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## EnerChain: A decentralized knowledge management framework for smart energy systems with smart manufacturing agents via blockchain technology

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### ABSTRACT

Energy management can be designed from different perspectives including production, distribution, and consumption. Focusing on consumption perspective, manufacturing systems can be enhanced by enabling smart machines as agents which operate with their own knowledge representation models in a shopfloor. These agents can benefit from industry 4.0 enablers like IoT including sensors, controllers, and actuators. This paper focuses on how these agents can interoperate with each other and exchange knowledge to optimize energy consumption. Since different knowledge models may not be capable of interacting with other ones based on their different provider semantics. This paper explores the application of blockchain technology for secure, decentralized storage and sharing knowledge models in smart energy systems. The research introduces EnerChain as a blockchain-integrated and a decentralized application (DApp) system prototype that employs smart contracts for access management and conflict resolution. It also incorporates the InterPlanetary File System (IPFS) for efficient off-chain storage, addressing scalability concerns. The feasibility and practicality of this approach are demonstrated through the development of EnerChain. The findings highlight the significant potential of blockchain technology in facilitating efficient knowledge model management for smart shopfloors. Additionally, an operational scenario has been evaluated as a case study for the proposed conceptual model to illustrate how it can solve energy conflicts in a smart environment. An impact analysis at the end of this research shows that EnerChain can make annual 27.5 TWh reduction in residential energy consumption which yields to annual 7.8 million tonnes reduction in CO<sub>2</sub> emissions and annual €8.25 billion financial benefits.

### 1. Introduction

The escalating demand for energy efficiency and the rapid expansion of renewable energy sources have spurred the evolution of smart energy systems (SES). Distinguished by the integration of advanced information and communication technologies, SES enables superior energy management and the optimization of energy consumption (Alsaigh et al., 2023). An integral facet for the effective functioning of such systems is the administration of knowledge models—computer-interpretable standard specifications pertaining to processes, facilities, or products (Rezapour Niari et al., 2021; Valilai and Houshmand, 2013). Additionally, smart agents play a pivotal role within smart energy systems, undertaking responsibilities such as collecting, monitoring, analyzing, and

executing actions based on system and stakeholder requirements. Consequently, the knowledge models employed by these agents become crucial for the adept management and optimization of smart energy systems (Karnouskos et al., 2012).

The convergence of innovative technologies, such as blockchain and knowledge management, holds significant promise in addressing challenges within energy management systems. Blockchain's decentralized and secure ledger system provides a transparent and tamper-resistant platform for recording and verifying energy-related transactions. This not only enhances data integrity but also promotes trust among stakeholders (Wu and Tran, 2018). Furthermore, the utilization of knowledge management systems facilitates the efficient organization, retrieval, and utilization of critical insights within the energy sector. By harnessing

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these technologies synergistically, organizations can streamline the flow of information, optimize decision-making processes, and foster collaborative efforts in managing and optimizing energy consumption (Nupap, 2022). The integration of blockchain and knowledge management emerges as a dynamic solution, offering enhanced reliability, transparency, and strategic insights for tackling complexities inherent in modern energy management systems (Mofatteh et al., 2021).

However, navigating the intricacies of knowledge model management within smart energy systems presents unique challenges. The potential for inconsistencies or contradictions arises from conflicting information or rules, as observed by Hicks, Dattero, and Galup (Hicks et al., 2002). Additionally, the demand for an efficient, secure, and transparent system capable of seamlessly storing, sharing, and resolving conflicts within knowledge models across diverse agents is a critical concern. The existing centralized system, according to Zheng et al. (Zheng et al., 2017), grapples with limitations like a lack of transparency and vulnerability to potential data manipulation. This scenario raises pivotal questions: Can blockchain emerge as a superior alternative to centralized knowledge management systems? And how can blockchain be effectively harnessed in the design of knowledge management systems to adeptly handle the storage, sharing, and resolution of conflicts within knowledge models?

This research is guided by several key objectives; Firstly, to conduct a comprehensive review of existing literature pertaining to knowledge management systems and blockchain. Secondly, to undertake an in-depth analysis assessing the feasibility of utilizing blockchain technology for the storage and sharing of knowledge models, considering it as an alternative to centralized databases. Thirdly, to propose a mechanism aimed at effectively resolving conflicts within knowledge models. Fourthly, to design and implement a practical prototype for the storage of knowledge models using blockchain technology, thereby contributing to the advancement of this innovative approach in the field. Lastly, to develop and evaluate a simple operational scenario describing how proposed conceptual model can resolve the detected conflicts among interoperable smart systems.

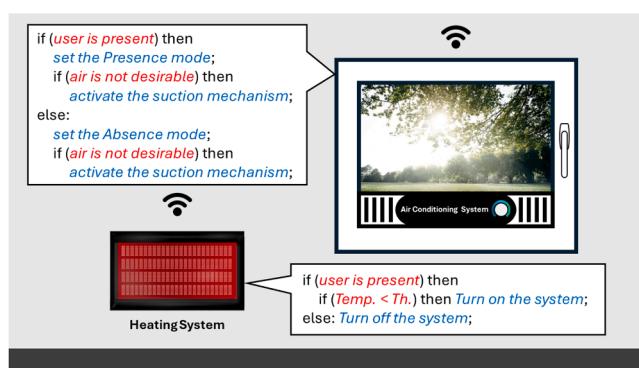
### 1.1. Research questions

To guide this investigation and address the challenges of integrating blockchain and knowledge management systems, this study explores the following research questions:

- How can blockchain technology enhance the transparency, security, and scalability of knowledge management systems in smart energy systems?
- What methods can be employed to detect and resolve conflicts among knowledge models from diverse providers?
- What role do smart contracts play in managing access, sharing, and incentivizing collaboration within a blockchain-based knowledge management system?

### 1.2. A simple scenario for problem illustration

Consider a smart home where various smart systems are connected to the Internet via Wi-Fi and operate based on their respective knowledge representation models. Fig. 1 illustrates two such smart systems in this home. On the right side of the Fig. 1, there is an advanced air conditioning system. This particular system, crafted by its manufacturer with a distinct knowledge representation model, functions based on three key parameters: ambient temperature, humidity, and cleanliness, obtained through interaction with the home's sensors. When occupants are present, the system engages a suction mechanism to mitigate temperature, humidity, or environmental pollutants (including particles, smoke, and other substances) when these exceed a predefined threshold. In contrast, in the absence of occupants, the system merely adjusts the temperature, humidity, and cleanliness to a predetermined standard, differing from



**Fig. 1.** Smart Air Conditioning and Heating Systems in the Smart Home with their brief knowledge model.

the configuration used when the home is occupied. On the left side of Fig. 1 is depicted a sophisticated heating system, developed by a separate manufacturer and employing an alternate knowledge representation model. This system monitors ambient temperature using room temperature sensors. Should the temperature decrease below a specified threshold, the system activates to elevate the room temperature to the desired level, as set within its knowledge model. Moreover, to enhance energy management, the system reduces the ambient temperature when the residence is unoccupied and restores it to the occupants' preferred level upon their return.

A potential conflict is observed upon an occupant's entry into the home: the air conditioning system, in accordance with its knowledge model, initiates the suction mechanism for air circulation, while the heating system concurrently activates to augment the ambient temperature. This concurrent operation results in energy inefficiency and a conflict concerning energy consumption. The primary objective of this research is to devise a strategy to mitigate this conflict.

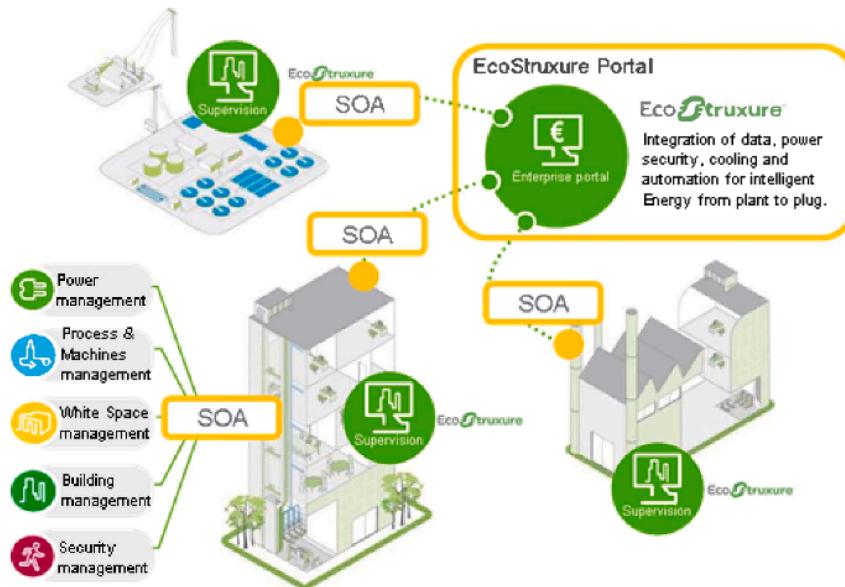
## 2. Literature review

The following section delves into the review of existing literature on various topics relevant to this thesis. It provides a comprehensive review of smart energy systems, knowledge models, IPFS, conflict resolutions, ontologies, and the challenges of developing a decentralized application. By critically examining relevant topics, this literature review aims to construct a solid theoretical foundation for this research, examine the current state of knowledge in these fields, and identify the gaps that this thesis seeks to address.

