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Tailored Blockchain Applications for the Natural Gas Industry: The Case Study of SOCAR

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Abstract: Blockchain technology has emerging areas of deployment in diverse sectors and use cases. In this study, several potential application areas of blockchain with promising benefits have been identified in the natural gas industry. There is no single solution that can address different challenges and meet disparate requirements. Therefore, it is important to understand the needs of the natural gas industry and propose appropriate blockchain solutions. Moreover, in the literature, there is a lack of detailed case studies involving industrial experts from the natural gas sector. Expert opinion can be useful for prioritizing the most needed or expected blockchain application areas among several options. By considering privacy, authentication, speed, security, energy consumption, and costs, suitable blockchain types and consensus mechanisms can be determined. This study presents one of the first detailed case studies for tailored applications of blockchain in the natural gas industry. Through a two-staged semi-structured interview with executives from SOCAR Azerbaijan, the most important blockchain application areas and operational requirements were identified. Furthermore, the most suitable blockchain solutions that can address application-specific conditions and needs were determined. This study both, develops a replicable and reliable methodology to conduct detailed blockchain implementation case studies in the natural gas industry and various other sectors, and provides detailed insights into the primary application areas, operational expectations–requirements, and implementation challenges specific to each application.

Keywords: blockchain; case study; internet of things (IoT); natural gas; engineering

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1. Introduction

Natural gas is one of the major sources meeting world energy consumption and it is the only fossil-based source that has consistently increased its share among the other sources in the last half-century. Global natural gas production has steadily increased in the last decade, with an annual growth rate around 2.5%, except for minor drops encountered in 2009 by 2.6% and in 2020 by 2.5% [1]. The share of natural gas in the world total energy supply reached 23.2% of 606 EJ (exajoule, 10^{18} joules) in 2019, a considerable growth compared to 16.1% of 254 EJ in 1973. In OECD countries, despite the decline in the share of coal (from 22.5% in 1973 to 13.2% in 2019) and oil (from 52.6% in 1973 to 34% in 2019) of total energy supply by source, the share of natural gas has significantly increased, from 18.9% to 30.6%. In world gross electricity production, natural gas is the second largest source, with a 23.5% share, following the leader coal with a 36.7% share, ahead of all the other sources [2]. In OECD countries, it was the only source with a steadily increasing share in gross electricity production up to the beginning of the 2000s, and from around 2007 to today, it has continued to grow together with emerging renewable energy technologies (Figure 1) [2].

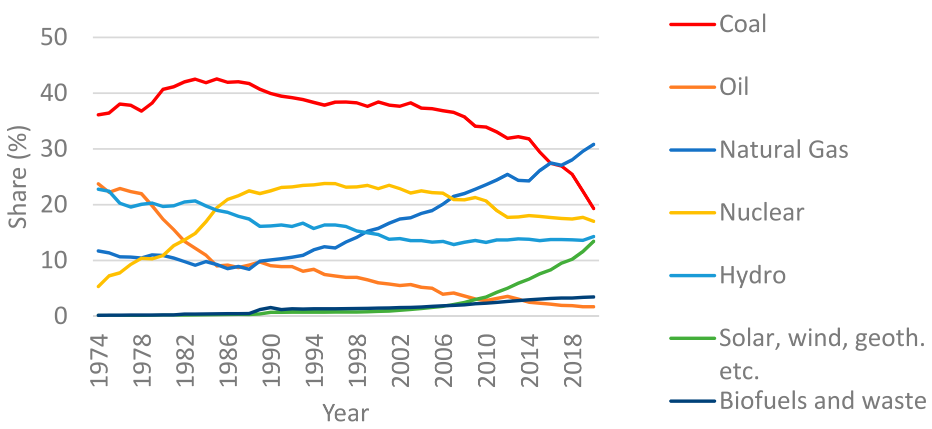

Figure 1. The share of OECD gross electricity production from 1974 to 2000 [2].

There are a number of major problems in the natural gas industry [3]. Obsolete infrastructure can be listed as one of the major issues. Outdated natural gas pipelines, a centralized structure, and cascaded software systems are not suitable for handling a massive number of devices and users. The unreliability of transactions due to third party inclusion is another point of concern. Gas orders are prepared and supervised by third parties and this does not guarantee the transparency, fairness, and traceability of transactions. The third problem is price fluctuations due to dynamic changes in natural gas resources. It is an important challenge for users to foresee reliable sales information, due to uncertainties related to fluctuations. Gas data inaccuracies are the fourth major problem. Delays being encountered in data collection from gas meters in the field trigger energy supply failures. The last major problem is user information security. The information provided by users during transactions, comprising personal information, gas consumption, and other details, is mainly stored in centralized databases, with the risk of being compromised, deleted, or modified. Similar concerns are listed in IBM's whitepaper in [4], defining the current business transactions as inefficient, expensive, and vulnerable due to the involvement of multiple stakeholders with individual ledgers compliant with their specific policies and procedures. Vulnerabilities are further detailed in terms of time, cost, and risk. Many transactions are stated as sensitive to time, as requiring considerable time to settle and reconcile, and prone to delays. From a cost perspective, high overhead costs due to inclusion of various companies and operating units, high costs of management and execution, and detailed documentation needs are listed. The related risks are ambiguity and not being able to verify, being open to errors and tampering, and lack of a single source of truth.

Sector experts agree on the possible benefits of wider automation and digitalization, to increase profitability [5]. Oil and gas companies are willing to adopt and implement new digital technologies and change their operating practices [6]. The World Economic Forum, in a whitepaper, stated that USD 2.5 trillion value could be derived from the digitalization of the oil and gas sector, including a 108,000 barrel reduction in pipeline spills, 120,000 barrel reduction in spills in upstream operations, a 370 million tonne reduction in CO_2 emissions, a 800 million gallon reduction in water consumption, a 16% reduction in accidents and injuries, by utlizing enhanced automation and remote operation, predictive maintenance, operation optimization, data analytics and modelling, field staff connections, supply/demand balancing, digital customer services, and others [7].

