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Blockchain Technology in the Oil and Gas Industry: A Review of Applications, Opportunities, Challenges, and Risks

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ABSTRACT Blockchain technology has been developed for more than ten years and has become a trend in various industries. As the oil and gas industry is gradually shifting toward intelligence and digitalization, many large oil and gas companies were working on blockchain technology in the past two years because of it can significantly improve the management level, efficiency, and data security of the oil and gas industry. This paper aims to let more people in the oil and gas industry understand the blockchain and lead more thinking about how to apply the blockchain technology. To the best of our knowledge, this is one of the earliest papers on the review of the blockchain system in the oil and gas industry. This paper first presents the relevant theories and core technologies of the blockchain, and then describes how the blockchain is applied to the oil and gas industry from four aspects: trading, management and decision making, supervision, and cyber security. Finally, the application status, the understanding level of the blockchain in the oil and gas industry, opportunities, challenges, and risks and development trends are analyzed. The main conclusions are as follows: 1) at present, Europe and Asia have the fastest pace of developing the application of blockchain in the oil and gas industry, but there are still few oil and gas blockchain projects in operation or testing worldwide; 2) nowadays, the understanding of blockchain in the oil and gas industry is not sufficiently enough, the application is still in the experimental stage, and the investment is not enough; and (3) blockchain can bring many opportunities to the oil and gas industry, such as reducing transaction costs and improving transparency and efficiency. However, since it is still in the early stage of the application, there are still many challenges, primarily technological, and regulatory and system transformation. The development of blockchains in the oil and gas industry will move toward hybrid blockchain architecture, multi-technology combination, cross-chain, hybrid consensus mechanisms, and more interdisciplinary professionals.

INDEX TERMS Blockchain, oil and gas industry, smart contract, oil and gas trade, track equipment, supervision.

I. INTRODUCTION

With the advancement of science and technology, the importance of oil and gas resources in promoting global economic and social progress is increasing. According to the ‘‘BP Statistical Review of World Energy’’ released by BP in June 2018 [1], oil and natural gas account for 57% of total energy consumption (Fig.1). Moreover, global oil consumption increased by 1.8%, exceeding the average growth rate of 1.2% for three consecutive years, while the consumption of natural gas has increased by 96 billion cubic meters, reaching the fastest growth rate after 2010. However, according to ‘‘BP Energy Outlook 2019 edition’’ [2], although the world is vigorously promoting the development of new energy, oil and gas will still occupy half of the world’s energy by 2040. Besides, the report also pointed out that with the continuous expansion of liquified natural gas (LNG) trade, LNG will account for 15% of total natural gas demand in 2040. Therefore, oil and natural gas will continue to dominate the global energy market in the next 20-30 years.

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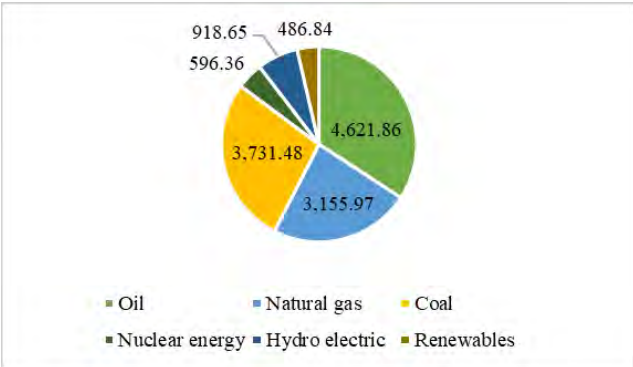


FIGURE 1. Energy consumption in 2017 (unit: million tonnes oil equivalent).

As oil and gas resources play an essential role in the energy field, the technologies of the oil and gas industry have also developed rapidly in recent years, such as intelligent drilling technology, intelligent oil and gas fields, and marine digital platforms [3], [4]. It can be seen that the oil and gas industry is gradually developing towards the direction of intellectualization, digitalization, and automation. However, its management mode is relatively old, and it has the characteristics of low efficiency, high cost, long period and high risk.

Oil and gas industry can be divided into three sections according to the market division: upstream, midstream and downstream. The upstream refers to the exploration and development of oil and gas, the midstream refers to the transportation of oil and gas, and the downstream refers to the storage and sales [5]. The value chain of the oil and gas industry is shown in Fig. 2. In different markets, there are still many shortcomings in management [6], which are concluded in Table 1.

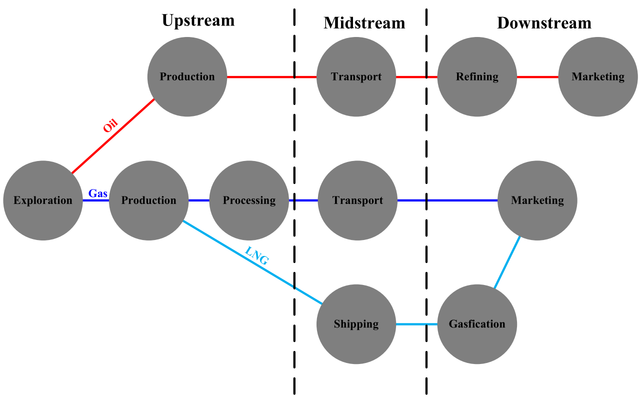


FIGURE 2. The value chain of oil and gas industry.

Except for the various management issues listed in Table 1, there are still other issues to be addressed. For example, since the oil and gas industry is a huge system, it involves multi-party transactions and trade, the paperwork and reconciliations generated in each link are very cumbersome and error-prone. In summary, the management issues of the oil and gas industry mainly involve the following four aspects:

TABLE 1. Management issues and consequence in different markets in the oil and gas industry [6].

Market	Issue	Cause	Consequence
Upstream	Equipment tracking difficulties	The number of devices is enormous, and the management of asset integrity is not perfect.	Human error, huge supervision fine.
	Data leakage	The location where the data is generated is different or the data is not well stored and processed.	Wrong data leads to wrong decisions.
Midstream	Data handling and replication	Duplicate third party transactions or duplicate contracts between different parties.	Increase operating costs, erroneous transactions, and delayed transactions.
Downstream	Integrity and security	Close networks are vulnerable to external attacks	Fraud, loss of Trust, increase validation cost.

- A large amount of paperwork and reconciliation work increases the monetary and time costs of the transaction.
- The oil and gas industry has the characteristics of multi-party investment and cooperation, and the risks of fraud, error, and inefficiency in transactions are relatively high.
- The third-party management costs in the oil and gas trade are relatively high, the trade negotiation process is inefficient, and the exchange of critical data is slow.
- Important data is at higher risks from cyber-attacks.

Based on the above problems, it is time for the oil and gas industry to change its management mode. A relatively new technology called blockchain has been found to have great potential for use in the oil and gas industry. In 2008, the emergence of Bitcoin triggered a boom in the development of blockchain technology. In this decade, the development of blockchain technology has been through three stages: the blockchain 1.0 era represented by Bitcoin, the blockchain 2.0 era marked by Ethereum and smart contracts, the blockchain 3.0 era for application in the social field [7]. Currently, blockchain technology has been applied in many industries. However, in the beginning, the oil and gas industry has been holding a wait-and-see attitude and rarely involved. Until 2017, British Petroleum (BP) began testing the blockchain project, and the oil and gas industry took the first step in applying blockchain technology. The rest of paper is organized as follows:

Section II describes the motivation and contributions of this paper. Section III presents the key technologies for blockchain. Section IV describes the potential application scenarios of blockchain technology in the oil and gas industry. Section V discusses the application status, opportunities, challenges and risks of blockchain technology in the oil and gas industry. Section VI summarizes the main conclusions drawn from this paper.