### 2.1. Knowledge management in the smart energy system

Knowledge models are computer-interpretable expressions of knowledge representation language or data structures that enable the knowledge to be interpreted by software and stored in a database or data exchange file. For instance, an energy consumption model in a smart building system, as shown in Fig. 2, monitors usage patterns by considering various factors such as power security, cooling, and automation patterns. These knowledge models interact with each other, make decisions, enhance energy efficiency, and minimize energy wastage (Mora et al., 2012).

Furthermore, efficient knowledge management models help optimize energy production, consumption, and saving in the energy system facility. Knowledge models help smart agents to collect, store, analyse, and share energy usage, transmission, and usage (Mostafa et al., 2022). This includes information about energy demand patterns and energy savings. The effective management and optimization of these knowledge models is an important step for the development of sustainable and efficient energy systems, which can help to save energy by reducing energy waste (Magyari et al., 2022).



**Fig. 2.** Smart Energy System management of Shopfloor (Mora et al., 2012).

## 2.2. Knowledge model ontologies and their role in knowledge management

Knowledge model ontologies provide a structured and formal representation of knowledge that is understandable by both humans and machines. They define classes, properties, and relationships between entities, enabling a semantic understanding of the model (Chandrasekaran et al., 1999). In smart energy systems, ontologies may be utilized to express complex ideas and relationships leading to advanced features like drawing conclusions and resolving conflicts. By offering a meaningful and well-ordered representation of knowledge that is accessible to everyone, including machines, ontologies improve knowledge management, making it more effective and efficient (Pritoni et al., 2021).

## 2.3. Conflict resolution strategies of the knowledge model

Knowledge Model conflicts can be defined as inconsistencies or contradictions within a knowledge model due to different or conflicting information or rules. For example, in a Smart Energy Management System, a conflict between two smart devices, such as a smart thermostat and smart air, may occur. For example, if the smart thermostat knowledge model may have the rule to increase the environ temperature by 20 degrees Celsius if the environ is unoccupied for 30 min and the smart air conditioner have the rule to maintain the temperature at 22 degrees Celsius, then there is a conflict between these two smart devices when the temperature is 22 degrees Celsius and the environ is left unoccupied for 30 min. This kind of conflict can create confusion in the smart energy system network and thereby challenge the integrity and consistency of the knowledge model shared across the network (Hicks et al., 2002).

There are various conflict resolution strategies that have been proposed to handle knowledge model conflict while maintaining the integrity of the knowledge base. The two common methods to resolve conflicts are manual resolution and automated resolution. Manual resolution involves human intervention for identifying and resolving conflicts in knowledge management (Mens, 2002). While this method might work for simple scenarios, it isn't scalable for large networks. Automated resolution involves algorithms to automatically identify and resolve conflicts. These can either be rule-based algorithms or machine learning based, where models are trained to learn conflict resolution strategies from data (Hicks et al., 2002).

One automated approach to solving the conflict in the knowledge

model is using Satisfiability Modulo Theories (SMT) solvers. Satisfiability Modulo Theories (SMT) problem is a decision problem for logical first-order formulas with respect to combinations of background theories such as arithmetic, arrays, and bit vectors. These solvers may be utilized on knowledge models by translating the constraints and variables into logical formulas and then verifying the satisfiability of these formulas using SMT solvers (Barrett and Tinelli, 2018).

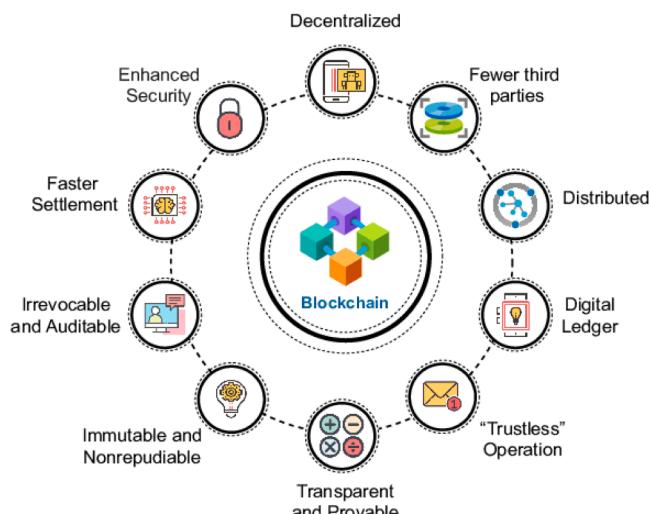
One such example of SMT solvers is Z3, which has been widely utilized for satisfiability problems. Z3 is a high-performance SMT solver that supports a variety of theories, including linear and non-linear arithmetic, arrays, and bit-vectors. In this study, it is explored the use of Z3 to solve the satisfiability problems in the knowledge model, focusing on one-degree conflicts. One-degree conflicts refer to situations where two or more knowledge models have contradictory information, and it aims to find a consistent solution that satisfies the constraint of both models. Using SMT solvers like Z3, it can be detected and resolve the first-degree conflicts in knowledge models while merging or interacting with multiple knowledge models (De Moura and Bjørner, 2008).

There are also various other applications, such as decentralized energy trading platforms like Power Ledger, which encode trading rules and grid constraints, and waste management systems in smart cities, which leverage blockchain for tracking and coordinating services (Paul et al., 2024). Intellectual property management platforms like Ascribe use blockchain for documenting ownership and licensing, while blockchain-enabled frameworks are applied in logistics to improve transparency and efficiency (Davenport and Uncu, 2022). These cases highlight the versatility of blockchain and knowledge models across different sectors.

## 2.4. Blockchain, its application, and its relevance in knowledge management system

Blockchain technology, initially introduced by an anonymous person Satoshi Nakamoto, in the context of creating a decentralized digital currency, Bitcoin, has evolved to a wide range of applications beyond cryptocurrency. Blockchain, as demonstrated in Fig. 3, is a decentralized, distributed, and tamper-resistant digital ledger that records transactions in a secure and verifiable manner. It consists of a chain of blocks, where each block contains a set of transactions, and each block is cryptographically linked to the previous one (Yaga et al., 2018).

Blockchain's core features like decentralization, transparency, and security have made it an interesting field of research not only for finance



**Fig. 3.** Properties and Advantages of Blockchain technology (Yaga et al., 2018).

and supply chain management but also for knowledge management systems (Zareravasan et al., 2020).

In knowledge management systems, blockchain can enhance various aspects, such as:

- **Data integrity and security:** By enabling cryptographic hashing and consensus mechanisms, blockchain ensures the integrity of knowledge assets, reducing the risk of unauthorized access and manipulation (Zikratov et al., 2017).
- **Decentralization storage and access:** Blockchain allows decentralized storage and retrieval of knowledge assets, making it resilient to system failure (Saberi et al., 2018).
- **Provenance and traceability:** The underlying transparent and tamper-resistant nature of blockchain allows tracking and analysing transactions of knowledge assets via ledger, which is important for intellectual property management and dispute resolution (Saberi et al., 2018).
- **Smart contracts:** Smart contracts are a set of programs that are self-executing, self-verifying, and tamper resistant. This enables various knowledge management processes such as access control, licensing, and usage tracking in real-time (Mohanta et al., 2018).
- **Collaboration and sharing:** Blockchain with smart contracts facilitate collaboration and knowledge sharing among stakeholders, providing a secure and transparent platform for managing shared knowledge resources (Zareravasan et al., 2020).

Research on decentralized storage and sharing using blockchain, including IPFS, offers valuable methods to implement knowledge model storage and sharing using Blockchain technology. However, most literature on blockchain applications is primarily focused on finance domains, and literature specific to knowledge model storage and sharing is scarce, highlighting the need for further exploration in this area (Yli-Huumo et al., 2016).

## 2.5. Knowledge storage models

Knowledge model storage and sharing play an important role in managing and distributing knowledge across different agents and stakeholders. These models can be stored in three ways, namely, Centralized, Decentralized, and Distributed systems, with each offering its sets of advantages and challenges.

- **Centralized storage model:** These storage models store and manage knowledge models in a single central location. Traditional databases

and content management systems are examples of centralized databases. These models provide efficient storage, retrieval, and access control but may face challenges in terms of a single point of failure, privacy, and transparency (El-Khameesy and Rahman, 2012).