Blockchain is one of the emerging technologies that can offer promising potential applications, with prospective benefits in several sectors, ranging from finance [8] to supply chains [9,10], health to mobility [11], public governance to cybersecurity [12], and infrastructure to energy [13]. A blockchain is a distributed and shared ledger that enables immutable transaction records [14], asset tracking, and common trust between several stakeholders and parties [15]. It combines cryptography, data management, networking, and incentive mechanisms to aid the verification, execution, and recording of transactions between parties [16]. A distributed ledger is an addition-only storage method of transactions distributed between many participating nodes. Blockchain represents a connected list of blocks. Each block stores an ordered set of transactions. Each transaction is recorded as a block of data, representing the movement of a tangible (product) or intangible (intellectual) asset. The data block can store the relevant information (sides, content, quantity, time, place, condition, and others) that is needed about the related transaction. Each new block is added to a chain of blocks and is connected to the blocks before and after it. Since the records have a specific time and sequence, any attempts to insert additional blocks between the existing blocks or to modify former blocks can be detected and prevented. None of the transactions can be changed or tampered with once they are recorded in the shared ledger. In case a record includes an error, a new transaction has to be added to reverse the error and both records will be visible. Smart contracts contain a number of rules determined to trigger and perform their related actions and transactions autonomously. A consensus protocol, algorithm, or methodology determines how a new block can be added to the network, resolving competing new blocks [16]. Smart contracts are used to perform autonomous actions based on predetermined rules, triggered by specific conditions. Smart contracts allow peer to peer transactions without any intermediaries, utilizing consensus protocols and software-based verification methodologies [17].

Blockchain technology can enhance data management [18], reduce transaction costs [19], avoid error and fraud [20], and improve system performance with enhanced monitoring and maintenance [21].

Blockchain is not a one-size-fits-all solution or a silver bullet with a single type of implementation that will be beneficial in all cases, applications, and conditions. It has several types and design varieties (characteristics, consensus mechanisms, and others), which are explained in detail in Section 2 of this paper, and which could be suitable or may not fit, based on the considered context of adoption. Moreover, it is a major challenge for industrial players and corporate executives to evaluate and decide on the most suitable blockchain type and design that will fit the targeted sectoral applications, among several potential integration options. Due to this difficulty, industry actors have formed non-profit organizations (such as the OOC Oil & Gas Blockchain Consortium [22], which later changed its name to Blockchain for Energy [23]) to explore the potential areas of use and determine the best solutions collaboratively. Additionally, blockchain brings together some inevitable risks and costs that should be carefully considered in potential applications [24].

Several studies have identified similar potential application areas of blockchain for the natural gas industry. The potential areas of use range from leakage detection in gas pipeline networks to the tracking and tracing of natural gas shipment; automation of gas exploration and production processes to gas asset life-cycle management; billing and payment simplification to operational and compliance auditing; and well abandonment and restoration tracing to waste collection and disposal [4,25–28]. The natural gas supply chain facilities that are considered for potential implementation of blockchain solutions are shown in Figure 2. A new concept of a micro ecosystem with blockchain and edge computing is explored in [29]. Integrated use of blockchain with AI and IoT is investigated from architectural and design perspectives in [3] and in gas prediction and transaction in the smart city context in [30]. A novel solution, aiming natural gas resource finance and sustainability, is presented in [31]. Ref. [32] implemented business process modelling, to investigate the implementation of blockchain in the midstream LNG supply chain. The existing studies have mainly explored the potential areas of use and prospective benefits of blockchain in the natural gas sector, without sufficiently detailing the suitable blockchain types (private, consortium, or public), consensus mechanisms (Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), Proof of Authority (PoA), Practical Byzantine Fault Tolerance (PBFT), and Proof of Elapsed Time (PoET)) and related risks specific to application areas. Moreover, there is a need for case studies that actively involve industry experts in prioritizing applications, identifying requirements, and tailoring solutions.

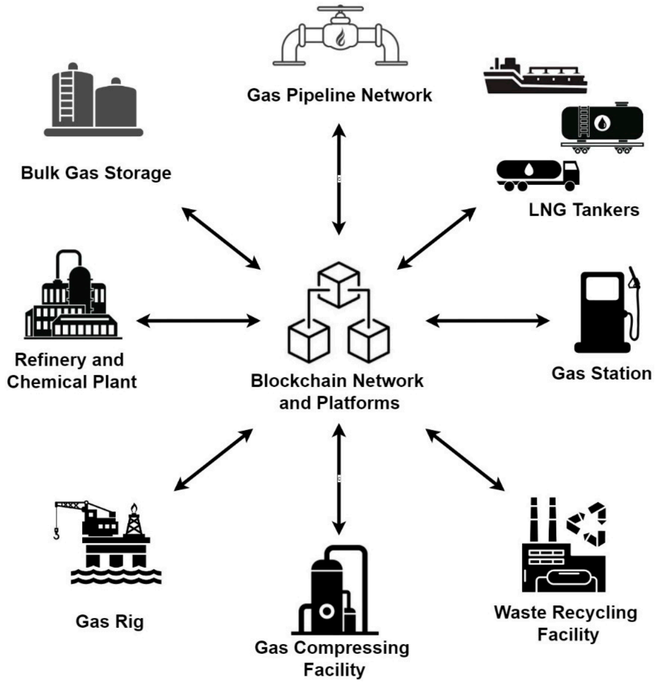

Figure 2. The natural gas supply chain facilities that considered for potential blockchain solution implementation [25].

Issues in the natural gas industry include

- conventional infrastructure challenges and limitations in monitoring, operating, and maintaining a large number of assets,
- gas price volatilities,
- gas stock tracking issues,
- dependency on third parties for financial transactions and gas exploration.

The two problems to be solved within the scope of this study are

- prioritization of application areas of blockchain, based on the requirements or desires of The State Oil Company of the Azerbaijan Republic (SOCAR) operations,
- the lack of clarity regarding the suitable blockchain solutions that would best fit natural gas sector applications.

This paper presents one of the first detailed case studies of the application of blockchain in the natural gas sector. Through a two-stage semi-structured interview conducted with the executives of SOCAR Azerbaijan, one of the top companies in the natural gas industry globally, the prominent application areas of blockchain for SOCAR were prioritized, the requirements for each use case were identified, and suitable blockchain types and consensus mechanisms were tailored, specific to each application, and considering the operational performance, costs, and risks. Section 2 describes the blockchain types and consensus mechanisms, risks of blockchain applications, and the potential areas of use, as well as the benefits of blockchain in natural gas procedures and processes. Section 3 explains the methodology used in the case study. Section 4 presents the results of the interviews and tailors the suitable blockchain solutions that can address the most prominent use cases and operational requirements. Section 5 discusses the findings of the study and provides directions for future research.

2. Literature Review

2.1. Blockchain Types, Consensus Mechanisms, Risks, and Natural Gas Industry Applications

This section explains the blockchain types, consensus mechanisms, associated risks, and potential applications in the natural gas sector under different subsections. The information presented in this section formed the basis for the semi-structured interview explained in Section 3.

2.1.1. Blockchain Types

There are four main types of blockchain, namely, private, consortium, public, and hybrid. A private (permissioned) blockchain provides access only to known participants, providing them with the ability to read and/or write data. A system provider, a single authority, is in charge of evaluating new applicants that request to join the network and giving them permission to access the data. The system provider also has the ability to roll back and reverse some processes. Private blockchains are faster in terms of speed and have lower costs compared to the other blockchain types. On the other hand, all the participants are known, the devices are authenticated, and dependence on a single authority has the risk of failure in case of being compromised through cyberattacks. Usually, Proof of Stake (PoS), Proof of Authority (PoA), and Practical Byzantine Fault Tolerance (PBFT) consensus mechanisms are used in private blockchains.

