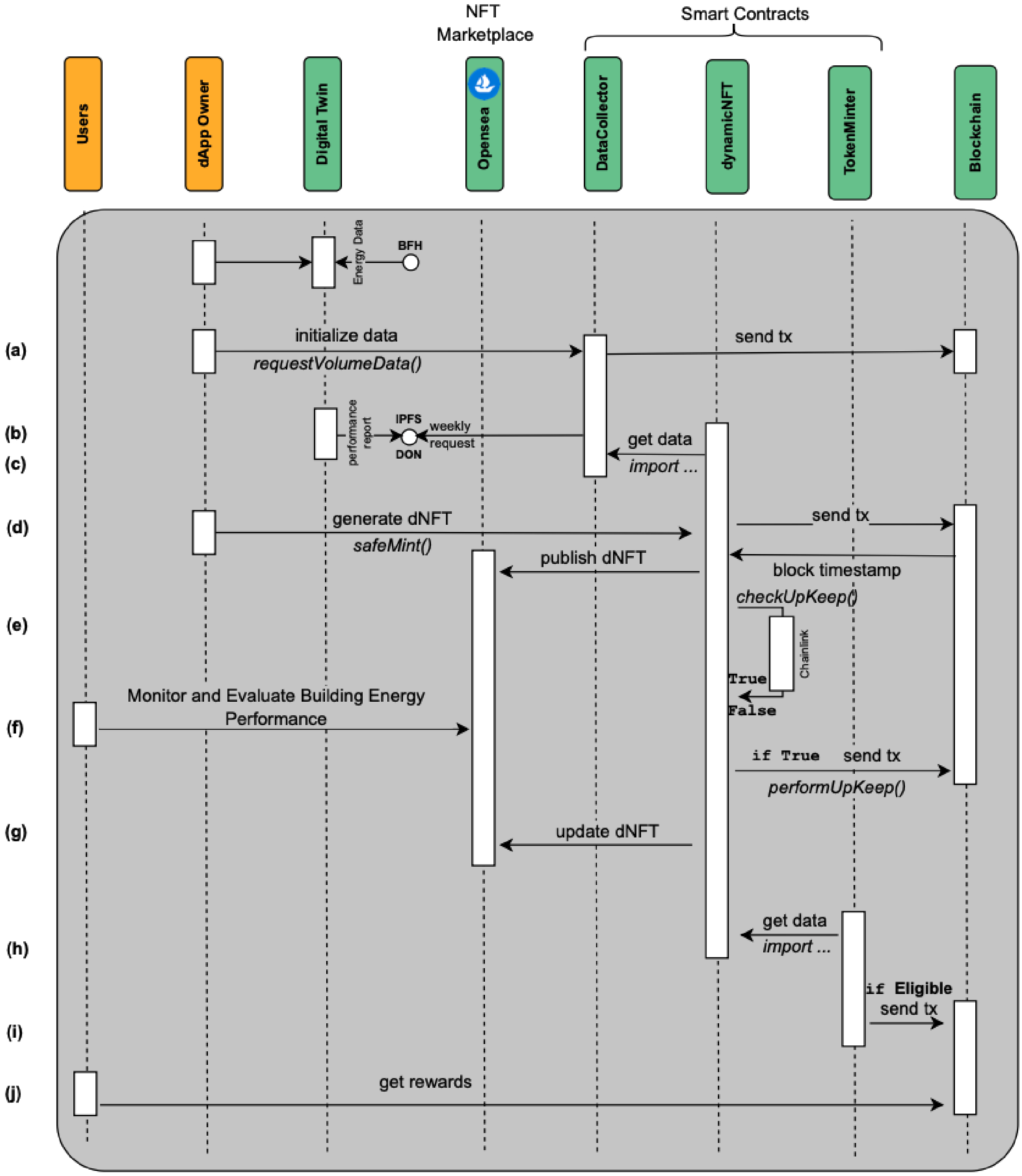
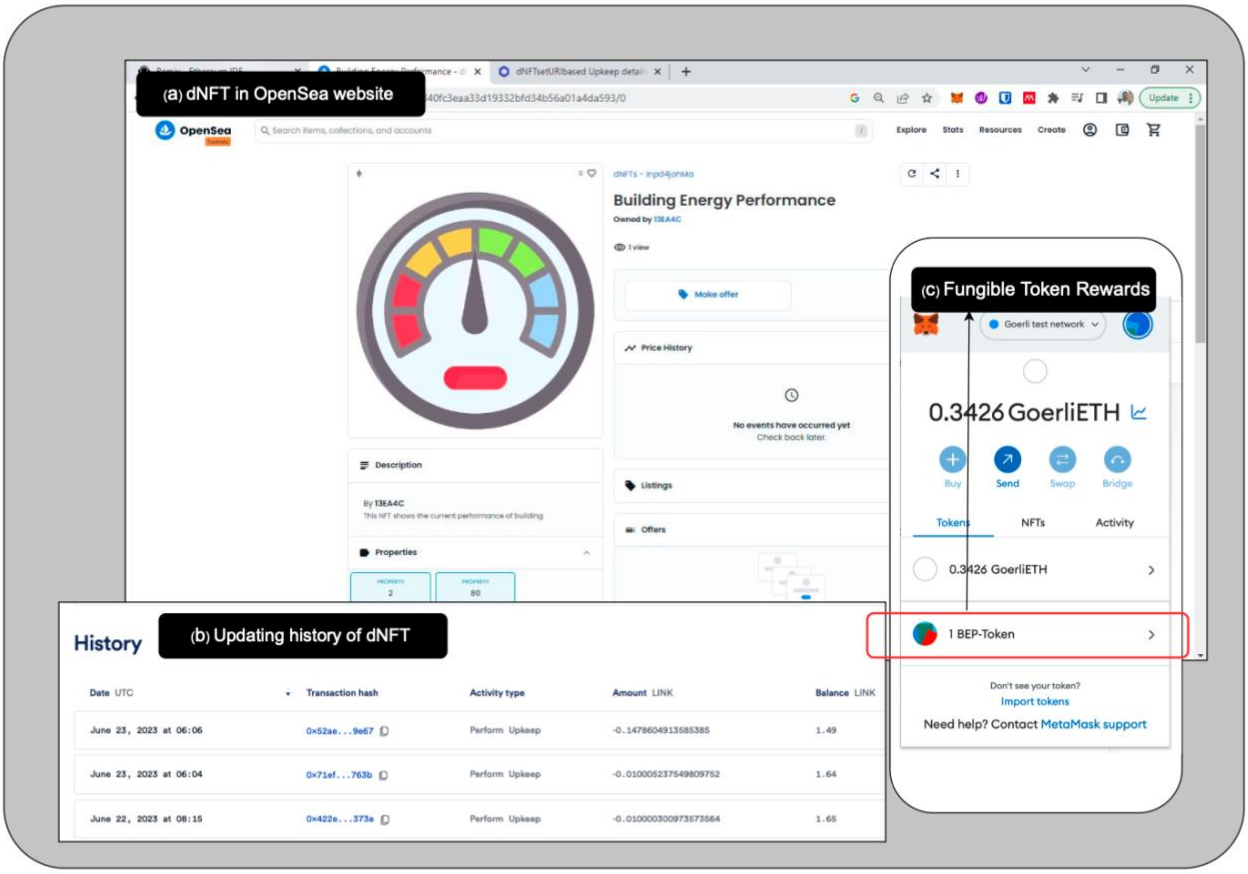