- **Decentralized storage model (IPFS):** Decentralized models distribute the storage and management of knowledge across multiple nodes or locations. One example is the InterPlanetary File System (IPFS) which is used to solve research questions. IPFS is a peer-to-peer decentralized file system. In contrast to conventional centralized storage systems, IPFS distributes and stores data through a peer-to-peer network. Since IPFS is built on content addressing, each file is given a distinct hash, which is then used to locate the file on the network. Since data is duplicated over numerous nodes and may be retrieved even if some nodes are unavailable, this method makes IPFS more resilient to failures (Mehta et al., 2023).
- **Distributed storage model:** Distributed models, like Blockchain technology, extend the concept of decentralization by incorporating consensus mechanisms and cryptographic techniques to ensure data integrity and immutability (Yaga et al., 2018). However, Blockchains are not practical for storing large data due to block bloat, transaction fees, and transaction processing speed (Mehta et al., 2023).

To address the interest in the development of a knowledge management system that is scalable and efficient, a combination of IPFS and Blockchain, Ethereum for desired prototype, can be employed. Ethereum, developed in 2015 by Vitalik Buterin, is an open-source decentralized blockchain platform that enables the development and execution of smart contracts and decentralized applications (Metcalfe, 2020).

## 2.6. Applications of blockchain and knowledge models in real-world cases

The integration of blockchain technology with knowledge representation models has been applied in various domains, addressing challenges like transparency, scalability, and interoperability (Radmanesh et al., 2023). In supply chain management, the combination of blockchain for traceability and semantic knowledge models for consistent data sharing among stakeholders enhances product provenance and fraud prevention (Mofatteh et al., 2024a; Radmanesh et al., 2021). Similarly, in hospitality, a Decentralized Autonomous and Smart Hotel System, successfully integrates disruptive technologies to create an innovative and automated hospitality experience (Aggarwal and Mittal, 2024). There are also various applications, such as supply chain financing (Kabir et al., 2021), trading (Abdennadher et al., 2024), commercial bank performance (Al-Dmour et al., 2024), Fintech (Renduchintala et al., 2022), smart and sustainable manufacturing (Nair et al., 2024), and intelligent e-commerce environment (Bernovskis et al., 2024).

## 2.7. Summary and research gaps

In recent years, there has been a growing interest in using blockchain technology in knowledge management systems to address the problems faced by various industries, including smart energy systems. This section provides a thorough summary of the present state of research and highlights potential research gaps. Table 1 presents and categorizes the literature related to this research based on the themes stated below.

- **Knowledge Model ontologies:** There has been limited research on the integration of knowledge model ontologies in Blockchain technology. Most Blockchain research is centred around finance. Research on the application of Blockchain in the knowledge management system is scarce (Yli-Huumo et al., 2016).
- **Blockchain and IPFS:** IPFS helps mitigate the limitations of storing large data on the blockchain due to storage costs and slows transaction time. The application of the use of Blockchain with IPFS has

**Table 1**

Literature review based on the main themes of this research.

Research	Knowledge Model	Blockchain	Conflict Resolution
(Stepanova et al., 2020)	Centered approaches of knowledge models are used as facilitating a common understanding of a problem and creating a necessary base for more productive collaboration across disciplines		An interdisciplinary knowledge typology for conflict resolution is presented.
(Muniandi, 2020)		A novel blockchain-enabled virtual coupling of automatic train operation is proposed.	The proposed solution is provided to address railway traffic conflicts to ensure both operator and passenger satisfaction.
(Monroe et al., 2020)	Some knowledge model methods used to simulate the energy trading systems.	An empirical agent-based modeling framework to simulate peer-to-peer electricity trades in a decentralized residential energy market is proposed.	
(Lin et al., 2022)	Different knowledge representation techniques for enabling energy knowledge trading are used.	A permissioned edge blockchain to secure the peer-to-peer energy and knowledge sharing is built.	
(Fang et al., 2021)		The solution proposed in a blockchain-based infrastructure.	A resolution algorithm is implemented through reconstructing the proposed weighted directed policy graph to improve the conflict resolution rate.
(AlBadri, 2022)	A knowledge management approach for systematic review of concepts and modelling knowledge is proposed.	A framework model for advancing the effectiveness of blockchain technology for systematic conducting information is developed.	
(Jin et al., 2023)	A secure continuous knowledge transfer approach to improve knowledge models by collaborating with multiple edge devices is designed.	The solution is designed in a decentralized and blockchain-based structure.	
(Hu et al., 2019)	A link between the two research areas of supply chain resilience and knowledge management processes is built.		A conflict resolution method used to enhance supply chain resilience.
(Pham et al., 2024)	Knowledge management enablers are identified to	The solution is integrated in a decentralized approach and based	

**Table 1 (continued)**

Research	Knowledge Model	Blockchain	Conflict Resolution
	enhance the efficiency food supply chain implementation.	on blockchain technology.	
(Norta et al., 2015)		The generated method is designed in a decentralized and blockchain-based approach.	A highly dependable conflict resolution model for organization collaboration is generated.
(Chen et al., 2023)	The proposed method for conflict detection is specified for knowledge graphs and their possible conflicts.		A pattern-based temporal constraint mining method for conflict detection is proposed.
(Zhang, 2023)	A visual cognitive model around knowledge graph and intelligent interactive data, proposes multiple structures, thinking cognition, multiple modules and intelligent data is built.		A conclusion of the multi-distributed and information intelligentized non-center model structure, makes the blockchain intelligent interactive data more visualization, intelligence, humanization and technicalization is drawn.
(Donate et al., 2023)	Factors based on organizational knowledge management; transactional memory systems and knowledge-oriented leadership that help firms to mitigate conflicts based on task management at work, with the aim to improve their innovation capabilities are analyzed.		A knowledge-based view of the firm, conflict management theory and cognitive collective engagement theory have been used to build a model of relationships that connects the development of positive knowledge management contexts and management of dysfunctional conflict with innovation capabilities improvement.
(Zhang et al., 2024)	A Zero-knowledge Proof of Learning consensus approach to channel the meaningless Proof of Work mining energy waste to valuable Deep Learning model training is proposed.	A blockchain and Deep Learning empowered cloud-edge orchestrated framework for an extremely resource-constrained IoT environment is built.	
This research	Different types of knowledge models are discussed and an approach for sharing them through blockchain network to resolve conflicts among knowledge models is proposed.	Blockchain capabilities for storing knowledge models are examined and a new method for exchanging knowledge through an established blockchain network in this research is designed.	An operational scenario for conflict detection and resolution based on using different knowledge model types and the established decentralized application (DApp) is evaluated.

also grown significantly but is limited to a few domains like the NFTs marketplace (Parham, 2021). The use of IPFS has been explored to a lesser extent and hence more research is needed to understand the trade-offs between decentralization, security, and performance when using blockchain technology in conjunction with IPFS (Kumar et al., 2021).

- **Conflict resolution Strategies:** The development and evaluation of conflict resolution strategies for knowledge models are yet to be investigated. Solutions like SMT solvers, such as Z3, have shown that they can resolve conflict in knowledge models. But more research is needed to understand the effectiveness of such solvers in large-scale real-world applications (De Moura and Bjørner, 2008).

In conclusion, although extant literature furnishes significant insights into blockchain applications, knowledge models, and conflict resolution strategies, considerable gaps persist. Research pertaining to the integration of blockchain and knowledge model ontologies is scarce, with the majority of studies concentrating on financial sectors as opposed to broader applications, such as energy systems. While blockchain and decentralized storage frameworks like IPFS present formidable solutions to challenges related to scalability and data management, the combined potential of these technologies for knowledge model storage and dissemination remains insufficiently explored. Likewise, notwithstanding the proposal of conflict resolution strategies such as SMT solvers, their efficacy in large-scale, real-world contexts has not been thoroughly assessed. These gaps underscore the imperative for further investigation to advance blockchain-based knowledge management systems and their practical applications in domains such as energy optimization and smart systems.

### 3. Designing a blockchain-based framework for knowledge model storage and sharing

This section aims to discuss in detail the overall design and architecture of a blockchain-based prototype for storing and sharing knowledge models. The proposed system consists of a blockchain for recording transactions and metadata, a distributed file system (IPFS) for off-chain storage of knowledge models, a smart contract to define rules and constraints for accessing and sharing knowledge models, and a decentralized application (DApp) developed with web development framework called Next.js for the user interface.

#### 3.1. Research methodology

This study employs a multi-phase research methodology to explore the integration of blockchain technology and knowledge management systems for energy optimization.