A consortium blockchain is another permissioned type of blockchain. Unlike private blockchains, a consortium blockchain is controlled by a group, rather than a single authority. It has a semi-decentralized structure [33]. Only trusted and verified participants can validate blocks. It is a mid-solution between private and public blockchains, with an intermediate energy consumption, cost, and transaction speed. Although it is more secure compared to a single authority-dependent private blockchain, the consortium formation process still has the risk of intrusion of undesired parties and entities. Personal information needs to be known, as in private blockchains. Proof of Work (PoW), PoS, and PoA are generally preferred as the consortium mechanisms.

A public (permissionless) blockchain is accessible to anyone [34]. The participants have random IDs and do not need to disclose their personal information (pseudonymity). It is the blockchain type used in Bitcoin and most of the Ethereum networks. There is no central entity that evaluates new applications or manages, the ongoing traffic. In this blockchain type, unknown devices can participate without any initial checks for trustworthiness. A large number of participants and highly decentralized structure provide more security, while decreasing transaction speed and increasing energy consumption and system costs. Usually, PoW and PoS consortium mechanisms are used.

A hybrid blockchain is a customizable solution, where the members can determine which participants can join the network and which transactions will be open to public. It aims to combine the desirable parts of public and private blockchains: freedom and controlled access [35]. It is positioned between the consortium and public blockchains, in terms of security, speed, and costs.

2.1.2. Consensus Mechanisms

There are over 30 mainstream consensus algorithms, six of which are commonly used in prominent applications [25]. This subsection describes the six most used consensus algorithms comparatively.

Proof of Work (PoW) allows every miner to validate new data blocks. Nodes can remain anonymous, and any willing participant can join mining. It requires extensive computation, which should also be verified by other nodes [36].

Proof of Stake (PoS) allows stakeholders owning coins or smart contracts to participate. The ones with high stakes are chosen to validate new blocks. "Minters" reserve some of their coins as a security deposit, to become a validator. A mistaken validation causes the validator to lose their staked tokens. This approach financially rewards the validators for acting fairly.

Delegated Proof of Stake (DPoS) is a considerably modified version of PoS, in which, token holders vote for a group to be responsible for validation of transactions [37]. This approach strengthens the decentralized aspect of the blockchain, as the network participants decide together who will validate transactions, while the actual validation is performed by a smaller delegated group, with improved speed.

Proof of Authority (PoA) is based on the validation of transactions by specifically authorized nodes. The authorized nodes have recognized organizational identities, which are subject to penalties based on external regulations outside the blockchain platform. It has a lower energy consumption and higher transaction speed compared to other consensus mechanisms [38]. It is a suitable mechanism for some private blockchain applications.

Practical Byzantine Fault Tolerance (PBFT) is implemented by authorization of a network of trusted validators (secondary nodes) by a single authority (primary node). This approach can provide reliable transactions as long as less than one third of the nodes are compromised [39]. The consensus is reached by voting.

Proof of Elapsed Time (PoET) randomly generates time delays, the reliability of which is checked at the hardware level. The nodes are allowed to stay idle or perform some other work for their randomly determined period, increasing the network efficiency. Random time determination allows every participating node an equal chance of winning the reward [40].

2.1.3. Risks

Blockchain applications have a number of risks that need to be considered during decision making and solution design. Deloitte lists the risks under three categories: standard risk considerations, value transfer risk considerations, and smart contract risk considerations [41].

There are eight standard risk considerations. Strategic risk is a firm's decision to either adopt technology at an early stage of development or wait until it matures. It is also related to deciding on the network to take part in and the platform to utilize. Business continuity risk is associated with network service interruption due to cyberattacks or operational issues. It requires the development and adoption of methods that can provide fast incident response and short recovery time. Reputational risk is related to compliance with legacy infrastructure. Information security risk is based on the vulnerability of participant account or wallet and the security of transactions in private blockchains. Regulator risk represents compliance with diverse regulatory requirements, particularly in international transactions. Operational and IT risks are concerned with the speed, scalability, and interoperability with legacy systems of implementations. Contractual risk is the need for service-level agreements between the participating nodes and the network administrator. Supplier risks are related to risks associated with third-party technology providers.

Value transfer risk considerations have four subtypes. Consensus protocol risk considers the disadvantages of the adopted consensus mechanisms and their vulnerabilities to cyberattacks or operational issues during deployment. Another risk is key management, which concerns the irreversible transfer of assets in cases of a hijacked account. The deployment component provides a complete working container infrastructure for the considered business application [14]. Continuous integration, delivery, and deployment approaches can help minimize related risks [42]. Continuous integration is the frequent integration and merging of work between the team members. This method reduces the release cycle, enhances software quality, and increases development team productivity. Continuous delivery aims to ensure that an application can be instantly deployed in the relevant environment. Continuous deployment autonomously and continuously deploys the applications for production or customer use cases. Data confidentiality risk concerns metadata leakage of participant transaction metadata to unauthorized network participants. Liquidity risk is related to resolving disputes in transactions, relying on pre-determined regulations.

There are four smart contract risk considerations. Business and regulatory risks are about the business, economic, and legal arrangements used in determination of smart contracts. Contract enforcement is the compliance with legal limitations and financial arrangements. Legal liability is the risk of fraudulent or mistaken use of smart contracts. Information security risks are related to cyberattacks that may target the access, modification, or deletion of information.

Similar risks can be found in another recent study [43]. Seven risks are identified, without any subcategories. Legal risk is related to the regulatory, legal liability, and business and regulatory risks explained in the above paragraphs. Technical risk is partially the same as operational and IT risks and part of strategic risk. Protocol risk is related to consensus protocol risk and partially to operational and IT risks. Cyber risk is similar to key management and information security risks. Privacy risk is related to data confidentiality risk. Validation risk is partially similar to legal liability. Finally, market risk is identical with strategic risk and reputational risk. The interrelations between the risks identified in the two mentioned studies are shown in Figure 2. The determination of very similar risks in two independent, prominent studies shows that these risks are highly likely to be encountered in future field applications and that it is of critical importance to consider them when tailoring blockchain solutions to a specific use case in an industry. In this paper, as part of the interviews conducted in the case study, the risks were mentioned to the executives and taken into account when identifying the most suitable blockchain solutions specific to each potential application.

2.1.4. Potential Applications in the Natural Gas Industry

The natural gas industry value chain consists of three main sections: upstream, midstream, and downstream. Upstream covers gas exploration, production, and processing (including gasification), while midstream is related to transport and LNG shipping, and downstream encompasses regasification, storage, and sale [28,32]. This subsection describes possible areas of use of blockchain in the natural gas industry.