II. MOTIVATION AND CONTRIBUTION

A. MOTIVATION

According to Deloitte's 2018 global blockchain survey [8], 61% of respondents in the oil and gas industry believe that ''blockchain is only a monetary database and a financial service application'', and only 15% of respondents have been applied blockchain to practice. The blockchain has been developed for ten years, but the oil and gas industry has only begun to implement and explore in the past two years, indicating that the current understanding of blockchain technology in the oil and gas industry is still in its infancy. Therefore, the motivation of this paper is to let more oil and gas industry people understand the blockchain and understand the benefits and applicable occasions of the blockchain, and to promote the development of blockchain technology in the oil and gas industry.

B. CONTRIBUTIONS

In the following, the contributions of this paper are concluded as:

(1) Firstly, the core technologies and characteristics of the blockchain technology are systematically discussed, including explaining what the blockchain is, how the blockchain works, the classification of the blockchain, and the blockchain security techniques. The primary purpose of this section is to let people understand the basic principles of the blockchain.

(2) Second, this paper introduces the idea of blockchain technology to the oil and gas industry. The application field is divided into four parts: trading, management and decision making, supervision, and cyber security. The content of this section will let people know how the blockchain will actually be applied to the oil and gas industry, and demonstrate the advantages of blockchain technology via examples.

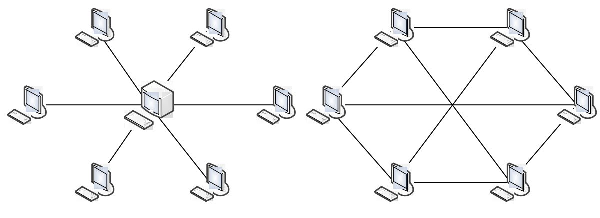
(3) Finally, this paper analyzes the application status of blockchain technology in the oil and gas industry, analyzes the opportunities, challenges, and risks that may be encountered, and analyzes the development trends.

III. THEORIES OF BLOCKCHAIN

This section introduces the basic theories and techniques related to blockchain. The basic theories include the concept of blockchain (Section III A), the characteristics (Section III B) and classification (Section III C) of blockchain. Related techniques include consensus algorithm (Section III D), cryptography and security technology (Section III E), data record model (Section III F) and distributed storage system (Section III G).

A. THE CONCEPT OF BLOCKCHAIN

The explanations of blockchain in different works of literature are not entirely uniform. Essentially, blockchain is a kind of mode to realize and manage transaction processing through transparent and trustworthy rules to construct non-forgeable, non-tampering and traceable blockchain data structure in peer-to-peer (P2P) network environment [9]–[13]. It is a new application mode combining computer technologies such as distributed data storage, consensus mechanisms, peer-to-peer transmission, and encryption algorithms. The biggest innovation of blockchain technology is that transactions are no longer stored in the central database, but are distributed to all participants.



(a) (b)

FIGURE 3. Transaction model. (a) Traditional model. (b) Blockchain model.

Peer-to-peer means that the computers in each node in the network have equal status, each node has the same network power, and there is no centralized server [14]–[16]. All nodes share some resources or information through specific protocols. Fig. 3 shows the traditional transaction model and blockchain transaction model [16]. In the traditional transaction model, transactions depend on the central authority, and transaction data is mainly stored by the central authority. In the blockchain transaction model, transactions can be conducted directly between the two parties without third party intervention, and all transaction data are stored in the distributed blockchain, and all relevant information is stored in each participant. Therefore, the blockchain can well eliminate the influence of third parties. However, if the central authority is removed, then how to verify the transaction and ensure the integrity of the ledger becomes a challenge. It requires a suitable verification process, a process called consensus algorithm, which will be mentioned in Section III D.

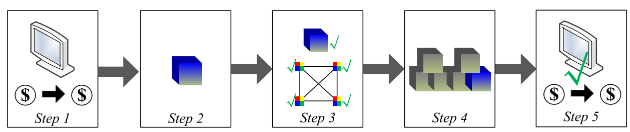


FIGURE 4. The blockchain process [16].

As shown in Fig. 4, if a person agrees to complete a transaction with another person (*Step 1*), they use the transaction-related data as a variable and combine with other transactions in the same period to form a new data block (*Step 2*). Each transaction is encrypted and distributed to multiple computers in a P2P manner. Network members use algorithms to validate transactions stored on individual computers. The algorithm appends a unique hash value to each block. If any information related to the transaction is tampered with, the correct hash value cannot be generated, and an error is reported (*Step 3*). When this block is successfully verified, it is combined with the block that was previously verified to form a blockchain (*Step 4*). Finally, both parties confirm the transaction, which means the transaction is successful (*Step 5*) [16], [17].

B. KEY CHARACTERISTICS OF BLOCKCHAIN

Blockchain technology has six main characteristics, including: decentralization, immutability, transparency, efficiency, security and anonymity [18].

1) DECENTRALIZATION

Decentralization is the most essential feature of the blockchain-based system, which means that the blockchain-based system no longer depends on the central processing node, which realizes the distributed recording, storage, and update of data [19]. The status of each node is the same, and the data blocks are maintained by the nodes with the maintenance function in the entire system. Stopping any node will not affect the overall operation of the system.

2) IMMUTABILITY

Information cannot be changed after the it is verified and added to the blockchain. For example, in the Bitcoin's blockchain system, unless more than 51% of the nodes in the control system can be simultaneously controlled, the modification is invalid, so the data stability and reliability of the block chain are extremely high [10], [20].

3) TRANSPARENCY

Transparency is the basis for blockchain to be trusted because data record and update are transparent to the nodes of the entire network. Therefore, network-wide nodes with high transparency can be used to review, track data records, and track operations [21], [22].

4) EFFICIENCY

The blockchain technology makes the system more transparent by distributing database records to users in the system, so it is more efficient in terms of risk, cost, and so on [23], [24].

5) SECURITY

If a centralized network is attacked, it is likely to affect the whole system. However, blockchain-based system has the characteristics of decentralization. If a node is attacked, it will not destroy the security of the entire system. Moreover, blockchains use public key infrastructure to prevent malicious behavior from changing data, thus providing better security [19].

6) ANONYMITY

In the blockchain systems, both parties can make the transaction anonymous because the program rules in the blockchain can automatically determine whether the exchange activities between nodes are valid [25].

C. CLASSIFICATION OF BLOCKCHAIN SYSTEMS

The blockchain-based system can be divided into two categories according to the openness: permissioned blockchain and permissionless blockchain (public blockchain) [26], [27]. The permissioned blockchain can be further divided into the private blockchain and consortium blockchain.

1) PRIVATE BLOCKCHAIN

The private blockchain refers to a blockchain whose write permission is only controlled by an organization or an individual, and the read permission may be open to the outside. The private blockchain system is the most closed and is limited to use by enterprises, state agencies or individuals. It does not fully solve the trust problem, but it can improve auditability [9].

2) PUBLIC BLOCKCHAIN

The public blockchain refers to a blockchain that can be read by anyone in the world, can send transactions and can be validated effectively, and anyone can participate in the consensus process. The public blockchain is the ultimate embodiment of decentralization [28].

3) CONSORTIUM BLOCKCHAIN

The consortium blockchain refers to a blockchain that is restricted to the participation of the members of the consortium. The read and write permissions on the blockchain and the participation of the accounting rights are determined according to the consortium rules. Each participant in the consortium blockchain does not have to worry about where their data exists. The data they generate can only be seen by themselves or by authorized people. In this way, it will solve data privacy and security issues and decentralize. It is a combination of public and private blockchains [29].

Table 2 summarizes the characteristics of the three kinds of blockchains [9], [30], [31]. When selecting the blockchain type, factors such as database requirements and multi-party writing should be considered. A white paper published in 2018 by China Academy of Information and Communications Technology and Trusted Blockchain Initiatives have a flow chart for choosing blockchain types [32], as shown in Fig. 5.