##### • Phase 1: Conceptualization

A comprehensive literature review was conducted to identify challenges and gaps in existing systems, particularly in the areas of conflict resolution, decentralized storage, and energy management. This informed us of the conceptualization of the EnerChain framework.

##### • Phase 2: System Design and Implementation

The EnerChain framework was developed as a decentralized application (DApp) with the following core components:

- **Blockchain Setup:** The Ethereum platform was selected for its robustness and support for smart contract functionality. A Proof of Stake (PoS) consensus mechanism was used to minimize energy consumption and ensure scalability.
- **IPFS Integration:** IPFS was integrated to store knowledge models off-chain, reducing blockchain storage overhead. Each knowledge model was hashed to generate a unique Content Identifier (CID), which was stored on the blockchain for metadata tracking.

- **Smart Contracts:** Smart contracts were implemented to manage critical operations, including access control, conflict detection, and incentive distribution. Key functions of the smart contracts included:
  - Providing governance mechanisms to update and validate knowledge models.
- **Phase 3: Testing and Validation**

The system was tested in a controlled environment simulating interactions among smart devices, energy experts, and supervisory systems. Key performance metrics included:

- **Transaction Latency:** The average transaction processing time was recorded at 3 s
- **Throughput:** The system supported up to 100 transactions per second.

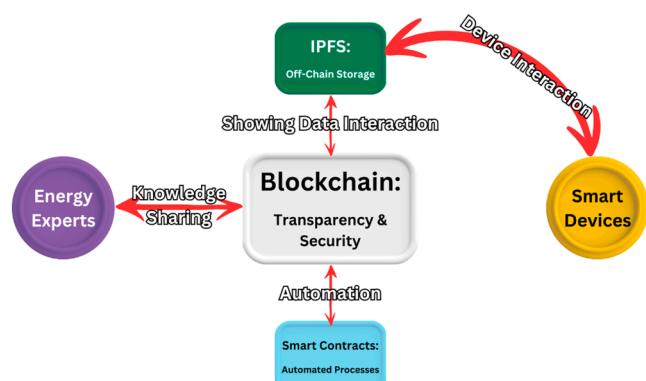
**Fig. 4** illustrates the conceptual framework of the blockchain ecosystem, showcasing its integration of blockchain technology, IPFS (InterPlanetary File System), and smart contracts to facilitate decentralized knowledge management and energy optimization. At the core of the framework is the blockchain, which ensures transparency, security, and immutable data storage for energy-related transactions and metadata. The IPFS component provides off-chain storage for large and complex knowledge models, reducing the storage load on the blockchain while maintaining accessibility and scalability. Smart contracts automate critical processes, including access control, conflict resolution, and incentivization mechanisms for stakeholders. The framework also highlights interactions with external stakeholders, such as energy experts, and smart devices, which feed real-time data into the system for dynamic decision-making. By integrating these components, the blockchain-based framework addresses key challenges in scalability, efficiency, and conflict resolution within decentralized energy management systems.

#### 3.2. Feasibility of storing and sharing knowledge models in blockchain

##### 3.2.1. Storing knowledge model

Blockchain is becoming a popular method for storing knowledge models because of its properties like decentralization, integrity, and transparent nature. The storage of Knowledge models on the blockchain can be achieved through on-chain or off-chain storage approaches.

**On-chain storage.** On-chain storage implies storing the knowledge model directly on the blockchain. Storing the knowledge model directly on the blockchain can ensure data integrity and security because each node in the blockchain network maintains a copy of all transactions, making unauthorized alterations impossible (Nakamoto, 2009). However, it is necessary to fully understand the strengths and limitations of on-chain storage to understand the feasibility of storing the knowledge



**Fig. 4.** Conceptual Framework of the Blockchain Ecosystem.

model using on-chain storage.

In the blockchain, each time the knowledge model is added, or the existing one is updated, a new transaction is created and added to the blockchain ledger. This transaction contains the knowledge model data and is distributed across all nodes in the blockchain network. Because each transaction is verified across multiple nodes before adding it to the blockchain, the chances of adding fraudulent data are very minimal. Furthermore, once the data is on the blockchain, it can't be altered or deleted, providing a reliable and tamper-proof record of the knowledge model. Any attempt to alter or delete the data is extremely difficult due to the decentralization nature of blockchain (Khaturia et al., 2022).

However, on-chain storage has two major limitations. The first limitation of on-chain storage is the limited storage capacity of the blockchain. Storing large amounts of data on-chain can lead to bloating of the blockchain, making it inefficient and expensive to maintain (Malik, 2019). Moreover, the replication of the data across all participating nodes, although strength in terms of data security and immutability, can be a disadvantage when it comes to storage efficiency. These characteristics can further exacerbate the storage capacity problem (Kaur et al., 2023).

In conclusion, though on-chain storage offers robust security and data integrity, its inherent limitations in terms of storage capacity and efficiency make it less feasible for storing large knowledge models. For such applications, alternative methods such as off-chain storage may be more appropriate.

**Off-chain storage.** An alternative solution for on-chain storage is off-chain storage. Instead of storing the actual data directly on the blockchain, which can be both costly and inefficient due to the limited storage capacity of blockchain, off-chain storage provides a way to store the data externally while maintaining the properties of blockchain like immutability and security (Kaur et al., 2023). One way to off-chain storage is by using a distributed file system called InterPlanetary File system (IPFS). IPFS is a peer-to-peer distributed file system. In IPFS, as shown in Fig. 5 (Naz et al., 2019), all computing devices with the same system of files are connected and hence making a network of nodes similar to a blockchain. This protocol of file systems replaces traditional location-based addresses with content-based addresses, meaning each file and all the blocks within the file system are identified uniquely with

an address called a cryptographic hash (Navendan et al., 2022).

When storing a knowledge model using an off-chain storage method, the data or file is uploaded in the IPFS (or a similar distributed file system). The IPFS then generates a uniquely identifiable content-addressable hash for the data or file. This hash acts as a permanent and immutable reference to the uploaded knowledge model. The retrieved hash is then stored as a reference to the uploaded Knowledge Model on the blockchain. By uploading the hash instead of directly storing the data or file, this approach reduces the storage burden, and slow transaction speed on the blockchain while also maintaining a secure link between the blockchain and off-chain data or file (Guidi et al., 2021).

This method of off-chain storage has several advantages. First, it enables the storage and retrieval of bulky data efficiently. Higher degrees and complex knowledge models can become bulky files. Since the data is stored off-chain, the blockchain is spared from storing large amounts of data, which can slow down transaction processing times and increase costs. Second, it makes the system more scalable. As the amount of data stored in the Knowledge Model grows, the system can effectively handle the increased data volume without affecting the performance of the blockchain (Henningsen et al., 2020).

Therefore, off-chain storage allows for more feasible and efficient storage and retrieval of large knowledge models without compromising on important properties like data integrity, security, and scalability.

### 3.3. Sharing knowledge model

The sharing of knowledge models among multiple devices or entities in a decentralized network is a critical functionality for systems like smart energy systems. The open nature of blockchain, with its distributed ledger technology, offers a transparent and trustable solution to this challenge (Nakamoto, 2009).

The properties of blockchain like immutability, decentralization, transparency, and security coupled with the decentralization of data, means that all participants in the network have access to the same information, reducing inconsistencies and conflicts (Dong et al., 2018).

Furthermore, blockchain's smart contract functionality enables the automatic execution of predefined rules and agreements, ensuring that

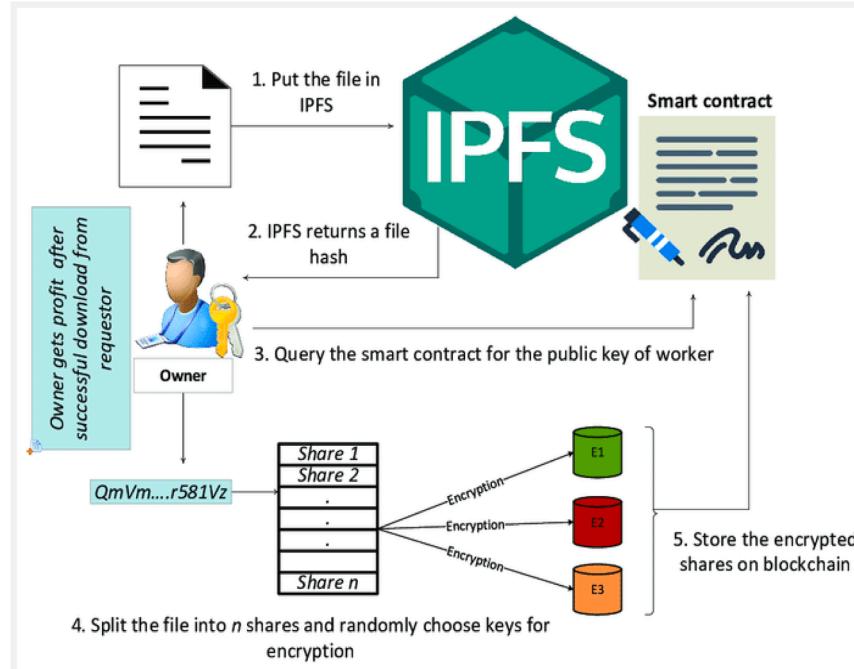


Fig. 5. Off-chain integration with on-chain storage.

knowledge models are shared in accordance with agreed-upon terms. This is particularly useful when different entities or devices have varying access rights to a knowledge model. With smart contracts, these access rights can be enforced programmatically, ensuring that the right data is shared with the right entity at the right time (Christidis and Devetsikiotis, 2016). Furthermore, incentive measures can be placed to encourage users to share the Knowledge Model and contribute to the growth of the network. Users can be rewarded with tokens or NFTs for their contributions like sharing the knowledge model (Parham, 2021).