One of the primary areas of use could be the monitoring of natural gas network pipelines. Leakage detection, theft, physical attack-intervention detection, and notification of system operators, with use of real-time monitoring systems operating with blockchains to ensure secure operation and timely maintenance of the critical infrastructure.

Compared to conventional centralized monitoring and storage of data collected from sensors in the field, which are vulnerable to physical and cyberattacks, blockchain can be used to authorize sensors to secure the source of data, and smart contracts can allow autonomous detection of leakages and abnormalities, notifying the related departments and staff instantly. Moreover, records related to maintenance and repairs can be stored in blockchain platforms, allowing traceability and auditing by other staff and entities in future related activities.

Monitoring systems can also be used for natural gas shipments by LNG carrier ships, trucks, and railroad tank cars. Logistic activities can be traced and tracked, ensuring compliance with regulations. Current location and followed route information can be obtained, estimating arrival times and providing notifications in case of any updates. Immutable shipment records enhance security and prevent fraud during shipping. The purity of the product can be verified and recorded at certain points of shipment, providing a traceable trail, to identify the time and place that impurities are added to gas and responsible parties. Similar to pipeline monitoring, LNG carriers' temperature, humidity, pressure, volume, and other parameters representing the state of health can be monitored.

Gas exploration and production is another potential area for implementation of blockchain solutions. Exploration, based on seismic techniques for identifying reserve locations, drilling of wells and testing of the quality and volume of reserve, generates big data, which can be collected, stored, and protected, for use in post-processing. Problems in the collected data can be identified through smart contracts. The related data can be shared with the stakeholders that participate in the exploration and production. Exploration and extraction automation systems are conventionally based on centralized solutions, which may have errors and data corruption issues. Furthermore, stakeholders mostly rent equipment from third party organizations. Blockchain can allow information sharing and payments among the stakeholders.

Gas asset life-cycle management is also listed among the primary potential areas for the application of blockchains. The procurement, shipment, installation, establishment, and repair activities of gas assets involve different subcontractors, requiring compliance with safety regulations. Asset inventory records need to be kept up-to-date. Even purchase and sale request can be processed over blockchain platforms, based on equipment supplier scores representing their reputation. Blockchain can allow the detection and prevention of fabricated, uncertified, or insufficiently performing equipment that does not meet standards. In this way, equipment costs, field staff safety issues, and service interruptions can be minimized.

There is potential for blockchain applications in the billing and payment processes as well. The current payment procedure in the gas industry is to give the stakeholders up to 90 days to complete a payment. The determination of such a long time window is due to the use of centralized systems that are vulnerable to cyberattacks, manual settlement, and non-transparent operations. The conventional systems are also not suitable for a high number of microtransactions. Blockchains can be used for verification of payment provision, receival, and updates, ensuring compliance with the related trading agreements and eliminating the need for intermediaries. It can also be utilized for joint billing in joint ventures.

In the area of regulatory compliance and auditing, the compliance of stakeholders with related state, regional, and international laws, as well as standards and regulations, can be checked. License cancellation, financial losses, or penalties related to non-compliance can be performed over blockchain too. Compliance with field staff safety precautions can be tracked and guaranteed over blockchain as well. The use of dangerous and forbidden chemicals can be prevented as part of the same process.

Well abandonment and restoration can be traced using blockchain solutions. Temporary or permanent abandonment of wells can be verified. Information, including date of abandonment, the reason for abandonment, and type of abandonment, can be stored in a blockchain and could be used at the restoration stage.

Gas waste disposal and recycling is the eighth identified potential area of use of blockchain in the natural gas sector. Compliance with waste treatment regulations, waste tracking, and stages such as gathering, processing, shipping, treating, recycling, and landfilling can be monitored. Successful delivery of waste to a determined recycling plant can be ensured, minimizing illegal dumping and shipments. In such applications, smart contracts can be used to manage delays, fraud and data forgery, and documentation. The amount of waste lost during disposal and recycling can be closely tracked.

2.2. Related Work

Blockchain integration into the natural gas industry is usually considered together with the oil industry [28,43]. The current studies mainly provide an industry-wide perspective about potential areas of use, without the prioritization of use cases and without conducting in-depth case studies involving participants or direct data from major industrial players. Some pilot projects and challenges are briefly introduced from such studies.

In application-specific studies, deterministically-decided single solutions are usually selected and investigated, usually combining IoT and AI [3,30,44]. Such studies usually focus on the design stage and do not employ a holistic approach, to foresee operational challenges.

The majority of the studies in this area have been conducted by Chinese researchers.

There are inspiring approaches from different sectors. One study considered a wide range of use cases in electric power and the energy industry, ranging from microgrids to wholesale electricity markets, green certificate trading to e-mobility charging infrastructure, and asset management to grid services [34]. Conducting interviews and identifying the critical criteria, such as transaction speed, transaction cost, transparency, integrity, confidentiality, suitable blockchain types, and consensus mechanisms, are specified. Such a methodology has not been conducted in an up-to-date manner in the natural gas sector.

The majority of the studies emphasized the advantages of blockchain applications, while a few studies looked into the details of the associated risks [41–43]. These risks also need to be taken into account when determining the most suitable blockchain solution for a use case in a selected sector. A combination of the methodology provided in [34] with the risks specified in [41–43] could progress blockchain adoption efforts further, highlighting the promising options. The inclusion of sector experts from a single company can provide insights that are closer to field, which can also help in deciding on the details of use-case-specific solutions.

Based on the related work, there are important gaps and requirements for further research in the natural gas sector for blockchain adoption. Detailed case studies need to be conducted, and wide range of solution options should be comparatively evaluated, considering advantages and associated risks, when determining solutions specific to a use case. This paper presents one of the first in-depth case studies for blockchain application in the natural gas sector. It contributes to the literature by,

- prioritizing the prominent application areas of blockchain for SOCAR operations,
- identifying the requirements for each use case,
- and determining suitable blockchain types and consensus mechanisms specific to each application, as well as considering the operational performance, costs, and risks.

This work provides a replicable and scalable methodology that can be used in future studies in the natural gas sector and other sectors with a potential adoption of blockchain, such as mobility, health, food, e-government, finance and others.

3. Methodology

Based on the contextual background explained in Section 2, a two stage semi-structured interview was prepared to be conducted with the executives of a natural gas company SOCAR, for a case study with the following main aims:

- identify the primary areas of use with the most urgent need or the highest potential benefits in applying blockchains,
- determine the operational performance, cost, and other related requirements specific to each prioritized area of application,
- tailor the most suitable blockchain solution for each identified area of use, including consensus mechanisms and considering the associated risks.