Figure 8: Sequence map of dApp implementation.

Table 1: Transaction results and associated computational expense of implementing dApp on Goerli testnet.

Operation Group	Number of Transactions	Step	Smart Contract	Gas Usage
Contract deployment	3	Preparation	All contracts	17,013,867
Fund DON and Chainlink contracts	3	Preparation	Datacollector dynamicNFT	232,496
retrieve BFH performance data for 3 weeks	3	(b)	Datacollector	6,172,187
Generate dNFT	1	(d)	dynamicNFT	1,725,180
Update dNFT	3	(e)	dynamicNFT	4,807,212
Send Reward to users	1	(i)	TokenMinter	269,940



Date UTC	Transaction hash	Activity type	Amount LINK	Balance LINK
June 23, 2023 at 06:06	0x52ae...9e67	Perform Upkeep	-0.1478604913585385	1.49
June 23, 2023 at 06:04	0x71ef...763b	Perform Upkeep	-0.010005237549809752	1.64
June 22, 2023 at 08:15	0x422e...373e	Perform Upkeep	-0.010000300973573564	1.65

Figure 9: Outputs of the dApp implementation: (a) Actual performance of BFH represented as a dNFT in the NFT marketplace; (b) History of dNFT updates based on performance reports; (c) FT reward received in the user's wallet.