However, sharing knowledge models via blockchain is not without challenges. Firstly, the size of the knowledge model can significantly affect the speed and cost of transactions. Large knowledge models may need to be broken down into smaller parts for efficient storage and retrieval. Secondly, privacy concerns may arise when sensitive data is shared on a public blockchain. While encryption can protect the data, it may not be sufficient in all cases, necessitating further research into privacy-preserving techniques in blockchain (Wang et al., 2020).

In conclusion, while blockchain presents a solution for sharing knowledge models, careful consideration and strategic planning are needed to address potential challenges. The inherent benefits of blockchain, such as immutability, traceability, and decentralized control, offer a strong foundation for the sharing of knowledge models. However, overcoming hurdles related to data size and privacy will be critical for the successful implementation of blockchain for knowledge model sharing.

#### 3.4. Knowledge models conflict detection

As discussed in the literature review, conventional knowledge models follow specific structural patterns that are not always mutually understandable. Therefore, identifying conflicts between knowledge models from different providers is crucial in resolving them. The solution proposed by Mofatteh et al. is particularly effective for conflict detection. This method introduces three semantic layers beyond the functional structure of the knowledge model: the interpretation layer, perception layer, and abstraction layer. According to this approach, knowledge models within the abstraction layer share semantic commonalities, allowing them to detect conflicts (Mofatteh et al., 2024b, 2023).

Given the modular nature of knowledge models, the conflicting components can be shared within a blockchain network for resolution. Energy experts then address these conflicts by processing transactions between intelligent systems and experts in the energy field.

#### 4. EnerChain: a decentralized application

The decentralized application, commonly called DApp, is a critical component of this energy management system for accessing all the components discussed so far. The Decentralized Application serves as a user interface to the proposed system. The EnerChain serves as the primary interface for the user to interact with the blockchain and IPFS. The practical implementation of the EnerChain involves integrating various sections to create a user-friendly interface for accessing Energy Management Systems. The implemented DApp shared as a repository on GitHub through the following link: <https://github.com/yasermofatteh/EnerChain.git>. A modern JavaScript framework like Next.js may be utilized to design the user interface, as can be seen in Fig. 6.

- **Interaction with Blockchain and IPFS:** The EnerChain serves as a user interface that simplifies the processes of uploading and searching for knowledge models, requesting access, and managing token balances. It facilitates the interaction between the users and the underlying Blockchain and IPFS.
- **Frontend Implementation:** The front of EnerChain is designed using a modern JavaScript framework called Next.js, a React-based framework. Next.js provides several features like routing, hook, and server-side rendering which are of great help when building efficient applications. Further, a design framework called React Bootstrap is used which enabled the creation of appealing user designs for a great user experience.
- **Backend implementation:** On the backend, the DApp interacts with the blockchain to upload and retrieve the knowledge models, manage transactions, and execute smart contracts. The interaction is facilitated with Ethers.js. Ethers.js is a JavaScript library that aims to be a complete and compact library for interacting with the Ethereum Blockchain and its ecosystem. It facilitates the communication of frontends with Blockchain.

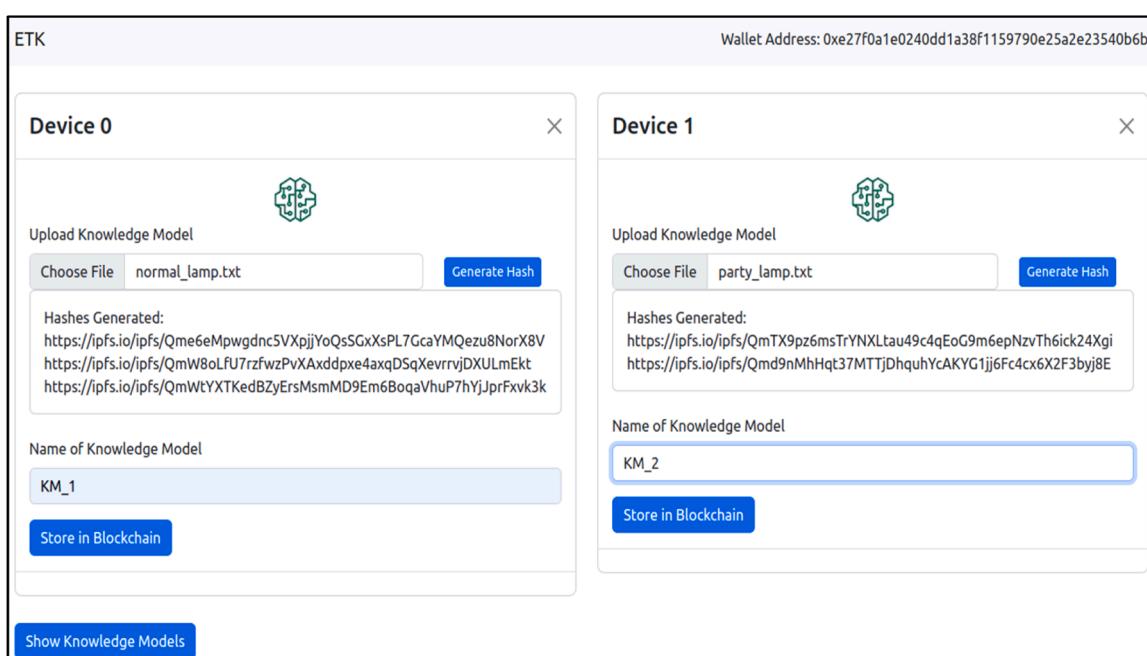


Fig. 6. EnerChain Homepage.

#### 4.1. System architecture

According to Fig. 7, the proposed system consists of the following components:

- **Blockchain:** A decentralized ledger like Ethereum that stores metadata about the Knowledge Model, access control information, and transactions related to sharing and accessing the models.
- **Distributed File System:** An actual decentralized storage, like IPFS, to store the Knowledge Models off-chain, chained to Blockchain via metadata, and reducing the storage burden on Blockchain.
- **Smart Contracts:** A self-executing contract that sets rules and conditions for sharing and accessing knowledge models. Programming languages like Solidity allow the creation of smart contracts.
- **Token-Based Incentive System:** A system implemented in Smart Contract to reward users for sharing Knowledge Models in the network.
- **Decentralized Application (DApp):** A user interface that facilitates the interaction between users and underlying Blockchain and Distributed File Systems.

##### 4.1.1. Storing knowledge models in EnerChain

Storing knowledge models in the proposed blockchain-based system involves a two-step process: first, the knowledge model is stored in the distributed file system (IPFS), and then the retrieved reference to this model is stored on the blockchain.

- **Storing in IPFS:** The first step is to upload the knowledge model. The knowledge model is uploaded by the user via the user interface of the Decentralized application. After uploading the knowledge model to the IPFS, it returns a unique content-addressable hash that acts as a reference to the off-chain data in the distributed file system.
- **Storing reference on Blockchain:** The next step is to create a new transaction on the blockchain, which includes the hash and metadata about the knowledge model. The transaction is signed with the user's private key to ensure the authenticity of the transaction. Further, the use of a private key for signing the transactions guarantees the integrity and non-repudiation of the transaction, as only the owner of the private key can sign the transaction, and once signed, the transaction can't be altered. Once the transaction is validated and added to the blockchain, it gets registered in the blockchain ledger.

By storing knowledge models off-chain and keeping only the reference on the blockchain, this approach ensures the scalability of the system. This enables the efficient storage and retrieval of large knowledge models while leveraging the security and immutability of blockchain technology.