D. CONSENSUS ALGORITHM

The verification process is to achieve a consensus on the content of the distributed ledger. It is a process of decentralization and automation. It can be said that the consensus algorithm is one of the most critical technologies in the blockchain. The blockchain consensus algorithm can be classified according to fault tolerance type and consistency degree. In order to facilitate the description of the core mechanism of the consensus algorithm, Yuan *et al.* [33] classified it according to the leader election strategy in 2018. Their classification and characteristics are shown in Table 3.

TABLE 2. Comparison of three blockchains.

Property	Private blockchain	Public blockchain	Consortium blockchain
Access	Public or restricted	Public	Public or restricted
Energy	Low	High	Low
Speed	Faster	Slower	Faster
Efficiency	High	Low	High
Security	Pre-approved participants and voting/multi-party consensus	Proof of work, proof of stake, and other consensus mechanisms	Pre-approved participants and voting/multi-party consensus
Immutability	Could be tampered	Nearly impossible to tamper	Could be tampered
Consensus process	Permissioned and known identities	Permissionless and anonymous	Permissioned and known identities
Consensus determination	Centralized organization	All miners	Leader node set
Network	Centralized	Decentralized	Semi-centralized
Asset	Any asset	Native asset	Any asset
Transaction approval	Order of milliseconds	Order of minutes	Order of milliseconds

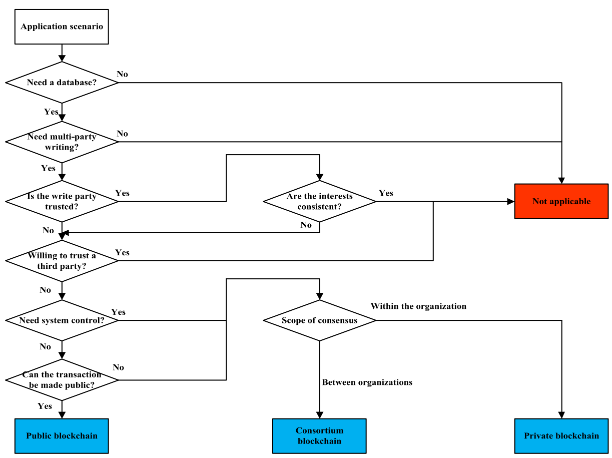


FIGURE 5. Flow chart for selecting blockchain type [32].

TABLE 3. Consensus algorithm type and characteristics [33].

Consensus algorithm type	Characteristics
Proof-based	Proof is usually competitive to accomplish a task that is difficult to solve but easy to verify.
Voting-based	Miners who first obtain more than half of the votes will receive the accounting rights.
Stochastic	Determine each round of accounting nodes directly according to a random method.
Alliance	A group of representative nodes are elected based on a specific method, and the representative nodes obtain the accounting rights in turn by rotation or election.
Hybrid	Use a mixture of multiple consensus algorithms to select accounting nodes.

This paper presents six commonly used consensus algorithms, of which proof of work (PoW) and proof of stake (PoS) are the most used. Table 4 lists the characteristics of these six consensus algorithms [33]. There are many consensus algorithms and their extension algorithms. Appendix A lists the emergence time, basic algorithm, and Byzantine fault tolerance performance of 32 mainstream consensus algorithms.

1) PROOF OF WORK (PoW)

The proof of work (PoW) can be simply understood as a proof to confirm a certain amount of work done. However, the original intention of the algorithm is to solve the spam problem. PoW is a consensus mechanism adopted by Bitcoin, Litecoin, etc. The idea of PoW algorithm is to let the initiator consume a certain amount of computing power and economic resources, thereby greatly increasing the overhead required for the attack and avoiding service abuse and attacks. Apparently, in order to increase the probability of obtaining reward, it is necessary to increase the computing power of nodes (miners) to solve a complex but easy-to-verify SHA256 mathematical problem. Under this mutual stimulation, the whole system will continue to increase the computing power. On the one hand, it increases the difficulty of attack of the whole system, on the other hand, it wastes many computing resources [34]–[36].

2) PROOF OF STAKE (PoS)

PoS is a consensus algorithm that is commonly applied to public blockchains and depends on the economic rights of the verifier in the network [34], [37], [38]. In a blockchain, a set of verifiers alternates and votes for the next block, and each verifier's voting weight depends on the size of its guaranteed amount (i.e., stake). In the PoS algorithm, the blockchain tracks a set of verifiers, and anyone who holds the cryptocurrency of the blockchain can become a verifier by sending a cryptocurrency lock as a margin. Subsequently, the process of creating and recognizing new blocks can be done by all current verifiers. Significant advantages of the PoS algorithm include higher security and higher energy efficiency.

3) DELEGATED PROOF OF STAKE (DPoS)

DPoS is a consensus algorithm based on the development of PoW and PoS. In this algorithm, each holder can vote, thereby generating a certain number of nodes or pools, and their rights are completely equal, and the holder can change these representatives at any time by voting. It manages the entire chain operation in a low-cost way, thus solving the problem of a large amount of energy consumption of the PoW during the mining process. At the same time, the more "decentralized" management method distributes the decision-making power of the blockchain network operation to each node of the whole network, and can also avoid the problem of uneven trust in the PoS algorithm [39].

4) PRACTICAL BYZANTINE FAULT TOLERANCE (PBFT)

PBFT algorithm was put forward by Miguel Castro and Barbara Liskov in 1999. It solves the problem of inefficiency of the original Byzantine fault-tolerant algorithm and reduces the complexity of the algorithm from exponential level to polynomial level, which makes Byzantine fault-tolerant algorithm feasible in practical system applications.

TABLE 4. The characteristics of the six consensus algorithms [43].

Characteristic	PoW	PoS	DPoS	PBFT	PoET	Tendermint
Consensus type	Proof-based	Proof-based	Alliance	Voting-based	Stochastic	Voting-based
Energy cost	High	Low	Low	Low	Low	Low
Computation cost	High	Low	Low	High communication complexity	Low	Low
Openness	Permissionless	Permissionless and permissioned	Permissionless and permissioned	Permissioned	Permissioned	Permissionless and permissioned
Byzantine fault tolerance	<1/2	<1/2	<1/2	<1/3	<1/2	<1/3

In PBFT algorithm, security is guaranteed by all nodes of the system. The consensus is mainly determined by three votes between nodes. One node represents one vote and achieves consensus among nodes in a majority rule. PBFT algorithm allows no more than 1/3 of the nodes to fail, that is, in the environment of $(3f + 1)$ nodes, if there are $(2f + 1)$ normal nodes, the whole system can operate normally [39], [40].

5) PROOF OF ELAPSED TIME (PoET)

PoET is a lottery protocol built by Intel in a trusted execution environment. The core is CPU hardware that supports Intel SGX (Software Guard Extensions) technology. It randomly generates some delays in a controlled security environment, and the CPU proves the reliability of the delay from the hardware level. Whoever has the lowest latency will receive accounting rights. In this way, the only way to increase accounting rights is to increase the number of CPUs. At the same time, the increased CPU will increase the resources of the entire system, thus achieving a proportional relationship between the accounting rights and the provided resources [41].

6) TENDERMINT

The Tendermint algorithm is optimized for the traditional PBFT algorithm and requires only two rounds of voting to reach a consensus: pre-vote and pre-commit. In the same round of commit, only more than two-thirds of validators pre-commit the same block can submit the block to the chain.

Sometimes the validator may fail to submit a block because the current proposer is offline or the network is slow. Tendermint allows them to verify that a validator should be skipped. Before the next round of voting, the validator waits for a short time to receive a complete proposal block from the proposer. This dependence on timeouts makes Tendermint a weak synchronization protocol rather than an asynchronous one. However, the rest of the protocol is asynchronous, and only when more than two-thirds of the set of validators is received, will the validator take the next step. One reason Tendermint can simplify is that it uses the same mechanism to submit a block and skip directly into the next round [42].