The first stage interview had questions related to

- the occurrence and importance of the challenges, which can be addressed by blockchain applications, encountered in the company's operations and processes,
- the importance of the needs and potential improvements that can be achieved in the company's operations and processes,
- the sensitivities of the company's financial operations and processes to different factors,
- the importance of the potential benefits of blockchain applications for the company's operations and processes, from the perspective of the executives,
- the priority of the potential blockchain applications in the natural gas industry, from the perspective of the company's executives,
- the importance of the data that could be collected through blockchain for the company's operations and processes,
- the importance of the risks (based on the content provided in Section 2.1.3) associated with blockchain applications for the company's operations and processes.

The second stage of the interview was prepared based on the insights gained from the answers provided in the first stage interview. It had more in-depth questions, aiming to highlight the needs and requirements per primary area of use of blockchains for the company, and determining the most suitable blockchain applications for each area of use. It had questions related to

- the network participants that will be allowed to access and view the data collected for each primary blockchain area of use identified by the company executives in the first stage of the interview,
- the network participants that will be allowed to hold distributed ledger records, even those not authorized to access the information available in the records, to increase the number of copies for enhanced security for each primary blockchain area of use identified in the first stage of the interview,
- the need for pseudonymity of the network participants that will hold distributed ledger records for each primary area of use identified by the company executives,
- the number of assets or nodes that will be monitored, provide information to the system, and communicate with others for each identified primary area of use,
- the number of transactions per second (TPS) and the transaction speed that will be needed for each identified primary area of use,
- any energy consumption-related expectations of the blockchain application for each identified area of use,
- the risk of being targeted by cyberattacks of the blockchain application for each identified area of use (as part of the risk considerations explained in Section 2.1.3),
- the relative operational cost expectations of blockchain applications for each identified area of use.

A general diagram of the methodology is provided in Figure 3.

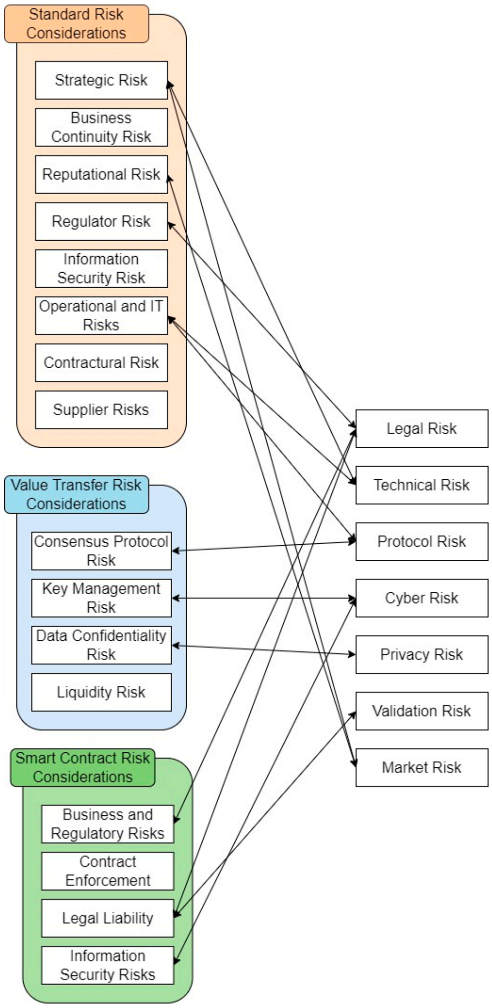

Figure 3. Interrelations between the blockchain risks identified in two prominent studies [41–43].

Both interviews were prepared to be conducted with the same participants, meaning that the executives which took part in the first interview were the participants of the second interview too. The second interview was performed one month later than the first interview. Prior to both interviews, no specific information about natural gas sector challenges listed in the literature, potential blockchain application areas, or benefits of blockchain applications were provided to any of the interviewed executives, to prevent any biases and to solely gain their individual insights based on their operational and procedural experience.

4. Case Study

A case study was conducted with The State Oil Company of the Azerbaijan Republic (SOCAR). The company runs oil and gas exploration, production, processing, transport, and marketing in both Azerbaijan and international markets. It has various activities in Turkey, Georgia, Ukraine, Germany, Switzerland, and Romania, in addition to trading activities mainly in Switzerland, Singapore, and Nigeria. With roots back to the 1950s and beyond, under different organizational names and structures, today's SOCAR was officially established in 1992, after the Republic of Azerbaijan restored its independence [24,45–48]. The first oil wells in the country were drilled in Bibiheybat in 1847, and shortly after in Balakhany. In 1901, Azerbaijan was the world's leading oil producer with 11 million tons of annual oil production, while the US was producing 9.1 million tons annually. In 1941, Azerbaijan produced 23.5 million tons of oil, representing 71.4% of the Soviet Union's production. Azerbaijan was also the world's first offshore oil producer. In 1949, 40 km offshore and 90 km from Baku, a field named "Neft Dashlari (Oil Rocks)" was discovered, which was followed by several other offshore fields in the following years. Currently, offshore production provides more than 60% of SOCAR's oil. Starting in 1994, SOCAR has signed 32 production sharing agreements so far, with foreign oil companies all over the world. The company has around an EUR 50 billion annual revenue, more than 90% of which is recorded in foreign markets.

The two stage semi-structured interviews were conducted with executives from gas distribution. Eleven executives took part in the interviews and provided their opinion.

In the first stage interview, regarding the challenges that are encountered in operation, all the executives emphasized the infrastructure, stating that the management and monitoring of massive numbers of customers and assets is important and becomes challenging from time to time. The reliability of financial transactions due to the involvement of third parties and the need for intermediaries is collectively an area that does not cause any challenges; but it has importance and needs to be carefully considered in the future operations and technological adaptations of the company. Similarly, inaccuracies in gas data, due to delays in gathering data from the meters in the field and related supply challenges collectively, were stated as an area which does not cause any problems; but has importance and should be carefully considered in future operations

Three operational improvements were emphasized by the interviewees. In particular, the storage and verification of the certification of technical field staff (related to hydrogen sulfide (H2S), a poisonous, corrosive and flammable gas, commonly found in drilling and production of natural gas, first aid training, welding, and others) for safe operation of field equipment and devices was given the highest importance. This was followed by the reduction of operational costs and delays, enhanced transparency with the industrial stakeholders, and improvement of employee hiring processes and work performance.

Among the potential benefits of blockchain applications, higher transparency, improved auditability, and traceability were considered the most important by the interviewed executives of the company.

Among the application areas of blockchain, automated leakage detection in natural gas pipelines was stated as the most prominent, followed by gas assets life-cycle management.