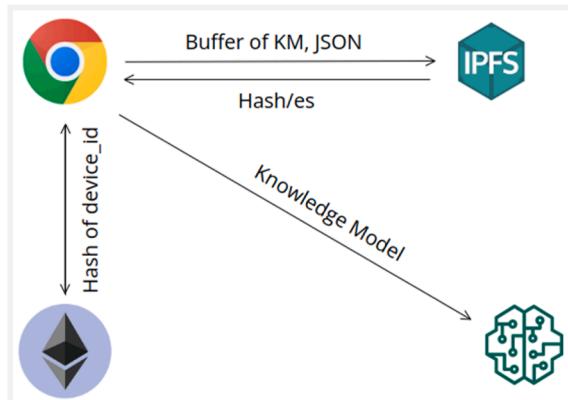


Fig. 7. System Architecture of EnerChain.

##### 4.1.2. Smart contract

Smart contracts are self-executing contracts with the terms of the agreement directly written into code. They verify and enforce the negotiation or execution of an agreement without a third party (Gruda and Mostafa, 2022). In this context, smart contracts are used to specify rules for storing and managing access rights and rules for sharing the knowledge models (Zheng et al., 2019).

- **Smart contract language:** Smart contracts in the proposed system would be written in Solidity programming language. Solidity is an object-oriented programming language for implementing smart contracts on various blockchain platforms, most notably, the Ethereum blockchain platform. Further, Solidity's syntax is like JavaScript, a web programming language, it is a suitable choice for integration with web projects like the decentralized application (von Wendland, 2018).
- **Access Control:** With smart contracts, the developer can specify rules on who can access the knowledge models stored in the blockchain. This is done by implementing access rules in the smart code. When a user requests access to a knowledge model, the smart code checks if the user meets the request conditions. If the conditions are met, the smart contract provides the respective hashes of the knowledge model stored in IPFS (Zheng et al., 2019).
- **Updating and managing knowledge models:** Smart contracts can also provide functions to add, update, and manage knowledge models. The state of a knowledge model can be alerted by implementing rules within the smart contract. The digital ledger of blockchain, however, is not modifiable, and always updated with every transaction being made. This enables a transparent and auditable history of all changes made to the blockchain that comply with the rules specified in the smart contract (Aggarwal, 2024).
- **Incentive mechanisms:** Furthermore, smart contracts can also be used to implement incentive mechanisms as illustrated in Table 2. Users can be rewarded with cryptocurrency or non-fungible tokens (NFTs) for their contribution to the network on sharing or creating knowledge models. This encourages active participation and growth of the network.

To summarize, smart contracts serve as an essential building block of the proposed system, providing the logic for managing and controlling access to knowledge models in a secure and decentralized manner.

#### 4.2. Sharing knowledge models in EnerChain

In EnerChain, sharing knowledge models is an important function to ensure that only authorized users can access the knowledge model, thereby maintaining data privacy and security. The processing of sharing of knowledge models is facilitated through the interaction of the associated smart contracts and the use of the content-addressable hash generated when storing the knowledge model.

- **Requesting access:** The process begins when an external user submits a request via the user interface to access a knowledge model. This request then becomes a transaction on the blockchain, where the user specifies the knowledge model they wish to access. The smart contract embedded in the blockchain network processes this transaction.
- **Access authorization:** The smart contract associated with the requested knowledge model will define the rules and conditions for access to the knowledge model. These rules can include various constraints and conditions like the number of tokens available, user level, authentication, and so on. Only if the requirements are met, the user is granted access.
- **Retrieving knowledge models:** Upon successful authorization, the smart contract provides the user with the content-addressable hash

**Table 2**

Exemplary token incentive pseudo code.