E. CRYPTOGRAPHY AND SECURITY TECHNOLOGY

Cryptography is also one of the most core technologies in the blockchain. It is mainly divided into two categories: hash algorithm and asymmetric encryption algorithm.

1) HASH ALGORITHM

Hash algorithm is the most commonly used cryptographic algorithm in the blockchain. In blockchain, hash algorithm is mainly used for data integrity, data encryption, proof of work in consensus computing, the link between blocks and so on. It can compress messages of arbitrary length into binary strings of fixed length in a limited and reasonable time, and output hash value. It is a one-way cryptosystem, that is, an irreversible mapping from plaintext to ciphertext (only encryption process, no decryption process) [44]. Hash function has the characteristics of unidirectionality (forward speed is fast, and the reverse is difficult), collision resistant, puzzle friendliness (there is no convenient method to produce a hash value to meet individual requirements). Several hash functions currently used in the blockchain include MD5, SHA1, SHA256, and SM3, and their characteristics are shown in Table 5.

TABLE 5. Commonly used hash functions and features.

Feature	SHA1	SHA256	MD5	SM3
Designer	National Security Agency	National Security Agency	Ronald Rivest	Xiaoyun Wang et al.
Year	1995	2002	1992	2005
Security	Medium	High	Low	High
Calculating speed	Medium	Slightly lower than SHA1	Fast	Slightly lower than SHA1
Output size (bit)	160	256	128	256
Reference	[45]	[46]	[47]	[48]

Since the blockchain records complete data information and cannot delete or modify the block record, the block will continue to increase and will occupy a large amount of storage space. Therefore, the way to use the Merkle Tree to store transaction hashes is proposed. The Merkle tree is similar

TABLE 6. Commonly used asymmetric encryption algorithms and features [51].

Feature	RSA	ECC	SM2
Designer	Ron Rivest, Adi Shamir, Leonard Adleman	Neal Koblitz and Victor S. Miller	Office of the Encryption Administration Leading Group, CPC Central Committee
Year	1977	1985	2010
Confidentiality level (CL)	80 or 112		
Key length	1024 (CL=80)	160 (CL=80)	160 (CL=80)
	2048 (CL=112)	224 (CL=112)	224 (CL=112)
Maturity	High	High	High
Security	Low	High	High
Calculating speed	Slow	Medium	Medium
Energy consumption	High	Medium	Medium
Reference	[52]	[52]	[53]

to the tree structure in the data structure, mainly binary tree and multi-fork tree. Each transaction record corresponds to a hash value and corresponds to the leaf node of the Merkle Tree [49]. The two leaf nodes are paired again with hash calculation. Recursively until the last hash value is stored in the block as the Merkle root. Therefore, you can reclaim hard disk space by simply removing old transactions from Merkle Tree.

2) ASYMMETRIC ENCRYPTION ALGORITHM

Asymmetric encryption algorithm refers to the use of public and private keys to encrypt and decrypt data storage and transmission [50]. The public key can be made public for the sender to encrypt the information to be sent, and the private key can be used for the receiver to decrypt the received encrypted content. Because of the dependence between the public key and the private key, only the authorized user can decrypt the information. Public-private key pairs take a long time to compute and are mainly used to encrypt fewer data. The commonly used asymmetric encryption algorithms are Rivest-Shamir-Adleman (RSA), Elliptic-curve cryptography (ECC) and SM2, and their characteristics are shown in Table 6.

F. DATA RECORD MODEL

There are two main ways to record data in the blockchain: the Unspent Transaction Output (UTXO) model and the Account model.

1) UTXO

UTXO is a core concept in the generation and verification of bitcoin transactions. The transaction constitutes a chain structure. All legal bitcoin transactions can be traced back to the output of one or more forward transactions. The source of these chains is the mining reward, and the end is the current unspent transaction output. All unspent output is the UTXO of the entire Bitcoin network [54]. The calculation of the model is off-chain, reducing the burden on the chain. Besides, the UTXO model is stateless and more accessible to handle concurrently. However, it cannot implement some complicated logic and the programmability is poor.

2) ACCOUNT MODEL

The Account model keeps the balance of each account global [55]. The state of the chain is generally agreed in the block in the form of StateRoot and ReceiptRoot [56]. The transaction is only the event itself, does not contain results, and the consensus of the transaction and the consensus of the state can be isolated in nature. The Account model has better programmability and the cost of bulk transactions is lower. However, there is no dependency between transactions, and the replay problem needs to be resolved.

G. DISTRIBUTED STORAGE SYSTEM

There are currently five large storage systems in the blockchain: Inter Planetary File System (IPFS), Sia, Storj, Maidsafe, and Genaro [57]. Their descriptions, advantages, and disadvantages are shown in Appendix B. Among them, IPFS is the most concerned system at present.

IV. BLOCKCHAIN IN OIL AND GAS INDUSTRY

According to the reports [58], [59] issued by Deloitte in April 2017, the blockchain has great potential in the oil and gas industry mainly in the following four aspects: trading, management and decision making, supervision, and cyber security. In the following subsections, the potential applications of these four aspects will be analyzed. At last, two examples are introduced in Section IV E.

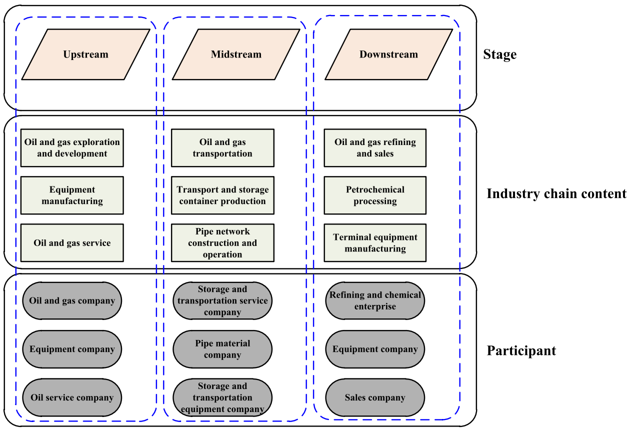


FIGURE 6. Oil and gas industry chain [61].

A. TRADING

According to EY's "Global oil and gas transactions review 2017", the total annual oil and gas transaction was $343.5 billion [60]. The report also carried out statistics and analysis based on the transaction volume of upstream, midstream and downstream. The composition of the oil and gas industry value chain has been introduced in Section I of this paper, while Fig. 6 shows the oil and gas industry from the specific content of the industry chain and participants [61].

It can be seen that the oil and gas industry is a multi-link industry including exploration, development, processing, wholesale, retail and so on. A large number of transactions and contracts are involved in these phases, resulting in a large amount of reconciliation work and tracking work. According to the survey, the application of blockchain technology in oil and gas trading mainly includes smart contracts and transactions.

1) SMART CONTRACT

Smart contract is a kind of contract that records terms with computer language instead of legal language, and it is one of the most important concepts in Ethereum [62]–[64]. Ethereum supports the development of smart contracts through Turing complete languages (Solidity, Serpent, Viper). As an application running in the Ethereum Virtual Machine, the smart contract can receive transaction requests and events from outside, and generate new transactions and events by triggering the running code logic in advance (Fig. 7). The results of the smart contract can be updated for the status of the ledger on the Ethereum network, and these modifications cannot be forged and tampered once confirmed. Also, it has one of the most significant advantages is that no third-party intervention is required.