The most important data that can be collected and stored by blockchain applications was stated as the current gas stock data, followed by the auditing of reconciliation, based on the tracking of sides that do not fulfill their responsibilities; verification of compliance with trade agreements; and, if required, charging penalties.

Among the blockchain risks introduced in Section 2.1.3, the security of smart contracts (information security as part of smart contract risk consideration category) was given the highest importance, followed by compliance with different systems and protocols (reputational risk), information security (as part of standard risk consideration category), and privacy (data confidentiality).

The first stage interview highlighted six primary application areas of blockchains for SOCAR's operations:

- pipeline leakage monitoring
- gas asset life-cycle management,
- current gas stock monitoring,
- auditing of reconciliation,
- field technical staff certification,
- employee hiring and working performance.

The first stage findings are summarized in Figure 4.

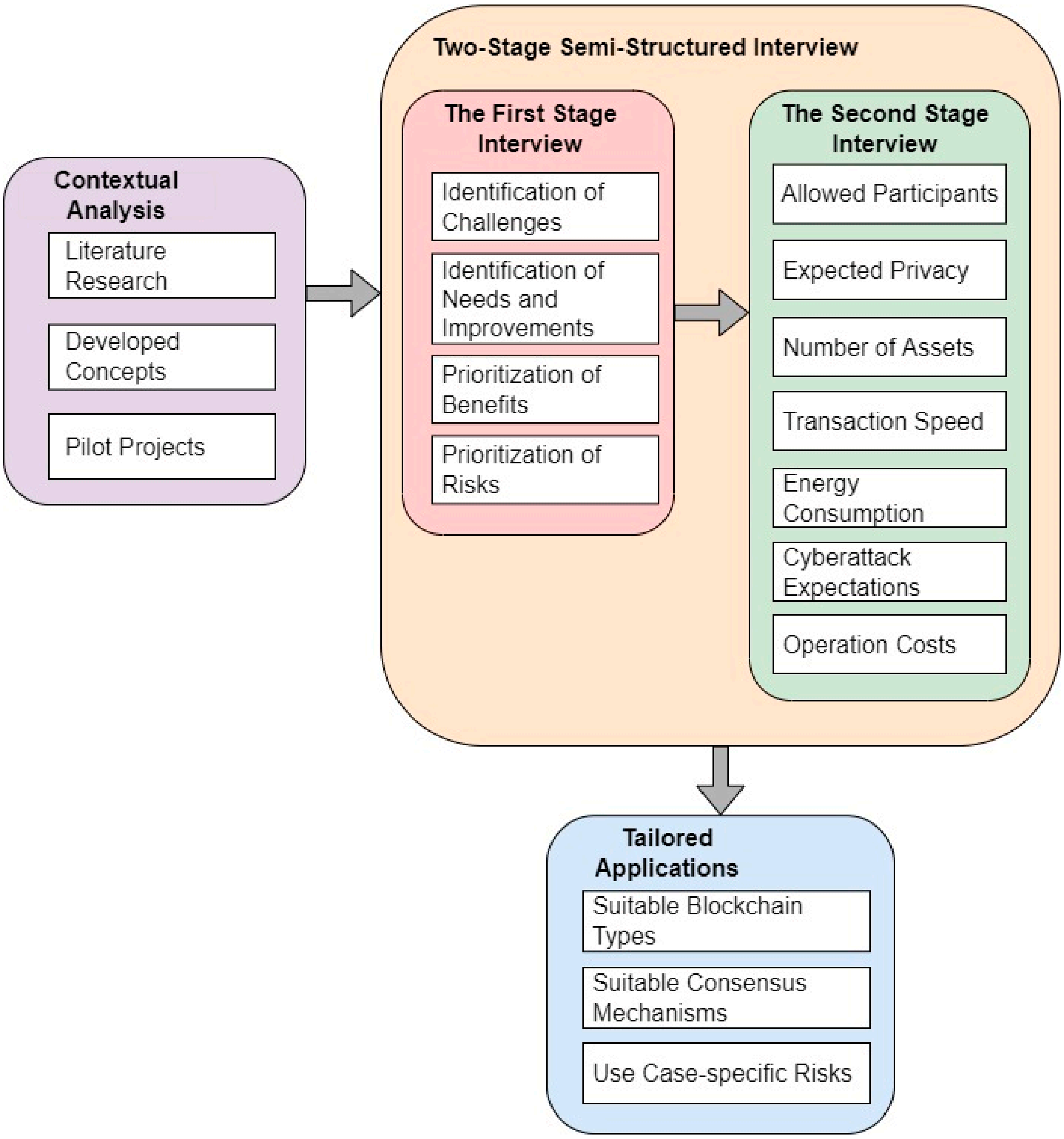

Figure 4. General diagram of the methodology followed.

In the second stage interview, the network participants that can be allowed to access and view the data were reported to be the internal departments and authorized reliable organizations for gas asset life-cycle management, current gas stock monitoring, auditing of reconciliation, field technical staff certification, and employee hiring and working performance application areas. Only for pipeline leakage monitoring were external participants with pseudonymity accepted by the majority of the interviewees.

The only network participants that would be allowed to hold the distributed ledger records for the application areas mentioned in the previous paragraph were stated by all the executives as nodes that belong to the company itself.

The personal information of the network participants that would hold the distributed ledger records were desired to be known by all the executives.

The executives stated that there would be thousands of assets or nodes that would be monitored, provide information to the system, and communicate with others; and less than tens of thousands.

The number of transactions per second (TPS) was stated as thousands for all the applications, except field technical staff certification and employee hiring and working performance. For these two application areas, less than ten to several tens of TPS was stated by the majority of the executives, while a considerable number of executives still thought that thousands of TPS could be needed, as in the other applications.

Low electric energy consumption was collectively stated as a desired aspect of the blockchain solutions that would be implemented for each area of application.

Current gas stock monitoring and the auditing of reconciliation potential applications were stated to have a higher risk of being targeted by cyberattacks, followed by employee hiring and working performance applications. The other applications were stated to have moderate risks, similar to other systems, platforms, and infrastructures.

The relative operational cost expectations were similar to the other systems, meaning that blockchain applications are not required to have low costs; but high costs would not be accepted either.

Based on the insights, experiences, and expectations provided by the company executives, tailored blockchain solutions were determined for each primary application area. The overall findings of the second stage interview with use case-specific applications and mechanisms are summarized in Figure 5.

The suitable blockchain types and consensus mechanisms are shown in Figure 6. In the figure, each arrow color represents dependence to different blocks (such as blue used for any arrow leaving the block "transaction speed") for better visualization of dependencies. Solid line is used to show strong suitability, while dashed line is used to represent partial suitability. For natural gas network pipeline monitoring applications, a hybrid blockchain with authorized company nodes to create blocks, and with external participants allowed to access and view data, seemed to be the suitable solution.