The proposed system achieves decentralized architecture through the integration with the blockchain foundation, as shown in Figure 8. Unlike centralized systems that rely on intermediary-based workflows, our implementation distributes data across the blockchain network, ensuring resilience and eliminating single points of failure. Transactions, such as data retrieval and dNFT updates, are securely processed on-chain, guaranteeing immutability and tamper-proof records. For instance, every transaction submitted, including minting and updating dNFTs, is time-stamped and integrated into a specific block. This chaining of blocks ensures that once data is recorded, it cannot be altered without consensus across the entire network. This immutability directly addresses reliability issues in centralized systems, where data manipulation or loss can compromise trust. By decentralizing operations, the system enhances transparency, making energy performance data verifiable by all stakeholders without relying on a single governing authority.

The integration of smart contracts and tokens adds significant layers of automation, traceability, and user engagement to the system. The DataCollector, dynamicNFT, and TokenMinter smart contracts automate critical processes, including data retrieval, dNFT generation, performance updates, and reward distribution. For example, the performUpKeep() function ensures the automatic updating of dNFTs based on energy performance, while the TokenMinter contract incentivizes users by rewarding energy-efficient behavior with FTs. This traceable and automated workflow minimizes human intervention, reducing errors and ensuring consistent execution. Furthermore, the use of dNFTs for visualizing energy performance provides traceability by linking real-time performance data to a transparent and immutable blockchain ledger. Users can securely view performance reports on platforms like OpenSea, enhancing trust in the system. By combining decentralization, automation, and tokenization, the proposed framework effectively addresses the challenges of reliability, transparency, and engagement outlined in traditional systems.

5. DISCUSSION

5.1 Cost Effectiveness and Scalability

Evaluating the financial efficiency of proposed system is crucial, especially given that each transaction on a blockchain network is subject to a fee (NIST, 2022). This assessment plays a pivotal role in determining the dApp's adoption rate and scalability within the industry. The transaction fee is derived by multiplying the gas usage with the gas price. (Ethereum, 2022). In our experiments conducted on the Goerli testnet, the observed gas price was about 5 gwei, which translates to 5×10^{-9} ETH. Utilizing the ETH to USD exchange rate at the time of testing ($1,846), we have calculated the transaction costs, which are detailed in the last column of the provided table. However, it is imperative to acknowledge that these costs are significantly influenced by the choice of blockchain network for the dApp's execution. When deployed on the Mainnet network, transaction fees are subject to variation. Furthermore, gas usage is dependent on the network's condition during the execution of these operations. As a result, the initial cost for deploying the smart contracts and their preparation was estimated at approximately $160, as indicated in the first two rows of Table 2. The ongoing weekly expenses for data retrieval and dNFT updates are roughly $40 per building.

Table 2: Transaction cost of implementing dApp on Goerli testnet.

Operation Group	Step	Gas Usage	Total Tx fee (eth)	Total Tx fee (USD)
Contract deployment	Preparation	17,013,867	0.0850693	157.038
Fund DON and Chainlink contracts	Preparation	232,496	0.0011625	2.146
Retrieve BFH performance data for 3 weeks	(b)	6,172,187	0.0308609	56.969
Generate dNFT	(d)	1,725,180	0.0086259	15.923
Update dNFT	(e)	4,807,212	0.0240361	44.371
Send reward to users	(i)	269,940	0.0013497	2.492

Table 3 presents a comparison of transaction fees between the Ethereum Mainnet and two Layer 2 blockchain networks: Polygon and Binance. At the time this discussion was drafted, the average gas fees for Ethereum and Polygon were recorded at 50 gwei (ETH, 2024; Polygon, 2024) while Binance exhibited a lower rate of 4 gwei (Binance, 2024). These gas fees, in conjunction with the unit prices of the respective blockchain networks, serve as the basis for calculating the associated costs. The costs for each network are divided into two main categories: preparation costs and weekly costs. Preparation costs include all transaction expenses incurred before the dApp becomes operational, such as contract deployment, smart contract linking, and initial funding. On the other hand, weekly costs account for the expenses related to data updates and the distribution of rewards to users for one building.

Table 3: Comparison of costs of implementation on our testnet with Ethereum, Polygon, and Binance networks.