Because of the huge and complex nature of the oil and gas industry, long and complicated contracts may arise in the trade of all parties, and the number of contracts will be considerable. Smart contract can greatly reduce paperwork, simplify

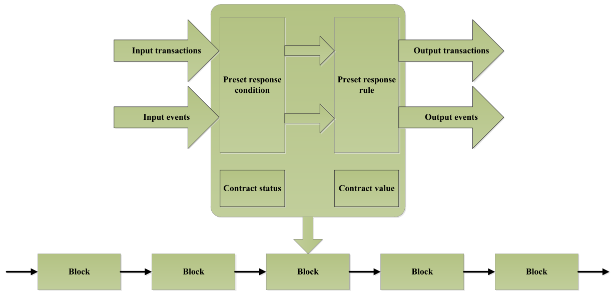


FIGURE 7. Smart contract model [65].

the process, improve efficiency, and save costs. However, smart contracts should be audited when using smart contracts and follow smart contract security development principles because the improper design will lead to severe loss. From the statistical data of blockchain security incidents, smart contract security incidents accounted for 6.67%, although accounting for a relatively small proportion, the resulting financial losses accounted for 43.3%. In February 2018, several researchers in Singapore and the United Kingdom pointed out that more than 34,000 Ethereum smart contracts may have vulnerabilities [66].

2) TRANSACTION

In the environment of oil price fluctuation, many oil and gas enterprises are facing tremendous pressure to reduce costs and improve productivity, to maintain an acceptable profit margin. In the oil and gas trading, the traditional way makes the transaction inevitably produce errors, and the transaction is prone to fraud and compromise. Blockchain technology can solve the problem well [67]. It can also make the transaction more transparent. Both sides of the transaction can view all the transaction records and evaluations of the other side, thereby can improve the success rate of the transaction. In addition, both sides of the transaction can also see the specific situation of each stage in the transaction process, to be more able to control the overall situation [68]–[70].

However, from a more macro point of view, there are currently international crude oil futures such as Brent, market participants include refineries, refined oil consumption enterprises and so on. The purpose of trading can be either hedging or cross-term or cross-variety arbitrage. These commodity futures transactions involve many processes such as account opening certification, clearing and so on, which makes the blockchain more useful.

Moreover, another major application of blockchain in transactions is cross-border payments. Oil and gas are usually sold in large quantities, especially between countries, and the frequency of transactions is also high, which is different from the scale of transactions between banks. Cryptographic currency (e.g. Bitcoin and Ether) can significantly reduce the cost of cross-border payments, in addition to instant transfers, they can also reduce the time required for intermediaries, as well as for verification and liquidation of funds.

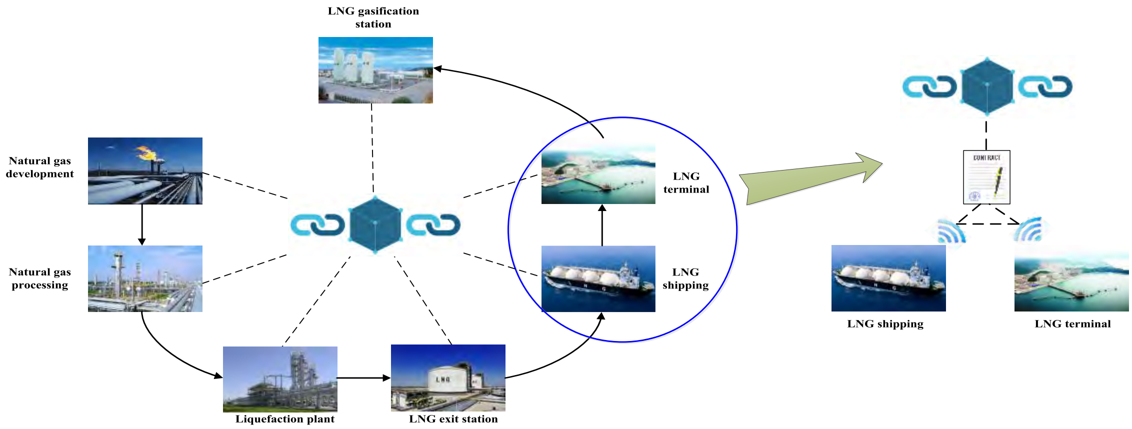


FIGURE 8. Example of using the blockchain to track LNG industry chain products.

B. MANAGEMENT AND DECISION MAKING

1) DECISION MAKING

Blockchain also has important application potential in decision making. In the exploration and development of oil and gas, many design-related problems are involved, such as three-dimensional data scanning of underground reservoirs, oil and gas development programs, and design and maintenance of oil and gas related devices. In current way, it usually takes months to years from feasibility study to implementation. However, the efficiency will be greatly improved if blockchain technology is used to not only prove the workload, but also calculate the relevant data. Besides, in each stage, the blockchain can also provide a record that cannot be tampered with, greatly helping the design process [71].

In management decision-making, many decisions need to be made according to the information and data of the whole system. However, it is challenging to obtain data in real time, and a lot of information is stored in an independent system. The structure, protocol and data format of these systems are not necessarily the same or interoperable. Blockchain technology can make data exchange and transmission more efficient, thus improving the correctness of decision-making. Additionally, many decisions in the oil and gas industry require management level to vote, and smart contracts in the blockchain enable automated, transparent voting applications. The voting sponsor can initiate a vote and give voting rights to the voter. The voter can vote or entrust their votes to others, and anyone can publicly check the result [72].

2) MANAGEMENT

The blockchain can simplify the management process and make the management method more scientific. As we all know, oil and gas pipeline networks occupy a vital position in oil and gas systems, and the pipeline network is complicated and difficult to manage, especially regarding resource allocation. If the relevant demand data and supply data are uploaded to the blockchain and form a smart contract, the deployment of oil and gas resources can be made more scientific. If the relevant information of the pipe network can form a blockchain, the integrity or reliability management of the pipe network will become more successful.

C. SUPERVISION

1) TRACKING

Globally, many oil and gas products are stored, ordered, transported and distributed through various channels such as producers, suppliers, contractors, subcontractors, oil and gas refiners and retailers. Once there are slips, productivity and production level will decline, and serious cases may occur such as loss of goods [24]. The blockchain not only tracks products in the oil and gas supply chain, but also provides audit trails of equipment used throughout the lifecycle, making all aspects of the supply chain more transparent, saving logistics costs and improving operational efficiency, this is also the most essential function of the blockchain to solve the oil and gas industry chain management. In recent years, LNG has become the mainstream of natural gas trade. Due to its low-temperature characteristics, the import and export carriers are mainly shipping. Fig. 8 shows a tracking case of LNG in the supply chain. Natural gas is extracted from the gas field and then transported to the natural gas treatment plant for dehydration or decarbonization. The purified natural gas is transported to the liquefaction plant for LNG production and then to the LNG export station for storage. LNG is loaded at the export station and enters the shipping phase. After arriving at the LNG terminal at the target location, LNG is then gasified into the application phase.

This process involves multiple stakeholders, each of whom maintains their own database to track the product. This blockchain not only means that there is a shared database that can track the product, but also means that it is an auditable information tracking system (because it can be encrypted and verified). For example, from the LNG shipping to the LNG terminal stage, when the LNG arrives at the LNG terminal, the shipping personnel will send the signed information to the smart contract, so that everyone in the chain will know that the LNG has arrived at the LNG terminal of the target location.

On the other hand, when the transaction is signed, it is sent to the recipient in an encrypted manner to let them verify that the LNG has indeed arrived. At this time, the staff of the LNG terminal issues the same smart contract for confirmation. Similarly, the same method also can be used for tracking related devices.

The tracking function of blockchains can be applied not only to the product or asset tracking, but also to intellectual property tracking. Due to advances in technology, the oil and gas industry will involve much content related to intellectual property. However, the legal copyright registration fee is high, and even if the copyright registration is applied, the approval time is long. Blockchain technology can store and track related content, realize the traceability of ownership, and thus achieve the role of intellectual property protection.

2) COMPLIANCE

Due to the high degree of transparency of blockchain technology, it can improve compliance in the oil and gas trade [73], such as increasing the consistency of the Dodd-Frank Act [74], the Extractive Industries Transparency Initiative [75], and the European Union directives [76]. The data generated by the blockchain is shared within the "Trust::Data" framework proposed by the Massachusetts Institute of Technology, which significantly reduces compliance costs and increases speed [77].