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;
contract KnowledgeModel {
    struct Model {
        string ipfsHash;
        address owner;
    }
    mapping(uint256 => Model) public models;
    uint256 public modelCount;
    function uploadModel(string memory ipfsHash) public {
        models[modelCount] = Model(ipfsHash, msg.sender);
        modelCount++;
    }
    function getModel(uint256 modelId) public view returns (string memory) {
        require(modelId < modelCount, "Model not found");
        return models[modelId].ipfsHash;
    }
}
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;
import "@openzeppelin/contracts/token/ERC20/ERC20.sol";
contract TokenIncentive is ERC20 {
    constructor() ERC20("KnowledgeToken", "TKN") {
        _mint(msg.sender, 1,000,000 * (10 ** uint256(decimals())));
    }
    function rewardUser(address recipient, uint256 amount) public {
        _transfer(msg.sender, recipient, amount);
    }
}
```

of the knowledge model stored in the IPFS. The user can then retrieve this hash and share it with other agents or stakeholders.

The implementation of smart contracts in this process allows for programmable, automated control over the access and sharing of knowledge models. This mechanism not only enhances data privacy and security but also enables efficient, transparent, and trustworthy sharing of knowledge models among users in the network.

#### 4.3. Front-end development

In the initial phase of the software solution implementation, the focus lies on front-end development. Next.js was selected as the technology stack for its recognized flexibility, scalability, and strong community support. A pivotal aspect of the user interface design is the inclusion of two forms resembling distinct devices, providing users with a seamless experience for uploading their knowledge models. These forms are designed with clarity and accompanied by precise instructions.

A key element within the DApp UI is the creation of the device form as shown in Fig. 8. This component features an input field enabling users to upload their knowledge models efficiently. Leveraging modern web technologies, the form incorporates a robust mechanism for handling file uploads securely. Additionally, a "Generate Hash" button is strategically integrated into the form, initiating the process of parsing the knowledge model and storing its sections in IPFS.

The implementation progresses with the development of an upload function tailored for knowledge models. Users can seamlessly upload a text file containing their knowledge model, and the system intricately reads and parses the uploaded file into distinct sections. Each section corresponds to a different function of the device, ensuring a comprehensive breakdown and organization of the knowledge model.

During the upload process, special attention is given to parsing the knowledge model text file into batches. This meticulous parsing involves segregating the text file into individual sections, each representing a specific function. These parsed sections serve as discrete units for subsequent storage in IPFS, contributing to an efficient and organized knowledge model management system.

#### 4.4. Integration with IPFS

In the context of software solution implementation, the integration with IPFS assumes a pivotal role. This phase is designed to facilitate the seamless storage and management of knowledge model sections. Following the parsing of the knowledge model into distinct sections, each section is stored in IPFS. Interaction with IPFS is facilitated through its API, allowing for direct data uploads from the DApp. Notably, the IPFS service provided by Infura is leveraged in this process, resulting in the generation of a unique hash for each uploaded section. These unique hashes serve as content-addressable pointers, precisely indicating the location of each section in IPFS.

Once each knowledge model section is successfully stored in IPFS, the system proceeds to retrieve the unique content-addressable hashes, a process referred to as the retrieval of hashes of the knowledge model in EnerChain (see Fig. 9). These hashes are locally stored for the subsequent step in the process, namely the creation of the JSON object.

One notable advantage of employing multiple hashes, where each section is associated with its unique hash, lies in the enhanced identification capabilities during conflict resolution. This approach facilitates precise pinpointing of the section causing a conflict, streamlining the resolution process. Additionally, the use of multiple hashes provides a more granular level of control over the knowledge model. Updates can be targeted to individual sections without impacting others, affording flexibility and precision in managing the knowledge model.

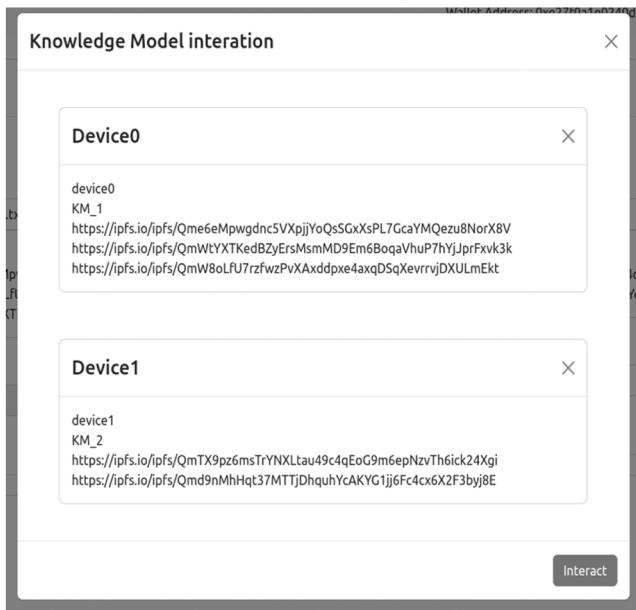
#### 4.5. Association of hashes and managing the knowledge models

Upon obtaining the unique hashes from IPFS, the next step involves the creation of a structured JavaScript object. This object encapsulates essential information, including the device ID, knowledge model name, and an array of unique hashes, each representing distinct sections of the knowledge model. This JSON object serves as a coherent and organized representation, establishing a clear association between the device and its corresponding knowledge model.

Subsequently, the prepared JavaScript object undergoes a transformation for storage in the blockchain. This process may entail converting the JSON object to a format suitable for blockchain storage, possibly involving the stringification of the object. Leveraging the

The screenshot shows a user interface for managing knowledge models. At the top, it displays the wallet address: 0xe27f0a1e0240dd1a38f1159790e25a2e23540b6b. Below this, there are two sections labeled 'Device 0' and 'Device 1'. Each section contains a 'Generate Hash' button and a 'Show Knowledge Models' button at the bottom. In the 'Device 0' section, there is also a 'Choose File' button and a message 'No file chosen'.

**Fig. 8.** Proposed Form for uploading the knowledge model in EnerChain.



**Fig. 9.** EnerChain interface showing the retrieval of hashes of knowledge model.

functions provided in the smart contract, the JSON object is then securely stored in the Ethereum blockchain. This action results in the creation of a permanent and tamper-proof record, ensuring the longevity and integrity of the knowledge model for the specified device. The device ID is the key for storing this JSON object, facilitating easy retrieval in subsequent operations.

For the retrieval of the knowledge model associated with a specific device, the blockchain is queried using the device ID. The stored JSON object is retrieved, and subsequent parsing returns the object to its original JSON format for seamless integration within the application. Furthermore, the hashes within the JSON object play a crucial role in retrieving the actual sections of the knowledge model from IPFS, completing the cycle of knowledge model retrieval and utilization within the application.

#### 4.6. Transactions structure

In a blockchain network, knowledge exchange occurs through transactions. Each transaction consists of at least four main components, described as follows:

- **Sender:** In every transaction, one stakeholder (with a dedicated address in the blockchain network) acts as the sender, and this address is recorded in the transaction details. When detecting conflicts, the conflicting smart systems serve as the sender. Conversely, when proposing a solution, the energy expert assumes the sender's role.
- **Recipient:** On the other end of the transaction is the recipient, whose specific address is also recorded in the transaction details. During conflict detection, the energy expert is the recipient, while in the solution phase, the smart systems take on this role.
- **Information:** Each transaction involves information exchanged between the sender and the recipient. This information is derived from the knowledge models of smart systems and is shared with energy experts during conflict detection or solution development. As outlined in the previous section's conceptual model, only the conflicting portions of the knowledge models are converted into hash codes in the form of IPFS (InterPlanetary File System) links. These are then exchanged as a chain of digits between the sender and recipient, then decoded and utilized by both energy experts and smart systems.

- **Token:** Every transaction incurs a cost, represented by a certain amount of tokens deducted from the sender's wallet. The economic model of the blockchain network is designed so that smart systems pay the cost of implementing optimal energy solutions through these tokens. The savings generated from reduced energy consumption help offset the token cost. Additionally, energy experts receive rewards for the solutions they provide, creating an incentive.

**Fig. 10** illustrates the user interface for the blockchain network stakeholders. **Fig. 10-a** shows the interface for initiating a transaction, where tokens are deducted from the sender's wallet upon confirmation. **Fig. 10-b** displays the interface for searching transactions based on the stakeholders' addresses, allowing users to monitor related transactions and exchanged tokens.

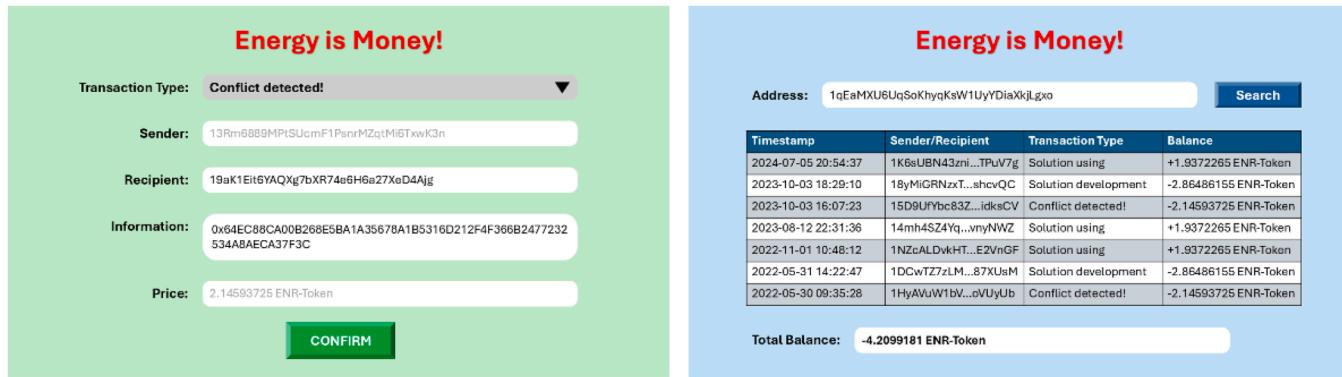
As shown in **Fig. 10**, in addition to conflict detection and solution development, reusing an existing solution can also be considered as a transaction. Once a solution is provided, the energy expert and the involved smart systems are registered as the owners of that solution. If a similar conflict arises between two smart systems elsewhere in the world, the new conflicting systems can use the existing solution to update their knowledge models, rather than consulting the energy expert again, thereby saving time. A portion of the token paid as a reward for resolving the conflict is then allocated to the original solution owners. This approach allows each smart system to potentially make money by actively detecting conflicts and contributing solutions.

#### 5. Evaluation

In the first part, a simple scenario was presented to describe a conflict between two smart systems in a smart home. Based on the conceptual model discussed in the previous sections, once a conflict between two systems is detected, the conflicting portions of their knowledge representation models are first isolated and stored in an IPFS link. The systems then create a transaction to request conflict resolution within the blockchain network. Upon accepting this request, an energy expert gains access to the conflicting portions of the knowledge models. Due to the decentralized structure of the network, any qualified energy specialist, regardless of location or other limitations associated with centralized systems, can apply to resolve the issue.

In the current design of EnerChain, conflict resolution is managed by a human energy expert. This individual is responsible for analyzing conflicting knowledge models, identifying the source of the conflict, and proposing resolutions. The energy expert accesses supervisory control systems through decentralized identifiers (DIDs) and secure API endpoints, allowing them to propose updates to the knowledge models. For example, in a conflict between the heating and air conditioning systems, the energy expert might recommend a sequential operational strategy: activating the air conditioning system first to circulate air, followed by the heating system to adjust the temperature. This approach minimizes energy waste and ensures efficient resource utilization.

Once this solution is implemented, it can be applied globally whenever a similar conflict arises between an air conditioning system and a heating system, regardless of their manufacturer. The original smart systems that registered the conflict, along with the energy expert who provided the solution, will receive rewards from the tokens paid by the new conflicting systems. In this way, smart systems can not only optimize energy consumption but also make money within the blockchain network. While the current design relies on human expertise, future work will focus on transitioning this role to an AI-based decision support system. Such AI agents could leverage machine learning algorithms and historical data to autonomously detect and resolve conflicts. This shift would enhance scalability and enable real-time conflict resolution in complex, large-scale smart energy systems.



**Fig. 10.** Transaction structure interface showing details of components. (a) Transaction user interface for every stakeholder in EnerChain. (b) Transactions search possibility for each stakeholder.

## 6. Discussions

The implementation and evaluation of the application of Blockchain in Knowledge Management Systems have revealed several key findings, implications, and limitations. The EnerChain framework demonstrates significant potential to optimize energy management and reduce CO<sub>2</sub> emissions, supported by a functioning prototype and real-world testing. A demo implementation of the system validated its core functionalities, including secure knowledge model storage, conflict resolution, and stakeholder interaction via smart contracts. The system's performance metrics, such as transaction throughput and latency, meet the requirements of real-time decision-making in smart environments. While the results from the prototype testing align with the projected impacts, future large-scale deployments will further substantiate these outcomes.