Operation Category	Goerli Total Tx fee (USD)	ETH Mainnet Total Tx fee (USD)	Polygon Total Tx fee (USD)	BSC Total Tx fee (USD)
Preparation cost	$159.18	$1,563.77 (+882%)	$1.08 (-99%)	$39.59 (-75%)
Weekly cost	$39.92	$392.15 (+882%)	$0.27 (-99%)	$9.93 (-75%)

Ethereum displays an average cost increase of +882% across all operations compared to our tests. This substantial rise underlines the financial implications of deploying and managing our proposed system on the Ethereum Mainnet, attributed to its elevated gas prices. Such a significant cost surge suggests that full-scale adoption on this platform might not be economically feasible for many small to medium-sized enterprises (SMEs). However, opting for alternative networks like Polygon could mitigate these financial challenges. Polygon shows a remarkable cost reduction, averaging -99.3% across all operations in comparison to our test network, demonstrating its efficacy in creating a cost-effective environment conducive to scalable future adoption (DeNicola & Farran, 2022). Similarly, Binance records a cost decrease of -75.1%. Although not as pronounced as Polygon, the Binance Smart Chain (BSC) provides a less expensive alternative to the Ethereum Mainnet, offering a compromise between cost, performance, and security.

The current version of our development retrieves building performance data on a weekly basis. Consequently, the system must execute step (b) of the transaction operation group (as outlined in Figure 8), specifically the “getData” function, each week. While the current weekly update schedule results in a manageable volume of transactions between smart contracts and the Decentralized Oracle Network (DON) for data retrieval, an increase in the number of users could alter this situation. Such a change may necessitate the adoption of a more scalable blockchain network than Ethereum, such as Polygon. Notably, Polygon is capable of processing over 65,000 transactions per second, a significant improvement over Ethereum's capacity of 30 transactions per second (Blockchain Council, 2022).