Besides, some bidding or management issues during oil and gas exploration and development can also be solved by blockchain. For example, the problem of invalid bidding, the liability of contracting negligence in project bidding, and the civil liability for refusing to sign the contract after winning the bid.

3) DATA RECORD

Oil and gas companies need to obtain land use rights before conducting exploration, development and other activities. However, understanding the source of the land can be difficult, and there may be multiple records of ownership conflicts in a separate database. In this environment, land transactions are highly vulnerable to fraud. Blockchain technology can create an invariable audit trail of land mobility, value and ownership. This will reduce the loss or mismatch of ownership, the occurrence of ownership disputes, and provide tax authorities with the transparency of land transactions, real-time record of the accurate transfer of value [78].

D. CYBER SECURITY

According to statistics, in 2016, nearly three-quarters of oil and gas companies in the United States experienced at least one cyberattack. For hackers, oil and gas companies have many vulnerable breakthroughs (oil and gas enterprise structure is shown in Fig. 9), such as complex operating system and production process, little intersection of information technology (IT) and operation technology (OT), delay of real-time system caused by firewall, inconsistency of network standards among departments, irregular updating of system security patches (especially vendor's security system), and

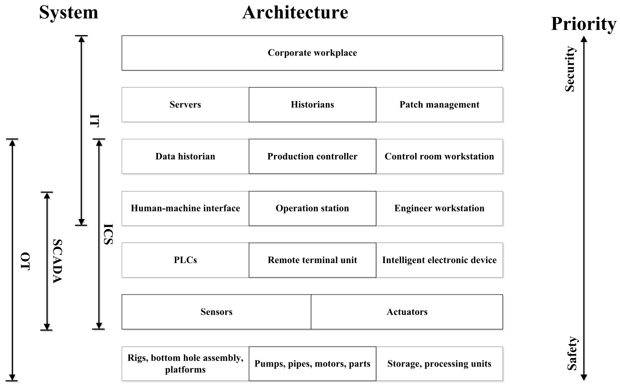


FIGURE 9. Oil and gas enterprise structure [79].

historical legacy problems [79]. For example: intelligent sensors can provide important information such as the real-time status of offshore oil field operations, but these sensors are currently the most insecure part of the enterprise network because it is possible for industry competitors to obtain such information through espionage activities. If blockchain technology is used to store important data in a distributed manner, the risk of network attacks can be effectively reduced. In order to increase the data security of enterprises, financial technology developers are developing projects in the "Trust:: Data" framework, including OPAL, Digital Personas and Identity, Tradecoin, MIT Enigma, OpenPDS [80].

E. EXAMPLES: VAKT AND KOMGO SA

At present, the application of blockchain technology in the oil and gas industry is in its infancy. Two well-known related blockchain projects are: Vakt and komgo SA [81].

Vakt is a blockchain-based commodity trading post-processing company. On November 29, 2018, it announced the world's first enterprise-level blockchain platform for the crude oil industry. Its first users include BP, Equinor, Shell, Gunvor, and Mercuria, and will launch larger products in January 2019. Their goal is to increase speed and security, which benefits everyone in the supply chain from market participants to customers. VAKT uses J.P.Morgan's Quorum blockchain technology. Quorum is a blockchain platform based on Ethereum, but it has higher privacy and a variety of voting-based consensus mechanisms [82].

Another important project, komgo SA, is a blockchain platform for commodity trading that is supported by commodity supply contracts. It is also jointly developed by many companies, and the first operation of komgo SA will be crude oil transportation in the North Sea. It is expected that in early 2019, the platform's transactions will expand to new areas: metals and agricultural products. Since then, the scope of the platform will continue to expand [83].

V. DISCUSSIONS

This section will discuss issues such as the application status, opportunities, challenges, risks and development trends of blockchain technology in the oil and gas industry.

TABLE 7. Major oil and gas blockchain projects [87].

Continent	Location	Gas/Oil	Stage (Mid 2018)	Name/Company	Remark
Asia	Xiamen, China	Oil	Test	Sinochem Group	Simulated gasoline export from Quanzhou to Singapore
Asia	Abu Dhabi	Oil and gas	Test	ADNOC and IBM	Oil and gas production automation
North America	Houston	Gas	Test	S&P Global Platts	Platform for confirming transactions, reporting prices
Europe	London	Oil	Pre-launch	Vakt	Platform to cut post-trade costs
Europe		Gas	Pre-launch	OneOffice (BTL)	Platform to cut post-trade costs
Europe	Hamburg	Gas	Pre-launch	Enerchain	Platform for P2P wholesale trading
Asia	Fujairah	Oil	Live	FOIZ, S&P Global Platts	Oil terminal stock levels reporting
Africa		Oil	Test	Mercuria, ING, SocGen	Digital documents used for cargo traded three times on way to China
South America	Chile	Oil and gas	Live	Energia Abierta	Regulator tracking national energy data
Europe	Britain, Italy, Austria	Oil and gas	Live	Interbit [89]	Oil and gas trading
North America	America	Oil and gas	Live	PetroBLOQ [90]	Oil and gas supply chain management
Europe	Switzerland	Oil and gas	Live	komgo SA [83]	Trading platform

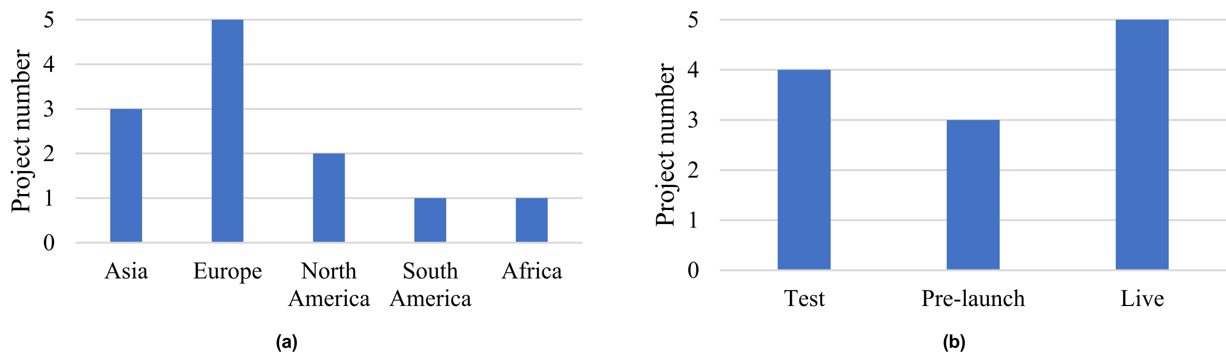


FIGURE 10. Statistics on 12 major oil and gas blockchain projects. (a) By region. (b) By status.

A. APPLICATION STATUS

In the past two years, blockchain technology has begun to emerge in the oil and gas industry. Many energy giants have begun to invest in the development of this technology. Among them, BP and Shell are pioneers in blockchain application technology in the oil and gas industry.

At the end of 2017, Sinochem Group successfully completed China's first blockchain crude oil import trading pilot project from the Middle East to China [84]. There are two major applications in the project – digital bill of lading and smart contracts, which can significantly improve the efficiency of crude oil trading execution and optimize the transaction financing cost by 20% to 30%. In addition, the blockchain platform jointly developed by Abu Dhabi National Oil Company (ADNOC) and IBM will be the first application of blockchain technology in global oil and gas production accounting [85], [86]. Unlike other projects, it will apply to the entire oil and gas life cycle, not just a critical part of the commodity supply chain. ADNOC expects to automate the transaction process through the platform, and by deploying advanced technology resources, it will reduce its drilling time by 30% in 2019 and achieve savings of up to $1 billion.