Contrary to the perception that blockchain systems are inherently slow, EnerChain leverages a hybrid architecture—combining blockchain with off-chain storage through IPFS—to optimize both scalability and performance. This ensures efficient handling of complex energy data without sacrificing security or transparency. By grounding the claims of energy savings and CO<sub>2</sub> reduction in the demonstrated capabilities of the prototype, EnerChain offers a compelling case for real-world applicability and serves as a steppingstone for future advancements in decentralized energy systems.

### 6.1. Key findings

This study brings out several findings:

- Scalability and Efficiency:** The use of blockchain offers an alternative to traditional centralized databases. These alternatives come with more appealing advantages like immutability, transparency, decentralization, and security. Furthermore, the integration of distributed file systems like IPFS, allows the solution to store data in off-chain storage, making it scalable and efficient.
- Conflict Resolution:** SMT solvers like Z3 enable the automatic identification of conflict in knowledge models allowing smart stakeholders and smart agents to resolve it beforehand to develop an efficient energy system. Further, the division of knowledge models into different batches and the use of ontology models allow the easy identification of the batches causing the conflict.
- Security and transparency:** The use of blockchain and smart contracts enables a high level of security and transparency that wasn't possible in older knowledge management systems. The properties of blockchain along with rules, constraints, and functionality of smart contract, the knowledge model access, and sharing can be highly regulated.

### 6.2. Implications

This study also has several implications:

- For industry:** This implementation may be utilized in various industries where knowledge management is important. For example, in the Energy management system and the Internet of Things (IoT), where multiple devices with different knowledge models interact, it can be a practical option.
- For Research:** The research highlights the limited research of Blockchain in finance, contributing to the limited study of Blockchain in knowledge management. It also paves the way for further research into the storage of blockchain, conflict resolution, and ontology models.

### 6.3. Limitations

Despite its contribution, this study is not without limitations:

- Scalability issues:** Although the system is more scalable than storing the data directly into the blockchain, blockchain still is inherently slow, and has low storage capacity. And this can be a problem when dealing with a large number of devices and knowledge models.
- The complexity of conflict resolution:** The use of SMT solvers like Z3 is effective when dealing with first-degree knowledge models, but as the knowledge model gets complex better and viable solutions might be required.

### 6.4. Impact analysis

In this research, a conflict scenario among smart energy systems is evaluated and the capabilities of EnerChain to make efficient management of Energy consumption possible is discussed. The potential for energy reduction is substantial in Germany and Europe, considering blockchain integration into smart systems for household energy management ([Blockchain Technology, 2024](#)). As a rule of thumb, considering the market growth trends of the blockchain in Europe, it can be estimated that a new solution provided as a platform like EnerChain, can be trusted by 2.5 % of households in the first year ("Blockchain Technology Market Size & Growth Report, 2030," 2024).

- Germany:** If 2.5 % of German households (approximately 1 million homes ("[Households by size in Germany, 2023](#)," 2023)) adopt the blockchain-based energy platform, considering an annual average of 18000 kWh consumption for each household in Germany ("[Private Households](#)," 2024), an estimated **1.8 TWh reduction** in

heating-related energy consumption could be achieved. This corresponds to a reduction of approximately **0.3 %** of Germany's total household energy consumption, which is significant given that heating accounts for about 70 % of household energy use.

- **Europe:** Across Europe, assuming 2.5 % adoption (approximately 5 million homes ("Household composition statistics," 2024)), considering an annual average of 5500 kWh consumption for each household in Europe ("Energy statistics - an overview," 2024), the platform could yield a **27.5 TWh reduction** or **0.4 %** of total residential energy consumption.

#### 6.4.1. CO<sub>2</sub> emission reductions

The energy savings from this platform also translate directly into reductions in CO<sub>2</sub> emissions. In Germany, the average CO<sub>2</sub> emission from energy production is **0.354 kg CO<sub>2</sub> per kWh** ("CO<sub>2</sub> emissions per kWh in Germany - Nowtricity," 2024), while in Europe it stands at **0.283 kg CO<sub>2</sub> per kWh** ("EU carbon intensity of electricity by country, 2023," 2023) due to a more diversified energy mix.

- **Germany:** A reduction of 1.8 TWh of energy consumption would lead to an estimated reduction of **~638,000 tonnes of CO<sub>2</sub> emissions**, accounting for **~0.3 %** (Jacksohn et al., 2023) of the country's total emissions from residential energy use (CO<sub>2</sub> emissions per kWh in Germany, 2024).
- **Europe:** A 27.5 TWh reduction across Europe would prevent the release of **~7.8 million tonnes of CO<sub>2</sub>**, equivalent to **0.5 %** (Bianco et al., 2024) of total residential emissions.

#### 6.4.2. Financial savings on energy

The reduction in energy consumption also leads to significant financial savings, particularly in heating costs, which account for a large proportion of energy expenditure in households. With an energy price of about **0.30 €/kWh** ("Electricity price statistics," 2024), the savings potential is considerable.

- **Germany:** A 1.8 TWh reduction could result in savings of **€540 million**, or **0.5 %** ("Electricity bill in a 3-person household Germany, " 2024) of the national residential energy bill.
- **Europe:** The savings from a 27.5 TWh reduction could total **€8.25 billion**, representing **0.65 %** ("Energy prices and costs in Europe - European Commission," 2024) of Europe's total household energy expenses.

#### 6.5. Future works

While the EnerChain framework presents significant economic and environmental benefits, its widespread adoption depends on market adaptability and user acceptance. One of the primary challenges in deploying blockchain-based energy solutions is consumer trust, particularly regarding data security, usability, and cost-effectiveness. Transitioning to EnerChain may require initial infrastructure investments and stakeholder education to ensure smooth adoption. Therefore, future work should explore strategies such as incentive mechanisms, government subsidies, and industry partnerships to enhance adoption rates.

Additionally, ensuring long-term sustainability is crucial for maintaining an active and functional ecosystem. Platforms like EnerChain rely on multi-party collaboration, necessitating robust incentive structures to keep participants engaged. Token-based rewards, decentralized governance mechanisms, and transparent policy enforcement can help sustain participation over time. Moreover, periodic assessments of system efficiency and user satisfaction will be essential for adapting the platform to evolving market needs. Addressing these factors will strengthen EnerChain's long-term viability and scalability in decentralized energy management.

## 7. Conclusion

Effective energy consumption management is increasingly critical in today's world, where energy resources are finite and environmental concerns are growing. The integration of smart systems in homes and industries offers significant potential for optimizing energy use, but it also introduces complexities, particularly when different systems operate independently. Blockchain technology emerges as a powerful tool to address these challenges by facilitating decentralized, secure, and transparent transactions between smart systems. Through blockchain, conflicts between smart systems can be detected and resolved efficiently, enabling a more coordinated approach to energy management.

The blockchain network not only allows for the seamless exchange of knowledge and solutions among systems but also incentivizes innovation by rewarding participants who contribute effective solutions to energy conflicts. This decentralized model transcends geographical limitations, allowing energy experts from around the world to contribute their expertise, further enhancing the efficiency of energy management processes (Bhat et al., 2021). By leveraging blockchain's capabilities, it can become achievable to have a more sustainable and efficient energy ecosystem where smart systems not only optimize energy consumption but also contribute to a collaborative network that continuously evolves and improves (Wu et al., 2023). This approach not only helps in reducing energy waste but also provides economic benefits to those involved in the process, making it a viable and forward-thinking solution to the pressing issue of energy consumption management.

In conclusion, the practical implementation of EnerChain as a DApp for a knowledge management system demonstrates the integration of various technology components to create a platform that not only fulfills its intended purposes but also offers an approach to design a knowledge management system. This practical endeavour has offered invaluable insights into the opportunities and challenges posed by this technology, paving the way for future research and development.

This research aimed to leverage the capabilities of blockchain and knowledge management in smart systems by exploring a simple operational scenario within a smart home environment. The focus was on developing a conceptual model to resolve conflicts between smart interoperable systems that operate with their specific knowledge representation models in different, often incompatible ontologies. Using blockchain technology, the proposed solution enables the exchange of knowledge through a specially designed transaction structure within the blockchain network. Conflict resolution is facilitated by energy experts, who update the knowledge models of smart systems, ensuring smooth and efficient interoperability between them. The proposed EnerChain model achieves economic benefits primarily by reducing energy waste, optimizing resource allocation, and creating a token-based incentive system for collaboration. By resolving conflicts between smart systems and enabling more efficient energy usage, the platform directly contributes to financial savings for households and industries. For instance, in the European Union, adopting EnerChain in just 2.5 % of households could lead to an estimated reduction of 27.5 TWh in residential energy consumption annually, translating to approximately €8.25 billion in cost savings based on average electricity prices (0.30 €/kWh).

Additionally, the decentralized model fosters a collaborative network where stakeholders, such as energy experts and system providers, are rewarded for their contributions through tokens. This incentivization encourages the adoption of optimized energy practices and further reduces operational costs. These savings, combined with reductions in CO<sub>2</sub> emissions (~7.8 million tonnes annually), not only offer financial benefits but also position the EnerChain platform as a sustainable and economically viable solution for smart energy management.

## 8. Compliance with ethics guidelines

The authors declare that they have no conflict of interest and

financial conflicts to disclose.

## Ethics

This study involves data obtained from shared public repositories. The authors confirm that there is no private or personal data and also the commercial data has been fully anonymized.

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## CRediT authorship contribution statement

**Mofatteh Mohammad Yaser:** Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Khadka Ujjwal:** Writing – original draft, Visualization, Methodology, Conceptualization. **Omid Fatahi Valilai:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

## Declaration of Generative AI and AI-assisted technologies in the writing process

The authors confirm that no generative AI or AI assisted technologies have been used for generating content by authors. The authors take full responsibility for the content of the publication.

## Declaration of Competing Interest

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

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## Availability of data and material

Data will be made available on request.

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