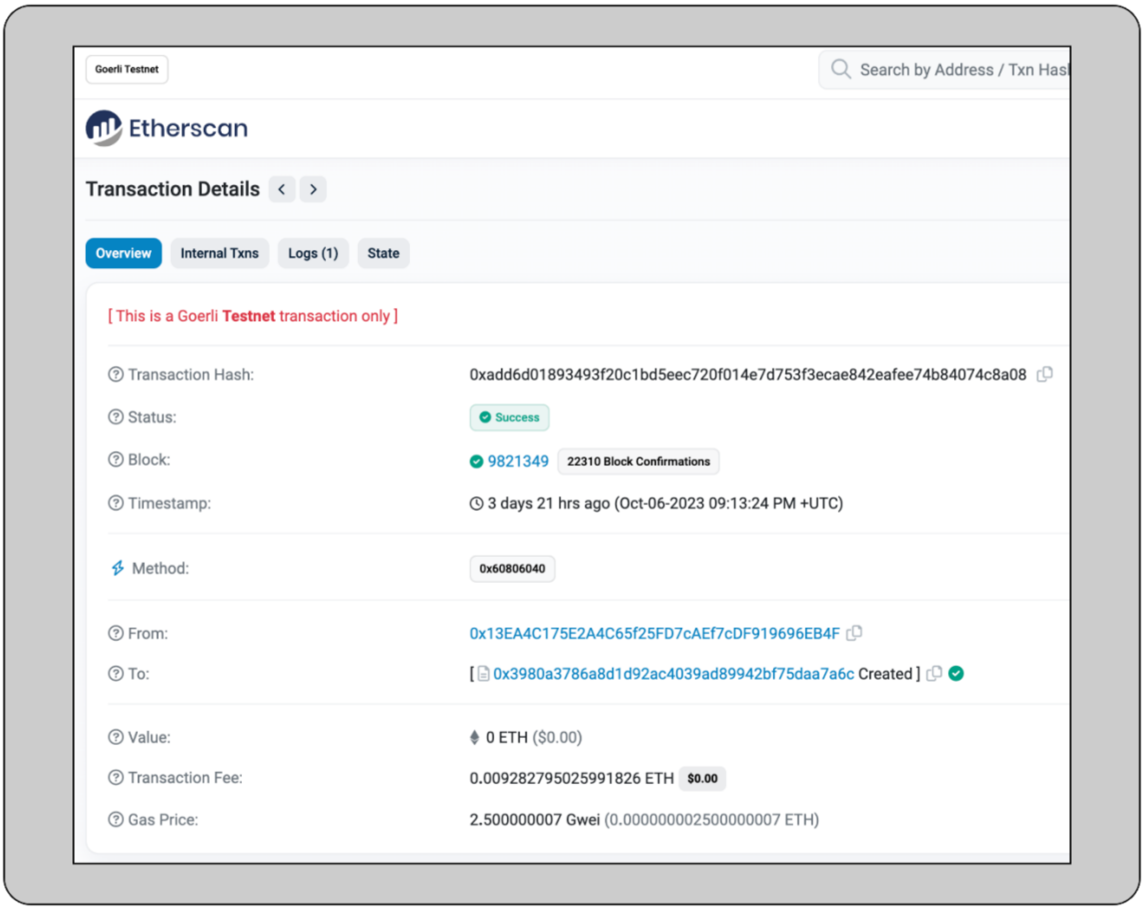
5.2 Security and Privacy

When handling building and occupant data, it is crucial to ensure security and privacy. In this study, public-private key cryptography is employed for transaction signing, allowing only authorized entities to interact with the system. This approach ensures that creating transactions or adding data on-chain is feasible only when the private key is utilized for signing. Consequently, this method secures transactions against forgery. Maintaining the anonymity of users' identities is a challenge in permissionless blockchains. The prototype proposed in this study is developed on the Ethereum network, which operates on a pseudonymous system. This characteristic of public blockchains preserves users' anonymity, linking all activities to their public keys (W. Wang et al., 2019). For instance, Satoshi Nakamoto, the pseudonymous founder of Bitcoin, remains unidentified, illustrating the anonymity provided by such systems (Adams & Powell, 2023). Therefore, under the current proposed system, the identities of all companies, owners, and other participants are referred to by their public keys to ensure their protection. However, participants have the option to disclose their names and share the energy tracking of their buildings publicly. This disclosure can validate their building's performance and potentially increase its value based on demonstrated efficiency. Such transparency enables building owners to foster an energy-conscious image, thereby attracting more customers in a competitive market.

Another critical aspect concerning security and privacy is the accessibility of data within transactions, which depends on the nature of the transaction content. The platform in question categorizes transactions into two main types: (1) transactions related to the receipt of FTs as rewards; and (2) transactions involving data retrieval from DON. For the first category, transactions are exclusively initiated by participants who sign the transaction with their private keys to claim their FTs. These transactions merely record the quantity and timing of the FTs distributed, which is the information intended to be public to enhance occupant engagement. Conversely, the second category involves interactions between smart contracts and the DON. These transactions safeguard confidential information because: (1) the DON's public keys are dynamic and cannot be tracked; and (2) performance data is processed through the private functions of “checkUpKeep()” and “updateDNFT()”. Furthermore, access control policies can be applied on IPFS system in to limit the exposure of sensitive data to only authorized entities, thereby maintaining the public verifiability of the hashes stored on the blockchain. For exceptionally sensitive data, encryption can be utilized on IPFS, with the decryption keys managed off-chain by authorized individuals. The encrypted hashes recorded on-chain would thus conceal the actual content. In summary, through public-key signatures, pseudonymous interactions, encrypted off-chain storage and private computation functions - the system enables securing transactions while also catering to variable privacy priorities based on data sensitivity levels. Participants maintain control over what information they wish to disclose publicly vs keep restricted.

5.3 Reliability

Although there is no major standardized metric for measuring reliability in the context of this study (Hripcsak & Rothschild, 2005), the proposed system demonstrates higher reliability compared to centralized systems in several key ways. First, as seen in Figure 6 and Table 1, the system successfully created 12 transactions, all of which were securely submitted to the blockchain network as on-chain transactions. The Figure 10 showcases one of these 12 transactions, submitted on block 9821349, with a timestamp marking its creation. The inclusion of this transaction in a block ensures that it is part of a sequential, immutable chain of data. Unlike centralized systems, where data is stored on a single server and is vulnerable to tampering or unauthorized changes, the blockchain's decentralized architecture ensures that this transaction is cryptographically secured and cannot be altered, enhancing the overall reliability of the system. Moreover, the screenshot demonstrates key transaction details, including the "From" address (0x13EAC...E4F) and the "To" address (0x3980a...a7a6), both of which are unique identifiers on the blockchain. These addresses not only verify the origin and destination of the transaction but also provide complete transparency and traceability of the data exchange process. This again shows the differences between this system and centralized systems, where the origin and destination of data are often obscured and susceptible to misrepresentation or manipulation. The ability to publicly verify transaction origins and destinations on the blockchain reinforces trust in the system, ensuring that stakeholders can rely on the accuracy and authenticity of performance data without intermediaries.