For the other five prioritized application areas, a private blockchain can be primarily preferred, due to restricted access, low energy consumption expectations, no pseudonymity, and fast TPS requirements. For applications that need higher transparency, are expected to have a higher risk of being targeted by cyberattacks (current gas stock monitoring, auditing of reconciliation and optionally for employee hiring and working performance applications), or that require high scalability (gas asset life-cycle management), a consortium blockchain was preferred, with authorized organizations taking part in validation of new blocks, providing a higher level of security, trust, scalability, and transparency.

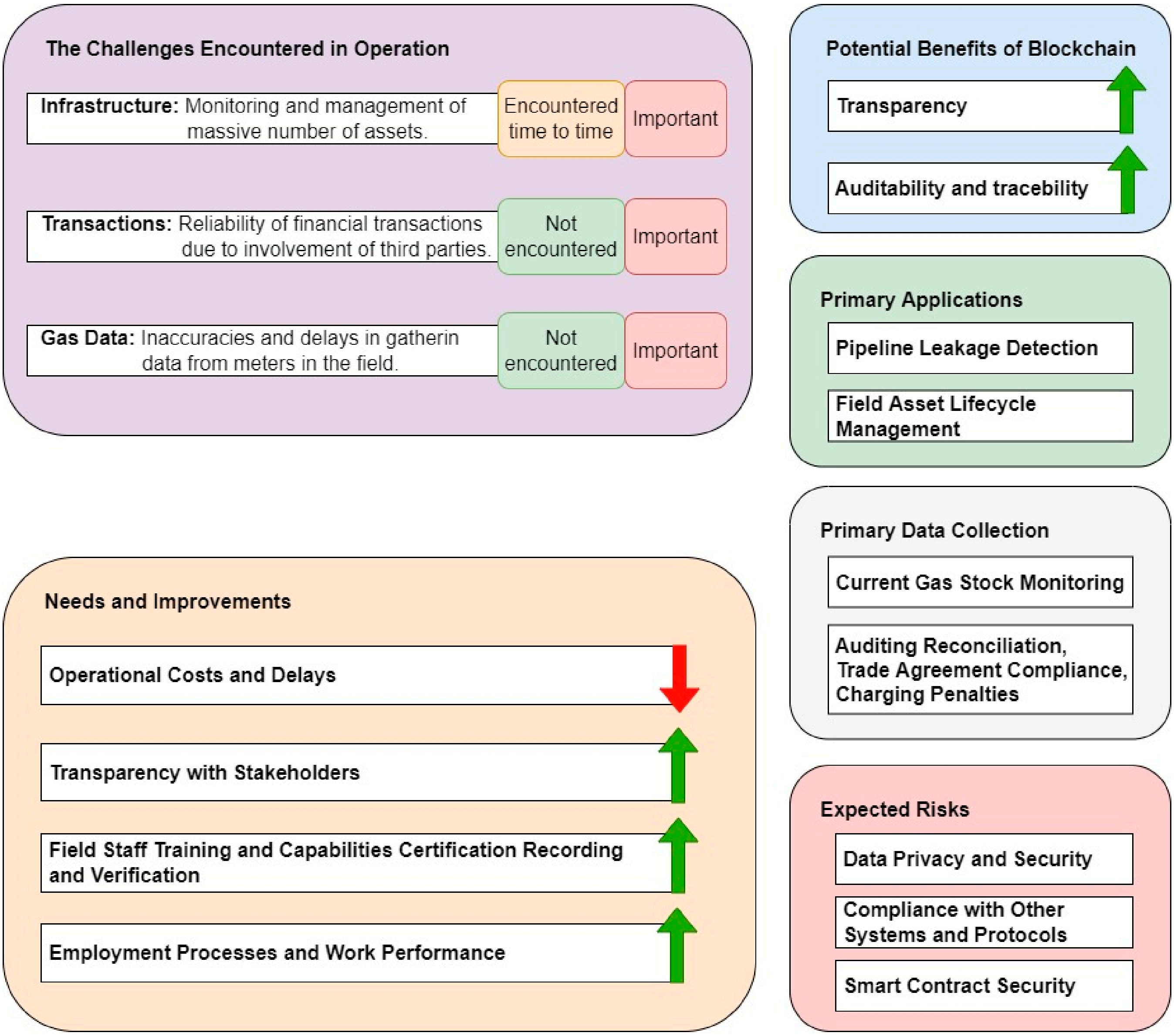

Figure 5. The summary of the prominent findings of the first stage interviews with the company executives, where red arrow represents the need for reduction and green arrow represents the need for improvement.

In none of the applications was PoW considered to be suitable, due to high energy consumption and costs. PoS and DPoS was preferred for applications requiring higher security (current gas stock monitoring, auditing of reconciliation and optionally for employee hiring and working performance applications) and moderate TPS (field technical staff certification and employee hiring and working performance), while PoET, PBFT, and PoA were preferred for the other four applications requiring a high transaction speed.