Table 7 lists 12 major oil and gas industry blockchain projects worldwide [87], and Fig. 10 summarizes the status of these projects from the region and status. It can be seen that as of mid-2018, most of the blockchain projects in the oil and gas industry are in operation and commissioning, and some are in the testing stage. Europe has the largest number of projects, and Asia and Europe have the fastest development in the application of blockchain in the oil and gas industry. But overall, there are few blockchain projects in the oil and gas industry relative to other industries.

B. UNDERSTANDING LEVEL

From the perspective of understanding blockchain in the oil and gas industry, this paper summarizes the following information from the statistical records of 1053 respondents in "Deloitte's 2018 global blockchain survey" [8]:

TABLE 8. Common misunderstandings about blockchain [88].

Misunderstanding	Reality
Blockchain is distributed ledger technology.	Blockchain is a form of distributed ledger technology, and not all distributed ledger technologies use blockchain technology.
Blockchain is bitcoin.	Bitcoin is a type of cryptocurrency and an application of blockchain.
Blockchain is absolutely impossible to tamper with	The blockchain is not absolutely unalterable, but the cost of tampering is very high.
Smart contracts are legally binding	Without a separate contractual agreement, smart contracts are not legally binding.
Blockchain is currently the best database	Blockchains are not necessarily better than traditional databases.
Blockchain is absolutely safe.	Although the blockchain is based on encryption standards, the method of ensuring privacy is completely outside of any blockchain standards and implementation.

(1) 72% of respondents in the oil and gas industry believe that blockchain technology will have a big impact on the industry;

(2) 61% of respondents in the oil and gas industry believe that the blockchain is only a currency database and can only be used in the financial services sector;

(3) Regarding the level of understanding, 87% of respondents in the oil and gas industry believe that their understanding of the blockchain is ''Excellent'' rather than ''Expert'' (only two levels in this survey);

(4) In terms of investment in blockchain technology, 72% of respondents in the oil and gas industry invested between \$1 million and \$10 million, while only 9% invested more than \$10 million. In contrast, 38% of respondents in the automation field invested more than \$10 million in their organization;

(5) Only 15% of the organizations in the oil and gas industry have applied the blockchain to production, while 84% are only in the consciousness or experimental phase.

For another report [88], the World Energy Council interviewed 39 people in the energy field in 2018 and released a report called ''Is blockchain in energy driving an evolution or a revolution?''. They have a maturity model based on the interviewees' responses. It can be concluded from the two survey reports that the understanding of the blockchain by the oil and gas industry is not comprehensive enough (Table 8 summarizes some common misconceptions about blockchain), and the application of the blockchain is still in the experimental stage. In addition, the oil and gas industry's investment in the blockchain is not strong enough.

C. OPPORTUNITY AND CHALLENGE

Due to the decentralization and transparency of the blockchain, it can bring many opportunities to the oil and gas industry [91]. However, a new technology will inevitably encounter many challenges when it is first applied, as shown in Table 9.

D. RISK

Although the blockchain technology has many advantages, the current operating system is still not perfect, and there are many risks. Risks can be divided into operational risks, cyber risks, and legal risks [92]–[95].

Operational risk means that if the blockchain is applied to the oil and gas industry, technical or social problems may produce bad results. It may be reflected in:

- Loss of data and identity.
- The transaction costs of the public blockchain are high.
- Lack of recipients and users.
- Lack of long-term experience leads to imperfect management.
- Initial applications may have technical problems.
- Lack of a standardized mode of operation, function and security deficiencies.

Cyber risk refers to bad behavior such as fraud due to insufficient security or design flaws, it is reflected in:

- There may be fraud in the interface between the real world and the blockchain world.
- The exchange may be attacked by hackers, and the user's password may be hacked and funds transferred.
- The hard fork of the block will cause the trust of the entire network system to be questioned.

Legal risk refers to some illegal acts that may occur in the operation of block chains, it is reflected in:

- Tax evasion may be triggered.
- Illegal use of information.
- Blockchains are used for illegal transactions.

E. DEVELOPMENT TRENDS

The blockchain has been in development for a decade, from the earliest application to bitcoin to the present application in various industries. However, blockchain technology is continually improving and is striving to find a better application experience. This paper summarizes the future development trends of blockchain technology in the oil and gas industry from five aspects.

1) HYBRID BLOCKCHAIN ARCHITECTURE [100]

Consortium blockchain is currently the main implementation of the blockchain project, but it does not have the scalability and anonymity of the public blockchain. However, with the development of blockchain technology, the oil and gas

TABLE 9. Opportunities and challenges of blockchain in the oil and gas industry [16], [96]–[99].

Opportunity or challenge	Item	Cause
Opportunity	Low transaction costs	Eliminated the involvement of third parties.
	Commodity price decline	Reduced transaction costs.
	Resource transfer is more convenient	Customers will be more convenient to become suppliers and sell excess resources.
	Convenient transaction	A large number of documents, contracts and payments are simplified.
	High transparency	Decentralized data storage and blockchain tracking.
	Standardized language	Data sharing is fast and convenient. It can provide standardized language, exchange information in a secure way, and facilitate the sharing of infrastructure.
	Asset integrity management	Data cannot be tampered with and traceable. It can be used to track assets such as oil and gas production equipment and pipelines.
Challenge	Way of thinking	As mentioned in Section V B, people in the oil and gas industry do not have a thorough understanding of the blockchain and hold a wait-and-see attitude.
	Adapt to new market model	The introduction of blockchain will change the mode of operation of the oil and gas industry, and even change the mode of other related industries, it will take some time to adapt and coordinate.
	Supervision	As the current management mode of the oil and gas industry is still relatively old. Blockchain technology is currently difficult to adapt to the current management environment.
	Technology and security	As the application of blockchain technology in the oil and gas industry is still in its infancy, there will be many technical problems and data security issues. Specific performance: high-frequency business needs are difficult to meet; consensual algorithms consume massive energy; lack of relevant development, integration and maintenance systems; privacy protection, smart contract loopholes, and other security issues.
	Trust	There is no legal or regulatory framework yet.
	Data quality	Blockchain cannot guarantee the quality of data, but can only guarantee the accuracy of data.
	Cost	If blockchain technology is adopted, it will involve many management systems and databases that have been maturely applied in the oil and gas industry. The replacement requires much costs, and the development of technology also requires numerous money.
	Professional	In the overall environment, there are not many professionals in blockchain applications, especially for the oil and gas industry.

industry will not be satisfied in the future by applying blockchain only between enterprises, and a hybrid architecture of "Public blockchain for the masses and consortium blockchain for enterprises" can be formed.

2) COOPERATE WITH OTHER TECHNOLOGIES [101]–[105]

In recent years, not only blockchain technology is rapidly developing, but other technologies such as artificial intelligence, big data, and cloud computing are also advancing rapidly. However, these techniques can aid in the development of blockchains. For example, artificial intelligence based on blockchain uses smart contracts in terms of user equipment registration, authorization, authentication, and value exchange to improve security. The combination of blockchain and cloud computing will effectively reduce the cost of blockchain deployment. In addition, the blockchain will promote the development of other technologies. For example, various artificial intelligence modules can implement links through blockchains and can learn on the chain to promote the evolution of artificial intelligence.

In a practical case, the Blockchain as a Service (BaaS) system developed by the combination of blockchain and cloud computing aims to provide users with better blockchain services. Therefore, BaaS service providers pay more attention to the vertical industry connection, to provide reasonable smart contract templates, good account system management, good resource management tools, and customized data analysis and reporting systems.

3) CROSS-CHAIN AND HIGH-PERFORMANCE BLOCKCHAIN [106]

At present, each blockchain network is a relatively independent network, and data information cannot be interconnected. Cross-chain technology makes blockchain suitable for industries with complex scenarios. Current mainstream cross-chain technologies include Notary schemes, Sidechains/relays, Hash-locking, and Distributed private key control. Due to the complexity of the oil and gas system, multiple blockchains can be established according to different scenarios. Cross-chain technology can realize digital asset transfer between multiple blockchains, thereby improving efficiency.