[This is a Goerli **Testnet** transaction only]

Transaction Hash: 0xadd6d01893493f20c1bd5eec720f014e7d753f3ecae842eafee74b84074c8a08

Status: Success

Block: 9821349 22310 Block Confirmations

Timestamp: 3 days 21 hrs ago (Oct-06-2023 09:13:24 PM +UTC)

Method: 0x60806040

From: 0x13EA4C175E2A4C65f25FD7cAEf7cDF919696EB4F

To: [0x3980a3786a8d1d92ac4039ad89942bf75daa7a6c Created]

Value: 0 ETH ($0.00)

Transaction Fee: 0.009282795025991826 ETH $0.00

Gas Price: 2.500000007 Gwei (0.000000002500000007 ETH)

Figure 10: Transaction sample for implementing the proposed system.

Furthermore, the timestamp and block number, combined with the immutable nature of the blockchain, highlight the resilience of the system. Each transaction, once validated and included in a block, is permanently recorded on the blockchain, which operates as a decentralized ledger distributed across multiple nodes. This means that even if one or more nodes in the network fail or are compromised, the data remains intact and verifiable across the remaining nodes. Compared to centralized systems, where a single server outage or data breach could compromise the integrity of the entire system, the blockchain-based approach offers a significantly more reliable and robust infrastructure for energy performance monitoring. This ensures the trustworthiness of the system for both energy performance tracking and user engagement in energy efficiency programs.

5.4 Implications

Sustainable built environment: While the proposed framework primarily focuses on monitoring energy as a key performance indicator (KPI) for building sustainability, it has the potential to be expanded to include other KPIs. By incorporating additional factors such as Indoor Air Quality (IAQ), a comprehensive collection of dNFTs can be generated to fully represent the sustainability of a built environment. This extension would be beneficial to both building owners and occupants. Occupants seeking specific KPIs, such as a certain level of IAQ and energy performance, can rely on the dNFT reports and historical KPI data. Additionally, building owners can showcase the excellent performance of their buildings to prospective occupants, thereby increasing demand and potentially commanding higher prices. Furthermore, the framework can be extended to embrace the next era of AEC industry and metaverse. It holds the potential to fully represent DTs within a virtual world, enabling the ownership of DTs and their associated information. Therefore, it opens up new possibilities for collaboration, innovation, and enhanced experiences in the AEC industry and the metaverse. This evolution can contribute to the advancement of sustainable built environments and propel the industry into the next era.

Carbon credit market for built environment: The lack of a comprehensive, transparent, and verifiable platform for evaluating building energy credits has hindered the establishment of a successful carbon credit market in the building industry (Blaufelder et al., 2021). This knowledge gap also limits our ability to effectively select strategies for reducing carbon footprints in the built environment (Vara, 2010). To address these challenges, the proposed platform in this study can be leveraged to bring a carbon credit market to the built environment. Instead of presenting dNFTs on the OpenSea website, a new web3 platform based on carbon credits can be designed. On this platform, each building would be associated with its dNFT, representing its carbon credits. Through the blockchain-based market, carbon credits can be securely exchanged between different buildings, incentivizing them to improve their carbon footprint and ultimately reducing the overall carbon emissions in the built environment. By leveraging the proposed platform, the establishment of a carbon credit market in the built environment becomes feasible, paving the way for increased transparency, accountability, and reduced carbon emissions.

Novel building sustainability certifications: Various building sustainability certifications, such as Leadership in Energy and Environmental Design (LEED) (Soomro, 2022), the Building Research Establishment Environmental Assessment Method (BREEAM), Green Star, and WELL, have been developed to assess and mitigate the environmental impact of buildings (Casey, 2023). LEED, a widely recognized certification, evaluates buildings based on factors such as energy efficiency, water use, and materials, while BREEAM emphasizes lifecycle performance and sustainable practices throughout design, construction, and operation. Similarly, WELL focuses on health and well-being, and Green Star considers environmental and social impacts specific to regional conditions (DesignHorizons, 2024). Despite their success, these certifications often rely on static evaluations and periodic audits, which may not reflect real-time performance or address data accessibility and transparency challenges.

In contrast, our decentralized and NFT-based platform provide a dynamic approach to certifying buildings based on real-time performance data, enhancing transparency and trust in the certification process. By leveraging the traceability and accessibility of NFTs, the proposed platform ensures unique and reliable identification for each building, reducing potential discrepancies and fostering trust among stakeholders. This approach complements and extends the capabilities of existing certifications, providing a more granular and dynamic evaluation that aligns with evolving sustainability goals. In conclusion, integrating decentralized and NFT-based technologies into building sustainability certifications holds promise for achieving more accurate, transparent, and trustworthy assessments of environmental performance across the built environment (Shojaei & Naderi, 2024).