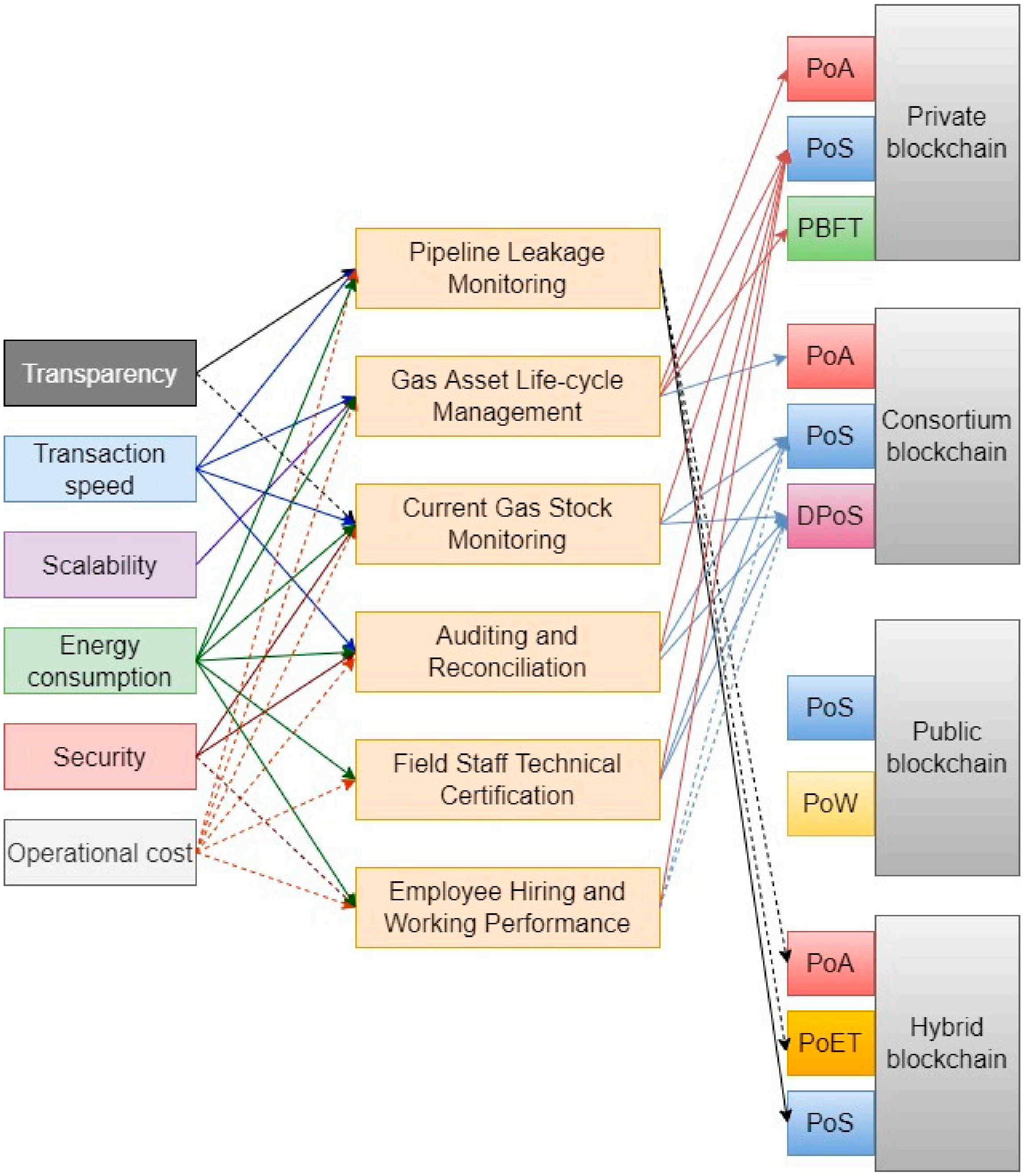

Figure 6. Summary of the findings of the second stage interview with use case-specific applications.

5. Discussion and Limitations

This study showed that the primary areas of implementation of blockchain in the natural gas industry, from the perspective of the industrial experts, are considerably different compared to the past related conceptual studies available in the literature. Contrary to the literature expectations about a wide deployment of blockchain for fostering investments in gas exploration and enhancing billing and payment, the company executives gave a much higher priority to pipeline leakage monitoring. Moreover, two areas of use, field staff technical certification and employee hiring and working performance, which were briefly mentioned as potential areas in the past conceptual studies, were found among the prominent application areas for the company in this case study. Another important finding is that the industry experts gave more importance to transparency, traceability, and auditability, compared to enhancing transaction speed, stakeholder integration, and supply chain processes automation. The study shows the value of conducting detailed case studies involving industrial experts and stakeholders to highlight unique priorities and expectations regarding industry- and company-specific challenges and opportunities.

This study focused on a single large enterprise, to highlight the primary potential use cases of blockchain and determine the most suitable blockchain solutions. This was the method adopted in several other studies in the literature, to conduct detailed studies and determine tailored solutions based on the challenges and priorities of a single company. The primary use cases may differ from company to company, and it would be useful to follow an approach similar to the one presented in this study when working with different natural gas companies. Moreover, sector-wide general suitable areas of blockchain adoption might be highlighted if several industry players were included in future case studies.

The interviews were conducted with 11 executives from the company. Further interviews with team managers and field staff might highlight some distinct challenges and different potential areas of use. Alternatively to conducting interviews, in case of extensive IoT sensor and meter availability and historical meter recording access, data analytics could be implemented to highlight the challenges and determine potential areas of use. Such data are currently not widely available, but it could become easier to access this in the near future, with increasing digitalization efforts.

This study covered a three month period, in the first quarter of 2022. In time, based on the sectoral trends, or based on experiences of pilot applications, the executives' views may change and the primary areas of use of blockchain from their perspective may differ. The methodology described in this paper could be periodically repeated, to obtain up-to-date views and determine appropriate solutions about blockchain adoption in SOCAR operations.

This study considers some of the most commonly used consensus algorithms. However, there are many other consensus protocols, and new approaches will emerge in time. Different algorithms can offer unique advantages specific to an application area, and any potentially suitable algorithm can also be included in such decision making processes.

6. Conclusions

This study represents one of the first detailed case studies on blockchain applications in the natural gas industry. A two-stage semi-structured interview was conducted to identify the primary areas of use and operational expectations and to determine tailored blockchain solutions specific to each application area. The case study with SOCAR executives highlighted the six primary application areas of blockchain for the operations of the company. Pipeline network monitoring, gas asset life-cycle management, and field technical staff certification were prioritized over billing, shipment tracking, and other potential applications mentioned in the literature. Higher transparency, improved audibility, and traceability were stated as the most important benefits of blockchain from the perspective of the interviewed executives. Based on the expectations and requirements, predominantly private blockchain (especially for field technical staff certification, employee hiring, and working performance), optionally and contextually consortium blockchain (particularly for current gas stock monitoring, auditing of reconciliation, gas asset life-cycle management), and rarely hybrid blockchain (pipeline leakage monitoring) seemed to be suitable. Public blockchains and PoW are not likely to be suitable for any of the six identified primary areas of application; while PoS and DPoS could be used for applications that have a higher risk of being targeted by cyberattacks, and PoET, PBFT, and PoA could be used in applications requiring high TPS.

This study provided valuable insights into SOCAR's potential areas of use of blockchain and the suitable solutions that could address the challenges and requirements of specific application areas. The methodology developed in this study could be used in future case studies in the natural gas industry or similar sectors, and the findings of this study could be useful for similar organizations. Future works could focus on conducting detailed case studies in other promising sectors for blockchain applications and pilot demonstrations of the tailored applications for the gas industry use cases in the field. It would also be valuable to explore the unique advantages of the emerging consensus mechanisms, as a result of modified work-based (such as Proof of Meaningful Work, Proof of Edit Distance and other), stake-based (Leasing PoS, Variable Delayed PoS and other), burn-based (Proof of Processed Payments, Proof of Disintegration), capacity/space-based (Proof of History, Proof of Research, Proof of Reputation, Proof of Zero, Proof of Value, Proof of Quality, Proof of Presence and other), BFT-based (Federated Byzantine Agreement, Ouroboros, and others), and directed acyclic graph-based (Hashgraph, Block-Lattice-Directed Acyclic Graphs) consensus mechanisms or their hybrid versions (Proof of Activity, High Interest Proof of Stake and other). Layer 2 blockchain applications could also be considered in future research and implementation efforts, to overcome potential scaling issues.

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