In addition, in order to improve the throughput of the blockchain system, many scholars and experts are developing high-performance blockchain solutions. There are currently three ideas for improving performance. The first is to change the blockchain topology to a transaction-based Directed Acyclic Graph (DAG). The second idea is to change the consensus strategy to increase throughput by reducing the number of nodes participating in the consensus. The third way is to improve the overall throughput of the system by increasing the horizontal scalability of the system.

4) HYBRID CONSENSUS MECHANISM [107], [108]

Due to the critical position of the consensus mechanism in the blockchain, it will continue to develop. There are many

TABLE 10. The emergence time, basic algorithm, and Byzantine fault tolerance performance of 32 mainstream consensus algorithms [33].

Algorithm name	Appearance time	Presenter	Basic algorithm	Byzantine fault tolerance	Reference
Viewstamped replication	1988	Barbara Liskov and James Cowling	/	/	[110]
Paxos	1990	Leslie Lamport	/	/	[111]
Practical Byzantine Fault Tolerance (PBFT)	1999	Miguel Castro and Barbara Liskov	Byzantine Fault Tolerance (BFT)	<1/3	[112]
Proof of work (PoW)	1999	Markus Jakobsson and Ari Juels	/	<1/2	[113]
Proof of stake (PoS)	2011	Quantum Mechanic	/	<1/2	[114]
Delegated Proof of Stake (DPoS)	2013	Dan Larimer	PoS	<1/2	[115]
Raft	2013	Diego Ongaro and John Ousterhout	/	/	[116]
Ripple	2013	Vitalik Buterin	/	<1/5	[117]
Tendermint	2014	Jae Kwon	PoS+PBFT	<1/3	[118]
Tangaroa	2014	Christopher Copeland	Raft+PBFT	<1/3	[119]
Proof of activity (PoA)	2014	Iddo Bentov et al.	PoW+PoS	<1/2	[120]
Proof of burn (PoB)	2014	Slimcoin	PoW+PoS	<1/2	[121]
Proof of space (PoS)	2014	Burstcoin cryptocurrency	PoW	<1/2	[122]
Proof of stake velocity (PoSV)	2014	Larry Ren	PoW+PoS	<1/2	[123]
Casper	2015	Vitalik Buterin, Vlad Zamfir and Greg Meredith	PoW+PoS	<1/2	[124]
Stellar	2015	David Mazières	Ripple+BFT	<1/3	[125]
Algorand	2016	Silvio Micali	PoS+BFT	<1/3	[126]
Bitcoin-NG	2016	Ittay Eyal et al.	PoW	<1/2	[127]
ByzCoin	2016	Kokoris Kogias, Eleftherios et al.	BTC-NG	<1/3	[128]
Delegated Byzantine Fault Tolerance (dBFT)	2016	Neo	PoS+pBFT	<1/3	[129]
Elastico	2016	Loi Luu et al.	PBFT+PoW	<1/3	[130]
HoneyBadger	2016	Andrew Miller et al.	Tendermint	<1/3	[131]
Proof of elapsed time (PoET)	2016	Intel	PoW	<1/2	[132]
Proof of luck (PoL)	2016	Mitar Milutinovic et al.	PoW	<1/2	[133]
2-hop	2016	Tuyet Duong et al.	PoW+PoS	<1/2	[134]
Sleepy consensus	2016	Iddo Bentov et al.	PoS	<1/2	[135]
Scalable Byzantine Fault Tolerance (SBFT)	2017	Hyperledger Fabric	Tangaroa	<1/3	[136]
ByzCoinX	2017	Eleftherios Kokoris-Kogias et al.	ByzCoin+Elastico	<1/3	[137]
Proof of authority (PoAu)	2017	Gavin Wood	PoS	<1/2	[138]
Proof of useful work (PoUW)	2017	Marshall Ball et al.	PoW	<1/2	[139]
Ouroboros	2017	Aggelos Kiayias et al.	PoS	<1/2	[140]
Proof of reputation (PoR)	2018	Jiangshan Yu et al.	PoW	<1/2	[141]

consensus mechanisms, each with its own advantages and disadvantages. The application of a single consensus mechanism has other flaws. In order to improve efficiency and security, the consensus mechanism will be developed towards a hybrid consensus mechanism and will be dynamically configured according to different situations in different application scenarios or running processes.

5) MORE INTERDISCIPLINARY PROFESSIONALS [109]

The global demand for blockchain talents has grown since 2015 and experienced explosive growth in 2016-2017, but for now, its share of global talent market demand is still meager. Blockchain technology is a multi-disciplinary and cross-disciplinary technology. Compared with the talents of R&D technology, the blockchain underlying system architecture design talents need to master several interdisciplinary professional skills and understand the underlying design principles of blockchains, which means that the oil and gas market needs professionals who have both the experience of system architecture design and know the specific business of application scenarios. Therefore, more professionals in the future will be more inclined to implement the blockchain, and more inclined to interdisciplinary.

VI. CONCLUSIONS

This paper does a systematic review to discuss the application prospects of blockchain technology in the oil and gas industry, and the main purpose of this paper is to expand the influence of blockchain technology in the oil and gas industry. In summary, blockchain technology has excellent potential in the oil and gas industry, but since it has just started in the last two years, there are many opportunities, challenges, and risks.

Specifically, this paper first introduces the core theory of blockchain technology in Section III, including the consensus algorithm of the blockchain, data record model and distributed storage system. Secondly, this paper demonstrates the possible application modes and scenarios of blockchain in the oil and gas industry from four aspects in Section IV:

TABLE 11. Introduction, advantages and disadvantages of five distributed storage systems [57].

System	Description	Advantage	Disadvantage	Reference
IPFS	It is a global, P2P distributed storage file system. Its goal is to replace the traditional Internet protocol HTTP. The principle is to use content-based address instead of domain name-based address.	The network is faster, safer and more open, and the cost is low.	There are challenges in content regulation.	[142]
Sia	It is a POW-based blockchain decentralized storage system. The original design of Sia is to decentralize cloud storage. Sia can unite a group of distrustful and ignorant computer nodes into a cloud storage platform with unified running logic and programs.	Convenient data sharing. Encrypted communities are stable.	Slower speed.	[143]
Storj	It is a decentralized, blockchain-based distributed cloud storage system. Storj encourages users to share their remaining space and traffic in order to get block rewards.	Private key encryption, high network information security.	Networks tend to be decentralized rather than distributed according to the amount of data used.	[144]
Maidsafe	It is not only a solution for decentralized storage, but also a new backbone for storing, accessing and exchanging data.	It integrates storage, access and exchange of data.	Hard to understand by users.	[145]
Genaro	It is a decentralized storage network based on blockchain. Through the Token mechanism set up by the network, when users use Genaro to store data in the storage node, the corresponding Token will transfer from his account to the verified host and storage node.	Ability to process large amounts of data.	Unknown	[57]

trading, management and decision making, supervision and cyber security. Finally, this paper discusses the application status, opportunities, challenges and risks of blockchain technology in the oil and gas industry, and also analyzes the future development trends in Section V. The following conclusions were drawn:

- Europe and Asia are the most powerful in promoting the blockchain in the oil and gas industry, and BP and Shell are pioneers in this field.
- At present, the application of blockchain in the oil and gas industry is still in the experimental stage, and many people in the oil and gas industry do not understand enough.
- Blockchain technology can bring many opportunities to the oil and gas industry, such as reducing transaction costs and increasing transparency. However, it also faces many challenges and needs to address many technical and regulatory issues.
- Blockchains may have operational, legal, and cyber risks in the oil and gas industry.
- In order to meet market and management needs, the blockchain will move toward the hybrid blockchain architecture, cross-chain, and hybrid consensus mechanism in the oil and gas industry.

APPENDIX A

See Table 10.

APPENDIX B

See Table 11.

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