BIM and Blockchain synergy: The integration of BIM with blockchain technology offers transformative potential for advancing sustainable building certifications (Dong et al., 2024; Idrissi Gartoumi, 2024). BIM can provide a repository of building data, such as geometry, spatial relationships, and material specifications, while blockchain ensures immutable, transparent, and decentralized storage of this information. By linking BIM data with blockchain, the proposed framework can support multiple certification systems, including LEED, BREEAM, WELL, and Green Star. This approach enhances trust in certification processes by providing verifiable data on building performance metrics. Additionally, using blockchain to store BIM data simplifies cross-platform accessibility, enabling seamless integration of various sustainability KPIs, such as energy efficiency, indoor air quality, and material lifecycle assessments. Building upon the synergy between BIM and blockchain, the incorporation of digital twins technology and NFTs can further enable the data ownership and knowledge exchange (Ly et al., 2024; Naderi, Ly, et al., 2024; Naderi & Shojaei, 2024), leading to improved productivity in the construction industry.

Innovative financing for sustainable projects: An exciting potential application of the proposed dNFT-based energy performance platform is the utilization of staking features for financing sustainable projects. The staking feature enables dNFT owners or building owners to generate funds and financial value. By staking their dNFTs, potential financiers or users can contribute to the financing and development of the owner's sustainable project. This process involves locking the dNFT in a smart contract for a specific period, subject to predetermined performance conditions, demonstrating a commitment to the dNFT owner. In this scenario, the owner of the dNFT or the building owner can receive funds if the specified performance criteria are met. In exchange for staking, users can earn additional tokens or monetary rewards derived from project savings and other financial benefits, incentivizing participation, crowdfunding, and enhancing the overall value of the sustainable project market. In conclusion, the integration of staking features within the dNFT-based energy performance platform introduces a novel approach to financing sustainable projects. It fosters collaboration between stakeholders, encourages financial support for environmentally friendly initiatives, and contributes to the growth and advancement of the sustainable project market. This innovative financing mechanism has the potential to drive positive change and accelerate the transition towards a more sustainable built environment.

5. DISCUSSION

The proof-of-concept section demonstrates the feasibility of the proposed framework. Nevertheless, there are still further steps remaining for scalable adoption and implementation of the proposed dApp. As a result, some of the main limitations of the framework and prototype is explored in this section. The framework is still reliant on the quality of data input. Thus, further assessments are needed prior to the establishment of the dApp to evaluate convergence and quality of energy data from buildings. Furthermore, although using a decentralized oracle as well as immediate upload of reports on immutable IPFS network improves decentralization and reliability, manipulation of input data can affect DT performance and consequently the whole dApp. Thus, a random check of input energy by the owner or an algorithm can address this limitation.

While the proposed token-based architecture offers valuable features such as immutability, provenance, and transparency, we acknowledge certain inherent limitations associated with blockchain technology that must be addressed. One significant drawback is the over reliance on miners for transaction ordering and the prevention of attacks like double spends through consensus mechanisms. Moreover, the blockchain itself is not optimized for data queries and analytics. Integrating data retrieval and processing with off-chain databases and analytics engines introduces additional potential vulnerabilities. Network congestion can also result in delays and lags in on-chain data flows. Lastly, key management remains a critical aspect that requires robust policies and secure storage practices to prevent the loss or exploitation of private keys. While the benefits outweigh the disadvantages for the specific use case discussed in this paper, these limitations must be considered when choosing technology and deploying configurations for industry-scale implementation.

Furthermore, evaluating building energy performance with proposed simple case is far from the real case performance assessment and a scalable implementation. Future studies are needed to define a real building energy performance assessment term into smart contract functions and dApp. The dApp structure is mainly designed to distribute FTs as a reliable way of incentivizing users; however, it doesn’t take any penalties, which can be considered as one of the framework limitations. However, the loss of receiving FTs in such an open-access system indirectly serves as a punishment tool. Another limitation of the framework is its applicability across different building typologies and states, such as newly built versus renovated projects. The variation in building designs, energy systems, and operational characteristics makes standardization of the framework across diverse cases challenging. Renovation projects, in particular, introduce complexities due to existing structural constraints, outdated energy systems, and incomplete digital records. These factors affect the accuracy and consistency of energy performance assessments within the dApp. Future work should explore methodologies that account for these variations, ensuring broader applicability across different building types and conditions.

To enhance practical implications, stakeholders, including architects, engineers, and building owners, can utilize this concept to bridge the gap between digital representations and physical performance. By integrating real-time energy performance data into blockchain-backed digital twins, architects can optimize designs for energy efficiency, engineers can monitor building systems transparently, and owners can demonstrate compliance with sustainability goals to stakeholders or regulators. Additionally, the framework can serve as a scalable tool for facility managers to incentivize occupants through tokenized rewards, ensuring active engagement in maintaining building performance.

Furthermore, the discussed comparative cost analysis has revealed significant economic considerations, particularly in the context of blockchain network selection. The study's demonstration on the Goerli testnet provides a baseline for understanding the cost dynamics at play, which are critical when considering the scalability of such a system. With Ethereum Mainnet exhibiting substantially higher costs and alternative platforms like Polygon and Binance Smart Chain offering more affordable transaction fees, our research highlights the importance of network choice in the wider adoption of blockchain applications in building energy performance.

We have published the source codes of this prototype under an open-source license to encourage the extension of dApp applications beyond the scope of this study. We have also identified four potential implications for advancing the sustainability of the built environment: (1) expanding the framework to include different key performance indicators (KPIs) that contribute to a better living space; (2) establishing a carbon credit market across the built environment to reduce carbon emissions; (3) utilizing the developed dNFTs as novel building sustainability certifications that address existing certification challenges; and (4) providing a new solution for improving financing in sustainability projects through the staking feature of NFTs.

In addition to these practical implications, this study sheds light on the broader relevance and future potential of blockchain technology in the AEC industry. The blockchain features can be utilized to develop potential solutions to address inherent challenges such as fragmented nature of industry, data ownership, and security, which are critical in overcoming current limitations in energy performance monitoring. The decentralized nature of blockchain allow to eliminate reliance on intermediaries, providing a robust foundation for real-time, verifiable performance tracking. As blockchain continues to evolve, its application in AEC can extend beyond energy monitoring to areas such as construction supply chain management, lifecycle asset tracking, and smart contract-based procurement. Future research should explore the integration of blockchain with emerging technologies, such as AI and IoT, to further enhance energy performance criteria and create a more sustainable built environment.

6. CONCLUSION

In this paper, we have introduced an automated dApp for building energy performance monitoring and engagement, which leverages the capabilities of digital twin and blockchain-enabled dNFTs and FTs. The proposed framework provides a novel solution that moves away from existing intermediary, silo-based, and tamperable monitoring mechanisms. The implementation of the framework consists of four main components: (1) the digital twin (DT); (2) the decentralized oracle network (DON); (3) smart contracts; and (4) the NFT marketplace. We have demonstrated a proof-of-concept based on a synthetic case study, utilizing the BFH building of Myers-Lawson School of Construction as a testbed for integrating the DT with a decentralized world in a reliable manner. The module automatically broadcasts the latest performance reports as JSON files on the immutable IPFS network. Addressing one of the main barriers in existing dApps, we have incorporated a decentralized oracle network (DON) to serve as a safe bridge between off-chain and on-chain worlds. This ensures the integrity and reliability of the data being utilized. For the third component, we have designed a network of smart contracts that automate the retrieval of data from the DON, generation and updating of dNFTs based on the latest performance reports, and the rewarding of FTs to engage users in building energy performance programs. To make the latest performance reports accessible and reliable, we have integrated the dNFTs with OpenSea, the largest NFT marketplace. This allows users to view the building's performance reports in the form of dNFTs, creating a real-time and trustworthy monitoring solution for building energy performance. Users who actively contribute to good energy performance are incentivized through FT rewards. The empirical results from our synthetic case study demonstrate the operational feasibility of our proposed solution. By seamlessly interfacing with digital twins and the DON, the system showcases an enhanced capacity for reliability, transparency, and occupant engagement in energy performance reporting.

Despite these implications, it is important to acknowledge that the current dApp has limitations and requires further steps to achieve widespread scalability. Future work should focus on incorporating real-world performance case assessments into smart contracts and reducing the dependence on the quality of input data. Furthermore, more research should be conducted to create a synergy between BIM, BEM, blockchain, and environment certifications. This can enhance the circularity and sustainability of our built environment, leading to an improved quality of life. In conclusion, this study presents a promising framework for building energy performance monitoring and engagement, driven by the integration of digital twin technology and blockchain-enabled tokens. The implications of this work extend beyond energy performance monitoring, offering opportunities to advance sustainability in the built environment through expanded frameworks, carbon credit markets, novel certifications, and innovative financing models.

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